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CONTROL ANALYSIS OF A REGENERATIVE CABIN ATMOSPHERE SYSTEM

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16. Abstract

The dynamic aspects of a typical atmosphere control system of the type suitable for earth-orbiting manned missions up to 1 year in length were studied. A dynamic, nonlinear model of the cabin atmosphere system was programed on an electronic analog computer and sample cases were run at various conditions with both proportional and on-off system controllers.

The study demonstrated that the cabin atmosphere control system model was basically stable with both types of controllers under normal operating conditions. Recovery of the system from assumed disturbances such as increased crew activity or cabin air-lock venting was marginal because of the limited capacity of the chosen components. Operation of the system with on-off controllers in an overloaded condition, representing an increase in the number of crew members during a resupply mode, resulted in a type of system instability with slight oscillations in cabin water vapor and carbon dioxide partial pressures. The results of the study indicate that transient system effects must be considered in future design studies of cabin atmosphere control systems for specific manned missions.

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CONTROL ANALYSIS OF A REGENERATIVE CABIN ATMOSPHERE SYSTEM[1]

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SUMMARY

The purpose of this study was to perform a control analysis of a regenerative cabin atmosphere system. A typical atmospheric control system of the type suitable for earth-orbiting manned missions up to 1 year in length was selected on the basis of recent studies of the most suitable components which were currently available. A dynamic nonlinear model of the cabin atmosphere system was developed and this model was simplified to a small-excursion linear model to apply classic stability criteria. The linear model showed that the individual control loops were very stable. The nonlinear model was programed on an electronic analog computer and sample cases were run at various conditions with both proportional and on-off controllers. The study demonstrated that the cabin atmosphere control system model was basically stable but that recovery from large transients was marginal because of the limited capacity of the chosen components. The study also demonstrated the possibility of an undesirable limit cycle condition which could result under certain load conditions and emphasized the need for stability studies of prospective life support systems with automatic control features.

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

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[1]Part of the information contained in this paper was presented as a thesis entitled "Control Analysis of a Regenerative Cabin Atmosphere Control System" by Robert D. Averill to the Faculty of the School of Engineering and Applied Science, The University of Virginia, in partial fulfillment of the requirements for the Master of Mechanical Engineering degree, August 1968.
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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 consumables from waste products.

Various degrees of regeneration are possible but the most profitable areas for reduction of weight are in water reclamation and 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 feasible for space missions of less than 1 year in duration; thus, most research effort has been on regenerative life support systems which provide only water and oxygen reclamation.

Several experimental ground facilities have been developed to evaluate regenerative life support systems for manned space flight. One such facility is the Integrated Life Support System (ILSS) at Langley Research Center. (See 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 is the atmospheric control system, which is the subject of this control 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: carbon dioxide, water vapor, and assorted contaminant gases. Figure 1 shows the relationship of an atmospheric control system to a typical life support system similar to the Langley ILSS.

The cabin atmosphere with 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 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. Potable water is supplied 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 byproducts such as carbon or methane which are discarded.

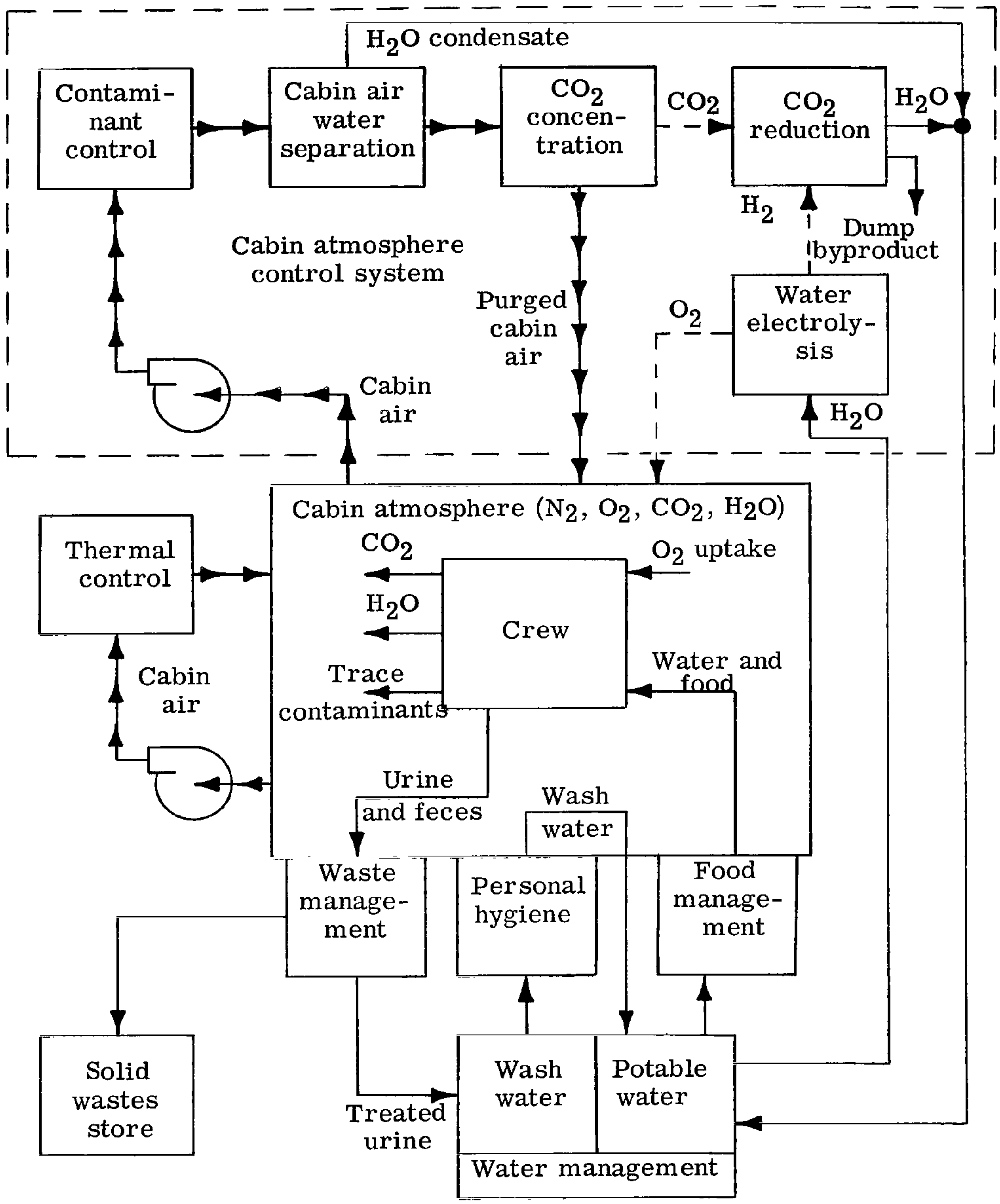


Figure 1.- Typical life support system.

Extensive work has been done since 1960 to develop components suitable for use in the regenerative cabin atmosphere control system. (See bibliography.) 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 involved.

The objective of the research reported herein was to perform a detailed control analysis of the regenerative cabin atmosphere system for manned spacecraft. The goal of the study was to advance the knowledge of 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 system with automatic controllers.

The space cabin for any long-range manned mission is expected to be reasonably spacious and 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. This is true for normal operation, but the system must also satisfy any extreme demands which are placed on it. Life support systems should have the capability to meet a variety of off-nominal conditions including variations in crew activity, depressurization, and component shutdown or failure. These conditions may 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 the inefficiencies of man as a primary control element in the space environment. Space travelers may be subjected to psychological or physiological factors which could compromise rational judgment. Variations in the cabin atmosphere, such as an excess of carbon dioxide or a shortage of oxygen (hypoxia), could result in unsuspected loss of judgment by the subject with serious consequences.

Some consideration of the dynamic requirements of cabin atmosphere control systems has been given in various prior studies; however, no rigorous control 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; however, lack of component performance data at the time of the study seriously limits the value of that study. Operation of the ILSS subsequent to the design study phase has produced some component performance data which were used to define the operation of typical components.

Although the ILSS is, in many respects, typical of the present state of art in life support systems and was used as the basis for this study, 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 control analysis of the regenerative cabin atmosphere 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 system is nonlinear in nature because of component saturation effects and cross coupling between the various loops. Machine analysis on the analog computer permitted the consideration of nonlinear effects and also provided the means for studying the on-off control modes. Although the analog study of the system was not exhaustive, sufficient machine runs were made to establish the general characteristics of the regenerative cabin atmosphere system.

One interesting facet of the study involved the simulation of the system transport delays on the analog computer. This problem has been reviewed in greater detail in the appendix.

SYMBOLS

G	gain of forward elements in system
H	gain of feedback elements in system
Im( )	imaginary part
$i = \sqrt{-1}$	
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, moles/sec (ft^3/min)
K_l	cabin air leakage constant, moles/sec (lb/hr)
K_m	N_2 makeup controller gain

K_u	partial-pressure sensor constant, $\frac{R_u T_c}{V_c}$
K_w	electrolysis water control gain
m	molal humidity of cabin air-water separator discharge air
N	gram moles (lb) of cabin atmosphere constituent
N_i	gram moles (lb) of ith cabin atmosphere constituent
N_T	total gram moles (lb) of cabin atmosphere constituents
N'	gram moles (lb) of cabin atmosphere constituent in accumulator
n	integer
p	partial pressure of cabin atmosphere constituent, mm Hg (N/m^2)
p_i	partial pressure of ith cabin atmosphere constituent, mm Hg (N/m^2)
p_t	space cabin atmosphere total pressure, mm Hg (N/m^2)
p_v	nominal cabin air saturated vapor pressure, mm Hg (N/m^2)
p_v'	saturated vapor pressure of cabin air water separator discharge air, mm Hg (N/m^2)
R	cabin atmosphere control loop reference
Re( )	real part
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, $\sigma + i\omega$

T_c	nominal absolute temperature of cabin atmosphere, ^oK (^oF)
t	time, sec
t_c	CO_2 concentrator transport lag, sec
t_d	cabin air duct transport lag, sec
t_e	water electrolysis unit transport lag, sec
t_r	CO_2 reduction unit transport lag, sec
V_c	cabin atmosphere volume, m^3 (ft^3)
X	mole fraction of cabin atmosphere constituent
X_i	mole fraction of ith cabin atmosphere constituent
x,y	variables
w_{C1}	total crew CO_2 output, moles/sec (lb/hr)
w_{C2}	mass flow leakage of CO_2 from space cabin, moles/sec (lb/hr)
w'_{C2}	CO_2 leakage rate during air-lock venting, moles/sec (lb/hr)
w_{C3}	mass flow of CO_2 from blower discharge, moles/sec (lb/hr)
w_{C4}	mass flow of CO_2 returned to space cabin from regenerative components, moles/sec (lb/hr)
w_{C6}	mass flow of CO_2 into bypass damper A, moles/sec (lb/hr)
w_{C7}	mass flow of CO_2 into bypass damper B, moles/sec (lb/hr)
w_{C8}	mass flow of CO_2 into CO_2 concentrator, moles/sec (lb/hr)
w_{C9}	mass flow of CO_2 into CO_2 reduction unit, moles/sec (lb/hr)

w_{H1} mass flow of H_2 from water electrolysis unit to CO_2 reduction unit, moles/sec (lb/hr)

w_{N1} mass flow of N_2 from makeup regulator to cabin atmosphere, moles/sec (lb/hr)

w_{N2} mass flow leakage of N_2 from space cabin, moles/sec (lb/hr)

w'_{N2} N_2 leakage rate during air-lock venting, moles/sec (lb/hr)

w_{O1} total crew O_2 uptake, moles/sec (lb/hr)

w_{O2} mass flow of O_2 from water electrolysis unit to cabin atmosphere, moles/sec (lb/hr)

w_{O3} mass flow leakage of O_2 from space cabin, moles/sec (lb/hr)

w'_{O3} O_2 leakage rate during air-lock venting, moles/sec (lb/hr)

w_{W1} total crew output of gaseous H_2O, moles/sec (lb/hr)

w_{W2} mass flow leakage of H_2O from space cabin, moles/sec (lb/hr)

w'_{W2} H_2O leakage rate during air-lock venting, moles/sec (lb/hr)

w_{W3} mass flow of H_2O from blower discharge, moles/sec (lb/hr)

w_{W4} mass flow of H_2O returned to space cabin from regenerative components, moles/sec (lb/hr)

w_{W5} mass flow of H_2O into bypass damper A, moles/sec (lb/hr)

w_{W6} mass flow of H_2O into cabin air water separator, moles/sec (lb/hr)

w_{W7} mass flow of H_2O from cabin air water separator to H_2O accumulator, moles/sec (lb/hr)

w_{W8} mass flow of H_2O from cabin air water separator to bypass damper B, moles/sec (lb/hr)

w_{W9} mass flow of H_2O recycled through cabin air blower, moles/sec (lb/hr)

w_{W10} mass flow of H_2O from CO_2 reduction unit to H_2O accumulator, moles/sec (lb/hr)

w_{W11} mass flow of H_2O into water electrolysis unit, moles/sec (lb/hr)

η_k CO_2 concentrator efficiency constant

η_r CO_2 reduction unit efficiency constant

η_s cabin air-water separator efficiency

η_s' reduction unit water separator efficiency

σ,ω real and imaginary parts of complex variable

τ_c CO_2 concentrator equivalent time constant, sec

τ_d cabin air duct equivalent time constant, sec

τ_e water electrolysis unit equivalent time constant, sec

τ_m chamber mixing time constant, sec

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

τ_r CO_2 reduction unit time constant, sec

τ_s partial-pressure sensor time constant, sec

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

SPACE CABIN MODEL

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

Space Cabin Characteristics

Many different manned space missions have been contemplated, but this study considers only the mission model defined by a recent NASA sponsored program to investigate manned earth-orbiting space flights of an extended time period. (See 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 repressurized to cabin conditions by admitting 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 was retained in this study since it represents a typical load on the atmospheric control system. For example, the air-lock venting cycle may be considered to be 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 because of 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 system by consuming oxygen and by generating carbon

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	117.5 m^3 (4150 ft^3)
Cabin atmosphere volume	101.9 m^3 (3600 ft^3)
Laboratory volume	99.1 m^3 (3500 ft^3)
Air-lock volume	2.8 m^3 (100 ft^3)
Air-lock operation	5 cycles/90 days
Air-lock venting rate	0.087 kg/min (0.192 lb/min)
Air-lock venting cycle	24 min
Space cabin leakage rates:	
Minimum	0.45 kg/day (1.0 lb/day)
Nominal	1.36 kg/day (3.0 lb/day)

dioxide, water vapor, and assorted contaminants. 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 basic metabolic factor is the oxygen uptake, or rate at which O_2 is actually extracted from the atmosphere. The CO_2 output is a function of diet and oxygen uptake and is based on an assumed respiratory quotient of 0.90. The H_2O 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 be introduced into the cabin atmosphere from sources within the space cabin. All trace contaminants are maintained at acceptable levels in the cabin atmosphere by special filters or by a catalytic burner

TABLE II.- CREW MODEL

Crew size:

Normal . . . . 4 men

Resupply . . . . 6 men for 4 hours

Metabolic criteria (100 percent BMR):

Oxygen uptake	0.74 gram-moles/man-hr	(0.052 lb/man-hr)
Carbon dioxide output	0.66 gram-moles/man-hr	(0.064 lb/man-hr)
Water evaporation . . . . (Respiration and perspiration)	4.13 gram-moles/man-hr	(0.164 lb/man-hr)

Respiratory quotient (R.Q.) 0.90
(R.Q. = CO_2 output/O_2 uptake)

Crew condition	O_2 uptake, gram-moles/hr (lb/hr)	CO_2 output, gram-moles/hr (lb/hr)	H_2O output, gram-moles/hr (lb/hr)
1 - Minimum activity	2.65	2.39	14.88
(4 men at 90 percent BMR)	(0.187)	(0.232)	(0.590)
2 - Normal activity	4.42	3.98	24.80
(4 men at 150 percent BMR)	(0.312)	(0.386)	(0.984)
3 - Resupply mode	6.63	5.97	37.19
(6 men at 150 percent BMR)	(0.468)	(0.580)	(1.476)
4 - Emergency schedule	13.27	11.94	74.39
(4 men at 450 percent BMR)	(0.936)	(1.159)	(2.952)

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 is not 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. (See ref. 2.) 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 condition is obtained 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 (68.9 kN/m^2) with an O_2 partial pressure of 160 mm Hg (21.3 kN/m^2).

Although 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 partial pressures of both these gases must also be controlled within the limits specified in table III to maintain a habitable atmosphere. Also shown in the cabin atmosphere specification is the desired range of values for H_2O partial pressure and the corresponding values for relative humidity at the nominal cabin temperature. If the relative humidity of the cabin atmosphere should exceed 90 percent, equipment degradation could occur locally because of 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 analysis. 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 values were calculated from the standard gas equation given below since, at the low pressures of the space cabin, the constituent gases behave virtually as ideal gases.

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

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

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

TABLE III.- CABIN ATMOSPHERE SPECIFICATION

Parameters	Maximum	Nominal	Minimum
Cabin total pressure, mm Hg (kN/m^2)	775 (103.3)	517 (68.9)	300 (40.0)
O_2 partial pressure, mm Hg (kN/m^2)	180 (24.0)	160 (21.3)	140 (18.7)
N_2 partial pressure, mm Hg (kN/m^2)	----------	342 (45.6)	---------
CO_2 partial pressure, mm Hg (kN/m^2	8 (1.067)	4 (0.533)	0
H_2O partial pressure, mm Hg (kN/m^2)	19 (2.53)	11 (1.47)	9 (1.20)
Relative humidity, percent	90	50	40
Cabin temperature, ^{o}K (^{o}F)	299.8 (80)	296.5 (74)	293.1 (68)
Moles of O_2, N_O			881.6
Mole fraction, X_O			0.3095
Moles of N_2, N_N			1884.3
Mole fraction, X_N			0.6615
Moles of CO_2, N_C			22.0
Mole fraction, X_C			0.0077
Moles of H_2O, N_W			60.6
Mole fraction, X_W			0.0213
Total moles, N_T			2848.5

Cabin Atmosphere Control System

The cabin atmosphere control system, with all major components, is shown in figure 2. A detailed description of each component is given later, but it is necessary to define the overall system mass balances before component requirements can be determined. In steady-state operation, the cabin atmosphere 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 in figure 2. The average daily mass flows required to maintain the balance of materials in the cabin atmosphere are 106.14 gram-moles/day (7.48 lb/day) of O_2 into the cabin and 95.53 gram-moles/day (9.27 lb/day) of CO_2 and 595.11 gram-moles/day (23.62 lb/day) of H_2O out of the cabin. To maintain the

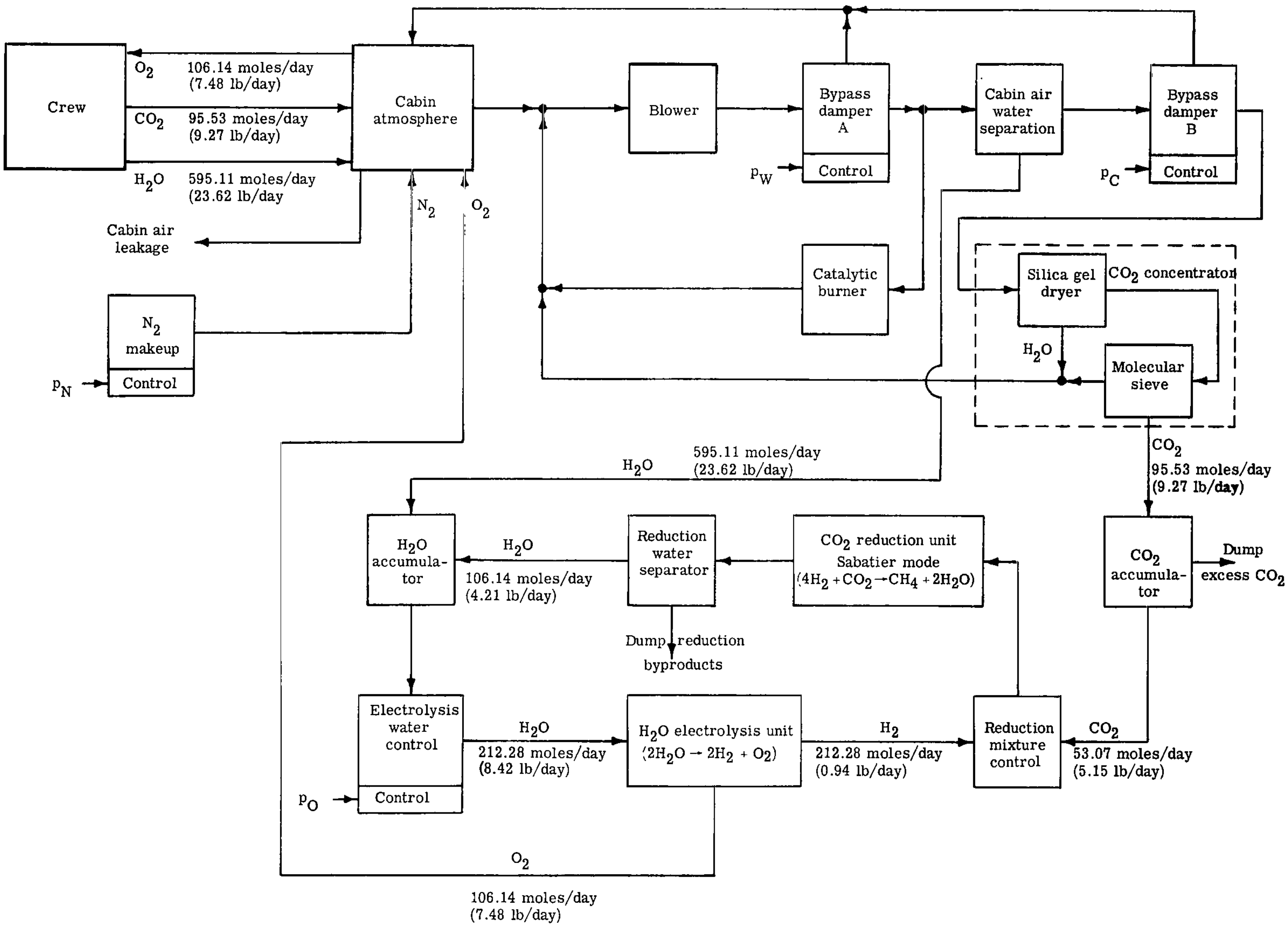


Figure 2.- Cabin atmosphere control system.

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 gram-moles/day (9.27 lb/day) and 595.11 gram-moles/day (23.62 lb/day), respectively.

The electrolysis unit produces two moles of H_2 for each mole of O_2; thus 212.28 moles/day (0.94 lb/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, methane, is also dumped. The apparent excess of H_2O in the cabin atmosphere control system is used to satisfy partially 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 earlier.

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.

COMPONENT DESCRIPTION

Descriptions of individual components in the atmospheric control system are contained in this section, including both a physical description and a mathematical description of dynamic response. Many of the components were found to have the dynamic characteristics of a first-order response with a relatively long time constant of about 360 seconds. To simplify the analysis, this characteristic time constant was assigned to all components where lack of specific data prevented determining a more unique value. The components described are typical for the type of system being considered and in many cases are similar to the components used in the Langley ILSS (ref. 1).

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 ideal gases and are mutually unreactive, each gas can be considered separately. The mass balance of each gas in the cabin atmosphere is determined from the net mass flow as represented by the following equations:

$$\frac{dN_N}{dt} = w_{N1} - w_{N2} \tag{3a}$$

$$\frac{dN_C}{dt} = w_{C1} + w_{C4} - w_{C2} - w_{C3} \tag{3b}$$

$$\frac{dN_W}{dt} = w_{W1} + w_{W4} - w_{W2} - w_{W3} \tag{3c}$$

$$\frac{dN_O}{dt} = w_{O2} - w_{O1} - w_{O3} \tag{3d}$$

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 forced 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 exchange completely the air in the space cabin about once each 15 minutes. (See ref. 1.) By 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, $K_f = 3.34 \frac{\text{moles}}{\text{sec}}$ (253 ft^3/min).

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 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 the obtaining of a representative sample of cabin air, it is lumped with the sensor time constant for analysis purposes.

Cabin air is removed from the space cabin by a system of exhaust ducts located so 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 because of 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, factors pertinent to the consideration include the physical size of the space cabin, the length of ventilation ducts, and also, crew comfort, which requires that air duct velocities be as low as possible to minimize duct noise and that air velocity over the crew be limited. Based on these factors, the duct transport lag t_d was conservatively estimated to be 360 seconds.

Bypass Damper A

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 when p_W becomes less than 10.75 mm Hg (1.43 kN/m^2) 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 at

p_W = 5.375 mm Hg (0.72 kN/m^2). 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 (1.15 kN/m^2) (40-percent relative humidity), at which point the valve will open. The damper then remains open until p_W reaches a value of 12.90 mm Hg (1.72 kN/m^2) (60-percent relative humidity). The resultant hysteresis loop is represented in figure 3 as the "wide deadband."

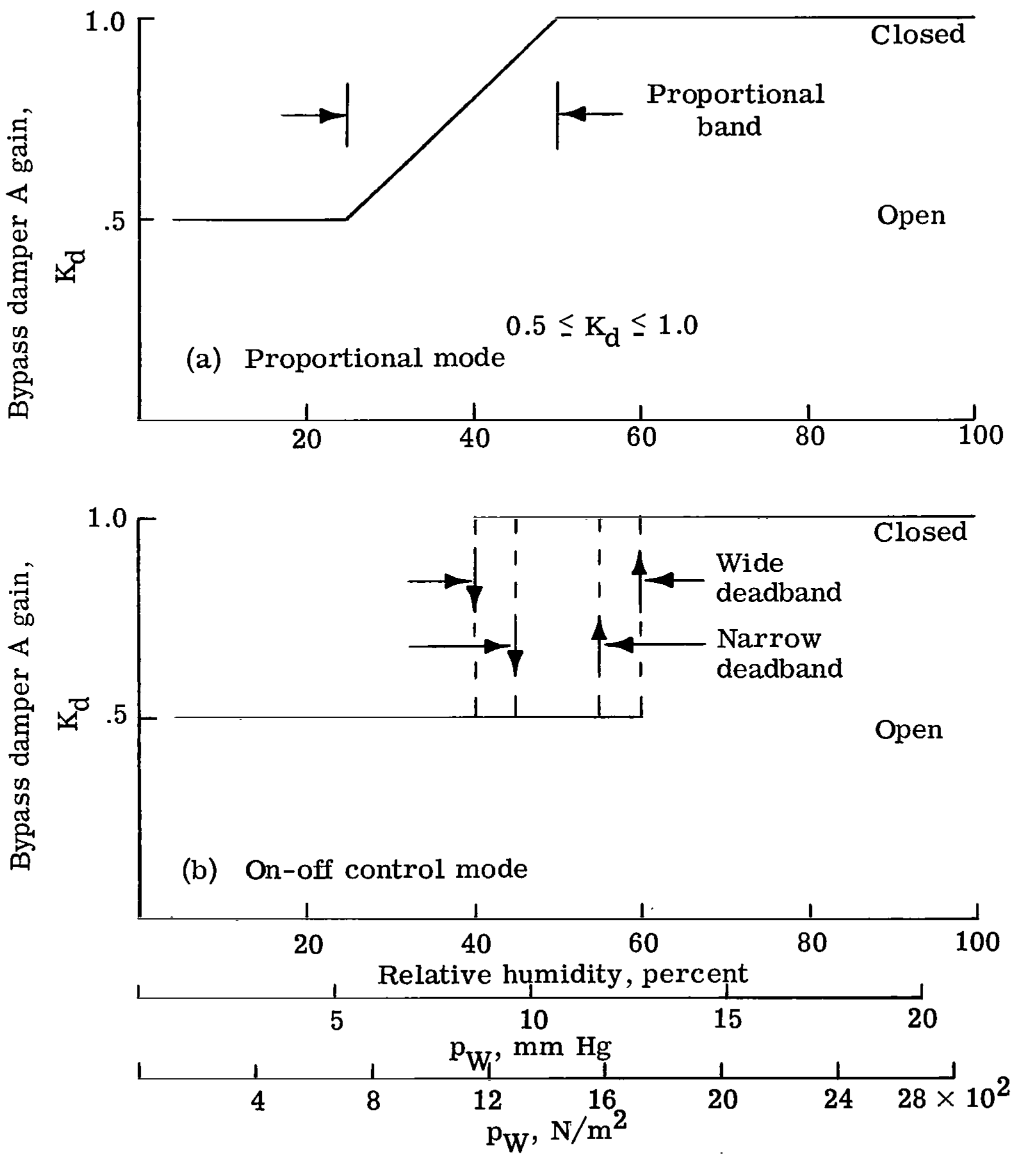


Figure 3.- Bypass damper A control modes.

Also shown in 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 relative 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):

$$m = \frac{p_v'}{p_t - p_v'} \tag{4}$$

At the nominal temperature of 277.6° K (40° F), $p_v' = 6.29$ mm Hg (0.84 kN/m^2) and $p_t = 517$ mm Hg (68.9 kN/m^2); thus, $m = 0.0123$. This value 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, the fraction of water vapor condensed by the heat exchanger is:

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

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 η_s may be about 33 percent; therefore, the fraction of water vapor removed from the airstream is

$$\text{Fraction of water vapor removed} = \frac{\eta_s\left(X_W - 0.0123\right)}{X_W} = \frac{0.33\left(X_W - 0.0123\right)}{X_W} \tag{6}$$

The total fraction of water vapor passed through the water separator is

$$\text{Fraction of water vapor passed} = 1 - \frac{0.33\left(X_W - 0.0123\right)}{X_W} \tag{7}$$

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. However, 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 compared with other system dynamics; thus, no transport lag is required at that point.

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 procedure 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 were considered for bypass damper B; these modes are shown in figure 4. The proportional bandwidth extends from $p_C = 2.67$ mm Hg (0.356 kN/m^2) to $p_C = 10.67$ mm Hg (1.423 kN/m^2). Operation in the proportional mode will result in control of CO_2 to values of p_C less than the specified maximum of 8 mm Hg (1.067 kN/m^2) for all normal conditions, and, in addition, provides an overload capacity for emergency conditions.

The on-off band selected extends from $p_C = 4$ mm Hg (0.533 kN/m^2) to $p_C = 6$ mm Hg (0.800 kN/m^2); thus, somewhat closer regulation of the CO_2 content in the cabin atmosphere is provided. A narrow deadband loop which extends from 4.5 to 5.5 mm Hg (0.600 to 0.733 kN/m^2) of p_C is also shown in figure 4.

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, and provides a large surface area to which the CO_2 molecules adhere

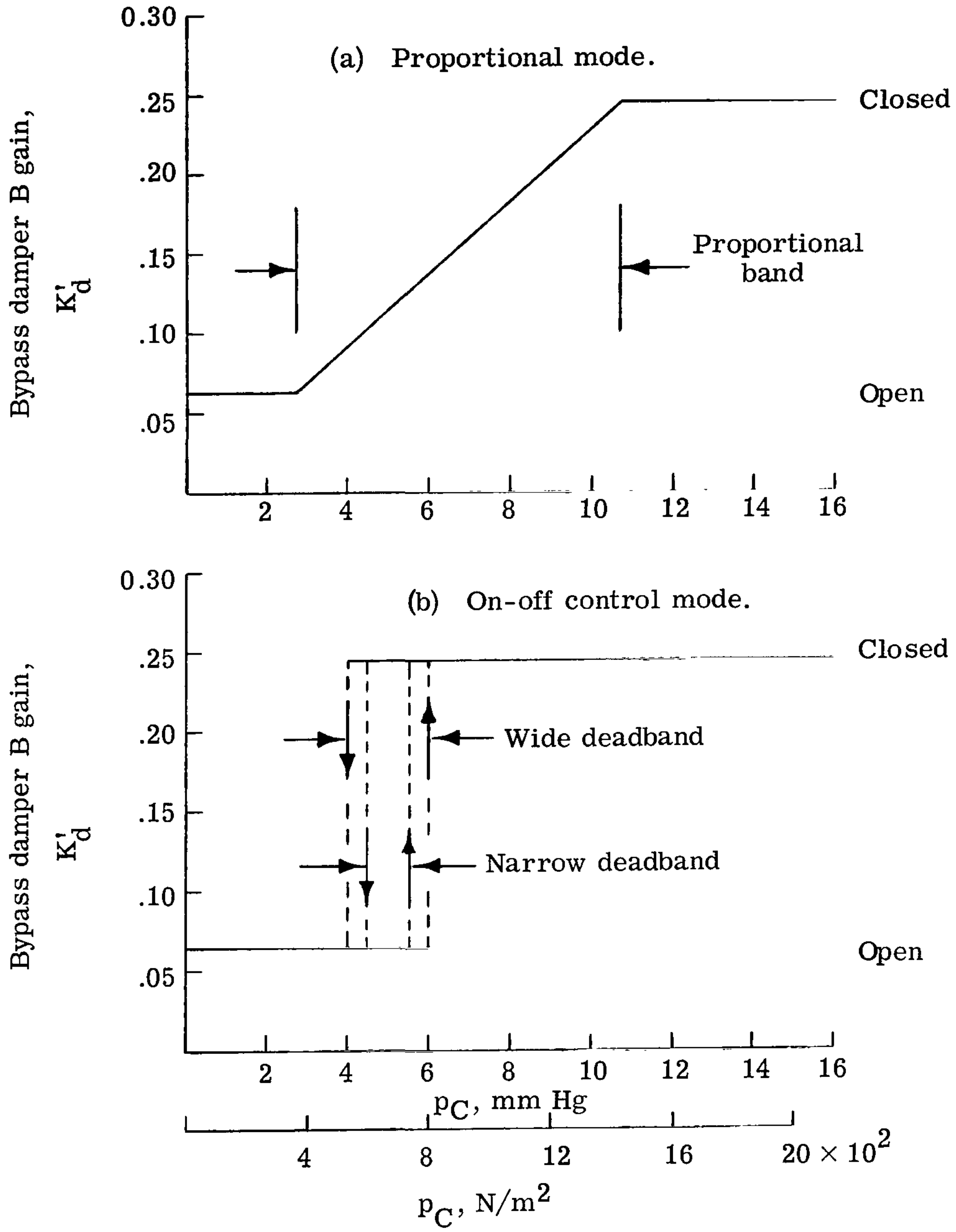


Figure 4.- Bypass damper B control modes.

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. (See ref. 3.) The rate of adsorption for a given concentrator is a function of gas flow rate and concentration, physical size, and time. (See ref. 4.)

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 rich" cabin airstream is cooled and allowed to flow through the concentrator until the molecular sieve becomes partially saturated. The inlet flow is then 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 low dewpoint. This drying 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 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 control analysis, the CO_2 concentrator can be represented by the concentrator constant $\eta_k = 0.40$ 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 lags 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 seconds. 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 appreciable time delay in the passage of CO_2 through the unit. This delay has no effect on the system dynamics since all the CO_2 is transferred to an accumulator and stored for later use.

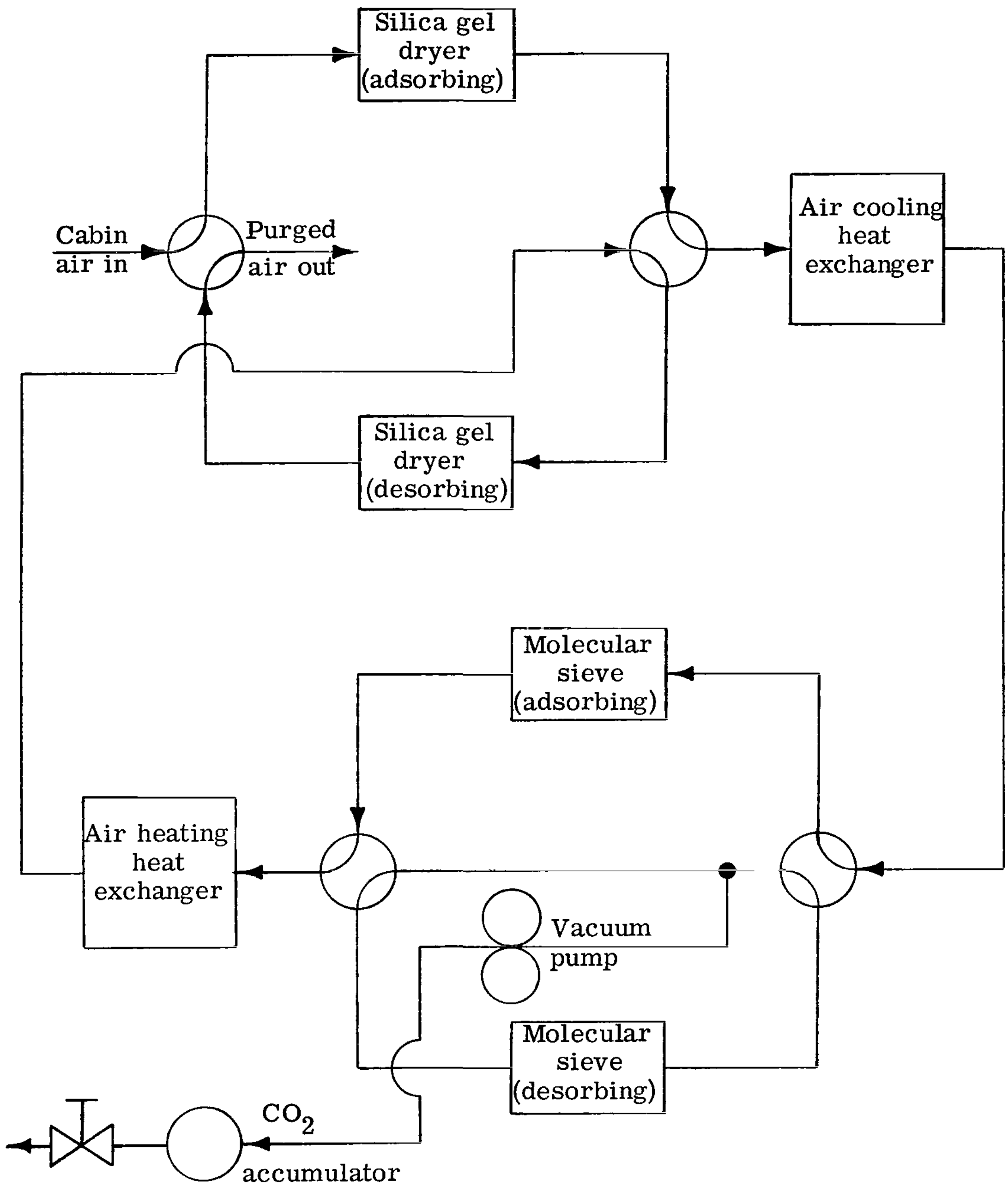


Figure 5.- CO_2 concentrator schematic.

Accumulators

The atmospheric control system includes two accumulators; the CO_2 accumulator is located near the CO_2 reduction unit and the H_2O accumulator is part of the water management system. Dynamically, these systems are represented by a differential equation relating the inlet and outlet flows of each accumulator, as

$$\frac{dN'_C}{dt} = \eta_k w_{C8} - w_{C9} \tag{8}$$

$$\frac{dN'_W}{dt} = w_{W7} + w_{W10} - w_{W11} \tag{9}$$

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

Note that there are no accumulators shown in figure 2 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. Although 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 to expect 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 Bosch process involves the reduction of CO_2 with H_2 over a hot iron catalyst according to the net reaction (ref. 5):

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

Although 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 to be 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 also 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). 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.

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, $\eta_r = 0.95$.

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 molal humidity $m = 0.0123$. 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, 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 so that approximately 95 percent of the condensed water is separated at this point or $\eta_s' = 0.95$. 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 in figure 6.

Both the proportional and on-off modes of control have been considered for this unit, the nominal operation being based on the desired value of $p_O = 160$ mm Hg ($21.3\ kN/m^2$). Four different types of on-off control were considered during the study. With the normal output, both wide deadband and narrow deadband control modes were compared. The modification 1 variation used wide deadband on-off control with a gain increase of approximately 50 percent. The modification 2 control increased the high gain output approximately 100 percent over the normal value. Both modification 1 and modification 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.

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 in figure 7. With the proportional control, p_N will reach an equilibrium point on the 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 (44.7 to $46.0\ kN/m^2$), 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 ($44.7\ kN/m^2$). 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.

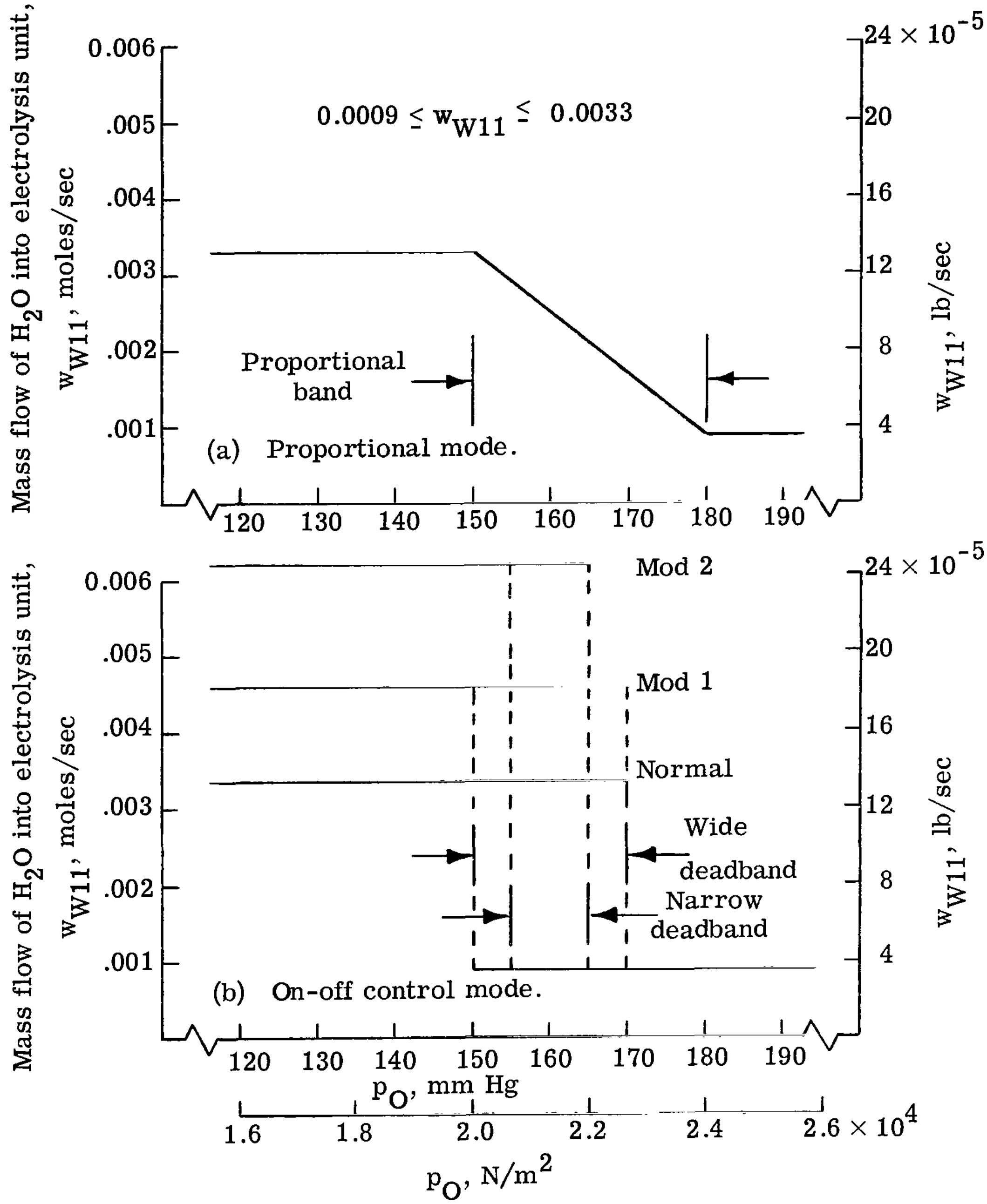


Figure 6.- Electrolysis unit control modes.

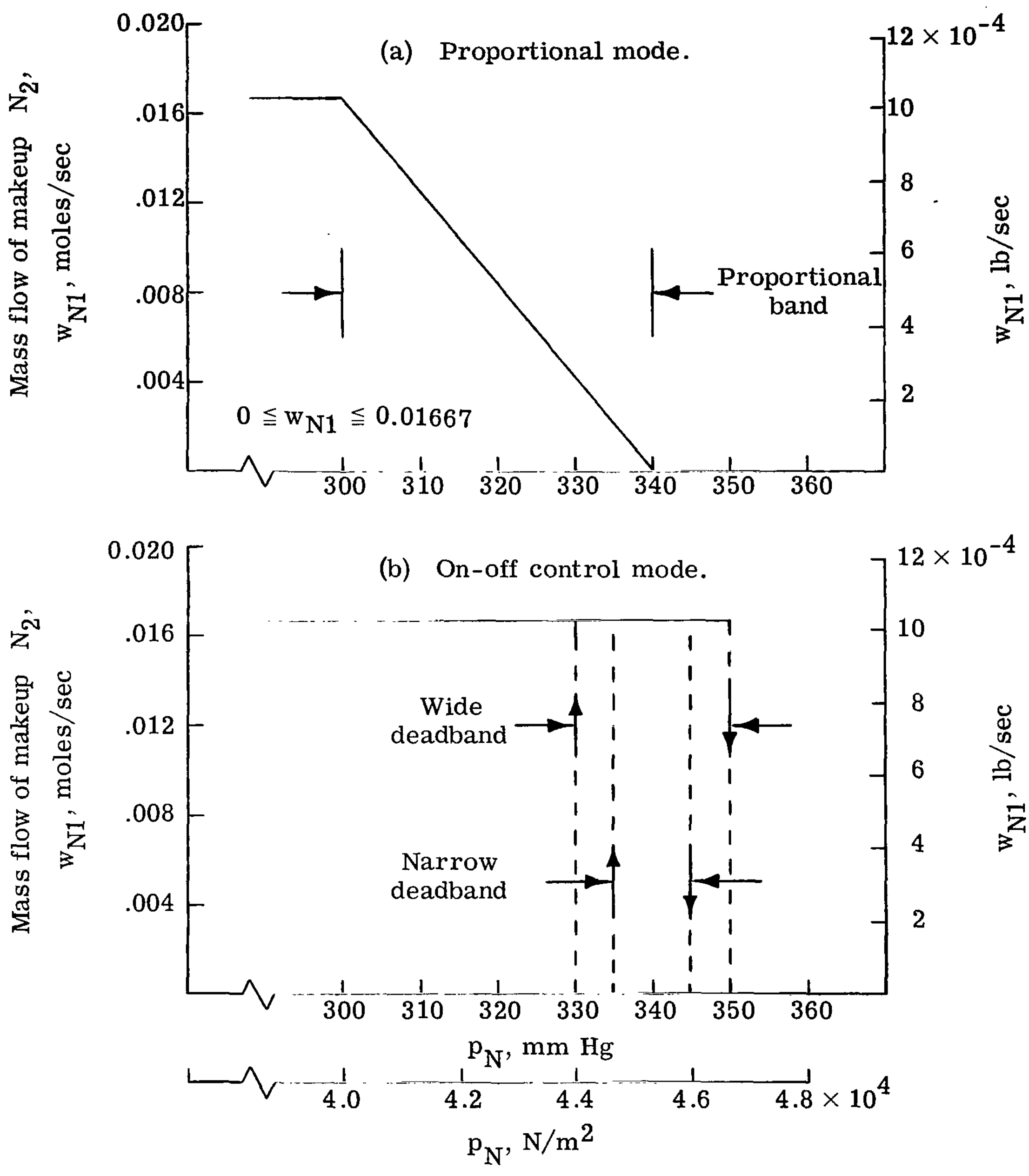


Figure 7.- Makeup N_2 control modes.

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 these pressure indicators give continuous readings 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 that provides an electrical output signal which is compared with p_O, p_C, and p_W to obtain the desired indication of p_N.

Although the individual instruments may vary slightly in performance, the same sensor time constant has been used for all pressure sensors, including p_N, since the other pressure indications are used to compute p_N. Evaluation of the partial-pressure sensors available at the time of this study indicated that they all had significant response times. Accordingly, the sensor time constant τ_S used in this study was conservatively set at the characteristic value of 360 seconds.

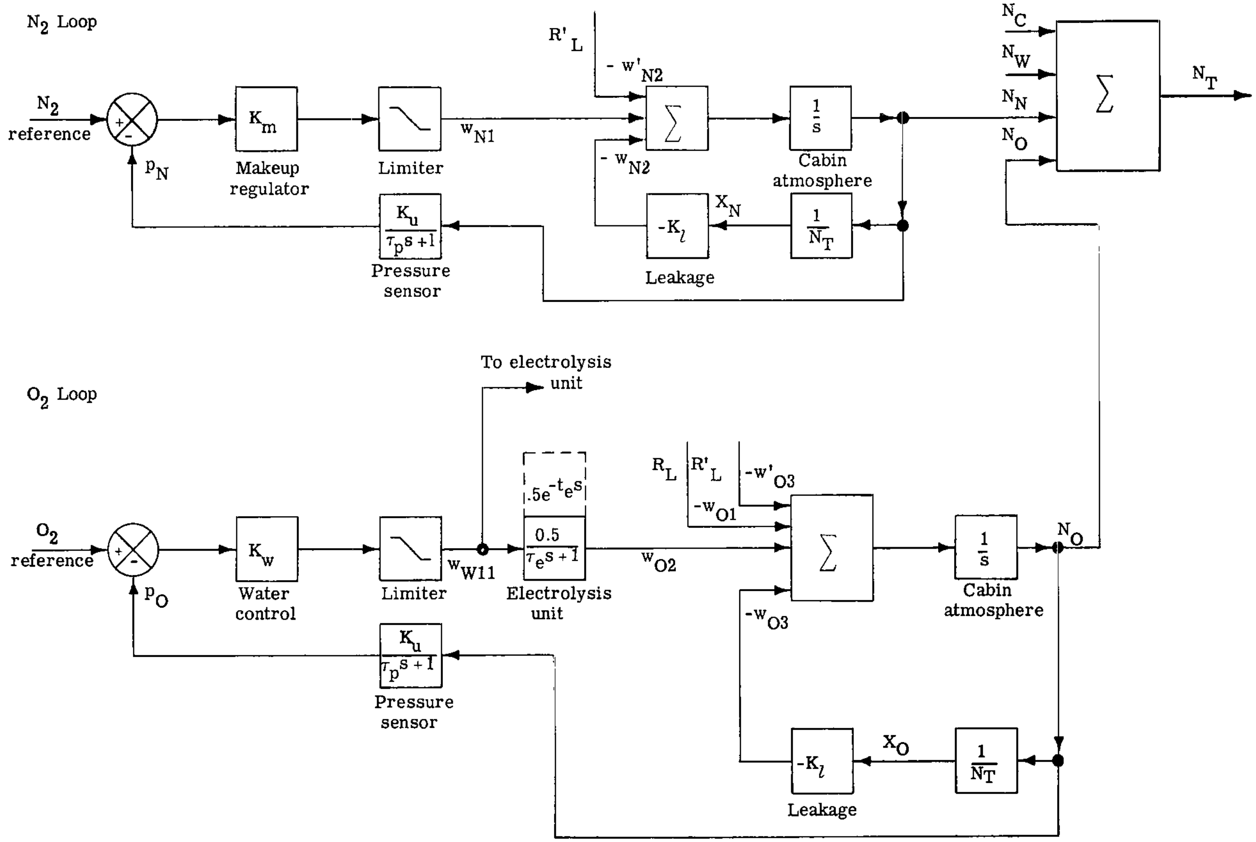
DESCRIPTION OF SYSTEM

The detailed system block diagram including all dynamic relationships is developed in this section. A simplified block diagram is defined from which linear system characteristics are determined. The basic criterion for the block diagram is conservation of mass at all points.

System Block Diagram

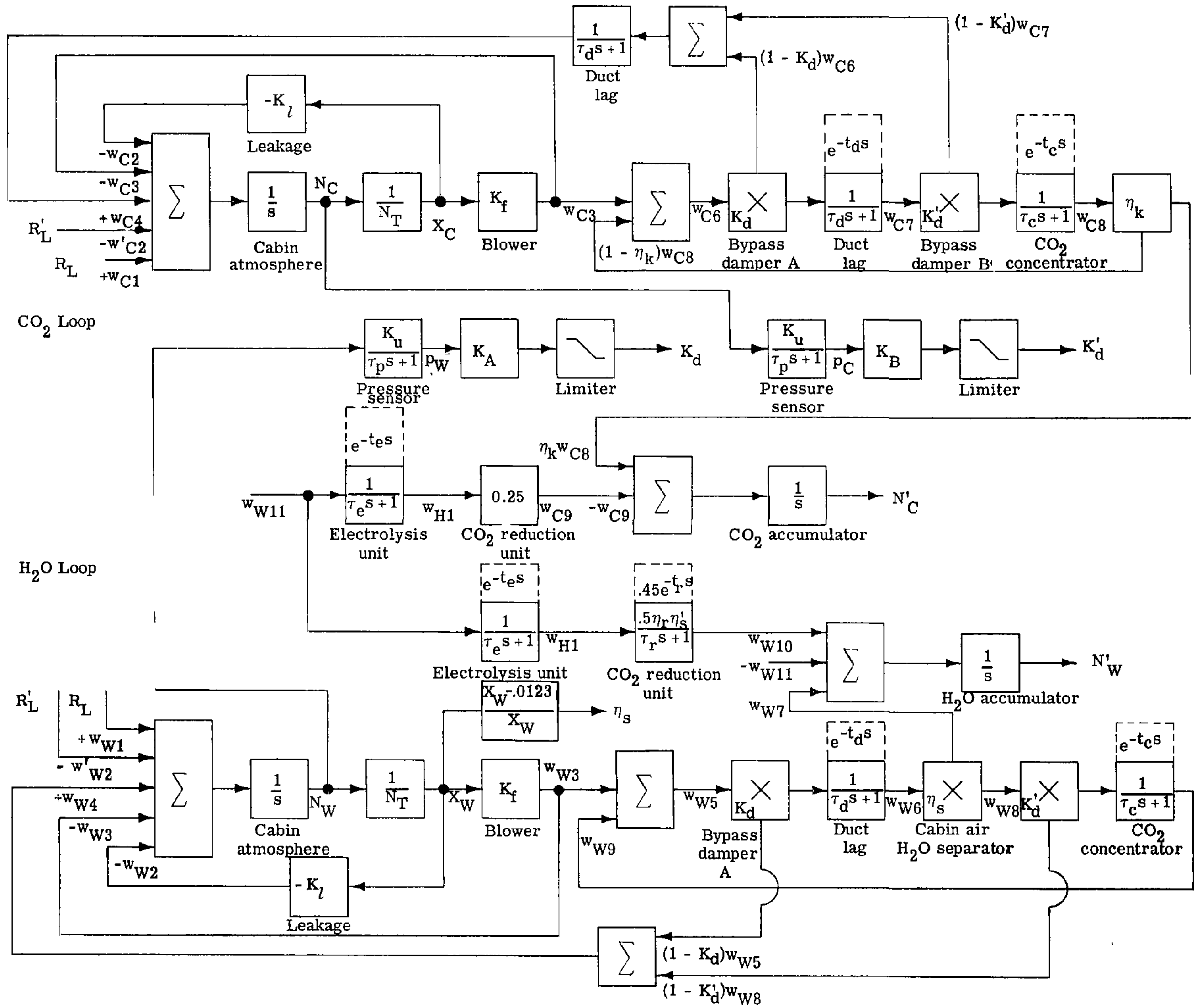
The system block diagram (fig. 8) shows all the mathematical operations which must be performed in the analysis of the proportional system. The assumption of ideal gas behavior in the cabin atmosphere and the fact that the major constituents of the cabin atmosphere are mutually unreactive permits independent consideration of each gas in the cabin. Thus, the block diagram (fig. 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 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



(a) N_2 and O_2 loops.

Figure 8.- System block diagram.



(b) CO_2 and H_2O loops.

Figure 8.- Concluded.

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 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 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 value 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 through the electrolysis unit and 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

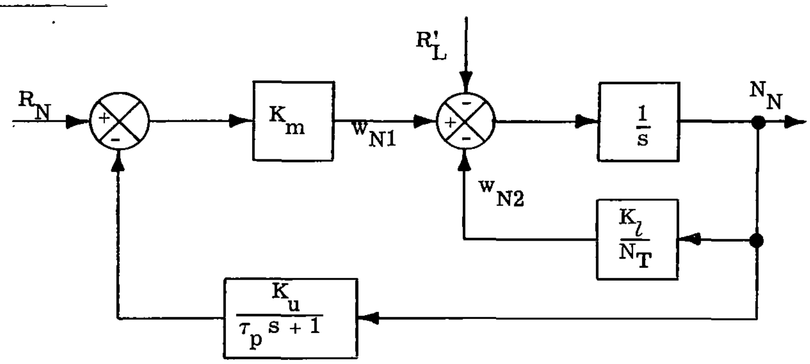
The cabin atmosphere control system described by the system block diagram is nonlinear because of the presence of limiting conditions (saturation) and because of some higher degree terms resulting from multiplication or division. However, for approximately steady-state operation with small departures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

The simplified block diagram is shown in 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' were assumed to be constant. Thus, the linear stability study will give an indication only of individual loop stability.

Linear System Characteristics

Each loop of the simplified block diagram is 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 criterion 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, is 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.

<u>N_2 loop reduction.</u>- The basic N_2 loop is



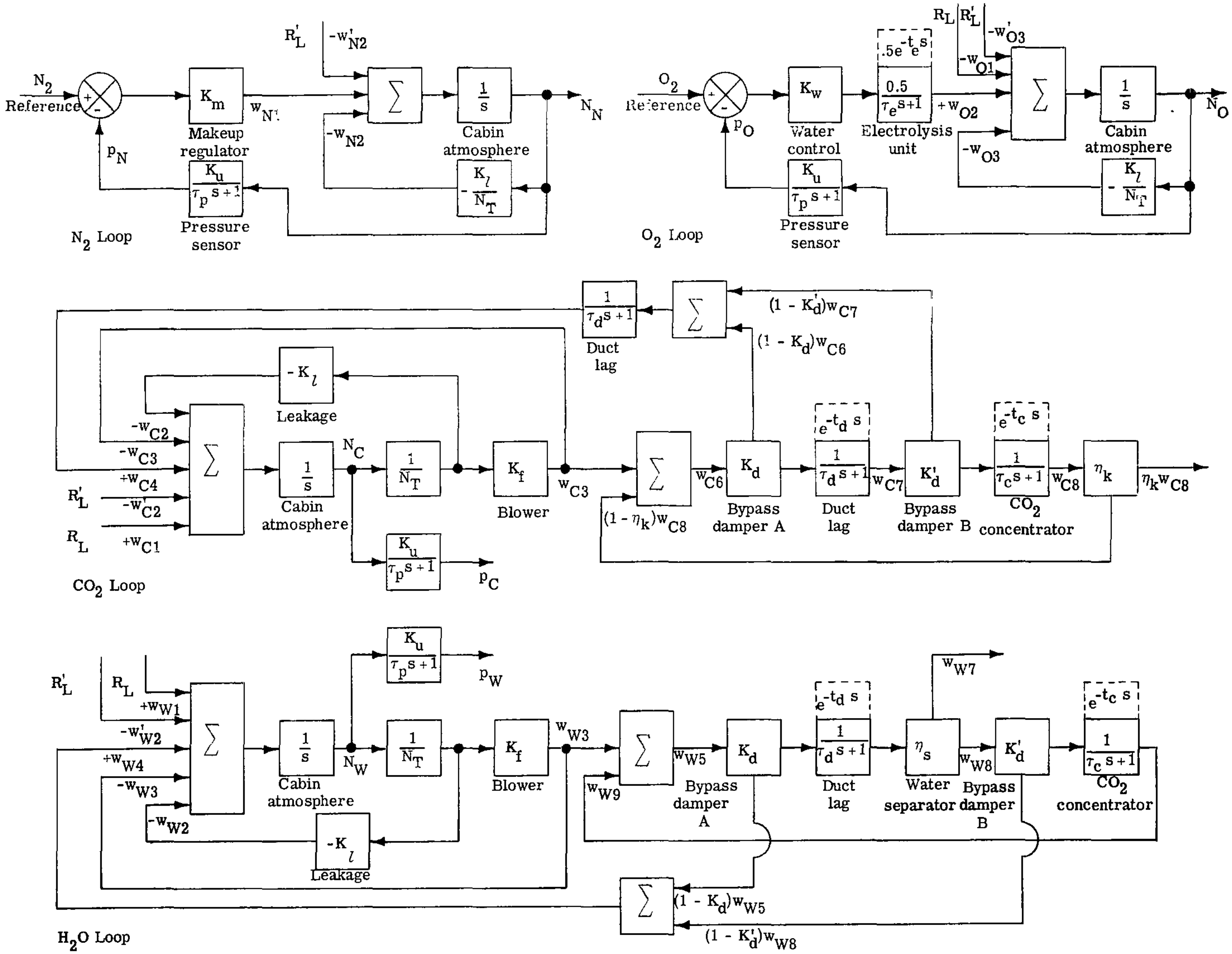
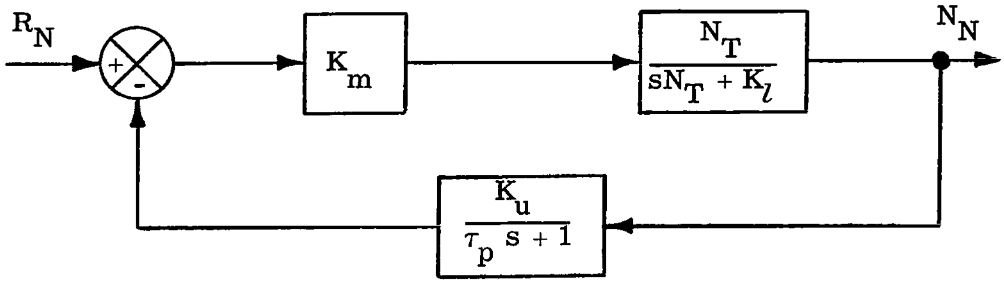


Figure 9.- Simplified block diagram.

The reference input only is

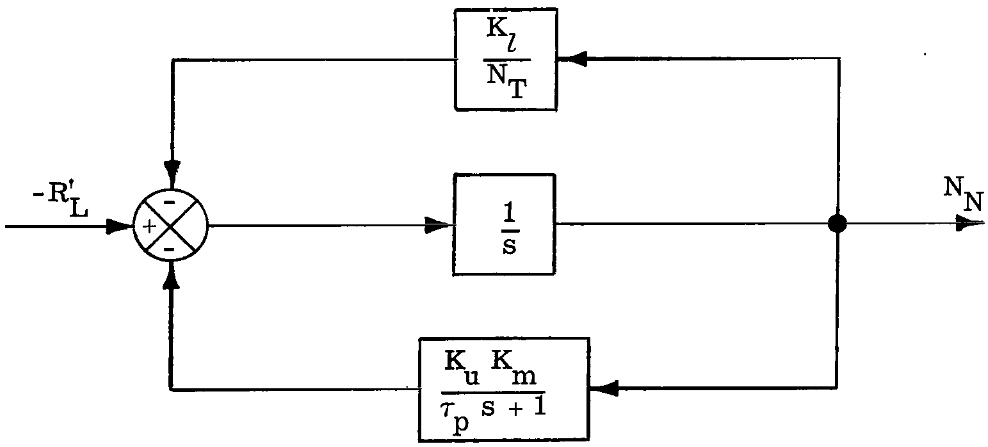


$$G = \frac{K_m N_T}{sN_T + K_l}$$

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

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

The disturbance load input only is

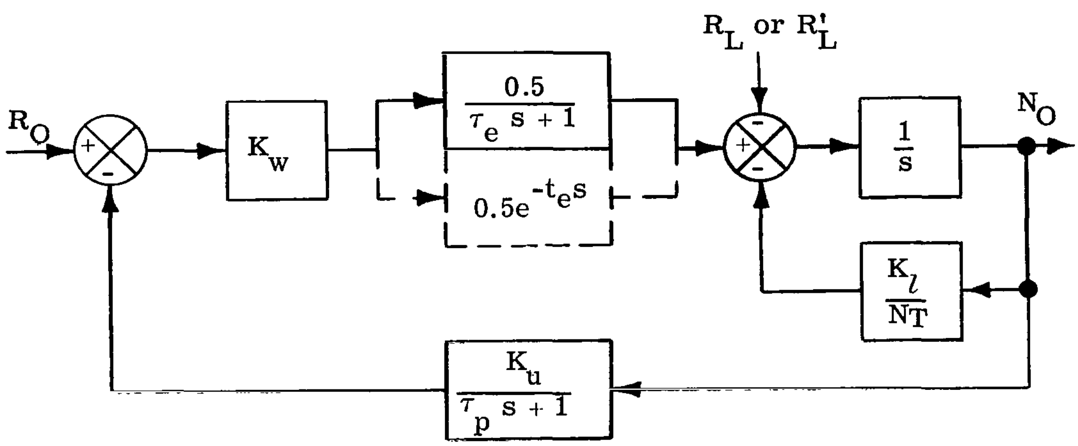


$$G = \frac{1}{s}$$

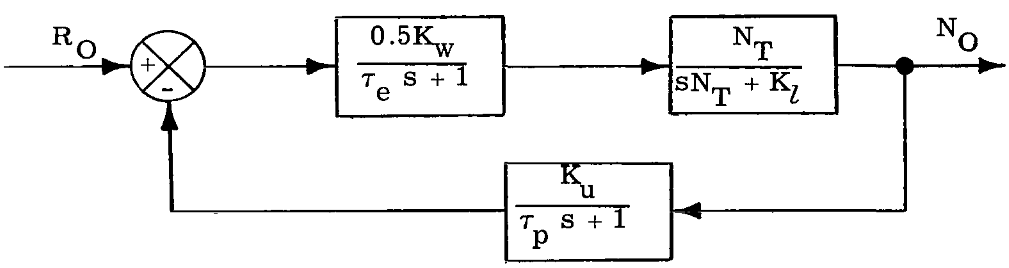
$$H = \frac{K_l}{N_T} + \frac{K_u K_m}{\tau_p s + 1} = \frac{K_l(\tau_p s + 1) + K_u K_m N_T}{N_T(\tau_p s + 1)}$$

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

<u>O_2 loop reduction.</u>- The basic O_2 loop is



The reference input only is

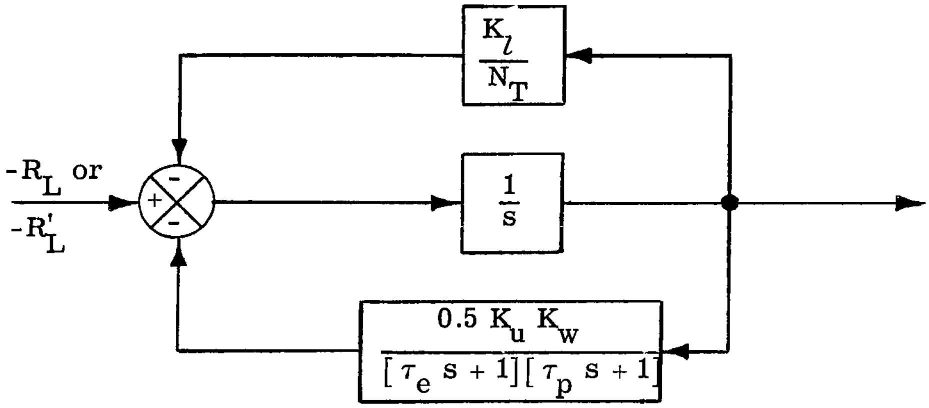


$$G = \frac{0.5K_w \frac{N_T}{K_l}}{(\tau_e s + 1)\left(s \frac{N_T}{K_l} + 1\right)} \quad \text{or} \quad \frac{0.5e^{-t_e s} K_w \frac{N_T}{K_l}}{s \frac{N_T}{K_l} + 1}$$

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

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

The disturbance load input only is



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

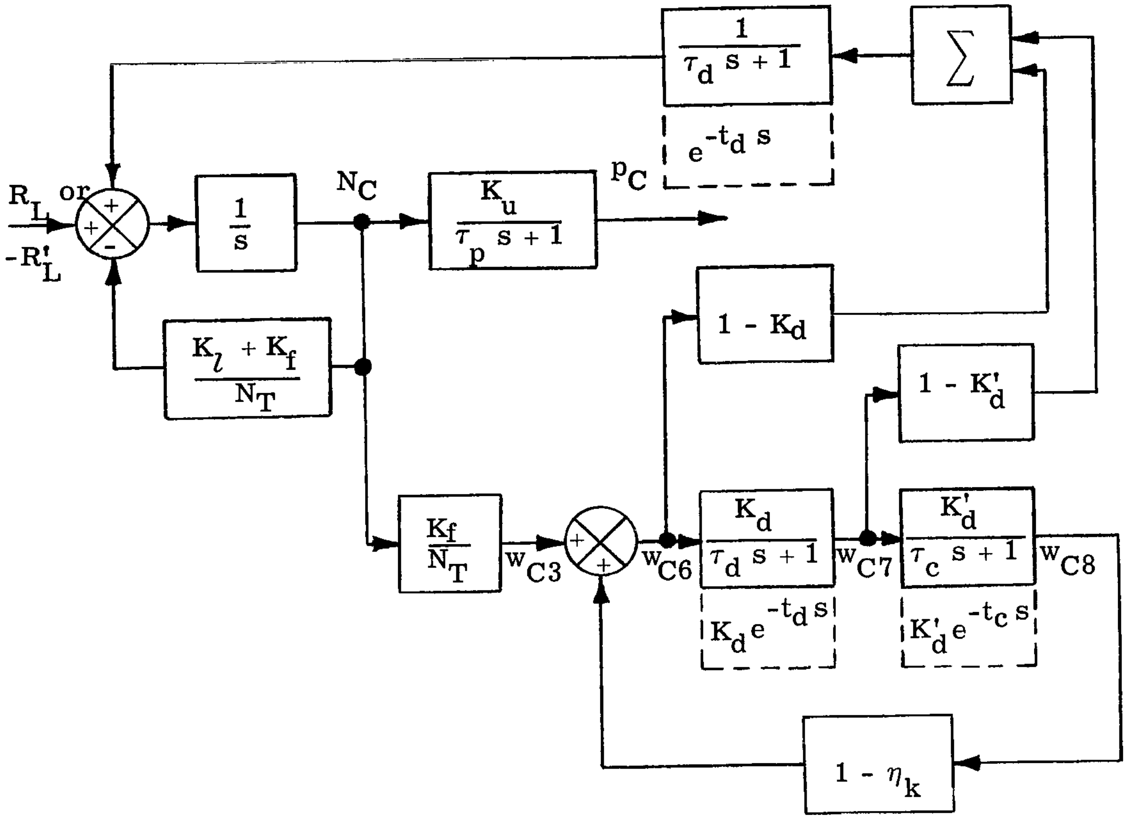
$$H = \frac{K_l}{N_T} + \frac{0.5K_uK_w}{(\tau_e s + 1)(\tau_p s + 1)} = \frac{K_l(\tau_e s + 1)(\tau_p s + 1) + 0.5K_uK_wN_T}{N_T(\tau_e s + 1)(\tau_p s + 1)}$$

$$GH = \frac{(\tau_e s + 1)(\tau_p s + 1) + 0.5K_uK_w \frac{N_T}{K_l}}{s\frac{N_T}{K_l}(\tau_e s + 1)(\tau_p s + 1)}$$

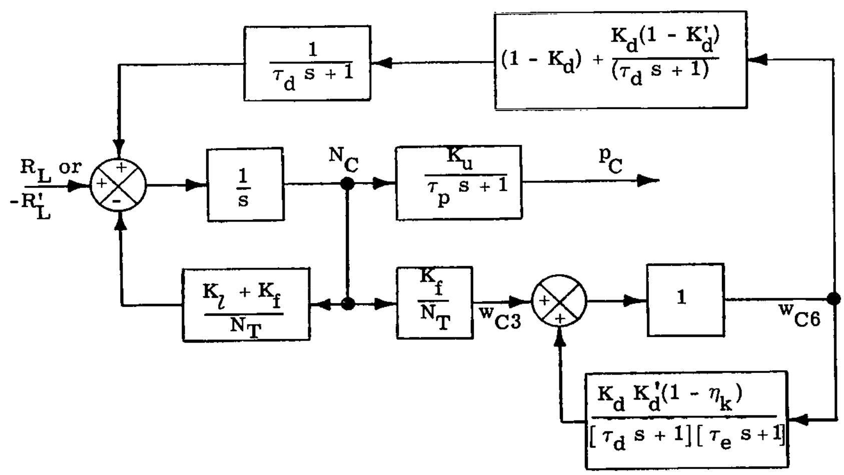
With transport lag in electrolysis unit,

$$GH = \frac{(\tau_p s + 1) + 0.5K_uK_w \frac{N_T}{K_l} e^{-t_e s}}{s\frac{N_T}{K_l}(\tau_p s + 1)}$$

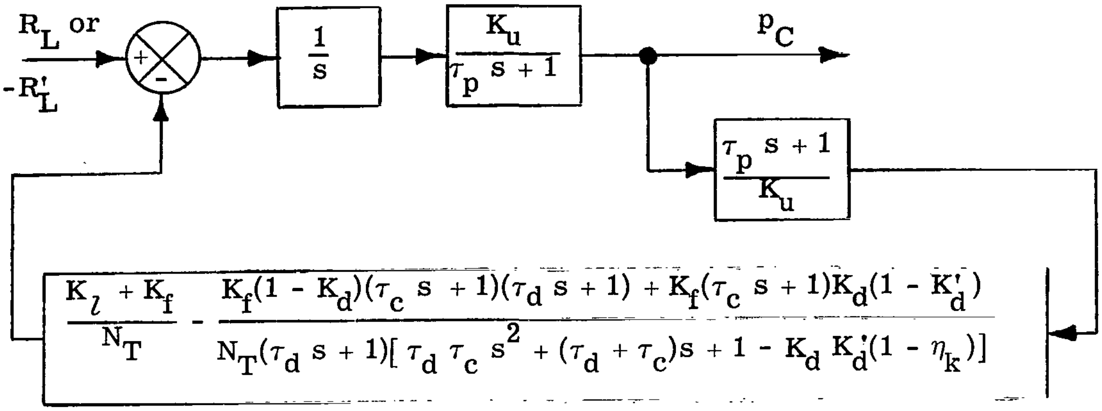
CO_2 loop reduction.- The CO_2 loop is



This CO_2 loop further reduces to



Combining feedback terms yield



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

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

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

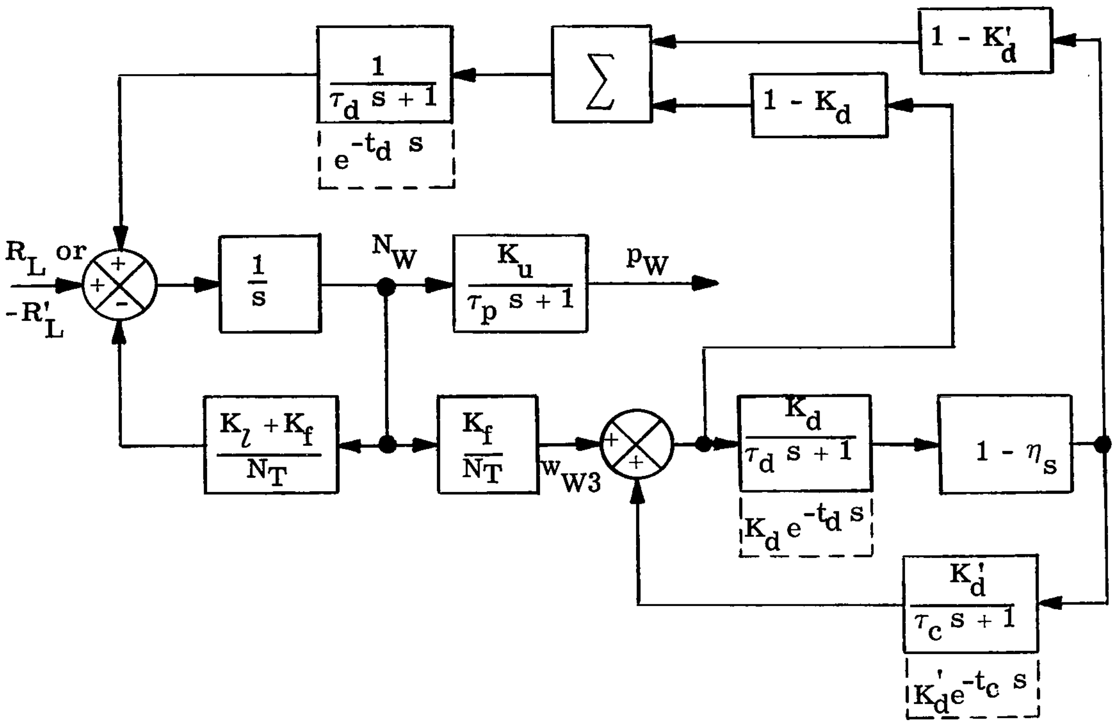
$$GH = \frac{\left(K_l + K_f\right)\left(\tau_d s + 1\right)\left[\tau_d \tau_c s^2 + \left(\tau_d + \tau_c\right)s + 1 - K_d K'_d\left(1 - \eta_k\right)\right]}{sN_T\left(\tau_d s + 1\right)\left[\tau_d \tau_c s^2 + \left(\tau_d + \tau_c\right)s + 1 - K_d K'_d\left(1 - \eta_k\right)\right]}$$

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

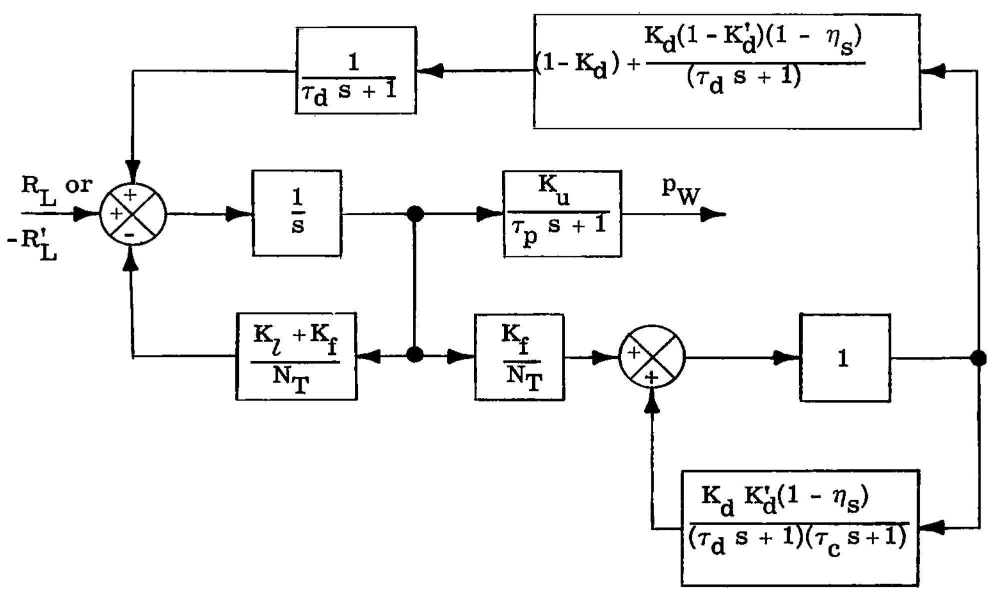
With transport lags included,

$$GH = \frac{\left(K_l + K_f\right)\left(e^{t_d s}\right)\left[e^{\left(t_d + t_c\right)s} - K_d K'_d\left(1 - \eta_k\right)\right]}{sN_T e^{t_d s}\left[e^{\left(t_d + t_c\right)s} - K_d K'_d\left(1 - \eta_k\right)\right]} - \frac{K_f\left(1 - K_d\right)e^{\left(t_d + t_c\right)s} + K_f K_d\left(1 - K'_d\right)e^{t_c s}}{sN_T e^{t_d s}\left[e^{\left(t_d + t_c\right)s} - K_d K'_d\left(1 - \eta_k\right)\right]}$$

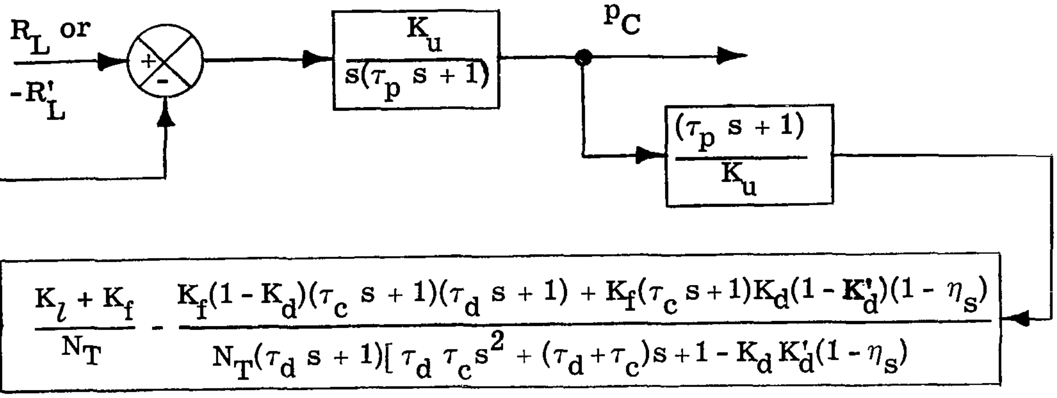
H_2O loop reduction.- The H_2O loop is



This H_2O loop further reduces to



Combining feedback terms yields



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

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

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

Combining terms in the denominator yields

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

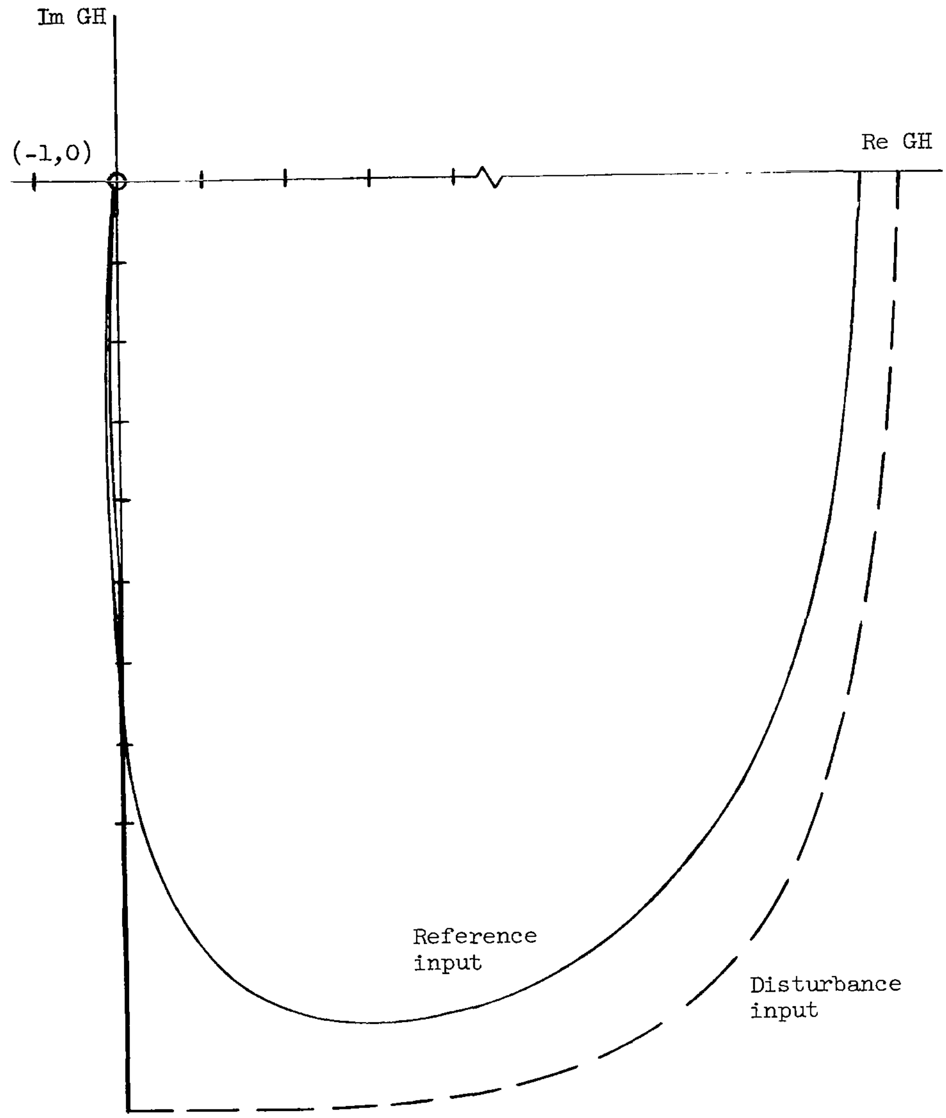
$$- \frac{K_f\left(1 - K_d\right)\left(\tau_c s + 1\right)\left(\tau_d s + 1\right) + K_f K_d\left(1 - K_d'\right)\left(1 - \eta_s\right)\left(\tau_c s + 1\right)}{sN_T\left(\tau_d s + 1\right)\left[\tau_d \tau_c s^2 + \left(\tau_d + \tau_c\right)s + 1 - K_d K_d'\left(1 - \eta_s\right)\right]}$$

With transport lags included, the equation becomes

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

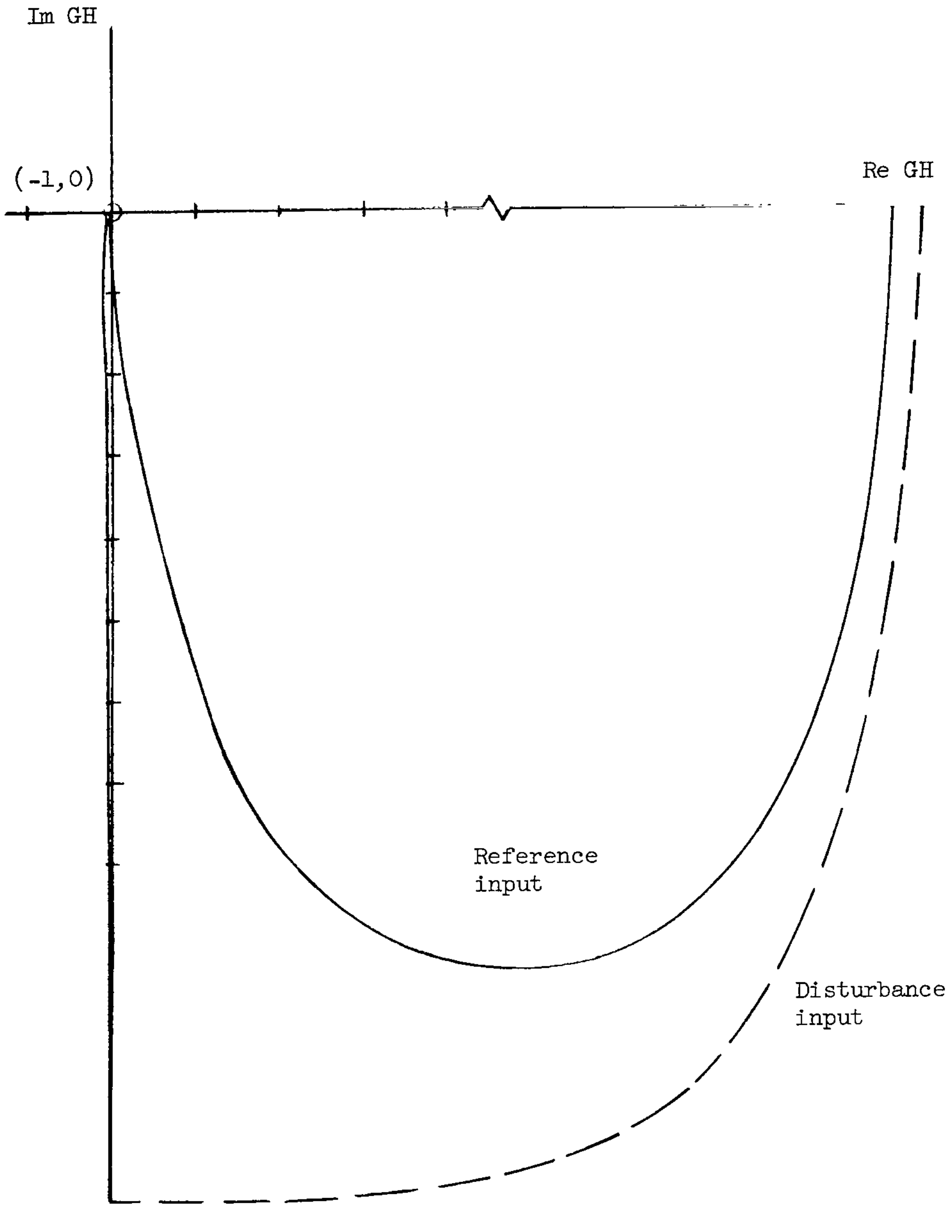
Complex Plane Plots

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



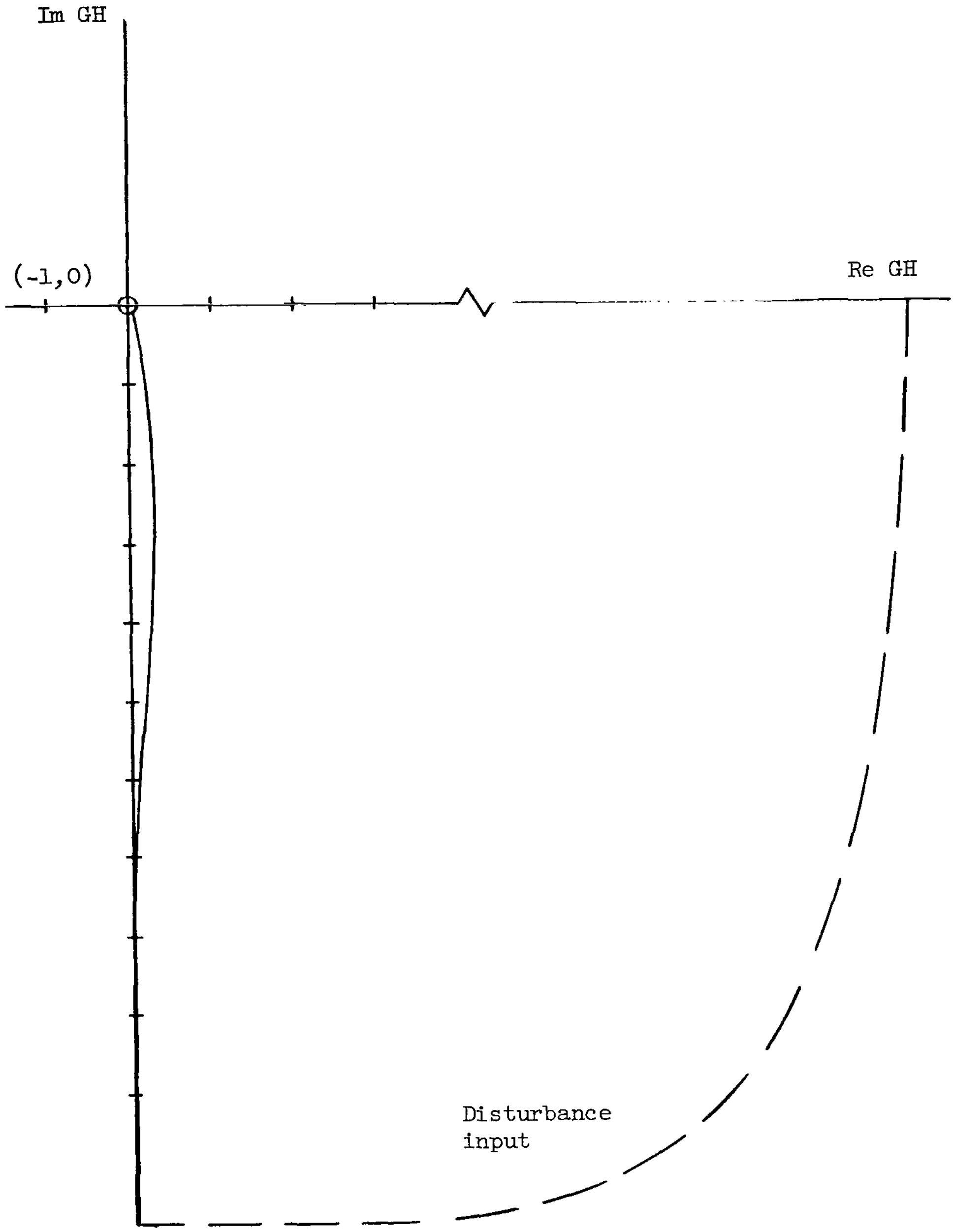
(a) N_2 loop.

Figure 10.- Nyquist plots.



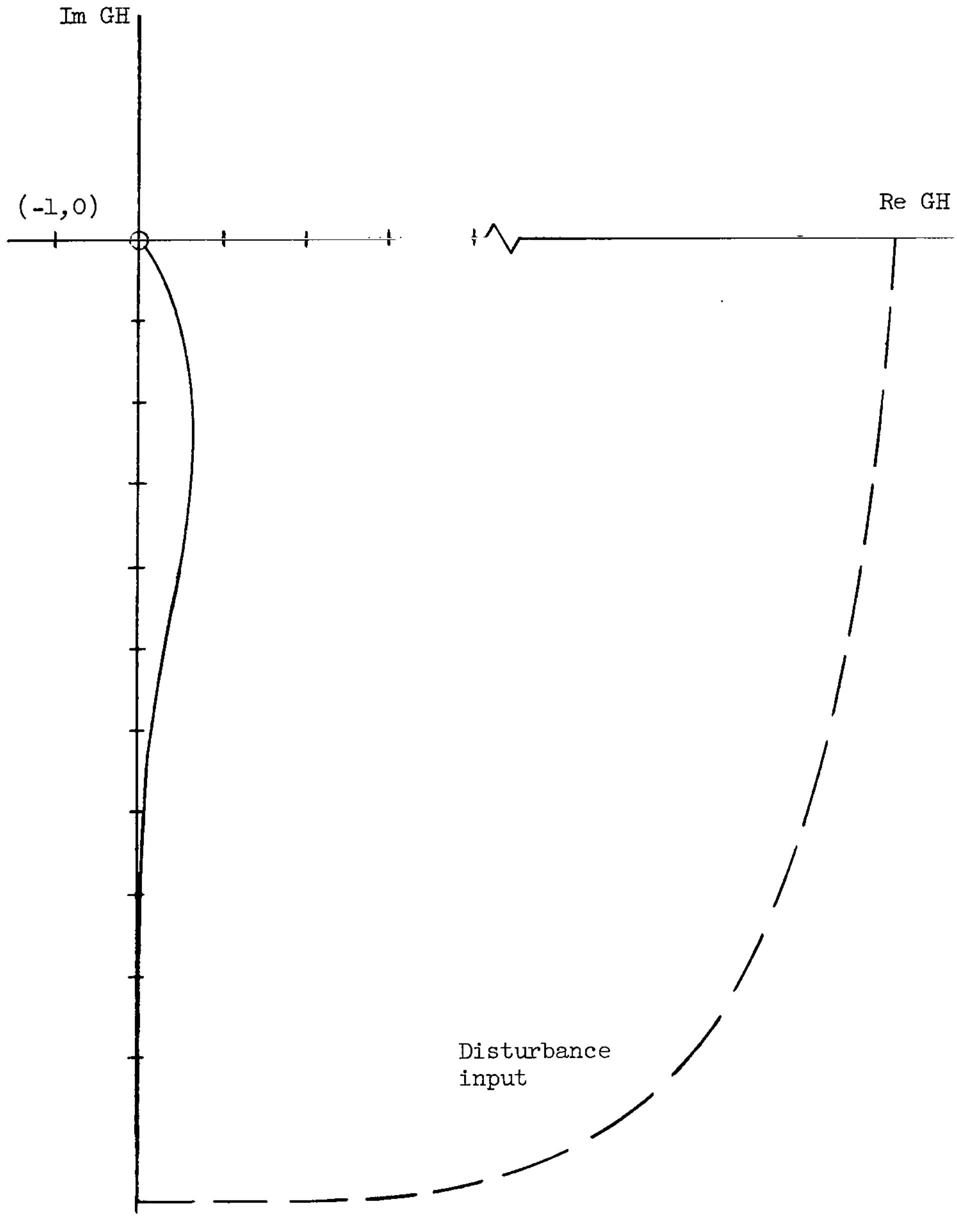
(b) O_2 loop.

Figure 10.- Continued.



(c) CO_2 loop.

Figure 10.- Continued.



(d) H_2O loop.

Figure 10.- Concluded.

Nyquist plots for the N_2 loop are found in figure 10(a). 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 in figure 10(b). 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 shift had no effect on the stability determination.

Complex plane plots for the CO_2 loop and H_2O loop are in figures 10(c) and 10(d), 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 confirmed that there were no positive roots in the system.

AUTOMATED SYSTEM ANALYSIS

Manual analysis of the regenerative atmospheric system beyond the simple methods previously shown was impractical because of the many variables involved, the nonlinearities of the various components, and 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. This section describes the analog system used to simulate the regenerative cabin atmosphere system, the operations performed with the analog computer, and the results obtained.

Analog Computer Simulation

The analog computer layout generally followed the system block diagram (fig. 8), 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 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 that it is 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 change involved the substitution of simple time constants for the transport lags of the various components. The system block diagram (fig. 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, as discussed in appendix A. For this reason, it was decided to simulate the transport lags by simple time constants equal in magnitude to the respective transport lags. The error introduced by this approximation was determined to be less than 5 percent.

Scaling of variables in the program was difficult because of 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; thus, 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 wide range of scale factors (for example, from $0.004N_N$ to $10\ 000w_{H1}$) emphasizes the wide range of physical quantities which were accounted for during the scaling operation.

Each integrating amplifier was provided with a suitable initial condition; these conditions 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.

The various input functions, such as crew load and air-lock venting, were controlled manually by potentiometers 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 runs were 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.

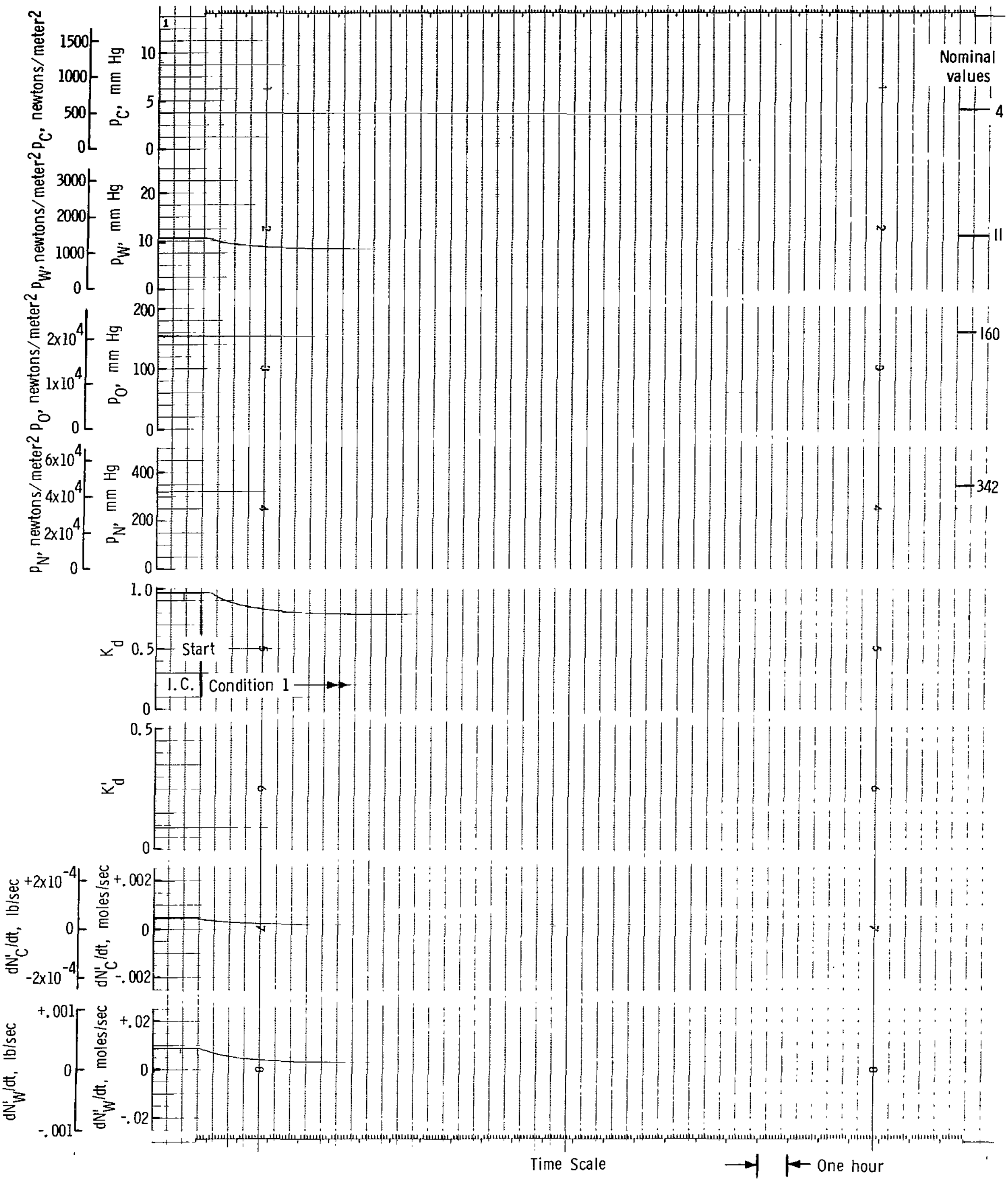
Figure 11 shows the effect of transient inputs on the atmospheric control system. Such transient inputs might be expected to occur routinely as the result of changes in the crew activity or as the result of operations such as air-lock venting. The traces basically show just a resetting of the system operating conditions to the new operating point in each case.

Figure 11(a) 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 and result in an appropriate adjustment of the bypass valve gains K_d and K'_d. The partial pressure of oxygen p_O shifts up slightly, and thus reflects the lower demand for oxygen. Lower rates of removal of CO_2 and H_2O from the cabin are indicated by the decreased rates dN'_C/dt and dN'_W/dt.

Figure 11(b) 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 metabolic load causes p_W and p_C to increase with a 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.

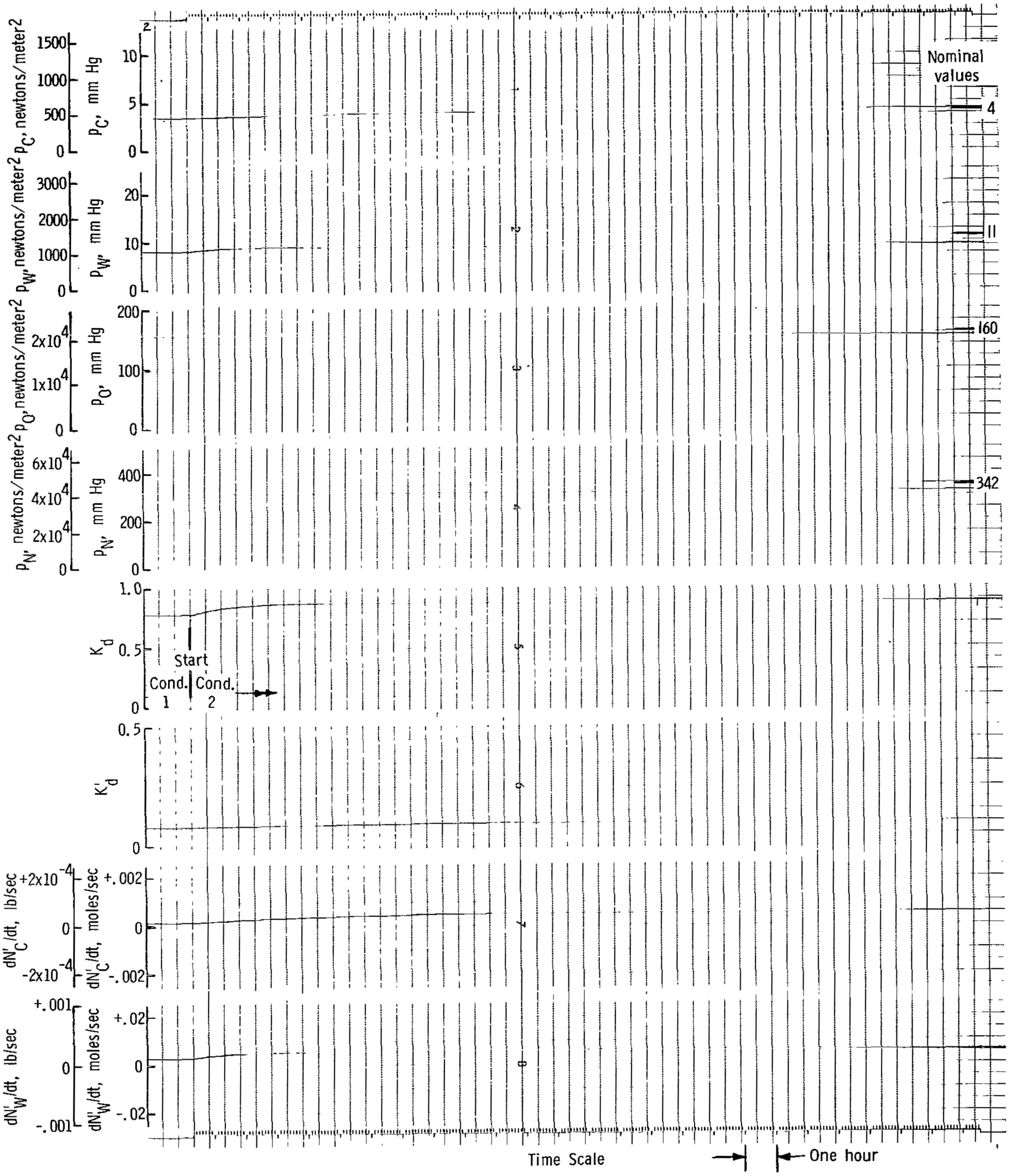
Transient response from crew condition 2 to crew condition 3, the resupply mode, is shown in figure 11(c). Although continuous operation is not required in condition 3, this load condition was imposed to evaluate the long term effects. Figure 11(c) shows that p_C and p_W will stabilize, but p_O continues to degenerate; thus, the oxygen demand exceeds the supply in this condition.

Figure 11(d) shows the transient response of the system from steady-state crew condition 2 to crew condition 4, and represents 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 overdamped system.



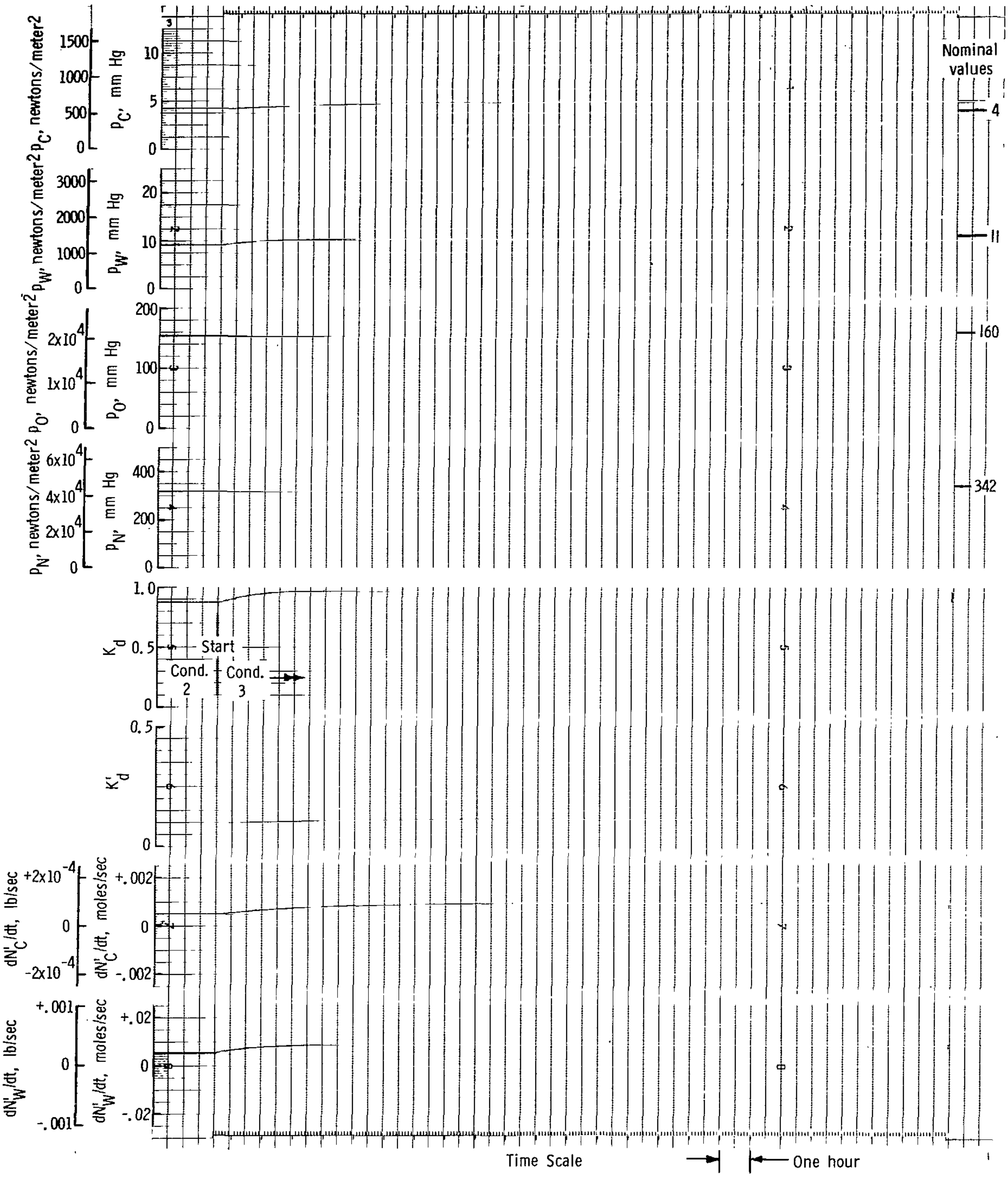
(a) Initial conditions to condition 1.

Figure 11.- Transient responses.



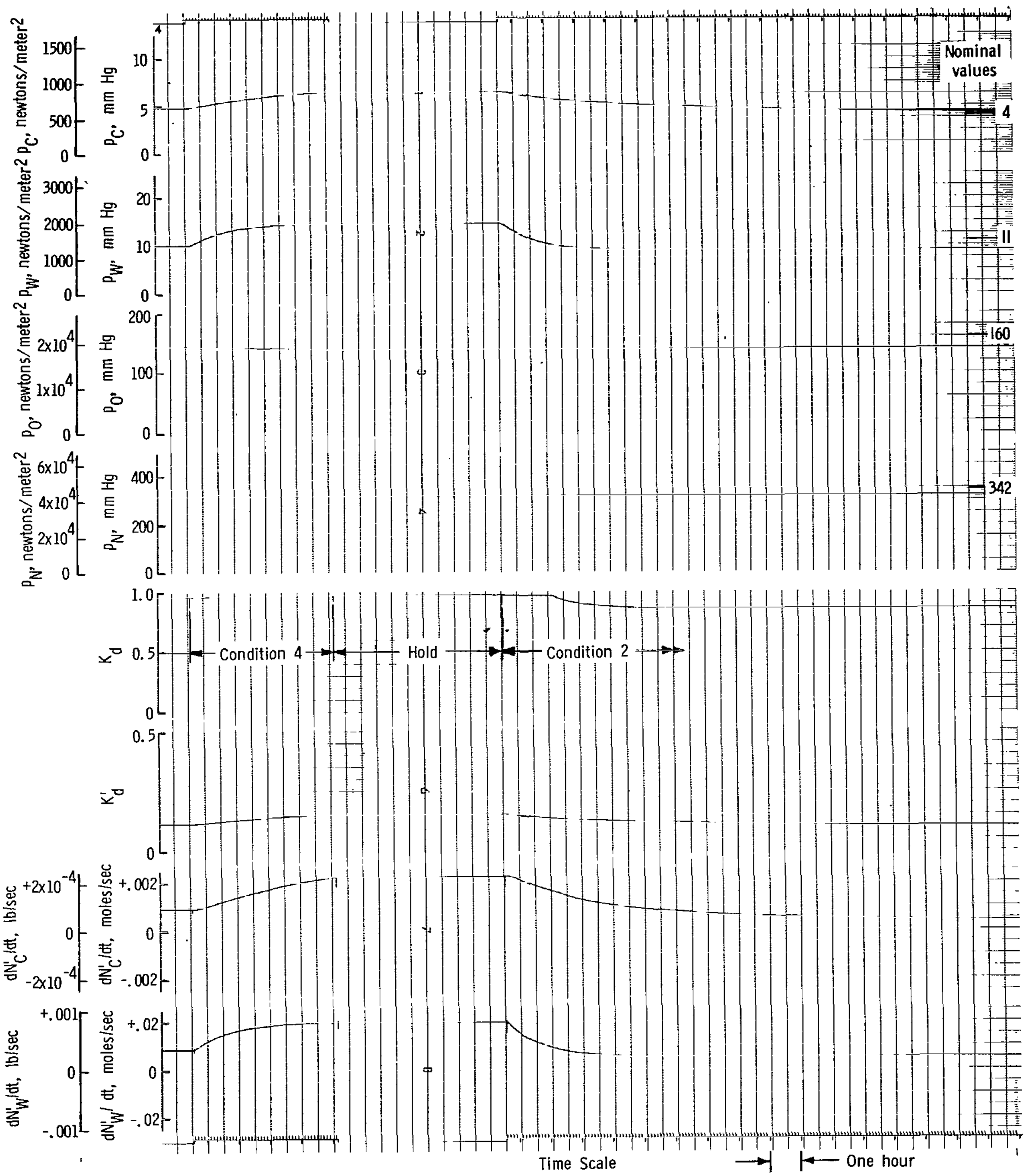
(b) Condition 1 to condition 2.

Figure 11.- Continued.



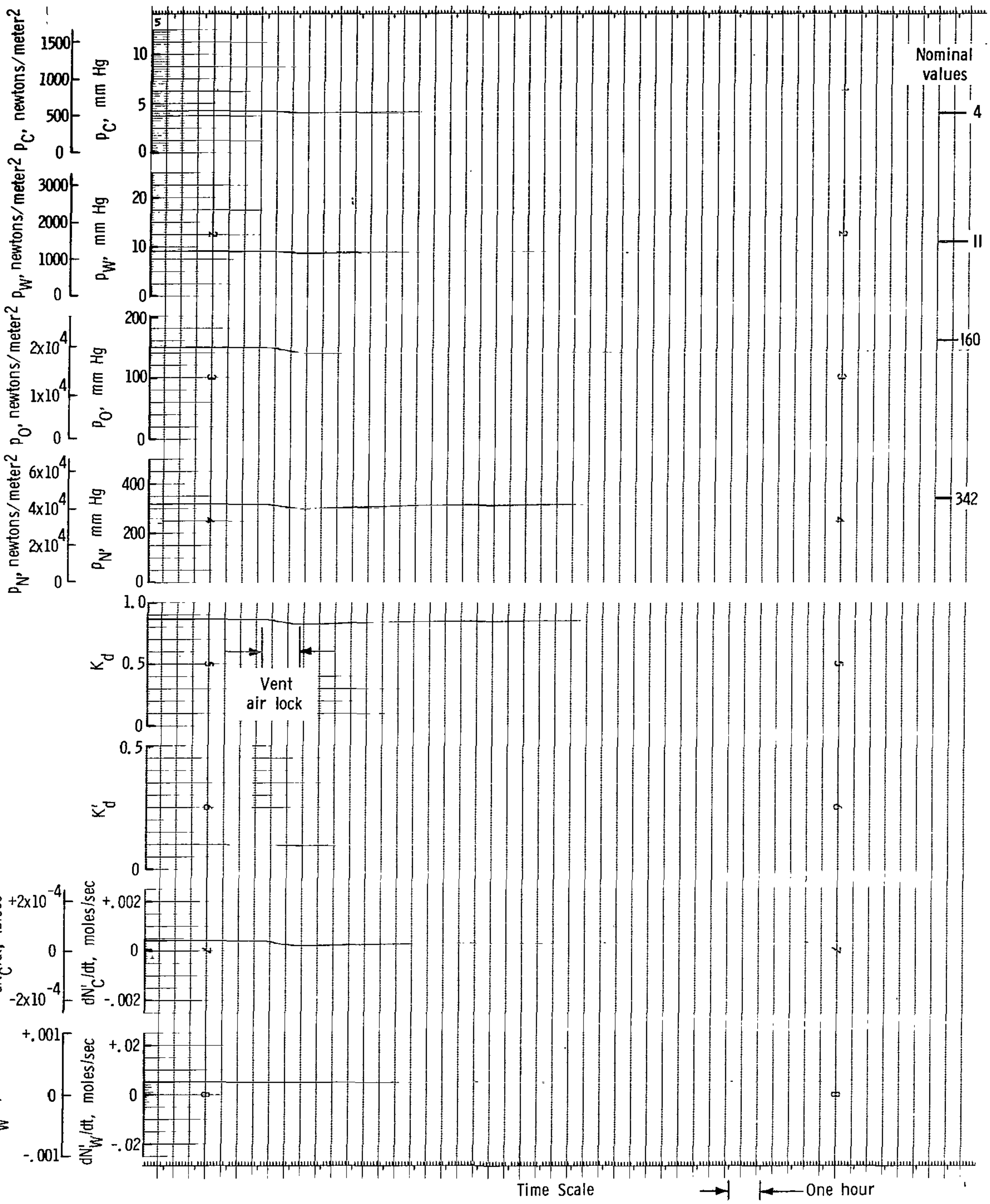
(c) Condition 2 to condition 3.

Figure 11.- Continued.



(d) Condition 2 to condition 4 to condition 2.

Figure 11.- Continued.



(e) Air-lock venting at condition 2.

Figure 11.- Concluded.

Figure 11(e) shows the response of the system to a simulated venting of the cabin air lock. Under this condition, all the atmospheric constituents are bled from the space cabin in proportion to their mole fraction, and, as a result, there is a decrease in the partial pressures. The most significant factor in this run is the extremely slow recovery of p_O following the transient and shows that the water electrolysis unit has very little reserve capacity for cabin repressurization.

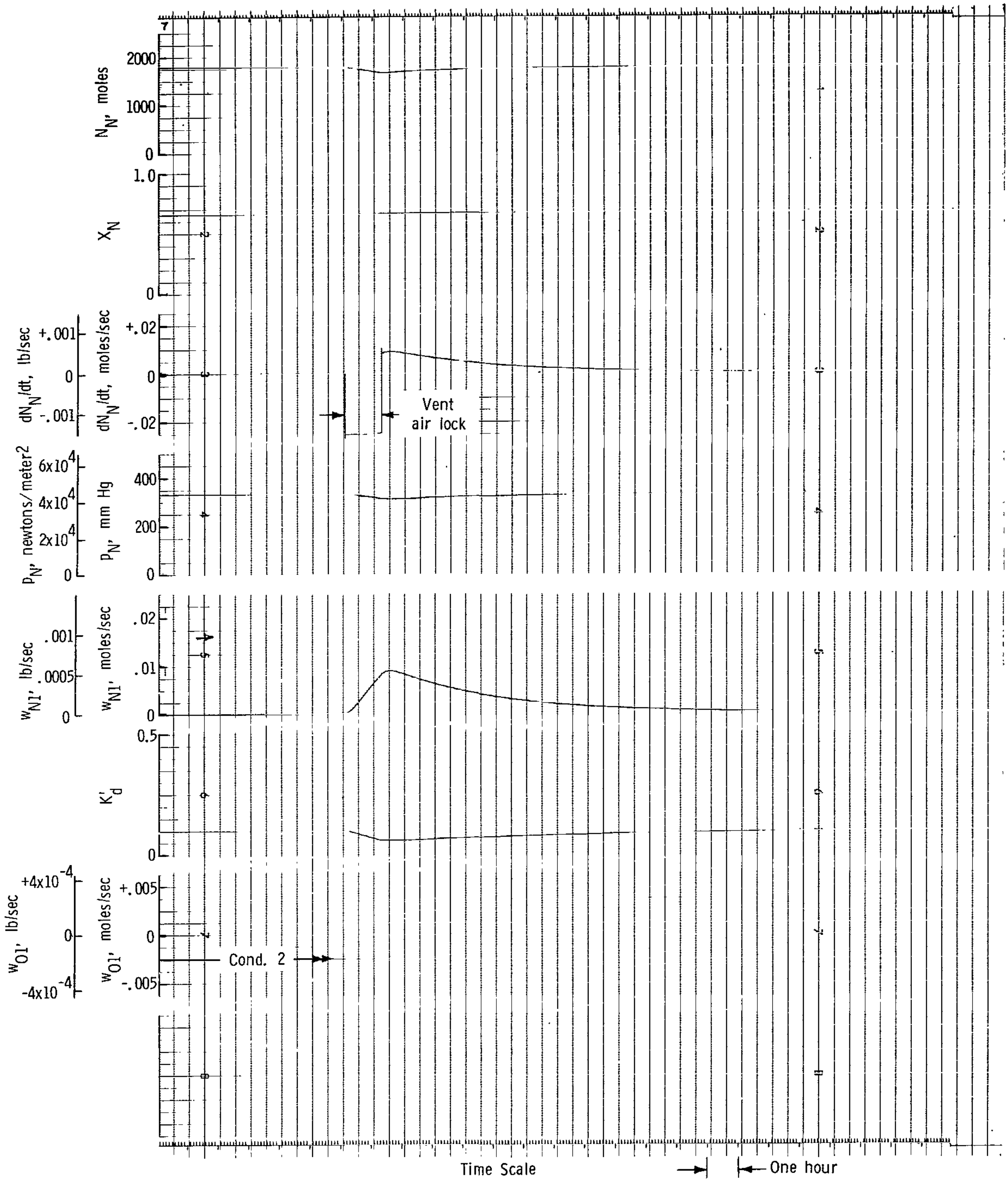
The transient tests in figure 11 have shown that the marginal nature of the assumed water electrolysis unit is apparent from two aspects: the oxygen output is insufficient to satisfy the system requirements at crew loads corresponding to condition 3 or above; and also, the recovery of p_O following a 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 12 and 13 provide data on the response of the individual control loops to transient loads, chiefly the leakage situation encountered during air-lock venting. Figure 12(a) shows the quick response of the N_2 loop to the air-lock venting condition. The N_2 makeup flow w_{N1} is seen to increase in proportion to the p_N deficit and then gradually decrease as p_N returns to normal. The mole fraction of N_2, that is, X_N, remains constant through the air-lock venting cycle since all atmospheric constituents are reduced by the same amount. However, X_N increases slightly during the recovery phase because N_2 recovers so much faster than O_2.

The run of O_2 loop response in figure 12(b) 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, that is, w_{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 w_{O1} was reduced during the run to hasten the recovery of O_2.

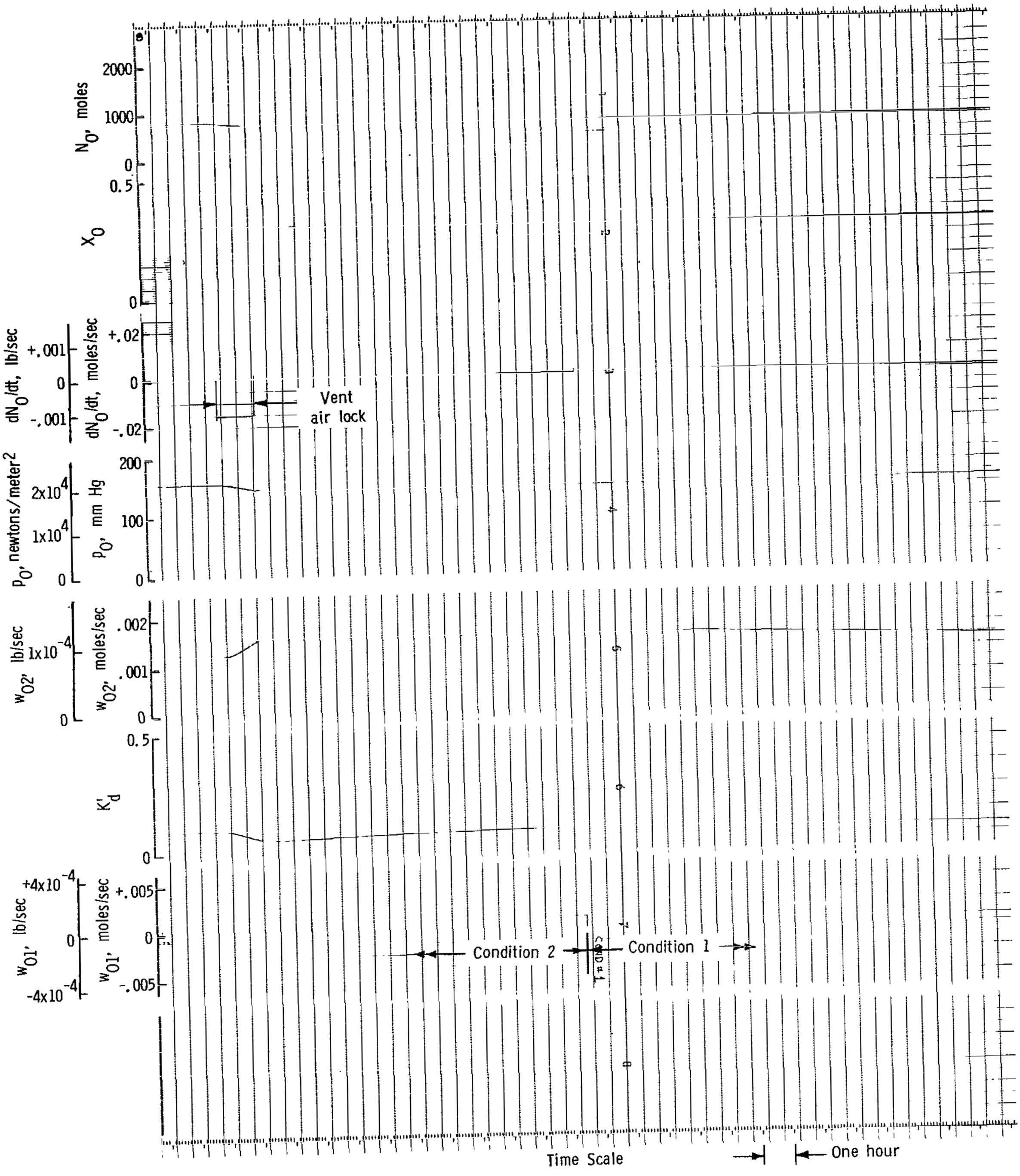
Figure 13(a) shows the response of the CO_2 loop to an increase in CO_2 production resulting from a 4-hour period in condition 4. The partial pressure of CO_2, that is, p_C, reaches a peak value of only 6 mm Hg (0.80 kN/m^2) during this time, and demonstrates adequate capacity for the peak load condition.

Figure 13(b) 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, that is, p_W, peaks at a value of about 13 mm Hg (1.73 kN/m^2), 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.



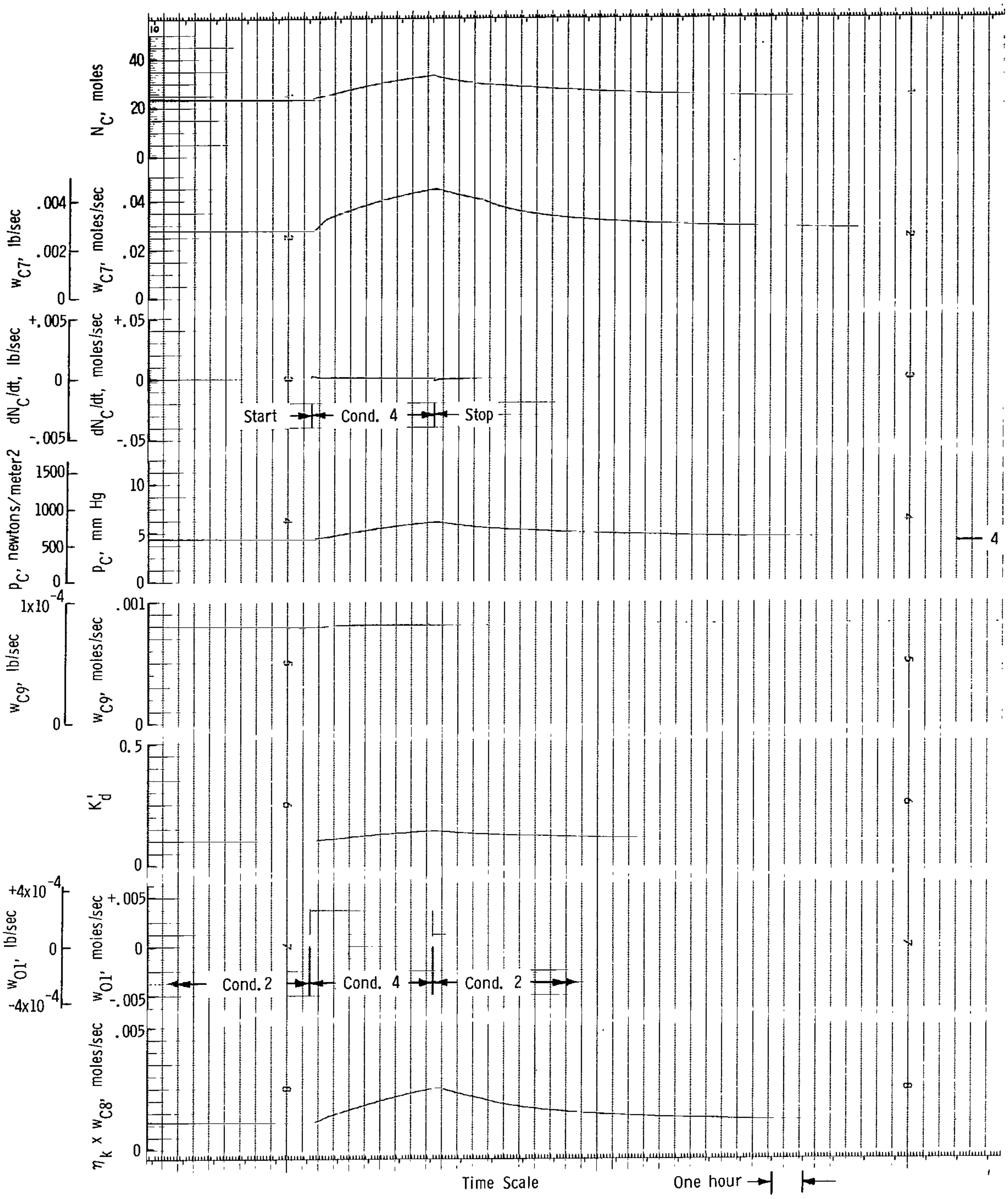
(a) N_2 loop.

Figure 12.- Response to air-lock venting.



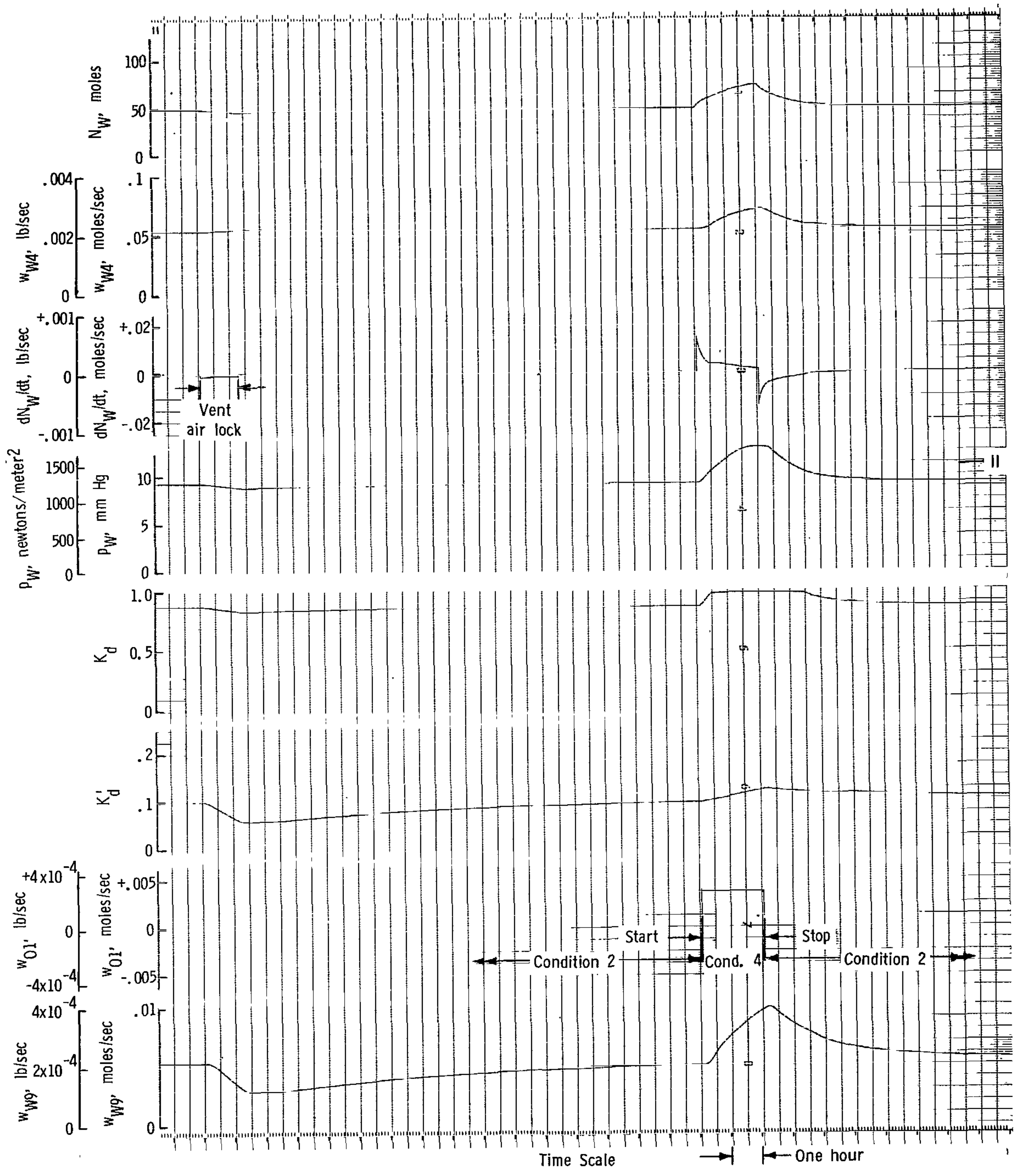
(b) O_2 loop.

Figure 12.- Concluded.



(a) CO_2 loop response from condition 2 to condition 4.

Figure 13.- Response to transient loads.



(b) H_2O loop response to air-lock venting and condition 4.

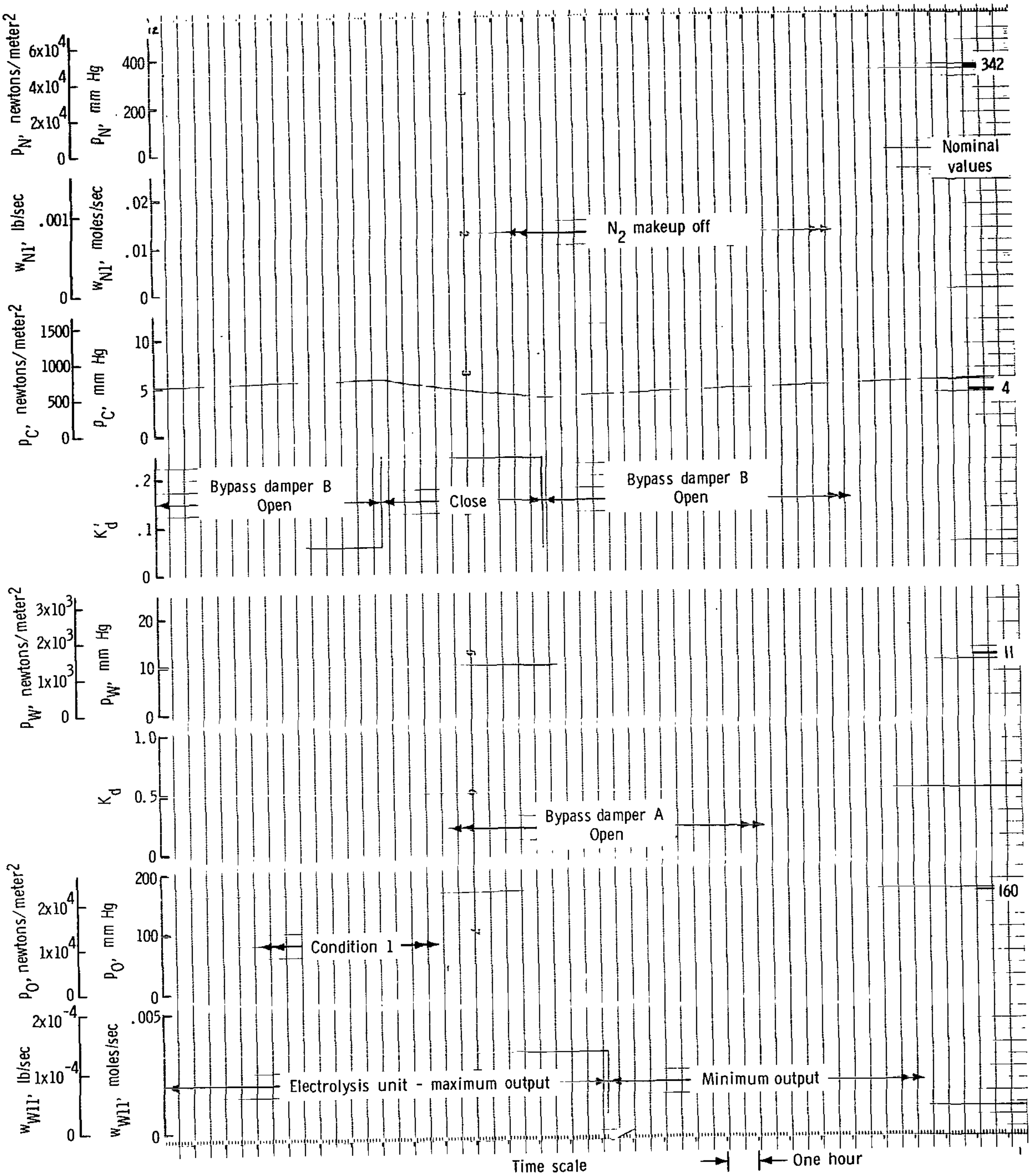
Figure 13.- Concluded.

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 previously. 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.

Figure 14 illustrates 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 emphasis, 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.

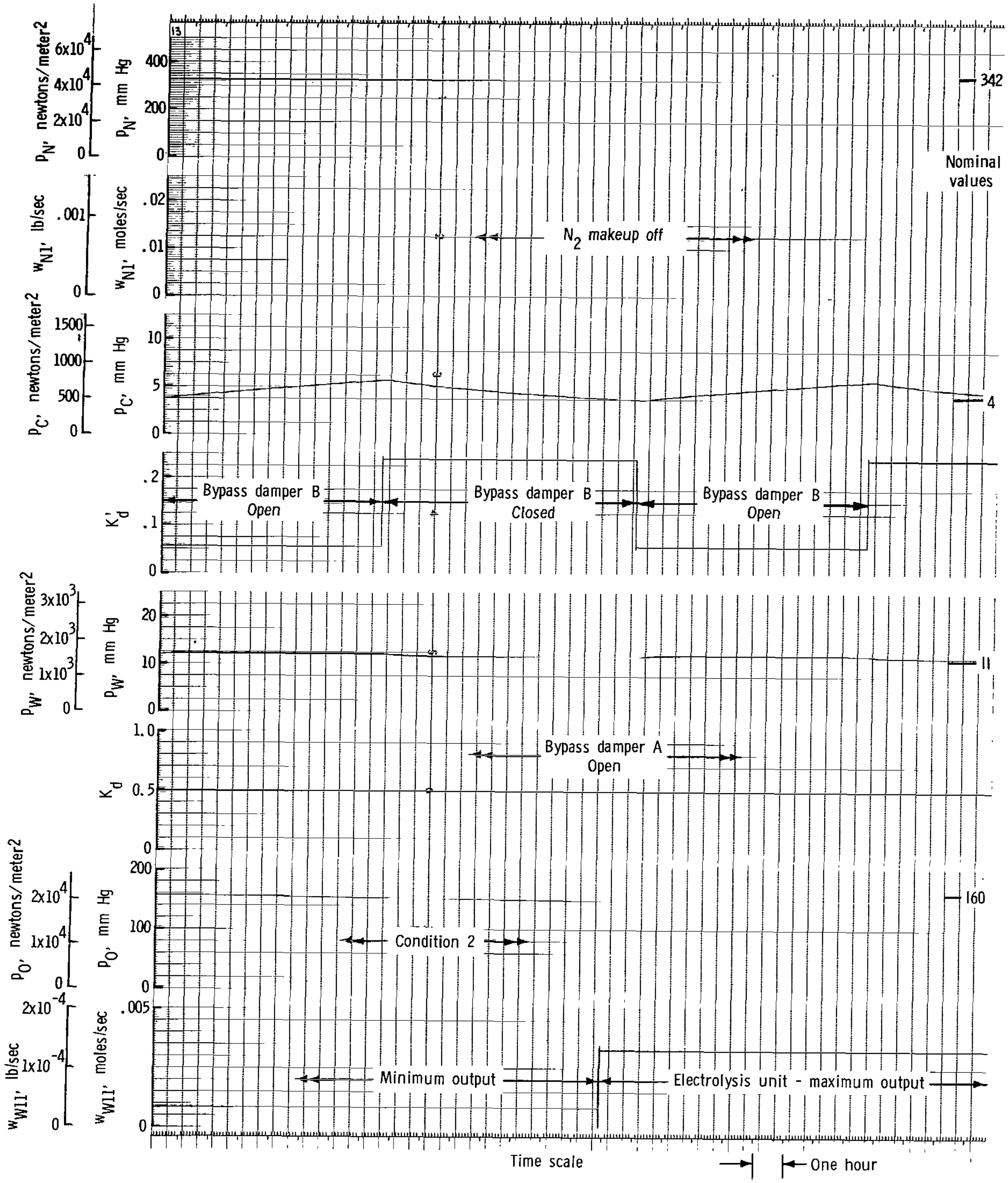
Figure 14(a) shows the steady-state operation of the atmospheric control system in crew condition 1, the minimum load condition. Operation of the various components is also at a relative minimum. The CO_2 concentrator operation, as shown by bypass damper B, is at a minimum with the exception of one 6-hour period when it operates at a maximum level to decrease the CO_2 concentration in the atmosphere. The water electrolysis unit is also operating at maximum output during the first few hours of operation but resets to the minimum output when p_O reaches the prescribed value. On-off control operation in crew condition 2, as shown in figure 14(b), is little different from condition 1, except that the cycling frequency of bypass damper B is increased because of 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 $\left(\text{that is, } K_d'\right)$ causes a sympathetic change in the value of p_W. This change results since the closing of damper B, 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 in figure 14(c), all control functions are active during various parts of the run. The N_2 controller actuates to replace N_2 lost because of normal cabin leakage; bypass damper B $\left(\text{that is, } K_d'\right)$ continues to cycle periodically; bypass damper A $\left(\text{that is, } K_d\right)$ resets to its maximum value; and the water electrolysis unit is operating at maximum but still is unable to maintain the value of p_O. Control system operation during and after a condition 4 load situation, as shown in figure 14(d), shows the expected response to the sudden disturbance of the system.



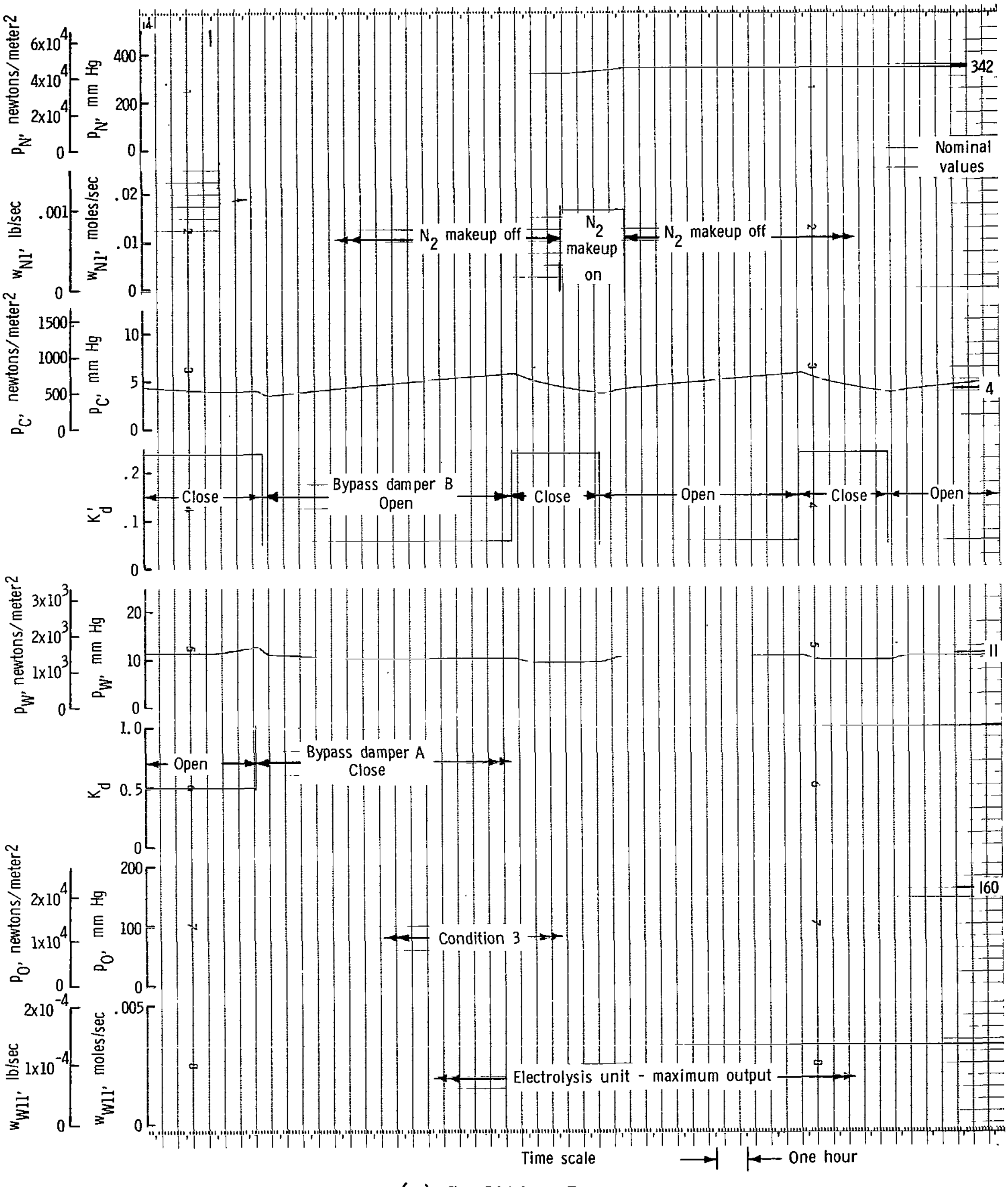
(a) Condition 1.

Figure 14.- On-off control operation.



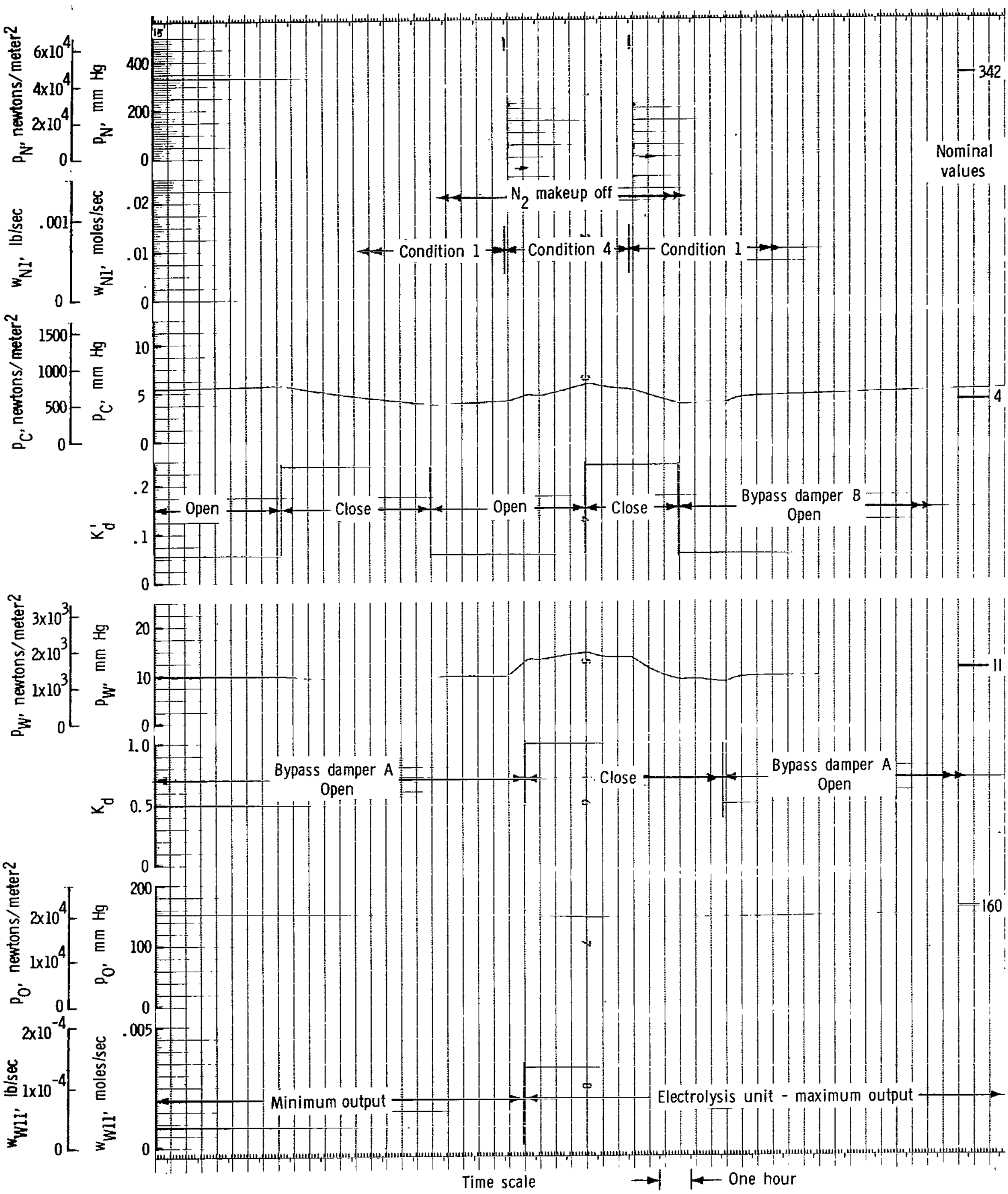
(b) Condition 2.

Figure 14.- Continued.



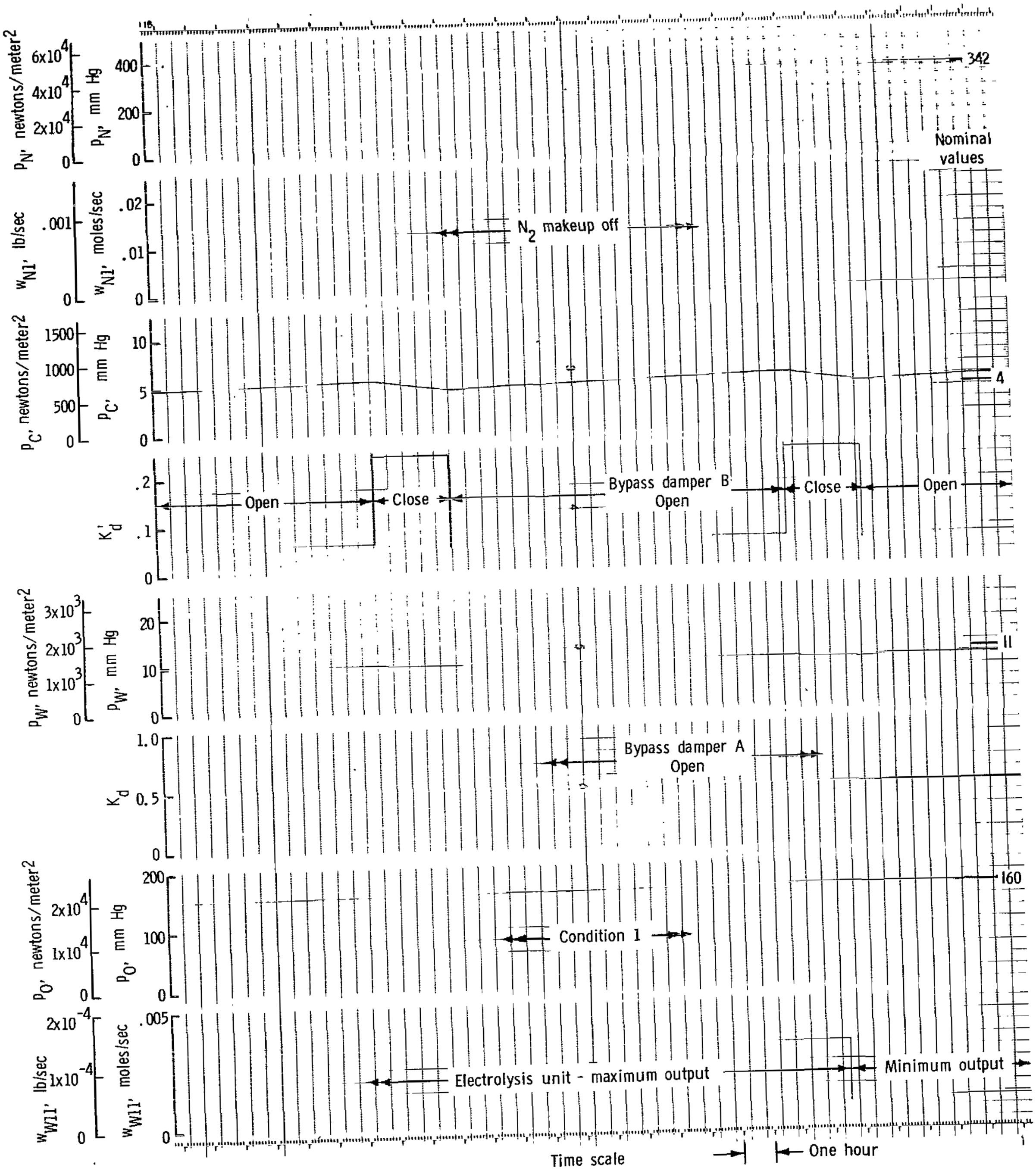
(c) Condition 3.

Figure 14.- Continued.



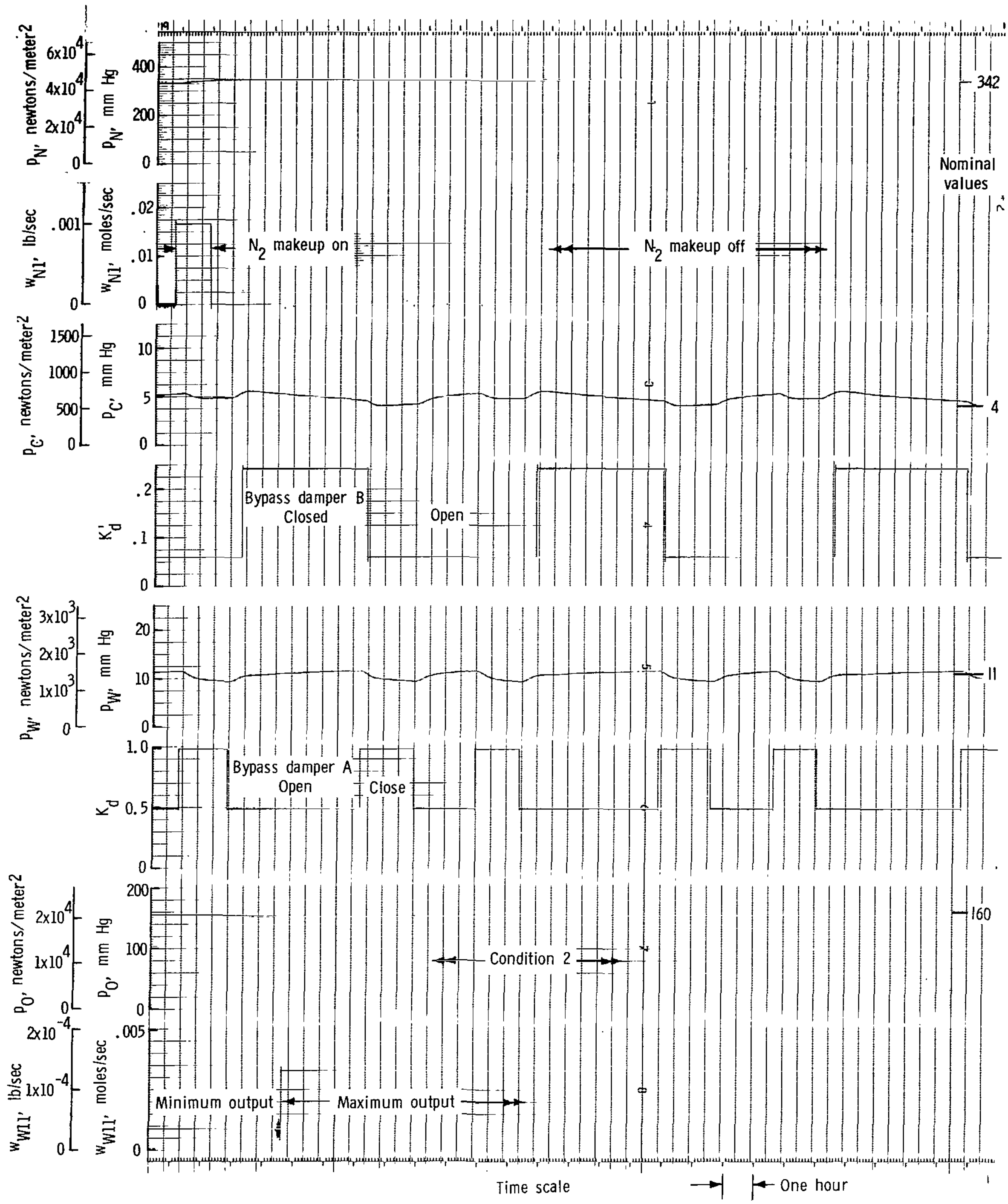
(d) Condition 1 to condition 4 to condition 1.

Figure 14.- Concluded.



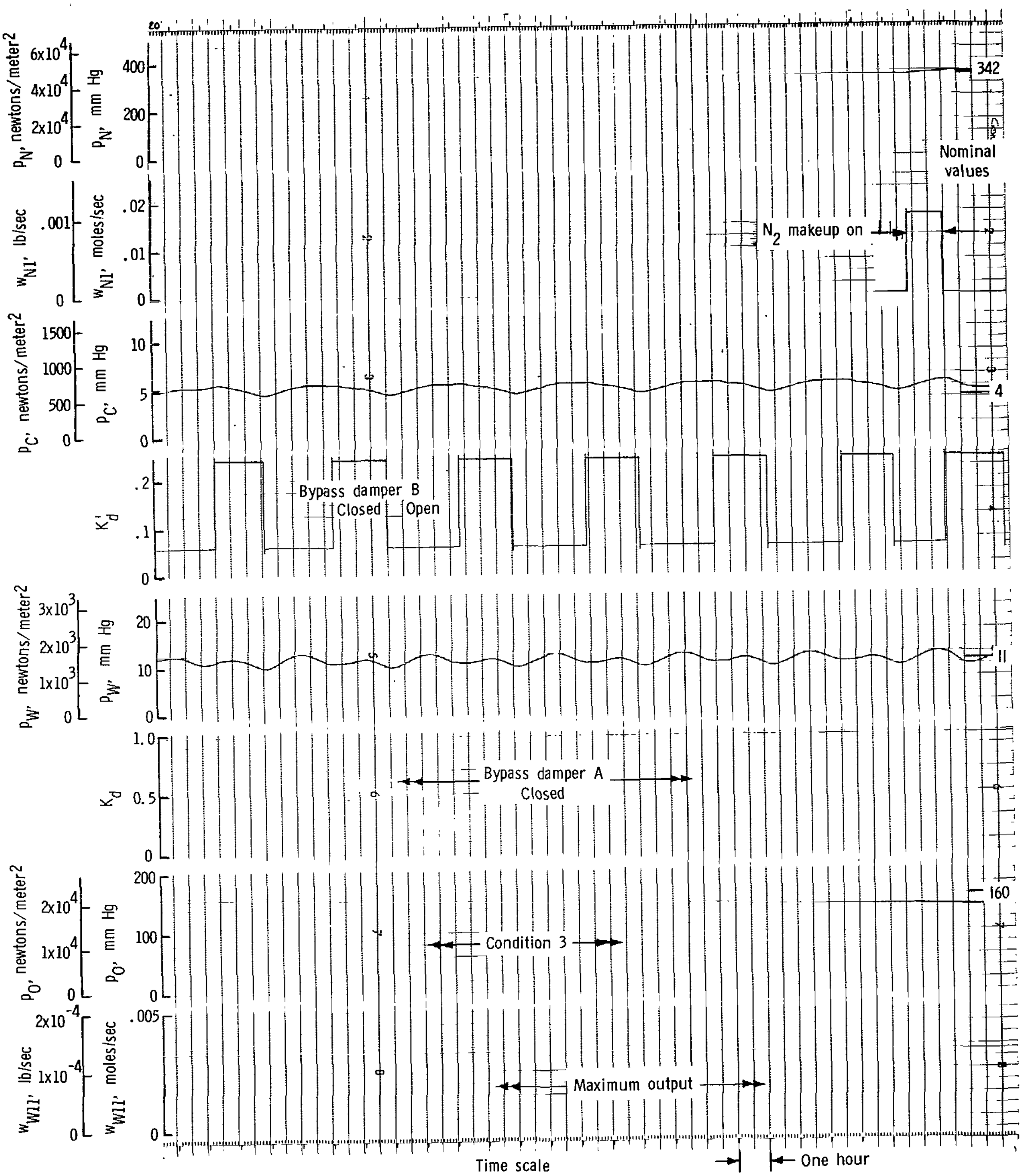
(a) Condition 1.

Figure 15.- Narrow deadband operation.



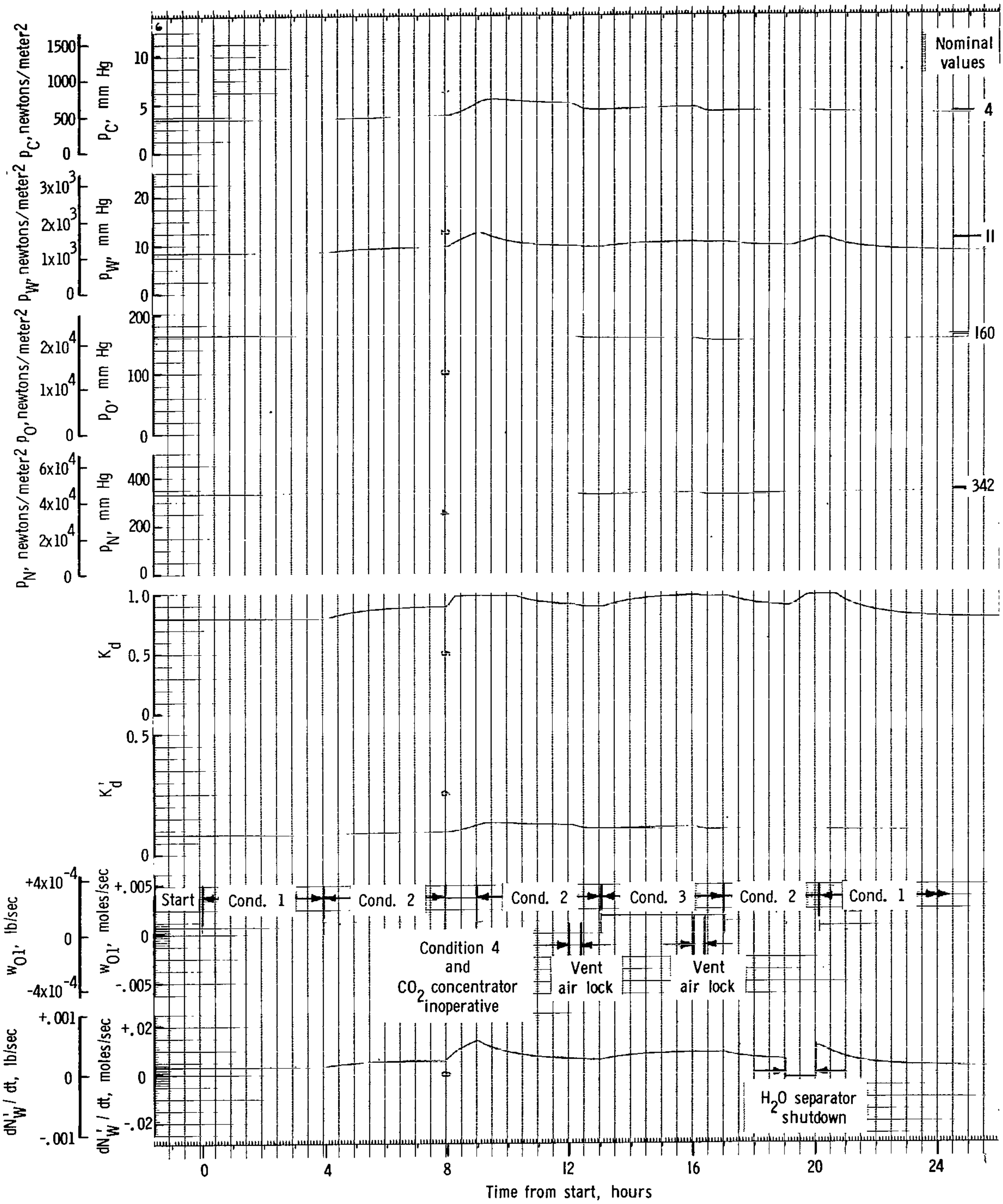
(b) Condition 2.

Figure 15.- Continued.



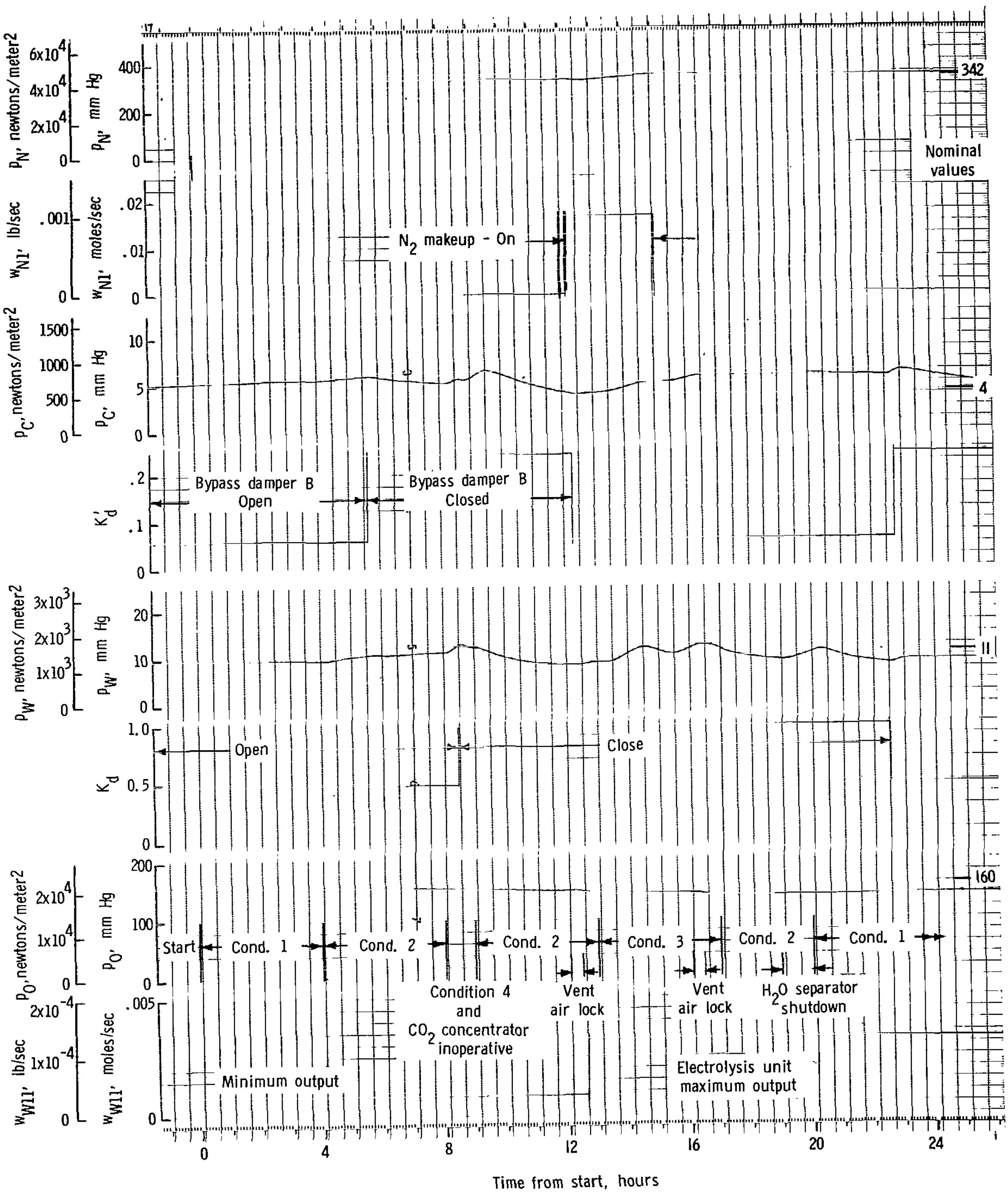
(c) Condition 3.

Figure 15.- Concluded.



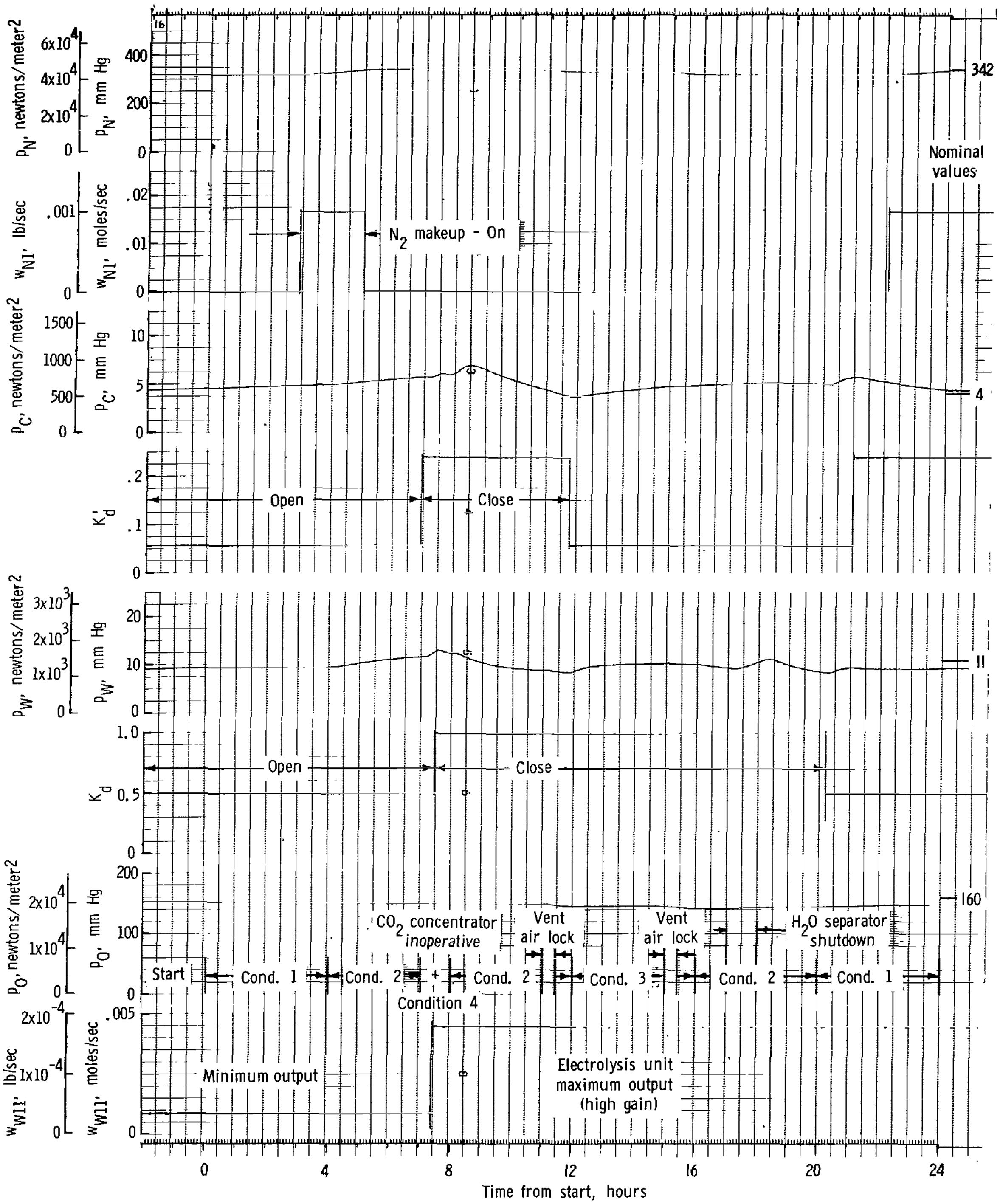
(a) Proportional control.

Figure 16.- Typical day run.



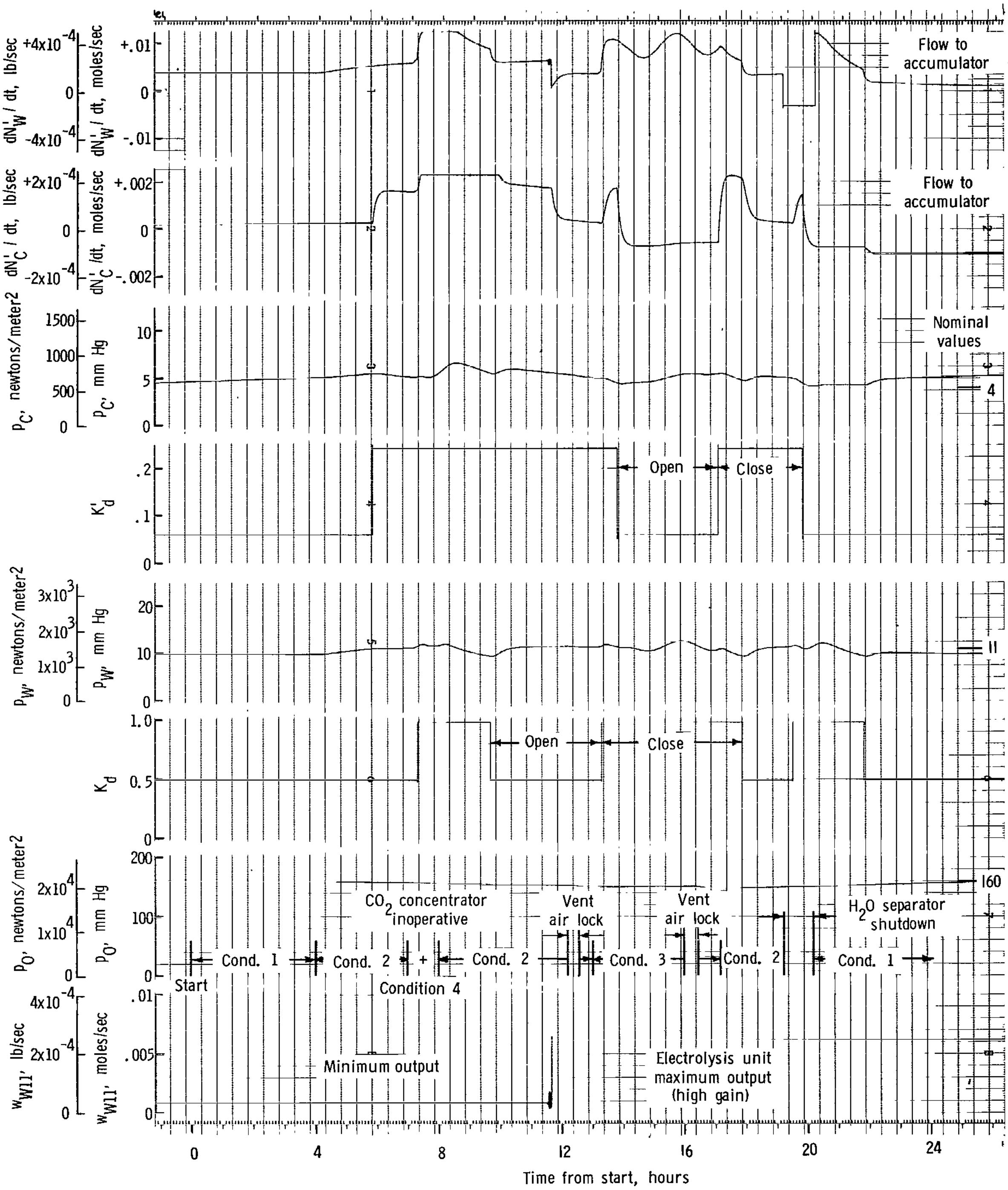
(b) On-off control.

Figure 16.- Continued.



(c) On-off control. Modification 1.

Figure 16.- Continued.



(d) On-off control. Modification 2.

Figure 16.- Concluded.

The effect of on-off deadband width on the system response is evident from figure 15. The reduced deadband width not only increases the cycling rate as could be expected, but also results in a type of system instability because of the interaction of the H_2O and CO_2 loops. The effect in condition 3 is particularly noticeable, since the oscillation results in variations of relative humidity from 45 to 60 percent over a 1.2-hour period. This case illustrates the value of checking system performance to determine the effect of changes in the control components.

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 in figure 16 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 system run with proportional control is shown in figure 16(a) and the corresponding run with an on-off control system is in figure 16(b). Comparison of the two runs 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 in figures 16(c) and 16(d). The modification 1 system of figure 16(c) features a water electrolysis unit with higher output to enhance the performance of the O_2 control loop. The modification 2 on-off system of figure 16(d) has a higher output electrolysis 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 seen to be greatly improved by the increased output of the water electrolysis unit. As discussed previously, such a wide variation in output of the electrolysis unit would probably require parallel redundant units on a standby basis. However, such an arrangement would seem to be most desirable since it would provide a redundant capability for this important component and could also provide the capability for partial cabin repressurization, although this is not a normal requirement.

CONCLUDING REMARKS

This study has resulted in the development of a relatively simple mathematical model for a regenerative cabin atmosphere 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 statement 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; thus, 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, principally because of 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 to allow the system parameters to 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.

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 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 stability studies 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 unless stored oxygen is available for repressurization.

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 should be considered. However, proportional control could be the choice if steady, continuous operation is desired with a minimum load fluctuation 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 nominal material balances.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., February 3, 1971.

APPENDIX A

SIMULATION OF TRANSPORT DELAYS

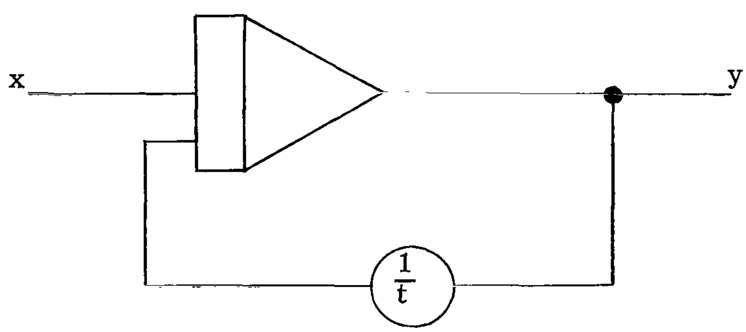
By Robert A. Smoak

There are a variety of methods for simulating transport delays. The discussion here is limited to simulations involving analog components.

The problem is that of making a circuit of computer components having a transfer function which approximates e^{-ts}. The accuracy of a given scheme is easily tested by comparing the actual transfer function with the Taylor series representation for e^{-ts}, as

$$e^{-ts} = 1 - ts + \frac{(ts)^2}{2!} + \ldots + \frac{(-ts)^n}{n!} + \ldots \tag{A1}$$

Evaluating this expression at $s = i\omega$ shows that the important parameter in a transport delay simulation is the product ωt. The magnitude of ωt determines the point at which the series (A1) can be truncated. Since the series (A1) is an alternating series, the error involved in truncating the series is always less than the first neglected term. For this simulation, $\omega t \leqq 0.3$. First, consider the circuit in sketch (a).



Sketch (a)

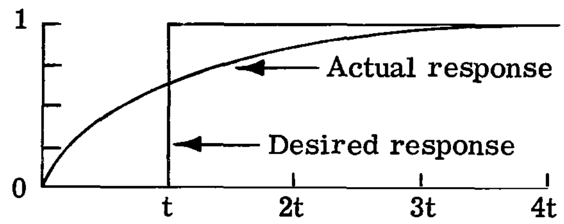
The transfer function for the circuit shown in sketch (a) with x and y as the variables is:

$$\frac{y(s)}{x(s)} = \frac{-1}{1 + ts}$$

If this transfer function is expanded in a Taylor series,

$$\frac{y(s)}{x(s)} = 1 - ts + t^2s^2 + \ldots \tag{A2}$$

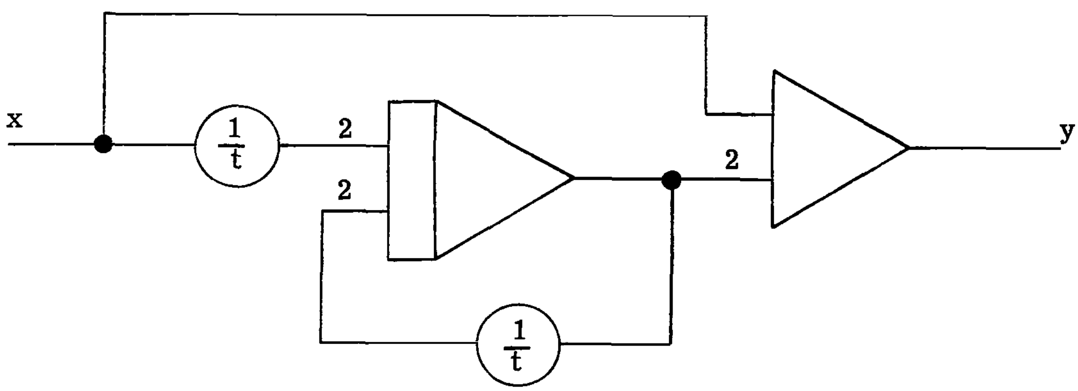
This expansion agrees with equation (A1) to the first order in ts. The step response is shown in sketch (b):



Sketch (b)

In this circuit, the amplitude of the variation of response with frequency is not a constant. A pure transport delay would not attenuate high-frequency signals. In the problem treated here, there is always the possibility of diffusion causing signal attenuation since high frequencies correspond to steep concentration gradients which make the diffusion effect stronger.

An alternative circuit, usually called a first-order Padé approximation, is shown in sketch (c).



Sketch (c)

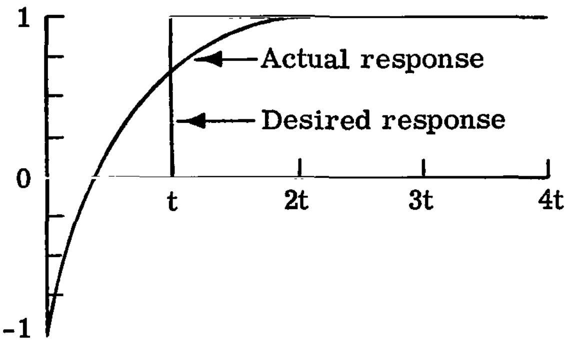
The transfer function for the circuit in sketch (c) is:

$$\frac{y(s)}{x(s)} = \frac{1 - \frac{ts}{2}}{1 + \frac{ts}{2}} \tag{A3}$$

Expanding equation (A3) in a Taylor series yields:

$$\frac{y(s)}{x(s)} = 1 - ts + \frac{t^2s^2}{2} - \frac{t^3s^3}{4} + \ldots \tag{A4}$$

Equation (A4) agrees with equation (A1) to second order in ts. The zero in the right half plane of the circuit causes a constant-amplitude response at high frequency. Sketch (d) shows the step response for this circuit.



Sketch (d)

This circuit gives a better approximation in terms of the series (A1) and in terms of amplitude response. The negative initial response and the additional equipment required make it undesirable in this application. With a linear controller, it would be satisfactory but the negative pulse could cause undesired effects with a switched controller involving hysteresis, such as the one used in this simulation. The first-order lag circuit was used in the simulation here because it does not cause problems with nonlinear controllers. The ωt product is less than 0.3 radian; thus, the errors involved in the use of the lag circuit are less than $4\frac{1}{2}$ percent.

Wierwille (ref. 6) offers a method of simulating transport delays which overcomes this difficulty. Unfortunately, the method uses so many amplifiers that it was not practical for this study.

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