A SYSTEMS ANALYSIS OF A REGENERATIVE

CABIN ATMOSPHERE CONTROL SYSTEM

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## LIST OF SYMBOLS

| | |
|---|---|
| B | space cabin atmosphere total pressure |
| G | gain of forward elements in system |
| H | gain of feedback elements in system |
| $K_A$ | bypass damper "A" control parameter |
| $K_B$ | bypass damper "B" control parameter |
| $K_d$ | bypass damper "A" gain |
| $K'_d$ | bypass damper "B" gain |
| $K_f$ | cabin air blower gain |
| $K_k$ | $CO_2$ concentrator efficiency constant |
| $K_l$ | cabin air leakage constant |
| $K_m$ | $N_2$ makeup controller gain |
| $K_r$ | $CO_2$ reduction unit efficiency constant |
| $K_s$ | cabin air water separator efficiency |
| $K'_s$ | reduction unit water separator efficiency |
| $K_u$ | partial pressure sensor constant, $K_u = \frac{R_u T_c}{V_c}$ |
| $K_w$ | electrolysis water control gain |
| m | molal humidity of cabin air water separator discharge air |
| N | gram moles of cabin atmosphere constituent |
| $N_i$ | gram moles of ith cabin atmosphere constituent |
| $N_T$ | total gram moles of cabin atmosphere constituents |
| N' | gram moles of cabin atmosphere constituent in accumulator |
| P | partial pressure of cabin atmosphere constituent |
| $P_i$ | partial pressure of ith cabin atmosphere constituent |

| | |
|---|---|
| $P_V$ | nominal cabin air saturated vapor pressure |
| $P_V'$ | saturated vapor pressure of cabin air water separator discharge air |
| R | cabin atmosphere control loop reference |
| $R_L$ | cabin atmosphere control loop reference metabolic load |
| $R_L'$ | cabin atmosphere control loop reference venting load |
| $R_u$ | universal gas constant |
| s | complex variable, $s = \sigma + i\omega$ |
| $T_c$ | nominal absolute temperature of cabin atmosphere |
| $T_C$ | $CO_2$ concentrator transport lag |
| $T_D$ | cabin air duct transport lag |
| $T_E$ | water electrolysis unit transport lag |
| $T_R$ | $CO_2$ reduction unit transport lag |
| $V_c$ | cabin atmosphere volume |
| X | mole fraction of cabin atmosphere constituent |
| $X_i$ | mole fraction of ith cabin atmosphere constituent |
| $x_{C1}$ | total crew $CO_2$ output |
| $x_{C2}$ | mass flow leakage of $CO_2$ from space cabin |
| $x_{C3}$ | mass flow of $CO_2$ from blower discharge |
| $x_{C4}$ | mass flow of $CO_2$ returned to space cabin from regenerative components |
| $x_{C6}$ | mass flow of $CO_2$ into bypass damper "A" |
| $x_{C7}$ | mass flow of $CO_2$ into bypass damper "B" |
| $x_{C8}$ | mass flow of $CO_2$ into $CO_2$ concentrator |
| $x_{C9}$ | mass flow of $CO_2$ into $CO_2$ reduction unit |
| $x_{H1}$ | mass flow of $H_2$ from water electrolysis unit to $CO_2$ reduction unit |

| | |
|---|---|
| $x_{N1}$ | mass flow of $N_2$ from makeup regulator to cabin atmosphere |
| $x_{N2}$ | mass flow leakage of $N_2$ from space cabin |
| $x_{O1}$ | total crew $O_2$ uptake |
| $x_{O2}$ | mass flow of $O_2$ from water electrolysis unit to cabin atmosphere |
| $x_{O3}$ | mass flow leakage of $O_2$ from space cabin |
| $x_{W1}$ | total crew output of gaseous $H_2O$ |
| $x_{W2}$ | mass flow leakage of $H_2O$ from space cabin |
| $x_{W3}$ | mass flow of $H_2O$ from blower discharge |
| $x_{W4}$ | mass flow of $H_2O$ returned to space cabin from regenerative components |
| $x_{W5}$ | mass flow of $H_2O$ into bypass damper "A" |
| $x_{W6}$ | mass flow of $H_2O$ into cabin air water separator |
| $x_{W7}$ | mass flow of $H_2O$ from cabin air water separator to $H_2O$ accumulator |
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| $x_{W10}$ | mass flow of $H_2O$ from $CO_2$ reduction unit to $H_2O$ accumulator |
| $x_{W11}$ | mass flow of $H_2O$ into water electrolysis unit |
| $x'_{C3}$ | $CO_2$ leakage rate during air lock venting |
| $x'_{N2}$ | $N_2$ leakage rate during air lock venting |
| $x'_{O3}$ | $O_2$ leakage rate during air lock venting |
| $x'_{W2}$ | $H_2O$ leakage rate during air lock venting |
| $\tau_c$ | $CO_2$ concentrator equivalent time constant |
| $\tau_d$ | cabin air duct equivalent time constant |
| $\tau_e$ | water electrolysis unit equivalent time constant |

$\tau_m$ chamber mixing time constant

$\tau_p$ total sensing time constant, $\tau_p = \tau_m + \tau_s$

$\tau_s$ partial pressure sensor time constant

Subscripts

First letter:

C cabin atmosphere constituent, $CO_2$

N cabin atmosphere constituent, $N_2$

O cabin atmosphere constituent, $O_2$

W cabin atmosphere constituent, $H_2O$

Second letter:

O initial condition for analog computer

## ABSTRACT

The purpose of this thesis was to perform a systems analysis of a regenerative cabin atmosphere control system of the type suitable for earth-orbiting manned missions up to 1 year in length. A typical atmospheric control system was selected based on recent studies of the most suitable components which were currently available. An extensive review of the literature indicated that very few pertinent references were available on the subject of the closed-loop response of atmospheric control systems for life support. A dynamic nonlinear model of the cabin atmosphere control system was developed and this was simplified to a small-excursion linear model for purposes of applying classic stability criteria. The nonlinear model was programed on an electronic analog computer and sample cases were run at various conditions. The study demonstrated that the cabin atmosphere control system model was basically stable but that recovery from large transients was marginal due to component limiting.

## CHAPTER I

## INTRODUCTION

In his natural surroundings on the surface of the earth, man lives in a vast ecological system or habitable environment which furnishes the sustenance for life and recycles the resulting waste products for future use.

Manned missions into space require artificial life support systems to supply man's needs for food, water, a controlled atmosphere, and for waste management. On the current short-range space missions, these needs are met by carrying sufficient stores of food, water, and oxygen to fulfill the requirements of the mission. Gaseous waste products are absorbed from the atmosphere by chemical means and liquid and solid waste products are collected and stored for disposal on earth.

As mission length is extended beyond a few weeks, the concept of expendable stores results in prohibitive weight requirements for any practical space system, since each crew member requires an average of 0.848 kg (1.87 lb) of oxygen and 3.502 kg (7.72 lb) of water each day. Thus, for long-term space missions, it will be necessary to provide space travelers with an artificial ecology to regenerate their own waste products.

Various degrees of regeneration are possible but studies indicate that the most profitable areas for conservation of weight are: first, in water reclamation; second, in oxygen reclamation. If regeneration of waste products into food is also included, a totally closed life support system is possible. However, such a system is not required for space missions of less than 1 year in duration, so most research effort has been on regenerative life support systems which provide only water reclamation and oxygen reclamation.

Several experimental ground facilities have been developed to evaluate regenerative life support systems for manned space flight. The Integrated Life Support System (ILSS) at Langley Research Center is typical of the best space chambers presently available for research in manned life support tests (Ref. 1). This facility was designed to be self-sufficient with a four-man crew for a 90-day test period, and includes systems for thermal control, atmospheric control, water management, waste management, food management, and personal hygiene.

The most critical of these systems from the viewpoint of life support is the atmospheric control system, which is the subject of this study. Crew safety demands that this closed-loop system continually maintain the proper atmospheric balance in the space cabin by supplying oxygen and by removing the metabolic waste products of carbon dioxide, water vapor, and assorted contaminant gases. Figure 1 shows the relationship of the atmospheric control system to the overall life support system.

The cabin atmosphere with its constituents of oxygen, nitrogen, carbon dioxide, and water vapor is the controlled variable in the system. This controlled atmosphere is disturbed by the oxygen uptake and the gaseous products output of the variable human load. The metabolic gaseous products are removed when the cabin air is circulated through

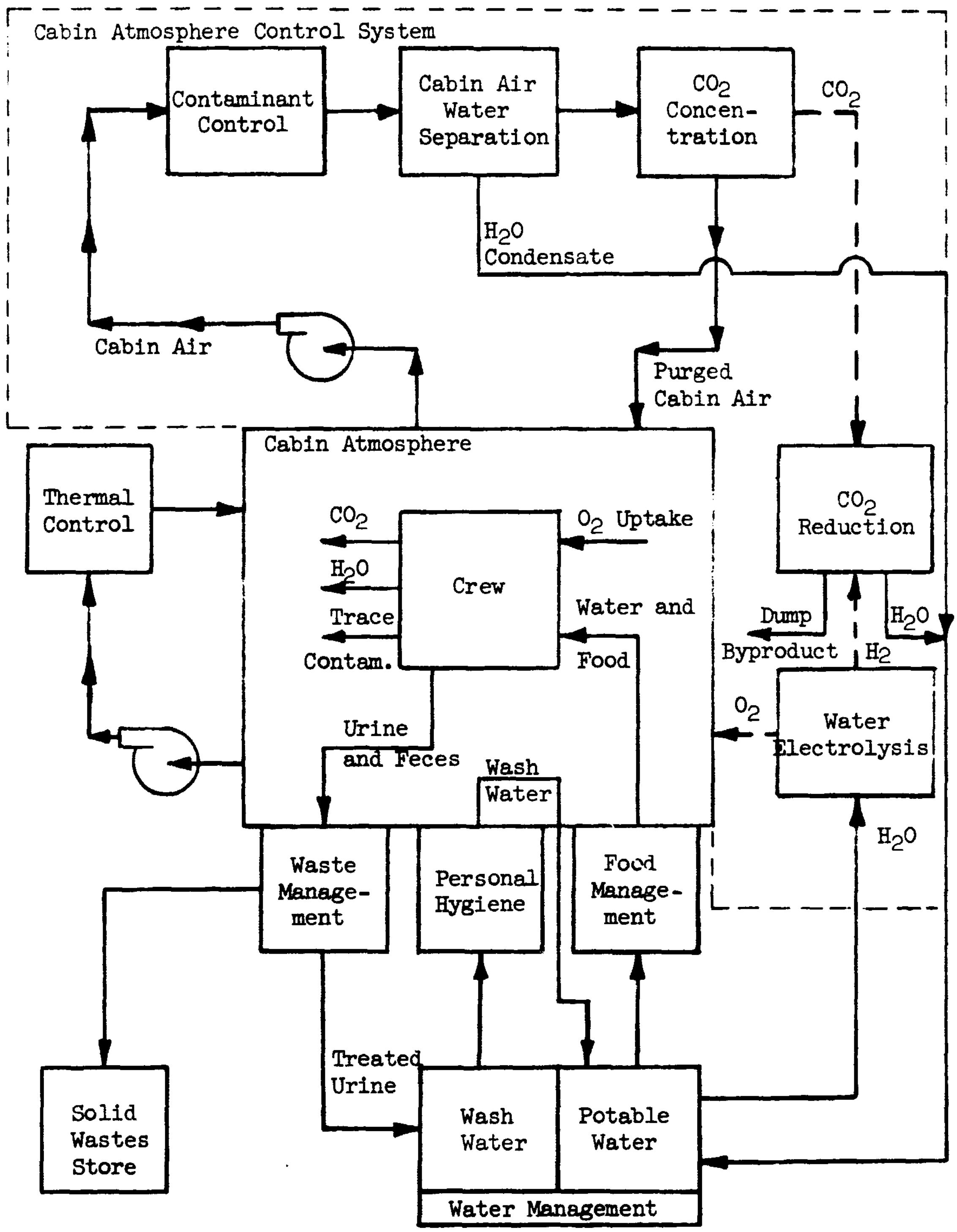



Figure 1.- Life Support System Orientation.

the atmospheric control loop containing the contaminant control unit, the water separator, and the carbon dioxide concentrator. The separated water is treated in the potable water side of the water management system, and a portion is transferred to the electrolysis unit where it is electrolyzed into oxygen for the space cabin and into hydrogen. Carbon dioxide from the $CO_2$ concentrator is reduced with hydrogen into water for the potable water supply and into carbon by-products which are discarded.

Extensive work has been done since 1960 to develop components suitable for use in the regenerative cabin atmosphere control system. Several of the more promising components have been included in the Langley ILSS. Since this prototype system was designed for laboratory test work, it provides a minimal automatic control capability. Fully automatic atmospheric control systems, with manual overrides, will be required for use on an actual space mission. However, there has been no rigorous analysis of the automatic control problems associated with space operation of the regenerative atmospheric control system.

The objective of this research was to perform a detailed systems analysis of the regenerative cabin atmosphere control system for manned spacecraft. The goal of the study was to significantly advance the state of knowledge on the dynamic characteristics of a system which includes man as a part of the active load. A further objective of the research was to provide a better understanding of the dynamic performance of the various system components.

Research to date has emphasized the steady-state operation of the various life support systems as might be expected in the initial test phase of any device. However, the dynamic aspects of the system operation are equally important and must be well understood before any life support system can be considered acceptable for manned use.

The space cabin for any long-range manned mission is expected to be reasonably spacious, with approximately 28 cubic meters allotted to each occupant. This large atmospheric volume serves as the "reservoir" from which the space passenger withdraws his oxygen supply on demand. Since the cabin atmosphere volume is relatively large, the change in cabin atmosphere constituents will normally occur at a slow rate. The dynamic load on the cabin atmosphere control system would thus appear to be minimal, and this is true for normal operation. But the system must also satisfy any extreme demands which are placed on it. Recent experiences with manned tests have demonstrated that life support systems should have the capability to meet a variety of off-nominal conditions, including cabin fires, depressurization, and component shutdown or failure. Frequently these conditions occur so quickly that automatic control systems offer the only possibility for recovery.

A further requirement for automatic control of the cabin atmosphere arises from known shortcomings of man as a primary control element in the space environment. Manned tests have demonstrated that space travelers may be subjected to psychological factors which could compromise rational judgment. In addition, variations in the cabin atmosphere, such as an excess of carbon dioxide or a shortage of oxygen (hypoxia), may result in unsuspected loss of judgment by the sub, ct which could be fatal in the space environment.

Some consideration of the dynamic requirements of cabin atmosphere control systems has been given in various prior studies, however, no rigorous systems analysis was found in a rather extensive survey of the open literature. A simple closed-loop analysis was performed in connection with the design of the Langley ILSS (Ref. 2), however, lack of component performance data at the time of the study and many simplifying assumptions seriously limit the value of that study.

Operation of the ILSS subsequent to the design study phase has produced some component performance data which can be used to define the operation of typical components. While the ILSS is in many respects typical of the present state of art in life support systems, it was not the intention to limit this study to a particular system. Rather a general life support system model was developed which could be typical for a variety of space missions. The desire for a meaningful analysis of the regenerative cabin atmosphere control system required that specific parameters be chosen for the model, but the analysis could easily be adapted to a system with slightly different parameters.

The regenerative cabin atmosphere control system is nonlinear in nature due to component saturation effects and cross coupling between the various loops. However, the system model was found to be basically linear for small excursions about a nominal operating point. The assumption of system linearity resulted in a reasonable model and facilitated the preliminary analysis of the system.

Subsequent machine analysis on the analog computer permitted the consideration of nonlinear effects and also provided the means for studying the on-off control modes. While the analog study of the system was not exhaustive, sufficient machine runs were made to establish the basic characteristics of the regenerative cabin atmosphere control system.

In the body of this thesis, Chapter II is concerned with development of the regenerative cabin atmosphere control system model. A description and analysis of the various system components is found in Chapter III. Chapter IV is concerned with the development of a detailed system block diagram and with a mathematical description of the dynamic relationships. Chapter V summarizes the automated system analysis and discusses the results of the various analog computer runs. Chapter VI provides a review of the most important references which have been included and concluding comments are presented in Chapter VII.

## CHAPTER II

## SPACE CABIN MODEL

This chapter defines the assumed space cabin model, the crew model, and the cabin atmosphere. The major components of the regenerative cabin atmosphere control system are specified and the steady-state materials balance is defined.

### Space Cabin Characteristics

The configuration of a space cabin is determined largely by the required space mission. Many different manned space missions have been contemplated, but this study will consider only the mission model defined by a recent NASA sponsored program to investigate manned earth-orbiting space flights of an extended time period (Ref. 1). Important characteristics of the assumed mission and of the space cabin are defined in Table I.

The specified total cabin volume represents an unloaded condition; the addition of equipment and expendable stores results in the reduced volume specified as cabin atmosphere volume. The cabin atmosphere volume includes the laboratory volume and the smaller air lock volume, which is assumed to be vented to space each time the air lock is opened to permit egress to the outside. The air lock chamber is returned to cabin conditions by venting air from the laboratory volume.

Various schemes to conserve the cabin air in the air lock chamber are possible, but the air lock venting cycle is retained in this study

TABLE I.- SPACE MISSION AND SPACE CABIN CHARACTERISTICS

| | |
|---|---|
| Mission Type | Manned earth-orbiting scientific satellite |
| Mission Duration | One year with resupply at 90-day intervals |
| Orbital Elements | Zero eccentricity; 250 nautical mile altitude |
| Vehicle Attitude | Controlled attitude; no rotation (Zero-g condition) |
| Space Cabin Volumes | |
| Total Cabin Volume | 117.528 $m^3$ (4150 $ft^3$) |
| Cabin Atmosphere Volume | 101.952 $m^3$ (3600 $ft^3$) |
| Laboratory Volume | 99.120 $m^3$ (3500 $ft^3$) |
| Air Lock Volume | 2.832 $m^3$ (100 $ft^3$) |
| Air Lock Operation | 5 cycles/90 days |
| Air Lock Venting Rate | 87 gm/min (0.192 lb/min) |
| Air Lock Venting Cycle | 24 min |
| Space Cabin Leakage Rates | |
| Minimum | 454 gm/day (1.0 lb/day) |
| Nominal | 1362 gm/day (3.0 lb/day) |

since it represents a typical load on the atmospheric control system. For example, the air lock venting cycle may be considered typical of the cabin depressurization which might occur as the result of micrometeorite penetration of the space cabin wall. The other space cabin leakage rates specified represent an estimate of normal leakage which will occur in space due to imperfect sealing and diffusion through the cabin walls.

## Crew Model

The basic purpose of the cabin atmosphere control system is to maintain a long-term habitable environment in the space cabin. The crew produces the most significant load on the cabin atmosphere control system by absorbing oxygen and by generating carbon dioxide, water vapor, and assorted contaminants in the cabin. The total metabolic production of the crew is determined by crew size and the level of activity. The assumed mission required a crew of four men; however, the space cabin must accommodate a total of six men during resupply operations.

Crew activity is defined with respect to nominal metabolic criteria, which are shown in Table II as a function of Basal Metabolic Rate (BMR). Consideration of the total life support system would require a complete definition of the crew metabolic balance, including all solid, liquid, and gaseous inputs and outputs and the heat output of the crew. Since this study is limited to the cabin atmosphere control system, the only concern is with the gaseous inputs and outputs of the crew. The most basic metabolic factor is the oxygen uptake, or rate at which $O_2$ is actually extracted from the atmosphere. The $CO_2$ output is determined from this, based on an assumed Respiratory Quotient of 0.90. The $H_2O$

TABLE II.- CREW MODEL

| | |
|---|---|
| Crew Size | Normal - 4 men<br>Resupply - 6 men for 4 hours |
| Metabolic Criteria (100% BMR) | |
| Oxygen Uptake | 0.7371 moles/man-hr* (0.0520 lb/man-hr) |
| Carbon Dioxide Output | 0.6634 moles/man-hr (0.0644 lb/man-hr) |
| Water Evaporation (Respiration and perspiration) | 4.1327 moles/man-hr (0.1640 lb/man-hr) |
| Respiratory Quotient (R.Q.) (R.Q. = $CO_2$ output/$O_2$ uptake) | 0.90 |

| Crew Condition | $O_2$ Uptake | $CO_2$ Output | $H_2O$ Output |
|---|---|---|---|
| | moles/hr (lb/hr) | moles/hr (lb/hr) | moles/hr (lb/hr) |
| No. 1 - Minimum Activity<br>4 men at 90% BMR | 2.6536<br>(0.1872) | 2.3882<br>(0.2318) | 14.8777<br>(0.5904) |
| No. 2 - Normal Activity<br>4 men at 150% BMR | 4.4226<br>(0.3120) | 3.9804<br>(0.3864) | 24.7962<br>(0.9840) |
| No. 3 - Resupply Mode<br>6 men at 150% BMR | 6.6339<br>(0.4680) | 5.9706<br>(0.5796) | 37.1943<br>(1.4760) |
| No. 4 - Emergency Schedule<br>4 men at 450% BMR | 13.2678<br>(0.9360) | 11.9412<br>(1.1592) | 74.3886<br>(2.9520) |

*Note: The term "moles" refers to gram-moles.

output includes the total gaseous production, including both respiration and perspiration.

The crew also generates other gaseous products such as hydrogen and methane in small amounts. In addition, other contaminants may occasionally be introduced into the cabin atmosphere from sources within the space cabin. All of these trace contaminants are removed from the cabin atmosphere by special filters or by a catalytic burner contained in the contaminant control unit. Since the quantities involved are so slight, the operation of the contaminant control unit generally has a negligible effect on the cabin atmosphere control system, and will not be considered in this study.

Four crew conditions are defined, ranging from the minimum activity associated with sleep to the maximum activity which could occur during a short emergency situation. The total range of activity represents a variation in the crew metabolic load of 5:1. The condition described as "Normal Activity" represents a nominal average for daily activity. The cabin atmosphere control system will be evaluated partly on response to changes in these various crew conditions.

## Cabin Atmosphere

Extensive studies have been performed to determine the most desirable atmosphere for a space cabin (Ref. 3). Long-term space missions, where a "shirt-sleeve" environment is desired, favor the use of a two-gas atmosphere which simulates the atmosphere on earth. However, a total cabin pressure less than sea level ambient pressure is desired to minimize structural requirements of the space cabin. This is accomplished by reducing the partial pressure of nitrogen in the cabin while the partial pressure of oxygen is maintained at sea level conditions. The nominal cabin atmosphere specified in Table III has a total pressure of 517 mm/Hg (10 psia) with an $O_2$ partial pressure of 160 mm/Hg.

While the oxygen-nitrogen combination is a nominal two-gas atmosphere, there are two other important constituents in the cabin atmosphere: carbon dioxide and water vapor. The concentration of both these gases must also be controlled to maintain a habitable atmosphere. The need for control of all the cabin atmosphere constituents is apparent from consideration of the "off-limit effects" defined in Table III. The partial pressures of oxygen, carbon dioxide, and water vapor must be controlled for physiological and equipment reasons.

At the nominal cabin total pressure of 517 mm/Hg, hypoxia effects would be noted at $O_2$ partial pressures below about 120 mm/Hg. On the high side, oxygen toxicity effects could occur at $O_2$ partial pressures above 270 mm/Hg.

Physiological effects due to $CO_2$ are more difficult to define since the onset of symptoms are dependent on time of exposure and concentration. For long-term exposure, physiological strain is usually noted at $CO_2$ partial pressures above about 8 mm/Hg; pathological changes occur above 20 mm/Hg. The absence of $CO_2$ in the atmosphere can cause hypocapnia effects but such a situation is unlikely to occur in a space cabin.

TABLE III.- CABIN ATMOSPHERE SPECIFICATION

| Parameters | | Maximum | Nominal | Minimum | Off-Limit Effects |
|---|---|---|---|---|---|
| Cabin Total Pressure (mm Hg) | | 775 (15 psia) | 517 (10 psia) | 300 | High: Cabin Structural Limit<br>Low: Increased $O_2$ Concentration |
| $O_2$ Partial Pressure (mm Hg) | | 180 | 160 | 140 | High: $O_2$ Toxicity Effects<br>Low: Hypoxia Effects |
| $N_2$ Partial Pressure (mm Hg) | | --- | 342 | --- | Diluent gas |
| $CO_2$ Partial Pressure (mm Hg) | | 8 | 4 | 0 | High: Physiological Strain and Hyper-capnia Effects<br>Low: Hypocapnia Effects |
| $H_2O$ Partial Pressure (mm Hg) | | 19 | 11 | 9 | High: Equipment Degradation<br>Low: Discomfort |
| Relative Humidity (%) | | 90 | 50 | 40 | |
| Cabin Temperature | ($^oK$) | 299.8 | 296.5 | 293.1 | |
| | ($^oF$) | 80 | 74 | 68 | |
| Moles of $O_2$ | ($N_O$) | | 881.568 | | |
| Mole fraction | ($X_O$) | | 0.309477 | | |
| Moles of $N_2$ | ($N_N$) | | 1884.352 | | |
| Mole fraction | ($X_N$) | | 0.661507 | | |
| Moles of $CO_2$ | ($N_C$) | | 22.039 | | |
| Mole fraction | ($X_C$) | | 0.007738 | | |
| Moles of $H_2O$ | ($N_W$) | | 60.608 | | |
| Mole fraction | ($X_W$) | | 0.021278 | | |
| Total Moles | ($N_T$) | | 2848.567 | | |

Also shown is the desired range of values for $H_2O$ partial pressure, and the corresponding values for relative humidity at the nominal cabin temperature. The relative humidity of the space cabin is defined as the ratio of the actual water vapor pressure to the pressure of saturated vapor at the prevailing dry bulb temperature. At the nominal cabin temperature of 296.5° K (74° F), $P_V$ = 21.4945 mm Hg. If the relative humidity of the cabin atmosphere exceeds 90 percent, equipment degradation could occur due to moisture condensation. Values of relative humidity below 40 percent for long periods of time could result in crew discomfort.

Table III shows the operating range of cabin temperature, which is separately regulated by the thermal control subsystem. Since the allowable temperature variation is only about ±1 percent, a constant cabin temperature has been assumed for the cabin atmosphere control system study. There is, of course, a definite relationship between the thermal and atmospheric control systems which results in certain constraints on the operation of the atmospheric control system. These constraints relate to the thermal integration of the total system, and were not considered in this study.

Also shown in Table III are the total number of moles of each constituent in the space cabin at the nominal condition. These were calculated from the standard gas equation since, at the low pressures of the space cabin, the constituent gases behave virtually as perfect gases. In subsequent calculations, it is necessary to know the number of moles of each constituent gas in the space cabin corresponding to a measured partial pressure. The equation of state for an ideal gas was used to perform the computation:

$$N_i = \frac{P_i \cdot V_c}{R_u \cdot T_c} \tag{1}$$

Table III also specifies the nominal mole fractions for the cabin atmosphere. The mole fraction for a given constituent is determined by the following equation:

$$X_i = \frac{N_i}{\Sigma N_i} = \frac{N_i}{N_T} \tag{2}$$

Cabin Atmosphere Control System

The cabin atmosphere control system, with all major components, is shown on Figure 2. A detailed description of each component will be included in Chapter III, but it is necessary to define the overall system requirements so that component requirements can be determined. In steady-state operation, the cabin atmosphere control system must maintain a balance of all constituents in the cabin atmosphere; that is, the mass of each constituent in the cabin must be held nearly constant to maintain a habitable environment.

The average daily mass flows in the cabin atmosphere resulting from metabolic loads are shown on Figure 2. The average daily mass flows required to maintain the balance of materials in the cabin atmosphere are 106.14 moles/day of $O_2$ into the cabin and 95.53 moles/day of $CO_2$ and 595.11 moles/day of $H_2O$ out of the cabin. To maintain the system

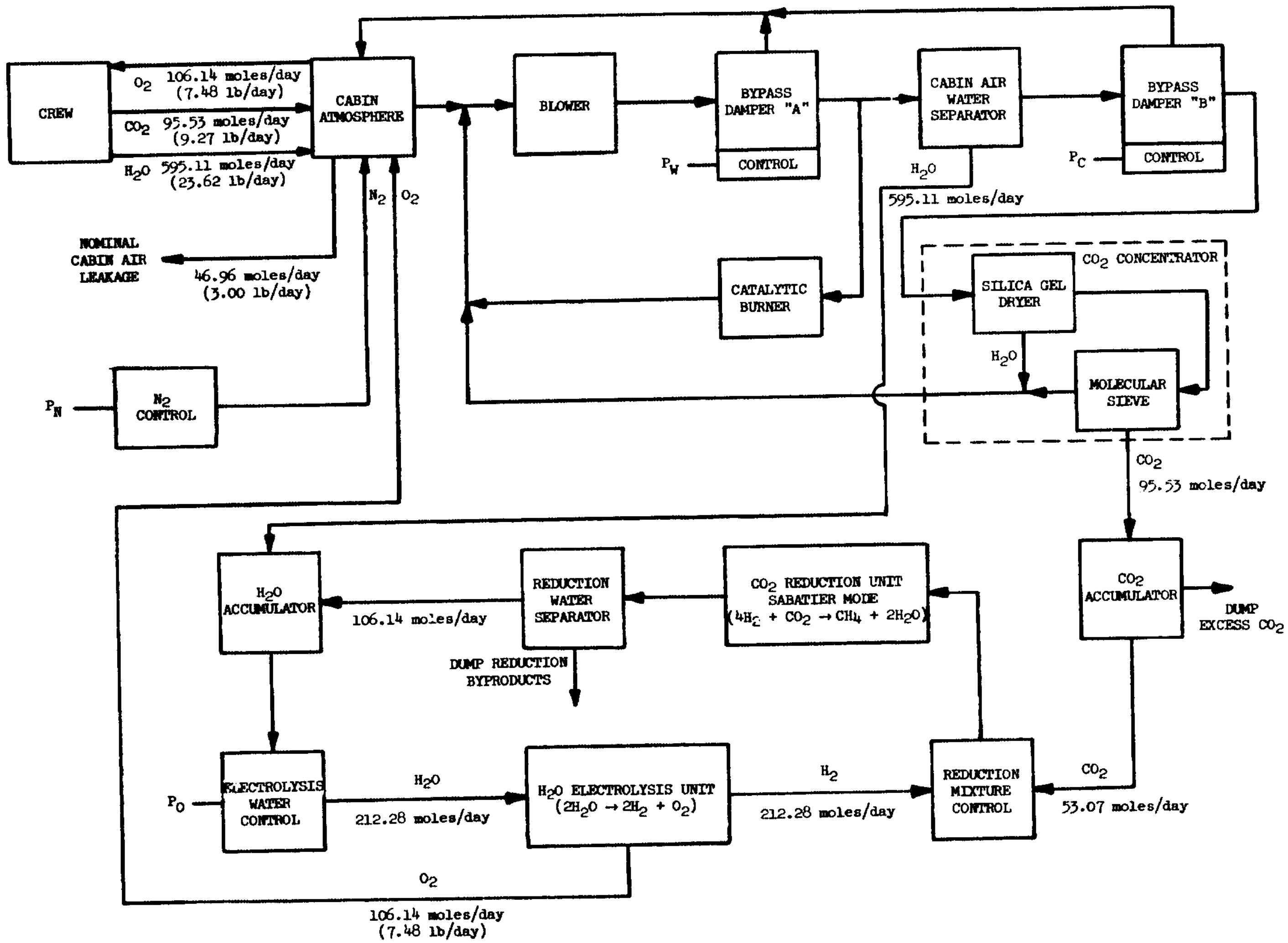



Figure 2.- Cabin atmosphere control system.

materials balance, the daily $CO_2$ removal rate from the $CO_2$ concentrator and the daily $H_2O$ removal rate from the cabin air water separator must also be 95.53 moles/day and 595.11 moles/day, respectively.

The electrolysis unit produces two moles of $H_2$ for each mole of $O_2$; thus 212.28 moles/day of $H_2$ are available for $CO_2$ reduction. If $CO_2$ reduction utilizes the Sabatier process, an excess of $CO_2$ will be available in the system and must eventually be dumped; the reduction byproduct of methane is also dumped. The apparent excess of $H_2O$ in the cabin atmosphere control system is used to help satisfy the crew potable water requirement, which is not shown.

The simplest approach to control of the cabin atmosphere would involve continuous, steady-state operation of the various system components at a rate compatible with the average daily mass flows of the system. This type of open-loop control has been used in ground-based life support systems such as the ILSS, but is unsuitable for flight systems for the reasons discussed in Chapter II.

This study considered closed-loop control systems which continually monitor the controlled variables and which automatically adjust the performance of the cabin atmosphere control system accordingly. The controlled variables used as control parameters in the system are $P_N$ for control of $N_2$ makeup; $P_O$ for control of oxygen production by the electrolysis unit; $P_W$ for control of bypass damper "A," which limits cabin airflow to the cabin air water separator; and $P_C$ for control of bypass damper "B," which limits cabin airflow through the $CO_2$ concentrator.

## CHAPTER III

## COMPONENT DESCRIPTION

Description of individual components in the atmospheric control system is contained in Chapter III. The description includes both a physical description and a mathematical description of each component's dynamic response. The components described here are typical for the type of system being considered and in many cases are similar to the components used in the Langley ILSS (Ref. 6).

### Space Cabin, Blower, and Ducting

The space cabin is the container and mixing chamber for the space cabin atmosphere constituents. The blower and ducting perform the vital functions of transporting cabin air through the regenerative components of the atmospheric control system and of maintaining air circulation within the cabin.

Since the cabin atmosphere constituents are nearly perfect gases and are mutually unreactive, each gas can be considered separately. The mass balance of each gas in the cabin atmosphere is represented by the following equations:

$$\frac{dN_N}{dt} = x_{N1} - x_{N2} \qquad (3a)$$

$$\frac{dN_C}{dt} = x_{C1} + x_{C4} - x_{C3} - x_{C2} \qquad (3b)$$

$$\frac{dN_W}{dt} = x_{W1} + x_{W4} - x_{W2} - x_{W3} \qquad (3c)$$

$$\frac{dN_O}{dt} = x_{O2} - x_{O1} - x_{O3} \qquad (3d)$$

Mixing of the constituents within the space cabin is accomplished chiefly by forced air circulation since normal convection currents are absent in the zero-g environment. The mixing process is aided by diffusion of the constituents from areas of concentration but this effect cannot provide the primary mixing. Adequate air movement in the cabin is also necessary for thermal control because excess heat must be removed from the various components by convection.

The mixing process is very complicated but is represented in this study by a simple time constant. The chamber mixing time constant is related to the rate at which cabin air is exchanged in the space cabin. Two blowers are used in the space cabin; one of these circulates cabin air through the thermal control system and the other circulates cabin air through the cabin atmosphere control system. These blowers have approximately equal flow capacity and both assist in mixing the cabin air.

A study of ventilation requirements in support of the ILSS program indicated that each blower should have the capacity to completely exchange the air in the space cabin about once each 15 minutes (Ref. 1). Using this criterion for the present space cabin model, and assuming that the blowers will operate on a continuous basis and under relatively constant conditions, the blowers can be dynamically represented by the constant gain term, $K_f = 3.34 \frac{\text{moles}}{\text{sec}}$.

With both blowers operating, the cabin air should be completely circulated about once each 6 to 7 minutes, since regenerated air is returned to the cabin through a system of inlet ducts and ventilators designed to provide continuous mixing and stirring of the cabin atmosphere. For the purpose of this study, the chamber mixing time constant will be based on the cabin air exchange rate; thus, $\tau_m = 360$ sec. Since this time constant relates to obtaining a representative sample of cabin air, it is lumped with the sensor time constant in this study.

Cabin air is removed from the space cabin by a system of exhaust ducts located such that a representative sample of cabin air is continually withdrawn for transport to the regenerative components of the system. Special exhaust ducts are also used in conjunction with the waste management system to minimize the dispersal of trace contaminants into the cabin atmosphere. Duct dynamics result in pure transport lags in the system due to the finite times required for gas movement through the ducts, through the regenerative cabin atmosphere control system, and back to the space cabin.

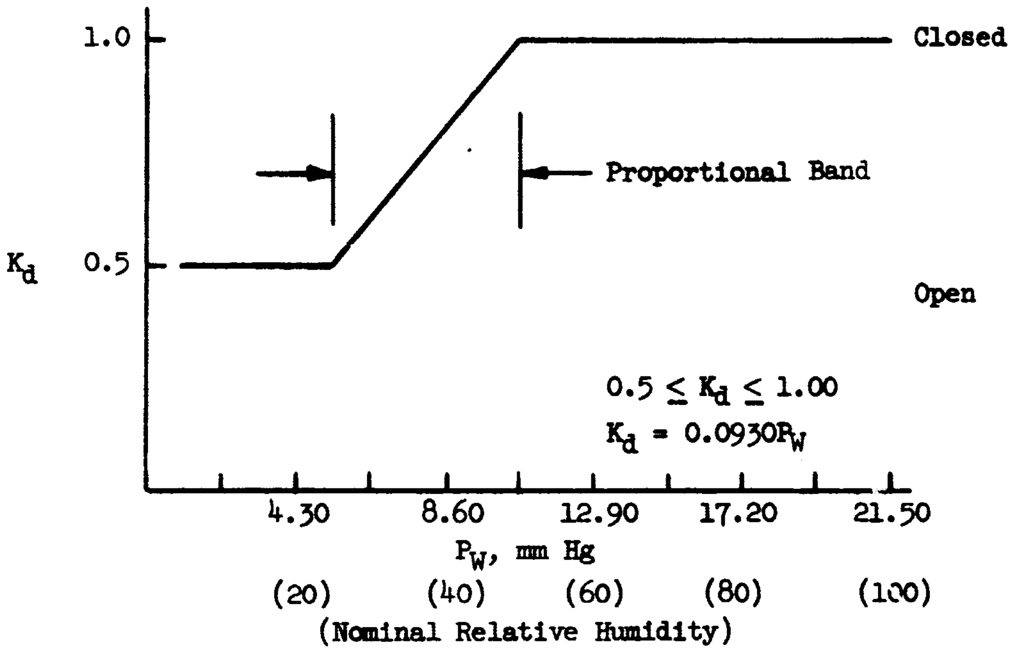
No data were available on the actual time required to transport cabin air around the cabin atmosphere control loop, however, several factors are pertinent to the consideration. The physical size of the space cabin dictates that certain ventilation ducts may be 5 to 10 meters in length. Also, crew comfort requires that air duct velocities be as low as possible to minimize duct noise and that air velocity over the crew be limited to approximately 3.0 meters/min. Based on these factors, the duct transport lag is conservatively estimated to be, $T_d = 360$ sec.

## Bypass Damper "A"

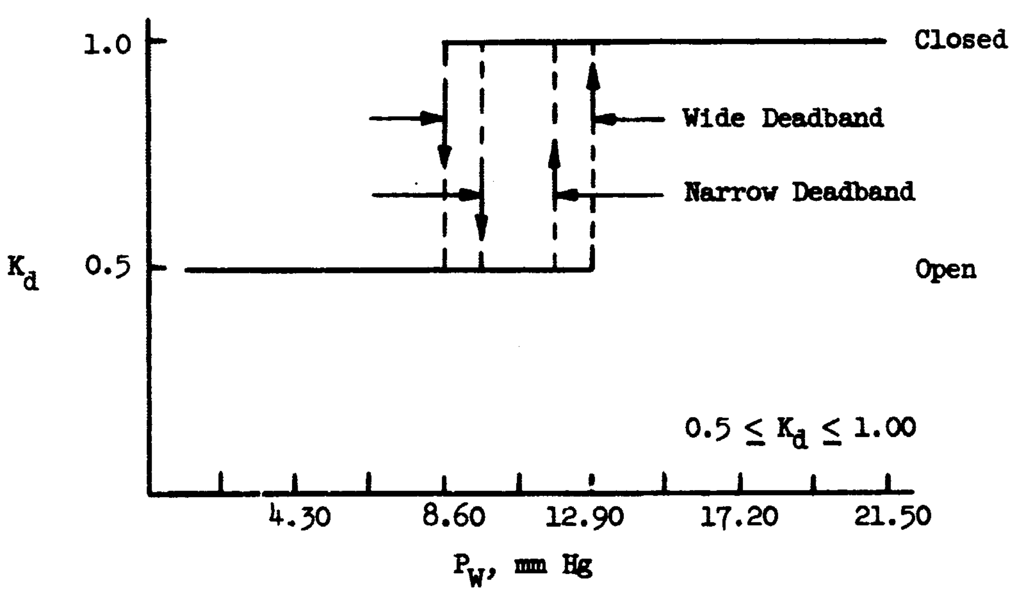
Bypass damper "A" provides a gross control of water vapor removal from the cabin atmosphere in the event that the nominal relative humidity approaches the lower limit of 40 percent. Such a control element was not used in the ILSS and water vapor removal was implicit in the removal of $CO_2$ from the cabin atmosphere. Bypass damper "A" was included in this study to provide active control of the partial pressure of water vapor since it is recognized as a distinct and independent constituent of the cabin atmosphere.

Under normal conditions, bypass damper "A" will be closed. If $P_W$ should drop below a specified value, the damper will start to open and allow blower discharge air to return directly to the space cabin without passing through the water separator. However, bypass damper "A" will never allow more than 50 percent of the blower discharge to return to the cabin without further regenerative treatment. This limit precludes the possibility of a rapid buildup of $CO_2$ in the atmosphere which could result if bypass damper "A" should "fail" in the open direction.

Two types of control are possible for bypass damper "A": proportional control with limits and on-off control. Figure 3 shows the two types of control with values of damper gain, $K_d$, plotted against the partial pressure of water vapor, $P_W$. In the proportional mode, bypass damper "A" starts to open in the decreasing direction when $P_W = 10.75$ mm/Hg, or a nominal relative humidity of 50 percent. The value of $K_d$ decreases linearly in proportion to $P_W$ until the limit of $K_d = 0.50$ is reached




(a) Proportional mode




(b) On-off control mode

Figure 3.- Bypass damper "A" control modes.

at $P_W$ = 5.375 mm/Hg. The entire range of proportional operation is termed the "proportional band."

On-off control operation is the simplest to mechanize since only two valve positions are required. Bypass damper "A" remains closed until $P_W$ falls to a value of 8.60 mm Hg (40 percent R.H.), at which point the valve will open. The damper then remains open until $P_W$ reaches a value of 12.90 mm Hg (60 percent R.H.). The resultant hysteresis loop is represented on Figure 3 as the "wide deadband."

Also shown on Figure 3 are limits for "narrow deadband" operation in the on-off control mode, wherein bypass damper "A" would close at a nominal relative humidity of 55 percent and open at a relavite humidity of 45 percent. The narrow deadband mode was evaluated to determine the effect of on-off deadband width on system performance.

## Cabin Air Water Separator

The cabin air water separator removes water from the cabin air by first condensing the water vapor in a heat exchanger and then separating the water droplets from the airstream by means of sintered metal plates. The saturated airstream is passed through a series of baffles in the water separator and the resultant centrifugal forces cause the water droplets to impinge on the sintered metal plates; capillary action forces the water through the plates and into the separator pump inlet while the cabin air is excluded.

The efficiency of the water separator is determined by the temperature of the heat exchanger and by the efficiency of water separation from the airstream. The heat exchanger will reduce the temperature of the airstream to a dewpoint of 277.6° K (40° F), and air leaving the heat exchanger will be a mixture of water droplets and saturated air. The molal humidity of the heat exchanger discharge air is calculated from equation (4):

$$m = \frac{P_V'}{B - P_V'} \tag{4}$$

At the nominal temperature of 277.6° K (40° F), $P_V' = 6.2908$ mm/Hg and $B = 517$ mm/Hg, so $m = 0.0123$. This represents the water vapor in the cabin air which is not condensed in the heat exchanger.

Since the water vapor mole fraction of the cabin air ($X_W$) is known, then the percent of water vapor condensed by the heat exchanger is:

$$\text{Percent water vapor condensed} = \frac{X_W - 0.0123}{X_W} \tag{5}$$

The water separator efficiency defines the fraction of condensed water vapor which is actually separated from the airstream. Data from Reference 1 indicate that the cabin air water separator efficiency ($K_s$) may be about 33 percent, so the total percent of water vapor removed from the airstream is:

$$\text{Percent water vapor removed} = K_s \frac{(X_W - 0.0123)}{X_W} = \frac{0.33(X_W - 0.0123)}{X_W} \tag{6}$$

The total percent of water vapor passed is:

$$\text{Percent water vapor passed} = 1 - \frac{0.33(X_W - 0.0123)}{X_W} \qquad (7)$$

The actual mass of water removed and passed is determined by multiplying equations (6) and (7), respectively, by the mass flow of water vapor through the water separator. The cabin air water separator also has a characteristic transport lag, since finite times are required for the passage of cabin air and separated water through the unit. Based on the cabin air mass flow rates and the physical size of the unit, the time delay to cabin air passing through the unit is negligible so no transport lag is required at that point. The time delay to separated water is larger, since the separated water must pass through the sintered metal plates and be transported to the water management system. But this transport lag has a negligible effect on the overall system performance, since the water output of the cabin air water separator is sent to the water accumulator of the water management system. For that reason, the water separator transport lag is not included in the system model.

## Bypass Damper "B"

The second bypass damper provides a control over the carbon dioxide removal rate by returning a large fraction of the dehumidified air from the water separator to the space cabin without passing through the $CO_2$ concentrator. This is possible since the actual $CO_2$ mass removal rate is much less than the $H_2O$ mass removal rate, in proportion to the difference in metabolic generation rates.

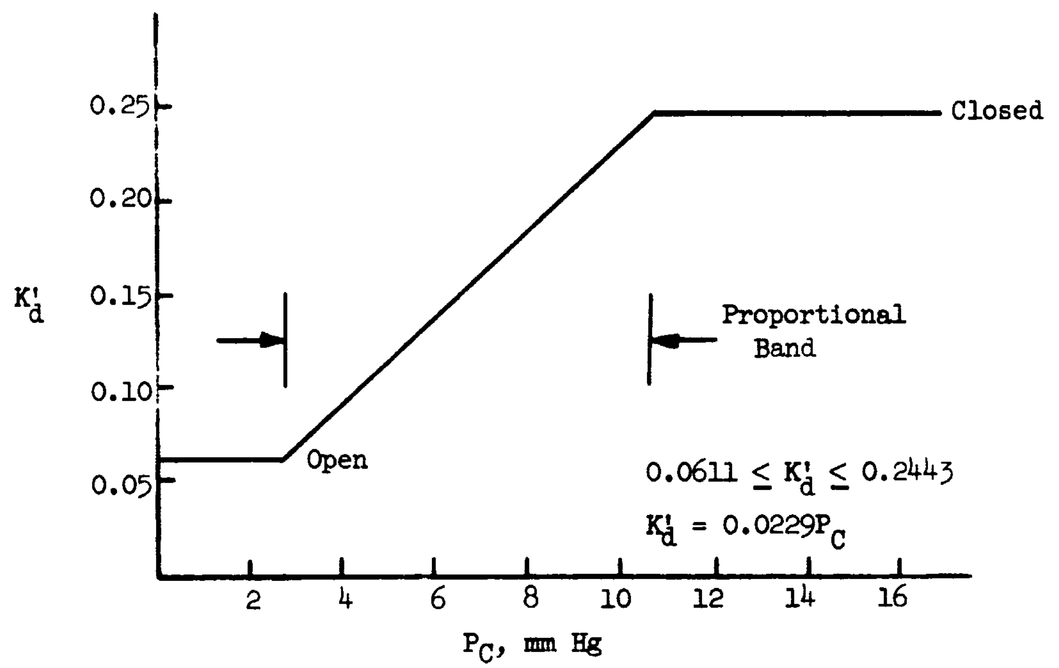
The bypass damper regulates the flow of cabin air to the $CO_2$ concentrator as a function of $P_C$ and within the operating range established for the $CO_2$ concentrator. The goal is to keep the airflow to the $CO_2$ concentrator at a minimum consistent with the need for $CO_2$ removal and thus minimize the thermal loads on the $CO_2$ concentrator heat exchangers.

As with bypass damper "A", both proportional and on-off control modes could be considered for bypass damper "B"; these are shown on Figure 4. The proportional bandwidth extends from $P_C$ = 2.67 mm Hg to $P_C$ = 10.67 mm Hg. Operation in the proportional mode will result in control of $CO_2$ to values of $P_C$ less than 8 mm Hg for all normal conditions, and, in addition, provides an "overload" capacity for emergency conditions.

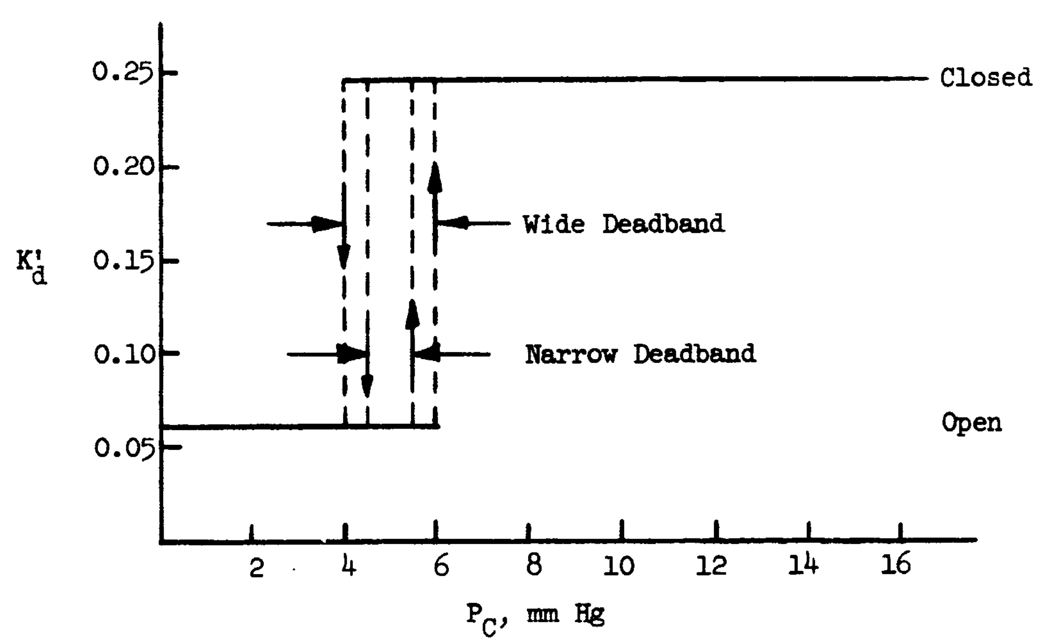
The on-off band extends from $P_C$ = 4 mm Hg to $P_C$ = 6 mm Hg, thus offering the possibility of closer regulation of $CO_2$ content in the cabin atmosphere, but with the penalty of the on-off operation. Figure 4 also shows a narrow deadband loop which extends from 4.5 to 5.5 mm Hg of $P_C$.

## $CO_2$ Concentrator

The $CO_2$ concentrator removes $CO_2$ from the cabin airstream by means of adsorption on a molecular sieve. The molecular sieve material contains a large number of molecule size voids, providing a large surface area to which the $CO_2$ molecules adhere without any chemical reaction. The adsorption load capacity of a given volume of molecular sieve is a function of pore size, bed temperature, and the partial pressure of $CO_2$ (Ref. 4). The rate of adsorption for a given concentrator is a function




(a) Proportional mode




(b) On-off control mode

Figure 4.- Bypass damper "B" control modes

of gas flow rate and concentration, physical size, and time (Ref. 5).

Desorption of $CO_2$ is accomplished by increasing the temperature of the molecular sieve material and by imposing a vacuum on the concentrator. The "batch" nature of the process is readily apparent: the $CO_2$ laden cabin airstream is cooled and allowed to flow through the concentrator until the molecular sieve becomes partially saturated; then the inlet flow is shut off and a combination of heat and vacuum is applied to the concentrator discharge until desorption is accomplished.

Since the molecular sieve will selectively adsorb water vapor, the inlet airstream to the concentrator must be predried to a dewpoint of less than 222.0° K (-60° F) or less than 50 ppm. This is accomplished by flowing the airstream through a hygroscopic material such as silica gel, which is subsequently desorbed by the cabin airstream on its return to the space cabin.

To satisfy the need for a continuous removal of $CO_2$ from the cabin airstream, the $CO_2$ concentrator utilizes two molecular sieve beds so that adsorption and desorption can be carried out simultaneously, with an arrangement similar to that shown in Figure 5. The internal operation of the $CO_2$ concentrator requires a somewhat sophisticated control system to regulate the time cycles and direct the airflows and coolant fluids to the appropriate units. However, this internal control problem has little effect on the operation of the overall system.

Typical $CO_2$ concentrators have a relatively short bed length to minimize air pressure drop but a relatively large capacity to assure

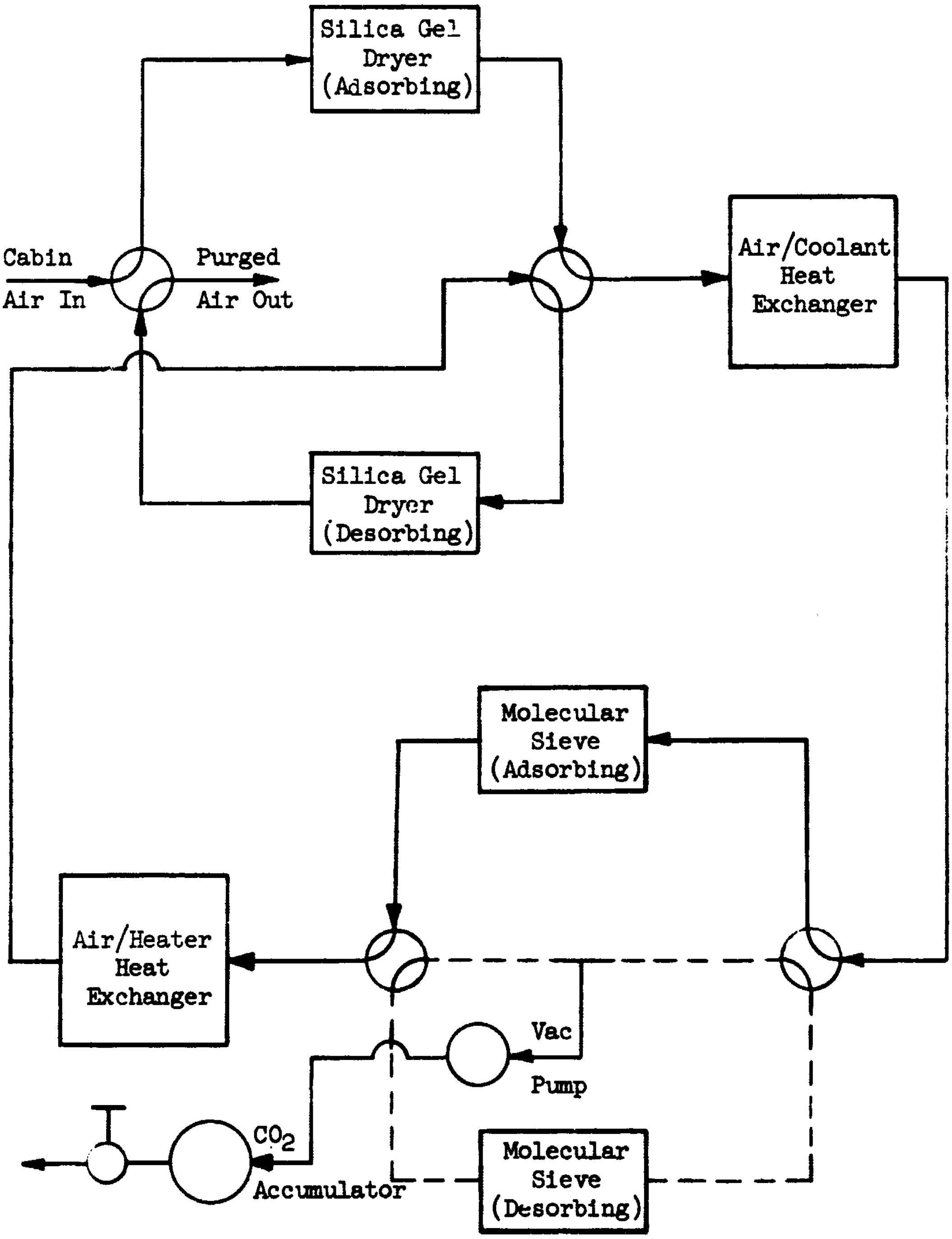



Figure 5.- $CO_2$ concentrator schematic.

that the adsorptive capacity will be adequate. Such a design results in a relatively linear adsorption rate over a wide operating range so that removal of $CO_2$ from the atmospheric control system can be considered to occur at a constant rate. Thus, for the purpose of the overall system analysis, the $CO_2$ concentrator can be represented by the concentrator constant, $K_k = 0.40$, which defines the fraction of $CO_2$ adsorbed from the airstream. The $CO_2$ concentrator has two transport lags associated with its operation. The most important of these is the time delay to the cabin airstream flowing through the unit. No data were available on the dynamics of the unit, but the concentrator transport lag ($T_C$) was estimated at 360 sec. The other transport lag occurs in the adsorption and desorption of $CO_2$ by the unit. Since the concentrator operates on a cyclic basis, there is often appreciable time delay in the passage of $CO_2$ through the unit. This delay has no effect on the system dynamics since all of the $CO_2$ is transferred to an accumulator and stored for later use.

## Accumulators

The atmospheric control system includes two gas storage accumulators; the $CO_2$ accumulator is located in proximity to the $CO_2$ reduction unit and the $H_2O$ accumulator is part of the water management system. Dynamically these are represented by a differential equation relating the inlet and outlet flows of each accumulator, as shown in equations (8) and (9):

$$\frac{dN_C'}{dt} = K_k x_{C8} - x_{C9} \qquad (8)$$

$$\frac{dN_W'}{dt} = x_{W7} + x_{W10} - x_{W11} \tag{9}$$

The effect of these accumulators is similar to that of a large capacitance in a system. The principal importance of the accumulators in this system study is to establish the range of mass flow rates and to determine if any gross material excesses or shortages exist in the system.

Note that there are no accumulators shown for hydrogen or oxygen produced in the electrolysis units as these elements are stored only in the form of water. The oxygen output of the electrolysis unit is sent directly to the cabin atmosphere; the hydrogen output is sent to the mixture control of the $CO_2$ reduction unit. While the space cabin would undoubtedly include an emergency supply of oxygen for the crew, this extra store would not normally be involved in operations of the cabin atmosphere control system and so is not represented in this study.

## $CO_2$ Reduction Unit

The purpose of the $CO_2$ reduction unit is to reduce the system byproducts of $H_2$ and $CO_2$ into water, which can be electrolyzed, and into a carbon product which can be discarded. The origin of $CO_2$ in the system is ultimately the metabolization of food. Since food is not being regenerated in the system, it is reasonable that there should be some system byproducts to discard.

Two types of physico-chemical processes have been considered for the reduction of $CO_2$. The so-called Bosch process involves the reduction of $H_2$ and $CO_2$ over a hot iron catalyst according to the net reaction:

$$2H_2 + CO_2 \rightarrow 2H_2O + C$$

The reaction is exothermic but only proceeds to about 30 percent completion at 866.5° K (1100° F). Several secondary reactions also occur such that $CH_4$ and CO are also products. The following reactions are typical (Ref. 6):

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$CO_2 + H_2 \rightarrow CO + H_2O$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

In steady-state operation, the reactions come to equilibrium and the exhaust gas contains a mixture of $CO_2$, $H_2$, CO, $CH_4$, $H_2O$, and usually $N_2$. The water vapor is separated and the reactor gas is recycled, with stoichiometric replacement of the $H_2$ and $CO_2$.

While the Bosch process provides the best material balance for the system, since only carbon is discarded, the mechanization of the Bosch process has not been successful. The relatively high temperature required by the process complicates the mechanical design and the continual deposition of the solid carbon on the catalyst poses a collection and removal problem. For these reasons, the Bosch process does not presently appear desirable for long missions where high reliability is required.

The alternate Sabatier process provides a less favorable material balance but is much easier to mechanize. The Sabatier reaction, which occurs as a side reaction in the Bosch system, is simply:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The Sabatier reaction is exothermic and greatly dependent on suitable catalysis but the reaction is approximately 95 percent complete at a reactor temperature of only 588.7° K (600° F). Again, the exhaust gases are cooled and water vapor is separated. The remaining gases, consisting of $CH_4$, unreacted $CO_2$ and $H_2$, and unseparated $H_2O$ are dumped overboard, so the process is completely continuous and no recirculation is required. When the materials balance for the overall life support system is considered, the hydrogen dumped overboard must be replaced from the water store, with some resultant weight penalty.

Dynamically, the $CO_2$ reduction unit has a transport lag representing the time delay of gases flowing through the Sabatier reactor and through the reduction water separator; and the further time delay of condensed water being transported to the water accumulator. For the purpose of this study, the $CO_2$ reduction unit is represented by the transport lag, $T_r$ = 360 sec, and by the constant efficiency factor, $K_r$ = 0.95.

## Reduction Water Separator

The water separator following the $CO_2$ reduction unit is similar to the cabin air water separator with the exception that it must be more efficient, since water which is not separated at this point will be dumped overboard. The dewpoint of the gases is reduced by a heat exchanger to a temperature of 277.6° K (40° F) with equivalent m = 0.0123. All water vapor above that value is condensed to water droplets. Since the mole fraction of water vapor in the exhaust gas is about 0.61, this means that approximately 98 percent of the water vapor is condensed from the exhaust gas stream.

Water separation is accomplished by means of baffles and sintered plates such that approximately 95 percent of the condensed water is separated at this point, or $K_s'$ 0.95. This higher efficiency is possible since the mole fraction of $H_2O$ is so much higher in the exhaust gas and air entrainment of the condensed water droplets is less of a problem.

## Electrolysis Unit

The electrolysis unit electrolyzes $H_2O$, as necessary, to maintain the partial pressure of $O_2$ in the cabin atmosphere, in accordance with the reaction:

$$2H_2O \rightarrow 2H_2 + O_2$$

The byproduct $H_2$ is used for $CO_2$ reduction. The electrolysis cells are a membrane type which separate the electrolyte from the gaseous products.

As with the $CO_2$ concentration unit, the detailed control of the electrolysis unit is very complicated, but the present study is concerned only with the overall operation of the unit in the system. The electrolysis control sets the electrical current to the cells in proportion to the sensed value of $P_O$, and makeup water is supplied as necessary. In normal operation, the electrolysis unit will operate over a range of slightly less than 4:1, as shown on Figure 6.

Both the proportional and on-off modes of control have been considered for this unit, with nominal operation based on the desired value of $P_O$ = 160 mm Hg. Four different types of on-off control were used. With the "normal" output, both wide deadband and narrow deadband control modes were compared. The MOD. 1 variation used wide deadband on-off control with a gain increase of approximately 50 percent. The MOD. 2 control increased the high gain output approximately 100 percent over the "normal" value. Both MOD. 1 and MOD. 2 represent the type of output which could be obtained if two or more electrolysis units were available to provide redundant and parallel operation in the system. The low level output would then represent the operation of one electrolysis unit and the high level outputs would require several units in parallel.

For simulation purposes, the electrolysis unit is represented by the transport lag, $T_e$ = 360 sec, where the time delay includes effects of the current controller, ion transport within the cells, and collection and transport of the product gases.

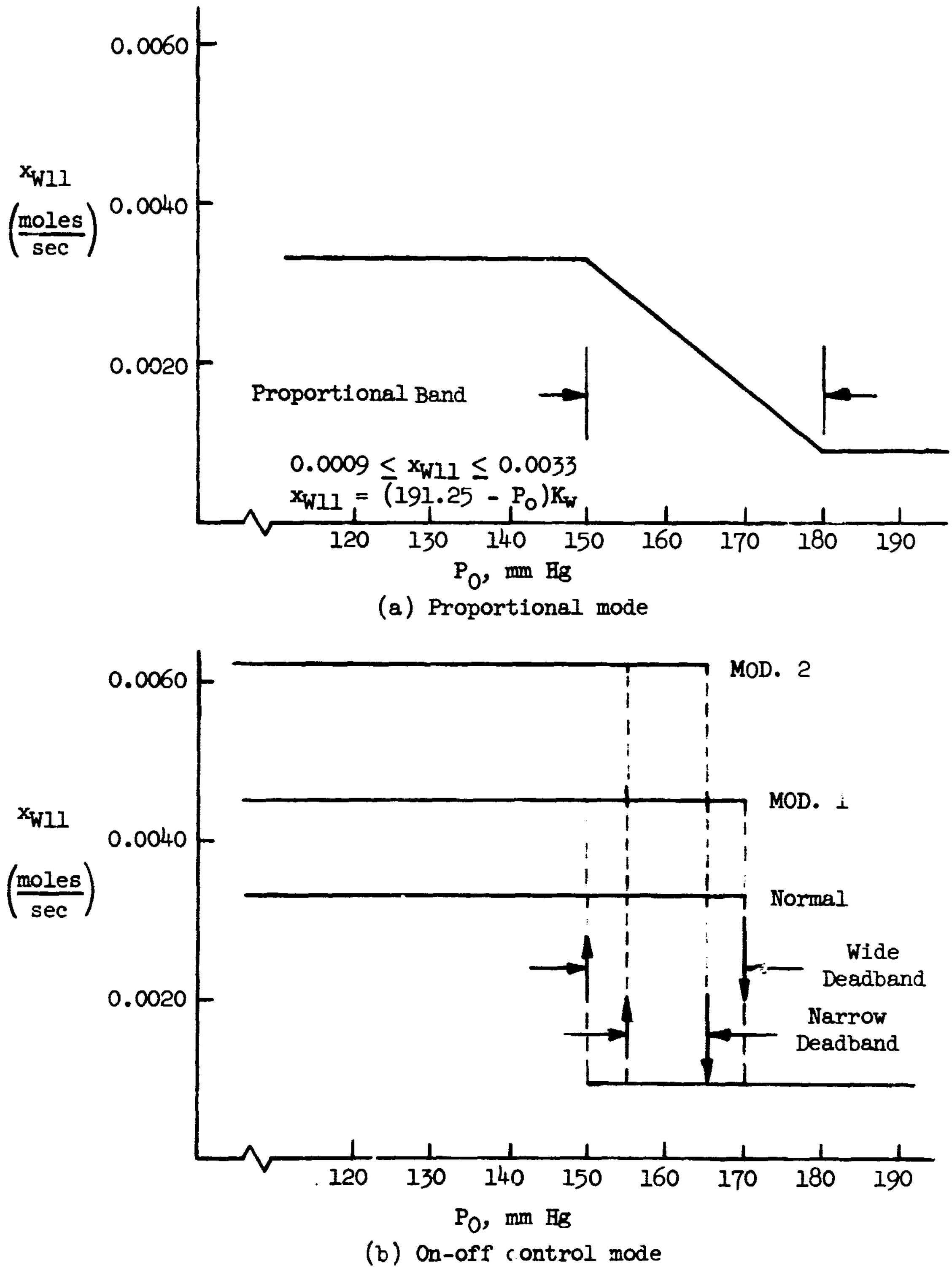



Figure 6.- Electrolysis unit control modes.

## $N_2$ Controller

The $N_2$ controller meters $N_2$ gas from storage as necessary to maintain $N_2$ partial pressure in the cabin atmosphere in accordance with the sensed value of $P_N$. Control of the makeup $N_2$ might be either proportional or on-off as shown on Figure 7. With the proportional control, $P_N$ will reach an equilibrium point on the droop curve depending on the magnitude of leakage. If on-off control is used, the value of $P_N$ will cycle from 335 to 345 mm Hg, depending upon the rate of leakage. When gross leakage occurs, as in air lock venting, the value of $P_N$ may temporarily fall below 335 mm Hg. The upper limit on $N_2$ flow is determined by the controller size, and there are no significant time delays associated with the $N_2$ controller operation.

## Pressure Sensors

To accomplish the desired control functions, it is necessary to have a continuous indication of the partial pressures $P_O$, $P_C$, $P_W$, and $P_N$. Direct reading of $P_O$ is possible by means of paramagnetic analysis of a gas sample aspirated from the cabin atmosphere. Measurement of $P_C$ and $P_W$ is possible by means of infrared analysis of a sample of the cabin atmosphere. All of these pressure indicators are continuous reading and can be represented as devices with simple time constants.

The best indication of $P_N$ is obtained by taking the difference of total pressure and the other known partial pressures. Total cabin pressure can be measured by means of a conventional strain gage pressure transducer, providing an electrical output signal which is compared with $P_O$, $P_C$, and $P_W$ to obtain the desired indication of $P_N$.

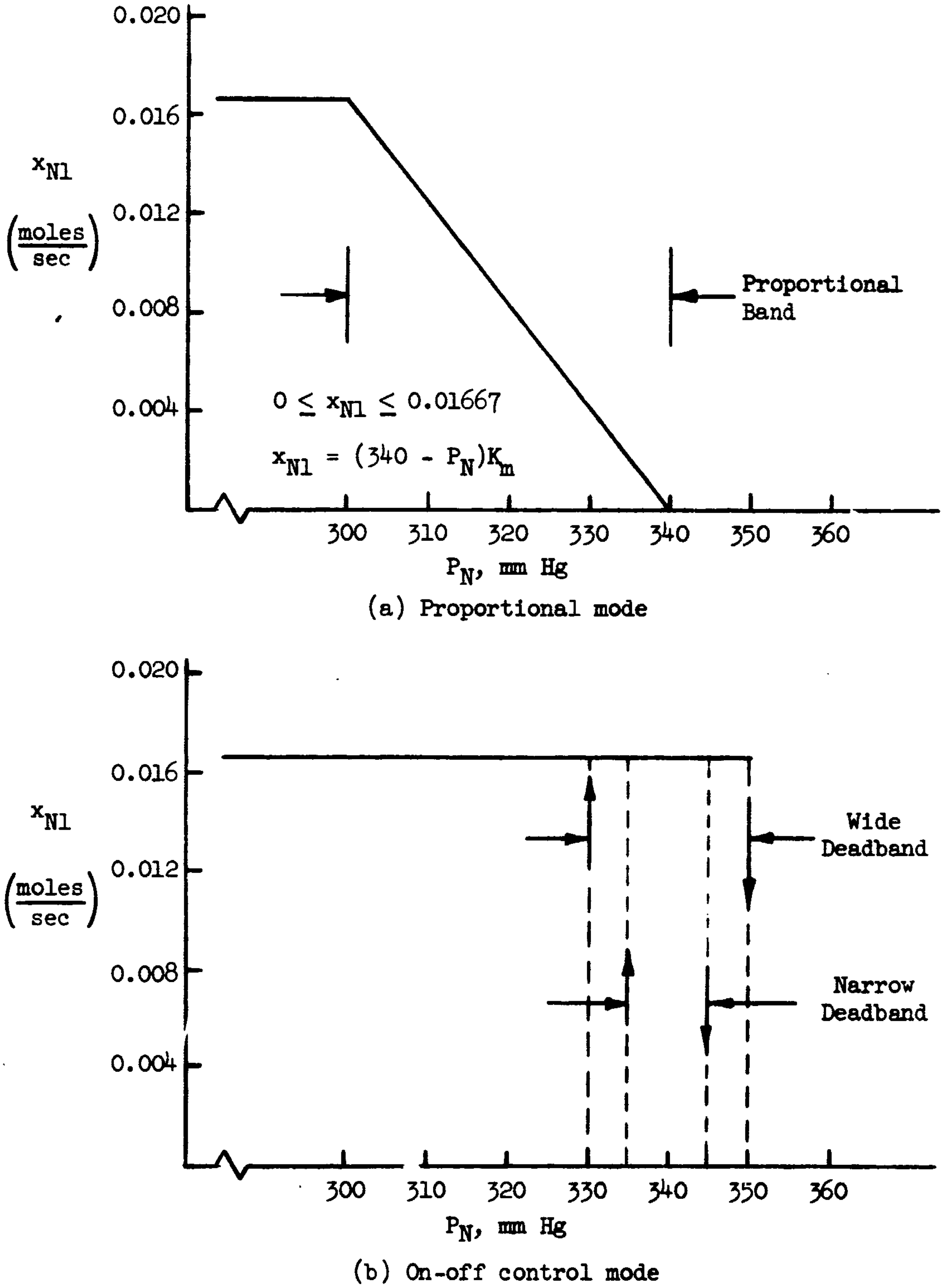



Figure 7.- Makeup $N_2$ control modes.

While the individual instruments may vary slightly in performance, the same sensor time constant has been used for all pressure sensors. Also, since the other pressure indications are used to compute $P_N$ the same time constant is applicable for determination of $P_N$. The sensor time constant has been conservatively estimated at $\tau_s = 360$ sec. The analytical computation of $P_i$ is based on the assumed time constant and on equation (1) as follows

$$\frac{dP_i}{dt} + \frac{P_i}{\tau_s} = \frac{R_u T_c N_i}{V_c \tau_s} = \frac{K_u N_i}{\tau_s} \qquad (10)$$

# CHAPTER IV

## DESCRIPTION OF SYSTEM

The detailed system block diagram is developed in this chapter including all dynamic relationships. A simplified block diagram is defined from which linear system characteristics are determined.

### System Block Diagram

The system block diagram shows all the mathematical operations which must be performed in the analysis of the proportional system. The assumption of perfect gas behavior in the cabin atmosphere and the fact that the major constituents of the cabin atmosphere are mutually unreactive, permits independent consideration of each gas in the cabin. Thus, the block diagram, Figure 8, shows separate operations being performed on $N_2$, $O_2$, $CO_2$, and $H_2O$ constituents. The separate loops are interconnected where necessary to satisfy the system equations. For example, the separate mole fractions of each constituent are based on the total number of moles of all constituents. The basic criterion for the block diagram is conservation of mass at all points.

The $N_2$ circuit has only two loops, describing the cabin leakage flow and the makeup flow. The flow of $N_2$ gas through the blower and regenerative components is not shown since this flow is not actively involved in any of the processes and since the requirement for conservation of mass is satisfied. The reference input to the $N_2$ loop in terms of partial pressure is compared with $P_N$ to determine the magnitude of

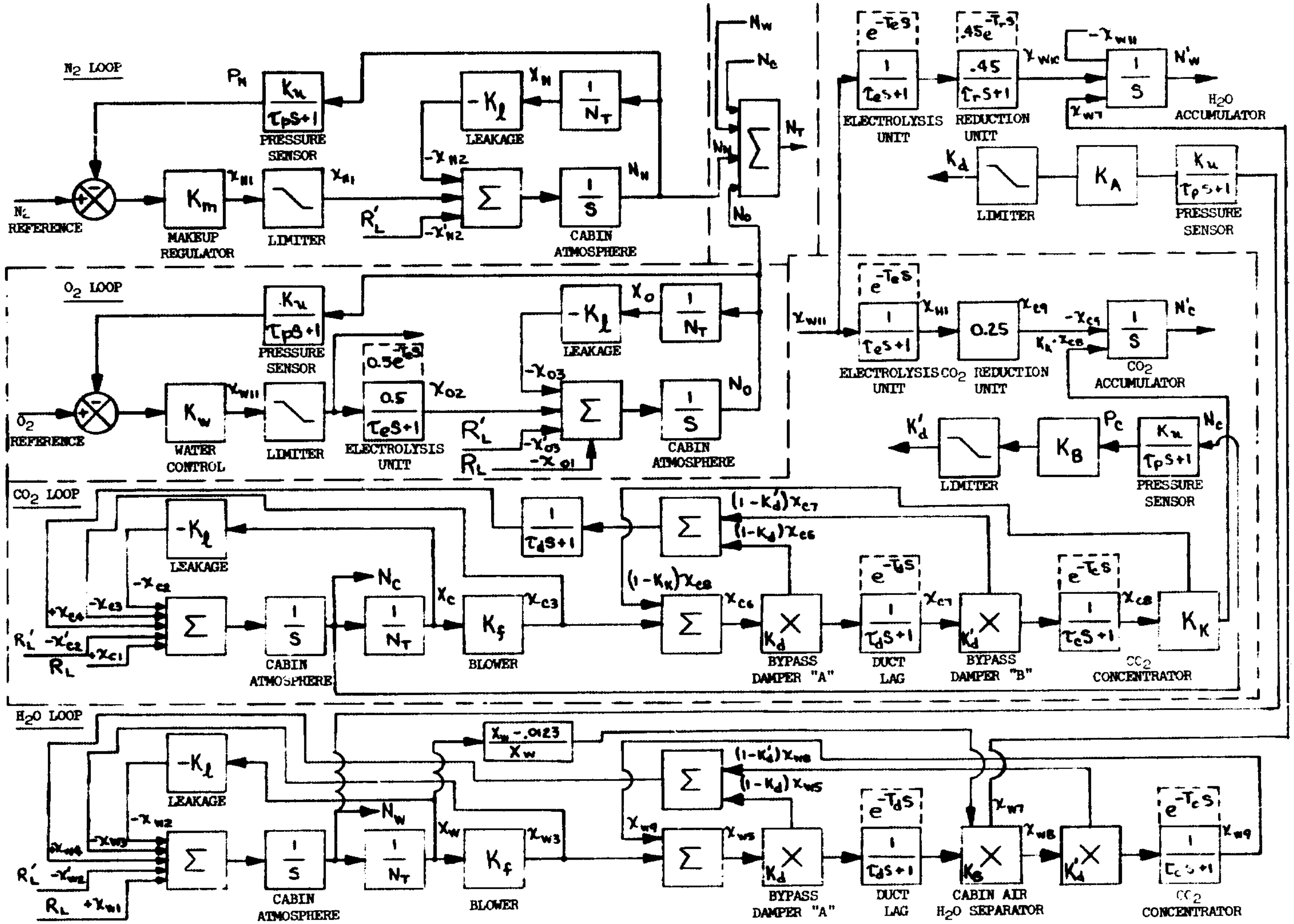



Figure 8.- System block diagram.

makeup flow. The steady $N_2$ leakage is calculated by multiplying $X_N$ by the leakage constant, $K_l$. The air lock venting leakage is shown as the reference load, $R_L'$.

The $O_2$ circuit has loops describing leakage and makeup flows and also includes the electrolysis of water. The flow of $O_2$ gas through the blower and regenerative components is not shown since this flow is not involved in any of the processes. The reference input, compared with $P_o$, determines the flow of water to the electrolysis unit and subsequent oxygen generation to maintain the desired value of $N_O$. The effect of the human load (oxygen uptake) is applied directly to the $O_2$ circuit as the reference load, $R_L$. The $O_2$ circuit includes one transport lag which represents the time delay of the electrolysis unit.

The $CO_2$ circuit includes the effects of human metabolic load, $R_L$, and cabin leakage; also $CO_2$ flow through the blower and regenerative components and the return flow which has passed through the $CO_2$ concentrator without being adsorbed. The $CO_2$ flow desorbed from the concentrator is transported to the $CO_2$ accumulator for storage.

Control of $CO_2$ removal rate is implicit in the setting of bypass damper "B," since the $CO_2$ concentrator removes a relatively constant percentage of the $CO_2$ inlet flow. The reference for the $CO_2$ circuit then is the setting of the constant, $K_B$, to determine the bypass gain, $K_d'$, as a function of $P_C$.

The mass flow of $CO_2$ to the regenerative components is the sum of normal blower discharge ($x_{C3}$) plus the $CO_2$ recycled from the $CO_2$ concentrator. This combined flow ($x_{C6}$) is passed through bypass damper "A" and immediately assessed with the duct transport lag, $T_D$. The delayed flow ($x_{C7}$) passes through bypass damper "B" where another fraction is returned to the space cabin. The remaining $CO_2$ flow enters the $CO_2$ concentrator and experiences another transport lag, $T_C$, before being divided by the $CO_2$ concentrator constant, $K_k$.

The $H_2O$ circuit also includes the human load, cabin leakage, flow through the regenerative components, and $H_2O$ flow from the cabin air water separator to the $H_2O$ accumulator. The rate of water removal from the separator is a function of the mole fraction of water vapor in the cabin and the mass flow rate through the separator. The flow rate is controlled by means of bypass damper "A" with the reference setting implicit in the gain, $K_A$, used with $P_W$ to compute $K_d$. The $H_2O$ loop is similar to the other loops with regard to the cabin atmosphere and the flow through the regenerative components. Note that the water separator has a unique "reference" input coming from the reference temperature of the water separator heat exchanger and determining the fraction of water vapor to be condensed.

The water accumulator shows the net accumulation of $H_2O$ from the water separator and from the $CO_2$ reduction unit less the water supplied to the electrolysis unit. This does not represent the water balance for the entire life support system since liquid consumption and liquid wastes generated by the crew are not included. The $H_2O$ accumulator as represented shows the mass balance for the atmospheric constituents of $H_2O$ only.

The system interrelationships between the major constituent loops are of special interest. All the loops are interconnected by the total moles computation which, of course, emphasizes that all the atmospheric constituents contribute to the total space cabin pressure. The $O_2$ loop and the $CO_2$ loop are interconnected by the electrolysis unit through the $CO_2$ reduction unit. The $CO_2$ and $H_2O$ loops have a strong interaction through the separately controlled bypass damper valves.

## Simplified Block Diagram

The cabin atmosphere control system described by the system block diagram is nonlinear due to the presence of limiting conditions (saturation) and due to some higher degree terms resulting from multiplication or division. However, for approximately steady-state operation with small departures from nominal, the nonlinear terms can be eliminated from the system, permitting the application of classical linear methods of determining the system stability.

The simplified block diagram is shown on Figure 9. Note that the simplifying assumptions eliminate all significant interaction between the major control loops; specifically, the bypass damper gains $K_d$ and $K_d'$ are assumed constant. Thus, the stability study will give an indication only of individual loop stability. Also shown on the simplified block diagram is an alternate representation of the transport lags as simple time constants. Elimination of the pure transport lags will be shown to be helpful in the analog simulation.

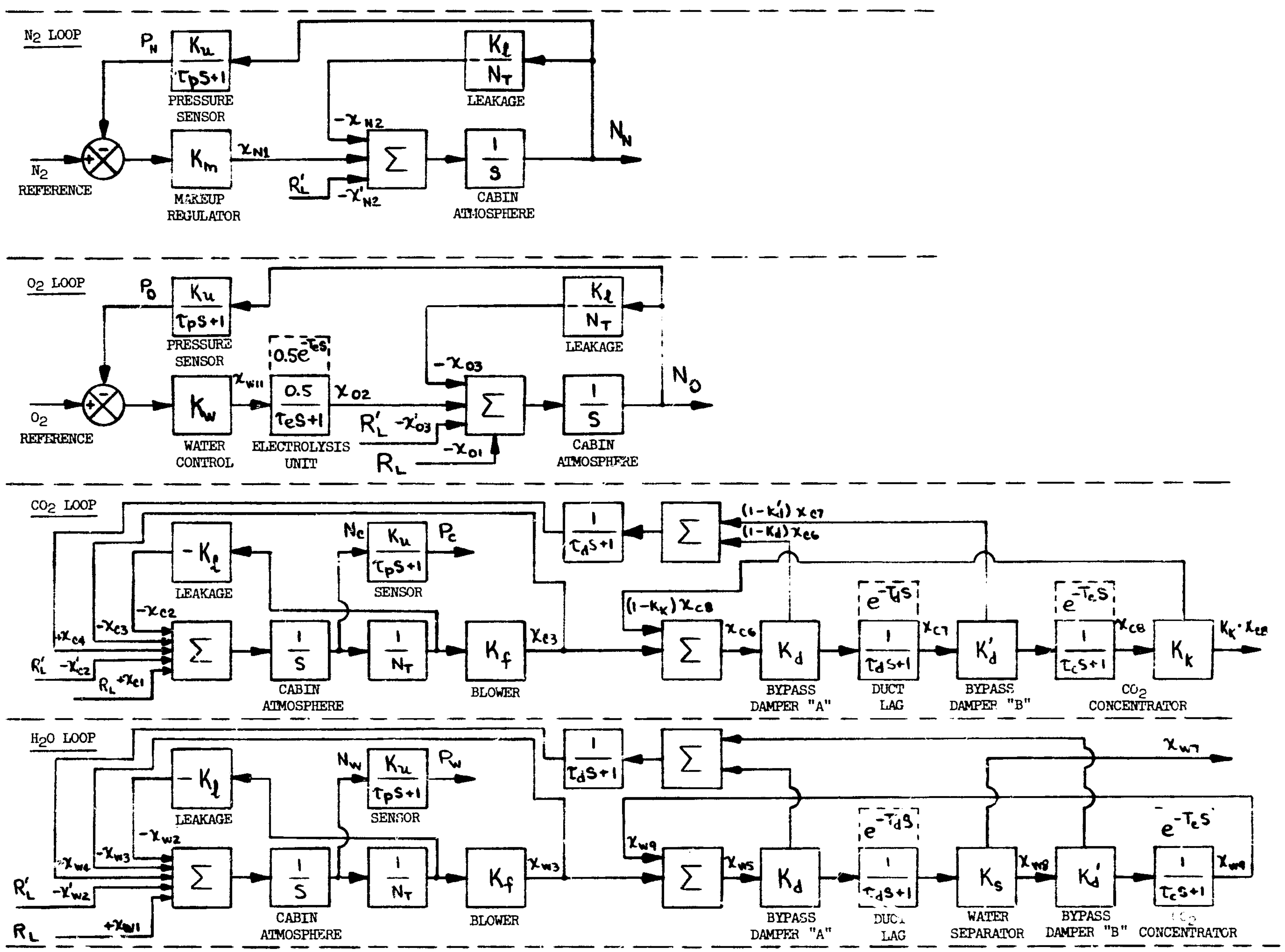


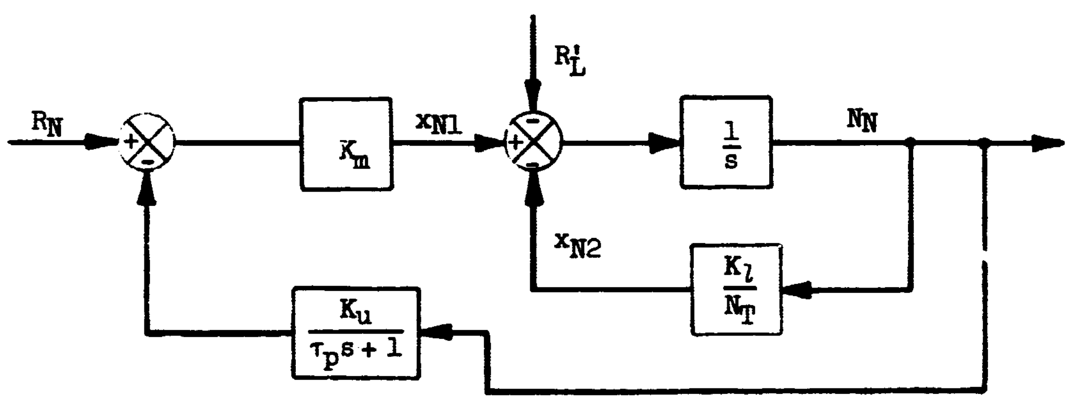

Figure 9.- Simplified block diagram.

## Linear System Characteristics

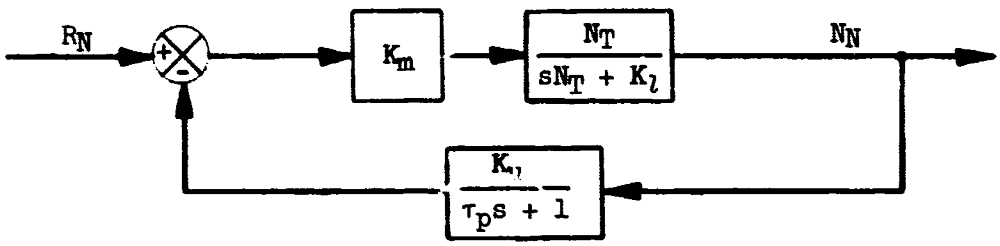
Each loop of the simplified block diagram will be further reduced to the point where linear stability criteria can be applied. Since the various control loops include transport delays as part of their transfer functions, the use of the Nyquist Criterion is appropriate to determine the stability of the system. This requires developing a loop gain function GH, for each control loop to be investigated. The effect of each reference input load, both the metabolic loads and the venting loads, will be considered separately. The linear assumptions would permit the superposition of the two inputs for determination of a resultant loop output but that was not done in this study.

(1) $N_2$ Loop Reduction

Basic $N_2$ Loop:



Reference input only:

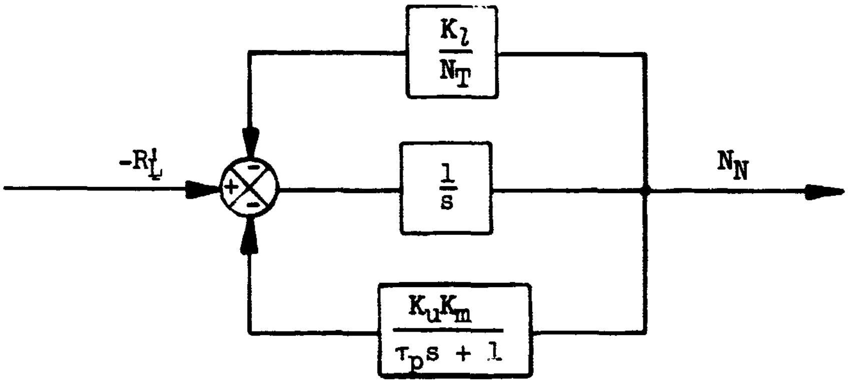



$$G = \frac{K_m N_T}{sN_T + K_l}$$

$$H = \frac{K_u}{\tau_p s + 1}$$

$$GH = \frac{K_m K_u N_T}{(sN_T + K_l)(\tau_p s + 1)} = \frac{K_m K_u \left(\frac{N_T}{K_l}\right)}{\left[s\left(\frac{N_T}{K_l}\right) + 1\right]\left[\tau_p s + 1\right]}$$

Disturbance load input only:



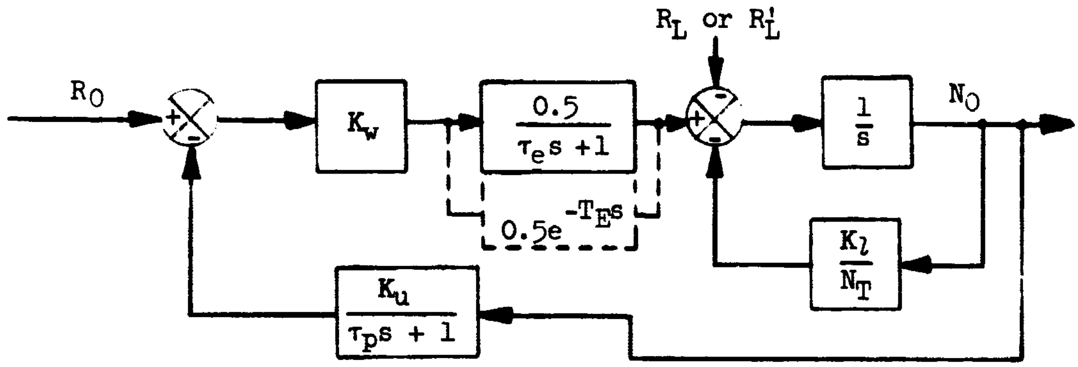

$$G = \frac{1}{s}$$

$$H = \frac{K_l}{N_T} + \frac{K_u K_m}{\tau_p s + 1} = \frac{K_l(\tau_p s + 1) + K_u K_m N_T}{N_T(\tau_p s + 1)}$$

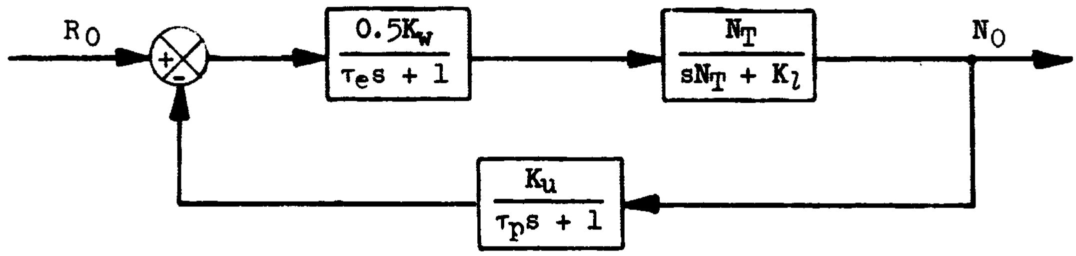
$$GH = \frac{(\tau_p s + 1) + K_u K_m\left(\frac{N_T}{K_l}\right)}{s\left(\frac{N_T}{K_l}\right)(\tau_p s + 1)}$$

(2) $O_2$ Loop Reduction

Basic $O_2$ Loop:




Reference input only:

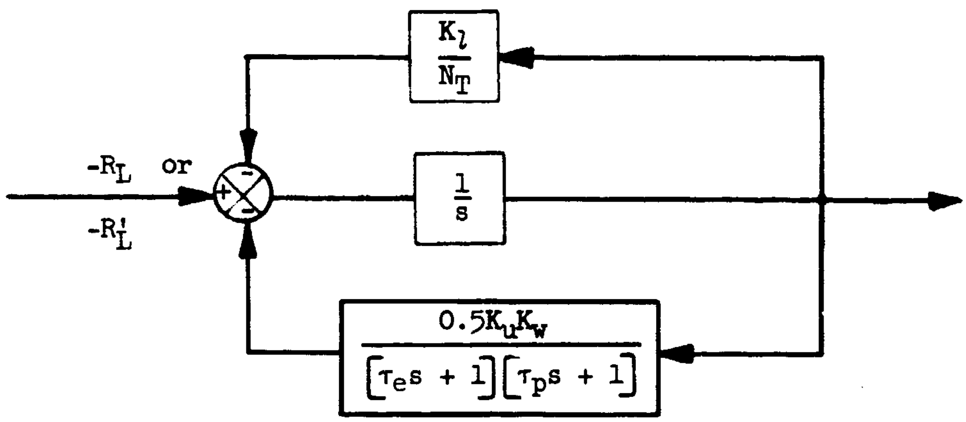



$$G = \frac{0.5K_w\left(\frac{N_T}{K_l}\right)}{\left[\tau_e s + 1\right]\left[s\left(\frac{N_T}{K_l}\right) + 1\right]} \quad \text{or} \quad \frac{0.5e^{-T_E s}K_w\left(\frac{N_T}{K_l}\right)}{\left[s\left(\frac{N_T}{K_l}\right) + 1\right]}$$

$$H = \frac{K_u}{\tau_p s + 1}$$

$$GH = \frac{0.5K_uK_w\left(\frac{N_T}{K_l}\right)}{\left[\tau_p s + 1\right]\left[\tau_e s + 1\right]\left[s\left(\frac{N_T}{K_l}\right) + 1\right]} \quad \text{or} \quad \frac{0.5e^{-T_E s}K_uK_w\left(\frac{N_T}{K_l}\right)}{\left[\tau_p s + 1\right]\left[s\left(\frac{N_T}{K_l}\right) + 1\right]}$$

Disturbance load input only:




$$G = \frac{1}{s}$$

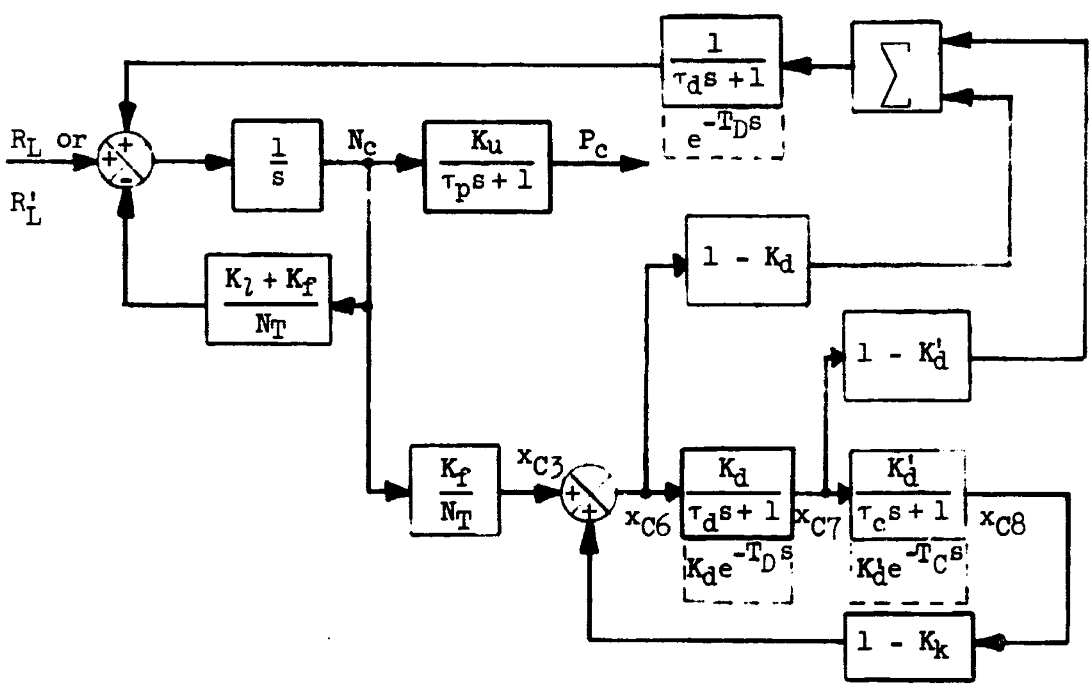
$$H = \frac{K_l}{N_T} + \frac{0.5K_uK_w}{\left[\tau_e s + 1\right]\left[\tau_p s + 1\right]} = \frac{K_l(\tau_e s + 1)(\tau_p s + 1) + 0.5K_uK_wN_T}{N_T(\tau_e s + 1)(\tau_p s + 1)}$$

$$GH = \frac{(\tau_e s + 1)(\tau_p s + 1) + 0.5K_u K_w\left(\frac{N_T}{K_l}\right)}{s\left(\frac{N_T}{K_l}\right)(\tau_e s + 1)(\tau_p s + 1)}$$

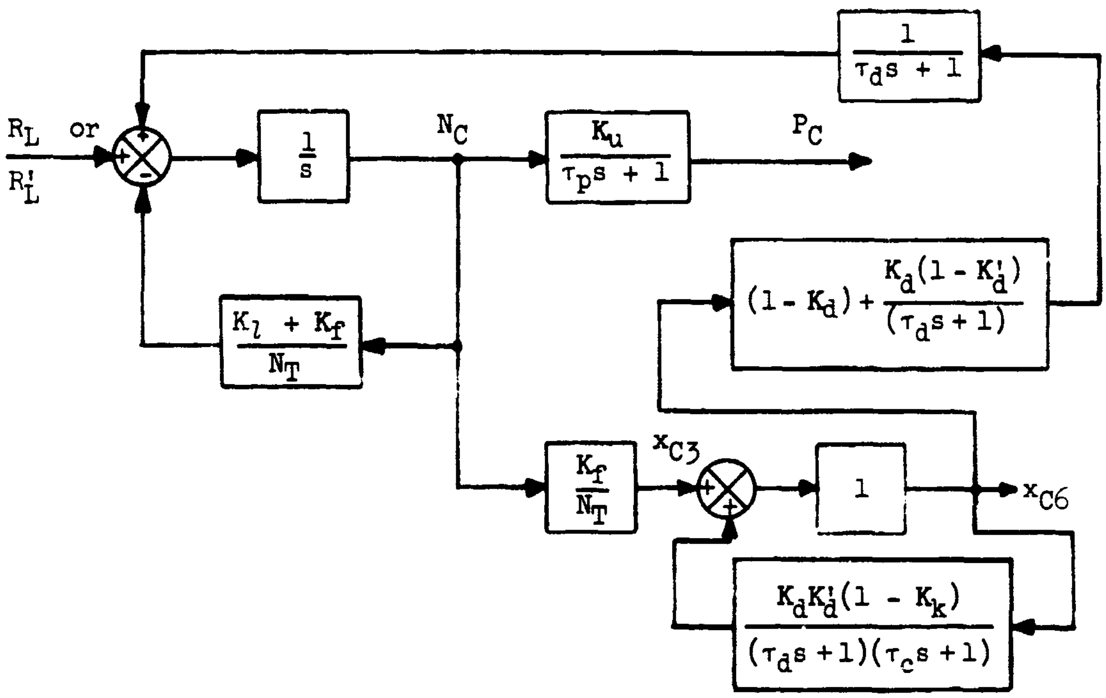
With transport lag in electrolysis unit:

$$GH = \frac{(\tau_p s + 1) + 0.5K_u K_w\left(\frac{N_T}{K_l}\right)e^{-T_E s}}{s\left(\frac{N_T}{K_l}\right)(\tau_p s + 1)}$$

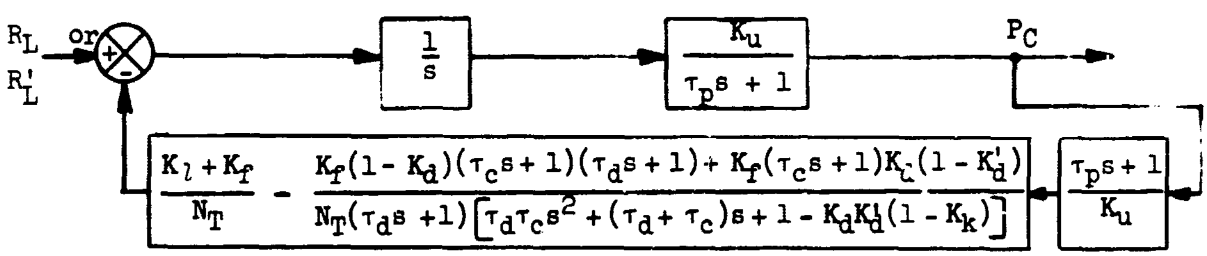
(3) <u>$CO_2$ Loop Reduction</u>



This further reduces to:




Combining feedback terms:



$$G = \frac{K_u}{s(\tau_p s + 1)}$$

$$H = \left[\frac{\tau_p s + 1}{K_u}\right] \cdot \left[\left(\frac{K_l + K_f}{N_T}\right) - \left(\frac{K_f(1 - K_d)(\tau_c s + 1)(\tau_d s + 1) + K_f K_d(1 - K_d')(\tau_c s + 1)}{N_T(\tau_d s + 1)\left[\tau_d \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d K_d'(1 - K_k)\right]}\right)\right]$$

$$GH = \left[\left(\frac{K_l + K_f}{sN_T}\right) - \left(\frac{K_f(1 - K_d)(\tau_c s + 1)(\tau_d s + 1) + K_f K_d(1 - K_d')(\tau_c s + 1)}{sN_T(\tau_d s + 1)\left[\tau_d \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d K_d'(1 - K_k)\right]}\right)\right]$$

$$GH = \frac{(K_l + K_f)(\tau_d s + 1)\left[\tau_d \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d K_d'(1 - K_k)\right]}{sN_T(\tau_d s + 1)\left[\tau_d \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d K_d'(1 - K_k)\right]}$$

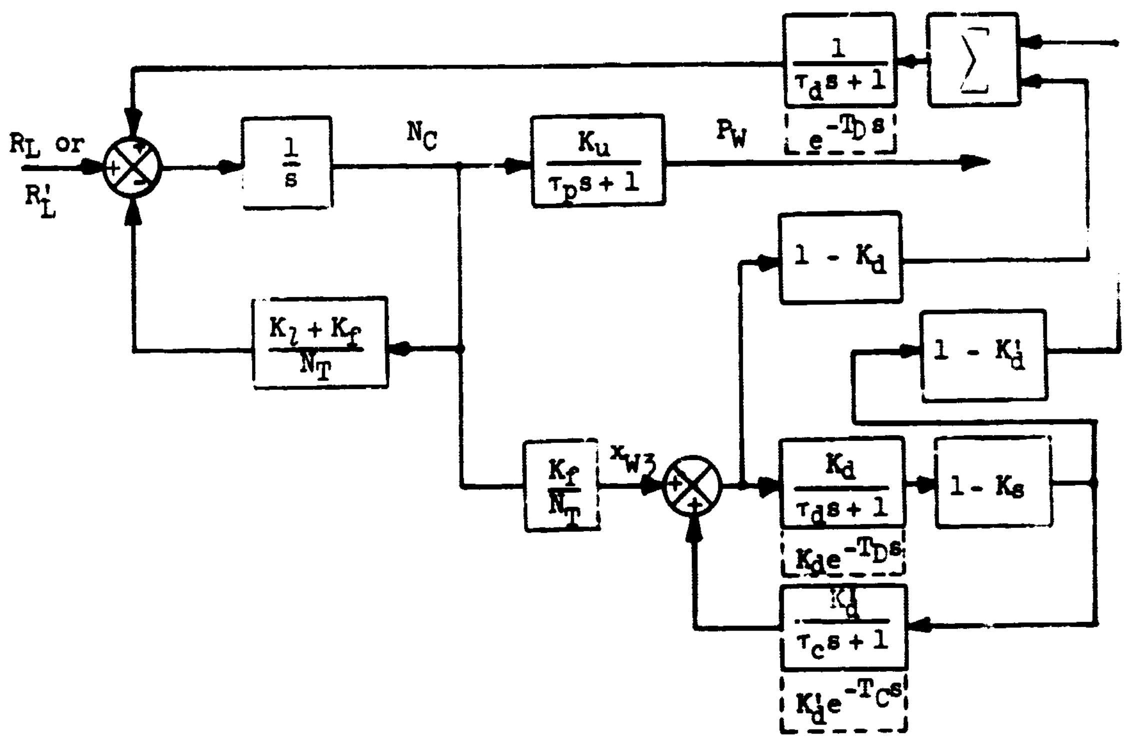
$$- \frac{\left[K_f(1 - K_d)(\tau_c s + 1)(\tau_d s + 1) + K_f K_d(1 - K_d')(\tau_c s + 1)\right]}{sN_T(\tau_d s + 1)\left[\tau_d \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d K_d'(1 - K_k)\right]}$$

With transport lags included:

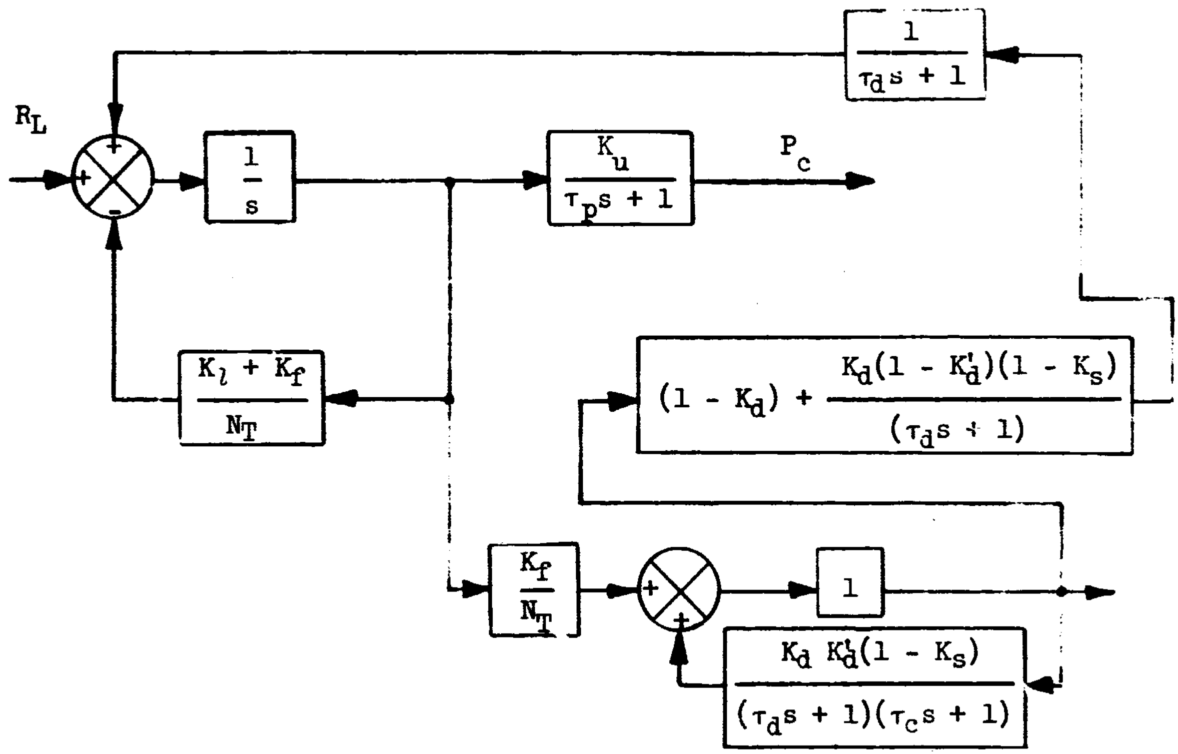
$$GH = \frac{(K_l + K_f)(e^{T_D s})\left[e^{(T_D + T_C)s} - K_d K_d'(1 - K_k)\right]}{sN_T(e^{T_D s})\left[e^{(T_D + T_C)s} - K_d K_d'(1 - K_k)\right]}$$

$$- \frac{\left[K_f(1 - K_d)e^{(T_D + T_C)s} + K_f K_d(1 - K_d')e^{T_C s}\right]}{sN_T(e^{T_D s})\left[e^{(T_D + T_C)s} - K_d K_d'(1 - K_k)\right]}$$

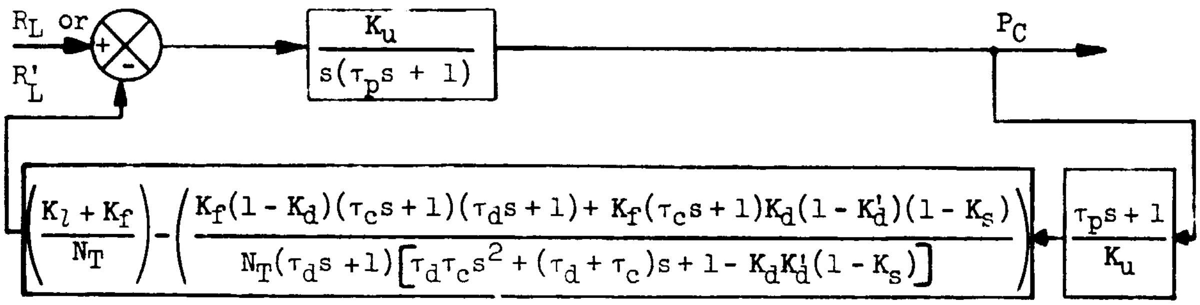
(4) $H_2O$ Loop Reduction



This further reduces to:



Combining feedback terms:




$$G = \frac{K_u}{s(\tau_p s + 1)}$$

$$H = \left[\frac{\tau_p s + 1}{K_u}\right] \cdot \left[\left(\frac{K_l + K_f}{N_T}\right) - \left(\frac{K_f(1 - K_d)(\tau_c s + 1)(\tau_d s + 1) + K_f K_d(1 - K_d')(1 - K_s)(\tau_c s + 1)}{N_T(\tau_d s + 1)\left[\tau_d \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d K_d'(1 - K_s)\right]}\right)\right]$$

$$GH = \left[\left(\frac{K_l + K_f}{sN_T}\right) - \left(\frac{K_f(1 - K_d)(\tau_c s + 1)(\tau_d s + 1) + K_f K_d(1 - K_d')(1 - K_s)(\tau_c s + 1)}{sN_T(\tau_d s + 1)\left[\tau_d \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d K_d'(1 - K_s)\right]}\right)\right]$$

Combining terms in the denominator:

$$GH = \frac{(K_l + K_f)(\tau_d s + 1)\left[\tau_d\ \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d\ K_d'(1 - K_s)\right]}{sN_T(\tau_d s + 1)\left[\tau_d\ \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d\ K_d'(1 - K_s)\right]}$$

$$- \frac{\left[K_f(1 - K_d)(\tau_c s + 1)(\tau_d s + 1) + K_f\ K_d(1 - K_d')(1 - K_s)(\tau_c s + 1)\right]}{sN_T(\tau_d s + 1)\left[\tau_d\ \tau_c s^2 + (\tau_d + \tau_c)s + 1 - K_d\ K_d'(1 - K_s)\right]}$$

With transport lags included:

$$GH = \frac{(K_l + K_f)e^{T_D s}\left[e^{(T_D + T_C)s} - K_d\ K_d'(1 - K_s)\right]}{sN_T e^{T_D s}\left[e^{(T_D + T_C)s} - K_d\ K_d'(1 - K_s)\right]}$$

$$- \frac{\left[K_f(1 - K_d)e^{(T_d + T_c)s} + K_f K_d(1 - K_d')(1 - K_s)e^{T_c s}\right]}{sN_T e^{T_d s}\left[e^{(T_d + T_c)s} - K_d K_d'(1 - K_s)\right]}$$

## Complex Plane Plots

The stability of each of the loop gain functions developed in the preceding section was checked by applying the Nyquist Stability Criterion. This involved substituting $j\omega$ for $s$ and calculating values of GH for various values of $\omega$ and for nominal values of the constants. The resulting points were plotted on the complex plane as shown on Figures 10 through 13.

Nyquist plots for the $N_2$ loop are found on Figure 10. The loop gain functions for both the normal reference input and for the disturbance load input appear to be very stable. It should be noted that the plots are not drawn to scale, since it was desired to show some detail of the trace near the origin and also to show the closure of the overall curve. Nyquist plots for the $O_2$ loop are on Figure 11. They are very similar to those for the $N_2$ loop, and demonstrate the basic stability of the assumed $O_2$ loop model. Separate plots of the gain functions with transport delays are not shown, since they were nearly the same as the plots with equivalent time constants. The transport delays contributed some additional phase shift near the origin but this had no effect on the stability determination.

Complex plane plots for the $CO_2$ loop and $H_2O$ loop are on Figures 12 and 13, respectively. The characteristics of these two gain functions are very similar and are determined basically by the integration term in the denominator of each. The traces on the complex plane approach the origin along the negative imaginary axis and cross into the right half plane before converging on the origin. However, the loop stability is established in accordance with the Nyquist criterion. Application of Routh's criterion to the loop gain functions also confirms that there are no positive roots in the system.

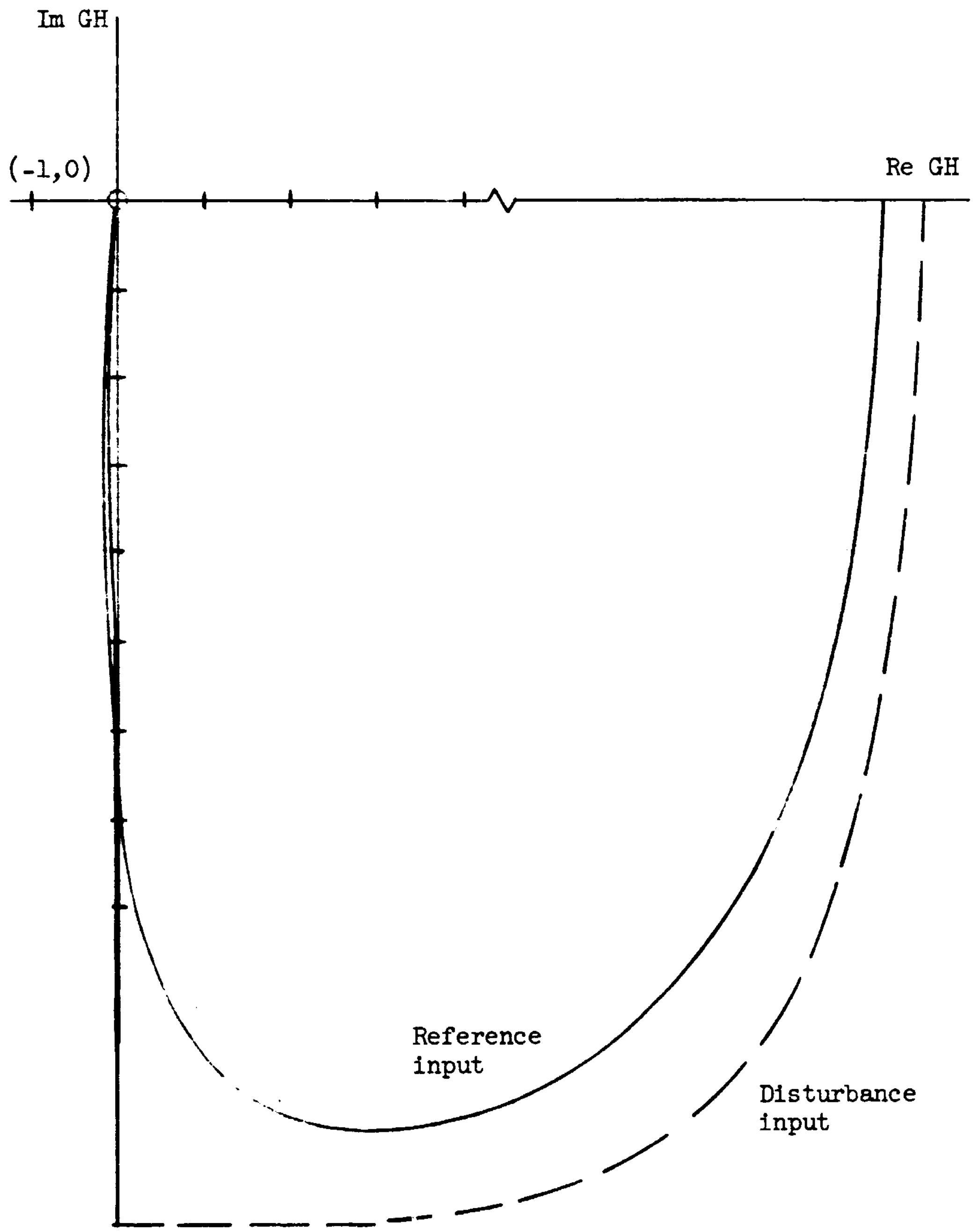



Figure 10.- Nyquist plot-$N_2$ loop.

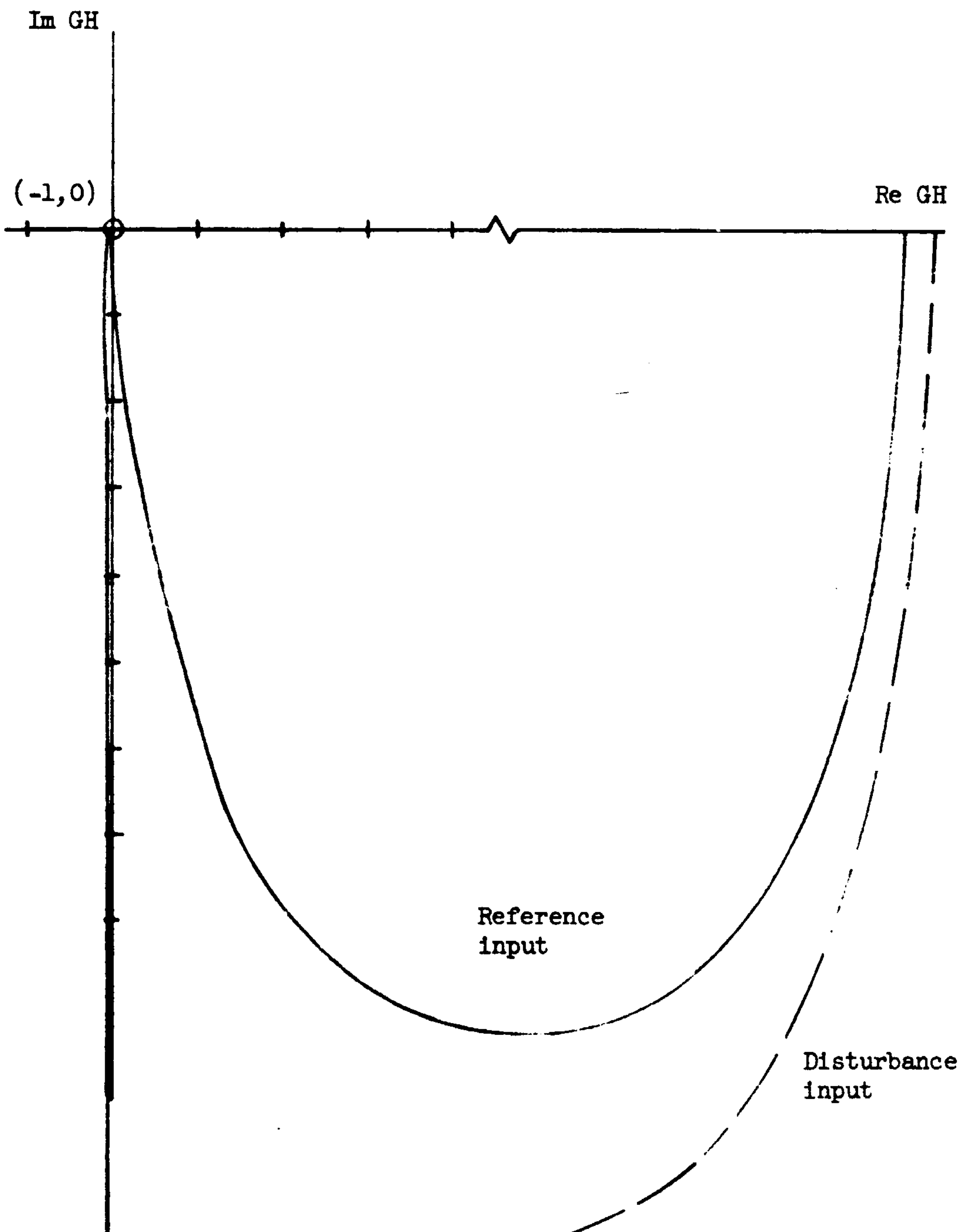



Figure 11.- Nyquist plot-$O_2$ loop.

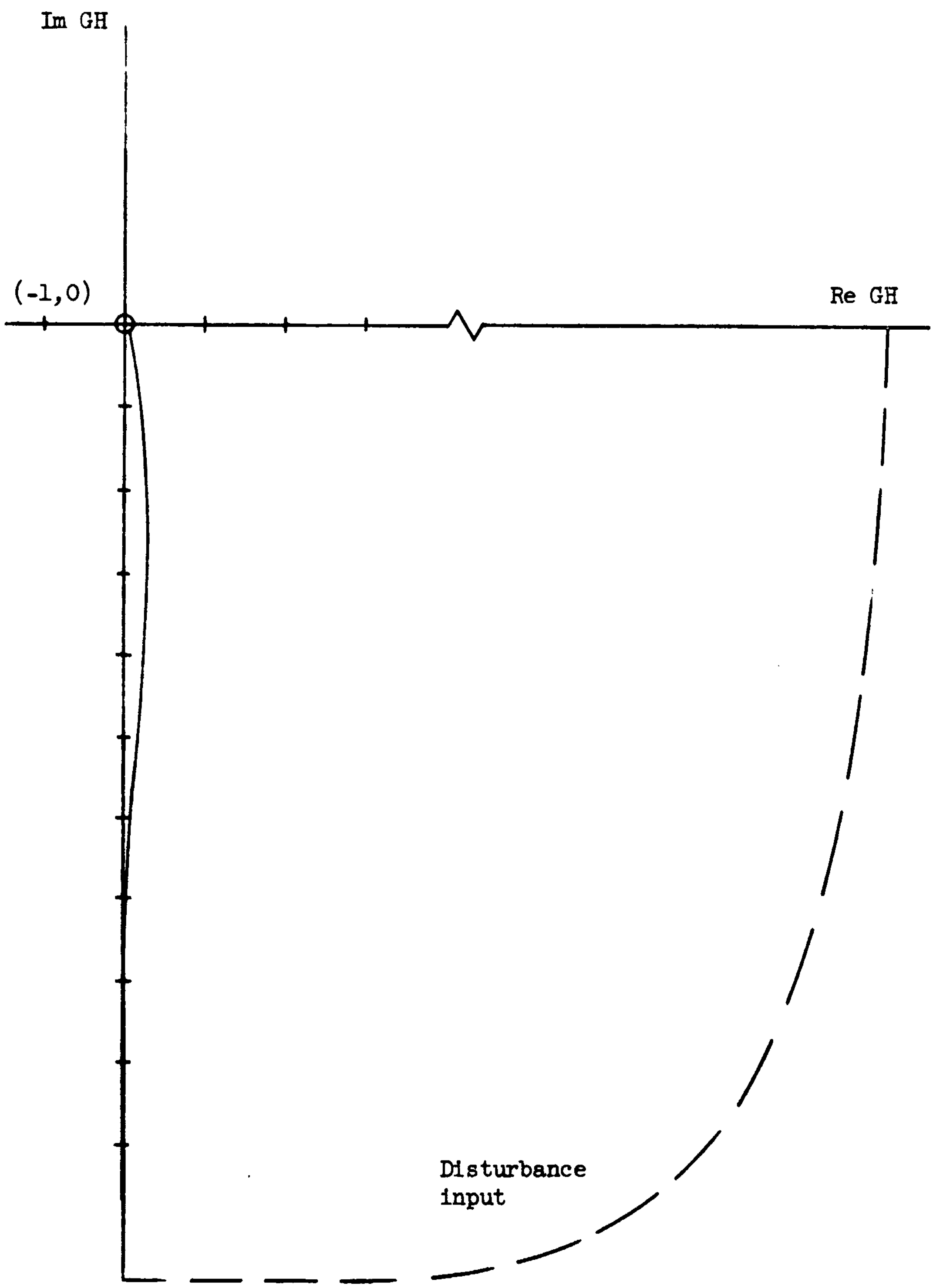



Figure 12.- Nyquist plot-$CO_2$ loop.

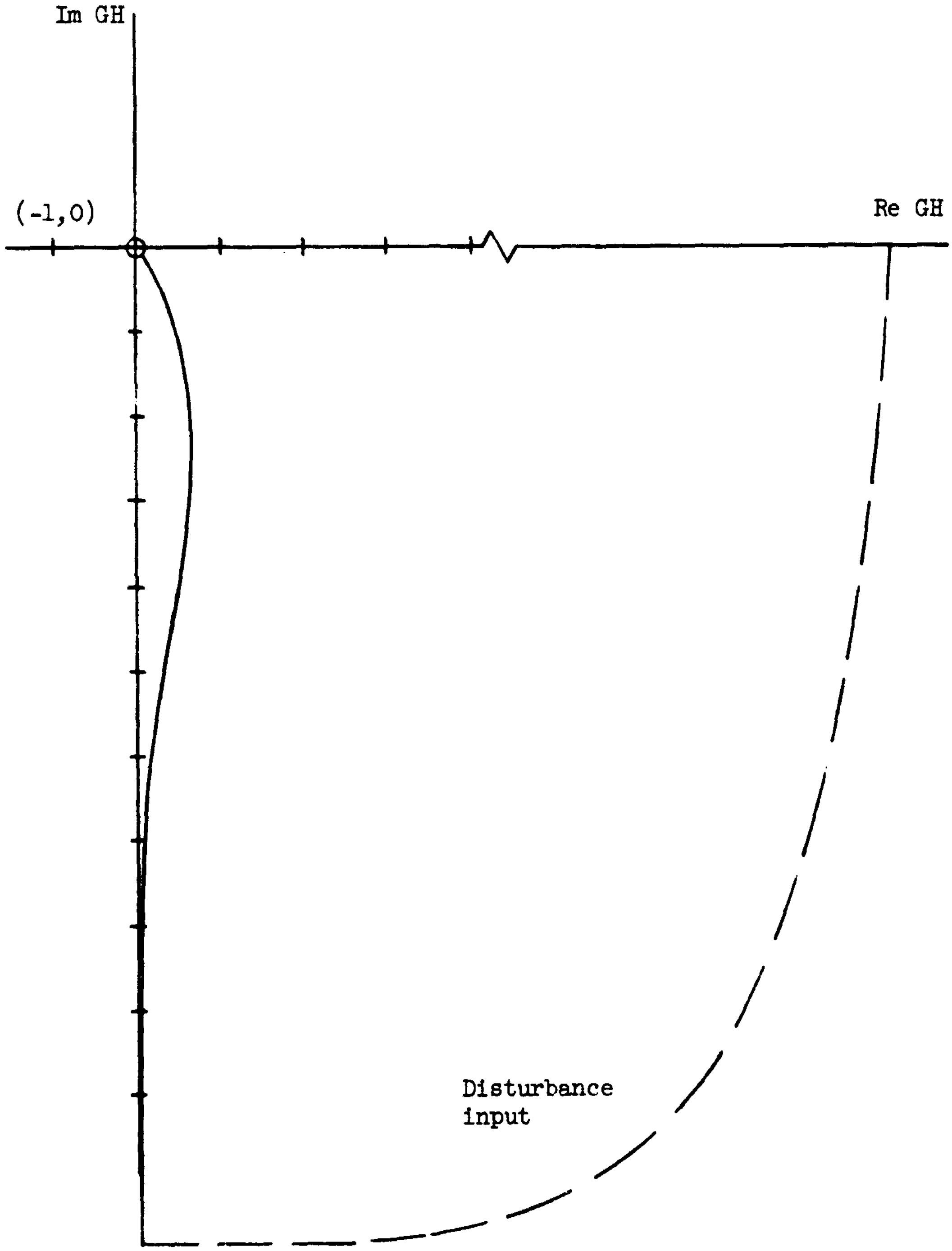



Figure 13.- Nyquist plot-$H_2O$ loop.

# CHAPTER V

## AUTOMATED SYSTEM ANALYSIS

Manual analysis of the regenerative atmospheric control system beyond the simple methods used in Chapter IV is impractical due to the many variables involved, because of the nonlinearities of the various components and because of the relatively slow response of the system. For these reasons, the detailed analysis of the system was accomplished by means of the electronic analog computer. The analog computer is particularly valuable for analyzing systems where many variables are changing with time, where component nonlinearities must be simulated, and where variations are to be examined over long periods of time. This chapter describes the analog system used to simulate the regenerative cabin atmosphere control system, the operations performed with the analog computer, and the results obtained.

### Analog Computer Simulation

The analog computer schematic is presented on Figure 14. The computer layout generally follows the system block diagram with separate loops representing the operations performed on the four major constituent gases and additional loops simulating the regenerative system components.

The analog computer mechanization was conventional in most respects. The analytical summing and integrating operations were performed on the standard operational amplifiers; multiplication and division operations were performed on quarter-square multipliers. The various limiting functions were accomplished by means of solid-state

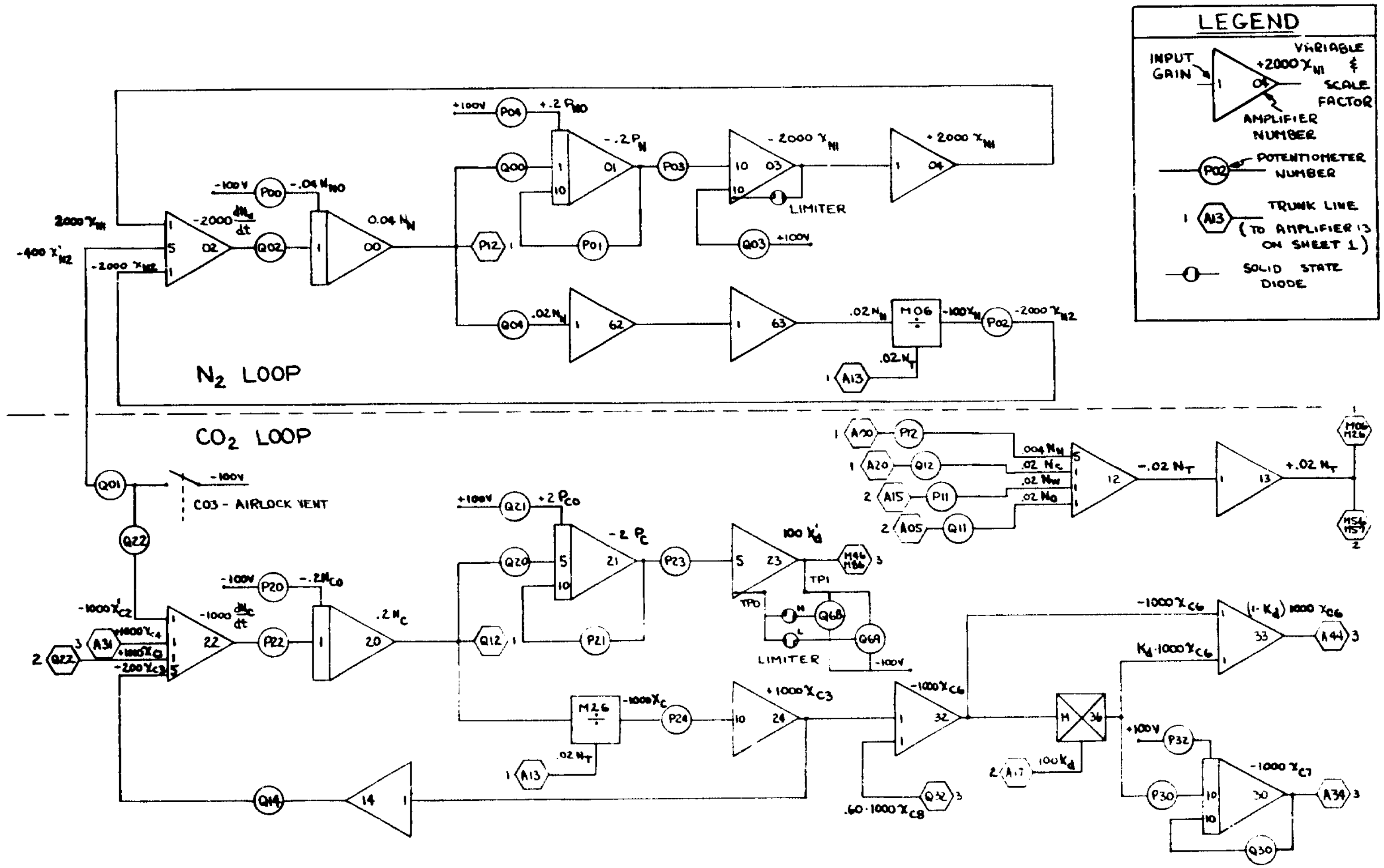



Figure 14.- Analog computer schematic.

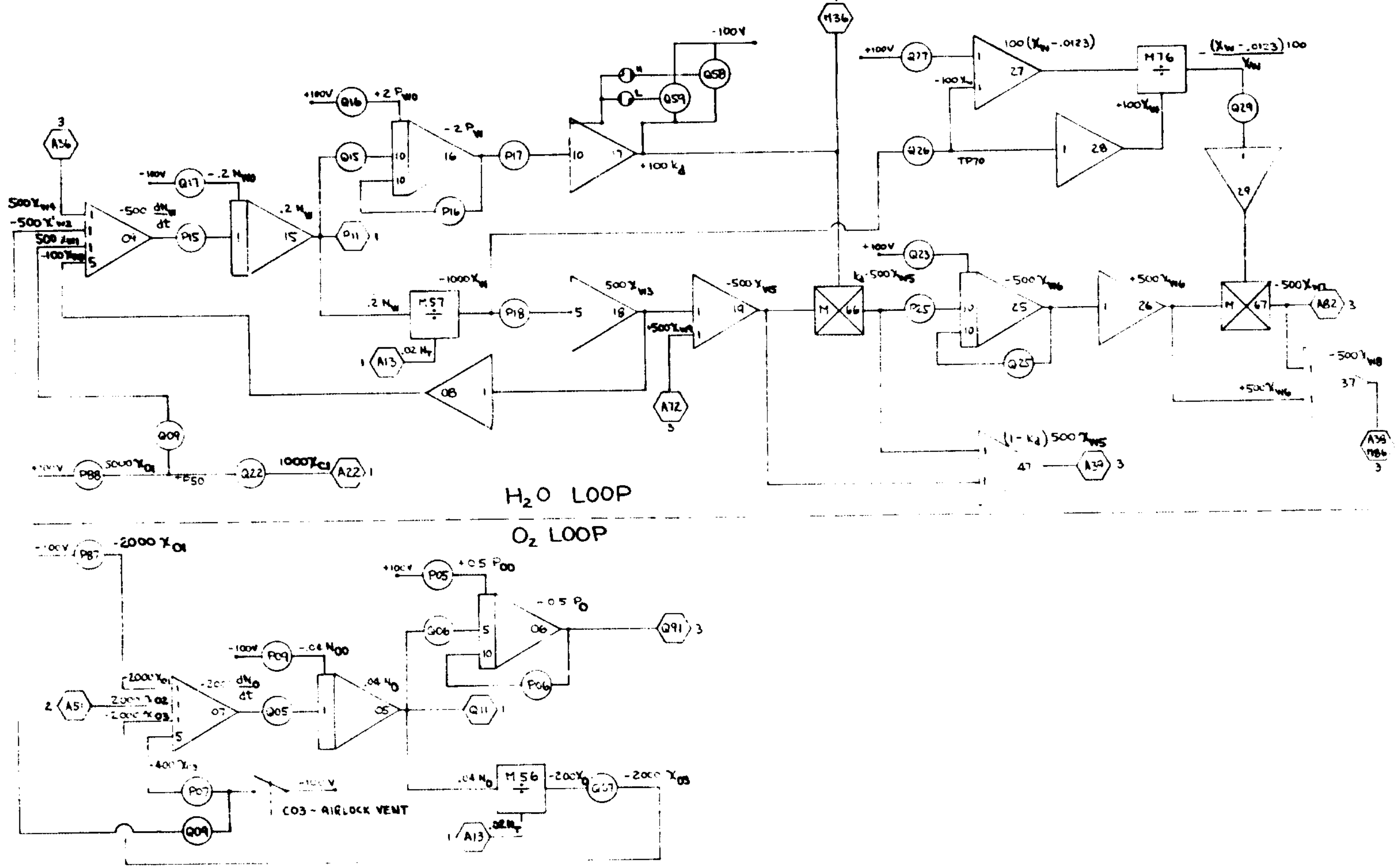



Figure 14.- Continued.

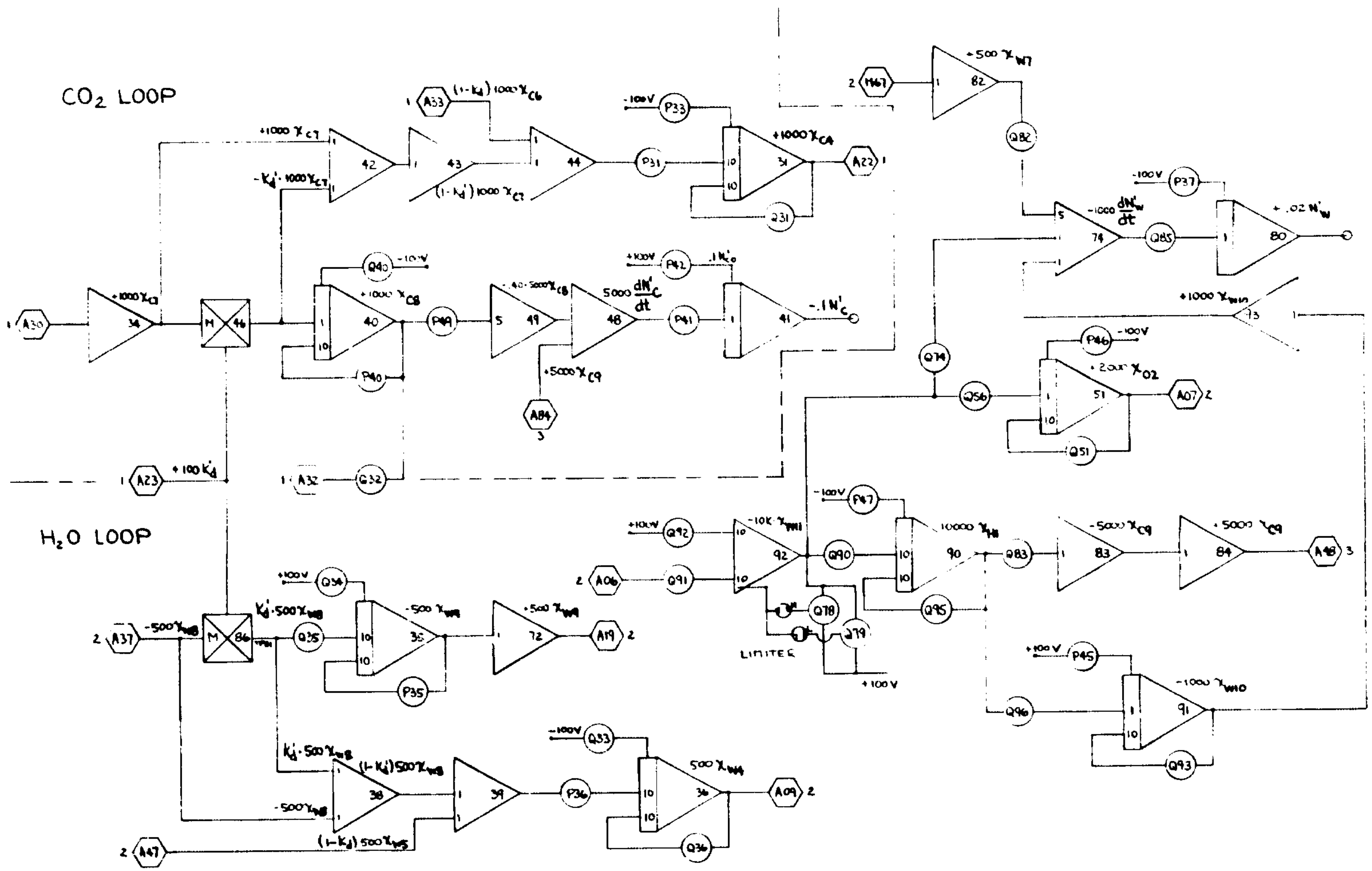



Figure 14.- Continued.

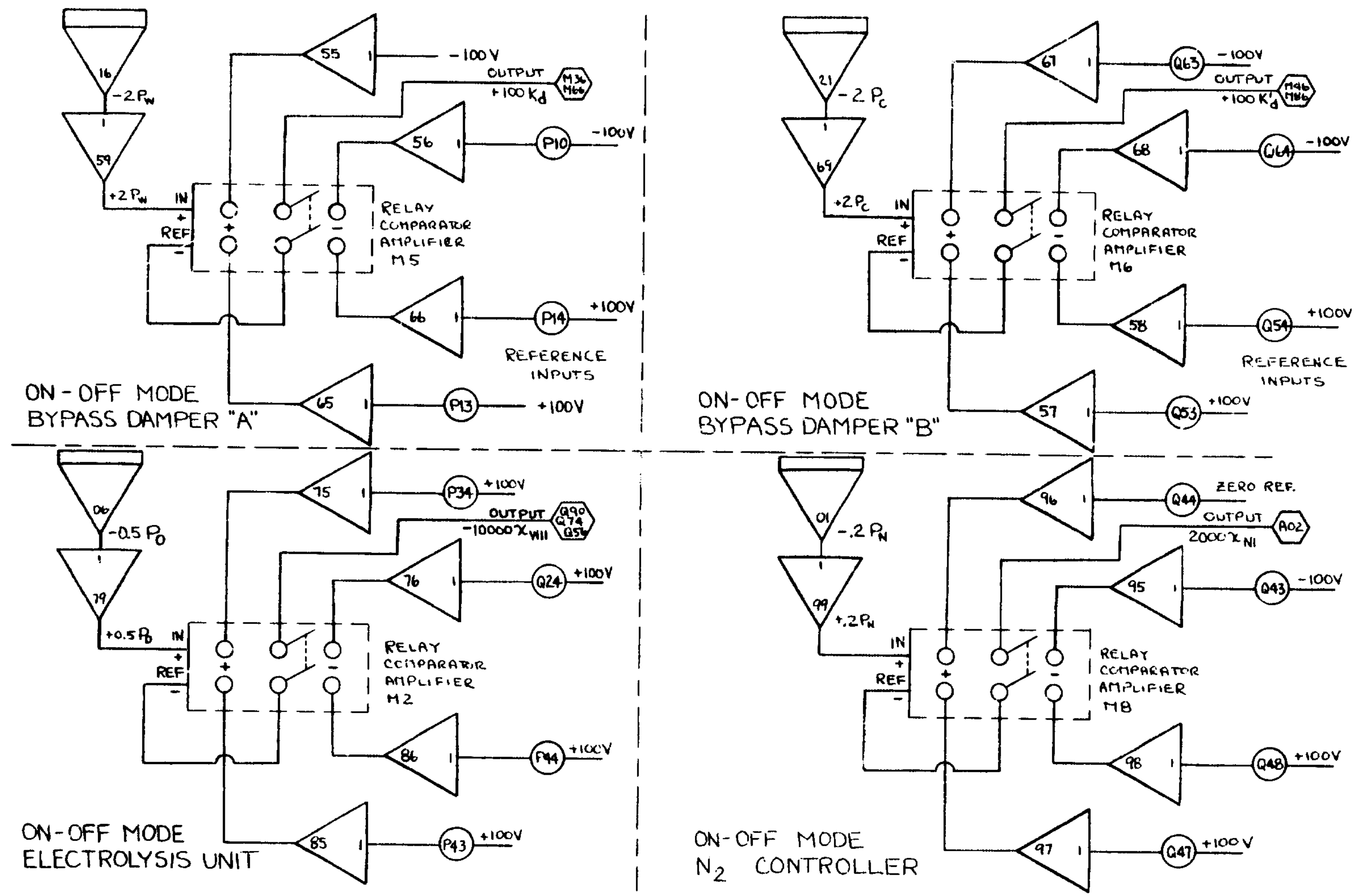



Figure 14.- Concluded.

diode circuits which provide what is called a "soft limit" rather than an absolute limit; that is, the actual limit will vary somewhat with the input, but the effect of this variation is so small as to be negligible. Relay amplifiers with reset circuits were used to simulate on-off functions during operation in the on-off mode.

One major departure from the system model was made during the analog computer programing. This involved the substitution of simple time constants for the transport lags of the various components. The System Block Diagram, Figure 8, showed several transport lags, including those associated with the water electrolysis unit, the $CO_2$ concentrator, the $CO_2$ reduction unit, and those associated with the ducts. Obviously, the transport lags are an important characteristic of the regenerative cabin atmosphere control system.

Unfortunately, the representation of transport lags on the analog computer is not totally satisfactory. Various circuits are available such as those based on series expansion and on the Pade'-type of expression. These circuits involve several amplifiers and other elements for each transport lag to be simulated, such that a Pade' simulation of all transport lags in the system would greatly increase the complexity of the computer simulation. However, even with such a simulation the faithful reproduction of step inputs would not be possible and these are the type of transient inputs of interest to the study.

For the above reasons, it was decided to simulate the transport lags by simple time constants equal in magnitude to the respective transport lags. This decision was further justified by the approximate nature of the transport lags themselves. As discussed in the various sections of Chapter III, the transport lags were generally based on estimates since no dynamic data were available on the components. In addition, the effect of time constants in the simulation is further minimized since the transport lags are so small in magnitude compared with the system response times - generally, minutes of operation compared with hours of system time.

Scaling of variables in the program presented a serious challenge due to the wide variation in magnitude between the various parameters. Time scaling was accomplished most readily since there was some physical experience with real systems to indicate that system changes would occur relatively slowly and that time periods in terms of hours of real time were of interest. A time scale factor of 360:1 was chosen; this means that 360 seconds of real system time were compressed into 1 second of machine operating time. Stated another way, each 1 second of machine time was equivalent to 0.1 hour of real system time, so that a machine run of 80 seconds was actually equivalent to 8 hours of system operation. The time scale factor was incorporated by manipulating the computer diagram to change every time constant by the desired factor.

Voltage scaling involved selection of suitable scale factors for each parameter, since the computer operation is based on having voltages proportional to the physical variable. The scale factor is simply a constant of proportionality relating the computer voltage to the physical variable. The scale factor of each variable is shown on the analog computer schematic. The wide range of scale factors (for example, from

$0.004\ N_N$ to $10{,}000x_{H1}$) emphasizes the wide range of physical quantities which were accounted for during the scaling operation.

As shown on the analog computer schematic, each integrating amplifier was provided with a suitable initial condition. The I.C.'s were useful in checking computer performance and were found to be necessary to prevent saturation of the multipliers. For that reason, computer operations simulating system startup from zero initial conditions were found to be impractical. In any event, one of the most interesting aspects of system startup is the effect on the various components. As previously noted, the individual components were not simulated in detail in this study, so the value of startup simulation would be limited and were not included in the computer operation.

As shown on the analog computer schematic, the various input functions such as crew load and air lock venting, were controlled manually by pots and switches. In some of the later computer runs, specifically in the simulated "typical day" runs, some variation may exist in the timing of events between the various runs. For that reason the comparison of results of the various control types must be qualitative in nature.

## Analog Computer Results

Analog computer operation consisted basically of observing the atmospheric control system response to the various effects of normal and off-limits operation. Test runs were made with both proportional mode and on-off mode system control. Runs were also made with conditions simulating those which might be encountered during a "typical day" of space cabin operation, including equipment changes and performance degradation.

The first series of runs was made with the system in a proportional control mode. The functions which were actually programed in a proportional manner included bypass damper "A," bypass damper "B," water electrolysis unit, and the makeup $N_2$ controller. The $CO_2$ reduction unit was programed to operate in proportion to the amount of $H_2$ supplied from the water electrolysis unit.

Figures 15, 16, 17, 18, and 19 show the effect of transient inputs on the atmospheric control system. Such transient inputs might be expected to occur routinely as the result of changes in the crew activity or as the result of operations such as air lock venting. The traces basically show just a resetting of the system operating conditions to the new operating point in each case.

Figure 15 shows the system parameters resetting from the nominal initial conditions to crew condition 1, the state of complete rest for the four-man crew. Values of $P_W$ and $P_C$ shift downward resulting in an appropriate adjustment of the bypass valve gains $K_d$ and $K_d'$. The partial pressure of $O_2$, $P_O$, shifts up slightly, reflecting the lower demand for oxygen. Lower rates of removal of $CO_2$ and $H_2O$ from the cabin are indicated by the decreased rates $\frac{dN_C'}{dt}$ and $\frac{dN_W'}{dt}$.

Figure 16 shows the transient response from crew condition 1 to crew condition 2, which represents the average condition for normal operations of the cabin atmosphere control system. The increased

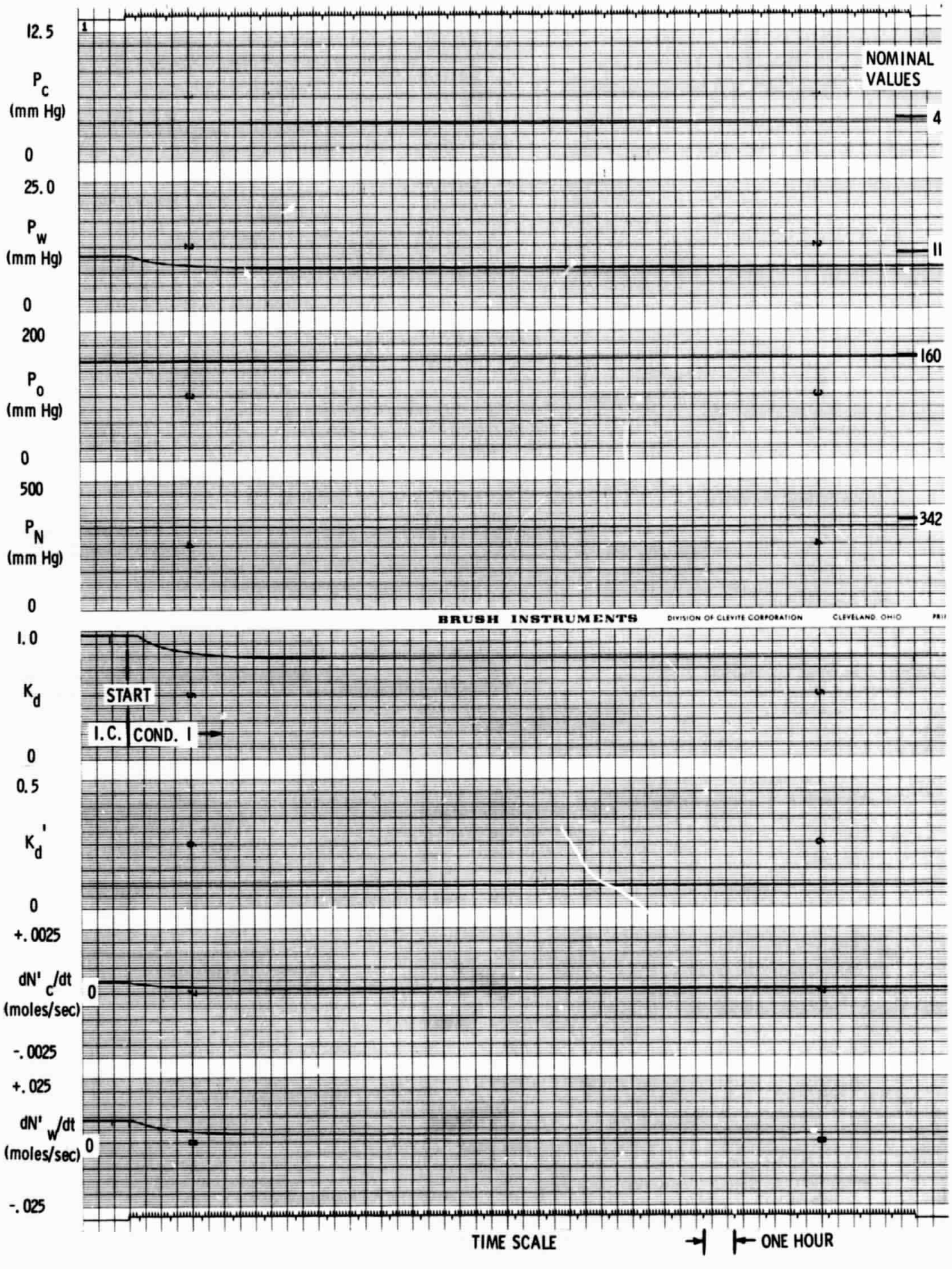



Figure 15.- Transient response from I.C. to COND. 1.

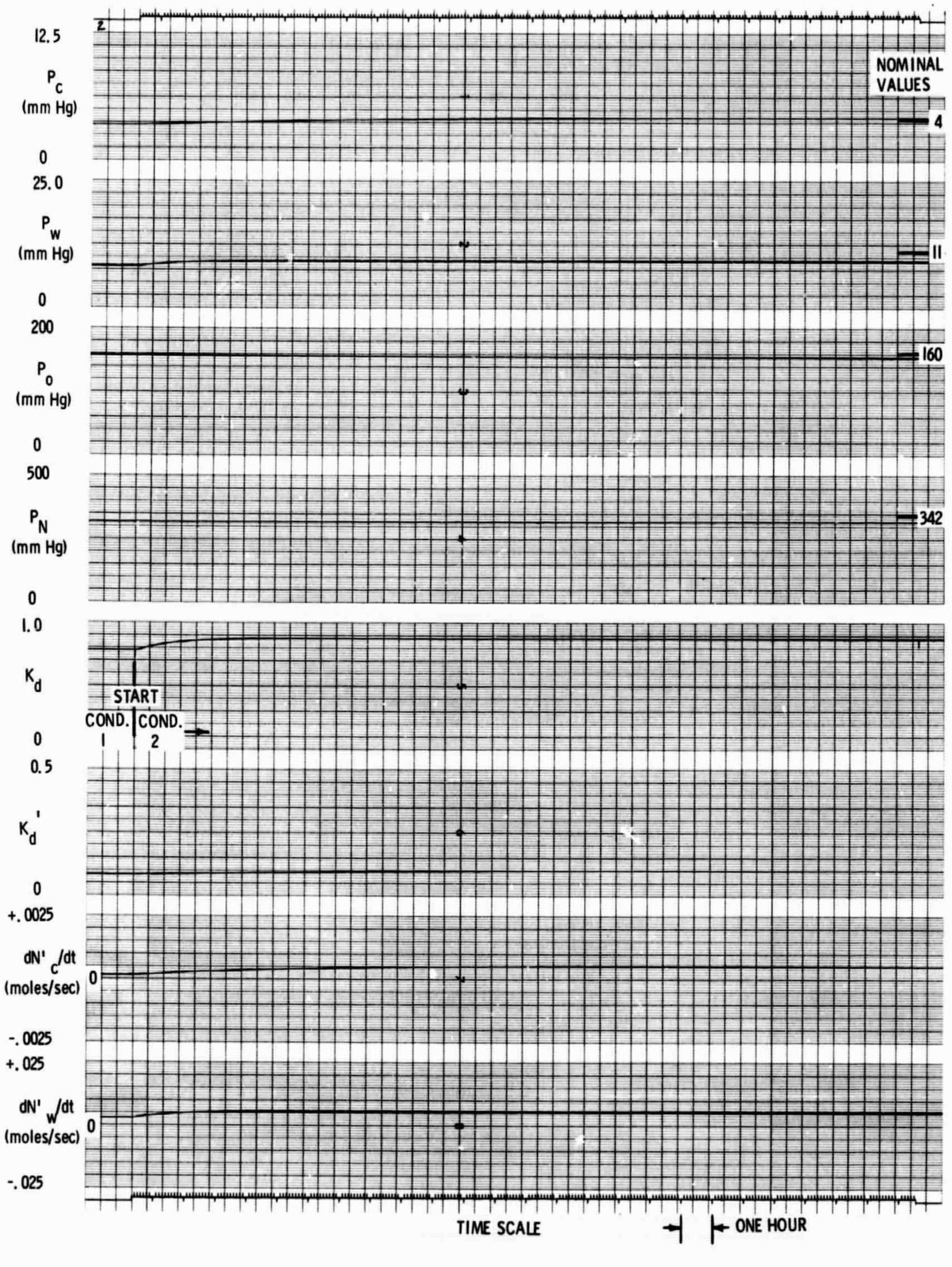



Figure 16.- Transient response from COND. 1 to COND. 2.

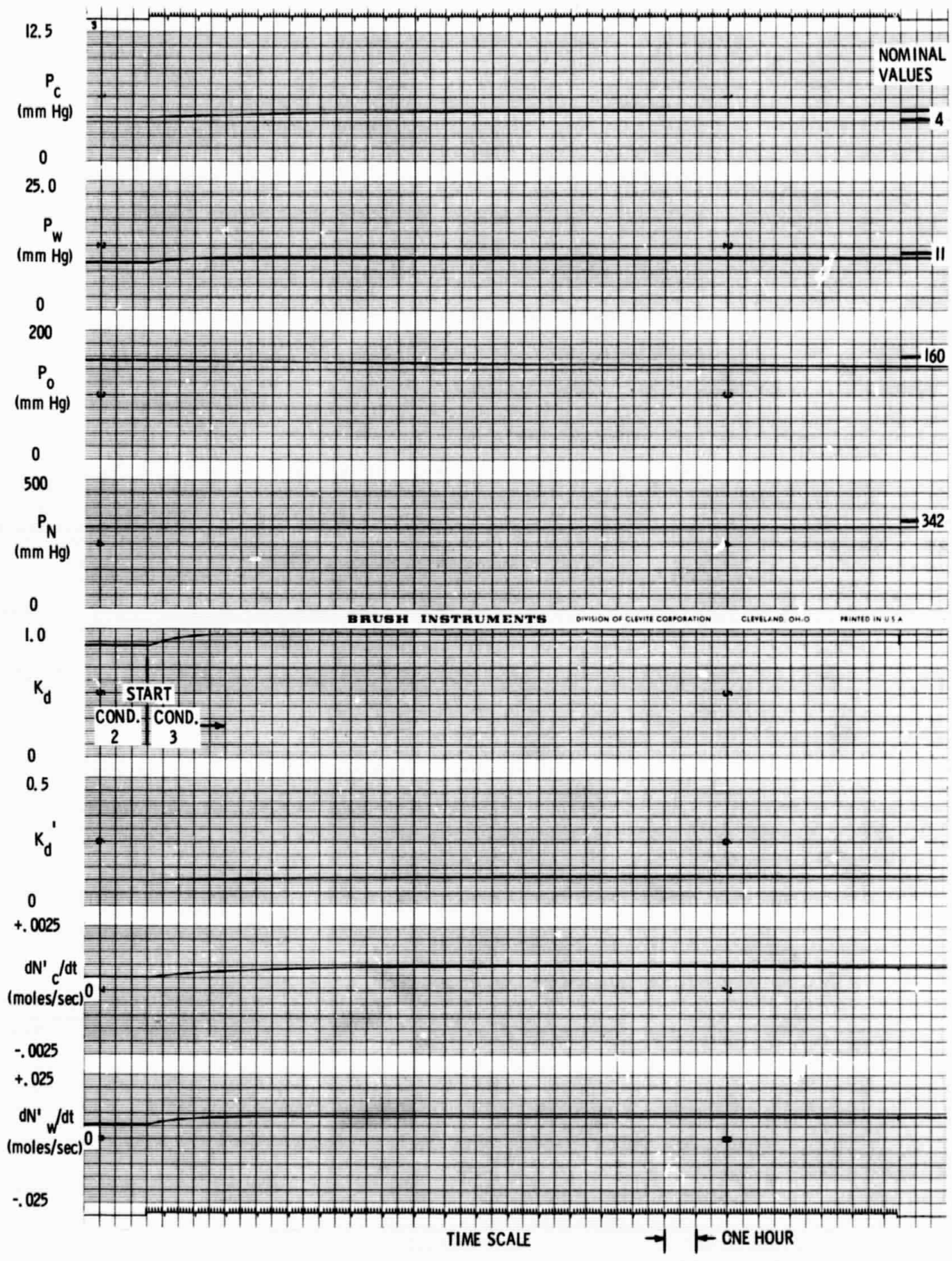



Figure 17.- Transient Response from COND. 2 to COND. 3.

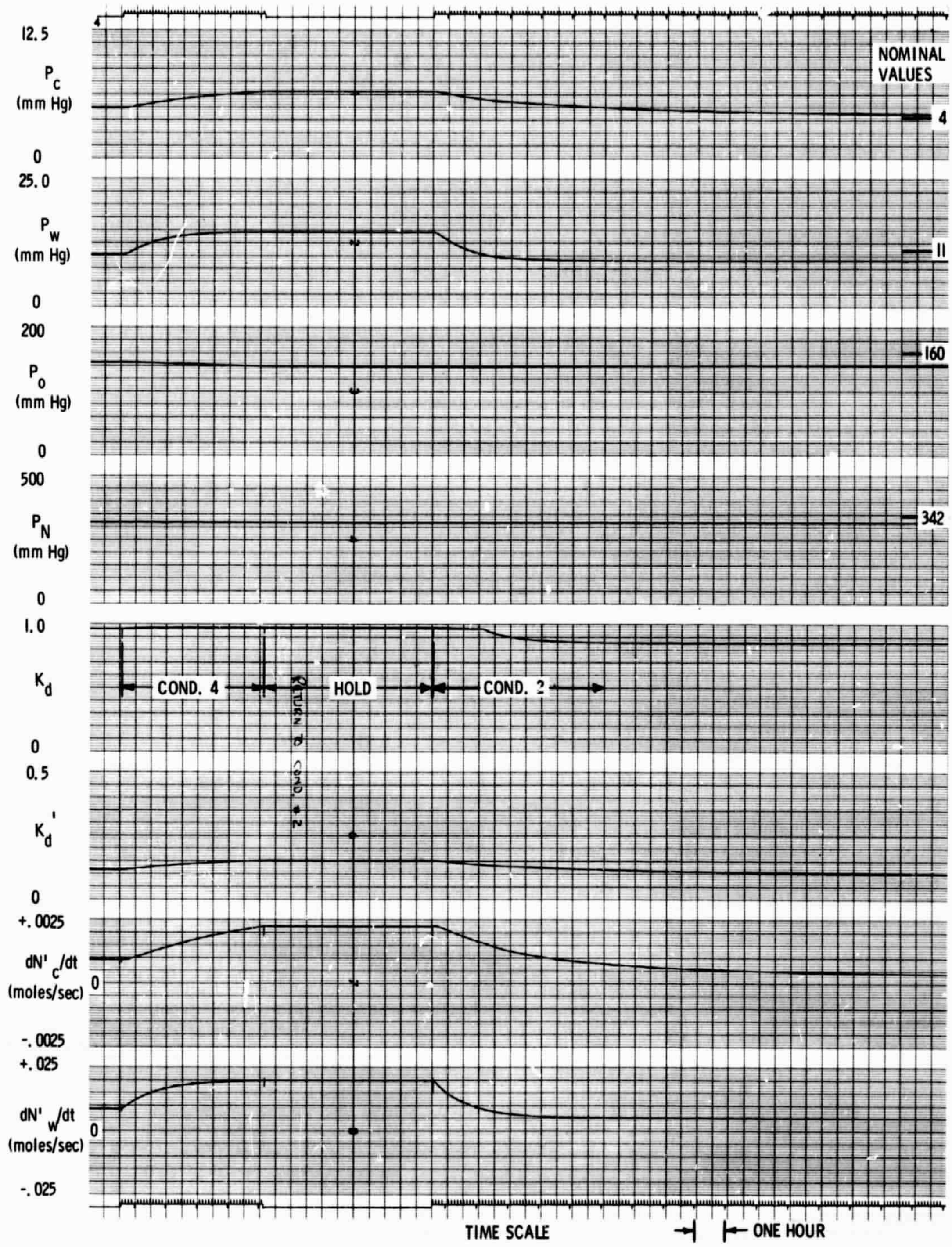



Figure 18.- Transient response from COND. 2 - COND. 4 - COND. 2.

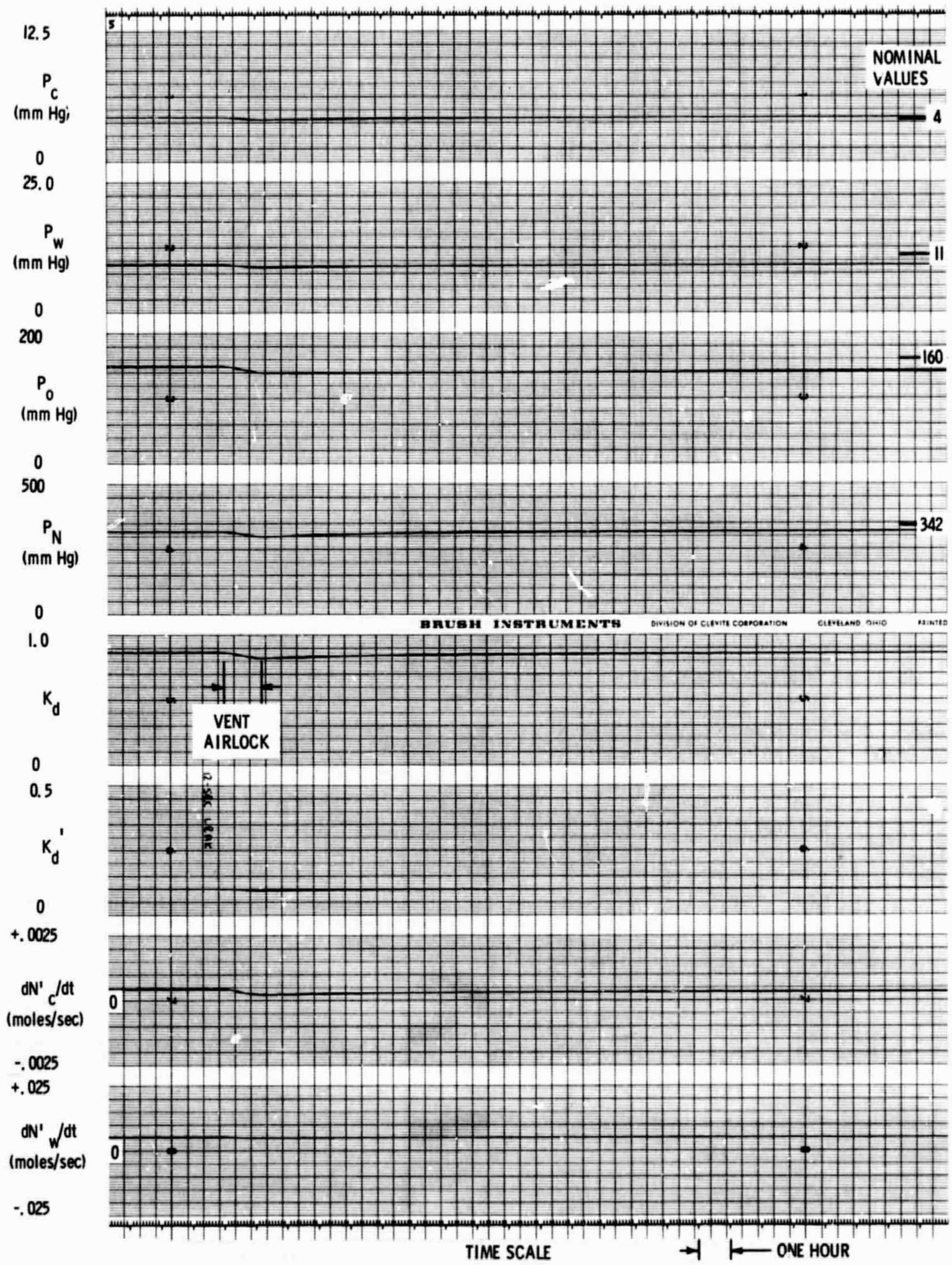



Figure 19.- Transient response to air lock venting at COND.2.

metabolic load causes $P_W$ and $P_C$ to increase, with resultant change in the setting of $K_d$ and $K_d'$. The partial pressure of $P_O$ decreases slightly as the electrolysis unit resets along the proportional curve to satisfy the increased demand for oxygen.

Transient response from crew condition 2 to crew condition 3 is shown on Figure 17. While continuous operation is not required in condition 3, this load condition was imposed to evaluate the long term effects. Figure 17 shows that $P_C$ and $P_W$ will stabilize, but $P_O$ continues to degenerate, indicating that the oxygen demand exceeds the supply in this condition.

Figure 18 shows the transient response of the system from steady-state crew condition 2 to crew condition 4, representing an emergency situation and not a continuous operating condition. However, even with this sudden transient condition, the cabin atmosphere control system is seen to be very stable and responds in the classic manner of an over damped system.

Figure 19 shows the response of the system to a simulated venting of the cabin air lock. Under this condition, all of the atmospheric constituents are "bled" from the space cabin in proportion to their mole fraction, with the resultant decrease in partial pressures shown. The most significant factor in this run is the extremely slow recovery of $P_O$ following the transient, indicating that the water electrolysis unit has very little reserve capacity for cabin repressurization.

The transient tests on Figures 15 through 19 have shown that the marginal nature of the water electrolysis unit is apparent from two aspects: the oxygen output is insufficient to satisfy the system requirements at crew loads corresponding to condition 3 or above; and also, the recovery of $P_O$ following a transient is extremely slow, even with the unit operating at full capacity. Later computer runs will show the effect of increased electrolysis unit gain on the system performance.

Figures 20, 21, 22, 23, and 24 provide data on the response of the individual control loops to transient loads, chiefly the leakage situation encountered during air lock venting. Figure 20 shows the quick response of the $N_2$ loop to the air lock venting condition. The $N_2$ makeup flow, $x_{N1}$, is seen to increase in proportion to $P_N$ and then gradually decrease as $P_N$ returns to normal. The mole fraction of $N_2$, $X_N$, remains constant through the air lock venting cycle since all atmospheric constituents are reduced by the same amount. However, $X_N$ increases during the recovery phase because $N_2$ recovers so much faster than $O_2$.

The run of $O_2$ loop response on Figure 21 shows the opposite effect: $X_O$ decreases following the air lock venting due to the extremely slow buildup of $O_2$. The makeup $O_2$, $x_{O2}$, is seen to reach the limit of the electrolysis unit and remain at the limit for several hours before $O_2$ recovery becomes effective. Note that the oxygen load requirement, $x_{O1}$, was reduced during the run to hasten the recovery of $O_2$.

Figure 22 shows the response of various parameters in the $CO_2$ loop to the effect of the air lock venting cycle. It is noted that the $CO_2$ venting rate experienced during this computer run was 10 times greater than it should be due to an error in pot setting on the computer.

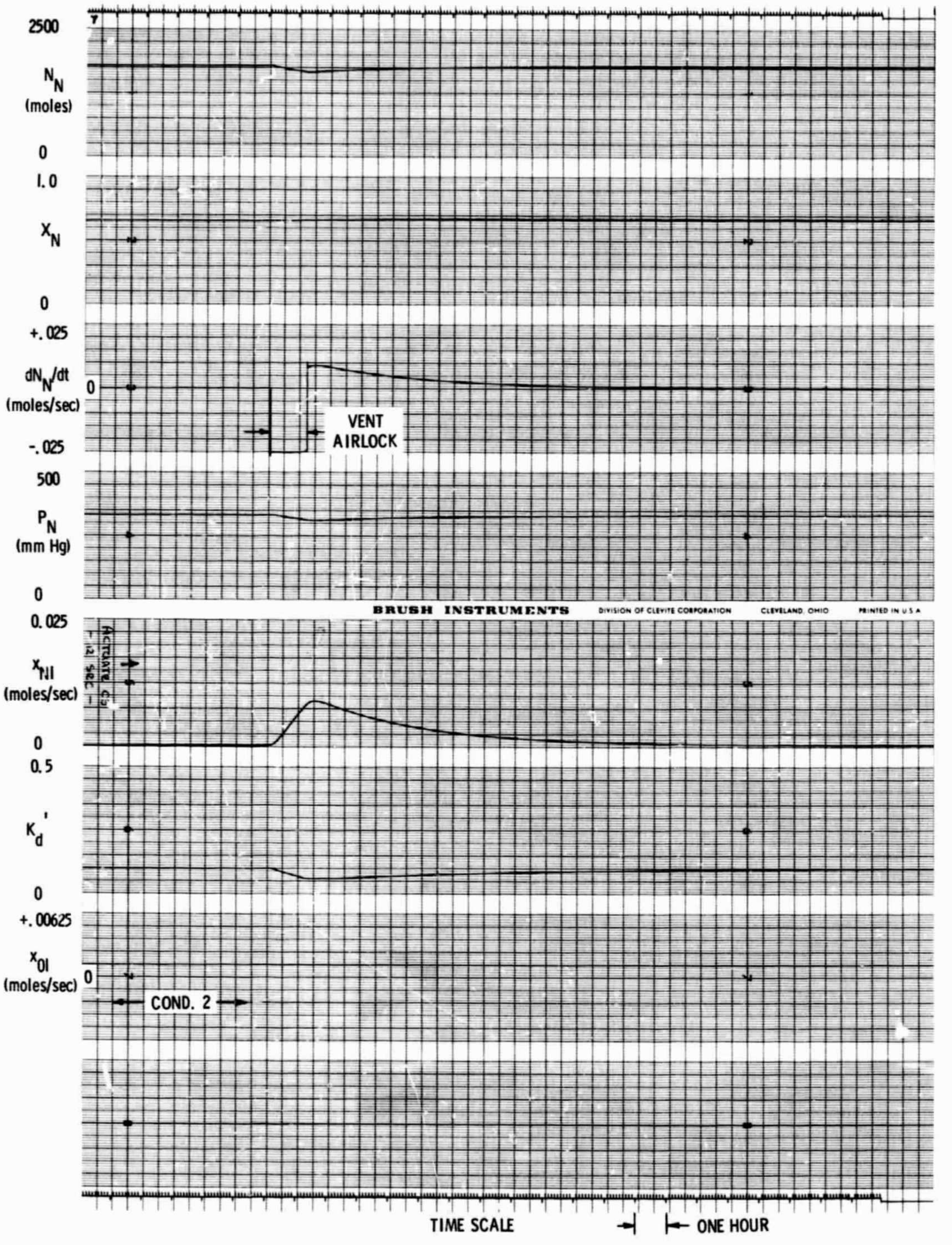



Figure 20.- $N_2$ loop response to air lock venting.

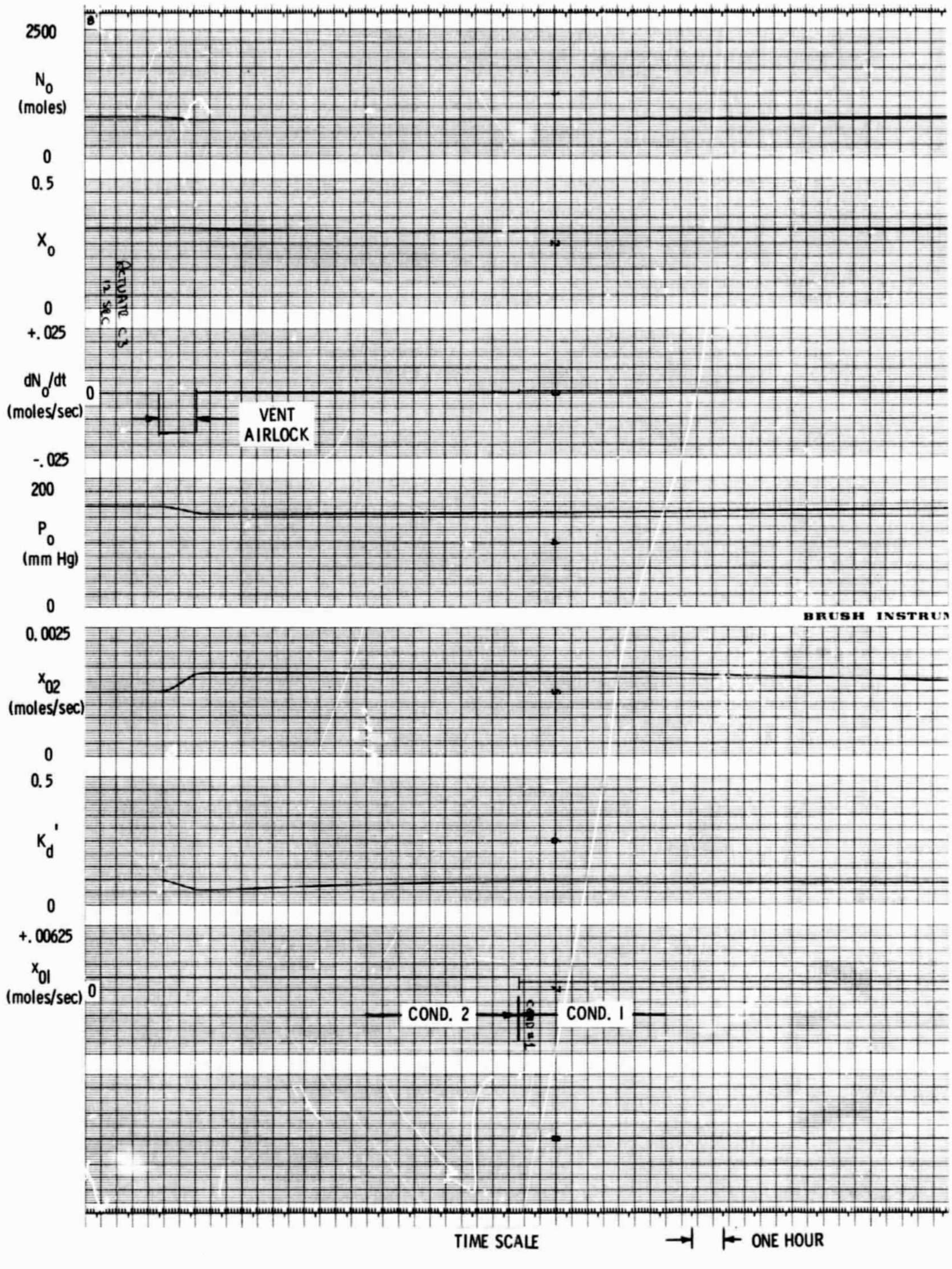



Figure 21.- $O_2$ loop response to air lock venting.

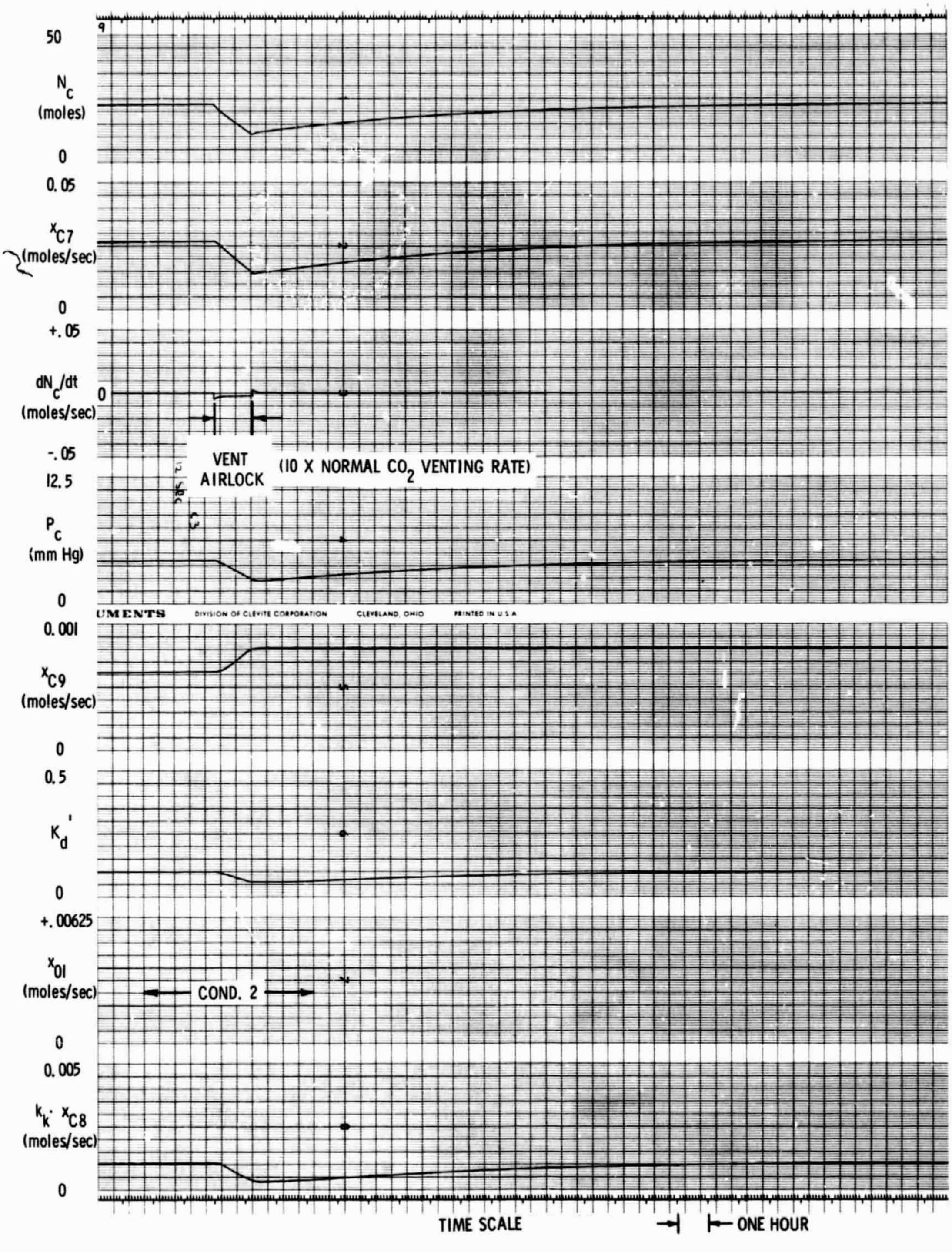



Figure 22.- $CO_2$ loop response to air lock venting.

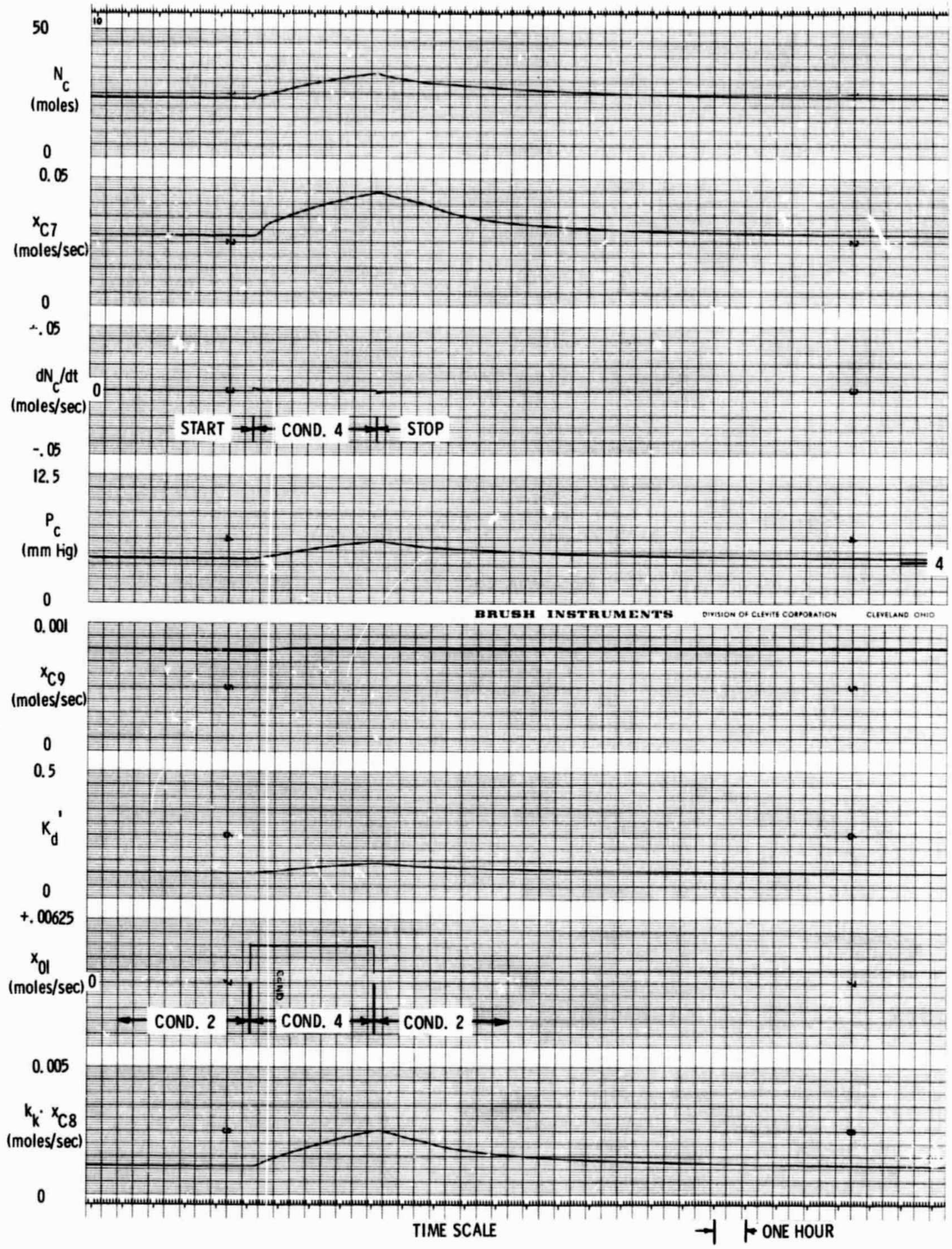



Figure 23.- $CO_2$ loop response from COND. 2 to COND. 4.

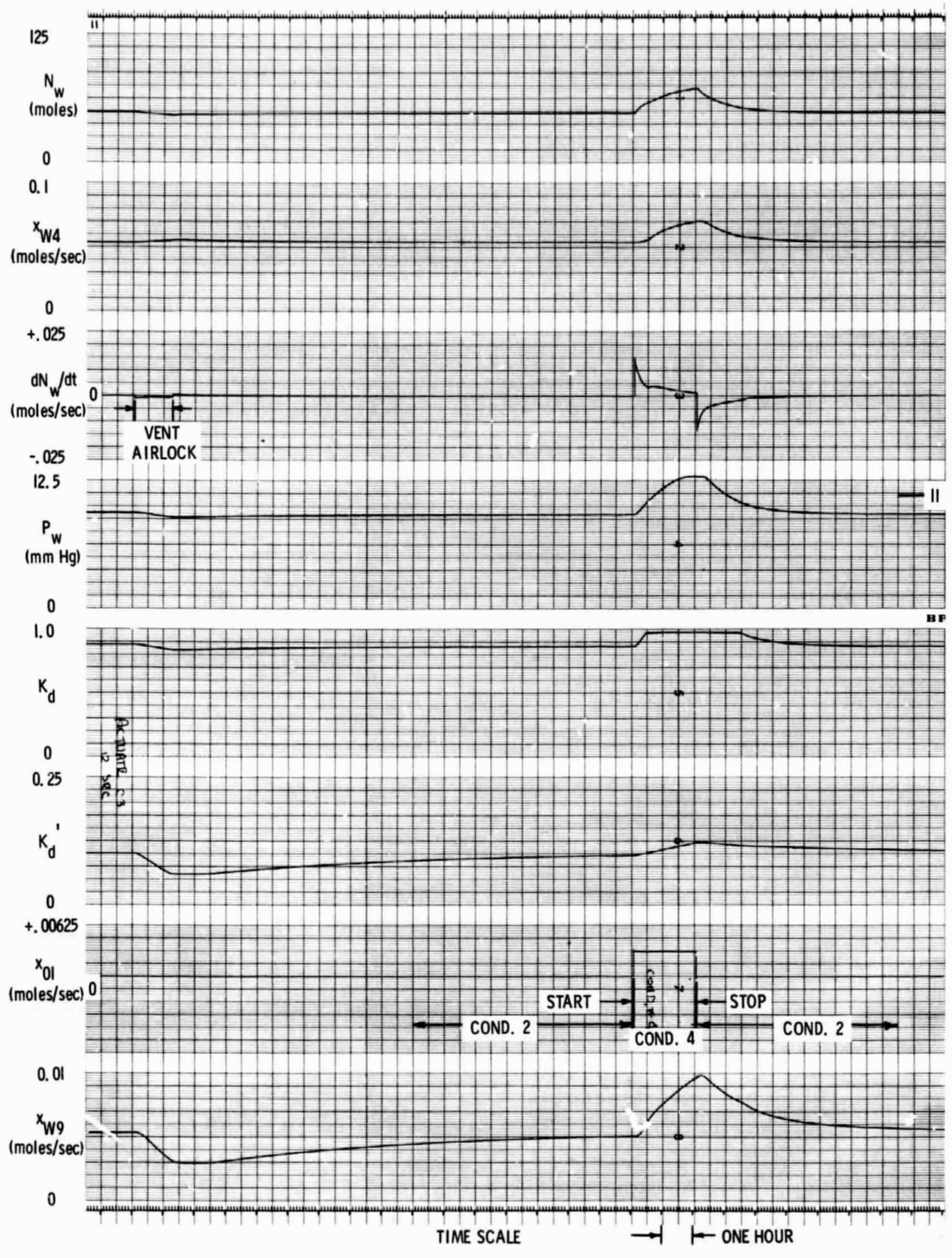



Figure 24.- $H_2O$ loop response to air lock venting and COND. 4.

This error does not appear in any of the other computer runs and computer scheduling problems, when the error was discovered, precluded a repeat of this run. The general information contained on this trace seemed to warrant including it in the thesis. The reduction of $P_C$ is seen to result in a reset of bypass damper "B" position, $K_d'$, to the maximum closed position. The rate of $CO_2$ removal from the cabin atmosphere, $K_k \cdot x_{C8}$, decreases accordingly. Meanwhile, the rate of $CO_2$ flow to the $CO_2$ reduction unit, $x_{C9}$, increases to accommodate the increased flow of $H_2$ from the water electrolysis unit which was shown on Figure 21 to be operating at its maximum rate.

Figure 23 shows the response of the $CO_2$ loop to an increase in $CO_2$ production resulting from a 4-hour period in condition 4. The partial pressure of $CO_2$, $P_C$, reaches a peak value of only 6 mm Hg during this time, demonstrating good capacity for the peak load condition.

Figure 24 presents the response of the $H_2O$ loop to both the air lock venting condition and a period of operation at condition 4, when the crew production of gaseous $H_2O$ is at a peak. During the latter condition, the partial pressure of $H_2O$, $P_W$, peaks at a value of about 13 mm Hg, or a nominal relative humidity of about 60 percent, well within the allowable range. Response of the system following both transient extremes is very rapid and satisfactory.

The second series of runs was made with on-off control mechanization of the cabin atmosphere control system. The same control functions which were provided with proportional logic for the previous computer runs, were converted to on-off logic as described in Chapter III.

The distinctive feature of the on-off control operation when compared with proportional control is the stable "limit cycle" type of oscillation within the prescribed on-off deadband with the frequency of oscillation ranging from 1 or 2 hours per cycle to many times that.

Figures 25, 26, 27, and 28 illustrate the operation of the atmospheric control system at the various different crew conditions, which are the reference loads to be considered. Previous computer runs in the proportional control mode emphasized the response of the atmospheric control system to transient loads, such as a change from one crew condition to another. With the on-off control system, more emphasis is placed on steady-state operation of the control system. The reason for this, of course, is that the on-off control elements operate in only two positions - either maximum function or minimum function. The transient response thus depends on the position of the controlled variable within the on-off deadband and the system response to a sudden change in load is not necessarily significant.

Figure 25 shows the steady-state operation of the atmospheric control system in crew condition 1, the minimum load condition. Operation of the various components is also at a relative minimum. The $CO_2$ concentrator operation, as shown by $K_d'$, is at a minimum with the exception of one 6-hour period when it operates at "maximum" to decrease the $CO_2$ concentration in the atmosphere. The water electrolysis unit is also at "maximum" during the first few hours of operation but resets to "minimum" when $P_O$ reaches the prescribed value. On-off control operation in crew condition 2, as shown on Figure 26, is little different from

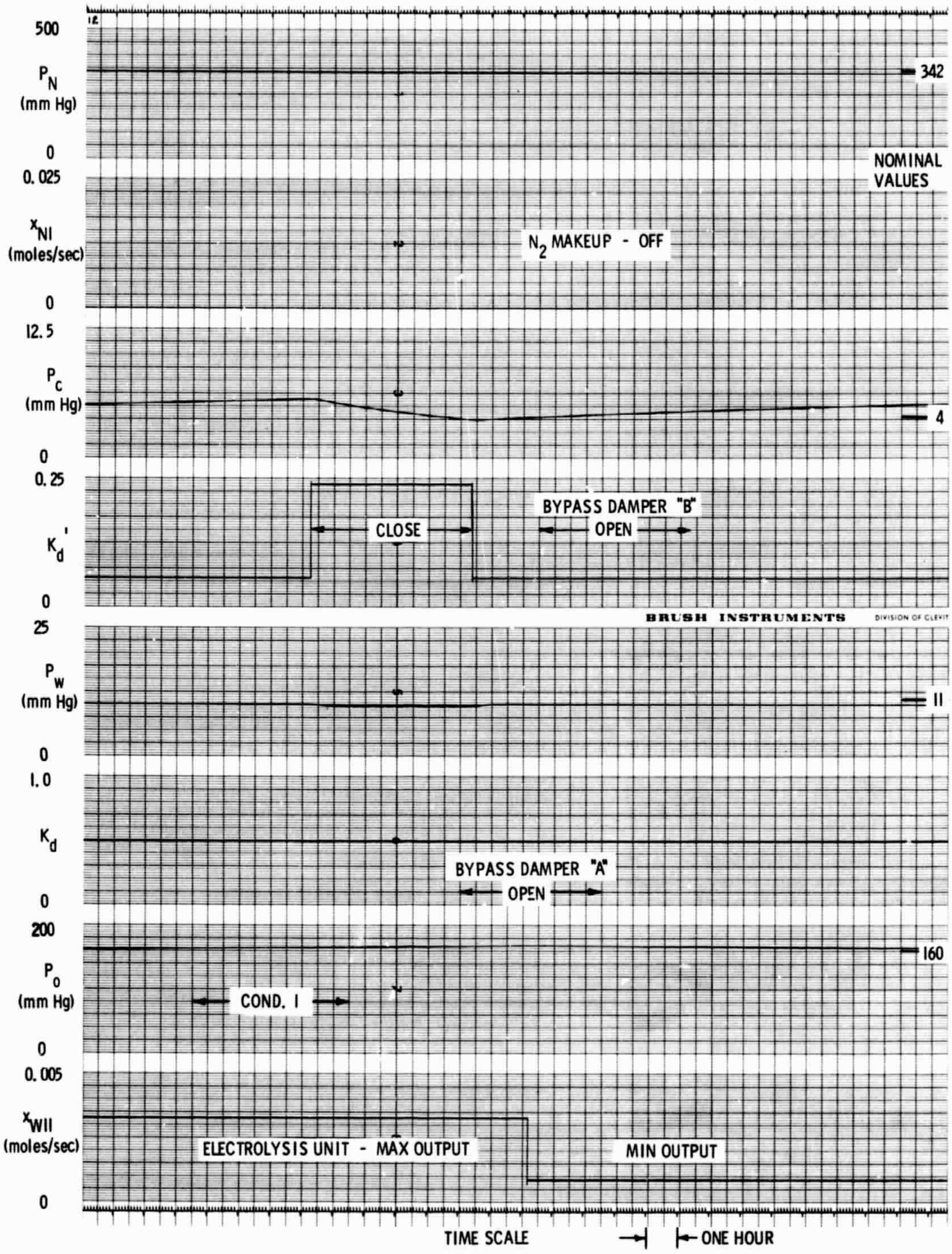



Figure 25.- On-off control operation in COND. 1.

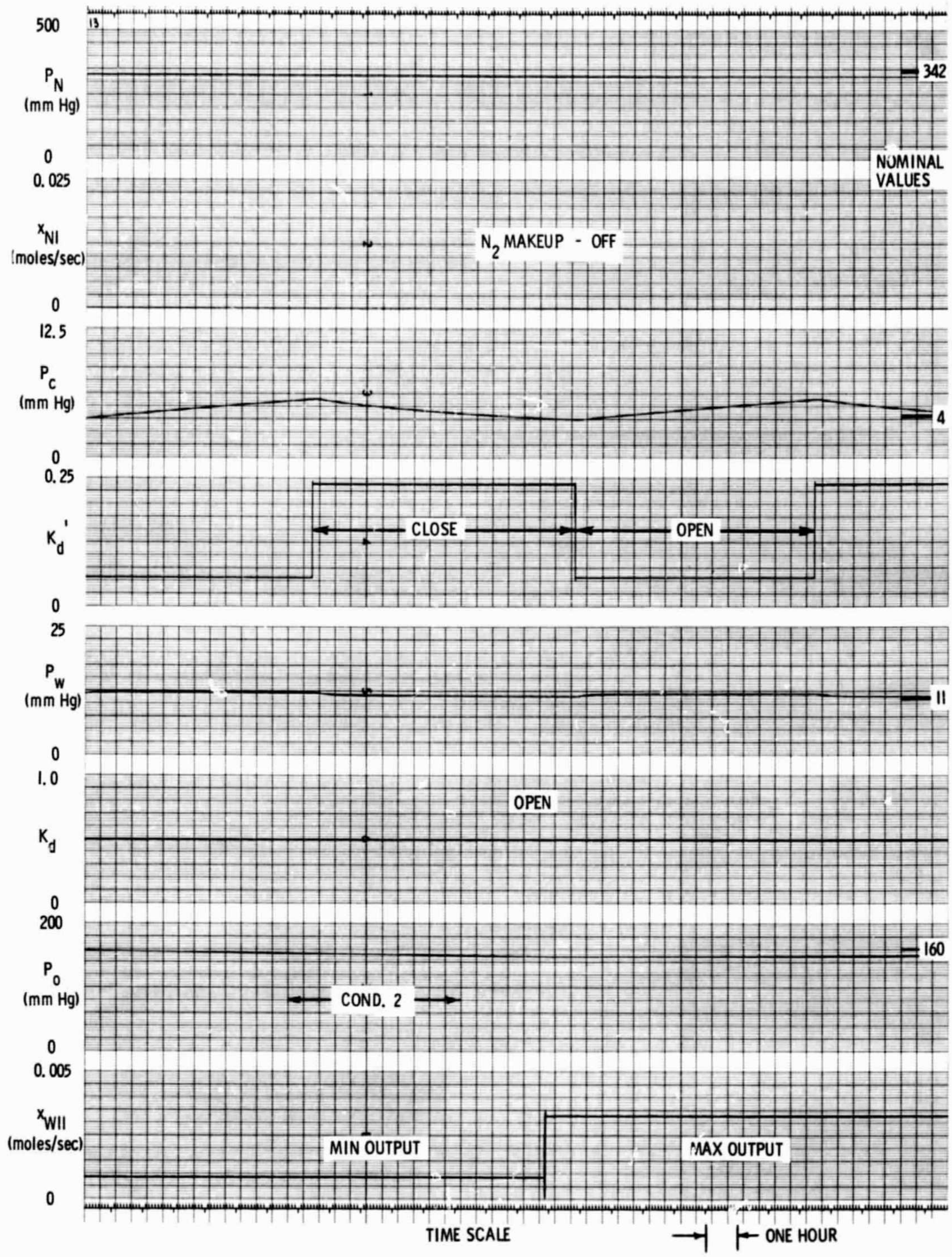



Figure 26.- On-off control operation in COND. 2.

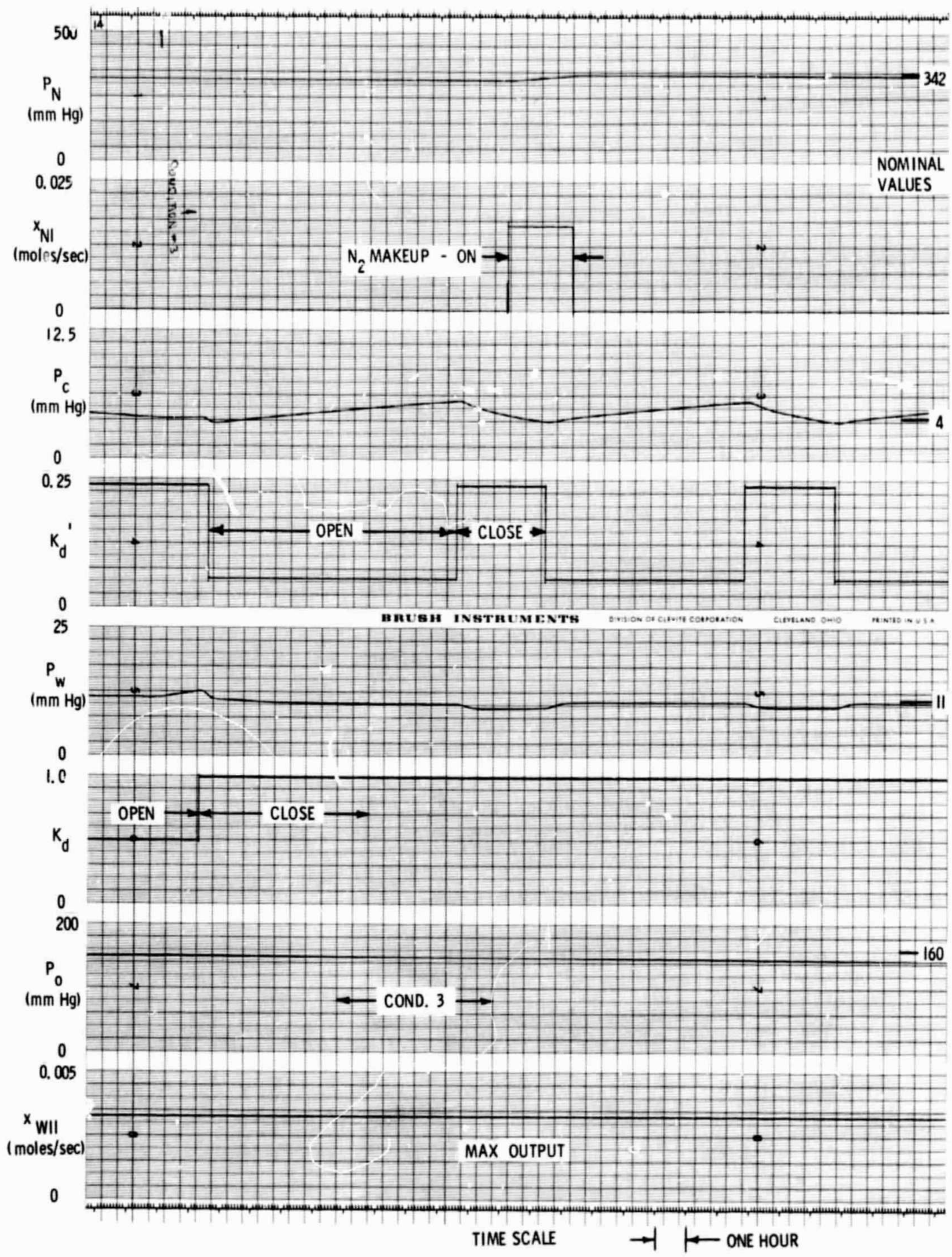



Figure 27.- On-off control operation in COND. 3.

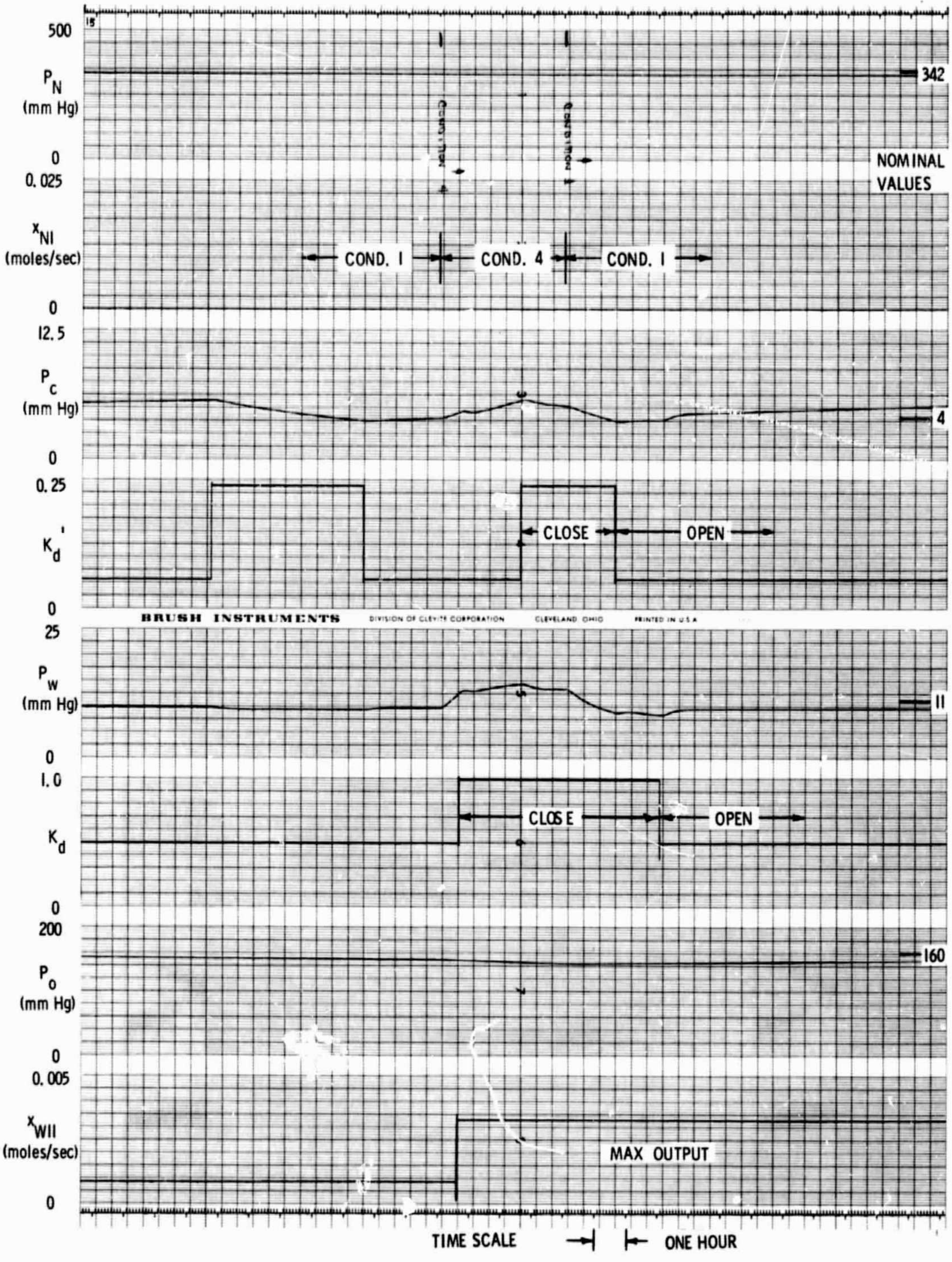



Figure 28.- On-off control response from COND. 1 - COND. 4 - COND. 1

condition 1, except that the cycling frequency of $K_d'$ is increased due to the increased rate of $CO_2$ generation. Some interaction between the $H_2O$ and $CO_2$ loops, and corresponding bypass damper "A" and bypass damper "B" is evident from the traces when actuation of damper "B," $K_d$, causes a sympathetic change in the value of $P_W$. This results since the closing of $K_d'$ to allow more $CO_2$ to pass through the $CO_2$ concentrator, also causes more $H_2O$ to recirculate back through the cabin air water separator.

In crew condition 3, shown on Figure 27, all control functions are active during various portions of the run. The $N_2$ controller actuates to replace $N_2$ lost due to normal cabin leakage; bypass damper "B" ($K_d'$) continues to cycle periodically; bypass damper "A" ($K_d$) resets to its maximum value; and the water electrolysis unit is operating at "maximum" but still unable to maintain the value of $P_O$. Control system operation during and after a condition 4 load situation is shown on Figure 28.

The effect of on-off deadband width on the system response is evident from Figures 29, 30, and 31. The reduced deadband width not only increases the cycling rate as could be expected, but also results in a type of system instability due to the interaction of the $H_2O$ and $CO_2$ loops. The effect in condition 3 is particularly serious, since the oscillation results in variations of relative humidity from 45 to 60 percent over a 1.2-hour period. This much change would probably be noticeable to the crew and thus would be undesirable. This case illustrates the value of checking system performance to determine the effect of changes in the control components.

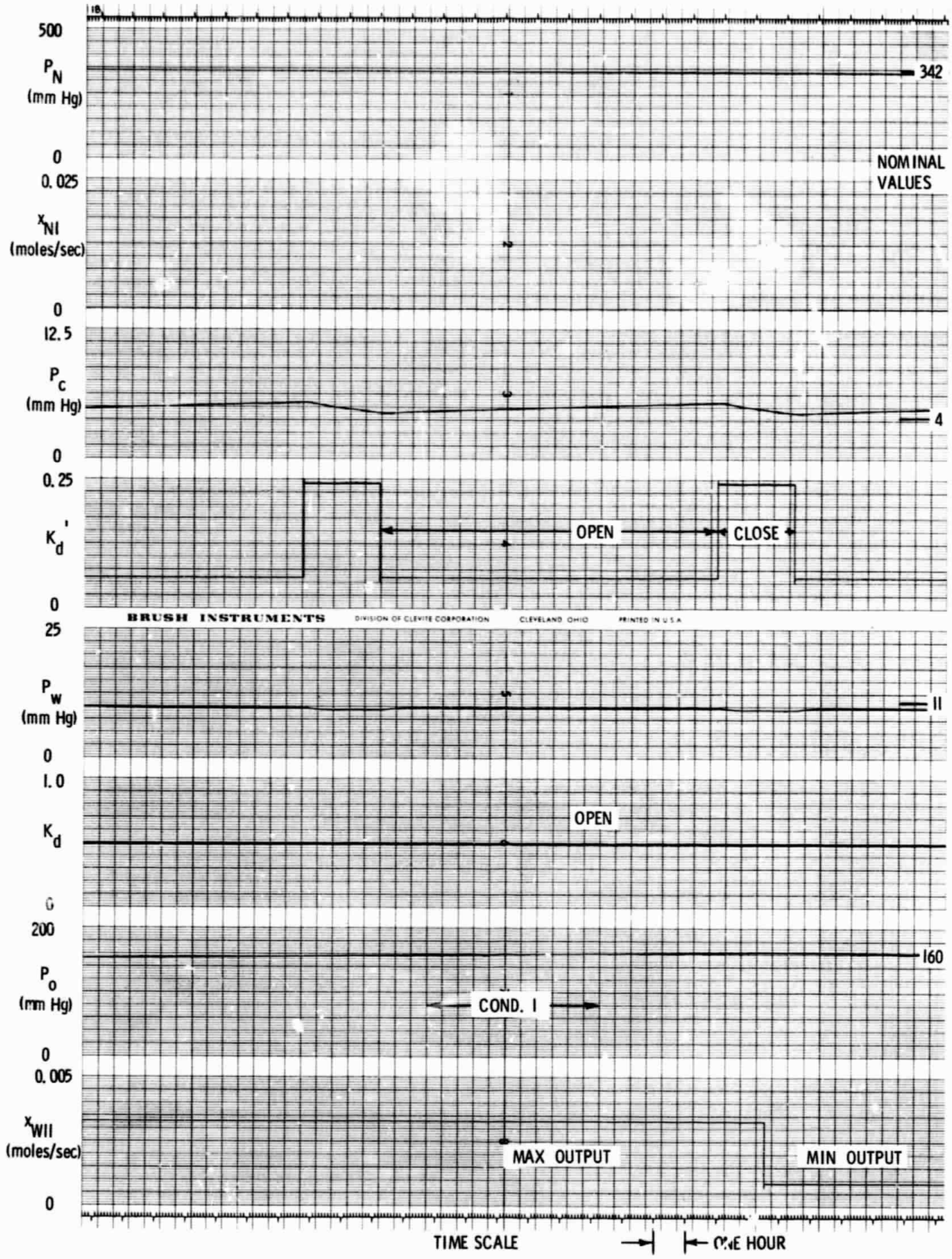



Figure 29.- Narrow deadband operation in COND. 1

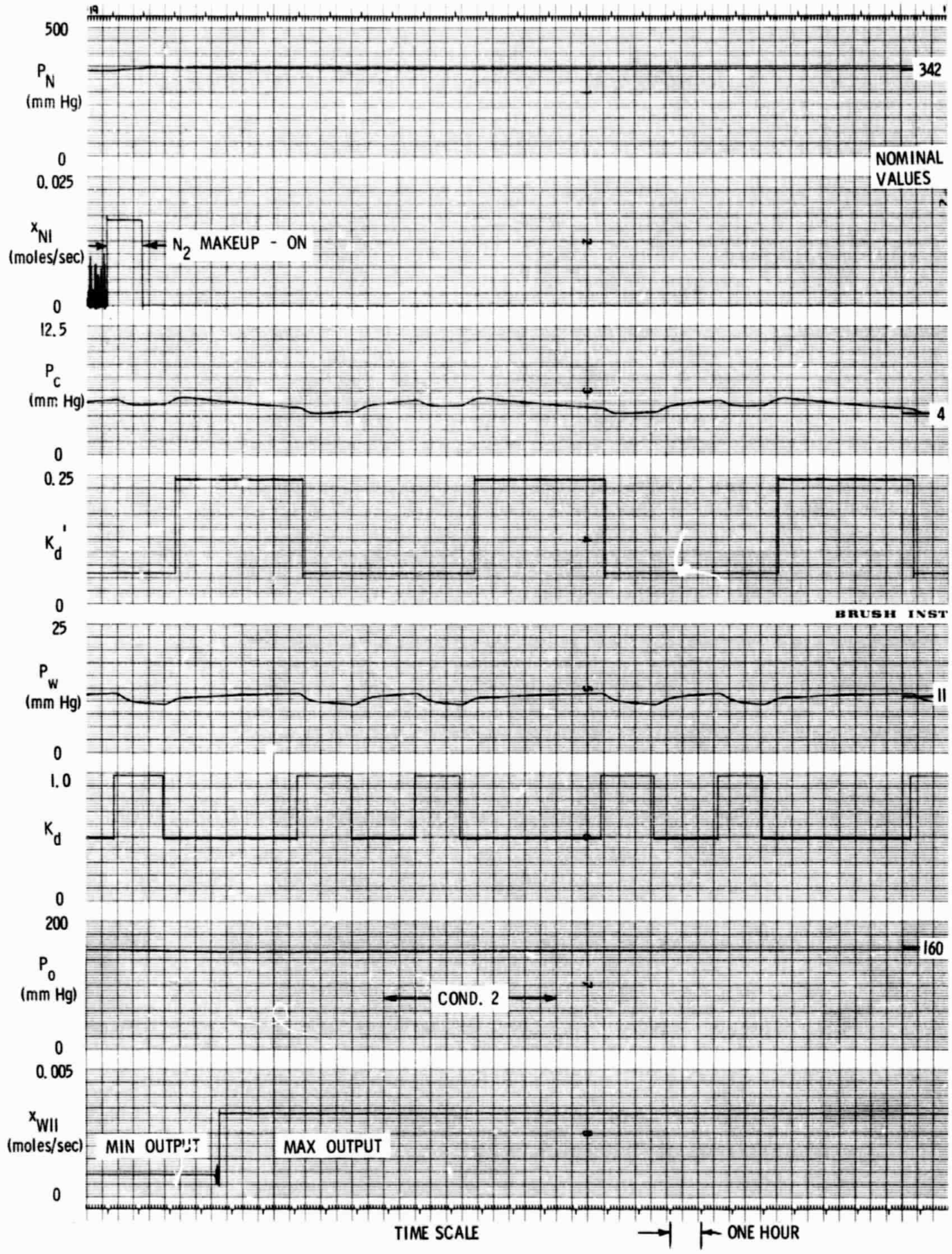



Figure 30.- Narrow deadband operation in COND. 2.

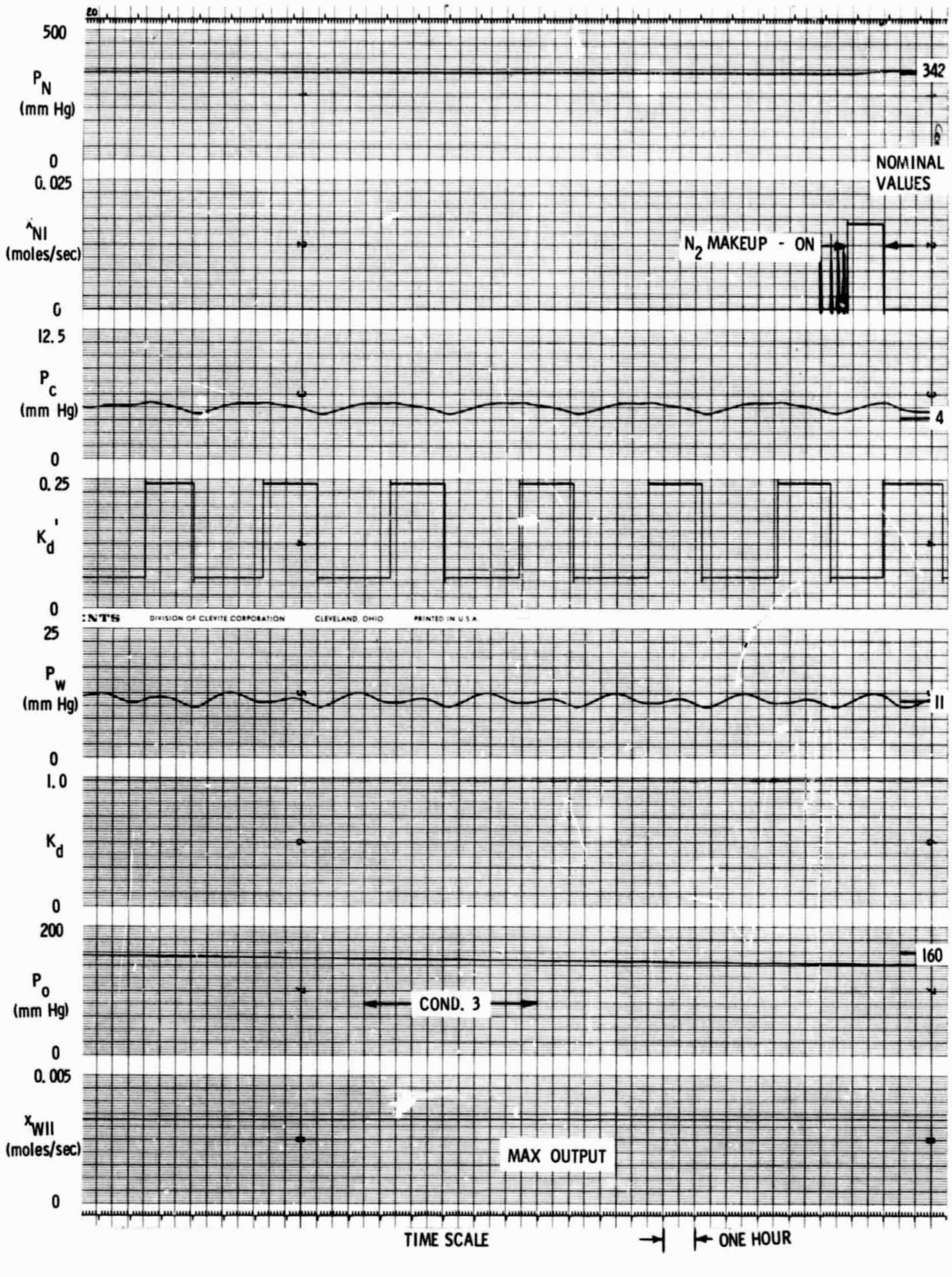



Figure 31.- Narrow deadband operation in COND. 3.

A direct comparison was made between the proportional mode of control and the on-off mode by means of a simulated 24-hour run of the system with load changes such as might occur in an actual space system. The selected schedule of daily events is shown on each chart and includes events such as an emergency situation with the $CO_2$ concentrator inoperative for 1 hour; two air lock venting cycles to permit two additional crew members to visit the space cabin for a 4-hour period; and the shutdown of the cabin air water separator for a 1-hour period for routine maintenance.

The proportional control system run is shown on Figure 32 and the corresponding on-off control system run is on Figure 33. Comparison of the two shows that the variation of controlled parameters appears to be slightly less for the proportional control system.

Additional "typical day" runs with variations of the on-off control system are found on Figures 34 and 35. The "Mod 1" system of Figure 34, features a water electrolysis unit with higher output to enhance the performance of the $O_2$ control loop. The "Mod 2" on-off system of Figure 35 has a higher gain unit with the narrow deadband feature, to provide closer regulation of the controlled variables. The two systems offer comparable performance and generally indicate the type of control which can be obtained with an active control system.

The control of $P_O$ is greatly improved by the increased gain of the water electrolysis unit. As discussed in Chapter III, such a wide variation in output of the electrolysis unit would probably require parallel redundant units on a standby basis. However, such an arrangement

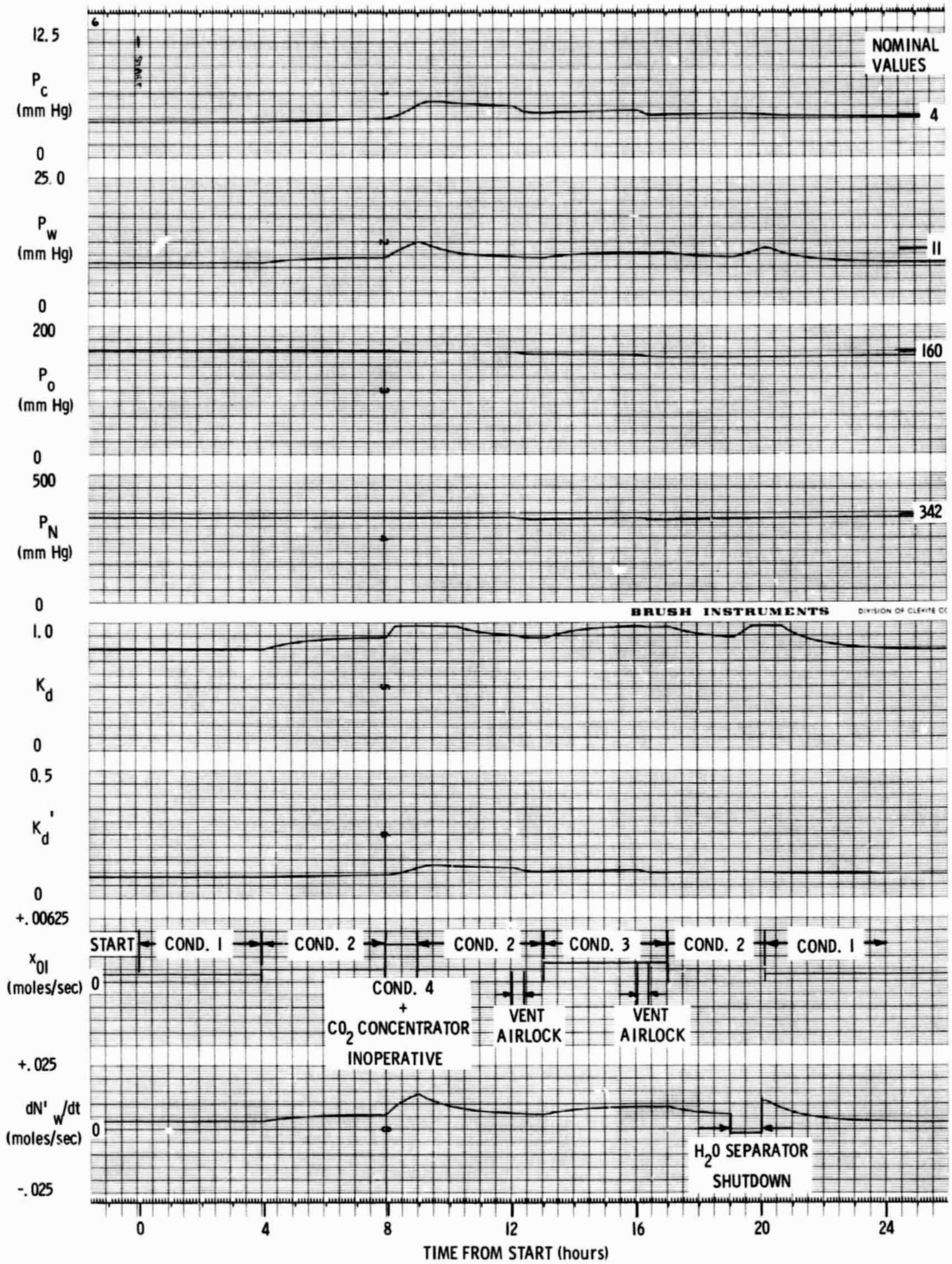



Figure 32.- Typical day run - proportional control.

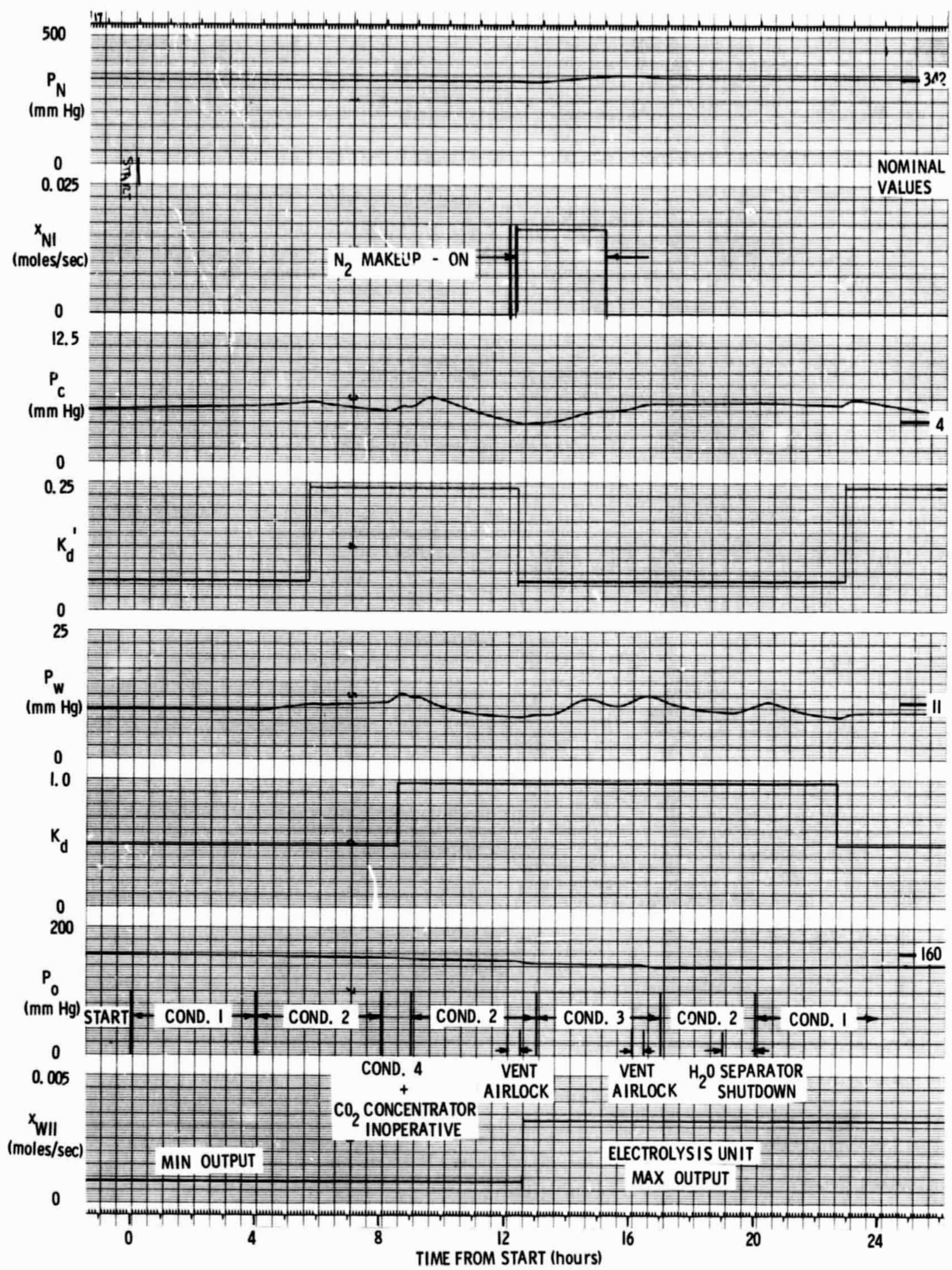



Figure 33.- Typical day run - on-off control.

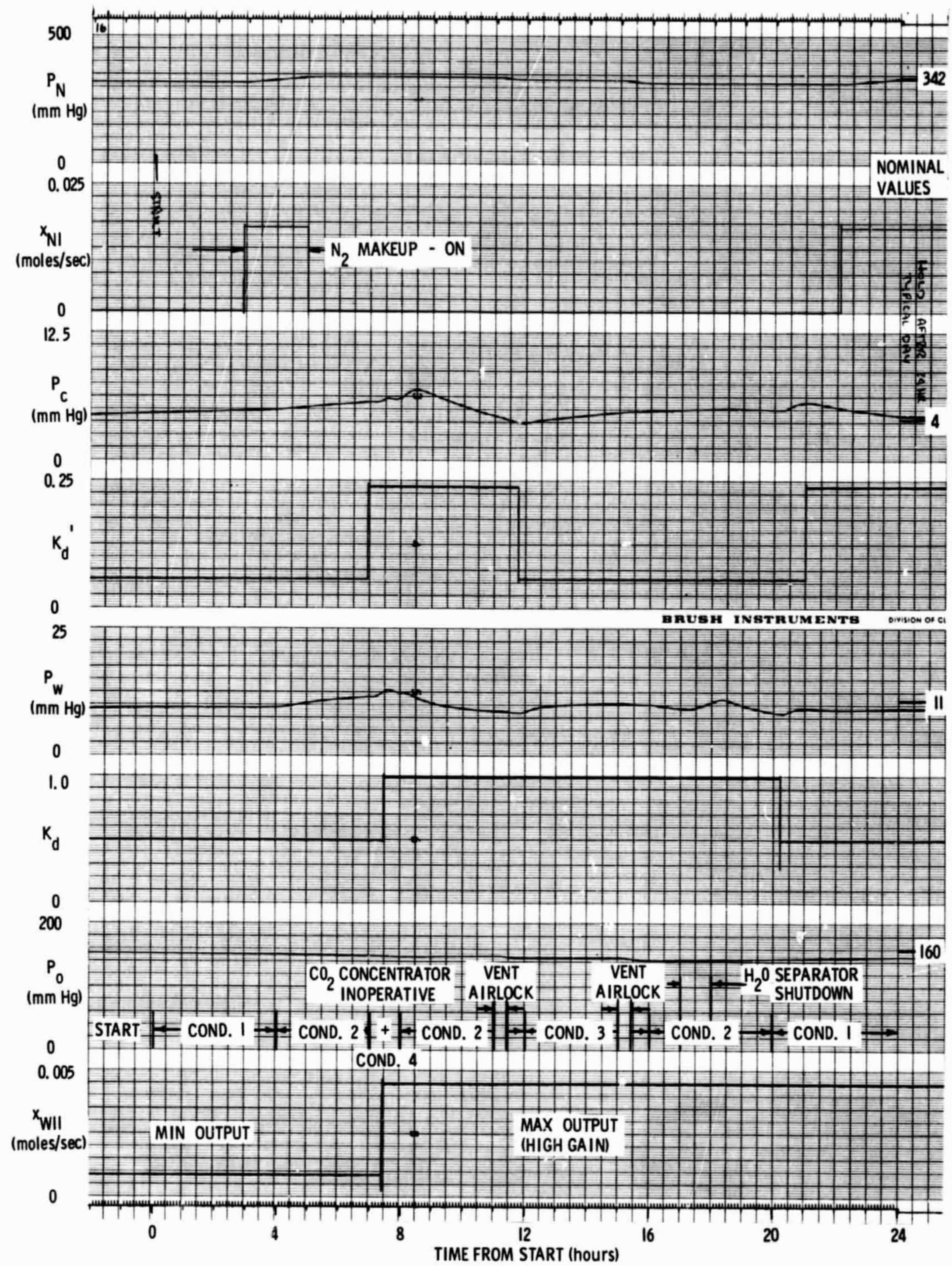



Figure 34.- Typical day run - on-off control - Mod. 1.

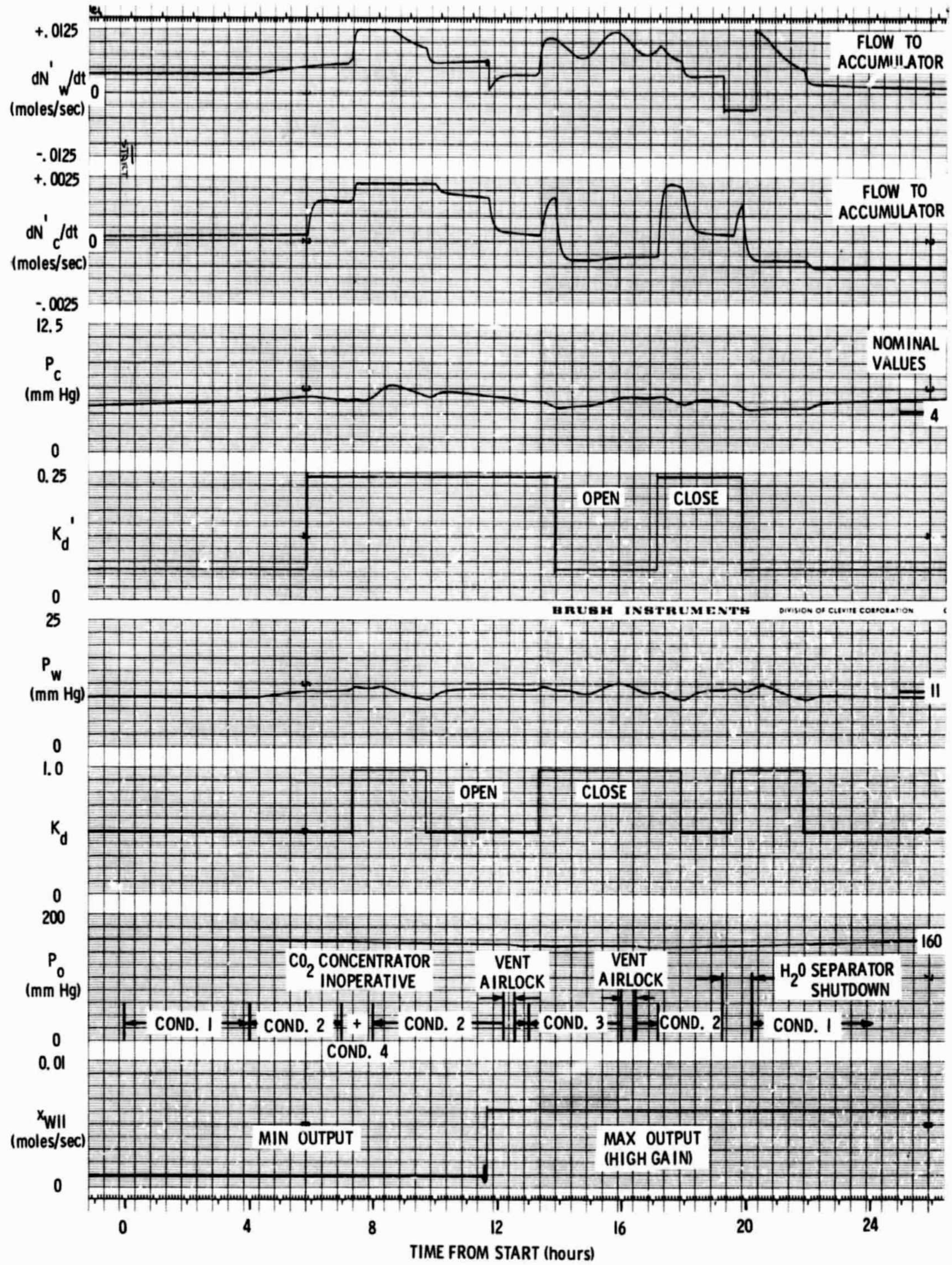



Figure 35.- Typical day run - on-off control - Mod. 2.

would seem most desirable since it would provide a redundant capability for this important component and would also provide the capability for partial cabin repressurization.

Figure 35 includes plots of $\frac{dN'_W}{dt}$ and $\frac{dN'_C}{dt}$, the mass flow rates of $H_2O$ and $CO_2$, respectively, to the system accumulators. These traces show the daily variations in mass flows to the storage elements of the system and can be used to determine the necessary sizes of the accumulators.

# CHAPTER VI

## REVIEW OF THE LITERATURE

This chapter summarizes the results of a literature survey on subjects related to the life support systems of interest. Three separate automated literature searches were conducted through information stored at the NASA Scientific and Technical Information Facility, and including references from 1962 to date. Older card files were also reviewed, but the most pertinent findings were generally of recent issue.

The topics covered in the literature searches included the following:

(1) Chemical Reactions of Hydrocarbons (NASA Literature Search No. 2916). This literature search identified references pertinent to chemical reactions of hydrocarbons including zero gravity effects and reduction of carbon dioxide. A total of 230 citations were identified by this search.

(2) Life Support Systems (NASA Literature Search No. L8030M). This search identified references in the general area of life support systems, closed ecological systems, carbon dioxide concentration and removal, and oxygen systems. A total of 350 references were identified by this search.

(3) Processes for Life Support Systems (NASA Literature Search No. L8032S). This search was designed to identify references about specific life support system processes including carbon dioxide reduction, oxygen regeneration, and methanation of carbon dioxide and

hydrogen (Sabatier process). This search identified more than 250 additional references pertinent to the study.

The most applicable references were selected from the above summaries for detailed review and are listed as References at the end of this thesis. The references of interest can generally be classified into four major categories as follows: human factors in life support systems, system aspects of life support, life support system components, and control and integration of life support systems.

The category of "human factors in life support systems" includes topics such as physiological effects of the cabin atmosphere and atmospheric control requirements. References in this category are of interest chiefly in determining the requirements of an atmospheric control system for use in manned space flight.

References classified under "system aspects of life support" deal with the total space mission requirements of life support, life support system constraints resulting from the overall mission, general life support system requirements applicable to all manned missions, or contain the results of actual life support system tests.

The category of "life support system components" includes references which are generally limited to the design considerations of specific components for use in life support systems. These components might include carbon dioxide concentrators and reducers, oxygen regeneration equipment, and instrumentation and control equipment. The chief value of these references is for the determination of typical characteristics for system evaluation.

The final major category of "control and integration of life support systems" includes references which relate directly to the subject of the thesis. These references, which are very limited in number, contain information on the control and regulation of life support systems, the system integration aspects of life support, or report on the closed-loop analysis of life support systems.

Many other references in the life support area were not included because they were not deemed directly pertinent to this study. References on life support systems utilizing active chemicals were generally not included because of the nonregenerative nature of such systems. References on the biological types of life support systems (algal systems) were not included since these totally closed systems were beyond the scope of this study. Other references dealing with relatively recent or advanced physico-chemical life support systems still in a state of development were also omitted. These include the solid electrolyte concepts, the electrochemical reduction cell, and systems using the higher order hydrocarbon reactions typified by the Fischer-Tropsch processes.

The category of human factors in space flight has received considerable attention, since the primary concern of any manned mission is for the well being of the crew. References in the area of human factors include those items numbered 1, 3, and 7 to 22.

Several good survey articles have appeared in the technical literature; References 7 and 8 are typical of these. There are also several text references which cover the various aspects of life support;

References 9 and 10 provide particularly good discussions on metabolic requirements; References 11, 12, and 13 relate human factors to the required life support systems.

Many excellent technical reports are available on the subject of human factors; the paper by Dryden, et al. (Ref. 14), was written primarily for aircraft application, but provides such extensive background data that it is considered by some to be a classic in the field. Another outstanding paper written under Air Force sponsorship is Reference 15.

There are many Russian papers available in the area of human factors but most of then tend to be descriptive in nature with few details. References 16 and 17 generally indicate that Soviet and American cabin atmosphere standards are virtually the same.

The question of a one-gas versus two-gas spacecraft atmosphere has received considerable attention. Reference 3 is probably the most authoritative and impartial on the subject. References 18, 19, and 20 also consider the problem for more specific missions.

References of a more general nature include the "Bioastronautics Data Book," Reference 21, which is a compilation of all types of data on the human organism. Reference 22 is an annotated bibliography which was helpful in reviewing some of the earlier references. Reference 1, the summary report on the Langley - ILSS system, provides a good discussion of the human factors considerations for the mission types of interest in this study.

The category of "system aspects of life suppor ɪas also received much attention, since any proposed manned mission must demonstrate the feasibility of integrating the life support function with the basic vehicle concept. References in this category include those numbered 1 and 23 to 49. Perhaps the most basic approach to the life support problem has been the attempt to compare space cabin life with man's ecological surroundings on earth; Reference 23 was very effective in this regard. Many articles have appeared in periodicals on life support systems; those listed here include References 24 to 32.

The Air Force has been interested in life support systems for many different types of missions. Reference 33 analyzed many different types of environmental control systems; the Space Vehicle Symposium reported in Reference provided several interesting papers.

Other papers have studied the life support requirements for a variety of missions; however, it seems that the studies are often biased by the author's familiarity with a specific type of system. Typical references which have considered various manned missions include References 35 to 42. The chief value of these references is in providing a background of the current thinking of those in the life support business.

A group of references relate to the design or testing of chamber facilities for manned or simulated manned testing in a closed environment. Work done on the ILSS at NASA-Langley Research Center is described by References 1 and 43; additional data which are not available for reference were also reviewed during this study. Early work done in the Douglas space cabin simulator is reported in Reference 44. Manned tests at Boeing are discussed in References 45 and 46; work at North American is described in Reference 47. Recent tests at Lockheed are described in Reference 48.

It is worth noting that all of these various tests have been operated on a laboratory type basis, generally under controlled conditions and with a minimum of automatic control functions. Off-limits testing or transient type of testing has rarely been attempted in tests run to date and so information on the automatic control problem is very limited.

In a general category, Reference 49 concludes that American and Soviet manned missions toward the same goals will result in similar life support approaches, due to the inherent mission constraints.

Extensive work has been done in the area of components for life support systems since some of the developments in areas such as submarine atmosphere control are relevant to the space life support problem. The references on components are numbered 1, 4, 5, 23, and 50 to 84. General survey type articles are represented by References 50 and 51. Reference 52 and the McConnaughey paper in Reference 53 are typical of reports available on the submarine work, but there is little mention of the automatic control problem in this area.

Many references were found relating to the adsorption of carbon dioxide by molecular sieve materials. References 4, 54, and 55 provide a fair theoretical background for the adsorption phenomena but emphasize the difficulty of an analytical approach. Other references on the problem of carbon dioxide removal from the atmosphere include References 5, 56 to 60, and the papers in Reference 53 by Hsu and Arnoldi.

The related problem of carbon dioxide reduction has also received ample attention in the literature. Some of the earlier work in this area was done at the Battelle Memorial Institute and was reported by Foster in References 53, 61, and 62. Background on the Sabatier reduction process can be found in Reference 63 and in the papers by Dole and Weller in Reference 53. Other papers on various aspects of carbon dioxide reduction include References 6 and 64 to 71

More general papers on various life support system components, including instrumentation and water electrolysis units, are listed here for their value as general background material and include References 23 and 72 to 82. Reference 83 provides some information on Russian work with active chemicals. Information on the components used in the Langley ILSS, as contained in References 1 and 84, was used extensively in this study since the components are so representative.

The final category of control and integration of life support systems relates most directly to the subject of the thesis. The available reports on this subject were very limited, partly, it is believed, because of the preoccupation with trying to simply understand how the basic systems perform. In addition, some of the work done in this area has been funded by individual companies who are reluctant to disseminate the detailed information for competitive reasons. Some of the references in this category have been previously cited and include References 1, 2, 6, 30, 53, 56, 63, 66, 67, 68, 73, and 85 to 93.

Several references have cited the need for automatic control of life support systems or have attempted to outline the control problem; References 56, 63, 66, 67, 68, 73, 85, and 86 are in this category. Some references have been concerned with the analytical description of component performance, such that control laws might be developed. The various reduction processes have been the object of much study in this regard. Reference 6 went to considerable length to develop a chemical equilibrium theory for the carbon dioxide reduction system (Bosch process). However, the conclusions regarding the actual model test results report that "the reaction . . . is predominantly influenced by kinetic effects rather than by chemical equilibrium effects." Reference 87 noted that "the research (on atmospheric control systems) has largely been centered about . . . development of analytical procedures for the steady state processes . . ."

Several references have stressed the need for integration of th life support systems with the overall spacecraft and mission. References 88 and 89 stress the need for overall system integration to achieve an optimized life support system design. Reference 88 also shows material balances for a typical four-man system (Langley ILSS) but dynamic system requirements are not mentioned. Reference 90 also points out the need for integration of the life support system with the overall system energy management. Such considerations have not been included in this study in an attempt to minimize the number of restrictions on the system. However, system energy considerations may be expected to impose further constraints on the operation of the life support systems.

A paper by Benaway, from the "Closed Circuit Respiratory Systems Symposium" held at Wright Field in 1960, describes some of the problems of maintaining cabin atmosphere composition and pressure, with emphasis on the need to control both cabin total pressure and oxygen partial pressure (Ref. 53).

Reference 30 describes some Boeing work in the field of life support systems. Reference is made to an analog computer study, but no specific information on the study results is given. Other Boeing documents, not available for reference, have been reviewed including the results of a computer simulation of a carbon dioxide adsorbent bed. The results indicate that analog models can be developed to any desired degree of sophistication; however, the approach in this study has been to use simpler component models and place more emphasis on system response.

Reference 1 describes some of the automatic control studies done in support of the Langley ILSS, with more detail provided in Reference 2. This study by General Dynamics/Astronautics was performed prior to the time when actual component data were available and, in addition, was primarily concerned with the internal control of the system components. Considerations of overall system control were based on the assumption of partial manual control and also on fixed-rate component operation. The results of this study were used to establish control procedures for normal operation, but transient effects on the system were not considered. The results provided show that the normal variations of the system are relatively slow; but off-nominal effects were not explored.

A recent reference released since the start of this study describes efforts to obtain a total computer representation of a life support system. Reference 91 by Houck discusses a NASA contracted study with Douglas to develop a digital computer program to solve the thermodynamic-chemical equilibrium equation of an integrated life support system. Emphasis is on the analytical solution of the steady-state mass and energy balance equations related to the Langley ILSS. Models used to simulate the various system components are relatively simple in nature and are similar to some of the approximations used in the thesis study. The program has been used to solve various energy balance problems associated with the Langley ILSS, but little transient system work has been done to date.

Reference 92 provides a good discussion of the general characteristics of automatic process control systems and also defines various types of control. Reference 93 is a general servomechanisms reference.

The review of the published literature in the field of life support systems has not identified any references providing the results of a systems analysis of the regenerative atmospheric control system of interest in this thesis study. The references listed have indicated that most systems effort on the life support systems has been concerned with the necessary preliminary, steady-state material and energy balance relationships. The few analog studies mentioned have generally been designed to explore facets of component control and studies of transient system effects have been neglected.

# CHAPTER VII

## CONCLUSIONS

This study has resulted in the development of a relatively simple mathematical model for a cabin atmosphere control system similar to systems presently being considered for extended, manned space missions. The cabin atmosphere with its human load was considered separately from other life support and spacecraft systems; there was no attempt to impose total system constraints of energy management or thermal management on the cabin atmosphere control system. Rather, the dynamic characteristics of the cabin atmosphere control system were studied with the intent of developing understanding of the system as a separate entity.

An extensive literature search revealed that the actual performance of some of the components proposed for use in the physico-chemical processes is not well defined at the present time. This is particularly true with the carbon dioxide reduction reactor where the process is dependent on suitable catalysis and the chemical equilibrium theory alone does not necessarily define the component performance. A simple empirical model of the reduction reactor was assumed for this system study, so the lack of a precise component model was no problem. However, for other systems studies which might consider the detailed control of the individual components, an improved definition of component performance is needed.

A simplified linear analysis of the model was performed in accordance with the Nyquist stability criterion. This analysis showed that the various individual control loops were very stable and also indicated that replacement of the characteristic system transport lags by "equivalent" time constants did not appreciably affect control loop stability.

However, the value of the Nyquist analysis is limited since, during the transient system operations of interest, many of the components operate in a nonlinear manner, due principally to component saturation. For that reason, the electronic analog computer was emphasized in the analysis of the system.

Two separate analog models were developed; one featuring proportional control with limiting and the other using on-off control methods with a specified deadband. Specific values of the various system parameters were used in the analog model so that some meaningful computer data could be obtained. However, the basic analog program provides sufficient versatility that the system parameters could be varied to suit the requirements of other space cabin models. Steady-state operation of the system at various crew conditions generally resulted in very stable operation, as was expected. Response to simple step changes in load were also very stable and resulted in a type of overdamped system response to a new point of stable operation. Component saturation, particularly in the water electrolysis unit, resulted in very slow recovery to large depletions of oxygen partial pressure.

The most responsive atmospheric components were water vapor and carbon dioxide since the relatively small fraction of these constituents permitted more rapid change in their mole fractions. The water vapor content of the atmosphere was particularly susceptible to increases in the human load or to simulated loss of the water separator function.

The various system transients were also reflected in the mass flows of carbon dioxide and water to the system accumulators. The analog computer provided a time history of these mass flow rates which were seen to vary over a wide range. Such data could be very useful in determining the necessary system storage capacity.

The atmospheric control system models were further evaluated under a simulated 24-hour "typical" day test condition. In comparative test runs, the proportional control generally provided smoother regulation of the controlled variables. The on-off control system, of course, permitted variations of the controlled parameters within the on-off deadbands. Narrowing the on-off deadband provided more accurate regulation but resulted in an undesirable limit cycle oscillation at certain load conditions. Interactions between the various control loops were more apparent in the on-off mode and these interactions undoubtedly contributed to the limit cycle condition.

The occurrence of this limit cycle condition emphasized the importance of system studies such as this to determine the effect of off-nominal operation on a control system. Another significant finding of the study was the marginal capacity of the electrolysis unit to replenish the cabin oxygen following a sudden depletion. It is concluded from this study that cabin atmosphere control systems should be designed with greater oxygen generating capacity and preferably with parallel redundant water electrolysis units.

Many considerations other than system performance will be required in the selection of the cabin atmosphere control system. Consideration of cost and reliability will favor the use of on-off control methods for many of the components. Where operating range and capacity is a problem, as with the electrolysis unit, on-off operation of several parallel units seems to be the answer. However, proportional control could be the choice if steady, continuous operation is desired with a minimum load fluctuction on the related thermal and electrical systems supplying the space cabin.

Future design studies on cabin atmosphere control systems will probably utilize more sophisticated analytical models, however, studies to date have generally deemphasized transient system effects. This study has demonstrated that transient loads can seriously disrupt a system designed solely on the basis of static material balances.

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