The Design of A Life Support Circulation System for Hyperbaric Chambers

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THE DESIGN OF A LIFE SUPPORT CIRCULATION SYSTEM FOR HYPERBARIC CHAMBERS

by

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This Thesis submitted by Kenneth P. Orchuk in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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ABSTRACT

The purpose of this thesis was to present the design of a Life-Support Circulation System for Hyperbaric Chambers as specified by the Themis Committee.

An important objective was to design a versatile circulation system which could be constructed from commercial products.

Circulation specifications were set by conditions required for the animals under observation in the hyperbaric chambers. Since these studies were to be conducted for prolonged periods, cost analysis warranted a closed system design.

The versatility of the system required investigation of several types of valves for satisfactory operation. Also, pressure monitoring controlled valves and pressure regulators had to be examined for precision of their settings along with their time response.

A schematic layout presenting the locations of three major circulation lines and various types of valves and regulators was constructed. Each valve and regulator, on the layout, was given two numbers; one number classified them as to size and type, and the second classified them as to order of operation.

From these operation numbers were constructed twelve flow charts depicting the entire operation routine for the maximum effective use of the circulation systems. These flow charts present the basic routines which could be converted to computer language.

The complexity of the system warrants controlled operation by a process computer. Since a process control computer was acquired by the Themis Committee for the purpose of controlling the systems, mechanized operators had to be investigated for both the valves and pressure regulators.

Chapter I

INTRODUCTION

The Purpose of the Hyperbaric Life Support System for Project Themis

The prime purpose of the hyperbaric life support system for Project Themis is to study the long term effects of high pressure helium-oxygen atmospheres on mammals. The responsibility of the Mechanical Engineering Department is: the design and selection of pressure vessels, the circulation system, and the purification system. It was the decision of the Themis Committee that the largest possible research facility be constructed from the funds available, therefore the design of the research facility was governed primarily by engineering decisions.

Past Development of High Pressure Circulation Systems

In the past very little importance was placed on deep-sea exploration. But in recent years more emphasis has been placed on this area, one of the reasons being the depletion of surface natural resources. As interest in deep-sea technology grew and as men strived to reach greater depths on the ocean floor, a necessity for high-pressure ocean simulation laboratories arose [1]. The need for these laboratories increased as accidents became more frequent in open dives at depths greater than 300 feet.

Questions then began to arise as to whether or not man could live under high-pressures for long periods of time [2]; thus, the need for long term high-pressure ocean simulators became a necessity. Project Themis is a direct result of these needs.

Since the field of study is relatively new, very little information on system designs is available and the existing information is mostly restricted to periodicals. Information on highly sophisticated systems such as the one being constructed here at the University of North Dakota is very limited. Another similar system is being constructed at Panama City, Florida. Although this system will be capable of testing men and submergible machines at simulated depths of 2,250 feet below sea-level, its basic function is the same [3,4]. It will provide long term exposure and also will have recovery, reclamation, and air conditioning systems.

Early development of Ocean Simulation Laboratories was only for short term studies, and in these cases gases were not recovered or purified, solid carbon dioxide absorbants were placed inside the pressure vessels to prevent carbon dioxide poisoning and oxygen levels were maintained by hand actuated needle valves [2]. Also, in the early development of Ocean Simulation Laboratories, compressed air was used [2]. These studies were mainly for the observation of the toxic effect of oxygen and nitrogen narcosis [5]. These early system designs essentially did not have circulation systems.

Statement of the Problem

In this project, it was the author's responsibility to design a circulation system for the research facility. The circulation gas will be helium, containing a constant partial pressure of 150-160 mm mercury of oxygen, at pressures ranging from 0 to 600 psig. These gases will be circulated through purification systems, humidification systems and through pressure vessels without any large losses in gas or pressure.

The first problem encountered was that of the decompression of the hyperbaric chamber. Since the chamber would contain living animals and organisms, the unit would have to be stage decompressed. This decompression would take place at the end of an experiment or at a time when difficulties arose in the systems operation. The idea of decompression brings us to the final stage of the problem. This is the problem of recovering the gas released at decompression, and also compression of the system gas back up to a normal operating pressure.

It is essential that the gas be recovered from decompression, since the one purpose of the overall design is that only minimum amounts of gas mixture be lost. The largest portion of the gases will be recovered, pressurized, cleaned, humidified, and recirculated into the system.

Emphasis has been placed on economic feasibility to insure that the research facilities' size would be maximized. Selection of suitable products for the facility was not only decided on for dependability and maintenance, but also on a cost basis. As will be noted in some chapters, decisions were finally reached by economic analysis, such as on the vessels selected for the high-pressure and low-pressure dirty storage. In situations where items were obtained from military surplus, the money saved was redistributed to areas that were short of funds. When deciding on purchases of items from private industry, it was decided that a cost decision would be made by selecting the lowest of three separate estimates, but where less than three suppliers were available, the lower estimate would be selected.

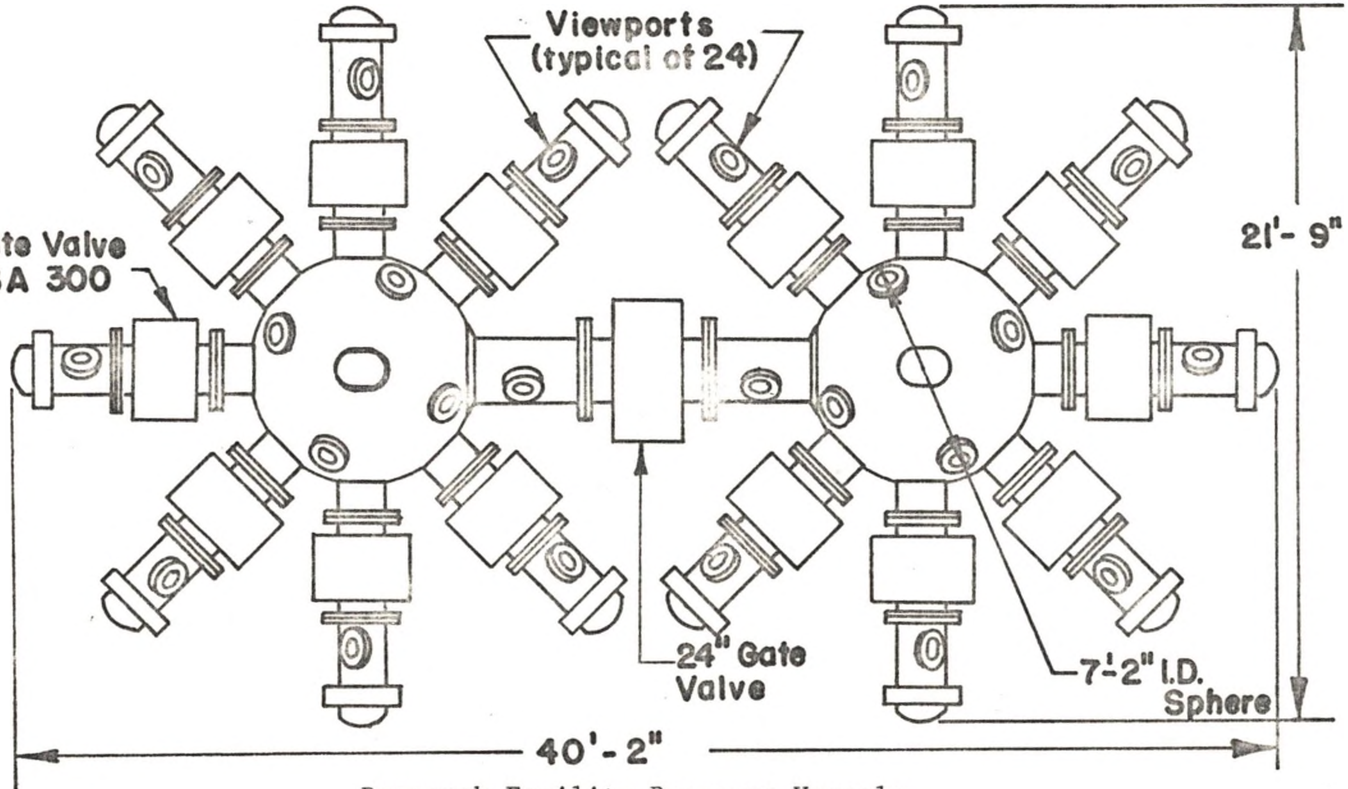
Chapter II

CIRCULATION REQUIREMENTS

Flow Capacities

Since the prime purpose of Project Themis is the long term study of mammals' existence under high-pressure helium-oxygen atmospheres, it is important that normal circulation conditions be maintained. Poor gas circulation would cause a build up of heat and also lead to toxicity problems [5]. It is also possible that the oxygen content would drop below the minimum level for life support before recovery is possible, causing suffocation.

Dr. Akers, of the University of North Dakota Physiology Department, stated that a minimum and sufficient circulation rate for animals is five volume changes per hour. This rate is in complete agreement with Baumeister and Marks Handbook which states that minimum circulation requirements should be five volume changes per hour [6]. Thus, before the actual flow capacities could be fixed, the final size of the pressure complex had to be fixed. It was finally decided that the unit would be of the design as shown in Figure 1. This system calls for fourteen piglets, each seventeen inches inside diameter and thirty-nine inches long. The piglet would be fastened to an eighteen inch gate valve which in turn would be fastened by a weld neck flange to a seven foot, two inch diameter sphere. The two spheres would be connected by a twenty-four inch



Research Facility Pressure Vessels

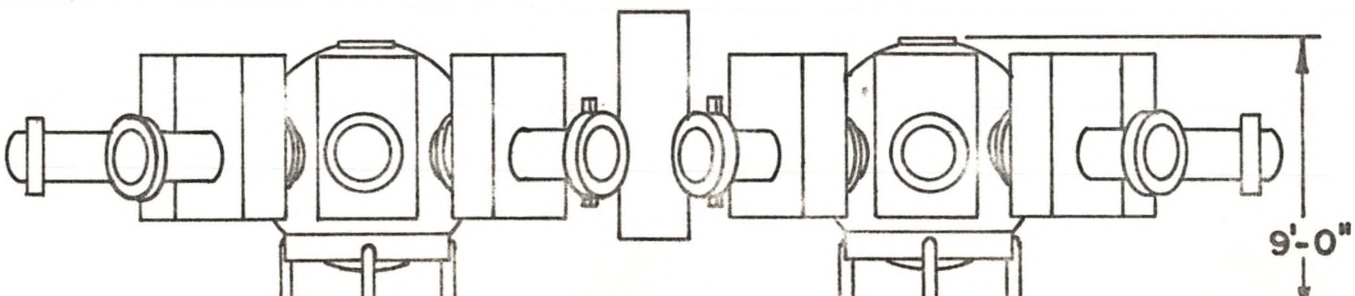


Figure 1

pipe with a twenty-four inch gate valve located midway between the two spheres. It was decided that one sphere and seven piglets would be referred to as a complex; the complex on the left being Complex A, and the complex on the right being Complex B. Complex A and B encompass a total volume of 581 cubic feet but since each complex will operate as an individual unit, the volume required for circulation will be five times 290. This gives a circulation flow rate of 24.2 cu. ft./min.. This means that each system will require one pump having the capabilities of moving 24.2 cu. ft./min.. The illustrated piping in Figure 2, for one circulation loop and two manifolds as shown in Figure 3, has an approximate equivalent length of 330 feet of half-inch black pipe plus 191 feet of 1½-inch black pipe. The half-inch pipe is used for distribution from the manifold, while the 1½-inch pipe is the main source gas line. This equivalent length is equal to 3.14 psi pressure drop; combined with the drop across the reclamation system of 1 psi, and the drop through the humidification system of 2.60 psi, this gives a total pressure drop, excluding the heat exchanger, of 6.75 psi. The heat exchanger pressure drop was estimated at 6 to 7 psi, therefore a conservative estimate of the pressure drop across the pump will be 15 psi (i.e., for calculations of pressure drop and equivalent length, see Appendix B). It is suggested that a high pressure pump be used for circulating the gases; its cost would be approximately equal to that of enclosing a standard pressure, high-gas-density pump in a pressure vessel. The disadvantages of enclosing a pump in a pressure vessel are those of inaccessibility in emergencies, large quantities of heat dissipated

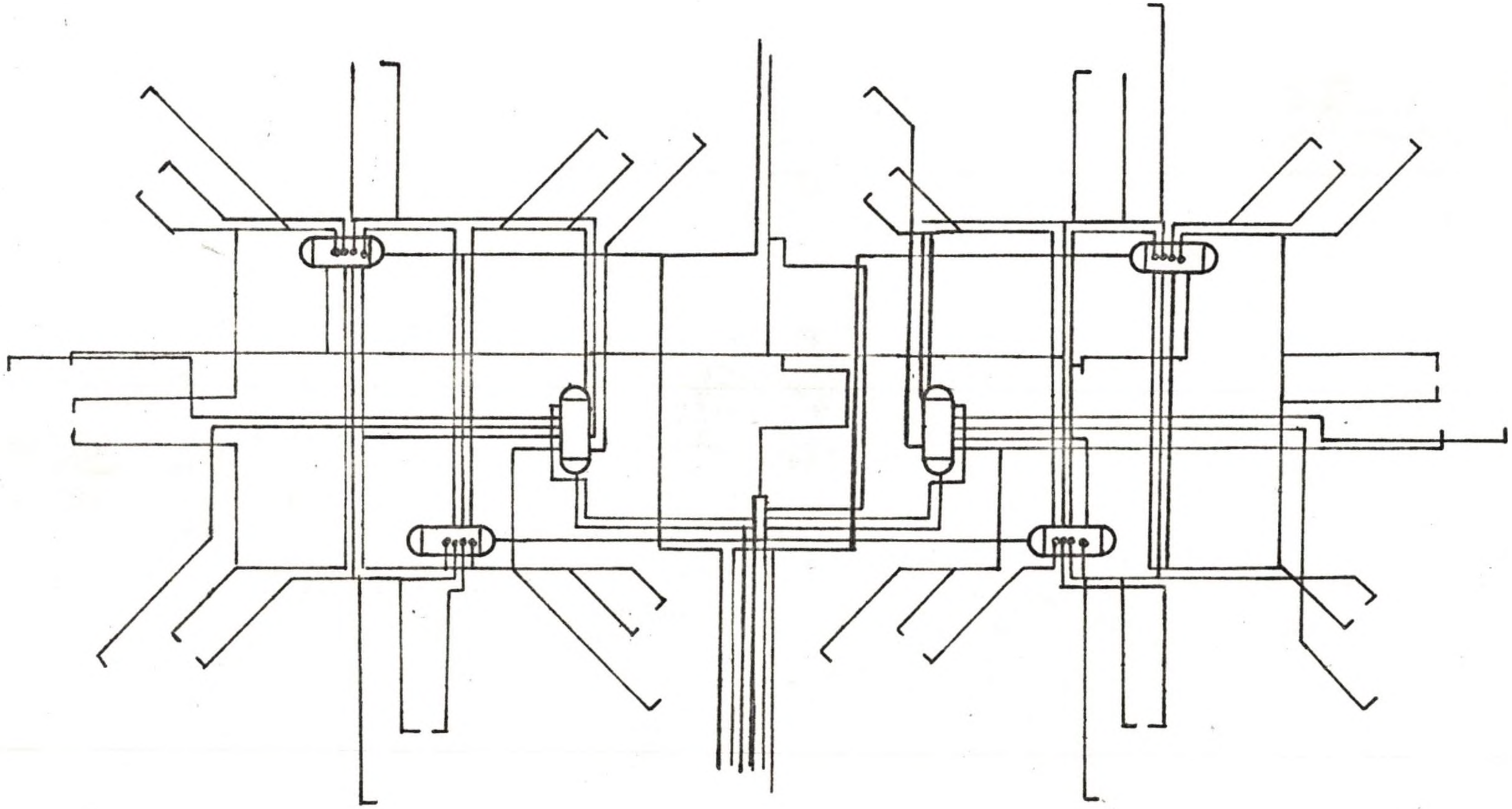


Figure 2 Schematic Layout of Circulation Piping

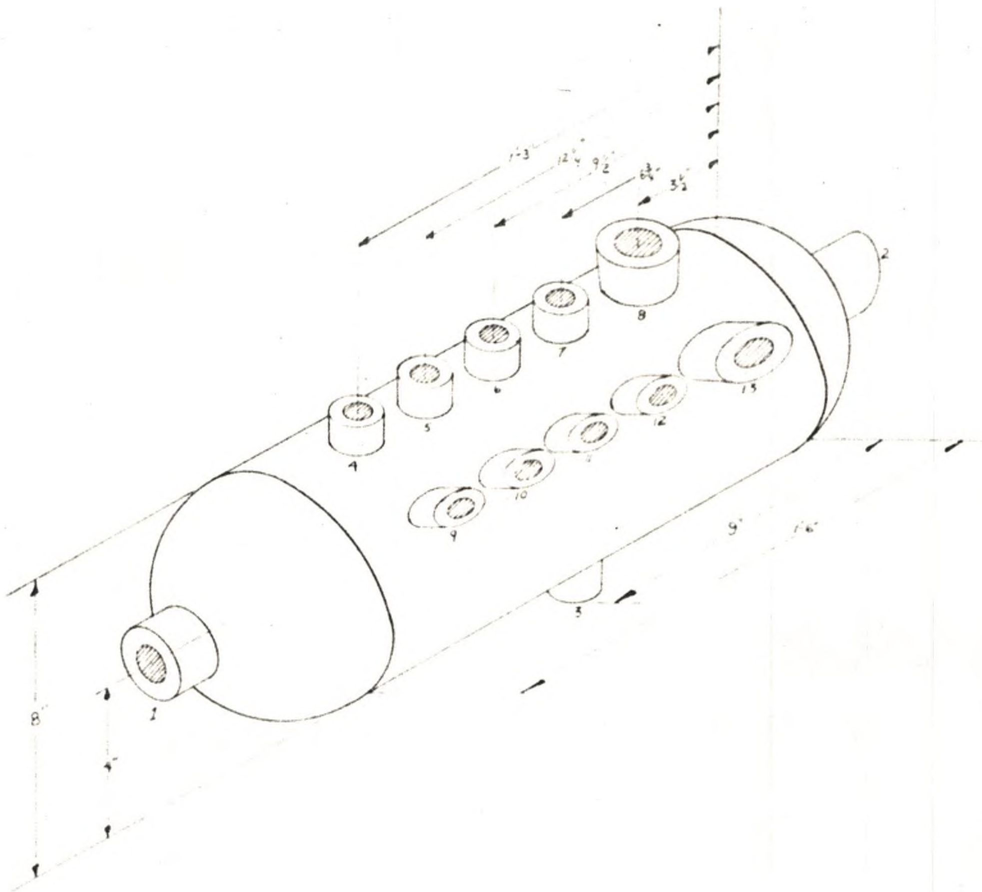


Figure 3 Distribution Manifold for Circulation Loop

into the system, and possible contamination from ozone and hydrocardons from the lubrication of the pump.

Pressure Limitations

In the area of pressure limitation, the Themis Committee decided on an upper limit of 600 psi. It was decided that long term studies at the present should be directed to the area of the continental shelf which varies from 800 to 1,800 feet below sea level. Six hundred psig pressure is equivalent to 1,380 feet, which is an average range for the continental shelf. It is believed that these long term experiments will furnish sufficient data as to whether or not man can survive at these depths for long periods of time [1].

The other pressure limitation would be that of a vacuum of 300 to 500 microns. The purpose of this low pressure would be strictly for reduction of contaminated gases that are introduced into the system on start-ups and for sampling.

Storage Requirement

It was first thought that the gases would be drawn directly from a high-pressure source or compressor, cleaned in molecular sieves, used and discarded, but after closer examination, it was decided that it would be more economical to store the dirty gases. The next concern was that of the capacity of storage. It was decided that there should be sufficient storage area to store 23,700 scf of helium gas. This is the amount of gas that would be in the chambers, Figure 1, if the total system was pressurized to 600 psig, since both of the complexes could be working at 600 psig. It was decided that the storage areas would be divided into two parts. The first area being a low-pressure dirty storage, later referred to as LPDS, will be able to store approximately half of the 23,700 csf (see Appendix F). This first storage area would be at pressures ranging from 0 to 200 psig. The low-pressure storage area would be accessible directly from the pressure chambers. This accessibility would provide a large gas storage in case an emergency should arise in either one of the complexes. It was first suggested that tanks be constructed from large diameter black pipe, which would be capped with weld caps. But an economic analysis revealed that propane tanks, which are ASME code pressure rated to 250 psig, were more economical (i.e., see Appendix F). It is suggested that these tanks be set vertically, as shown in Figure 4, with a base support of circular steel bands and with I-beam legs, (i.e., for calculation of leg support see Appendix D), as illustrated in Figure 4. These eight propane tanks, if pressurized to 200 psig, have the capability of storing 14,500 scf of gas which is more than either complex can handle at 600 psig.

The Themis Project acquired a high-pressure, helium compressor from United States Government surplus. This unit is capable of compressing 71 scfm to a pressure of 2,300 psig. Since large quantities of high-pressure, compressible gases such as helium can be stored in small volumes, the Themis Committee decided that the remaining storage area would be located after the compressor; the pressure of this storage area would range from 600 to 2,300 psig. The first direction of thought was toward the construction of high-

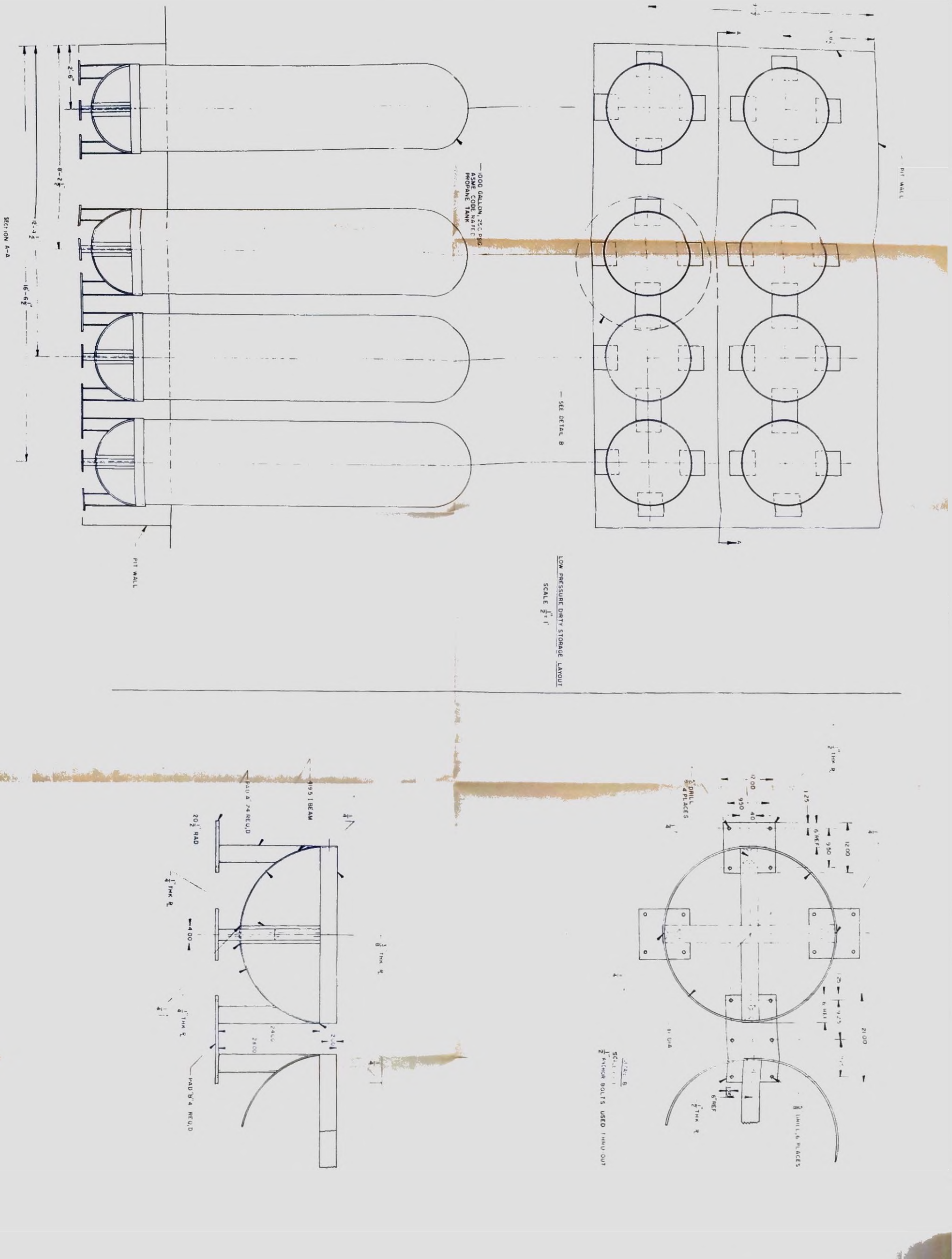


Figure 4 Layout of Low-Pressure Dirty Storage Tanks

pressure tanks from pipe and weld caps, but high-pressure tanks were made available from United States Government surplus. Therefore, for economic reasons, the surplus tanks were used, (i.e., storage capacity can be seen in Appendix G). This storage area would consist of thirteen tanks which are nine and five eighths inches in diameter by twenty-two feet. These tanks are ASME code rated to a pressure of 3,000 psig. A layout of the rack, which will support these tanks, is shown in Figure 5, (i.e., calculation for frame are given in Appendix C). This storage area will be referred to as the high-pressure dirty storage area or HPDS.

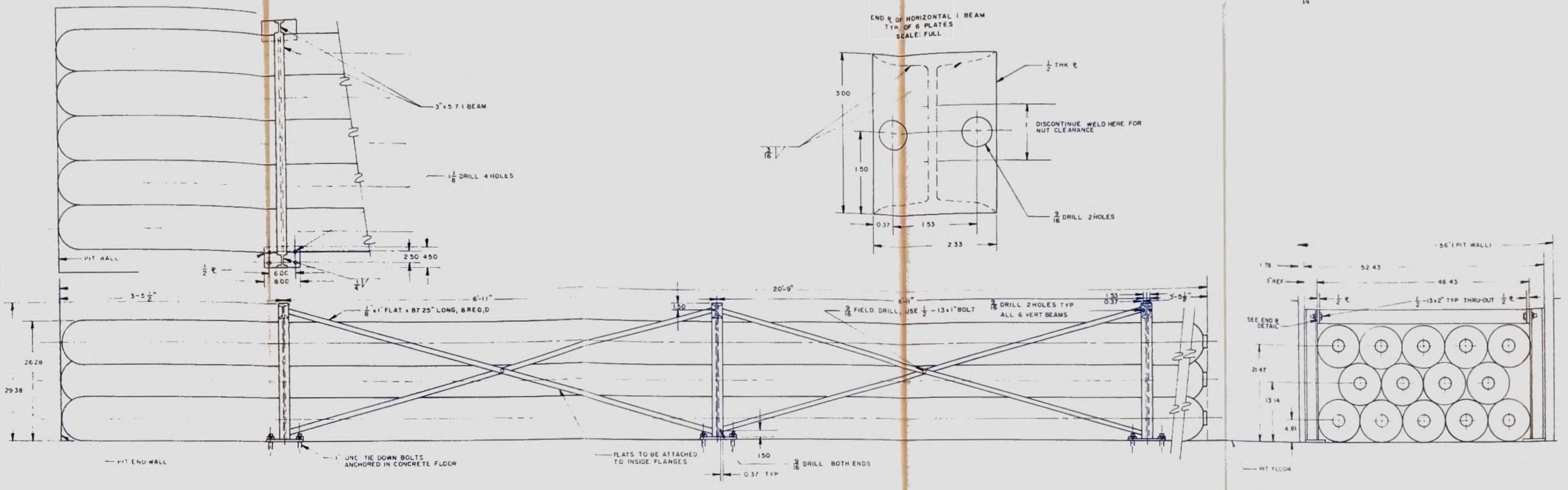


Figure 5. Layout of High-Pressure Dirty Storage Tanks

Chapter III

VALVE REQUIREMENTS

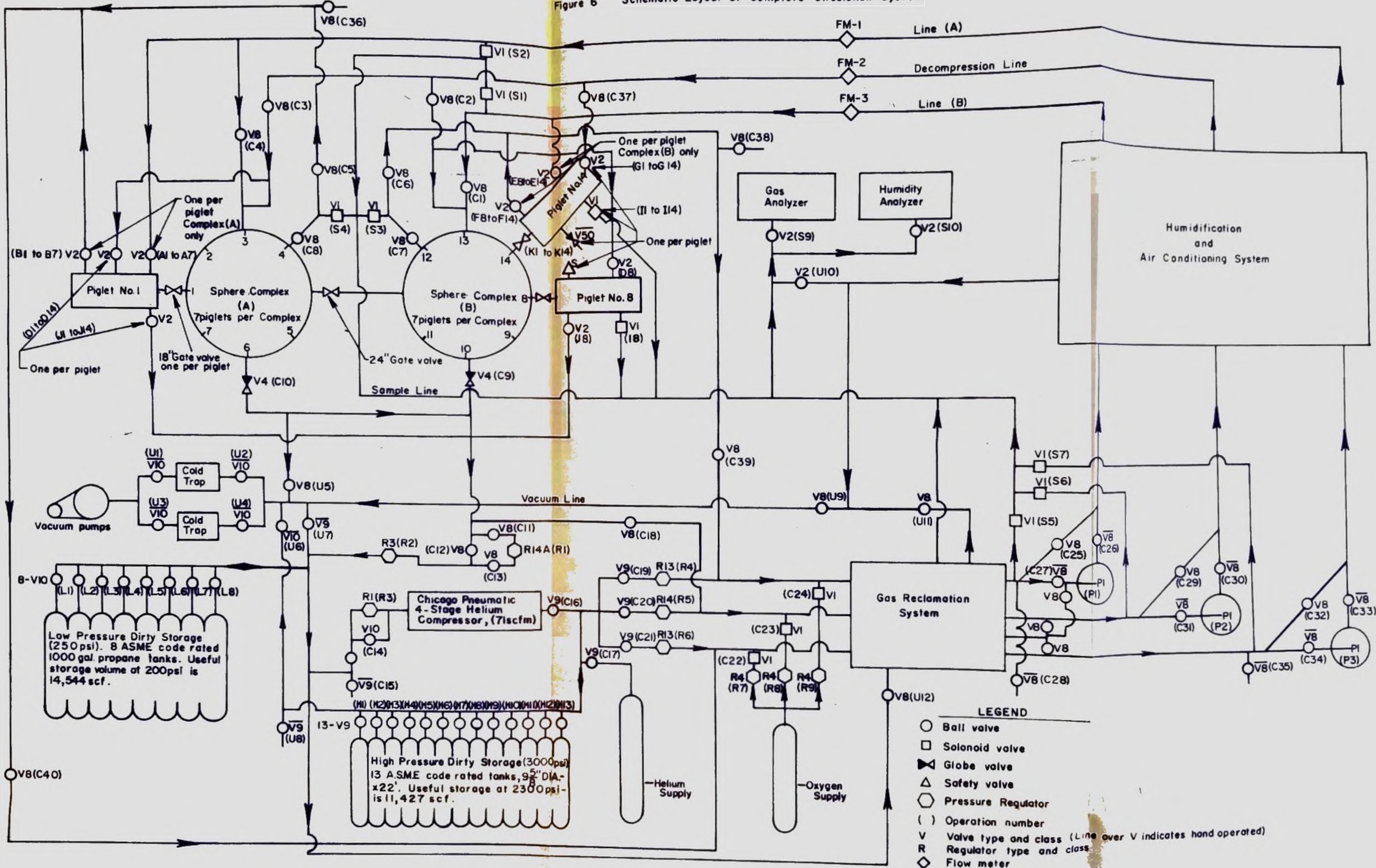
Actuator Controlled Valves

In the selection of the correct valves, the controlling factor was that of the pressure drops and pressure limitations for the valves of the piglets and the valves in the circulation system. These valves had to be able to withstand maximum pressure drops from 600 psig to 300 mm mercury vacuum from either side of the valve. In the low-pressure storage system, the maximum pressure drop could be from 200 psig to 300 mm mercury vacuum; while in the high-pressure storage, the pressure drop could be from 2,300 psig to 300 mm mercury vacuum.

These limitations preclude the use of solenoid valves since these valves will function correctly only if the pressure drop is maintained in only one direction. This means that under reversed flow conditions, a solenoid valve will not function as to meet project requirements. The only possible location for solenoid valves would be on the sampling system. Solenoid valves can be used here since the sampling system will always be at minimum pressure; one direction flow is guaranteed. The locations of these valves are illustrated in Figure 6.

Other possible choices of types of valves were: gate, globe, needle or ball valves. The globe and needle valves were not chosen

Figure 6 Schematic Layout of Complete Circulation System



for the circulation system because of the expense of the valves, and time required for opening and closing the valve. The gate valve was also excluded for the above reasons, but also due to excessive wear to the gate itself during repeated openings and closings of the valve. Another disadvantage of the gate and globe valve is that it is difficult to maintain a complete seal under a vacuum. The only remaining workable solution was to use the ball valve. The ball valve would fit into the circulation system, high-pressure, and low-pressure storage systems. This valve can withstand high pressures and vacuums extremely well, and the pressure drop can occur on either side of the valve. It is a quick response valve since to completely close or open the valve requires only a 90^{o} revolution. The ball valve is also much more compact and inexpensive than either the gate or globe valves. Locations for these ball valves are shown in Figure 6.

Pressure Monitoring Control Valves

Several unusual pressure monitoring control valves or pressure regulators will be required for this system. The first of these regulators is located before the compressor, (R1), Figure 6. This pressure regulator will be required to maintain a constant downstream pressure between 3 and 5 psig, (i.e., these are the compressor inlet requirements), while drawing from an upstream pressure source which will vary from 200 to 5 psig, (i.e., this will be drawn from the low-pressure dirty storage area). In this situation, a diaphragm controlled valve was selected. It is powered by air and controlled by a pressure controller that monitors the downstream pressure.

The diaphragm controlled valve was selected due to the fact that with the pressure control, almost constant downstream pressures can be maintained, and in the case of a pressure failure, the valve system is so arranged that it will automatically close. The greatest advantage of this regulator valve is that no monitoring equipment need be connected to the valve; as long as the pressure source is maintained, the valve will control itself. Another of this type of pressure regulator valve will be required before the low-pressure dirty storage, (R3), as shown in Figure 6. This valve will prevent pressures greater than 200 psig in the low-pressure dirty storage. The regulator valve will be set in such a manner that when the pressure in the LPDS drops below 200 psig, the valve will open; this will be accomplished by monitoring the downstream pressure. The upstream pressure according to test conditions will vary from 600 to 0 psig. The regulator valve will have the same safety feature as the valve before the compressor.

The most important pressure regulators are those of the decompression loop. Two regulators; one a pressure reducing regulator, (R14), shown in Figure 6, will maintain the pressure from the high-pressure dirty storage. The second, a back pressure regulator, (R14A), shown in Figure 6, will be located close to the low-pressure dirty storage. This valve would limit the pressure in the decompression line. The two valves would act in unison and would have to be set at the same pressures; thus, the first would open if the pressure should drop below the required pressure level, and the second would open if the pressure were to rise above the required pressure level.

One thing that will not have to be taken into account is the pressure drop that will occur between these two regulators. The pressure drop will be caused by the reclamation and air conditioning system and the piping and valve resistances. This drop does not have to be taken into account since the two regulators are located close together and very little pressure drop will occur between the two regulators. It is suggested that the following regulator, shown in Figure 7, be used. This type of regulator is controlled by an outside high-pressure source such as a small tank of air or nitrogen or some other inexpensive gas that is compressed to approximately 3,000 psig. This pressure source is controlled by a small volume, high accuracy pressure loader. This loader reduces the tank supply pressure to a set pressure, such as the system pressure. This set pressure is then fed to a regulator. This arrangement is shown in Figure 7. The section view of the back pressure regulator, Figure 7, shows that pressure from the loader loads a diaphram in the regulator. When the pressure of the upstream gas exceeds the load on the diaphram, it will raise up releasing the gas, and thus reducing the upstream pressure. The diaphram in the regulator prevents the pressure loading gas from mixing with the system gas. A small solenoid valve will be required, on the side of the regulator, to release the load on the regulator when the system pressure is to be reduced. This solenoid valve could be actuated at the same time the loader is set to a lower pressure. The pressure reducing regulator will be controlled in the same manner, except loading of the diaphram is reversed as seen in the section view, Figure 7. As the downstream pressure drops, the diaphram will move

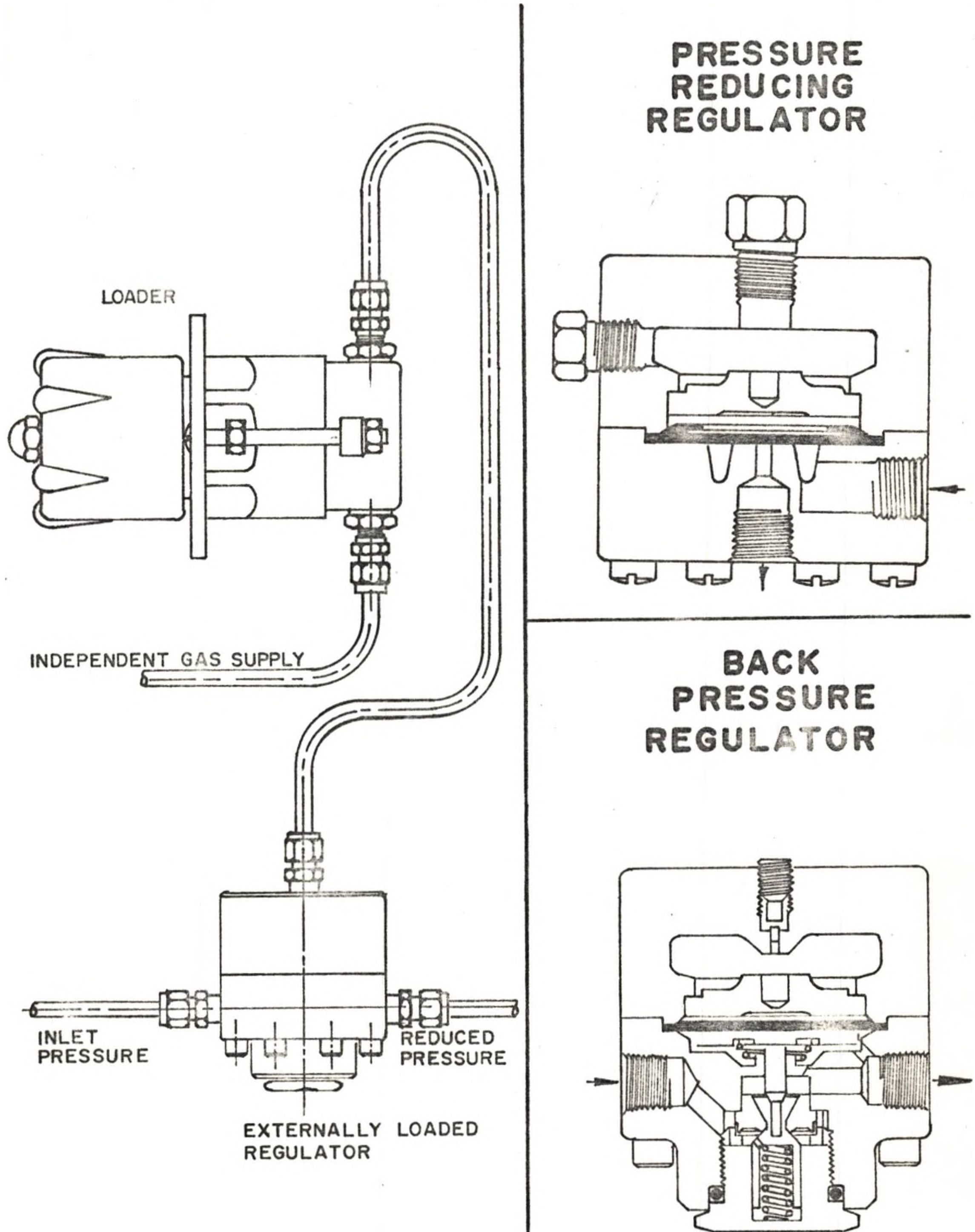


Figure 7 Pressure Loaded Regulators

down and open the valve allowing high-pressure gas to flow into the system. These two regulators will maintain the pressure in the decompression system. The regulators, which will limit the pressure in lines A and B, (R12), Figure 6, will be direct control regulators that are similar to the loader for the previous regulators, but larger in size to accommodate the corresponding larger volume flows. The Themis Committee decided to set the maximum flow rate at 71 scfm, which is the maximum output of the compressor. This restricts the flow such that no one regulator will allow more volume flow than the compressor output. In these regulators, the diaphragm is loaded by spring pressure, as shown in Figure 8. The regulators, which are located between the major circulation lines and the oxygen supply, (R4), Figure 6, will be of the same type used as a loader on the decompression system. The purpose of these regulators is to reduce the high-pressure, oxygen supply to a pressure slightly above that on each individual circulation line. This pressure drop between the regulator and the circulation line will permit a specific amount of oxygen to flow into the circulation line when the solenoid valves are given a pulse signal to open. As the pressure drop is increased, the amount of oxygen injected into the line will increase for the constant time interval that the solenoid valve is open. The amount of oxygen required in the system to maintain animal life is only 2.18 scf/hour, (i.e., see Appendix D for oxygen requirements). One important point is that these valves and regulators on the oxygen lines must be Super Cleaned in order to prevent any possible fires or explosions in the oxygen line.

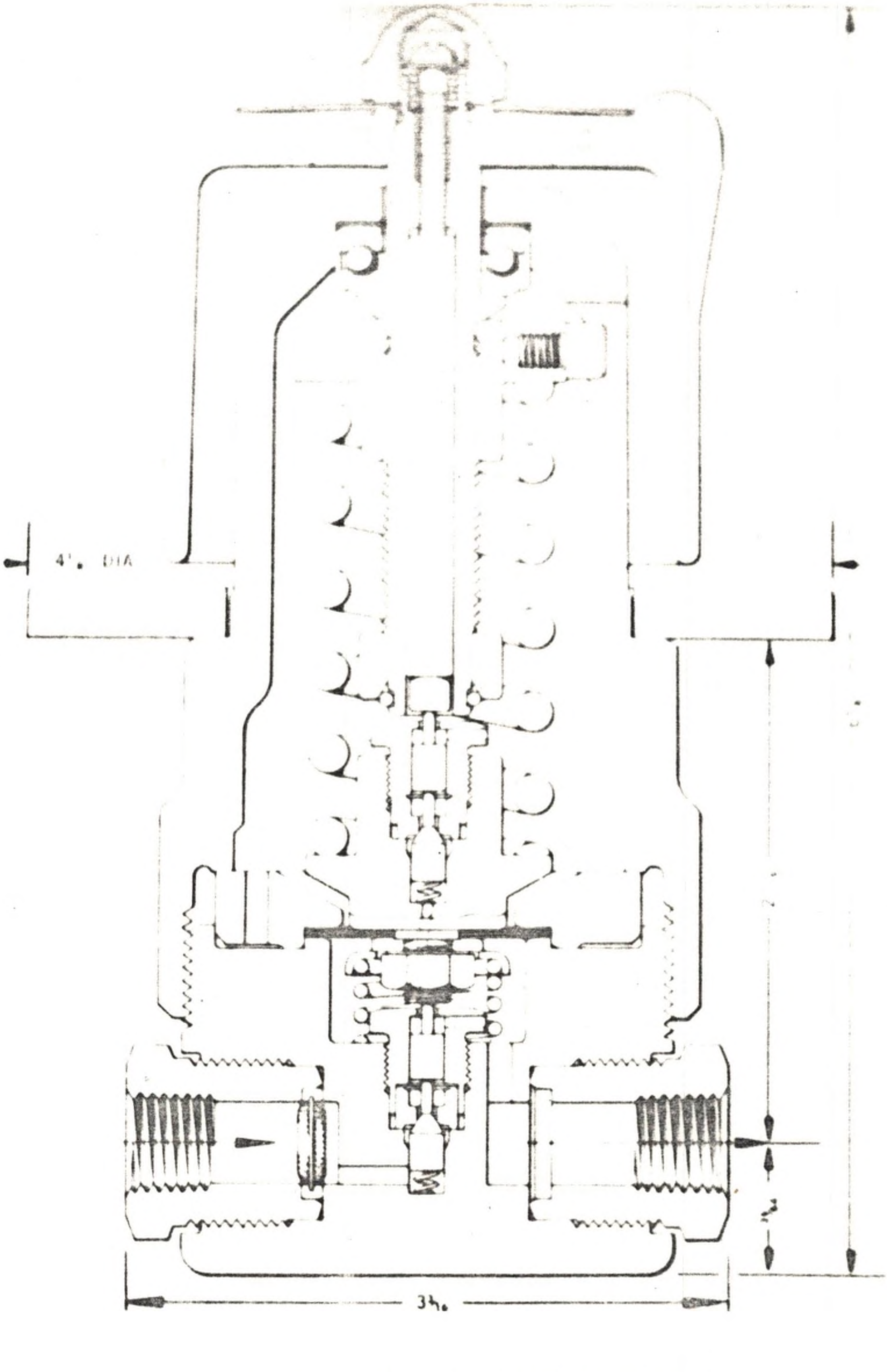


Figure 8 Spring Loaded Regulator

Actuator Requirements

One of the advantages of ball valves is in the area of operators since several different types of operators are available. The first of these is the pneumatic operator; it can be used for fast responses of less than one second, and used as a throttling control. The equivalent operation can be attained with a mechanical operator except for the actuation time of four seconds per ¼ turn. Another type of mechanical operator is available, but it is restricted to a complete open or close position. The ball in the valve rotates in one direction only. When an electric signal to open or close is given to the actuator, the actuator power source takes over and continues to operate the valve until it is either completely open or closed. Since it is intended that the total operation of the complex be controlled by a process computer, the last type of operator is suggested. It not only is the least expensive and simplest of the operators, but also it is easily controlled by a digital on-off signal. An operation time of four seconds per ¼ turn is sufficient for system requirements.

Solenoid valves will be located on the sampling system, (V1), Figure 6; since the sampling system will always be under vacuum, a one direction pressure drop is guaranteed. Also, since the oxygen source will always be above the line pressure, solenoid valves will be used at these locations too. The prime reason for the use of solenoid valves in these locations is the quick response time which an A.C. operation is between four and eight milliseconds to open or close. These valves can be manipulated as many as 600 cycles per minute.

The actuators of the pressure regulating valves will also be electric motor operators. For accurate operation, the pressure level of the line being regulated should be monitored by some electrical pressure sensing device. This will provide an accurate response to the computer. Then the electric regulator operator can be set accurately by the feed back from the sensor.

Chapter IV

SYSTEM DESIGN

Pressurizing System

In the design of the pressurizing system, it was important to keep in mind that other operations such as decompression and circulation had to be maintained at the same time. It was decided, by the Themis Committee, that the facility should be able to operate at two independent pressures, simultaneously. Thus, the overall experiment chambers were divided into two groups; one called Complex A, and the other called Complex B. This is shown in Figure 6. Since the two systems were to operate simultaneously, individual circulation systems had to be designed. In the operation of the pressurized system depicted in Figure 9, it can be seen that several other system operations such as: gas transfer, Figure 10; purging, Figure 11; or sampling, Figure 12; will also enter into the pressurizing system. The flow chart, Figure 9, gives the basic break down of the operations that have to be performed in the operation of the facility. These operations include certain valves that are numbered on the schematic drawing of the system, Figure 6. It should be noted that operations on the chart begin in the circled areas labeled control point, and from time to time, these control points will be referred to on other charts.

Figure 9 ANIMAL PRESSURIZATION CHART

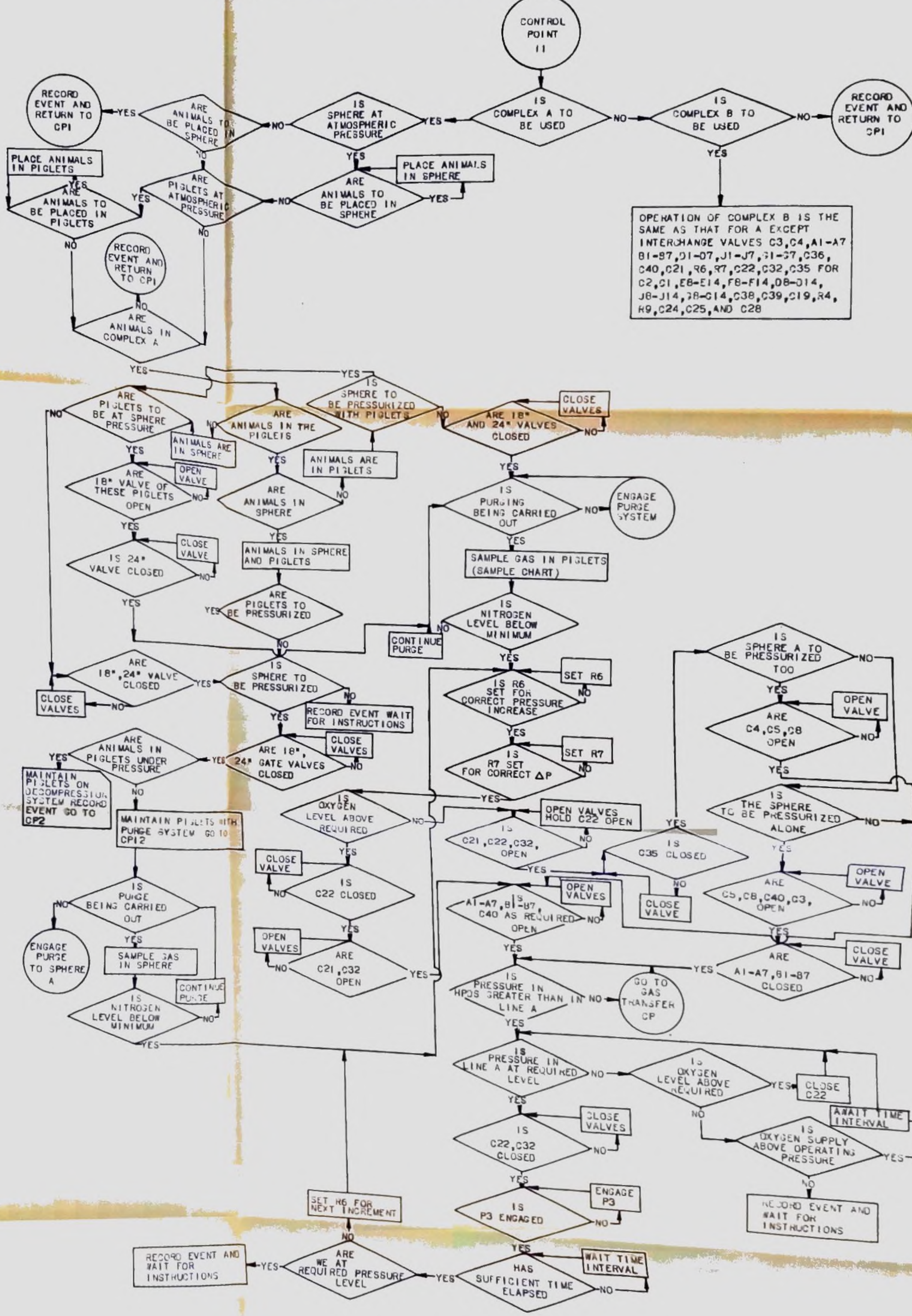


Figure 10 GAS TRANSFER CHART

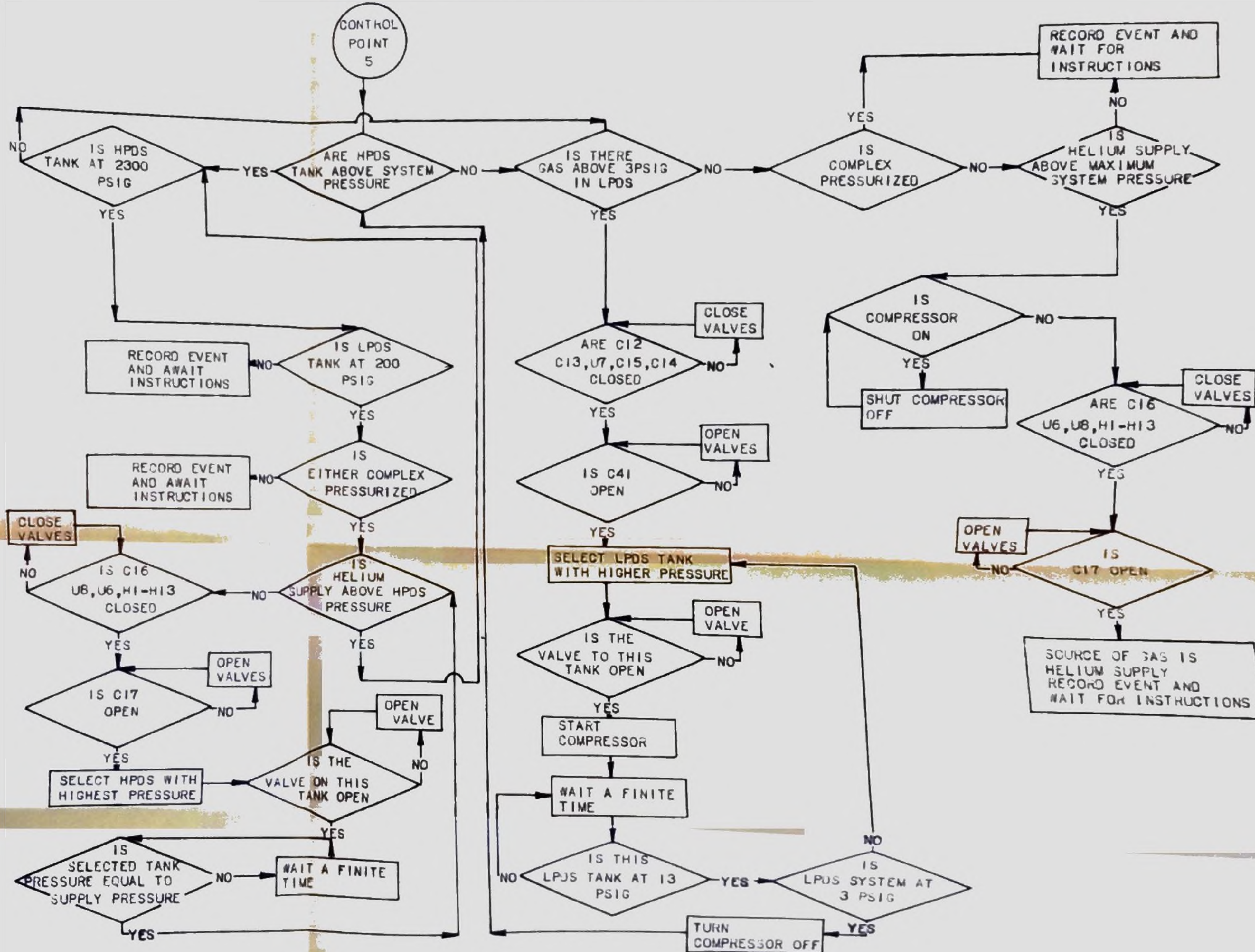


Figure II PURGE CHART

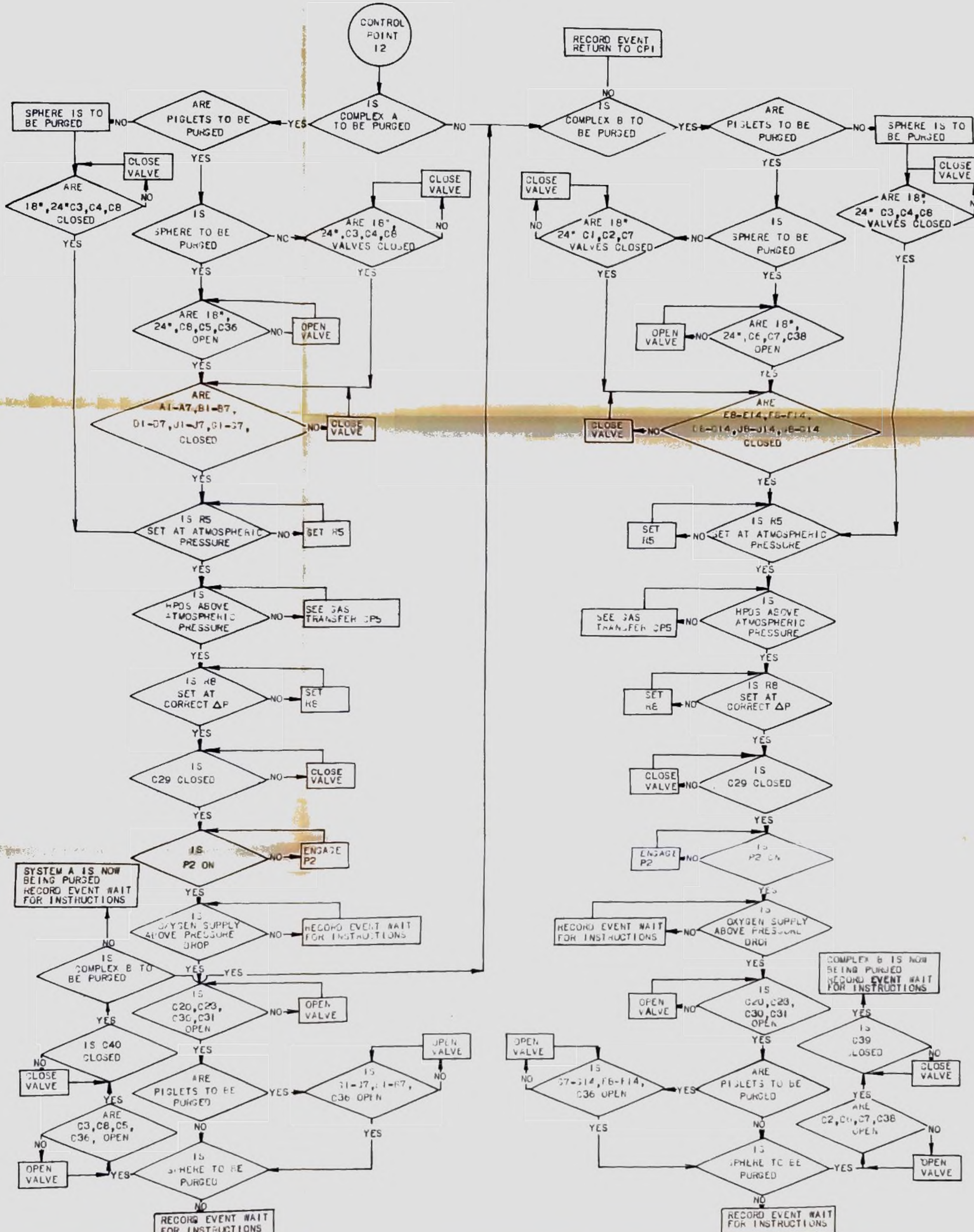
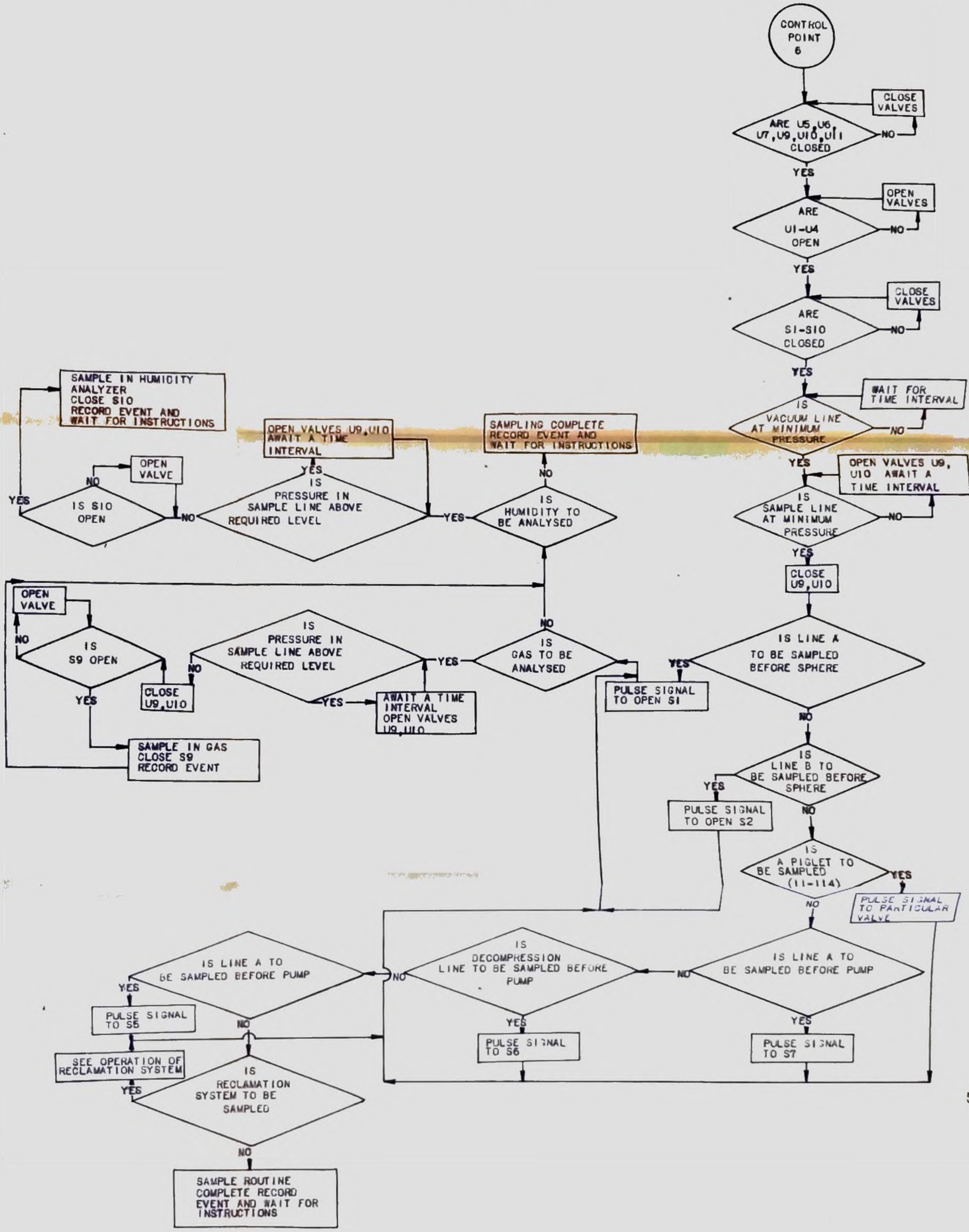


Figure 12 SAMPLE CHART



Circulation Systems

As in the pressurizing system, the two-unit division results in two circulation systems. As seen in Figure 6, the two circulation systems are an integral part of the pressurizing system. This results in the restriction of no circulation operation overlapping the pressurizing system for one complex. The major additions to the pressurizing system, for circulation, are the pumps and the existing lines returning from the contaminated gases to the reclamation system. The operation of the circulation systems is shown in the flow chart, Figure 13. This chart gives the major tasks that must be performed for the operation of the circulation system. It should also be noted that possible circulation of atmospheric air has been provided for both complexes. This systems operation is depicted in the flow chart, Figure 14. In the circulation system, the total complex is isolated from the pressurizing, storage, and air conditioning units by valves and is opened to the atmosphere using the pump as a circulating fan.

Decompression System

It was decided that the required operation areas of the decompression system be very flexible. In the design of this system, any one piglet, group of piglets, or either sphere may be decompressed. The only restriction is that all units to be decompressed, be at the same pressure level. The design of the decompression system is similar to the pressurizing and circulation system with these exceptions; the added manifold, the valves on the piglets, and the two special regulators whose operation has been described in the chapter on valve requirements. The operation of the decompression system is depicted in the flow chart, Figure 15. As in both the pressurizing and circulation systems, other operations shown on other flow charts may occur.

Figure 13 CIRCULATION CHART

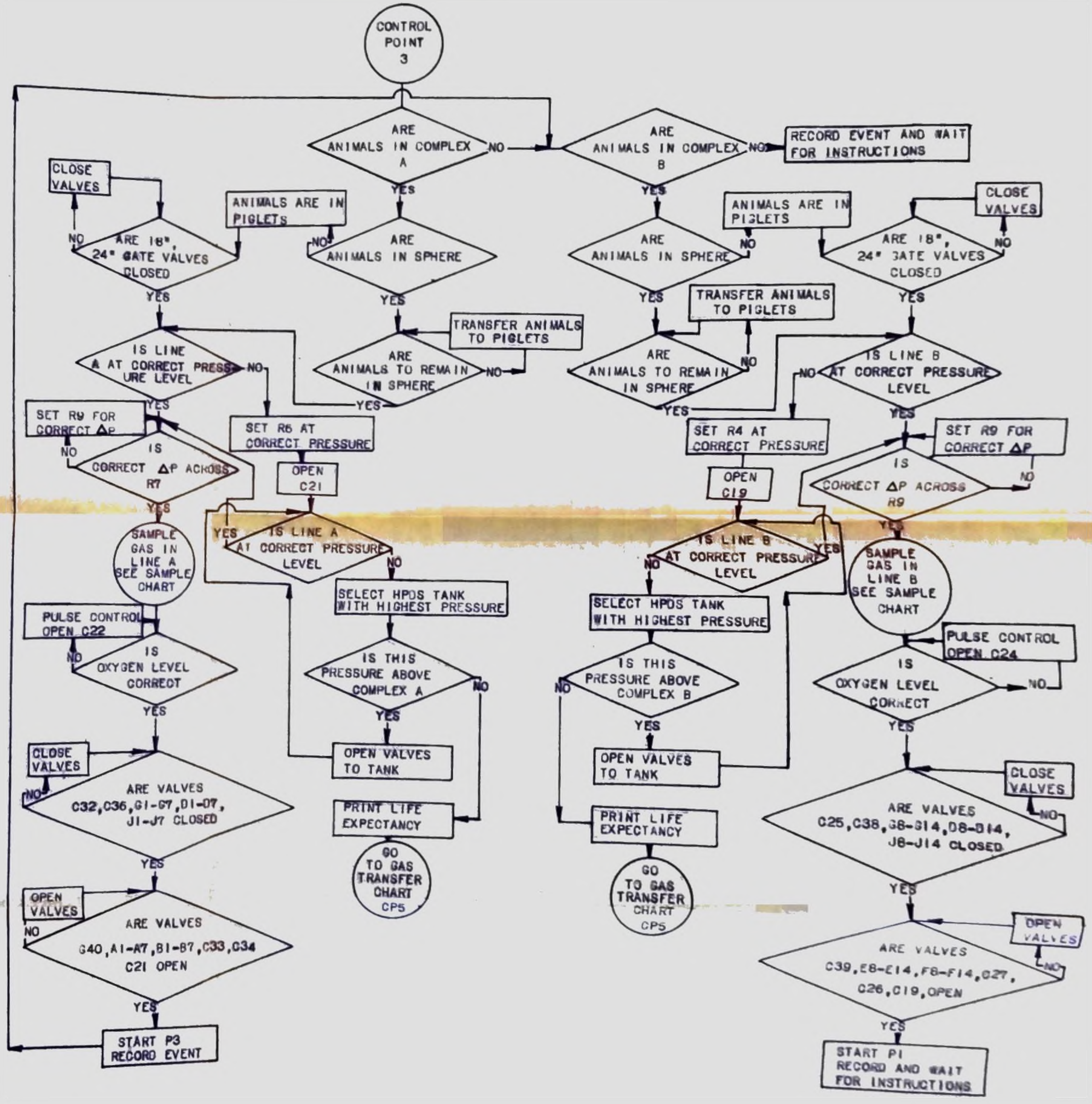


Figure 14 AIR OPERATION CHART

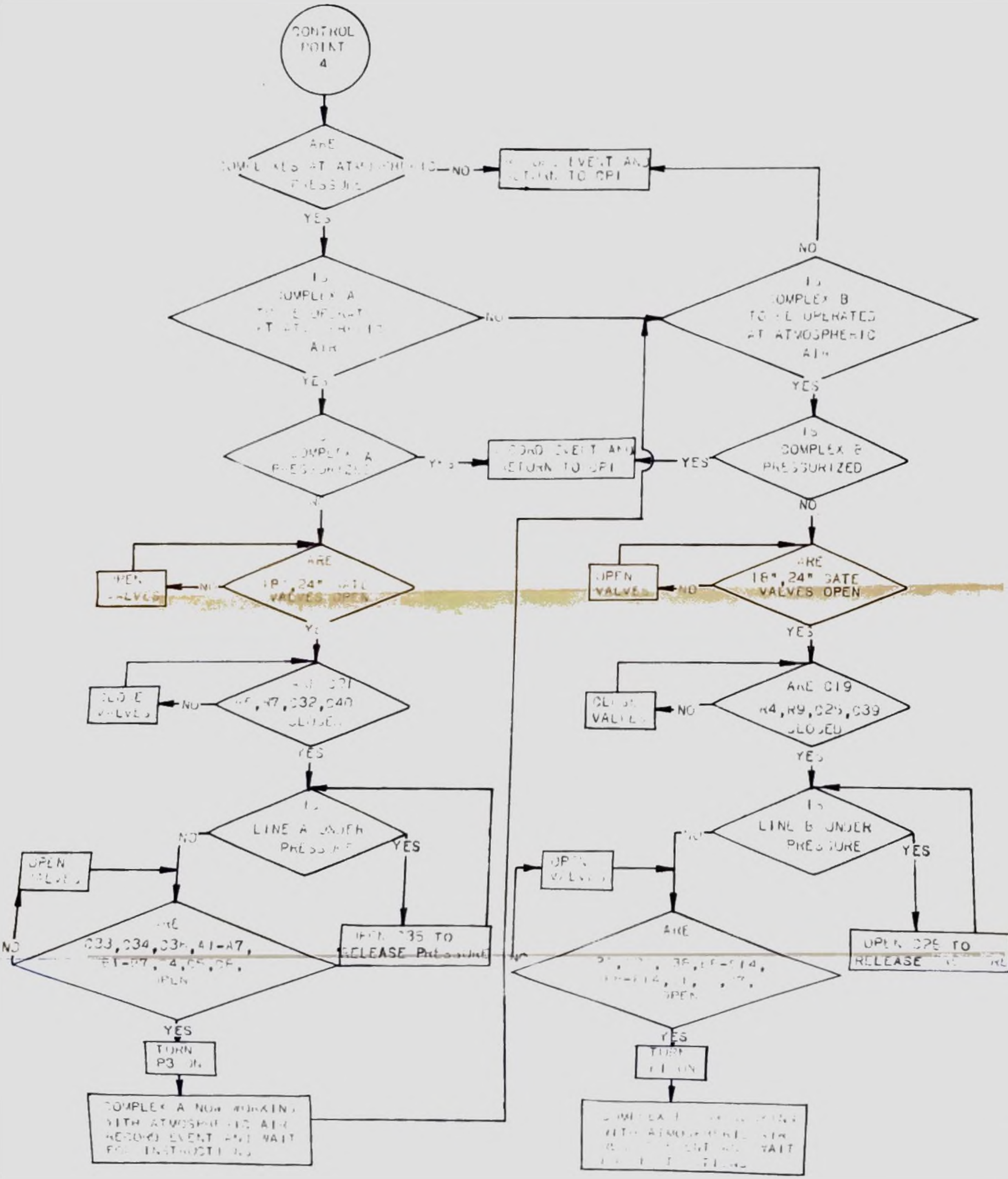
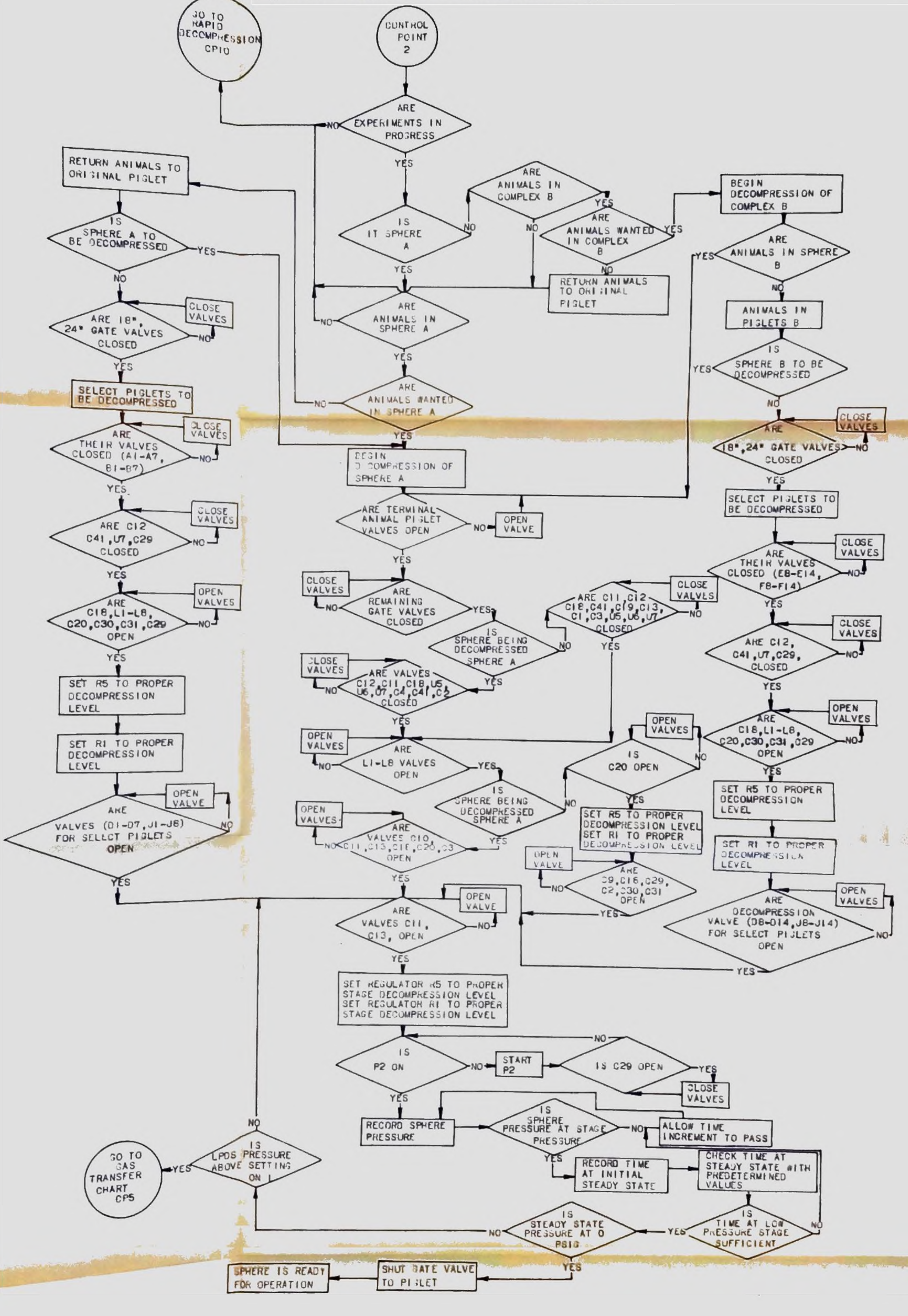


Figure 15 ANIMAL DECOMPRESSION CHART



Chapter V

RELIEF SYSTEMS

Reclamation and Storage of Gases

The relief system can be divided into the following operation; reclamation and storage of gas, and the returning of the system to normal operation. The reclamation and storage of gases would involve the low-pressure dirty storage area, Figure 4, and the high-pressure dirty storage area, Figure 5. The operation of these storage areas are an integral part of the total system and the various possible operations are shown in the Rapid Decompression Chart, Figure 16; Gas Transfer Chart, Figure 10; and Evacuation Chart, Figure 17. As may be seen on these charts, the operation of the entire facility is dependent upon these two storage areas. If the pressure vessels of the complexes should be overcharged, the discharge would be to the LPDS tanks and if the system pressure should drop, it is also possible that the HPDS may be the main source of gas to raise the system pressure to the correct level. The division of the storage areas into two individual systems provides the operation with a safety system, which is important in this type of installation [3]. If for some reason, the LPDS system should become inoperable, the discharge gases could be fed directly into the compressor. In this case the gases could be compressed and stored in the HPDS. On the other hand, if the HPDS became inoperable,

Figure 16 RAPID DECOMPRESSION CHART

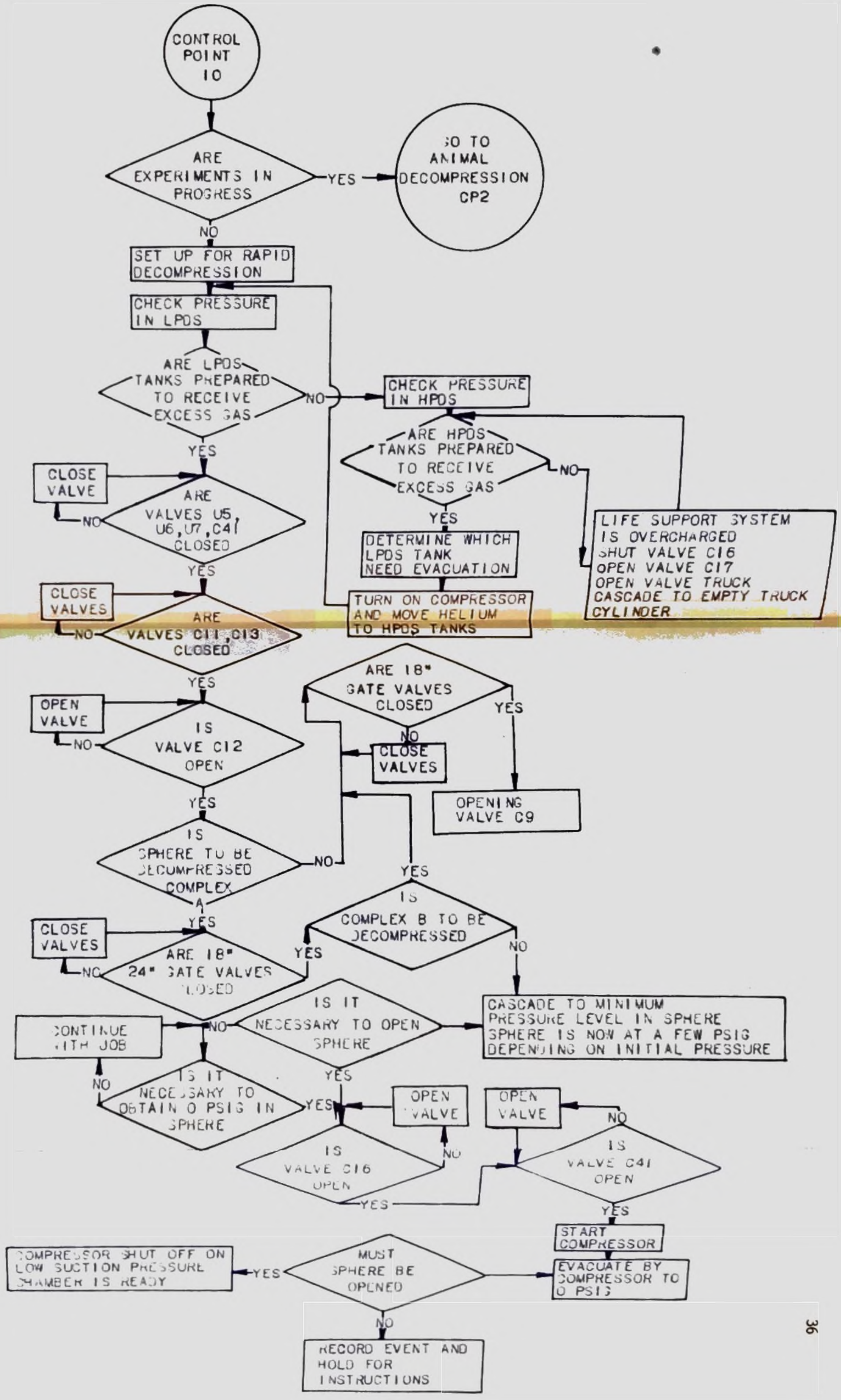
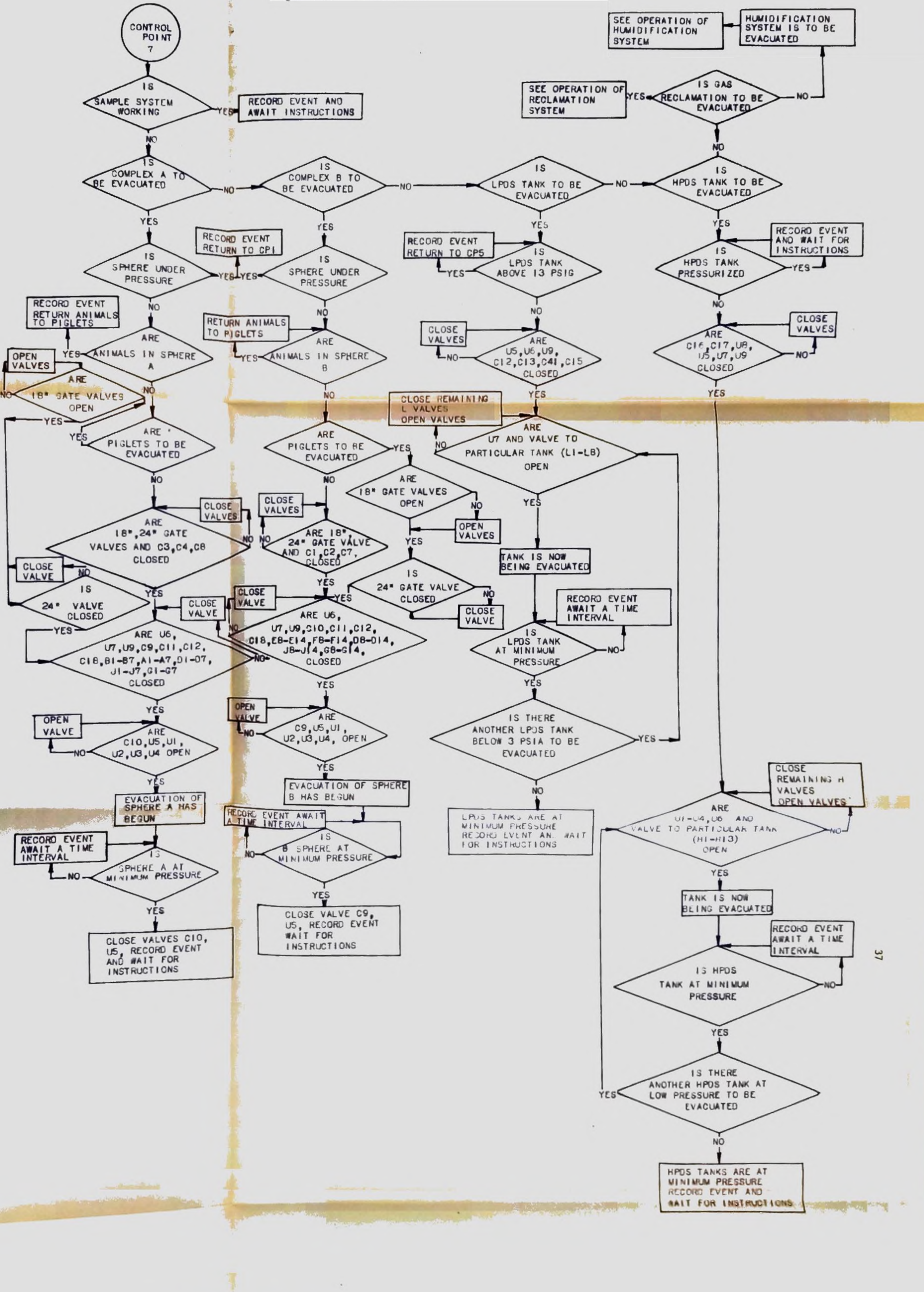


Figure 17 EVACUATION CHART

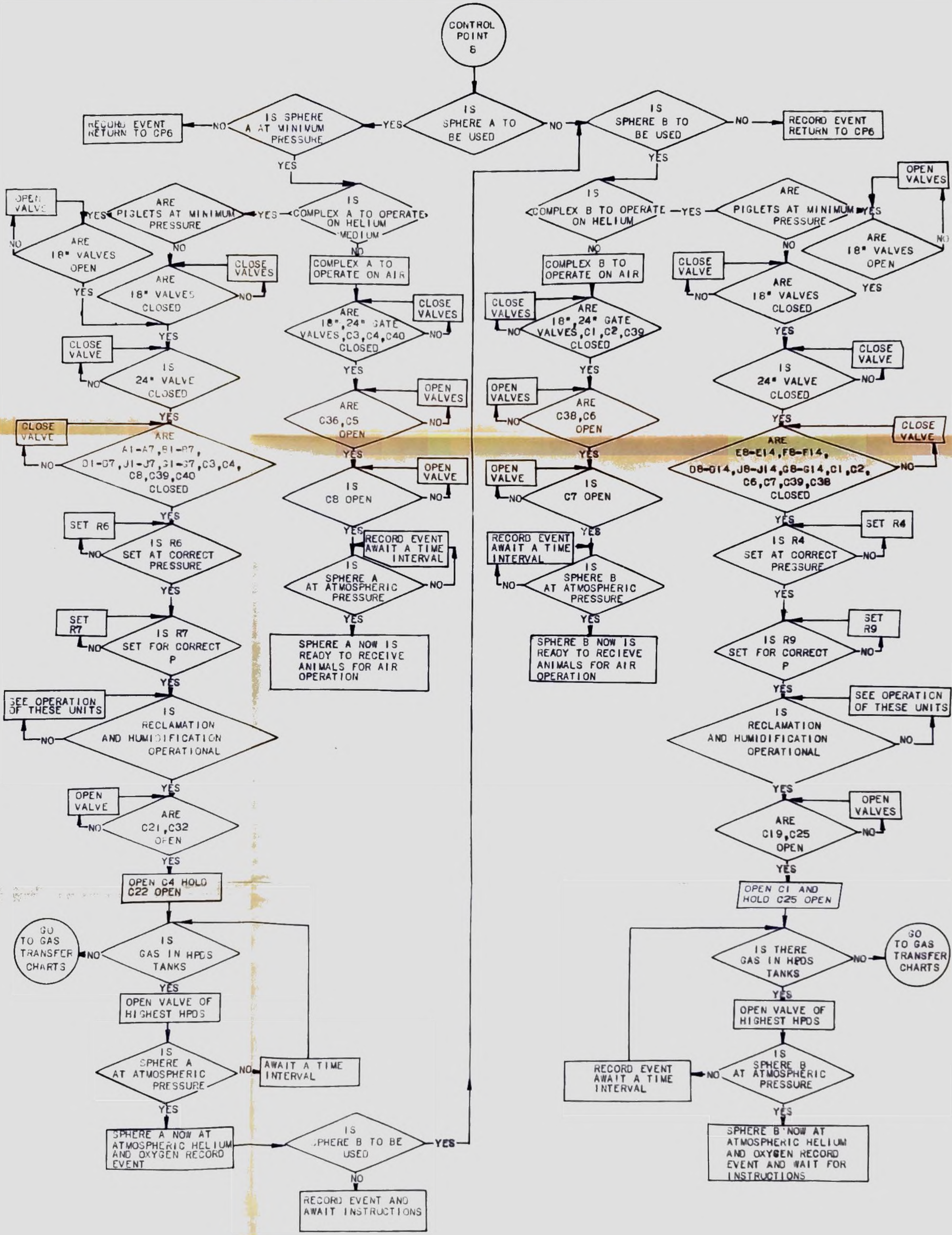


the gases could be stored in the LPDS area, then compressed by the compressor and fed into either of the complex feed lines or into the decompression line. One situation for which this design does not allow is the possibility that both Complexes A and B would fail while one of the storage areas was inoperable. The probability of this occurrence was considered not high enough to warrant the additional investment in another storage area.

Returning the System to Normal Operation

Returning the system to normal operation after an animal decompression and chamber opening, or after a rapid decompression and chamber opening, would be an extension of the pressurizing system. This would include the evacuation of the chamber, Evacuation Chart, Figure 17; the purge system, Purge Chart, Figure 11; and initial start up of the system which is shown on the Initial Start Up Chart, Figure 18. Again the difficulty of overlapping occurs; therefore, operation procedures become critical and must follow the Operational Charts in Figures 15, 16, 17, and 18.

Figure 18 INITIAL START UP CHART



Chapter VI

OPERATION OF INTEGRATED SYSTEM

The main operation of the integrated system is shown on the Control Chart, Figure 19, and begins at control point one. It is possible that situations could arise which are not outlined on these charts. These situations would be unusual and probably would be caused by malfunction of certain equipment, but they cannot be accounted for until actual construction of the complex is begun. It can be seen that the Control Chart joins together all other operation charts.

Figure 19 CONTROL CHART

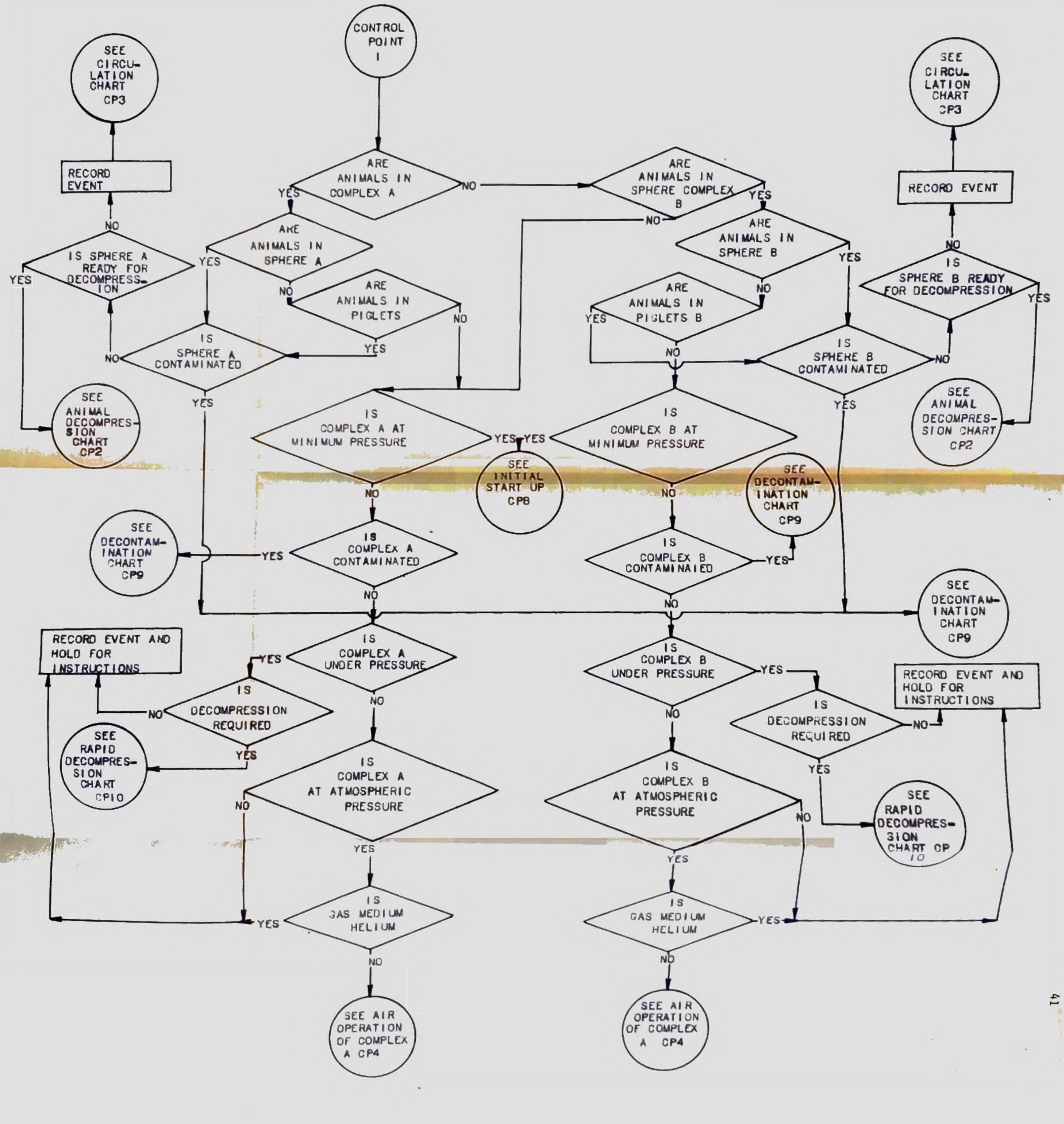
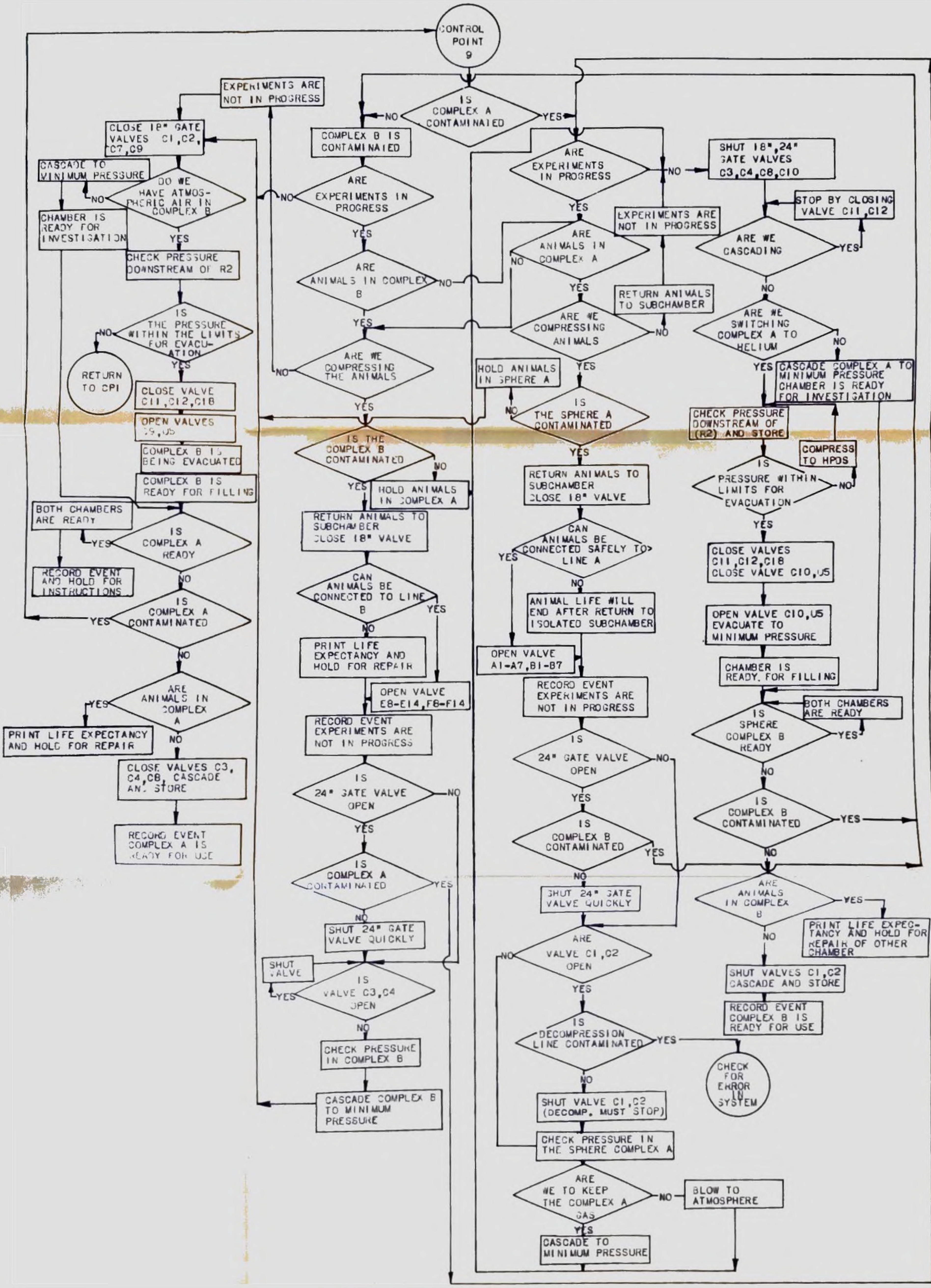


Figure 20 CONTAMINATION FLOW CHART



Chapter VII

CONCLUSION

In the circulation system very little difficulty was encountered in obtaining sufficient estimates except for circulation pumps. Difficulty was also encountered in locating suitable suppliers of pumps. Sufficient pump suppliers have been located but a decision as to the type of pump that will be used in the system has not been made. The possible choices of different types of pumps are those of diaphram, fan, or rotary types. The other consideration is to whether a high-pressure booster type pump should be used or should a standard high density pump be enclosed in a pressure vessel.

The circulation system does have certain disadvantages. Having only one decompression line limits the decompression operation to a group operation. This is a disadvantage since more decompression line would present the possibility of decompression of different units at different rates, and also at different time intervals. These systems were excluded due to the fact that they would increase the cost above the funds available. Another disadvantage is the fact that each piglet has its own individual valve per line. Large numbers of valves, in this situation, will cause complex operation methods for manual controlling. On the other hand, these valves make it possible to completely isolate a piglet. A piglet could be isolated for purposes of decompression, pressurization, circulation, or repairs.

Should the situation of a complete power failure arise, the controlled regulators would hold their position setting up an equilibrium condition. In the case of the self-controlled regulators, they would automatically be closed by the controller preventing over pressurizing of certain units, such as, the low-pressure dirty storage and the compressor. Other advantages are those of complete piglet operation while the sphere area is depressurized and inspected or visa-versa. One very important advantage is if an emergency should arise, both complexes could be rapidly decompressed to the storage areas at the expense of the animals' lives in the piglets, but with no possible bodily harm to individuals in the surrounding working area.

Since this research facility is one of the first of its kind, it is impractical to make comparisons to previous units, other than those under present construction, which also have recovery systems for gas, purification, humidification, air conditioning, and storage systems, or a process control computer.

It is possible that in the future, after these complexes have been completed and tested, vessels with higher pressure capabilities could be added into the complex since the compressor has pressure capabilities of up to 2,300 psig. It is entirely feasible that a pressure vessel be operated at this pressure. The addition would include valves, regulators, and piping of high-pressure capabilities, but there is no reason at present to prevent the addition of these units to the present designed facility. It would also be possible to add larger piglets to the spheres without any changes being made in the present designed circulation system.

APPENDIX A

NOTATION

Symbol	Quantity
A	Area
b	Breadth of beam [7]
D	Diameter
d	Depth of beam [7]
F	Force
f	Friction factor
g	Gravitational constant [8]
h_f	Head, vertical distance given in feet of air [8]
I	Moments of inertia [7]
K	Radius of gyration
L	Length of pipe
L_1	Unbraced length of member
M	Moments [7]
Max S	Maximum stress
P	Load [7]
p	Pressure
Δp	Pressure drop
r	Radius
S	Stress

$S_{c\ max}$	Maximum compressive stress [7]
Sb	Bearing stress [7]
Sw	Safe working stress [7]
t	Thickness of compression flange [7]
V	Velocity in pipe [8]
v	Volume rate of flow [8]
X	Distance from neutral axis [7]
y	Distance to remotest element [7]
Z	Section modulus [7]
Z_{x-x}	Section modulus from x axis [7]
ε	Roughness height [8]
ν	Kinematic viscosity [8]

APPENDIX B

PRESSURE DROP FOR CIRCULATION SYSTEM OF ONE COMPLEX

Since the volume of one complex is 290 cu.ft. which will be changed five times per hour; V = 24.2 cfm

$$V = \frac{v}{A}$$

$$A = \pi r^2$$

The radius of a ½-inch pipe is 0.31 in. [6] .

$$A = 0.304 \text{ in}^2$$

Since there are 7 lines per manifold;

$$V = \frac{v}{7A}$$

$$V = \frac{(24.2)(144)}{(0.304)(7)(60)}$$

$$V = 27.4 \text{ ft/sec}$$

An approximate value of 30 ft/sec will be used for the velocity in the pipe.

The equivalent length of a 90° elbow is 12D [9]. Therefore 107 ½-inch black steel pipe elbows is equal to (107)(0.622) = 66.6 feet. The straight length of ½-inch pipe used is 264 feet. The total equivalent length of ½-inch pipe used in this portion of the circulation system is 330 feet.

The Reynolds number for a ½-inch pipe at the specified velocity is:

$$Re = \frac{VD}{\nu} \quad [8]$$

$$Re = \frac{(30)(0.0518)}{(0.0014)} = 1110$$

Since the Reynolds number is below 2,000 the flow in the ½-inch pipe will be laminar flow [8]. The friction factor for laminar flow is [8]:

$$f = \frac{64}{Re}$$

$$f = 0.058$$

The equation used to find h_f is the following [8]:

$$h_f = \frac{fLv^2}{2Dg}$$

$$h_f = \frac{(0.058)(330)(900)}{(2)(0.052)(32.2)}$$

$$h_f = \frac{514D \text{ ft-lbm}}{lb_f}$$

The total pressure drop for this ½-inch pipe line is:

$$\Delta p = h_f p$$

Where p is the air pressure per foot.

$$\Delta p = (5140)(0.00052)$$

$$\Delta p = 2.7 \text{ psi}$$

Since the volume flow rate is 24.2 cfm, the velocity through the 1½-inch pipe will be:

$$V = \frac{v}{A}$$

The radius of a 1½-inch pipe is 1.5 in [6], giving an area of 1.77 in^2.

$$V = \frac{(24.2)(144)}{(1.77)(60)}$$

$$V = 32.9 \text{ ft/sec}$$

For simplicity the velocity in the 1½-inch pipe will be set at 35 ft/sec. The equivalent length of a 90° elbow for a 1½-inch pipe is 13.50 [9]. Therefore 46-90° elbows is equal to (46)(1.69) = 77.7 feet. The straight length of 1½-inch pipe used is 114 feet. This gives us a total equivalent length of 1½-inch pipe of 191 feet.

The Reynolds number for a ½-inch pipe at the specified velocity is:

$$Re = \frac{VD}{\nu} \quad [8]$$

$$Re = \frac{(35)(0.125)}{(0.0014)}$$

$$Re = 3125$$

Since the Reynolds number is in the middle of the transition zone, the turbulent flow will be considered for the greatest pressure drop [8].

The relative roughness is:

$$\frac{\varepsilon}{D} = \frac{(0.00015)}{(0.125)}$$

$$\frac{\varepsilon}{D} = 0.0012$$

From the moody diagram [8] we find that the friction factor is 0.046 at a Reynolds number of 3125 and a roughness of 0.0012.

The equation used to find h_f is [8]:

$$h_f = \frac{fLv^2}{2Dg}$$

$$h_f = \frac{(0.046)(191)(1225)}{(2)(0.125)(322)}$$

$$h_f = \frac{1340 \text{ ft-lbm}}{\text{lb}_f}$$

The total pressure drop for this 1½-inch pipe line is:

$$\Delta p = h_f p$$

Where p is the air pressure per foot.

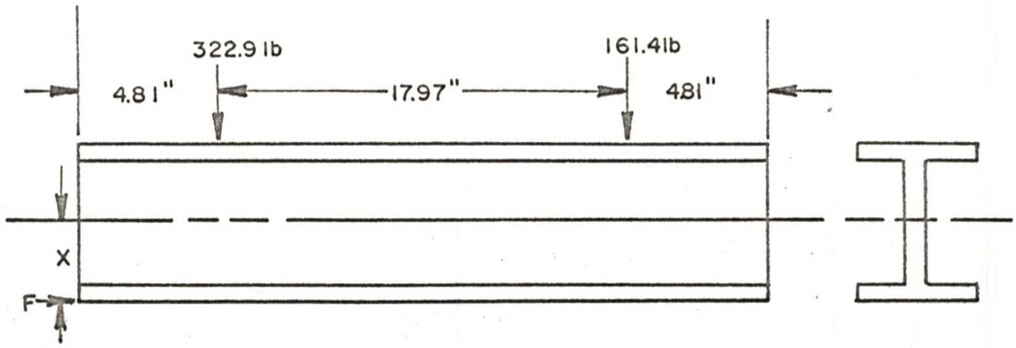
$$\Delta p = (1340)(0.000521)$$

$$\Delta p = 0.70 \text{ psi}$$

The pressure drop for the reclamation system will be less than 1 psi while the pressure drop in the humidification system will be 2.6 psi. The ½-inch pipe, 1½-inch pipe, reclamation system and humidification have a total pressure drop of 6.98 psi. This total pressure drop excludes the heat exchanger. It was decided to allow a 110% contingency for the heat exchanger and expansion of the circulation systems. This contingency would mean that a pump capable of producing a 15 psi pressure head be required for each circulation system.

APPENDIX C

CALCULATIONS FOR STRUCTURAL SUPPORT OF HIGH-PRESSURE DIRTY STORAGE VESSELS



The maximum withstanding stress in tension or compression for vertical steel supports will be set at 20,000 psi. The moment equation for the above member is given below [7].

$$\circlearrowleft + \Sigma M = (323)(4.81) + (161)(22.8) - (F)(X) = 0$$

$$M = (F)(X) = 5231 \text{ in-lb}$$

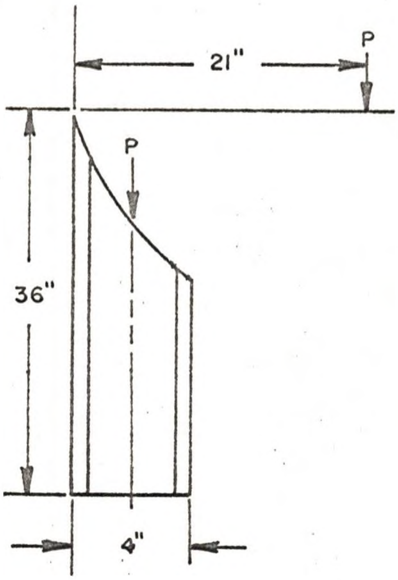
If we assume that we are using a 3-inch deep I beam, 3 I 5.7 [7], with a section modulus of 0.40, and using the equation below:

$$\text{Max } S = \frac{M}{Z}$$

we get a Max S of 13,076 psi. Since the maximum withstanding stress in compression is 20,000 psi, the 3-inch I beam gives us a safety factor of 1.529.

APPENDIX D

CALCULATIONS FOR STRUCTURAL SUPPORT OF THE LOW-PRESSURE DIRTY STORAGE VESSELS



For this vertical support we will assume a 4 I 9.5 [7] American Standard I Beam with an area of 2.76 in^2 and a section modulus Z_{x-x} of 3.3 and a radius of gyration of 0.58. The slenderness ratio for this type of member is given as:

$$\frac{L_1}{K} \ [7] = 62.069$$

For columns with slenderness ratios up to 120 the following formulas are used [7]:

$$\frac{P}{A} = 17{,}000 - 0.485 \left(\frac{L}{K}\right)^2$$

$$\frac{P}{A} = Sw = 15{,}109 \text{ psi}$$

$$Sw = \Sigma \frac{P}{A} + \left(\frac{Sw}{Sb}\right)\left(\frac{M}{Z}\right)$$

Since $L_1 d/bt$ is 175.775 for a 4 I 9.5 beam which is less than 600, Sb will be 20,000 psi [7]. Therefore the above equation will change to:

$$Sw = \Sigma \frac{P}{A} + \left(\frac{Sw}{Sb}\right)\left(\frac{21P}{Z}\right)$$

$$15{,}109 = .362P + 5.44P$$

$$P = 2{,}603 \text{ lb}$$

One low-pressure dirty storage tank weighs 2,000 lb. Since there will be four legs, each leg will cause a P of 500 lb which results in a safety factor of five. This large safety factor allows for hydrostatic testing if required and vertical stability.

APPENDIX E

OXYGEN CONSUMPTION BY ANIMAL IN COMPLEX

One complex has the capability of containing 140 rats. Since the average weight of a male rate is 500 grams [10], the total amount of rats by weight in the complex is 70,000 grams. The oxygen consumption per hour, per gram of rat is 0.88 mL [10]. This gives a total oxygen consumption of 61.6 L/hour or 2.1757 scf/hour.

APPENDIX F

COST AND VOLUME ANALYSIS OF LOW-PRESSURE DIRTY STORAGE

The propane tank specifications are listed below.

Dimensions	Cost	Volume	Class
30" dia x 88"	$185.00	250 gal	A
38" dia x 113"	$225.00	500 gal	B
40½" dia x 196"	$400.00	1000 gal	C

Class	Storage capacity scf	Storage capacity scf at 200 psig	Cost per scf stored
A	33.42 scf	455.00 scf	$40.66¢/scf
B	66.84 scf	910.00 scf	$24.72¢/scf
C	133.68 scf	1820.01 scf	$21.98¢/scf

From the list above we can see that the most economical selection for storage would be the Class C tank.

The small volume of gas in a complex at 600 psig is 11,860 scf, this would require 6.6 Class C propane tanks.

APPENDIX G

HIGH-PRESSURE DIRTY STORAGE TANK CAPACITY

The storage volume per tank is 7.83 scf. These tanks will be pressurized to 2,300 psi. The total storage area will be $\frac{(7.83)(2300)}{(14.7)}$ or 1225 scf. Since the circulation system could be operating at 600 psig and allowing a pressure drop of 50 psi to provide maximum flow, any gas in the tanks under 650 psig is unusable. This gives us an unusable storage of 346 scf per tank or a useful storage of 878 scf per tank. With a possible 11,860 scf of gas in a complex at 600 psig we will require $\frac{(11860)}{(879)}$ or 13.5 tanks.

It is recommended that the high-pressure storage area be fixed at thirteen tanks, while the low-pressure dirty storage area be fixed at eight tanks. Over flow from HPDS can be diverted to LPDS and also the larger LPDS area will provide faster rapid decompression.

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