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Mars Landing and Reconnaissance Mission Environmental Control and Life Support System Study

Volume 2

Subsystem Studies

R91

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

SLS 414-2

Mars Landing and Reconnaissance Mission Environmental Control and Life Support System Study

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FOREWORD

This is Volume Two of the final report of the "Mars Landing and Reconnaissance Mission Environmental Control and Life Support System Study." This study was conducted by Hamilton Standard under contract NAS 9-1701 for the Manned Spacecraft Center of the National Aeronautics and Space Administration. The study, conducted from July 15, 1963 to March 15, 1964, was directed by Mr. K. L. Hower, and the principal contributors were Messrs. V. J. Binks, R. L. Brown, R. Lamparter, M. R. Segal, J. F. Wilber, and J. Warner.

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The total report is contained in three Volumes as listed below:

Volume 1	Study Summary and Conclusions
Volume 2	Subsystem Study Results
Volume 3	System Study Results

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SECTION 1.0

INTRODUCTION

1.0 INTRODUCTION

This volume of the final report presents the results of the subsystem studies used as supporting data for the final system analysis. The results are presented in a parametric form to permit application of the data to the requirements of the Mars Mission in the future as the mission duration, power penalty, or crew size change. The specification used for these studies dictated a design point of 6 men for a 420 day mission with a power penalty of 500 pounds per kilowatt.

To allow full flexibility of use, the data illustrates the fixed weight, power, and expendable requirements in all possible cases. It is felt that this method of presentation will allow better evaluation of subsystem effects on vehicle weight and power supply and how they change with changes in mission duration.

General conclusions are presented on each approach considered to point out the preliminary assessment on the subsystem level. In most cases, the final selection is left to the system studies where the integration effects with other equipment may be considered.

The subsystems discussed in this volume include CO_2 removal, transfer, and reduction; water electrolysis; atmospheric storage; water reclamation; waste management; contaminant control; personal hygiene; radiators, heat exchangers, water separators; and fans.

SECTION 2.0

CARBON DIOXIDE REMOVAL

2.0 CO_2 REMOVAL

2.1 General

2.1.1 Objectives

The analysis of CO_2 removal equipment was performed on the candidate subsystems from a basis of CO_2 removal alone. In deciding the optimum method of analyzing subsystems for a study which considers an end use of a piece of equipment with more than one application (such as CO_2 collection or CO_2 disposal), certain ground rules had to be established to allow each system to be compared on an equal basis. In the case of the CO_2 removal equipment, the decision was made to investigate all subsystems initially on the basis that oxygen reclamation from the collected CO_2 would not be required; thus the CO_2 could be disposed of in any convenient manner. This approach allows comparative determination of system fixed weight, power, and expendable weights on an equal basis.

When a closed system which reclaims the oxygen from the CO_2 is considered, certain additions to the basic CO_2 removal equipment are required. During the course of the analysis, specific points of integration possibilities or integration problems were noted and retained for utilization in later CO_2 removal and transfer studies which are presented in Section 3.0 of this report. Thus, the data presented in this section and the analysis and discussion assumes that no requirement exists for CO_2 collection. In some cases, CO_2 collection enters the discussion from a feasibility basis, but no mention of its influence or detriment is made. This is considered in Section 3.0.

The comparative considerations and individual data presentations in this section are valid as design tools for CO_2 removal; thus, upon selection of a crew size, a mission duration, and a power source, one may easily determine the optimum CO_2 removal approach (based on CO_2 removal considerations alone) from the data presented. In many cases, additional summary plots are also presented to allow rapid comparison of system approaches within the report itself rather than causing a need for hand calculations and other time consuming effort. The system specification has called out a requirement to study the effect on subsystem selection of power supplies with penalties of 200, 300, and 500 lbs/Kw.

Since the study is organized into a subsystem phase and a system phase, it was decided that the CO_2 removal subsystem equipment should stand basically alone in the evaluation. The ground rule was established that during this analysis, electrical heating must be used for all heating requirements rather than counting on waste heat from other portions of the overall system. When final system integration was considered, this point was re-evaluated for the candidate systems in an attempt to lower the overall equipment weight. Many other variables considered in the overall specification were treated qualitatively at this time, since application of these variables to all subsystems, whether candidate or non-candidate, would have

2.1.1 (Continued)

created needless extra effort. Upon elimination of non-candidate systems, these other factors were considered more fully as selection criteria.

2.1.2 Discussion of Data Presentation

In organizing the data for this report, many methods of presentation were possible. The use of tables, charts, detailed calculations, curves, are all potential methods which could be utilized. It was decided to present the data in curve form to allow most rapid utilization. Thus, results of subsystem optimizations are plotted for the important parameters as variations with partial pressure of CO_2, crew size or metabolic rate, and mission duration. In analyzing any subsystem of this nature, the major considerations which must be determined are system fixed weight, system power requirements, and expendable requirements, if any. However, for clarity of presentation, additional cross plots of the basic data are included in this report. It is felt that presentation of summary curves at the design point mission length (420 days) allows rapid recognition of subsystem equivalent weight requirements. Also, to allow consideration of equivalent weight for varied mission lengths, additional curves showing equivalent weight variation with mission time have been prepared. These curves should allow extra flexibility in analyzing CO_2 removal equipment, without excess calculations on the part of the reader.

The schematic presented for each system is an individual system schematic without illustrating system integration possibilities in any great detail due to the previously mentioned ground rule of providing a system that would stand alone prior to the system integration phase. The schematics are essentially complete and operable schematics at this point; however, since candidate systems selection was the primary purpose of this analysis, the full degree of design and reliability detail afforded a final system selection is not included in this preliminary analysis.

In addition to data presentation for individual subsystems, a cumulative subsystem analysis is presented. This analysis and presentation will allow rapid determination of appropriate system choice for the design parameters being considered. Thus, the data takes two forms: 1) an individual system approach presenting considerable data on parametric variations, and 2) a comparative approach analyzing all subsystems considered at the existing mission design points.

2.2 CO_2 Removal By Membrane Diffusion

2.2.1 Introduction and Data Source

The analysis of a CO_2 removal system using membranes with selective permeability as the concentration media was based on previous Hamilton Standard design data and limited information available in current progress reports from the State University

2.2.1 (Continued)

of Iowa to the NASA on a current contract (Reports Number 1 through 6, Contract NASr-73). This system approach has not had the benefit of the advanced development work that many other CO_2 removal systems have undergone. The data presented for membrane diffusion is based primarily on a theoretical analysis backed by limited testing on membrane characteristics and membrane performance.

2.2.2 System Description

Figure 2-1 presents the schematic approach to the system considered in this analysis.

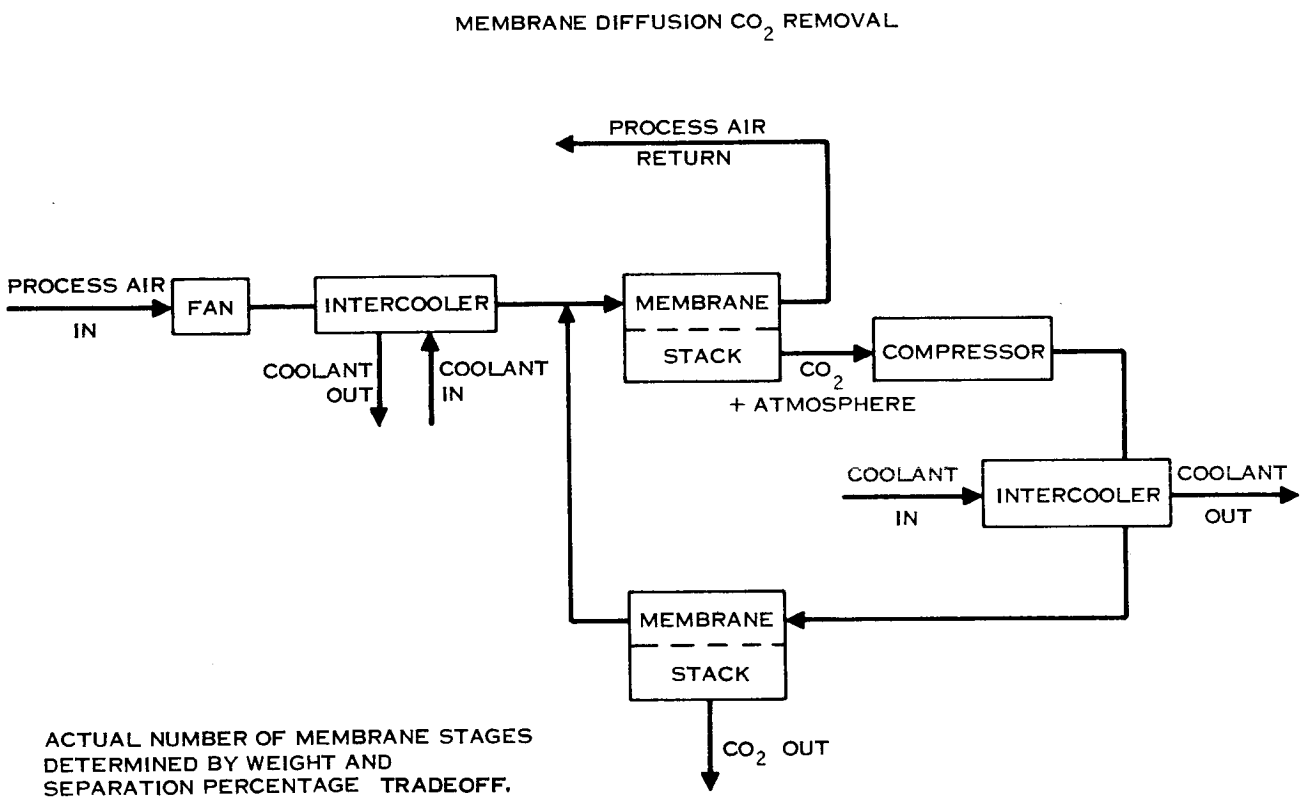

FIGURE 2-1

The system operation is based upon individual operation as a CO_2 removal device with integration aspects with other subsystems considered but not fully exploited. Referring to the schematic, the inlet air is drawn into the system at an assumed temperature of 50°F and forced through the system by a low pressure ratio fan which provides the necessary pressure rise for system operation. The process air then passes through an inter-cooler where the fan heat is rejected to a circulating coolant from the main thermal control system.

2.2.2 (Continued)

From the inter-cooler, the process air passes through the first stage of a membrane stack consisting of a large number of thin wall tubes. Silicone rubber membranes were chosen for this analysis. The air enters the first stage membrane stack through an inlet header and then passes through the tubes where a portion of the flow permeates through the tube walls. Since silicone rubber is more permeable to CO_2 than to oxygen and nitrogen, the gas permeates tube walls at a higher CO_2 concentration; and the air stream, upon leaving the membrane stack, is returned to the cabin or main environmental control system.

In reality, the membrane stack may require more than one stage to achieve the degree of separation required; thus, the CO_2 enriched air leaving the first stage will have to be recompressed and recooled prior to entering any of the subsequent stages. As shown in the schematic, the CO_2 enriched air passes through a compressor, another inter-cooler, and into a subsequent stage membrane stack. For simplicity, the CO_2 is shown being removed from this membrane stack, although actual determination of number of stages is dependent upon a trade-off of weight versus the efficiency of separation. For this study, an eight stage unit was considered. From the outlet of the second stage membrane stack and any further stack, the process air is returned to the inlet of the previous stage where the cycle is repeated. The gas permeated through the final stage membranes is discharged to either vacuum in the case where no CO_2 collection requirement exists, or to a CO_2 reduction system if the eventual usage requires reclamation of oxygen from the CO_2.

The primary weight of a system of the type shown is that of the fan and compressors, dependent upon the stages of diffusion required. For a six man system achieving a CO_2 cabin concentration of 5 mm Hg., this weight is approximately 90% of the total system weight. The membrane weight itself is quite small; however, the effect of adequate headering of the membrane inlet and outlet, and construction of the overall membrane stage device may offer considerable design problems, as well as considerable increases in weight. For this analysis, the tube diameter of the silicone rubber was taken as .01 inches with a membrane wall thickness of 2.5×10^{-4} inches. It is apparent from this sizing that placing many of these tubes in parallel in one membrane could lead to serious design and manufacturing problems.

2.2.3 Results

The results of the membrane diffusion analysis are presented in the next few pages. All results are presented parametrically to allow flexibility of use in the future. Figure 2-2 presents the estimated system weight as a variable with changes in CO_2 production rate and the cabin concentration of CO_2. To allow comparison of the weight data, the increase in weight due to expendable weight requirements is illustrated, as well as the fixed weight for a 420 day period. The range of production rates chosen allows determination of system weight variation for two to twelve man

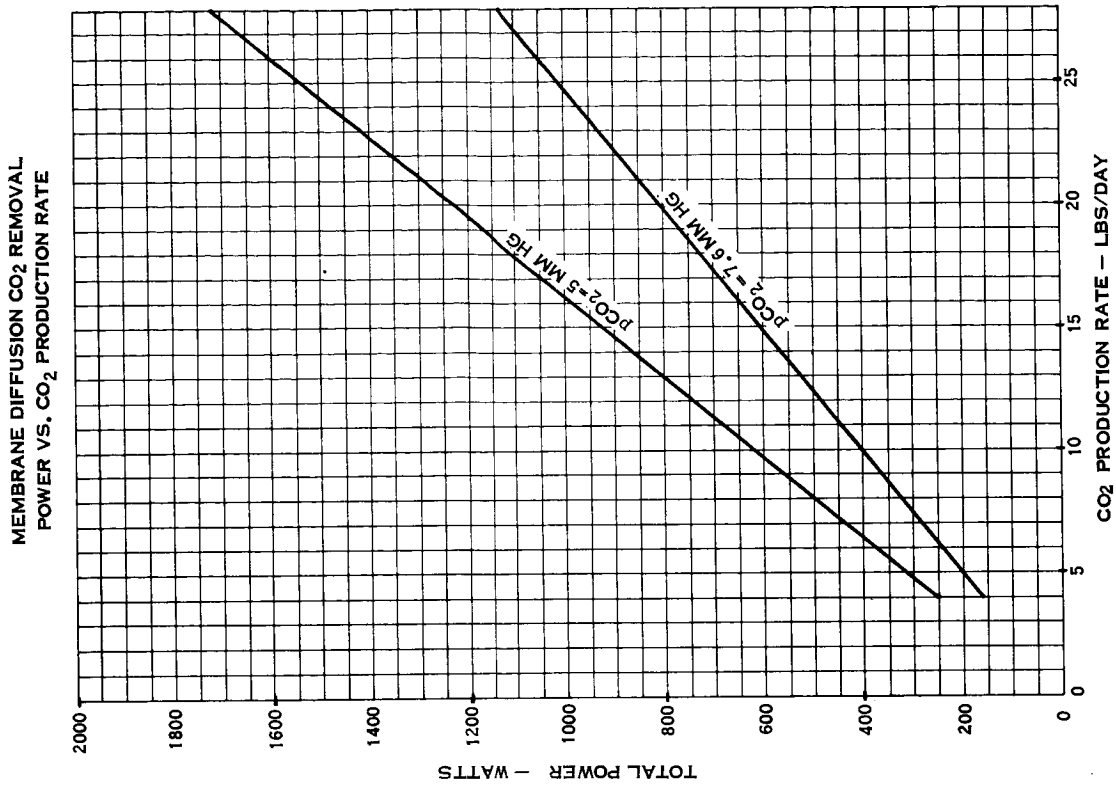

FIGURE 2-3

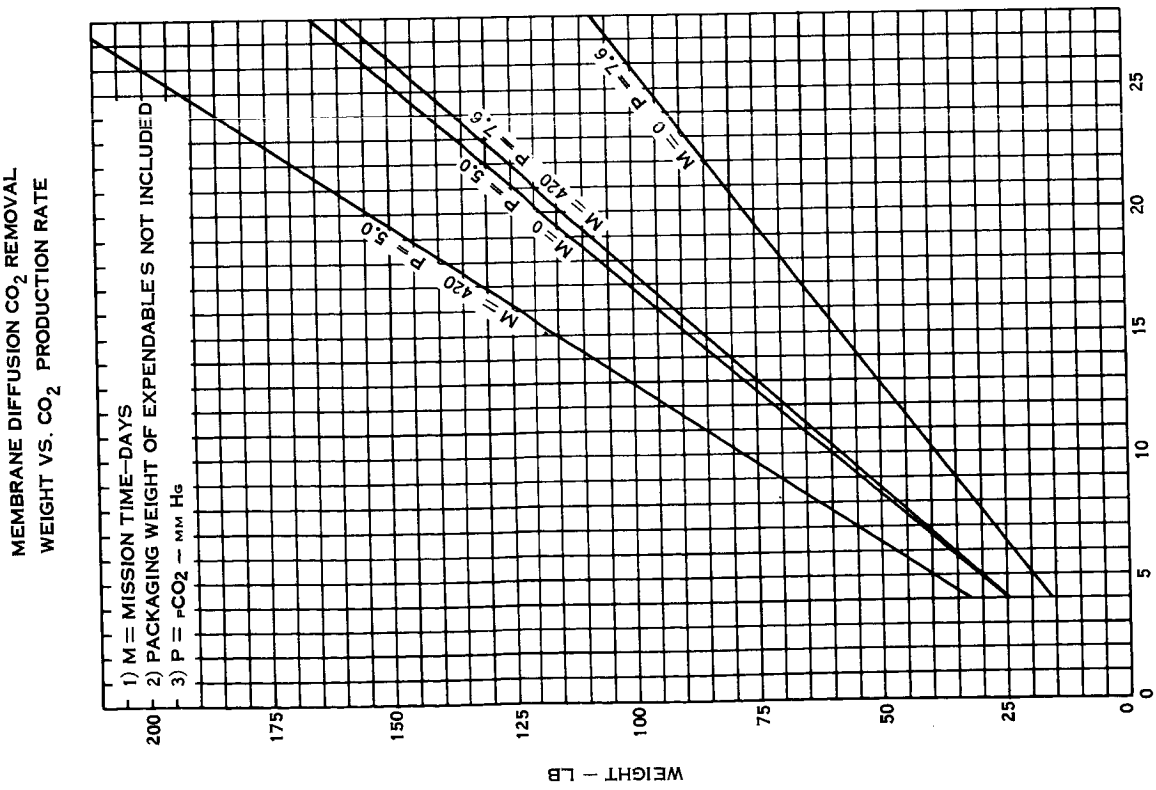

FIGURE 2-2

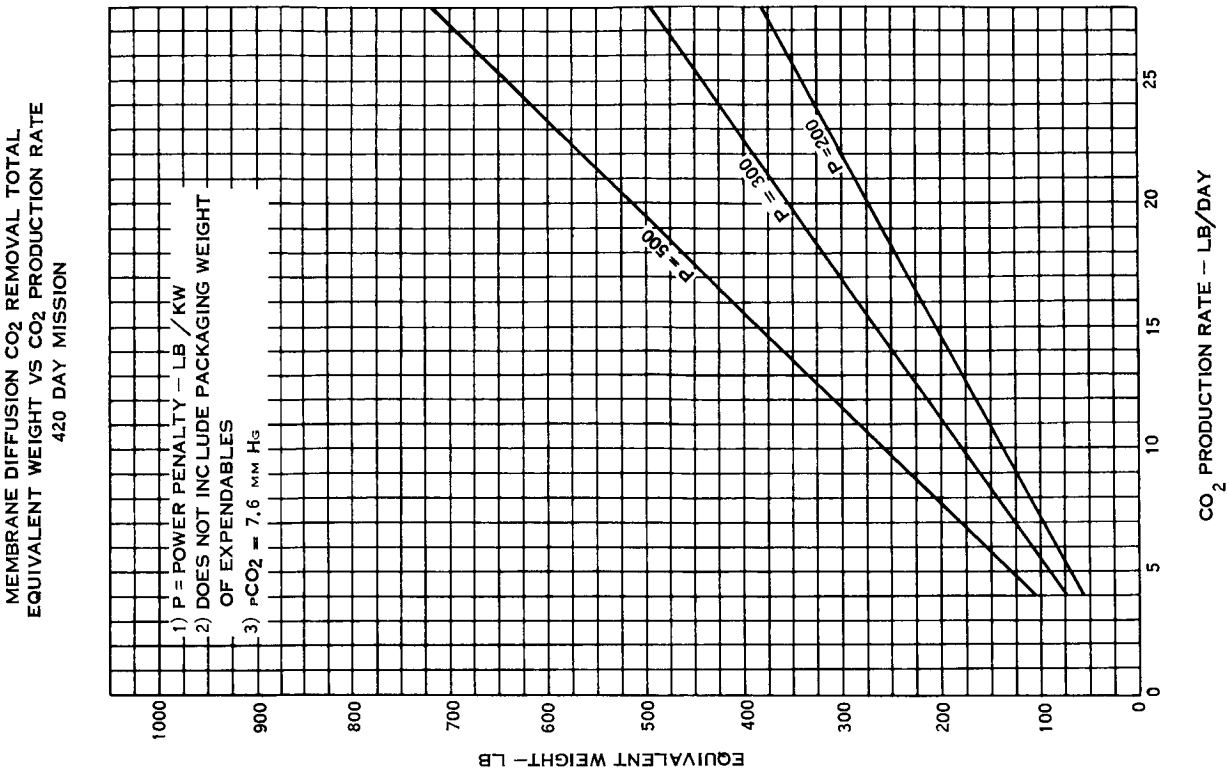

FIGURE 2–5

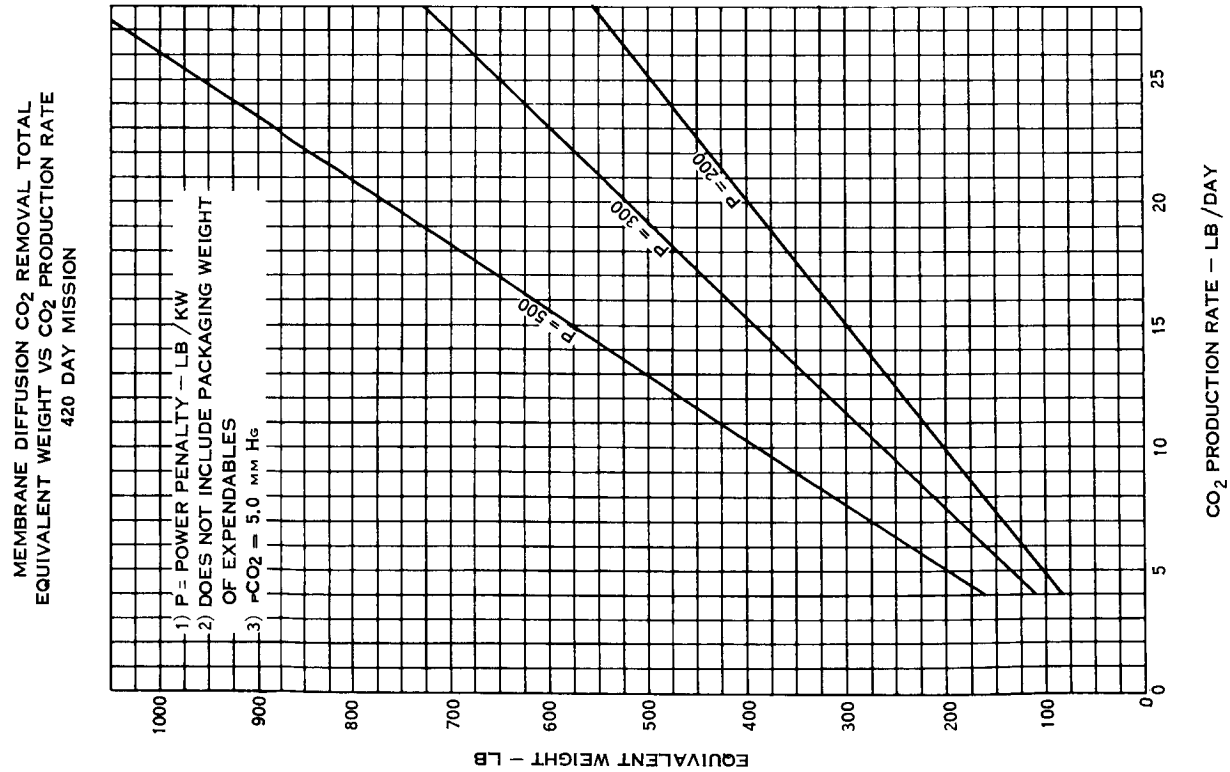

FIGURE 2–4

2.2.3 (Continued)

systems. Figure 2-3 illustrates the change in system input power requirements as a function of production rate and partial pressure of CO_2. Thus, with the combination of these two figures, a system launch equivalent weight can be determined for any range crew size from two to twelve men once a penalty for power is selected. Figures 2-4 and 2-5 sum up the preceding two figures in a total determination of equivalent weight variation with crew size for a 420 day mission for the power penalties specified for this study. It must be emphasized here that the expendable weight illustrated does not include the penalty for providing these expendables, such as packaging weight.

By treating the packaging weight as an additive value, the curve is valid for any method of packaging. To utilize this curve for consideration of a mission duration other than 420 days, an expendable weight of .009 lbs per man day may be assumed to allow a rough re-calculation of weight for the mission time considered. This expendable requirement is caused by the amount of O_2 and N_2 trapped in the CO_2 exhausted to space.

Figures 2-6 through 2-9 allow determination of approximate expendable weight and total equivalent weight for a given mission length for four different approximate crew sizes (2, 6, 9, and 12 men). This is illustrated in the figures by the 4, 12, 20, and 28 lbs per day CO_2 production rate lines. Thus, for a design point cabin partial pressure of CO_2 equal to 5 mm Hg, the weight required on board for any period from zero to 420 days may be determined from these figures. Figure 2-6 presents this from a weight only basis, including fixed systemweight and weight of expendables. Figure 2-7 presents total equivalent weight (charging power at 200 lbs per kilowatt) and Figures 2-8 and 2-9 present the same comparison with power charged at 300 and 500 lb/KW, respectively.

2.2.4 Conclusions

The membrane diffusion process is attractive in that it exhausts the CO_2 at a pressure compatible with CO_2 reduction equipment. Weight, development status, and complexity weigh heavily against it at this time. Compressor reliability as well as required compressor power are very unattractive when considering other possible approaches for CO_2 removal. In addition, the previously mentioned problem of construction of the membrane stack is a potential problem area and adequate structural members may prove to be a considerable design problem when faced with actual flight hardware design. In general, the system is unattractive for the Mars Mission application.

2.3 CO_2 Removal by Mechanical Freeze-out Processes

2.3.1 Introduction and Data Source

Mechanical freeze-out is one of the two freeze-out processes considered in this study.

MEMBRANE DIFFUSION CO_2 REMOVAL
WEIGHT VS MISSION TIME

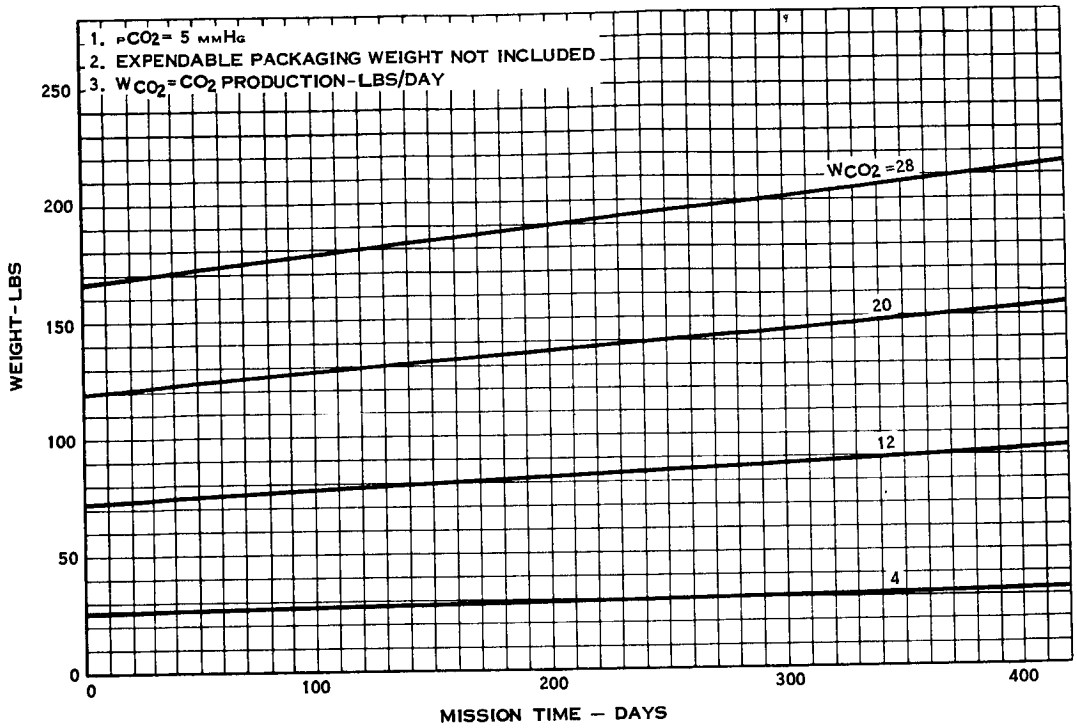

FIGURE 2–6

MEMBRANE DIFFUSION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

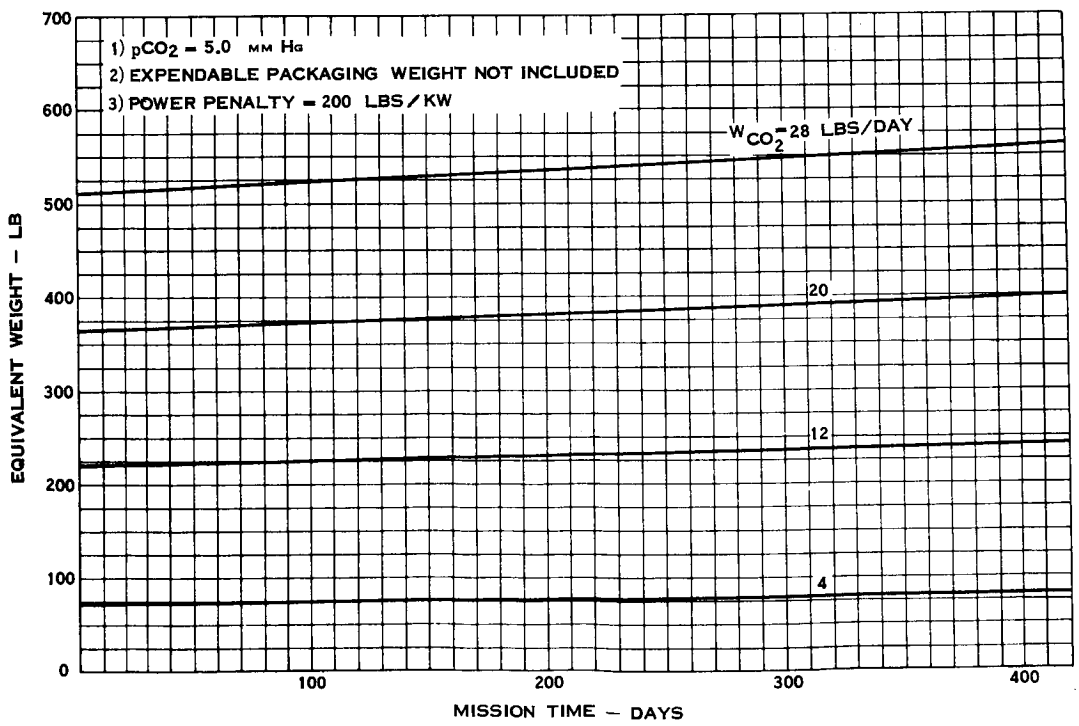

FIGURE 2–7

MEMBRANE DIFFUSION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

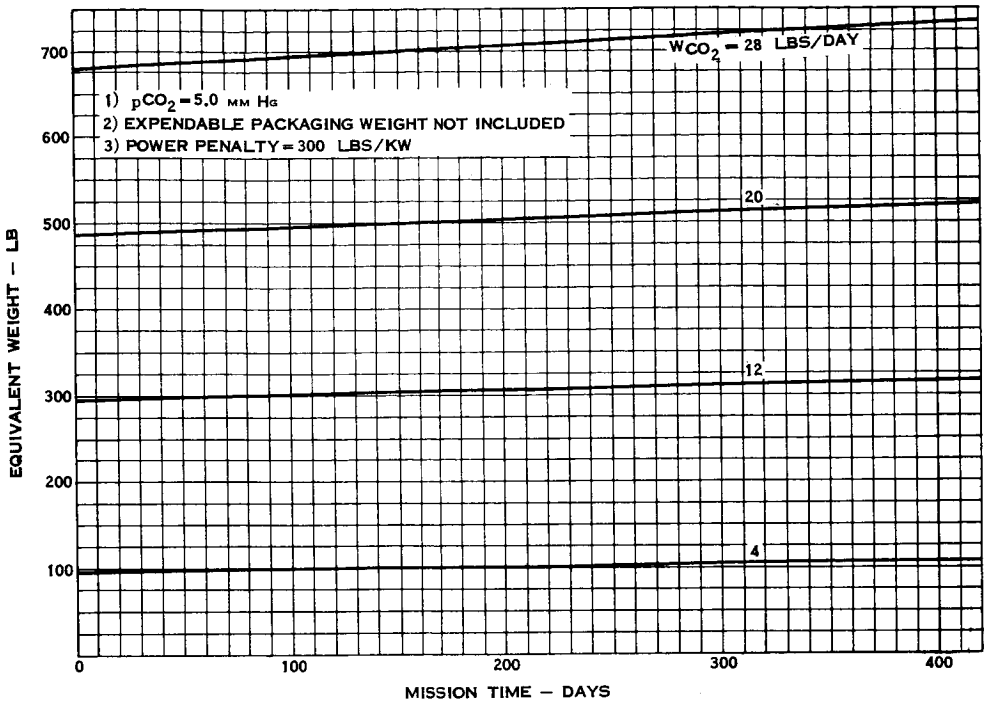

FIGURE 2–8

MEMBRANE DIFFUSION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

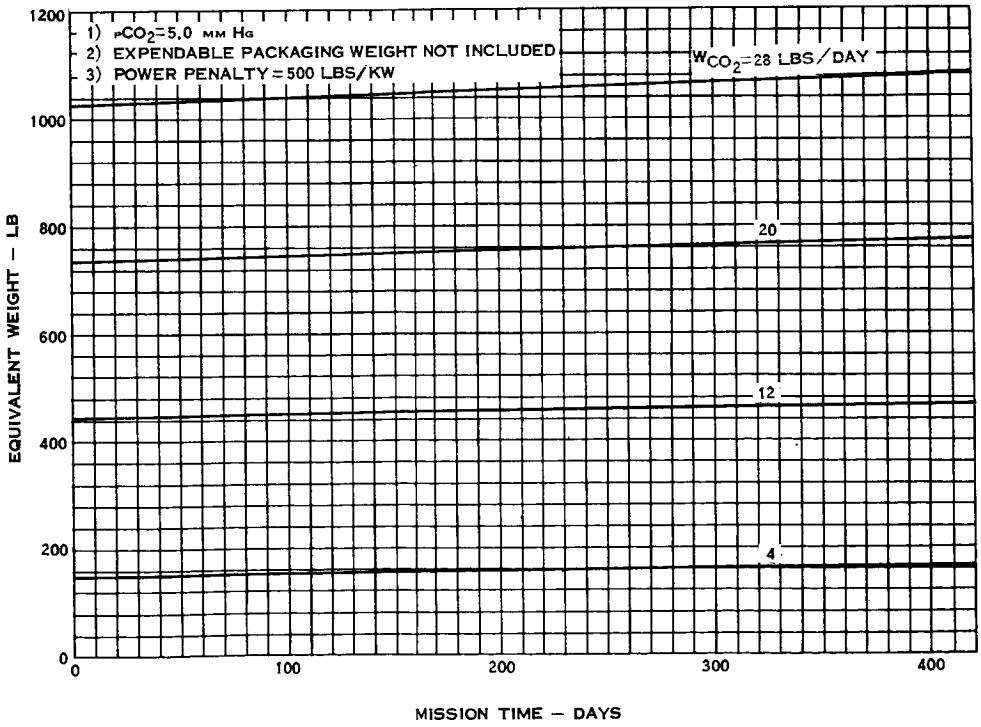

FIGURE 2–9

2.3.1 (Continued)

It is a somewhat attractive method of CO_2 removal in that the CO_2 may be withdrawn in a highly concentrated form; however, this particular system approach is relatively undeveloped at this time. Considerable theoretical analysis was performed to achieve an optimum system configuration. Primary data source for this analysis was previously in-house Hamilton Standard subsystem selection work in CO_2 removal.

2.3.2 System Description

The system considered in this analysis is presented schematically in Figure 2-10. The system includes many complex items, making reliable operation somewhat questionable. Inlet air from the cabin thermal control system at a temperature of 50°F is brought into the system through a silica gel or other desiccant bed where the water vapor in the process air is removed. Freezing out water vapor as well as the CO_2 is impractical due to the high heat of condensation of water. Eliminating water freeze-out reduces system operating pressure and compressor weight and power, since lower compressor temperatures can be utilized.

The process air is then compressed to provide a high pressure to operate the air motor. Prior to entering the motor, the stream temperature is decreased, in the regenerative heat exchanger, to just above the freezing point of CO_2. This cool high

MECHANICAL FREEZE OUT CO_2 REMOVAL

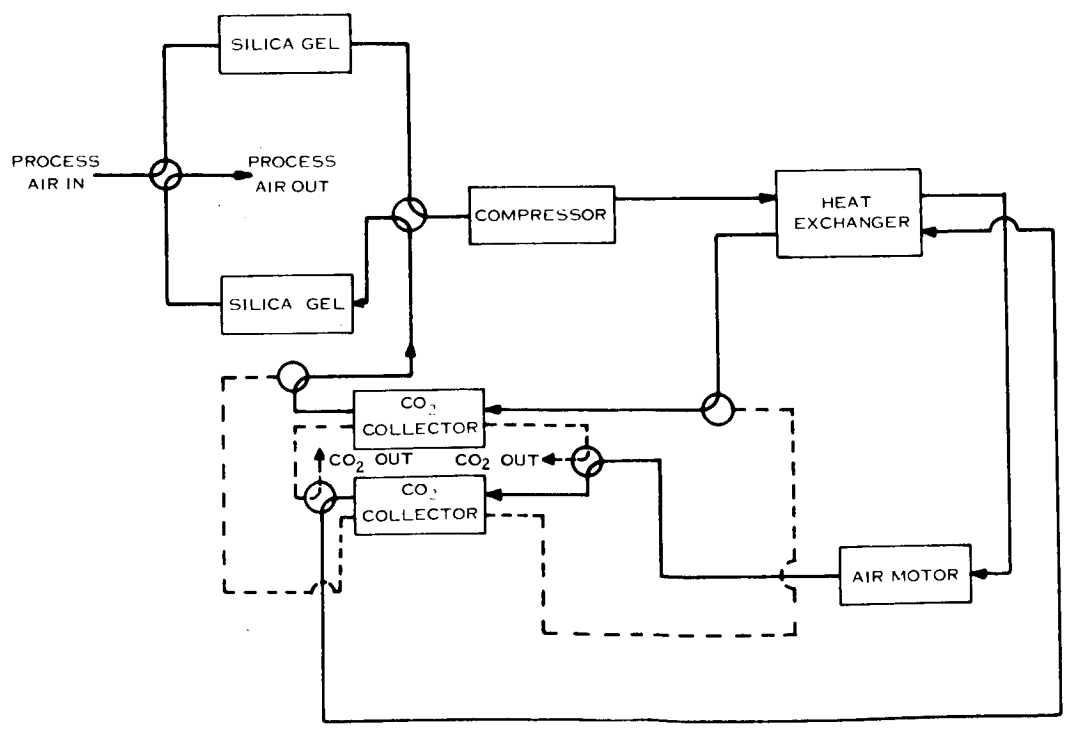

FIGURE 2-10

SECTION 1.0

INTRODUCTION

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SECTION 2.0

CARBON DIOXIDE REMOVAL

2.0 CO_2 REMOVAL

2.1 General

2.1.1 Objectives

The analysis of CO_2 removal equipment was performed on the candidate subsystems from a basis of CO_2 removal alone. In deciding the optimum method of analyzing subsystems for a study which considers an end use of a piece of equipment with more than one application (such as CO_2 collection or CO_2 disposal), certain ground rules had to be established to allow each system to be compared on an equal basis. In the case of the CO_2 removal equipment, the decision was made to investigate all subsystems initially on the basis that oxygen reclamation from the collected CO_2 would not be required; thus the CO_2 could be disposed of in any convenient manner. This approach allows comparative determination of system fixed weight, power, and expendable weights on an equal basis.

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The comparative considerations and individual data presentations in this section are valid as design tools for CO_2 removal; thus, upon selection of a crew size, a mission duration, and a power source, one may easily determine the optimum CO_2 removal approach (based on CO_2 removal considerations alone) from the data presented. In many cases, additional summary plots are also presented to allow rapid comparison of system approaches within the report itself rather than causing a need for hand calculations and other time consuming effort. The system specification has called out a requirement to study the effect on subsystem selection of power supplies with penalties of 200, 300, and 500 lbs/Kw.

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2.1.1 (Continued)

created needless extra effort. Upon elimination of non-candidate systems, these other factors were considered more fully as selection criteria.

2.1.2 Discussion of Data Presentation

In organizing the data for this report, many methods of presentation were possible. The use of tables, charts, detailed calculations, curves, are all potential methods which could be utilized. It was decided to present the data in curve form to allow most rapid utilization. Thus, results of subsystem optimizations are plotted for the important parameters as variations with partial pressure of CO_2, crew size or metabolic rate, and mission duration. In analyzing any subsystem of this nature, the major considerations which must be determined are system fixed weight, system power requirements, and expendable requirements, if any. However, for clarity of presentation, additional cross plots of the basic data are included in this report. It is felt that presentation of summary curves at the design point mission length (420 days) allows rapid recognition of subsystem equivalent weight requirements. Also, to allow consideration of equivalent weight for varied mission lengths, additional curves showing equivalent weight variation with mission time have been prepared. These curves should allow extra flexibility in analyzing CO_2 removal equipment, without excess calculations on the part of the reader.

The schematic presented for each system is an individual system schematic without illustrating system integration possibilities in any great detail due to the previously mentioned ground rule of providing a system that would stand alone prior to the system integration phase. The schematics are essentially complete and operable schematics at this point; however, since candidate systems selection was the primary purpose of this analysis, the full degree of design and reliability detail afforded a final system selection is not included in this preliminary analysis.

In addition to data presentation for individual subsystems, a cumulative subsystem analysis is presented. This analysis and presentation will allow rapid determination of appropriate system choice for the design parameters being considered. Thus, the data takes two forms: 1) an individual system approach presenting considerable data on parametric variations, and 2) a comparative approach analyzing all subsystems considered at the existing mission design points.

2.2 CO_2 Removal By Membrane Diffusion

2.2.1 Introduction and Data Source

The analysis of a CO_2 removal system using membranes with selective permeability as the concentration media was based on previous Hamilton Standard design data and limited information available in current progress reports from the State University

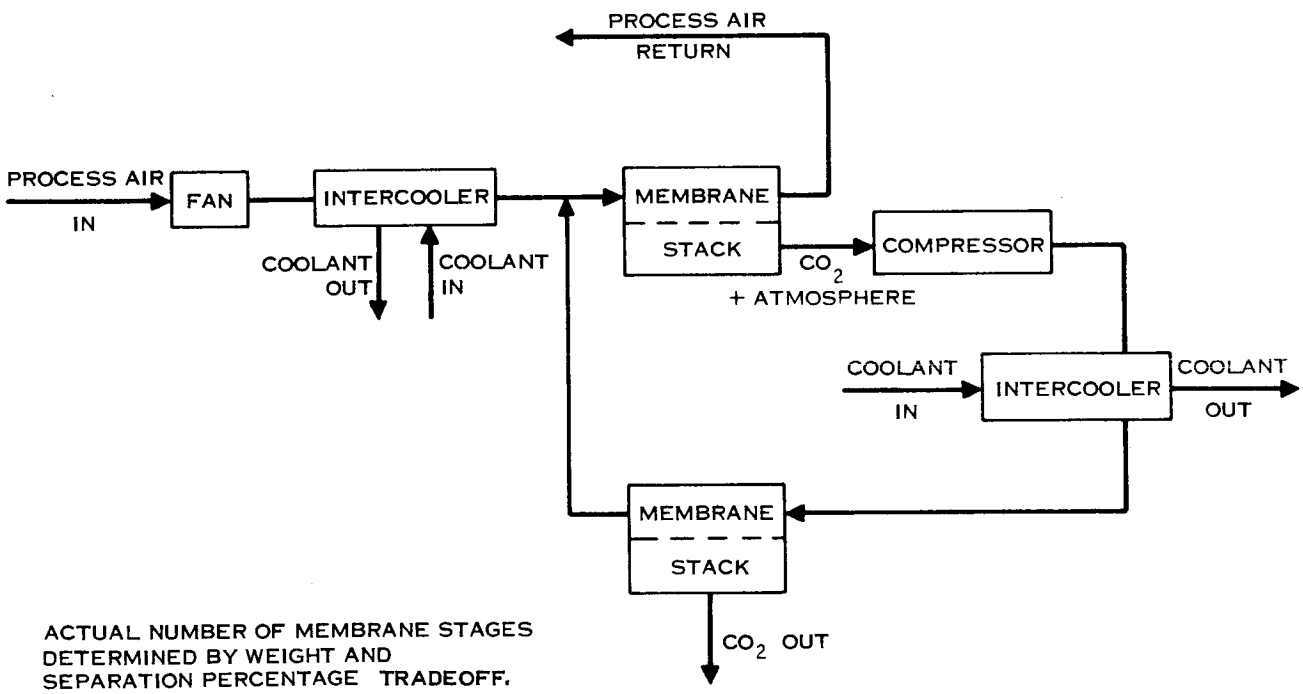
2.2.1 (Continued)

of Iowa to the NASA on a current contract (Reports Number 1 through 6, Contract NASr-73). This system approach has not had the benefit of the advanced development work that many other CO_2 removal systems have undergone. The data presented for membrane diffusion is based primarily on a theoretical analysis backed by limited testing on membrane characteristics and membrane performance.

2.2.2 System Description

Figure 2-1 presents the schematic approach to the system considered in this analysis.

MEMBRANE DIFFUSION CO_2 REMOVAL



ACTUAL NUMBER OF MEMBRANE STAGES DETERMINED BY WEIGHT AND SEPARATION PERCENTAGE TRADEOFF. 8 STAGES USED IN THIS COMPARISON

FIGURE 2-1

The system operation is based upon individual operation as a CO_2 removal device with integration aspects with other subsystems considered but not fully exploited. Referring to the schematic, the inlet air is drawn into the system at an assumed temperature of 50°F and forced through the system by a low pressure ratio fan which provides the necessary pressure rise for system operation. The process air then passes through an inter-cooler where the fan heat is rejected to a circulating coolant from the main thermal control system.

2.2.2 (Continued)

From the inter-cooler, the process air passes through the first stage of a membrane stack consisting of a large number of thin wall tubes. Silicone rubber membranes were chosen for this analysis. The air enters the first stage membrane stack through an inlet header and then passes through the tubes where a portion of the flow permeates through the tube walls. Since silicone rubber is more permeable to CO_2 than to oxygen and nitrogen, the gas permeates tube walls at a higher CO_2 concentration; and the air stream, upon leaving the membrane stack, is returned to the cabin or main environmental control system.

In reality, the membrane stack may require more than one stage to achieve the degree of separation required; thus, the CO_2 enriched air leaving the first stage will have to be recompressed and recooled prior to entering any of the subsequent stages. As shown in the schematic, the CO_2 enriched air passes through a compressor, another inter-cooler, and into a subsequent stage membrane stack. For simplicity, the CO_2 is shown being removed from this membrane stack, although actual determination of number of stages is dependent upon a trade-off of weight versus the efficiency of separation. For this study, an eight stage unit was considered. From the outlet of the second stage membrane stack and any further stack, the process air is returned to the inlet of the previous stage where the cycle is repeated. The gas permeated through the final stage membranes is discharged to either vacuum in the case where no CO_2 collection requirement exists, or to a CO_2 reduction system if the eventual usage requires reclamation of oxygen from the CO_2.

The primary weight of a system of the type shown is that of the fan and compressors, dependent upon the stages of diffusion required. For a six man system achieving a CO_2 cabin concentration of 5 mm Hg., this weight is approximately 90% of the total system weight. The membrane weight itself is quite small; however, the effect of adequate headering of the membrane inlet and outlet, and construction of the overall membrane stage device may offer considerable design problems, as well as considerable increases in weight. For this analysis, the tube diameter of the silicone rubber was taken as .01 inches with a membrane wall thickness of 2.5×10^{-4} inches. It is apparent from this sizing that placing many of these tubes in parallel in one membrane could lead to serious design and manufacturing problems.

2.2.3 Results

The results of the membrane diffusion analysis are presented in the next few pages. All results are presented parametrically to allow flexibility of use in the future. Figure 2-2 presents the estimated system weight as a variable with changes in CO_2 production rate and the cabin concentration of CO_2. To allow comparison of the weight data, the increase in weight due to expendable weight requirements is illustrated, as well as the fixed weight for a 420 day period. The range of production rates chosen allows determination of system weight variation for two to twelve man

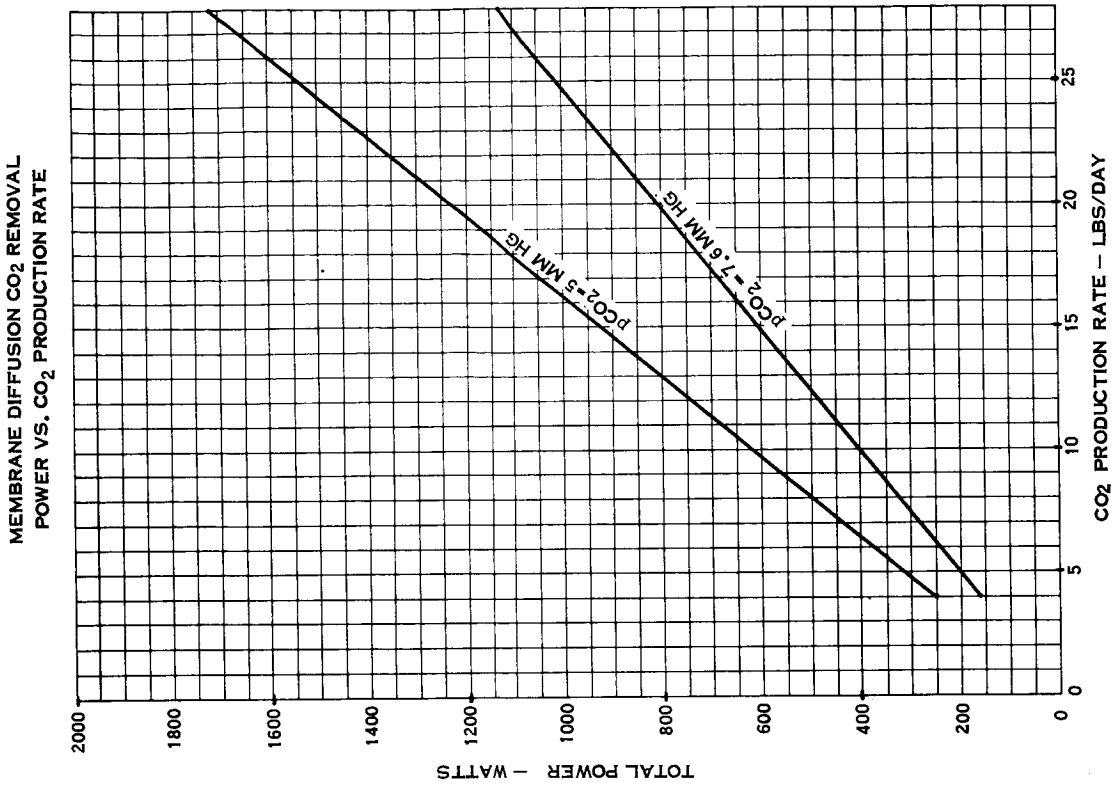


FIGURE 2-3

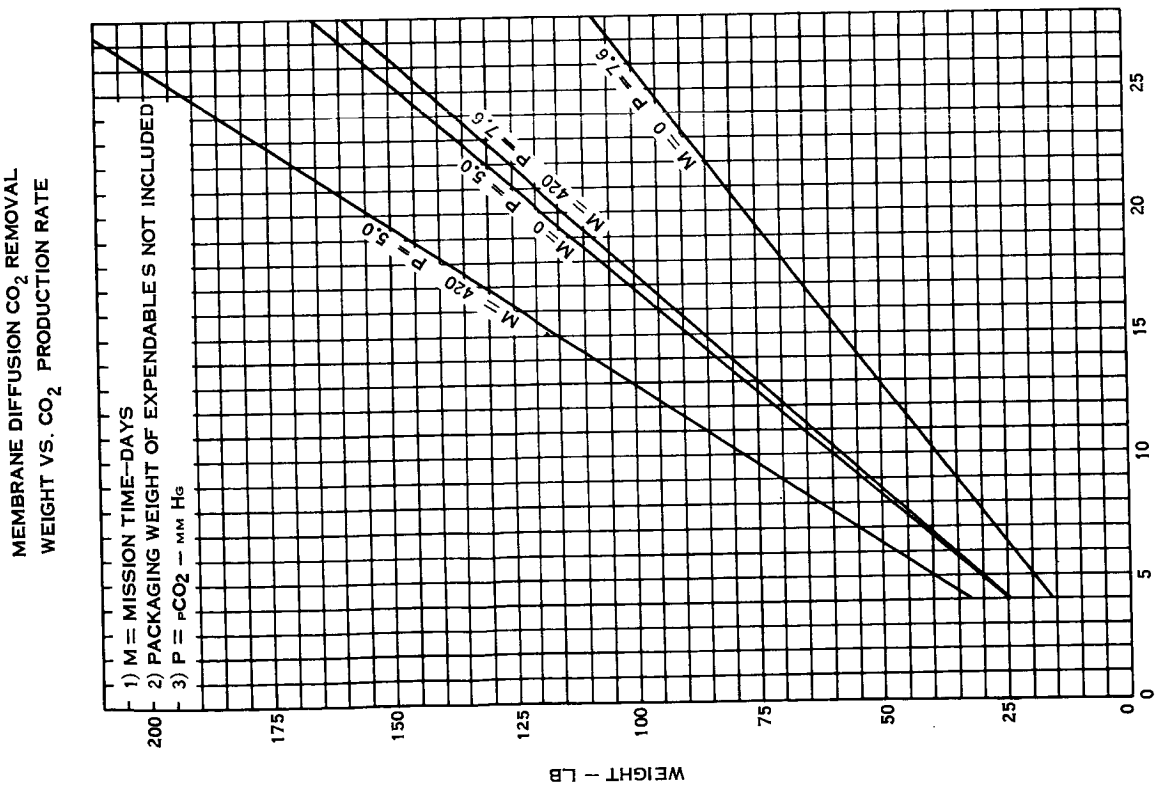


FIGURE 2-2

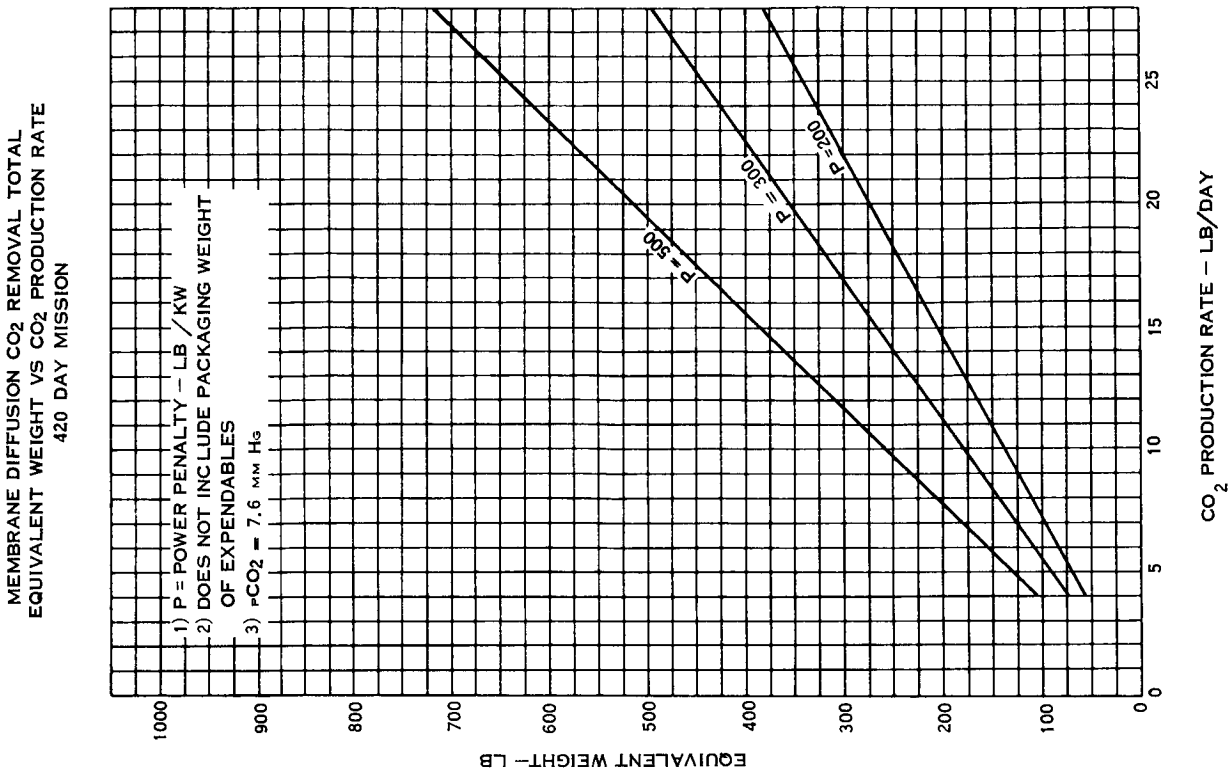


FIGURE 2–5

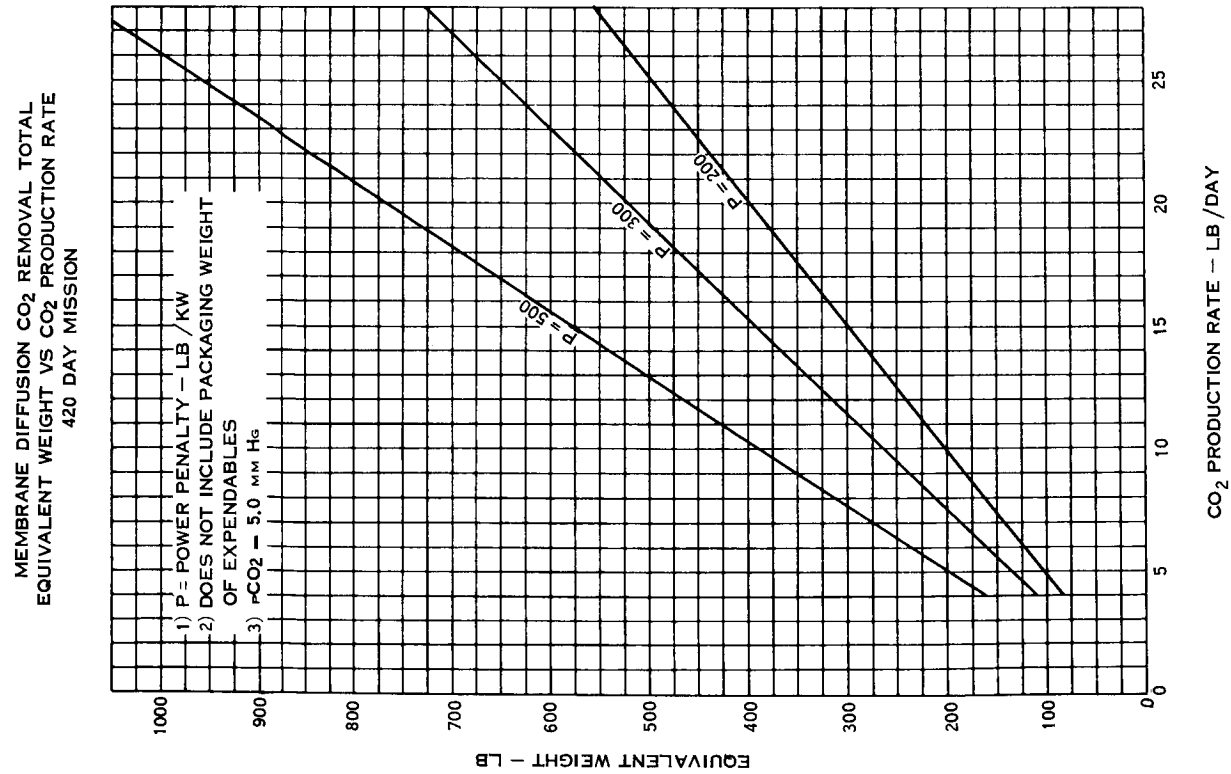


FIGURE 2–4

2.2.3 (Continued)

systems. Figure 2-3 illustrates the change in system input power requirements as a function of production rate and partial pressure of CO_2. Thus, with the combination of these two figures, a system launch equivalent weight can be determined for any range crew size from two to twelve men once a penalty for power is selected. Figures 2-4 and 2-5 sum up the preceding two figures in a total determination of equivalent weight variation with crew size for a 420 day mission for the power penalties specified for this study. It must be emphasized here that the expendable weight illustrated does not include the penalty for providing these expendables, such as packaging weight.

By treating the packaging weight as an additive value, the curve is valid for any method of packaging. To utilize this curve for consideration of a mission duration other than 420 days, an expendable weight of .009 lbs per man day may be assumed to allow a rough re-calculation of weight for the mission time considered. This expendable requirement is caused by the amount of O_2 and N_2 trapped in the CO_2 exhausted to space.

Figures 2-6 through 2-9 allow determination of approximate expendable weight and total equivalent weight for a given mission length for four different approximate crew sizes (2, 6, 9, and 12 men). This is illustrated in the figures by the 4, 12, 20, and 28 lbs per day CO_2 production rate lines. Thus, for a design point cabin partial pressure of CO_2 equal to 5 mm Hg, the weight required on board for any period from zero to 420 days may be determined from these figures. Figure 2-6 presents this from a weight only basis, including fixed systemweight and weight of expendables. Figure 2-7 presents total equivalent weight (charging power at 200 lbs per kilowatt) and Figures 2-8 and 2-9 present the same comparison with power charged at 300 and 500 lb/KW, respectively.

2.2.4 Conclusions

The membrane diffusion process is attractive in that it exhausts the CO_2 at a pressure compatible with CO_2 reduction equipment. Weight, development status, and complexity weigh heavily against it at this time. Compressor reliability as well as required compressor power are very unattractive when considering other possible approaches for CO2 removal. In addition, the previously mentioned problem of construction of the membrane stack is a potential problem area and adequate structural members may prove to be a considerable design problem when faced with actual flight hardware design. In general, the system is unattractive for the Mars Mission application.

2.3 CO_2 Removal by Mechanical Freeze-out Processes

2.3.1 Introduction and Data Source

Mechanical freeze-out is one of the two freeze-out processes considered in this study.

MEMBRANE DIFFUSION CO_2 REMOVAL
WEIGHT VS MISSION TIME

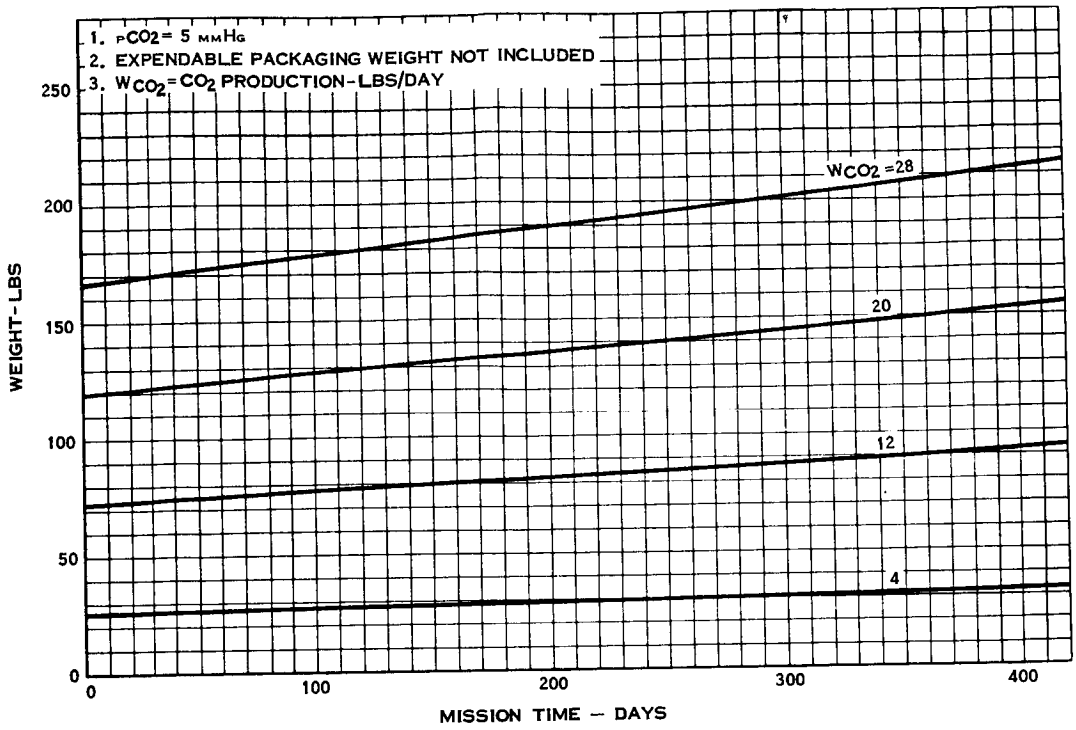


FIGURE 2–6

MEMBRANE DIFFUSION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

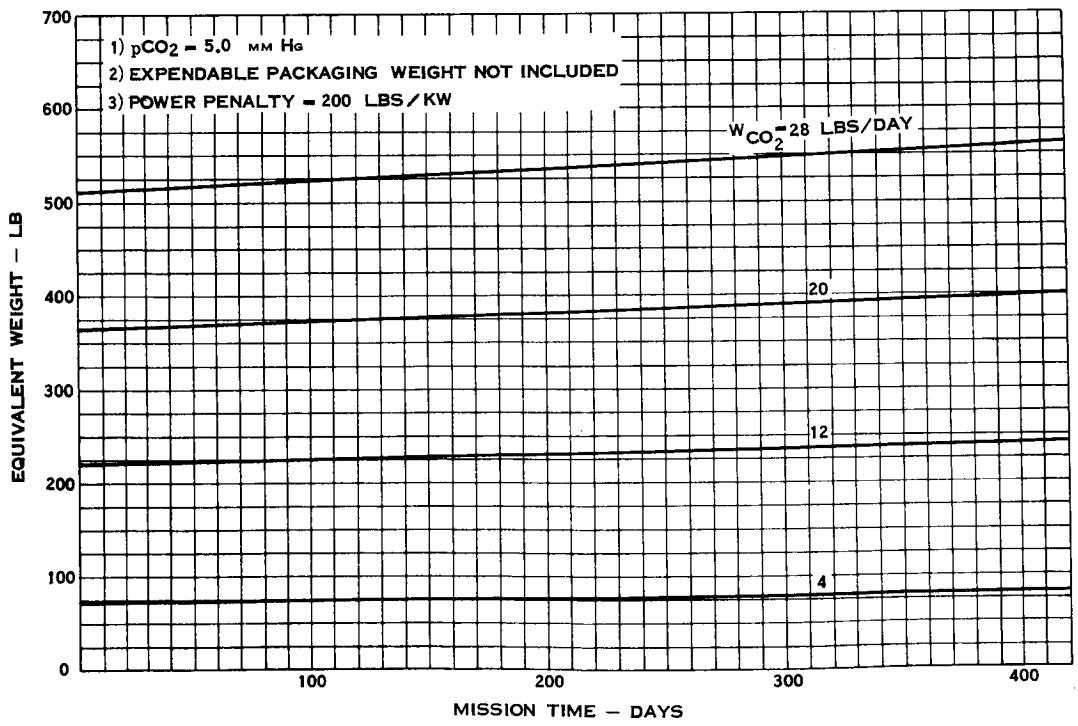


FIGURE 2–7

MEMBRANE DIFFUSION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

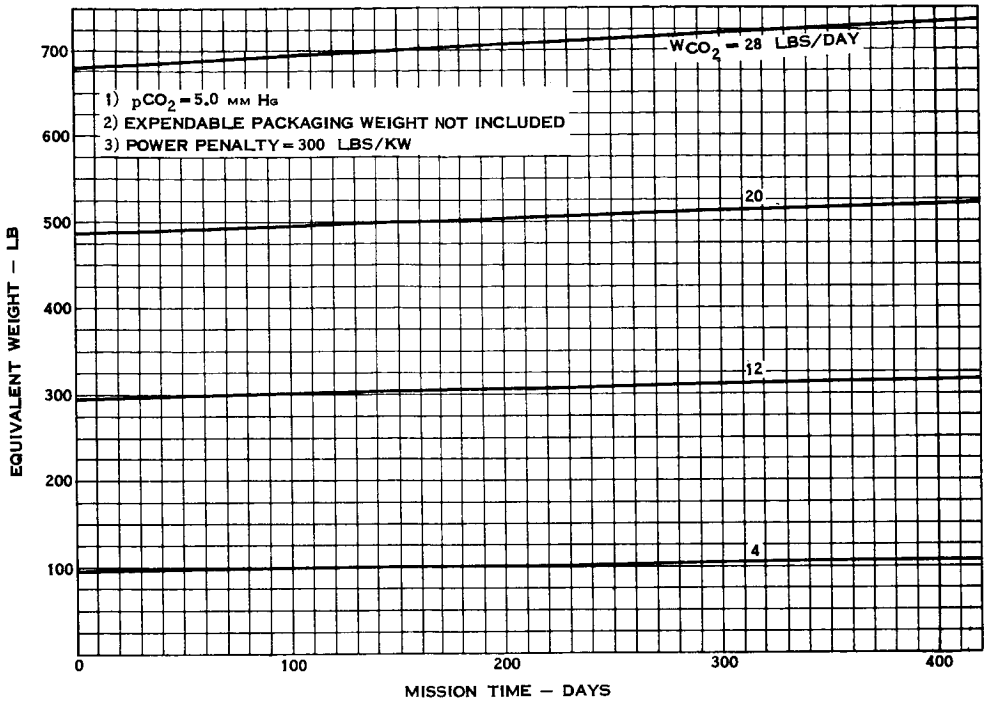


FIGURE 2–8

MEMBRANE DIFFUSION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

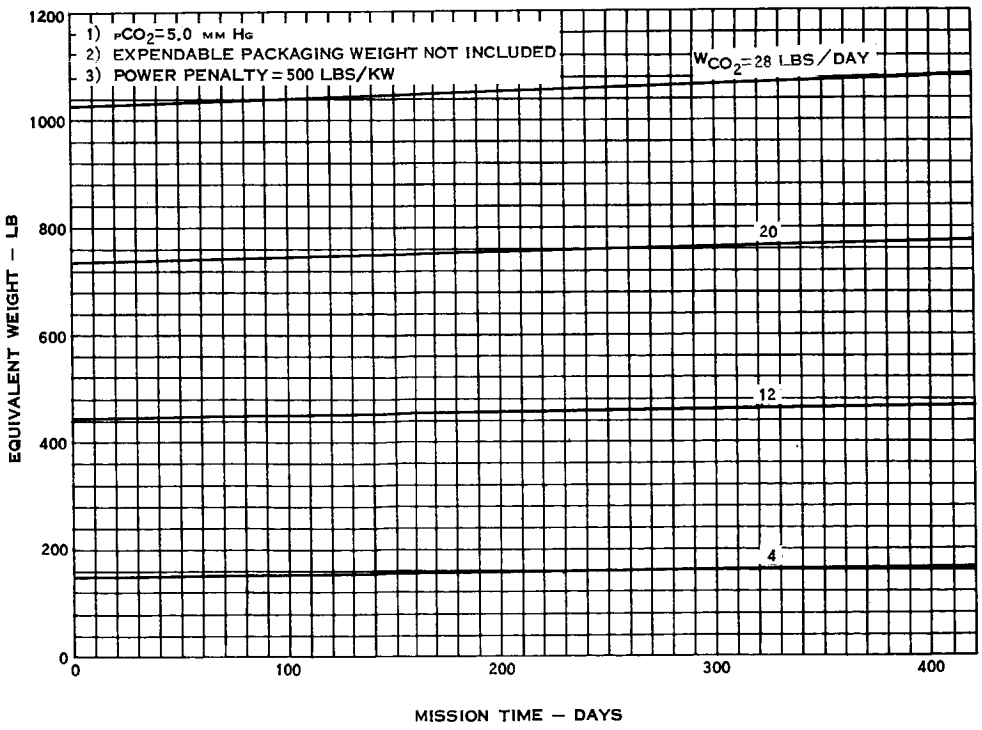


FIGURE 2–9

2.3.1 (Continued)

It is a somewhat attractive method of CO_2 removal in that the CO_2 may be withdrawn in a highly concentrated form; however, this particular system approach is relatively undeveloped at this time. Considerable theoretical analysis was performed to achieve an optimum system configuration. Primary data source for this analysis was previously in-house Hamilton Standard subsystem selection work in CO_2 removal.

2.3.2 System Description

The system considered in this analysis is presented schematically in Figure 2-10. The system includes many complex items, making reliable operation somewhat questionable. Inlet air from the cabin thermal control system at a temperature of 50°F is brought into the system through a silica gel or other desiccant bed where the water vapor in the process air is removed. Freezing out water vapor as well as the CO_2 is impractical due to the high heat of condensation of water. Eliminating water freeze-out reduces system operating pressure and compressor weight and power, since lower compressor temperatures can be utilized.

The process air is then compressed to provide a high pressure to operate the air motor. Prior to entering the motor, the stream temperature is decreased, in the regenerative heat exchanger, to just above the freezing point of CO_2. This cool high

MECHANICAL FREEZE OUT CO_2 REMOVAL

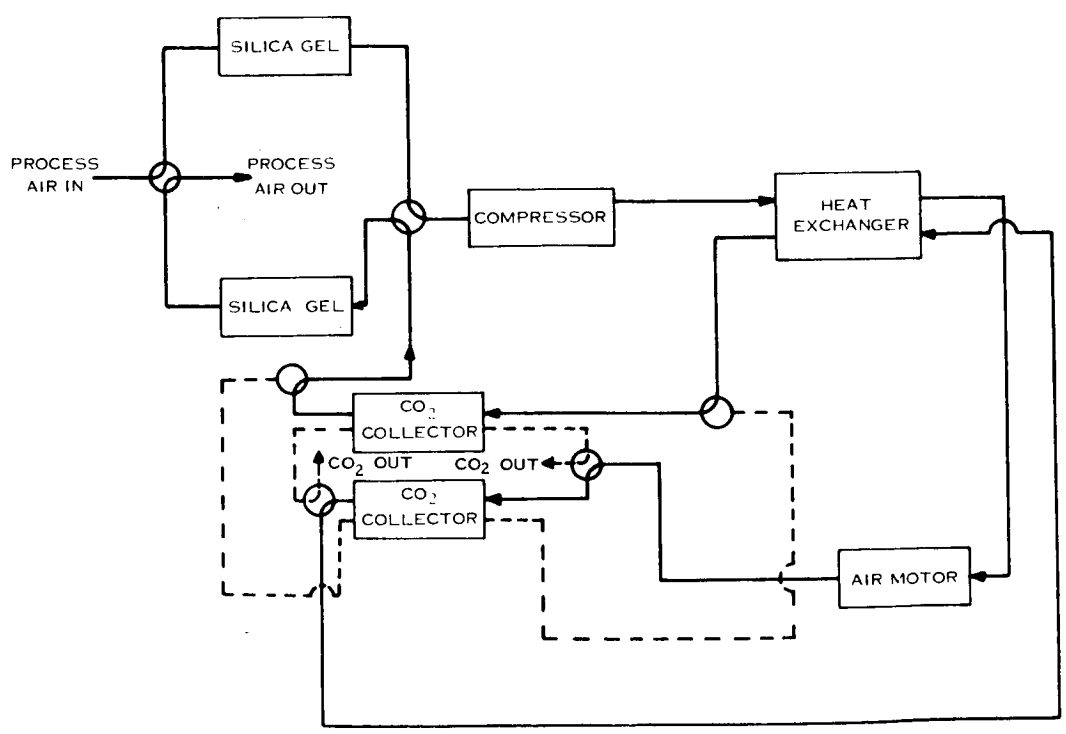


FIGURE 2-10

2.3.2 (Continued)

pressure air is expanded through the air motor, resulting in a drop in temperature and consequent freezing of the CO_2. The frozen CO_2 particles are filtered out in the CO_2 collector, and the CO_2 free process air is returned to the cabin through the regenerative heat exchanger and off line CO_2 collector and silica gel beds. In passing through the heat exchanger, the air absorbs heat from the hot compressor discharge air, which is then used to vaporize the CO_2 in the off line collector and to desorb the alternate silica gel canister.

The two CO_2 collection devices and two silica gel beds are alternated periodically to allow continuous system operation. Thus, in each case, while one is absorbing either water vapor or CO_2, the second is being desorbed to prepare it for future use. In this manner, indefinite system operation can be obtained, dependent only upon mechanical reliability.

The primary portion of system fixed weight for this process is attributed to the inlet compressor which raises process air pressure prior to expansion and freezing. This amounts to approximately 40% of the total system weight.

2.3.3 Results

Figure 2-11 presents the results of the analysis of mechanical feeeze-out system weight as a function of production rate or crew size and desired cabin concentration of carbon dioxide. Estimated fixed weight is presented alone as well as with estimates of total system expendable weight for a 420 day mission. Thus, the difference between an expendable weight curve at a particular concentration and the fixed weight curve allows approximation of system expendable requirements. Packaging penalties for the expendables are not included in this analysis due to the desire to allow flexibility in choice of the method of packaging of expendables. Thus, by presenting penalty of the expendables alone, more flexibility is allowed for future system integration work. Figure 2-12 illustrates the peak power requirements for this approach. A quick glance at this figure makes it obvious that power consumption is quite high in this system, making it unattractive for most presently conceived applications. To illustrate the overall picture of power, fixed weight and expendable weight, Figures 2-13 and 2-14 were prepared for 420 day missions. In these cases, power has been charged off with a weight equivalent to allow determination of total equivalent weight for any given crew size and CO_2 partial pressure. If 420 days does not remain as the ultimate mission length, expendables, consisting of O_2 and N_2 supplies for that lost with the CO_2 exhausted, can be charged at the approximate rate of .02 lbs per man day to arrive at a new figure.

Figures 2-15 through 2-18 illustrate the variance in system equivalent weight with mission time. In each case, four typical crew sizes are presented by the CO_2 production lines of 4, 12, 20, and 28 pounds per day. This is roughly equivalent

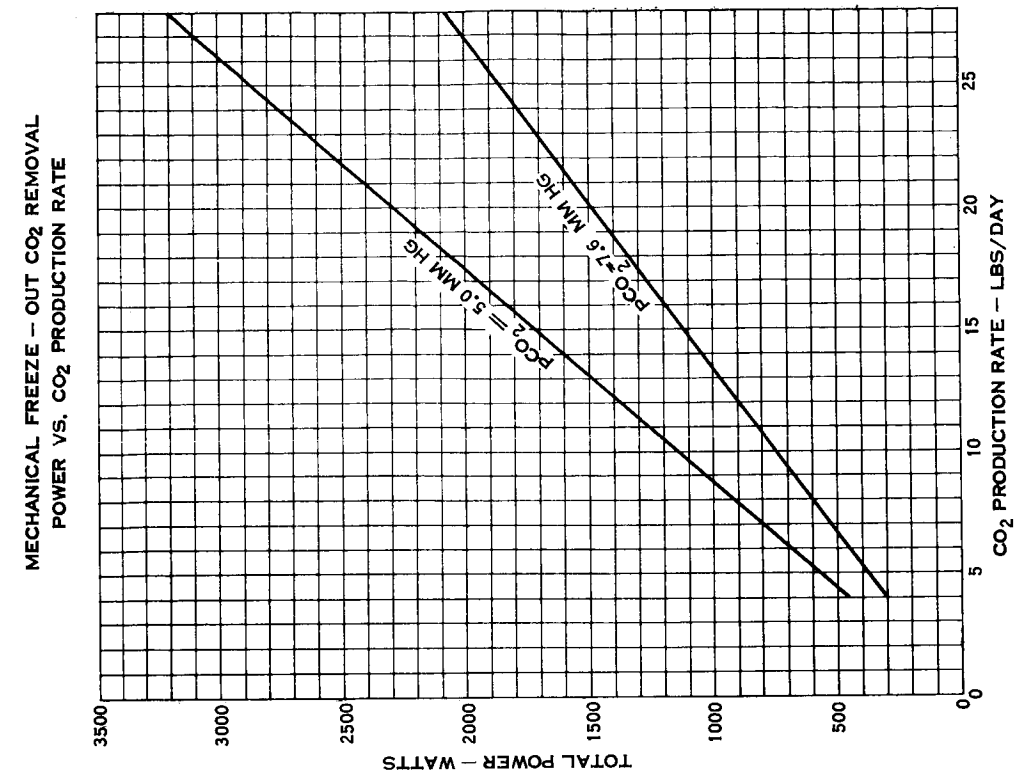


FIGURE 2 – 12

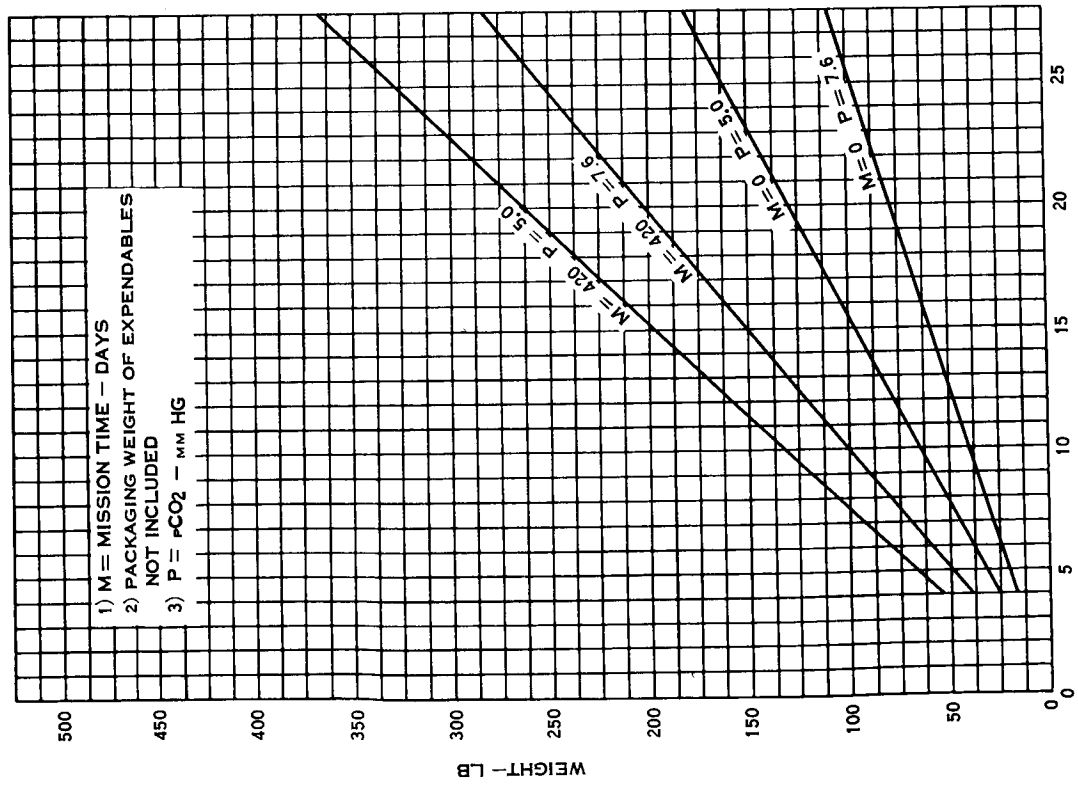


FIGURE 2–11

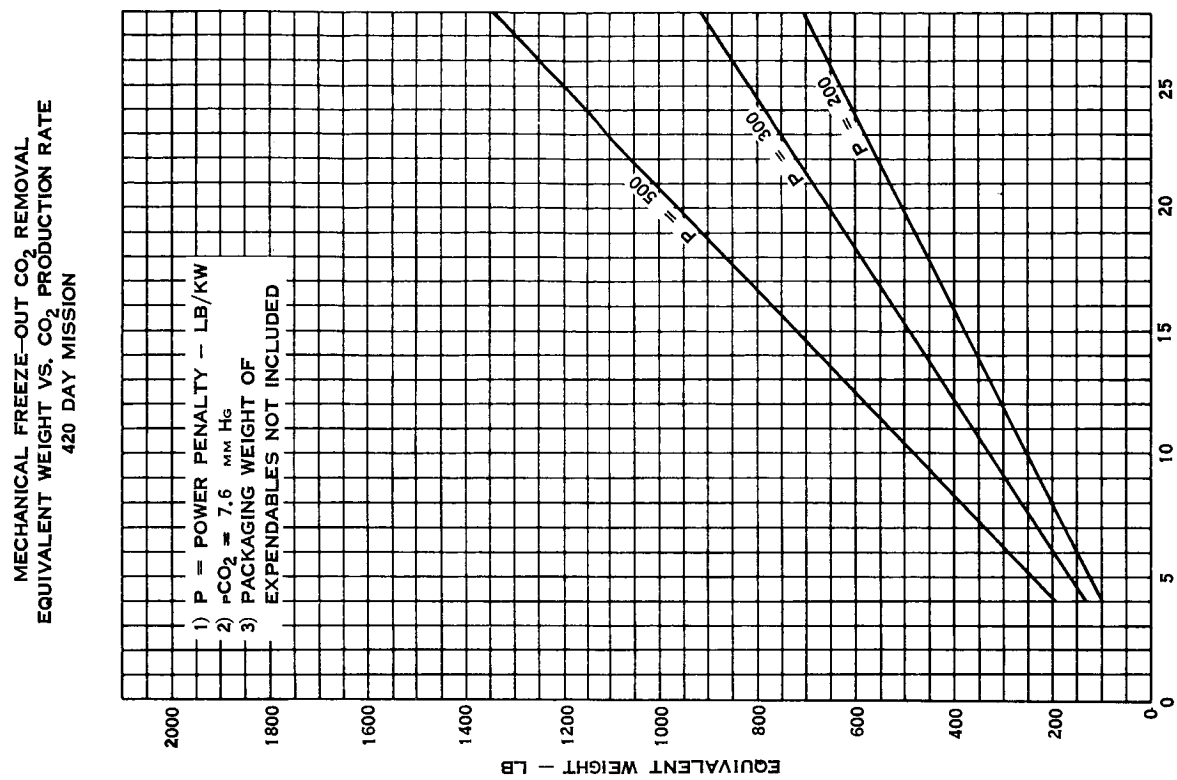


FIGURE 2–14

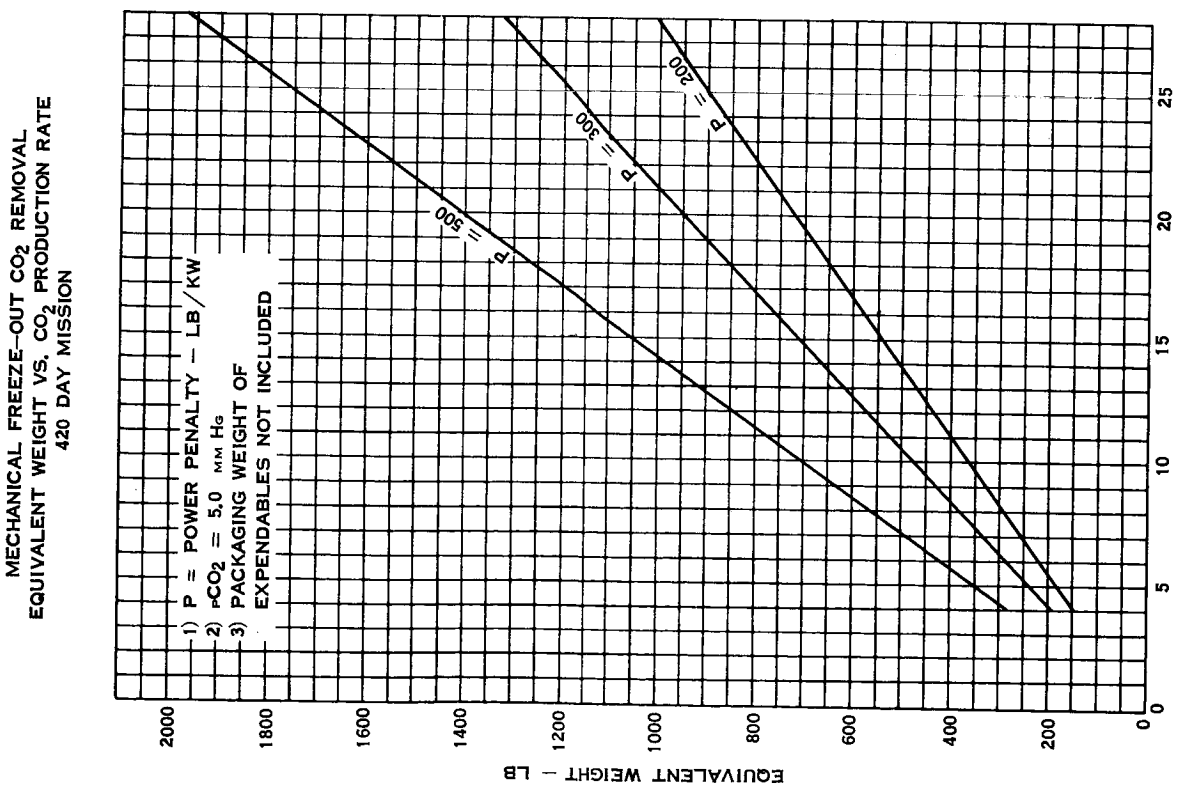


FIGURE 2–13

MECHANICAL FREEZEOUT CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

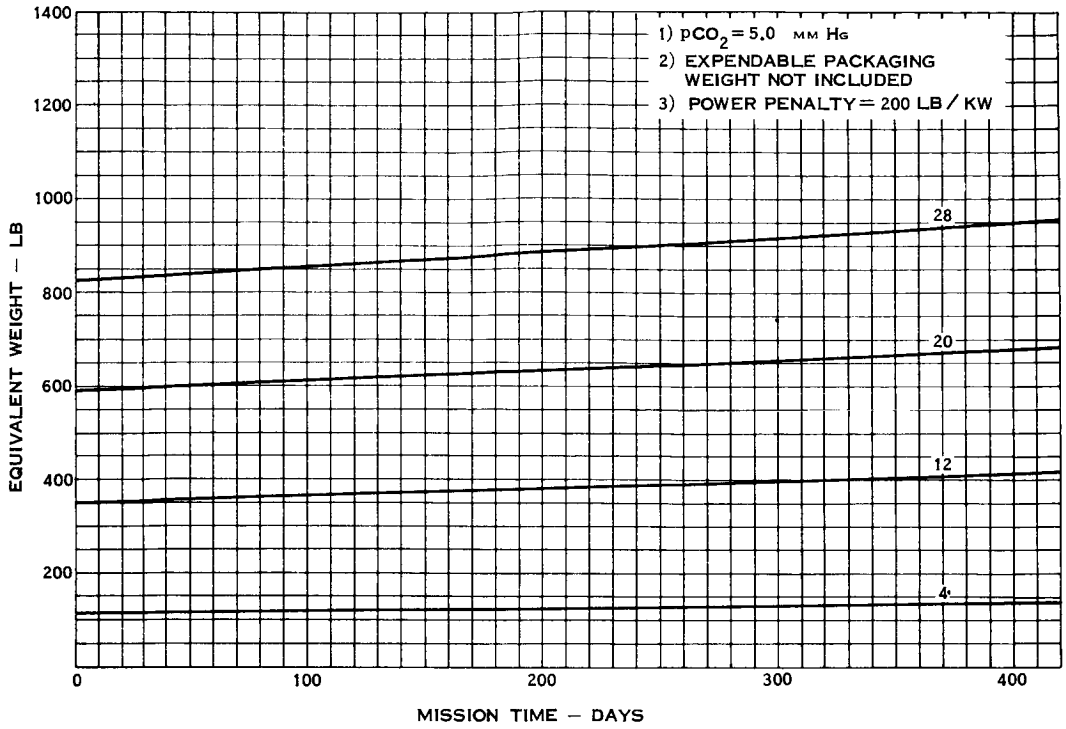


FIGURE 2–15

MECHANICAL FREEZEOUT CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

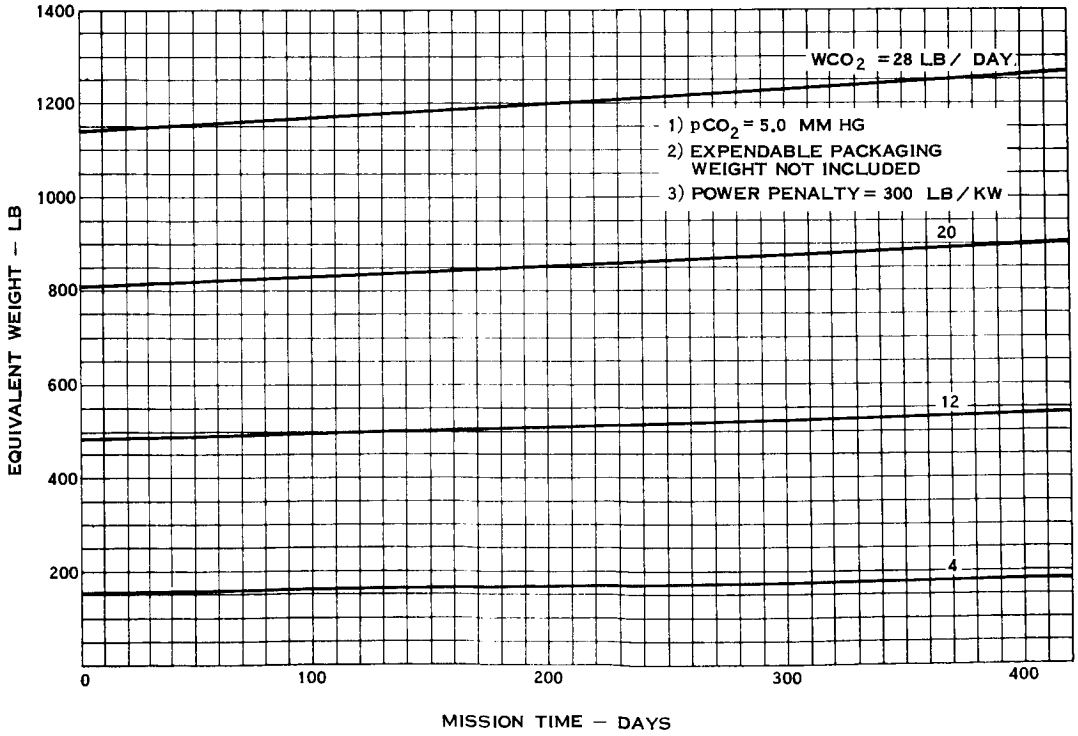


FIGURE 2–16

MECHANICAL FREEZEOUT CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

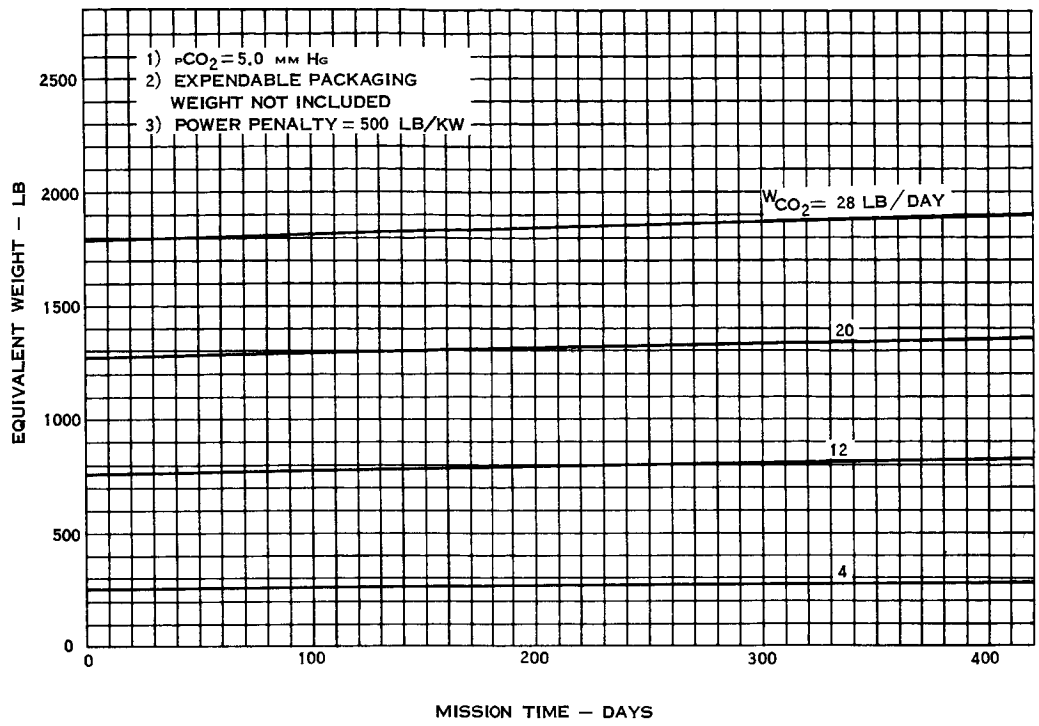


FIGURE 2–17

MECHANICAL FREEZEOUT CO_2 REMOVAL
WEIGHT VS MISSION TIME

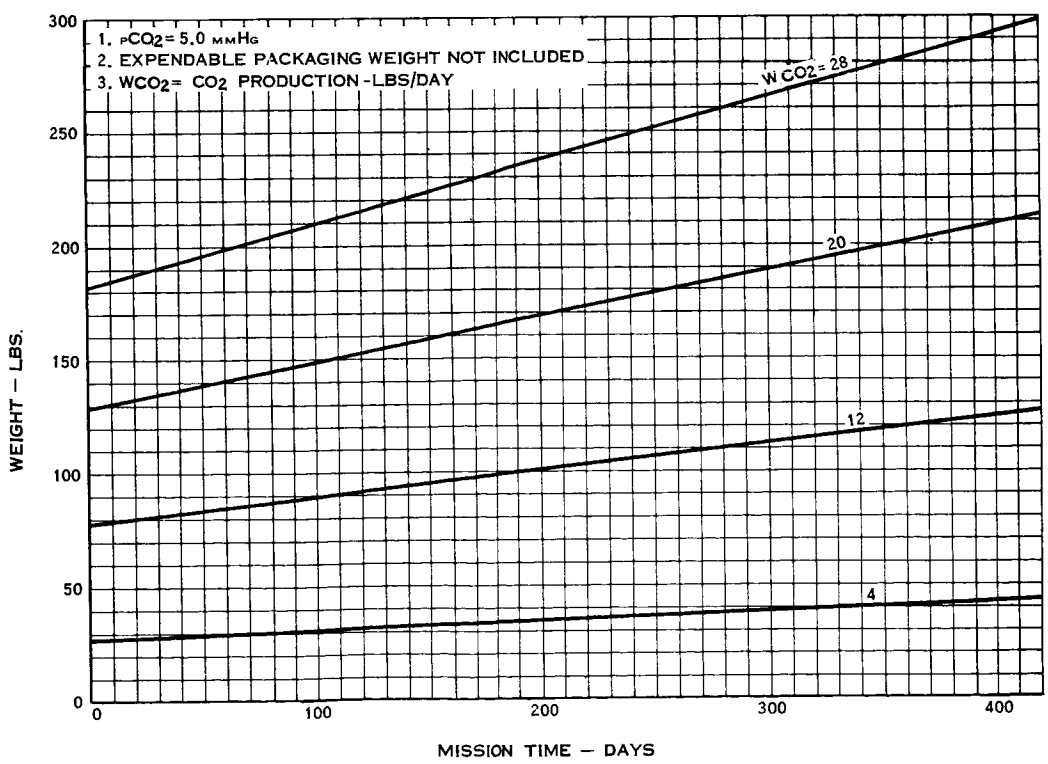


FIGURE 2–18

2.3.3 (Continued)

to a 2, 6, 9, or 12 man crew. Thus, for a given mission time and cost of power, the total equivalent weight can be determined from Figures 2-15 through 2-17 for power penalties of 200, 300, and 500 lbs per kilowatt, respectively. To allow determination of the subsystem weight penalty alone without the cost of power, Figure 2-18 is presented.

2.3.4 Conclusions

Mechanical freeze-out as a CO_2 removal method for the Mars vehicle is considered generally unattractive. The high power requirements of the system as well as large bulky equipment make it undesirable under present trade-off considerations of low weight and power. It will adapt itself to a CO_2 collection device better than other approaches being considered; however, this is not of sufficient merit to warrant its inclusion in further trade-off studies. The complex equipment required and compressor and expander development status lead to a poor rating of this approach at this time.

2.4 CO_2 Removal By Cryogenic Freeze-out

2.4.1 Introduction and Data Source

Cryogenic freeze-out is the other method of CO_2 freeze-out analyzed during the study. It becomes a desirable investigation for the Mars Excursion Module considering the possibility of cryogenic storage of some type on the vehicle. With this source of low temperature available, it is desirable to analyze applicability of its use in the CO_2 removal system. The primary source of data for this approach has been previous in-house work at Hamilton Standard and earlier state-of-the-art CO_2 removal subsystem selection work. The system described is presented primarily from a theoretical analysis due to limited development testing to date.

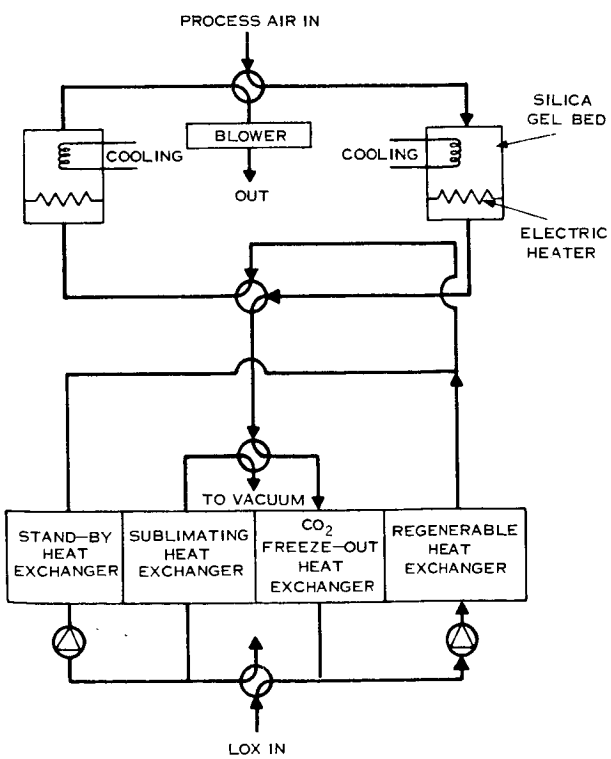
2.4.2 System Description

Initial considerations of cryogenic freeze-out investigated freeze-out of both the CO_2 and moisture, with subsequent sublimation to space. This proves unattractive for Mars Mission usage, however, due to the water lost with the CO_2 and the excessive amount of cryogenic fluid required. To remedy this, a system was investigated where the water was recovered by passing warm air through the ice side of the heat exchanger; however, this approach provides a large equivalent weight system due to the larger heat capacity of the moisture relative to that of the cryogenic fluid, i.e., the loss in cooling capacity of the moisture as vented to vacuum requires a relatively large increase in cryogenic flow. The most attractive system investigated utilizes silica gel or a similar desiccant for moisture

2.4.2 (Continued)

adsorption with a heated purge return to the cabin and cryogenic freeze-out for CO_2 removal only.

Figure 2-19 presents the system schematic analyzed in the study. Process air from the main thermal control system enters at a temperature of 50°F and proceeds to a moisture adsorption canister, where the moisture content is reduced to a few parts per million. The dry air then proceeds to a regenerative heat exchanger, where the temperature is reduced, causing the CO_2 to freeze-out on heat transfer surfaces. The process air continues from the heat exchanger and is mixed with the introduced cryogenic fluid, thus producing the minimum air temperature throughout the system. This flow then passes through the cold side of the regenerative heat exchanger, where a portion of the heat sink derived during cooling is regeneratively recovered. Cyclic operation is employed whereby that CO_2 frozen out in the heat exchanger is vented to the vacuum of space during the following half cycle; therefore, heat adsorbed during vaporization contributes to cooling of the air passing through the hot side of the exchanger. Upon leaving the heat exchanger, the air passes to the alternate desiccant bed, where it is heated by electrical heaters, purging the bed as it passes through it. The process air with the moisture from the desorbed bed then returns to the main system. Periodic cycling of the silica gel beds and the freeze-out heat exchanger maintains continuous system operation.



CRYOGENIC FREEZE-OUT CO_2 REMOVAL

FIGURE 2-19

2.4.2 (Continued)

Primary weight penalty associated with this system approach is in the silica gel canisters and the freeze-out heat exchangers. Weight of these items alone makes up about 70% of the total system weight. The overall system was found to be optimum for minimum weight when the cryogenic fluid flow equals that required for metabolic usage.

2.4.3 Results

This section introduces the results of the parametric analysis of cryogenic freeze-out systems. Figure 2-20 presents fixed weight variations as a function of crew size (shown by production rate) and cabin concentration of CO_2. This figure also includes total system weight for a 420 day mission. The difference between the two curves then represents the weight of expendables. Figure 2-21 presents the peak system input power requirements as a function of CO_2 partial pressure and carbon dioxide production rate. Both of these preceding figures allow sizing of a system for any change from the design point six man crew size or a change in the expected carbon dioxide production per man day. Figures 2-22 and 2-23 present the summation of the preceding two curves, illustrating equivalent weight for a 420 day mission as a function of crew size. Power has been illustrated at the penalties defined in the system specification. If the desire is to optimize for a mission length other than 420 days, it is necessary only to determine the mission length desired and calculate expendables from an estimated rate of .05 lbs per man day. These expendables represent the O_2 and N_2 lost to space during sublimation. In all of these cases, the packaging weight of expendables has not been included, since, by omitting it, more flexibility in use of results is allowed.

Figures 2-24 through 2-27 allow determination of equivalent weight with variation in mission duration. Figure 2-24 illustrates this weight as a combination of fixed weight plus expendable weight only for typical crew sizes of 2, 6, 9, and 12 men as illustrated by CO_2 production rate curves of 4, 12, 20, and 28 lbs per day. Figures 2-25 through 2-27 add the penalty for power to the preceding figure to provide a total equivalent weight. The slopes of these curves illustrate the expendable rate.

2.4.4 Conclusions

The cryogenic freeze-out approach appears quite attractive at the initial evaluation. However, it is limited by several factors which must be established. First, its best use is with subcritical storage, since this provides the maximum heat sink per pound of fluid; and, as such, the storage should be from a source with the flow rate equivalent to or greater than the crew metabolic requirements. Thus, it is somewhat limited to an overall system not utilizing oxygen reclamation from CO_2. This is also verified when the method of CO_2 removal from the system

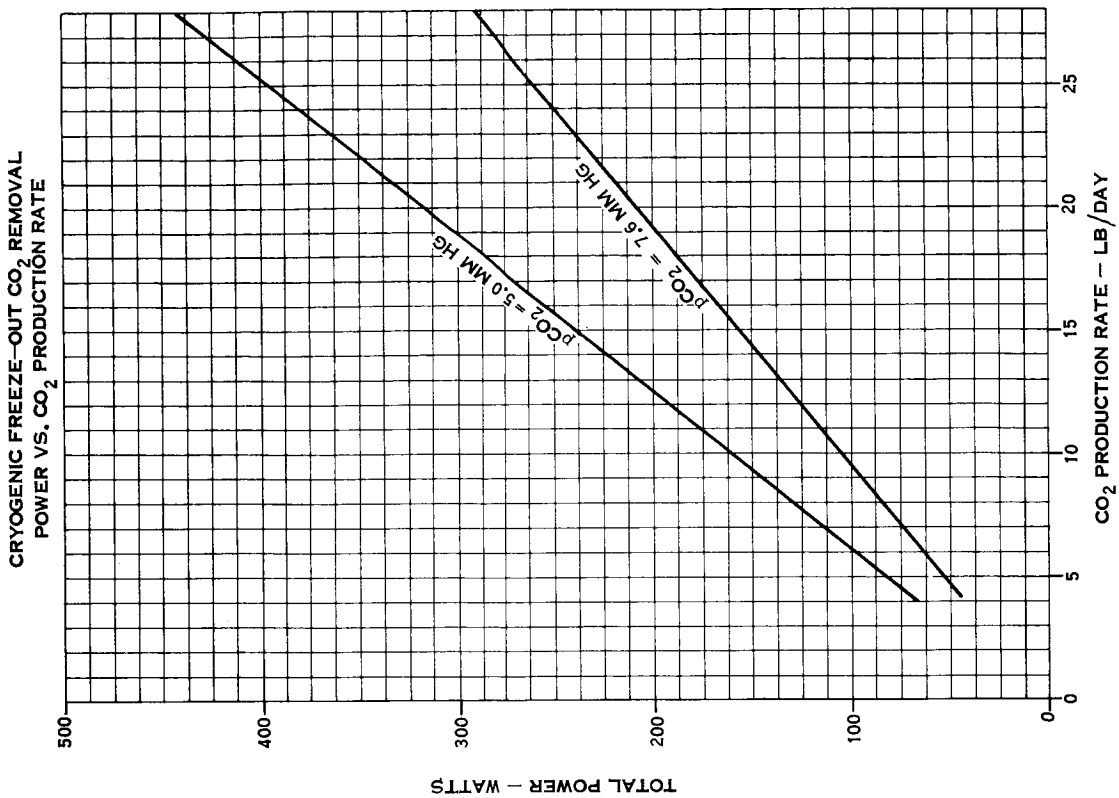


FIGURE 2–21

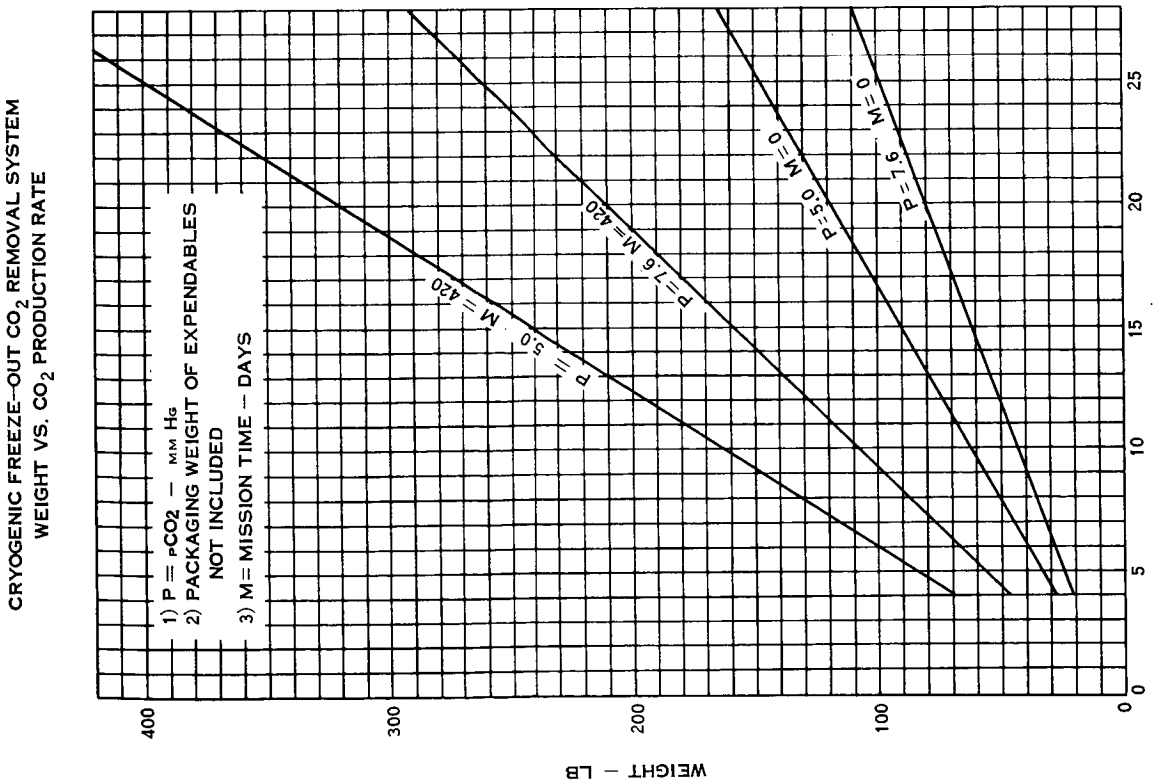


FIGURE 2–20

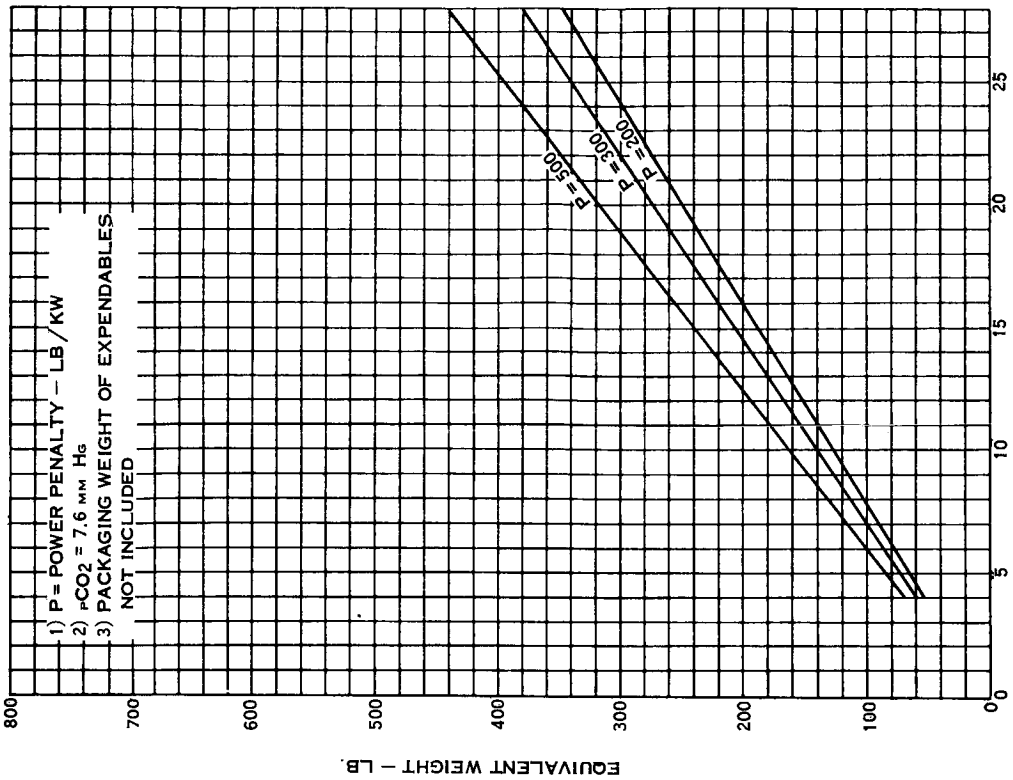


FIGURE 2-23

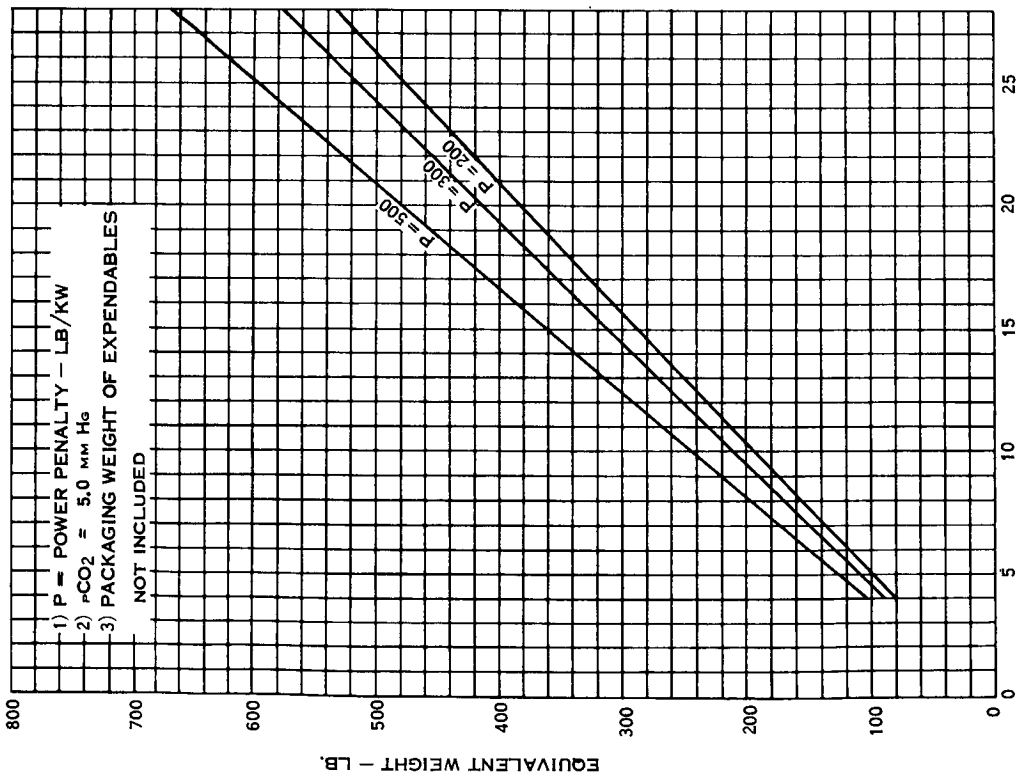


FIGURE 2-22

CRYOGENIC FREEZE CO_2 REMOVAL SYSTEM
WEIGHT VS MISSION TIME

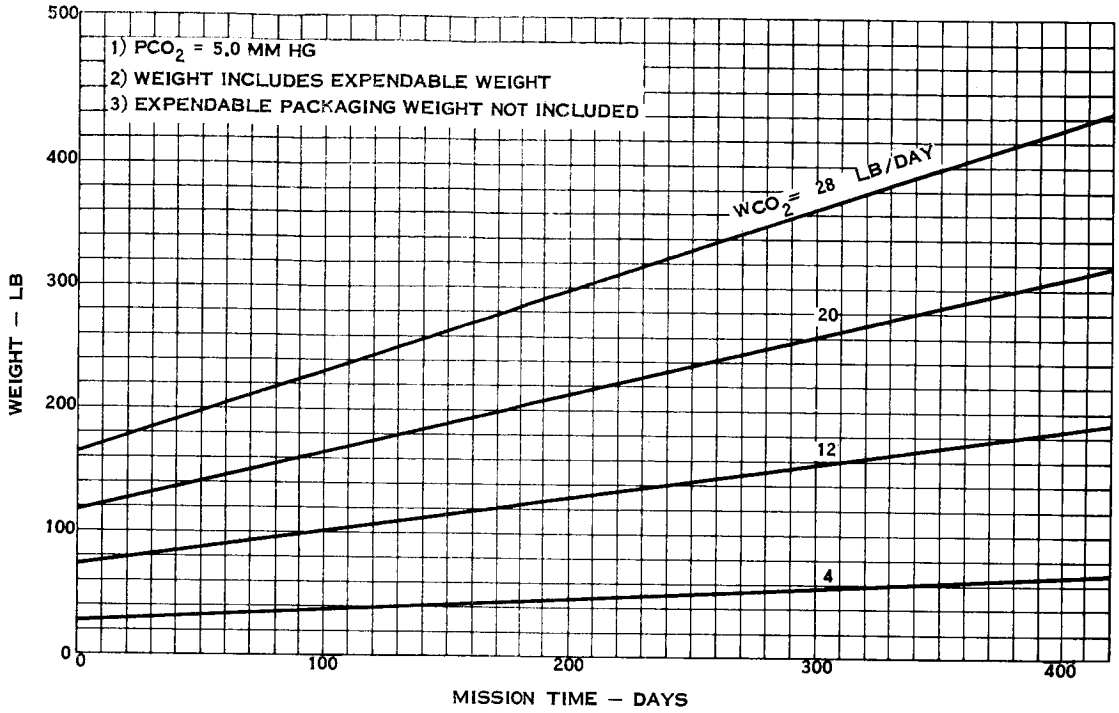


FIGURE 2–24

CRYOGENIC FREEZE–OUT CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

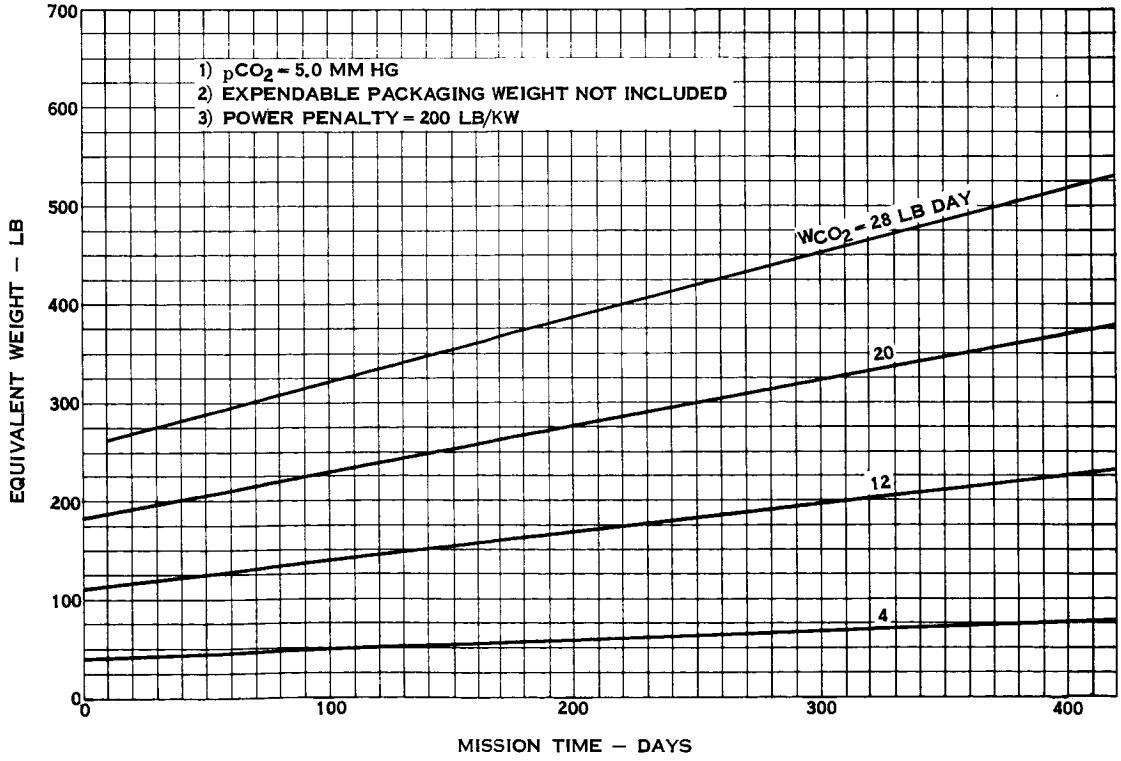


FIGURE 2–25

CRYOGENIC FREEZE-OUT CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

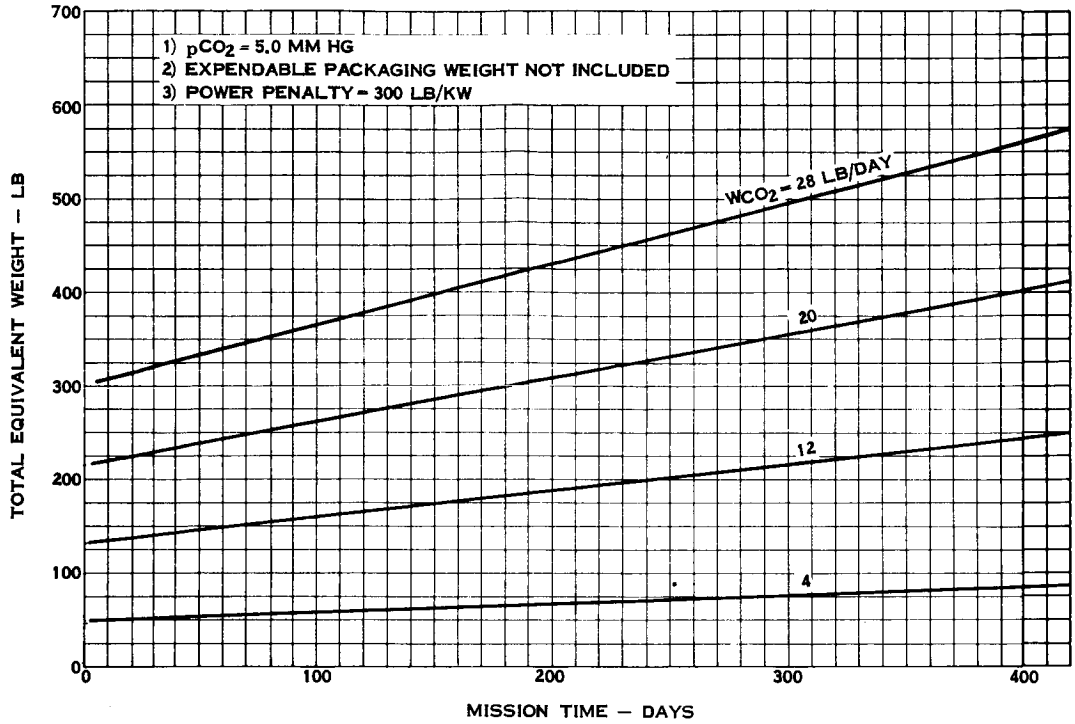


FIGURE 2–26

CRYOGENIC FREEZE-OUT CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

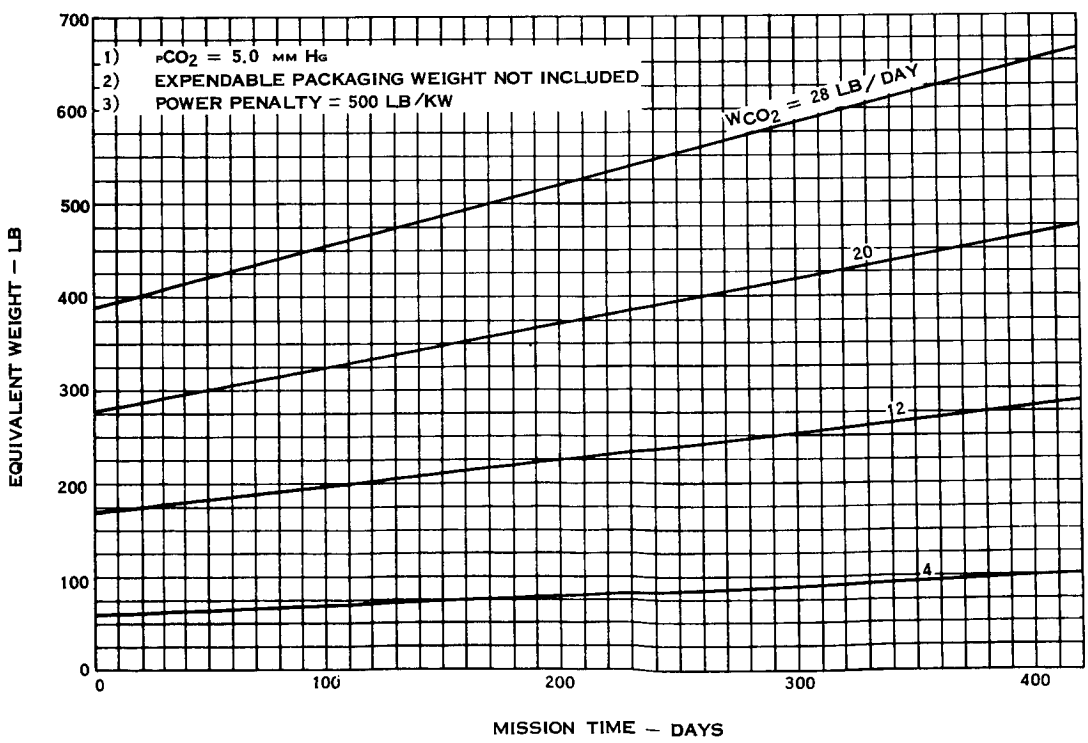


FIGURE 2–27

2.4.4 (Continued)

is investigated. Adapting of this system to a CO_2 collection device presents a problem, since the system as presented here desorbs the CO_2 to space vacuum. The weight and power penalties are quite attractive for this system and make it seem worthy of perhaps more development effort than that invested in it to date. Operation is independent of gravity, and the major power requirement for the entire system is that utilized for recovery of the moisture from the silica gel beds. Development status of the cryogenic heat exchanger is somewhat poor; thus, for accurate final evaluation of this system, considerably more test data should be produced on the CO_2 freeze-out heat exchanger.

2.5 CO_2 Removal With Regenerable Solid Adsorbents

2.5.1 Introduction and Data Source

The regenerable solid adsorption CO_2 removal system study for this application is based upon Hamilton Standard's extensive experience in design of these systems. Operating prototypes have been in existence since 1961, with breadboard equipment preceding that by some time; thus, data availability is the result of this test program over the years. The system itself has had many variations throughout industry; however, the basic intent of removal of the CO_2 by adsorption, and desorption by exposure to space vacuum or by utilization of thermal energy, is the same. Material selection for CO_2 adsorption varies from firm to firm, but not the principle.

2.5.2 System Description

The system is presented schematically in Figure 2-28. Process air from the thermal control system in the vehicle enters the CO_2 removal system at a temperature of 50°F. The flow is routed through the moisture adsorption canister, where its moisture content is reduced to a few parts per million by silica gel or another suitable desiccant. The moisture adsorption canister contains a coolant coil imbedded in the material to allow removal of the heat of moisture adsorption by a circulating coolant. By counter-acting this heat of moisture adsorption, the air stream temperature is reduced to provide a lower inlet temperature to the CO_2 adsorption canister. This procedure offers higher CO_2 removal performance by the zeolite material. The heat absorbed by the circulating transport fluid is eventually rejected in the thermal control system.

The CO_2 adsorbent is a zeolite material of the alumino-silicate family with open pores in the molecular structure. The zeolite exhibits a preferential affinity for moisture (to the exclusion of CO_2); thus, the requirement for a moisture adsorption canister upstream of the zeolite bed. After giving up its CO_2 to the zeolite, the process air passes through a heat exchanger, where its temperature level is

2.5.2 (Continued)

increased to the extent of the temperature available in the circulating heat transport fluid. The system circulating fan is also incorporated at this point to allow the fan heat to contribute to temperature rise in the process air.

Finally, the air stream passes through the off-line silica gel bed, where its temperature is increased further by electrical heaters to a level sufficient to purge the moisture from the silica gel beds. The CO_2 free air stream with the purged moisture then returns to the main system.

The system is provided with continuous operation by having dual sets of silica gel and zeolite canisters. In each case, one canister is adsorbing while the other is being desorbed (the silica gel by heat addition and the zeolite by exposure to vacuum). Zeolite may also be regenerated by heat addition; however, since this initial analysis is on the basis of no CO_2 collection, vacuum is the most economical method. Since the CO_2 is to be collected for later use in a CO_2 reduction system, an analysis was performed to determine an optimum transfer method

SOLID–ADSORPTION CO_2 REMOVAL

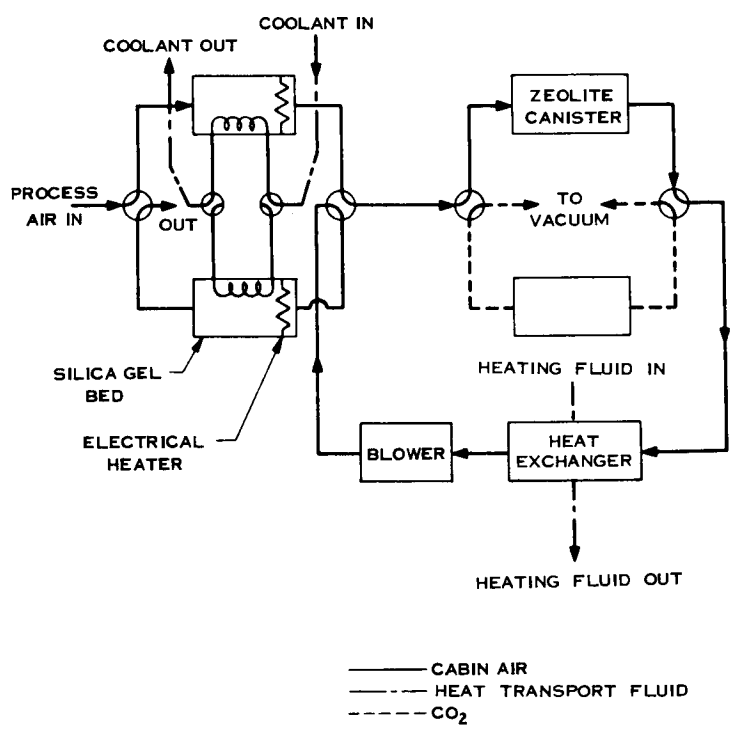


FIGURE 2–28

2.5.2 (Continued)

(whether by pumping from vacuum desorption or providing thermal desorption of the zeolite with a less stringent pumping power requirement). The primary weight associated with the CO_2 removal system is that of the moisture, the CO_2 adsorption canister and the included chemicals. This amounts to better than 50% of the total system weight, with the rest of the weight distributed between the other components.

2.5.3 Results

This section provides the results of the system comparative analysis. Figure 2-29 presents the fixed weight of the system as it varies with CO_2 production rate (crew size) and desired cabin CO_2 concentration. To allow determination of the overall fixed weight associated with this system, the weight with expendables for 420 days is also illustrated as a function of the CO_2 production rate. It must be pointed out here that the expendable weight does not include the packaging associated with these expendables to allow more flexibility of data usage. Figure 2-30 illustrates the peak power consumption of the system as a function of the production rate. This power is peak power for the system, and as such, must be considered somewhat differently than normal power usage. The electrical heaters in the silica gel canisters are the prime power consumer of the system. However, they are not in continuous usage, but rather are turned on only long enough to sufficiently heat the bed for purging while the rest of the half cycle is devoted to carrying off the moisture and allowing the bed to cool down to a sufficiently low temperature for adsorption of the moisture on the next half cycle. Thus, the average power requirements are considerably less than those shown. To allow consideration of a weight plus power penalty as a function of crew size changes, Figures 2-31 and 2-32 have been prepared. These figures illustrate the equivalent system weight as a function of crew size for a 420 day mission. This weight then includes fixed weight, a weight penalty for power, plus the expendable weight (O_2 and N_2 ullage) for 420 days. For consideration of a mission duration other than 420 days, one can simply adjust expendable weight at the rate of .067 lbs per man day to the period in question.

Figures 2-33 through 2-36 allow rapid determination of weight change as a function of mission duration. These figures illustrate initial launch weight as a function of mission duration. Figure 2-33 illustrates this weight as a total of fixed weight and expendable weight only for typical average crew sizes of 2, 6, 9, and 12 men as illustrated by the CO_2 production rate curves of 4, 12, 20 and 28 lbs per day. To provide an illustration of the effect of power on this total equivalent weight, Figures 2-34, 2-35 and 2-36 have been prepared which add the cost of power in pounds to the fixed weight plus expendables curve in Figure 2-33, at power penalties of 200, 300, and 500 lb/KW, respectively.

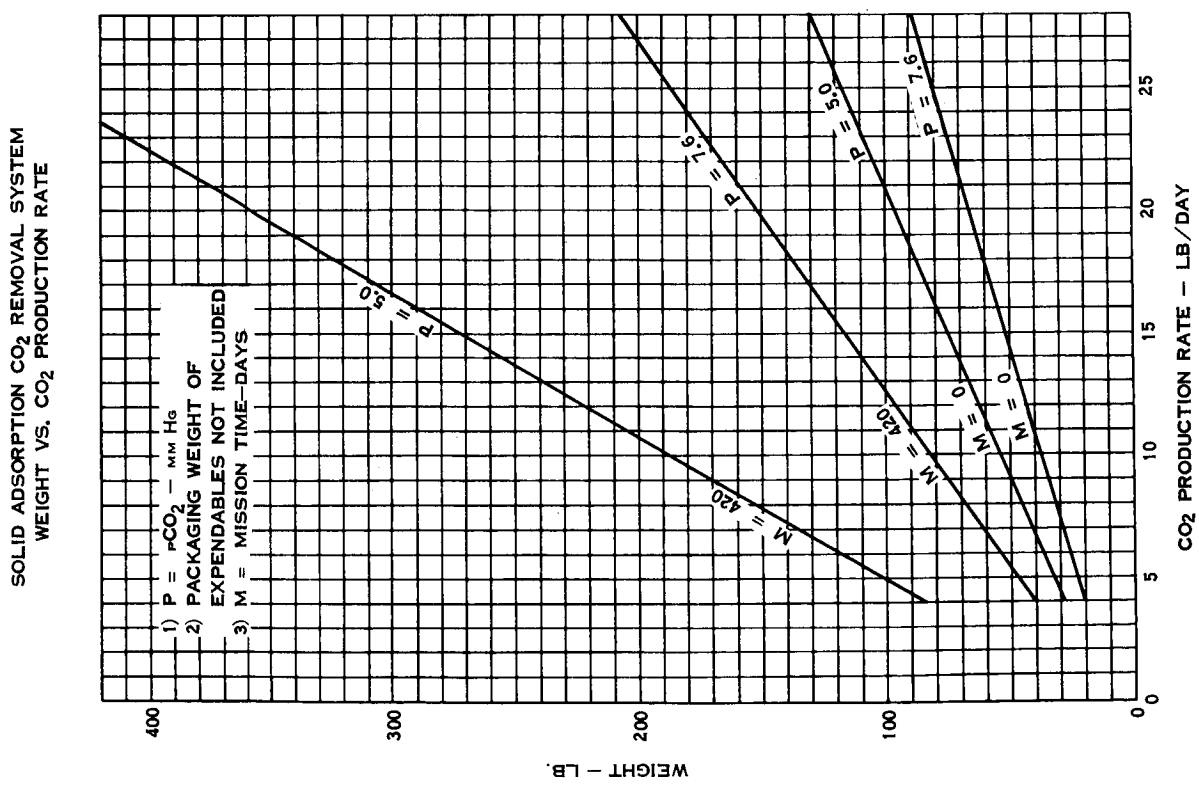


FIGURE 2–29

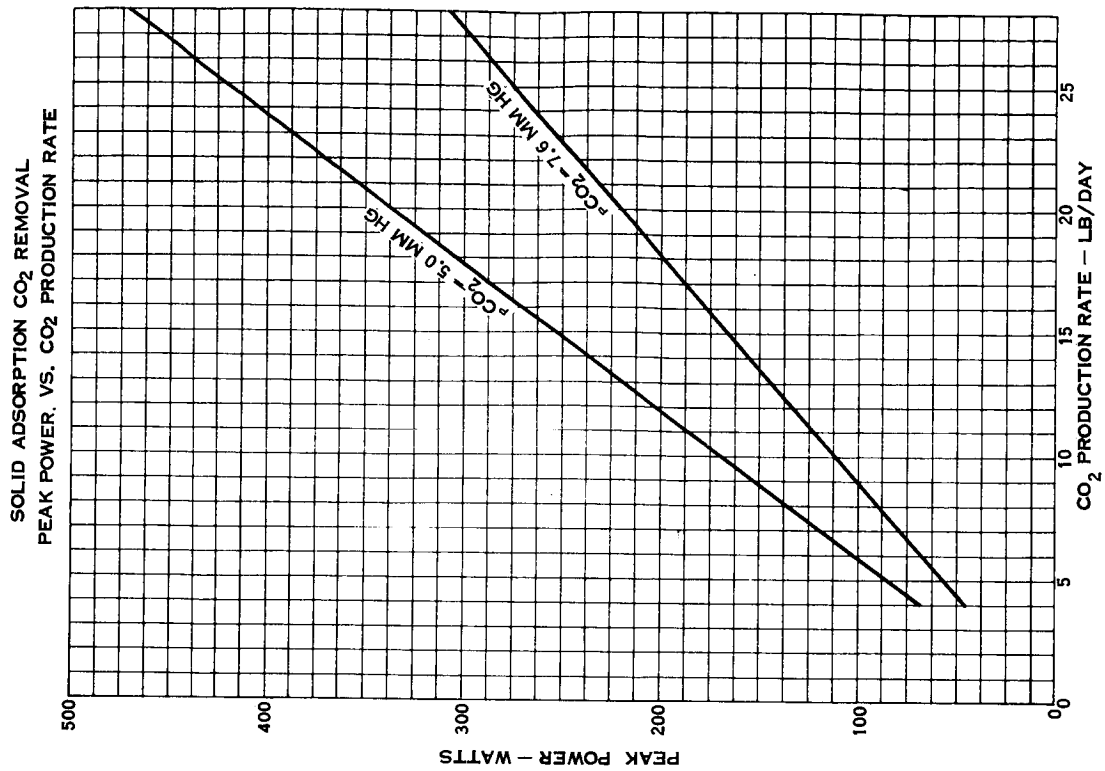


FIGURE 2–30

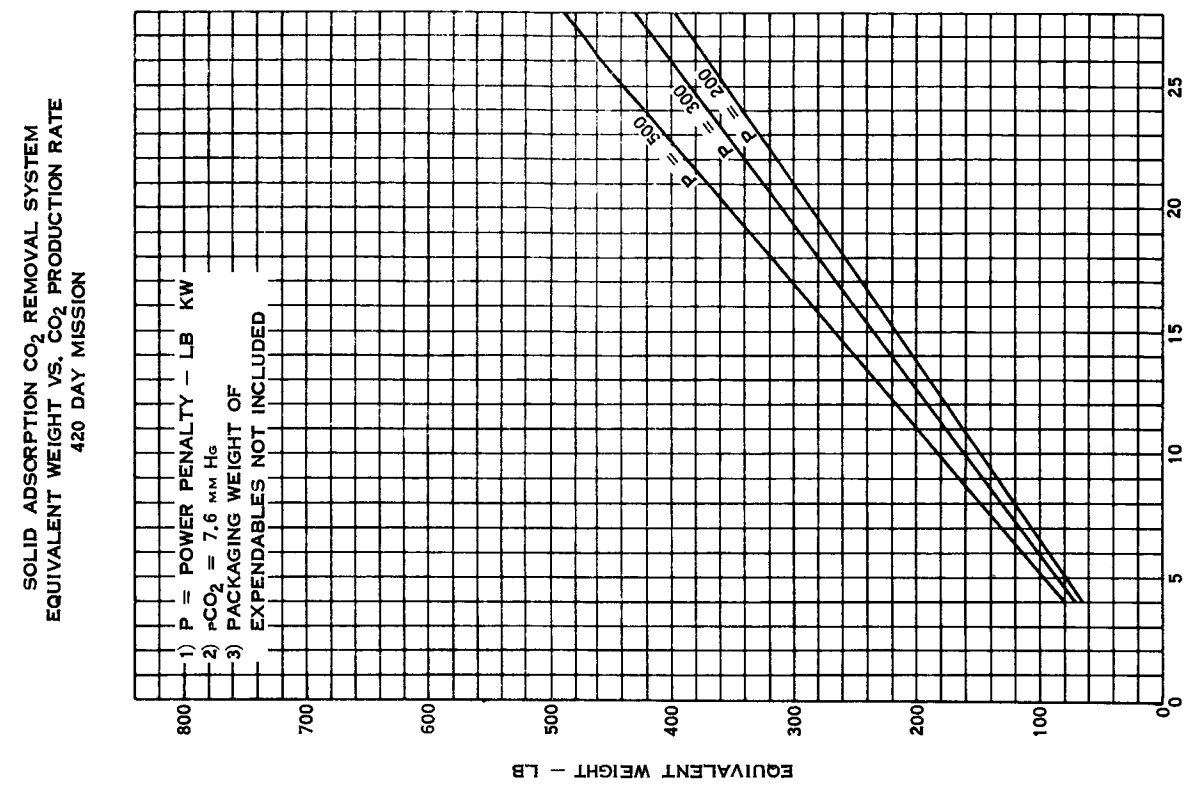


FIGURE 2-31

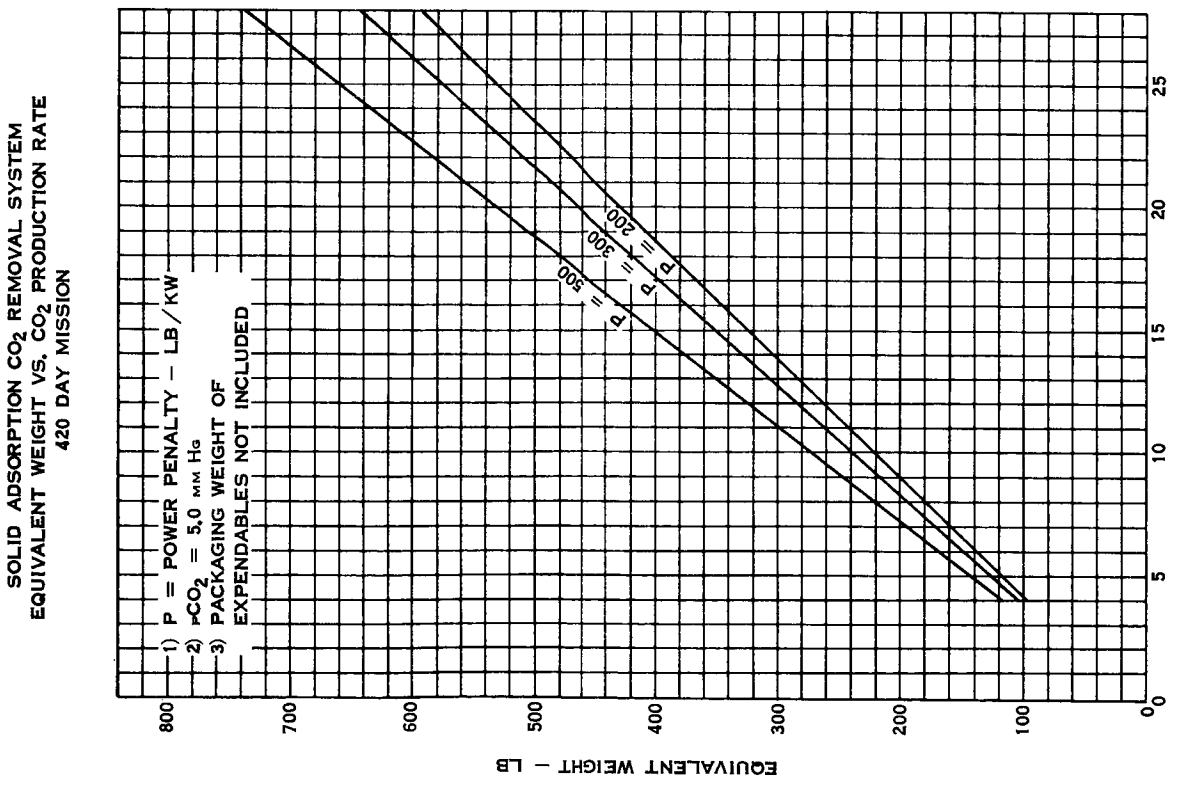


FIGURE 2-32

SOLID ADSORPTION CO_2 REMOVAL SYSTEM
WEIGHT VS. MISSION DURATION

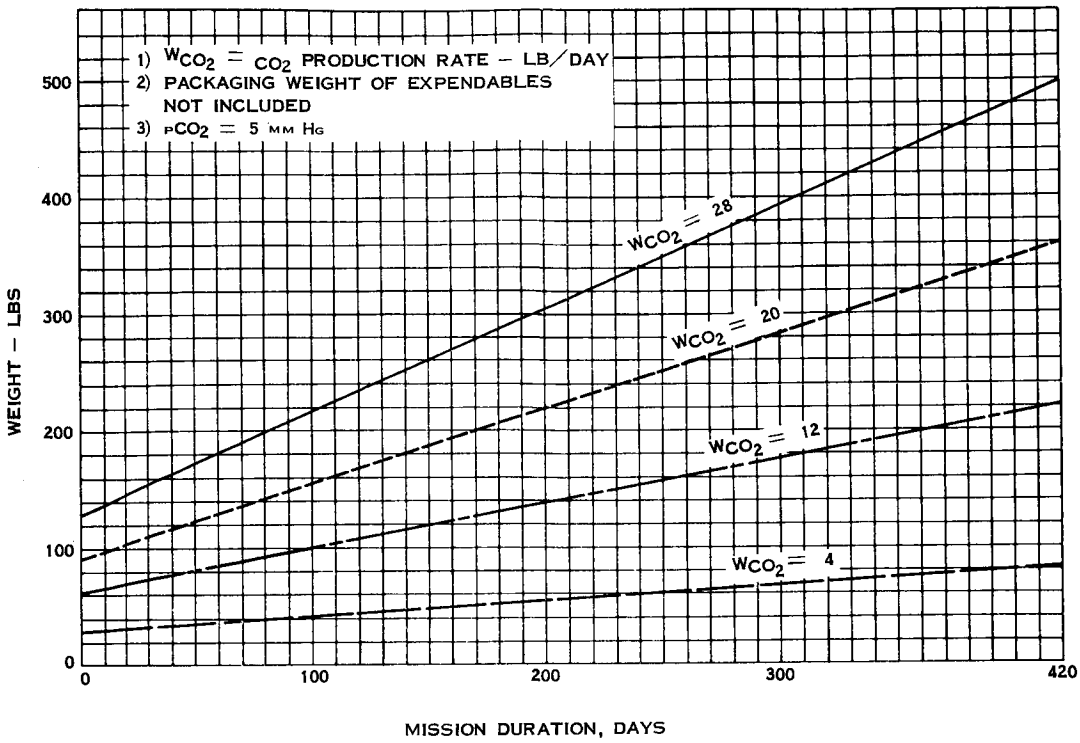


FIGURE 2–33

SOLID ADSORPTION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

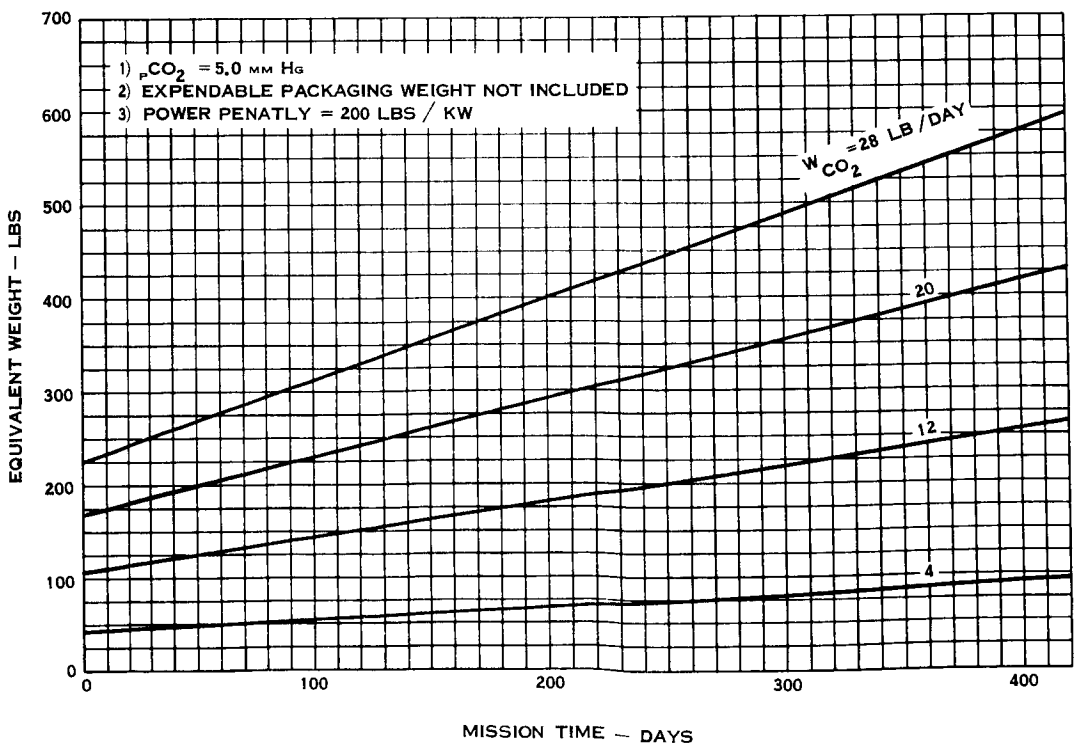


FIGURE 2–34

SOLID ADSORPTION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

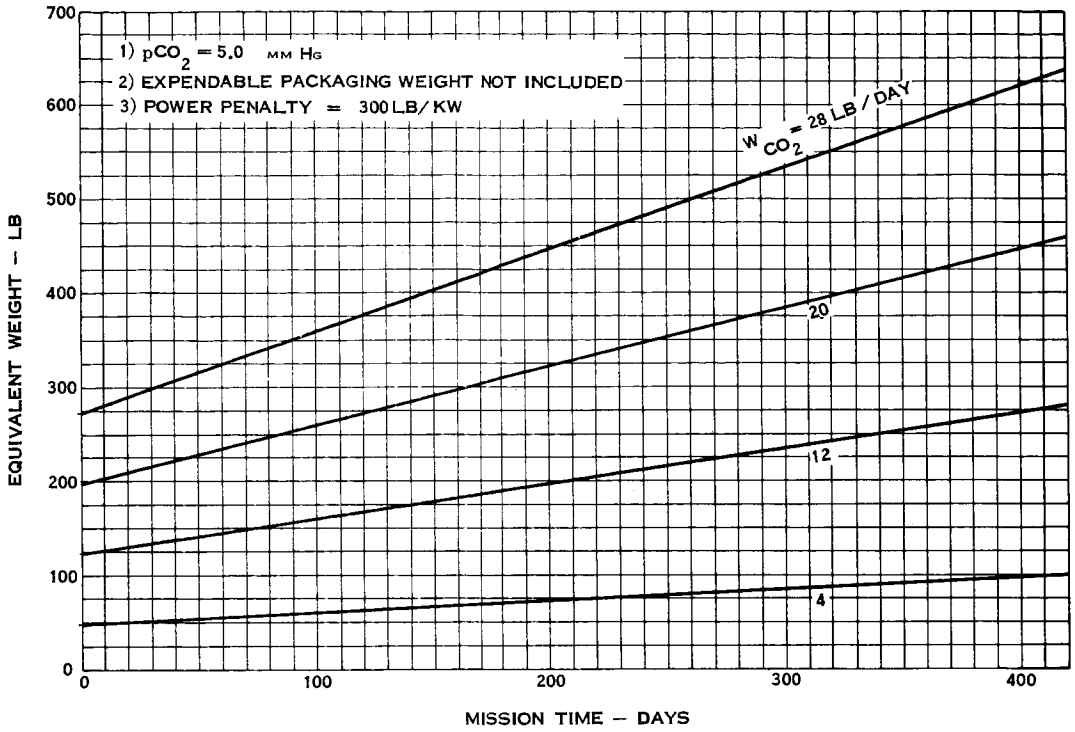


FIGURE 2–35

SOLID ADSORPTION CO_2 REMOVAL SYSTEM
EQUIVALENT WEIGHT VS MISSION TIME

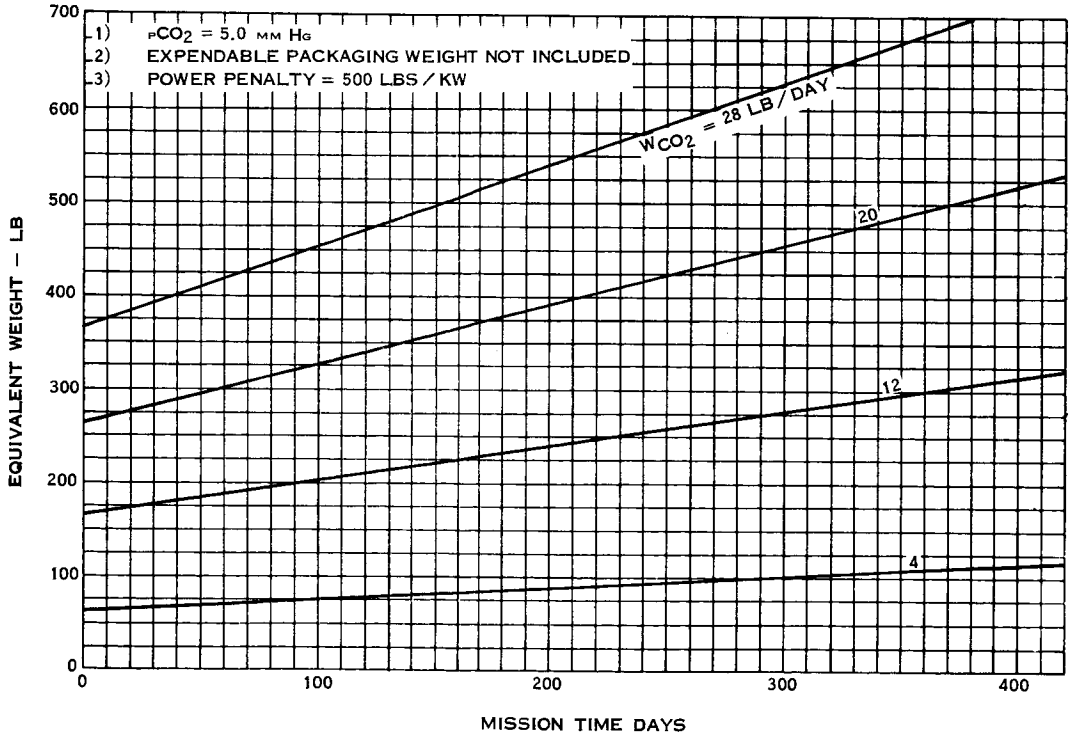


FIGURE 2–36

2.5.4 Conclusions

The trade-off presented here is a consideration of this system as used for CO_2 removal only, without regard to the rest of the life support system. Therefore, a possibility of system improvement from an equivalent penalty basis exists when total life support system integration is considered and waste heat availability is determined. The system is dependent upon inlet dew point for performance efficiency with improved operation at lower inlet points; thus, the process air delivery point from the main system is a major consideration for final system integration. Solid adsorption as a process is well advanced in state-of-the-art when compared with other methods of CO_2 removal.

Although Hamilton Standard had sufficient in-house data to analyze the system approach for this study, there are other competent organizations also working with this approach for CO_2 removal, thus assuring adequate development status of regenerable solid adsorption systems by 1973.

2.6 Liquid Absorption

2.6.1 Introduction and Data Source

The basic principle of a liquid absorption CO_2 removal process is similar to that of the solid adsorption in that CO_2 is removed by a regenerable absorbent contained within the system and is driven off to collection or disposal by regeneration of the absorbent. In this case, rather than a solid zeolite, a circulating liquid solution is utilized. Data availability for this system approach is somewhat limited due to the development status of liquid absorption systems; however, considerable theoretical analysis and state-of-the-art work at Hamilton Standard has provided an adequate foundation for system sizing.

2.6.2 System Description

Figure 2-37 presents a schematic diagram of the liquid absorption system. The circulating liquid chosen for this study is a potassium carbonate (K_2CO_3) solution. This was chosen as the best liquid absorbent after analysis of other potential candidates. Inlet air from the thermal control system at a temperature of 77°F enters the CO_2 removal system through a liquid contactor. The gas-liquid mixture at the inlet of the contactor is carried through the contactor, where mass transfer of the CO_2 from the process air to the liquid takes place. The CO_2 reacts with the potassium carbonate and water to form potassium bicarbonate. The potassium bicarbonate and CO_2 free process air leaves the contactor and enters a separator where the gas-liquid separation returns the air to the cabin and pumps the liquid through the rest of the system.

2.6.2 (Continued)

LIQUID ABSORPTION CO_2 REMOVAL

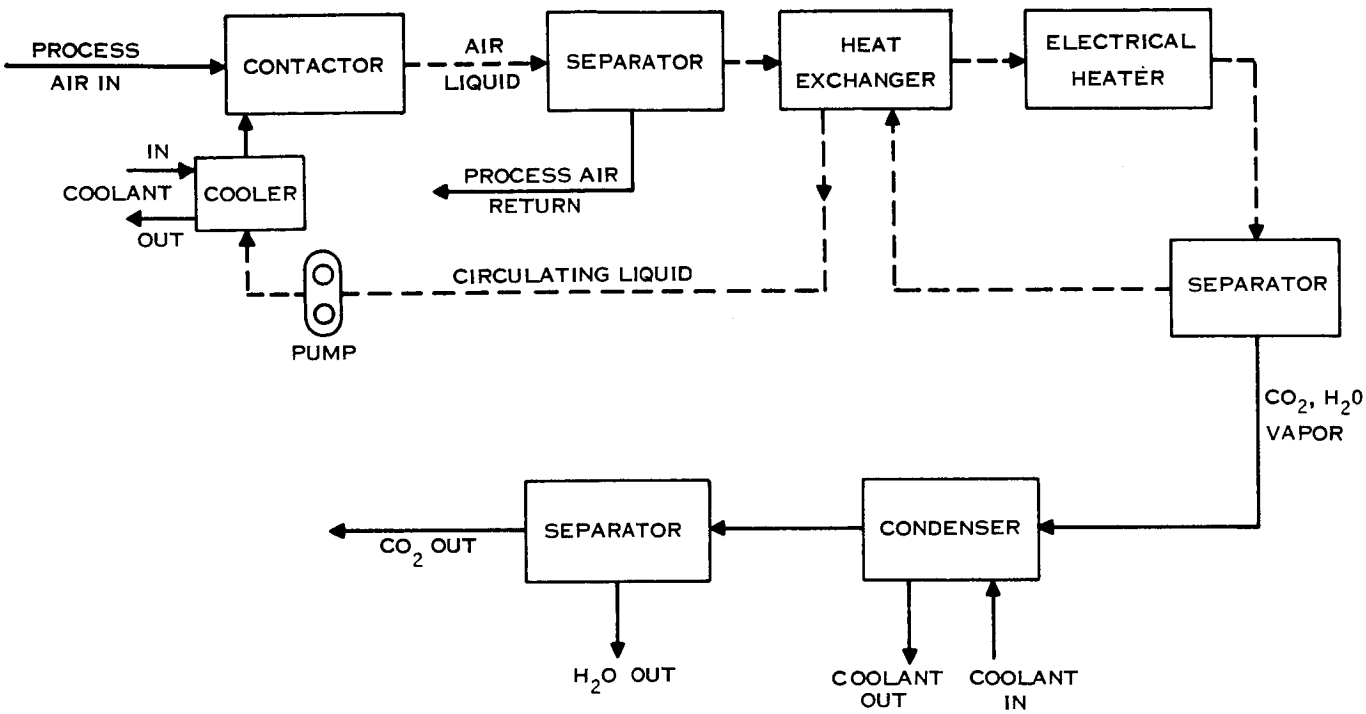


FIGURE 2-37

The liquid is now heated by a regenerable heat exchanger and an electrical heater to a temperature sufficient to dissociate the bicarbonate and release the carbon dioxide. From this point, the circulating solution now contains water vapor, carbon dioxide, potassium carbonate, and some potassium bicarbonate. A second separator is utilized to separate the gas and liquid phases and return the liquid through the second pass of the regenerative heat exchanger back to the contactor inlet. The CO_2 and vapor phase passes through a heat exchanger to cool the mixture and condense the water droplets. A third separator then removes the water from the CO_2. When CO_2 collection is desired, it may be necessary to incorporate a desiccant bed downstream of the third separator to further dry the CO_2 prior to entering the oxygen reclamation system. This is dependent upon reclamation system input requirements.

The basic principle involved in liquid absorption systems of this type is equilibrium between the carbonate and the bicarbonate, which is a function of temperature, potassium concentration and CO_2 partial pressure. This equilibrium relationship can be determined and, from this, a system sized. The relationship

2.6.2 (Continued)

between liquid flow rate and mean droplet size for a given pressure drop across a nozzle has been empirically determined, and curves are available in the literature. (See Perry's Chemical Engineers' Handbook, Third Edition, page 1175). A decrease in flow rate leads to a decrease in the mean droplet size in the normal operating range of the nozzle. It was assumed that a mean droplet radius of less than 70 microns could not readily be achieved, so this was taken as a minimum value of mean droplet radius. At an assumed pressure drop across the nozzle of 60 psi, this corresponded to a liquid flow rate of 575 lbs/hr. Since any further decrease in liquid flow rate will not lead to a further decrease in mean droplet radius, given the above assumptions, this rate provides the greatest possible surface area of liquid droplets created per second, and thus the most rapid rate of mass transfer per volume of contactor. An increase in liquid flow rate leads to larger droplets and less total surface area. Liquid phase mass transfer was considered to be the controlling step in this process, and the contactor size was therefore considered independent of the CO_2 removal rate for this range of interest. The maximum liquid temperature reached in the system is 159°F downstream of the electrical heater. System weight is made up of three major items in addition to the associated secondary items. The liquid inventory, the regenerable heat exchanger, and the contactor make up about 65% of the total system weight.

2.6.3 Results of Analysis

Figure 2-38 presents the weight considerations for the system as a function of CO_2 production rate and CO_2 partial pressure. To allow consideration of the design point mission duration, the weight, including 420 days worth of expendables, is also plotted in this figure to illustrate the expendable requirements for this approach. As mentioned for other systems, this expendable rate does not include packaging weight. Figure 2-39 illustrates the power requirements for the liquid absorption system. It can be noted that these requirements are relatively constant over the range of interest. This is because a large portion of the power requirement is for pumping the liquid absorbent, and this flow rate was held constant. Figures 2-40 and 2-41 illustrate the equivalent weight characteristics of the system as a function of production rate. These figures illustrate fixed weight plus expendable weight for 420 days, plus a weight penalty for power. Determination of weight for another mission duration is accomplished by changing expendable weight requirements in this figure at the rate of .022 lbs per man day to make up the water vapor lost during O_2 venting.

Figures 2-42 through 2-45 allow consideration of weight as a function of a change in mission duration for various crew sizes. In the illustration given, crew sizes of 2, 6, 9, or 12 men approximately may be determined from the CO_2 production rate of 4, 12, 20 and 28 lbs per day. Figure 2-42 presents fixed and expendable

LIQUID ABSORPTION CO_2 REMOVAL
POWER VS. CO_2 PRODUCTION RATE

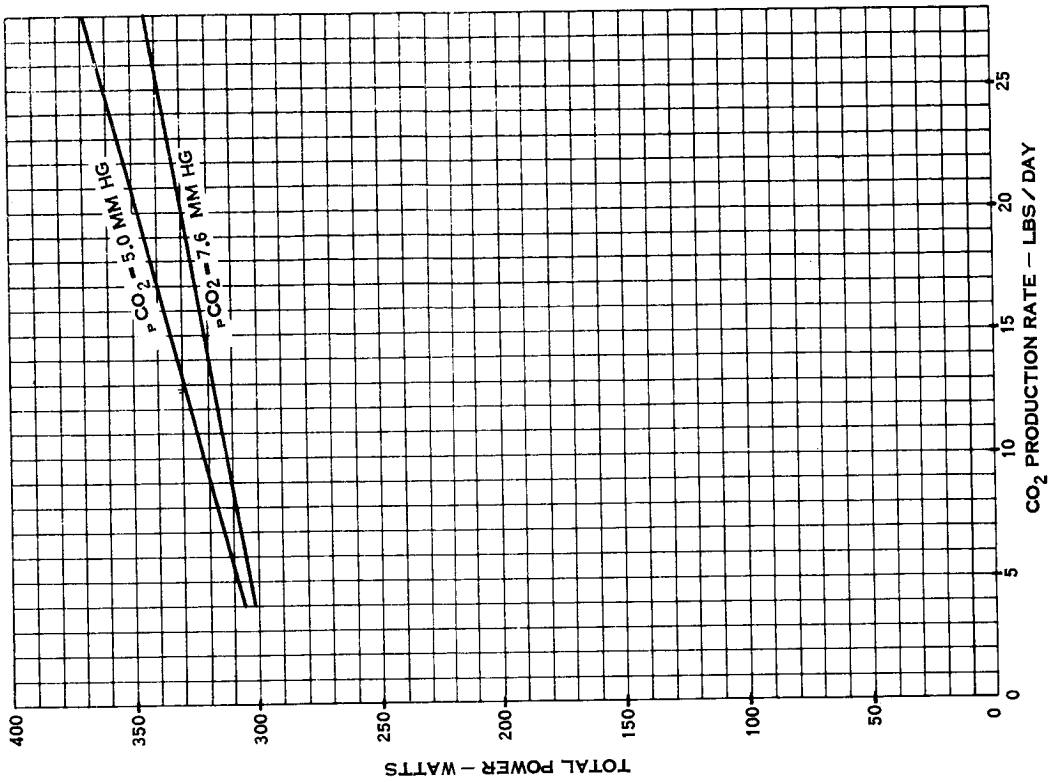


FIGURE 2-39

LIQUID ABSORPTION CO_2 REMOVAL
WEIGHT VS CO_2 PRODUCTION RATE
420 DAY MISSION

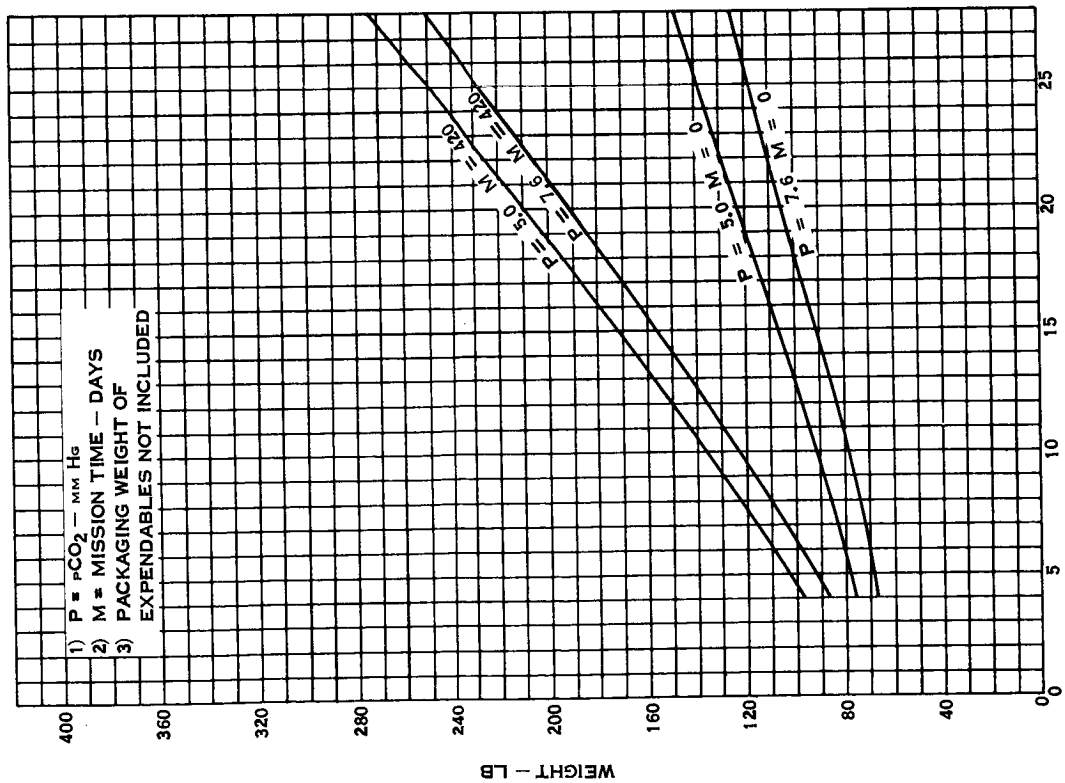
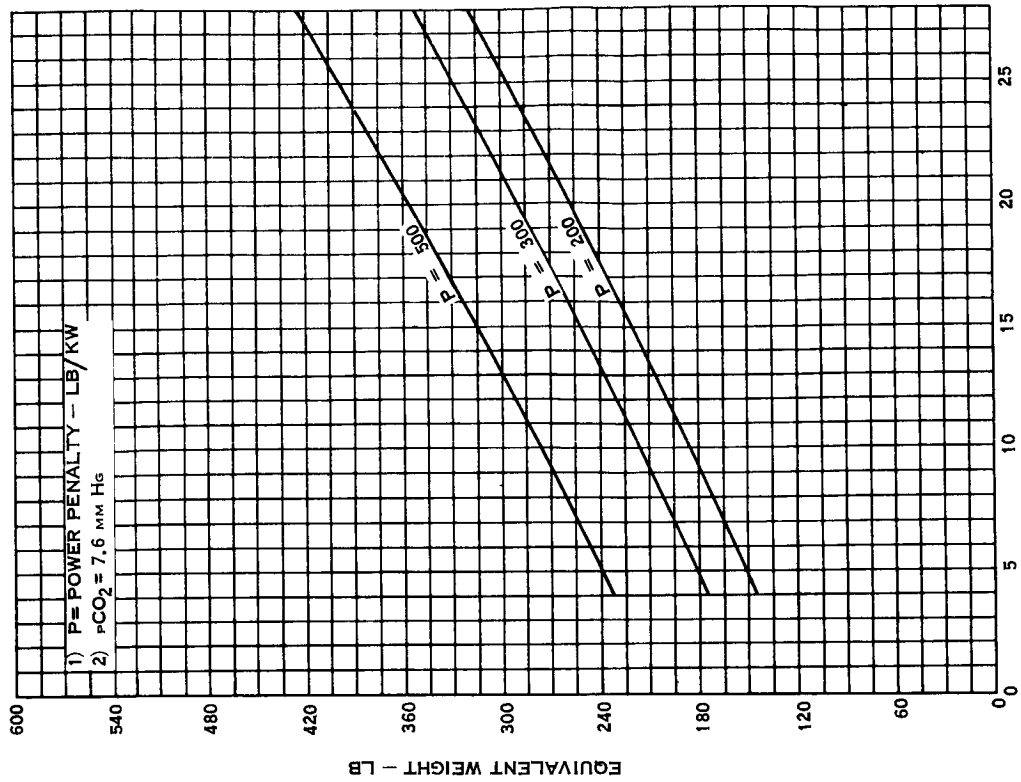


FIGURE 2-38

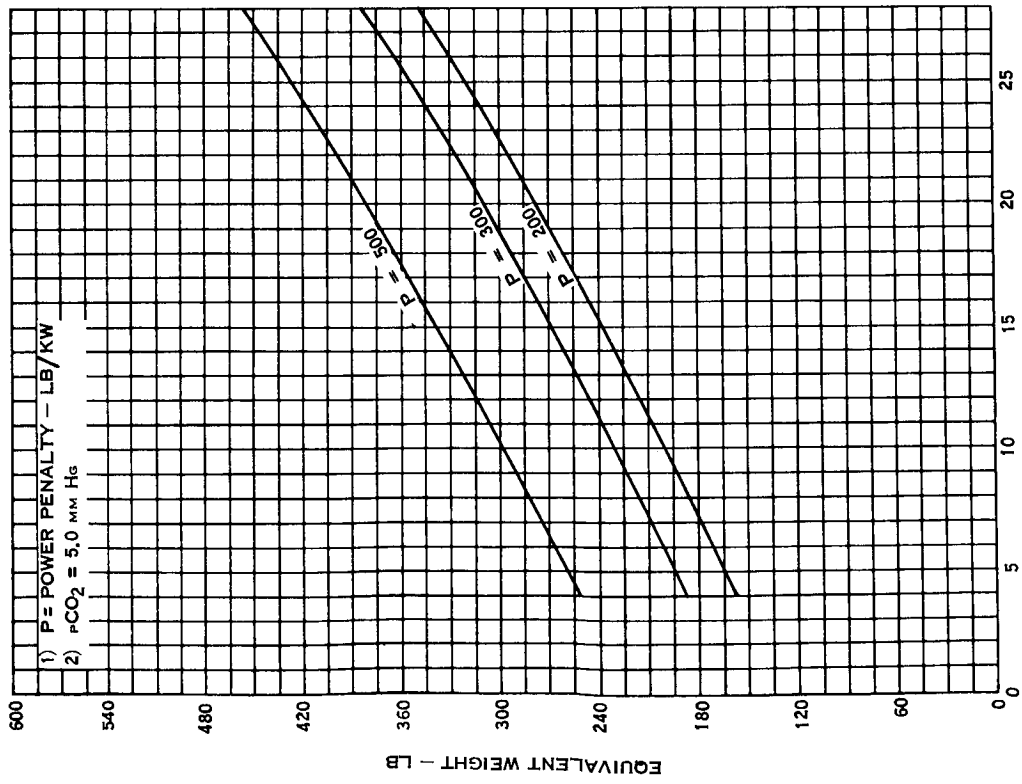
LIQUID ABSORPTION CO_2 REMOVAL
EQUIVALENT WEIGHT VS CO_2 PRODUCTION RATE
420 DAY MISSION



CO_2 PRODUCTION RATE – LB/DAY

FIGURE 2–41

LIQUID ABSORPTION CO_2 REMOVAL
EQUIVALENT WEIGHT VS CO_2 PRODUCTION RATE
420 DAY MISSION



CO_2 PRODUCTION RATE – LB/DAY

FIGURE 2–40

LIQUID ABSORPTION CO_2 REMOVAL
WEIGHT VS MISSION TIME

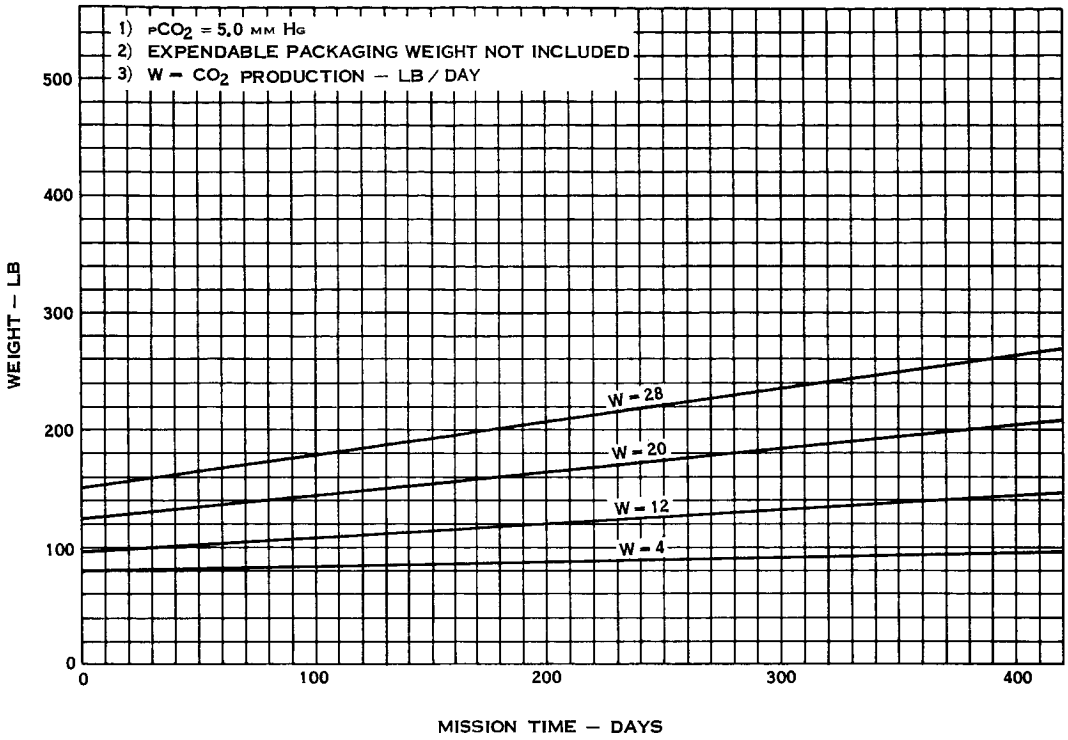


FIGURE 2–42

LIQUID ABSORPTION CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

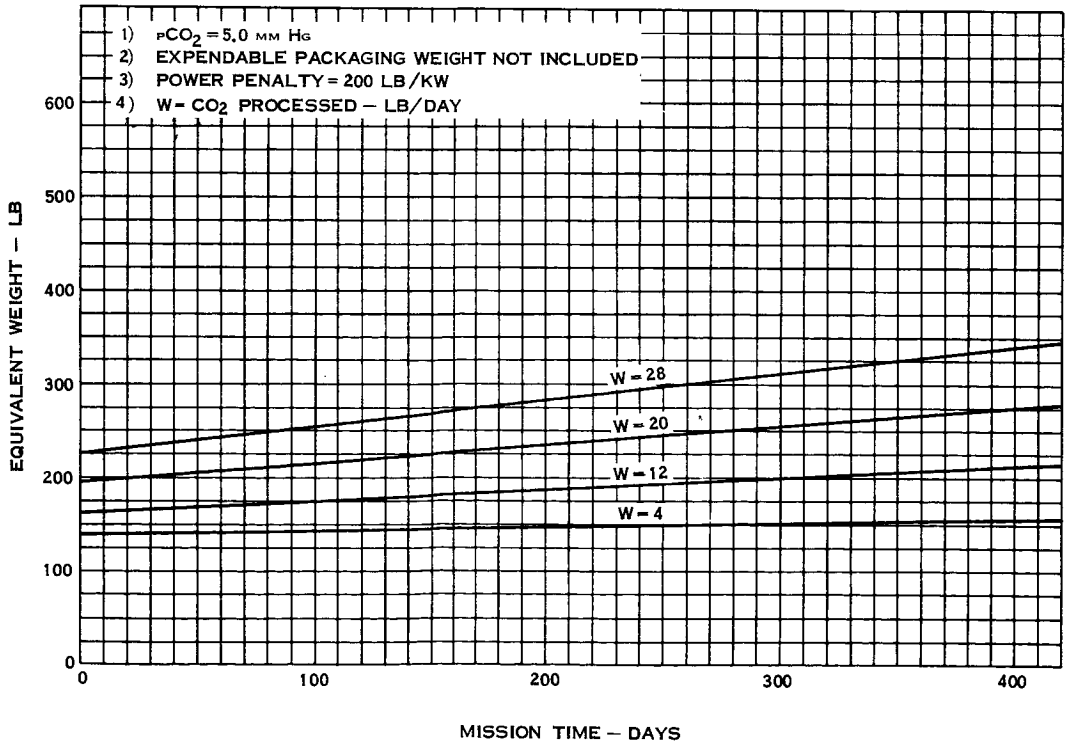


FIGURE 2–43

LIQUID ABSORPTION CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

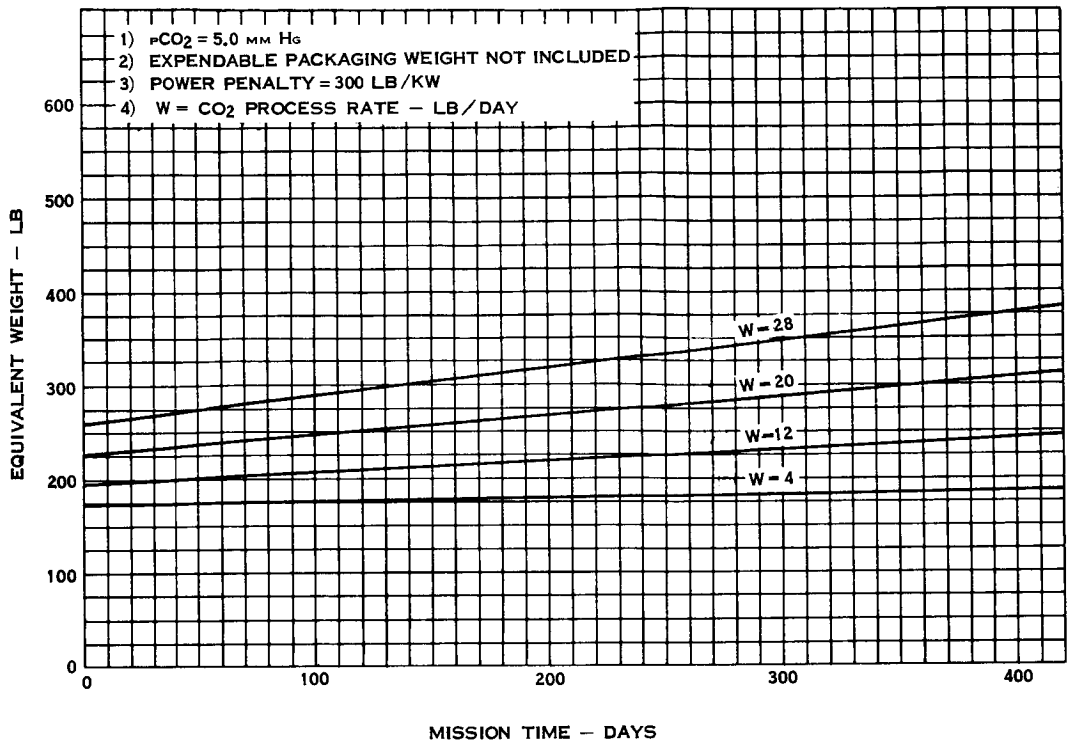


FIGURE 2–44

LIQUID ABSORPTION CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

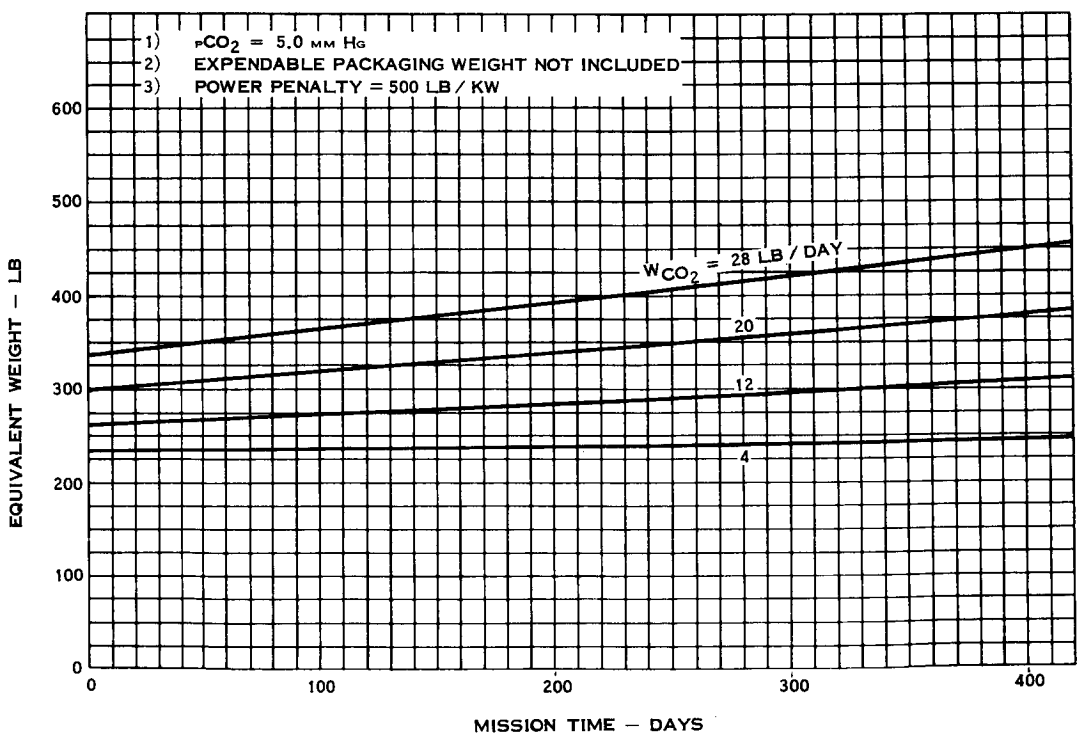


FIGURE 2–45

2.6.3 (Continued)

weight only, without power being charged to the system. Figures 2-43, 2-44, and 2-45 present launch equivalent weight including the penalty for power at the rates of 200, 300, and 500 pounds per kilowatt respectively. Thus, for any given mission duration, the equivalent weight may be determined from these curves.

2.6.4 Conclusions

The liquid absorption CO_2 removal approach has combinations of good and bad points which make it intriguing in some instances and non-competitive in others. The high power but relatively flat power characteristics eliminate the system from consideration at lower crew sizes, but bring it into competitive status at crew sizes of 10 or more men. A disadvantage of this system is its inherent complexity, with the contactor and the three liquid gas separators. Development status plus reliability problems with these items make system applicability somewhat questionable at this time. However, they do not inhibit it sufficiently enough to rule it out of further consideration. With a CO_2 reduction system included in overall system design, liquid absorption then becomes quite attractive due to its ease of delivery of the CO_2 to a collection or a reduction device. It supplies its own heat regenerably for the most part, thus reducing external electrical power requirements to a point lower than that of a system using electrical power for heating. Also, performance is independent of inlet dew point, which allows more flexibility of process air tap-off from the main life support system.

2.7 CO_2 Removal by Electrodialysis

2.7.1 Introduction and Data Source

The analysis of CO_2 removal by the electrodialysis method was based on recent data provided by Ionics, Inc. in Cambridge, Massachusetts. This system approach, which relies heavily on previous Ionics membrane technology, has been the subject of independent research work on their part and, more recently, a NASA research and development contract. Their report No. 11-P-63-26, "Carbon Dioxide Removal and Water Electrolysis Subsystems for Manned Vehicles Having Extended Missions," supplemented by discussions with their personnel, was the major source of the data in this analysis. The data presented represents a prediction of 1973 performance which represents a significant improvement over current state-of-the-art.

2.7.2 System Description

Carbon dioxide removal with this approach is accomplished by means of ion exchange reactions which convert the CO_2 to ionic species (e.g., carbonate or bicarbonate ions) and by electrodialysis, which causes the ionic species to migrate

2.7.2 (Continued)

out of the absorption zones. The CO_2 is recovered in a separate high purity stream. Under normal operating conditions, the equipment utilized for CO_2 removal will also generate up to 50% of the metabolic oxygen requirements, giving the system a dual purpose within the main life support loop. Most of Ionics' work has considered a water electrolysis system in conjunction with the CO_2 removal system to produce the rest of the metabolic oxygen requirements. This analysis has not considered both of these systems in operation together, but rather the CO_2 removal function alone. Their work in water electrolysis is discussed in Section 4.0 of this report.

Figure 2-46 presents a simplified schematic of this system. The primary component in the system is the electrodialysis stack which removes the CO_2 from the air and generates the supplementary oxygen. The inlet process air is humidified, to assure maintenance of wet membrane areas, and fed to absorber compartments where the CO_2 in the air is electrochemically converted to carbonate ions. Under the influence of an electrical potential, the carbonate ions are transferred out of the absorber into concentrator compartments where they react further to reform CO_2 gas. At the electrodes, water is electrolyzed to form oxygen and hydrogen.

The purified processed air returns from the absorber to the cabin system. The CO_2 leaving the concentrator is separated from the accompanying moisture by a gas-liquid separator and transferred to storage or removal as required. A second separator is used to separate the oxygen generated at the anode from the water and a third separator performs the same function with the hydrogen generated at the cathode. Thus, the inlet process air and water emerge as purified air, water, hydrogen, oxygen, and carbon dioxide gases.

Electrodialysis is a process in which ionized molecules or atoms are transferred through highly selective ion transfer membranes under the influence of electrical potential. If a solution containing positively and negatively charged ions is fed to an electrodialysis cell, the positively charged ions (cations) will be attracted to the negatively charged cathode, and the negatively charged ions (anions) attracted to the anode. The nature of the ion transfer membrane between the solution and electrode determines whether or not an ion can migrate through it or be retained in the solution.

The water is fed to the cathode compartment of the system at a rate sufficient to provide for the water lost by electrolysis at the cathode, and by electroendosmosis through the anion membrane into the absorber compartment. In any electrodialysis process, as ions migrate across the membranes, water is transferred in the same direction. This water is apparently transferred due to the hydration of the

2.7.2 (Continued)

ions as well as the electrical potential created by the movement of the ions through the pores of the membranes. The total water transfer is referred to as endosmotic water. Actually, the liquid flow rate will be in excess of the electrochemical requirements to provide cooling of the stack and a sweep stream for the evolved H_2 and O_2 gases.

The humidified cabin air is fed to the absorber compartment. In this compartment, which contains hydroxyl ions, CO_2 is scrubbed from the air by reaction with the hydroxyl ions to form carbonate ions and water. The anion exchange material is continually regenerated by the migration of hydroxyl ions from the cathode into the absorber compartment. Carbonate ions, excess hydroxyl ions and endosmotic water are transferred from the absorber into the concentrator compartment which contains cation exchange material. There the carbonate ions react with the hydrogen ions to form CO_2 and water. The reformed CO_2 gas, along with the endosmotic water, passes out of the compartment under its own pressure.

ELECTRODIALYSIS CO_2 REMOVAL

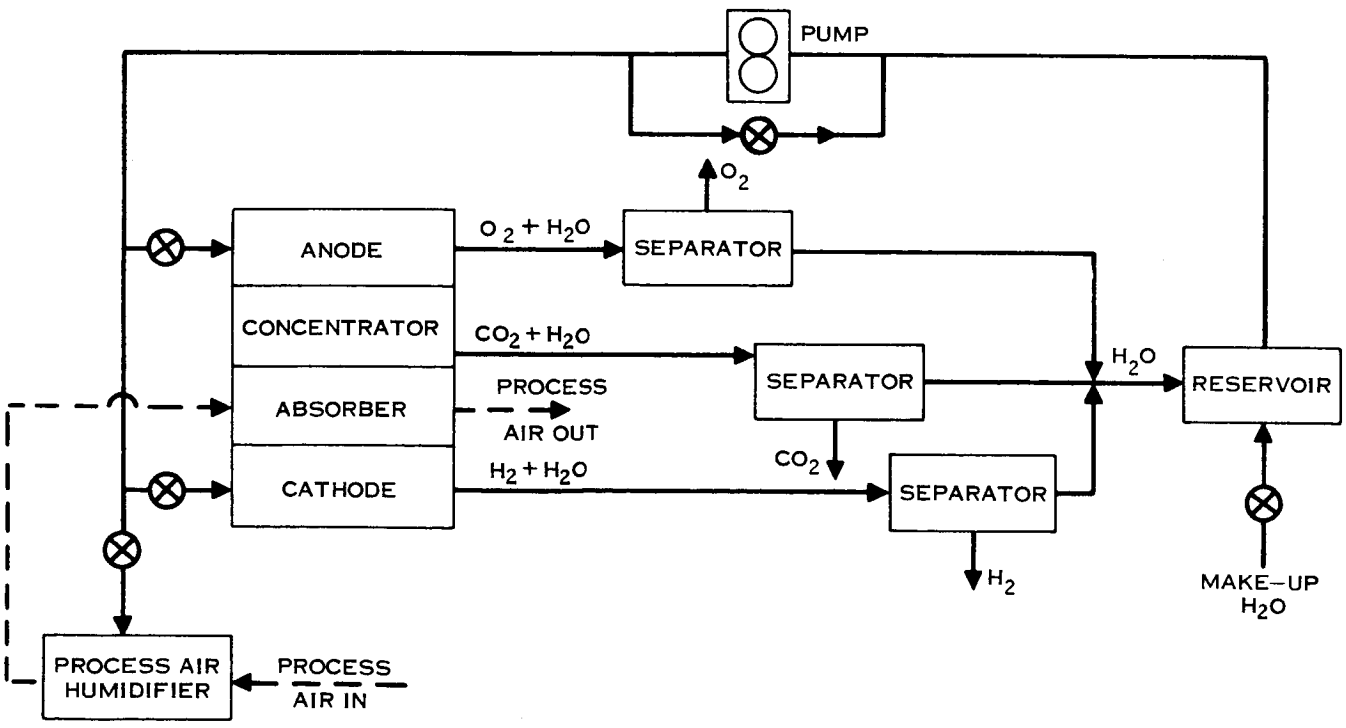


FIGURE 2-46

2.7.2 (Continued)

As previously mentioned, the liquid is separated from the CO_2 by a gas-liquid separator and returned to the inlet of the system. Similar separators perform the same function for the hydrogen and oxygen output streams.

2.7.3 Results

The analysis of the electrodialysis CO_2 removal approach is somewhat unrealistic when a system is considered for CO_2 removal alone. The ability to produce oxygen at the same time actually detracts from the system competitive position when compared with other approaches on CO_2 removal performance. In an attempt to negate this difference, the analysis credited the electrodialysis approach with the oxygen generated during the process. Since the eventual end use of all CO_2 removal systems also includes integration with CO_2 reduction systems, this oxygen generation capacity places electrodialysis in better light for that determination, as discussed in Section 6.0.

Figures 2-47 and 2-48 present the system weight as a function of the CO_2 production rate. Both fixed and expendable weight can be determined from these curves. Expendable utilization for electrodialysis is on the order of .04 lbs/man day due to the moisture lost with the CO_2. Figures 2-49 and 2-50 illustrate the input power requirements of the system as a function of the CO_2 production rate. Due to the water dissociation feature of the system, this inlet power requirement is quite high. Figures 2-51 and 2-52 present system equivalent weight as a function of the CO_2 production rate. As was the case with other systems, the weight of expendable packaging has not been included to allow more flexibility in later use of the data.

To illustrate the weight of the system as determined by the mission duration, Figures 2-53 through 2-56 have been prepared. Figure 2-53 presents the weight of the system as made up by the system fixed weight and the amount of expendables required. Since power is a consideration in determination of total equivalent launch weight, Figures 2-54 through 2-56 illustrate this total equivalent weight as a function of the mission time for power penalties of 200, 300, and 500 lbs/KW respectively. A design point crew size of 6 men was utilized for these curves.

2.7.4 Conclusions

Ionics seems to have achieved considerable success in system design and is currently in the process of performing a research and development contract for the National Aeronautics and Space Administration which should improve the development status of this approach. The membrane stack life may present some

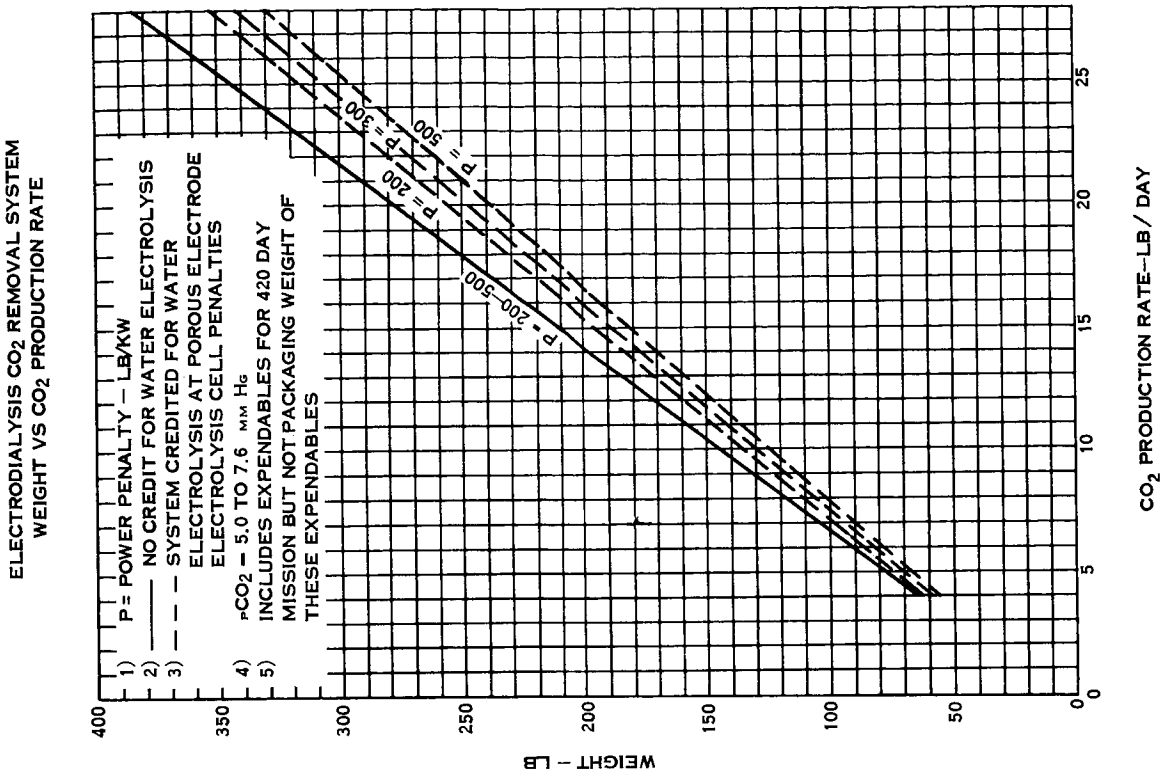


FIGURE 2 – 48

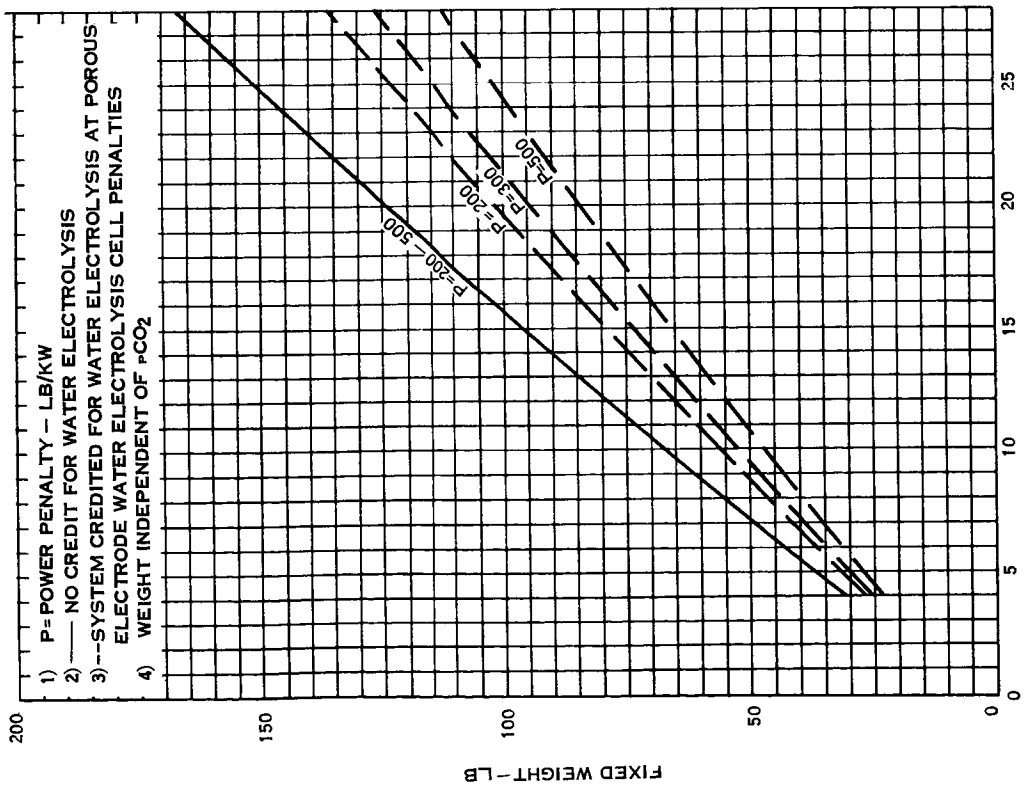


FIGURE 2 – 47

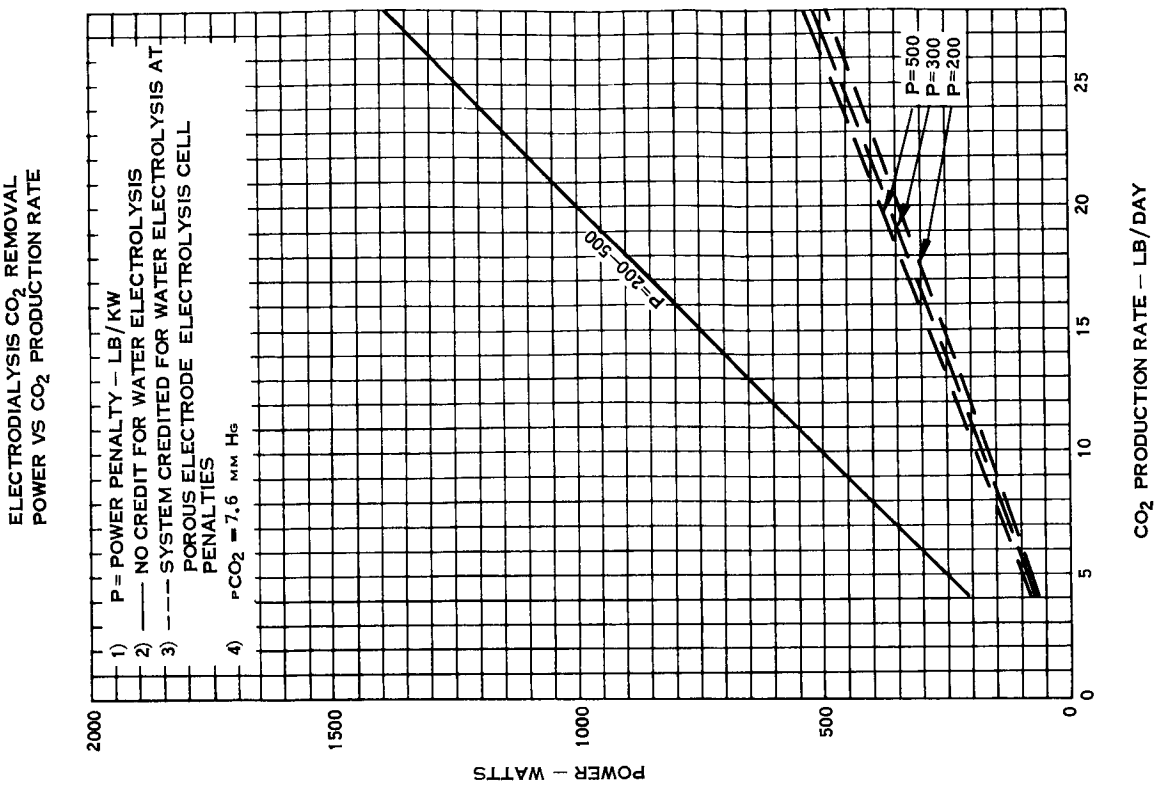


FIGURE 2–50

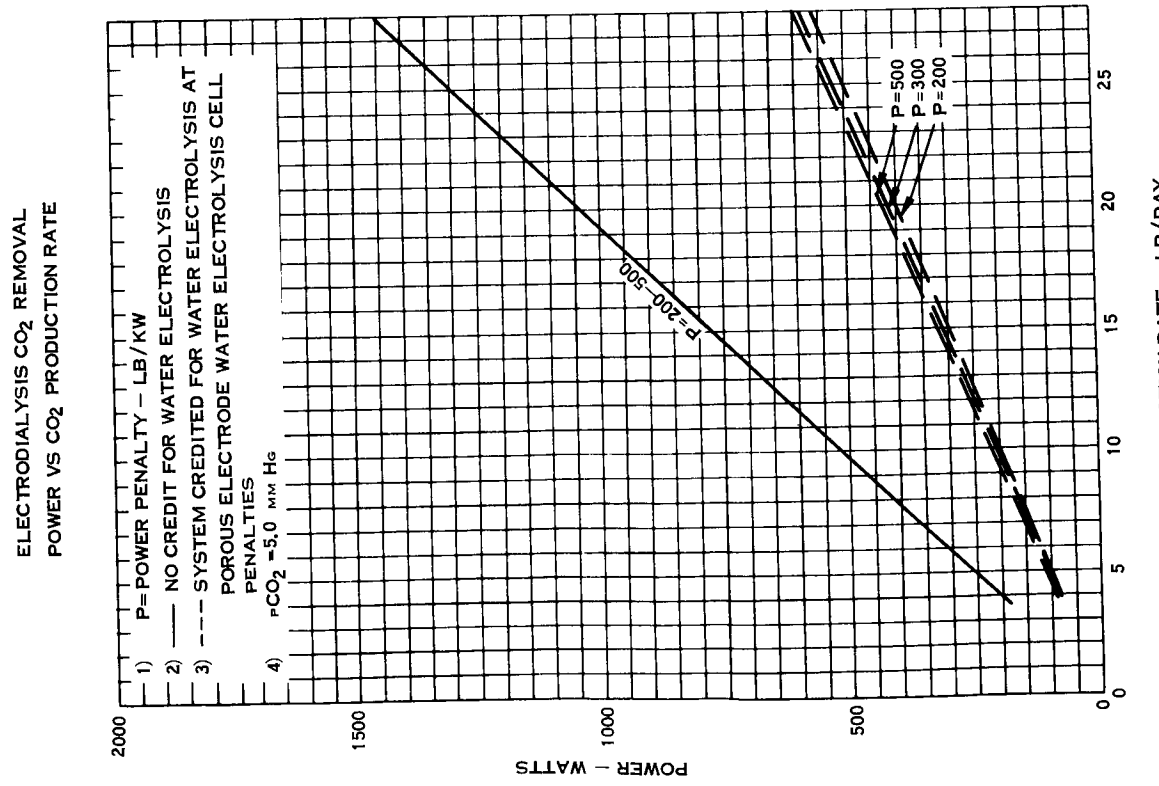


FIGURE 2–49

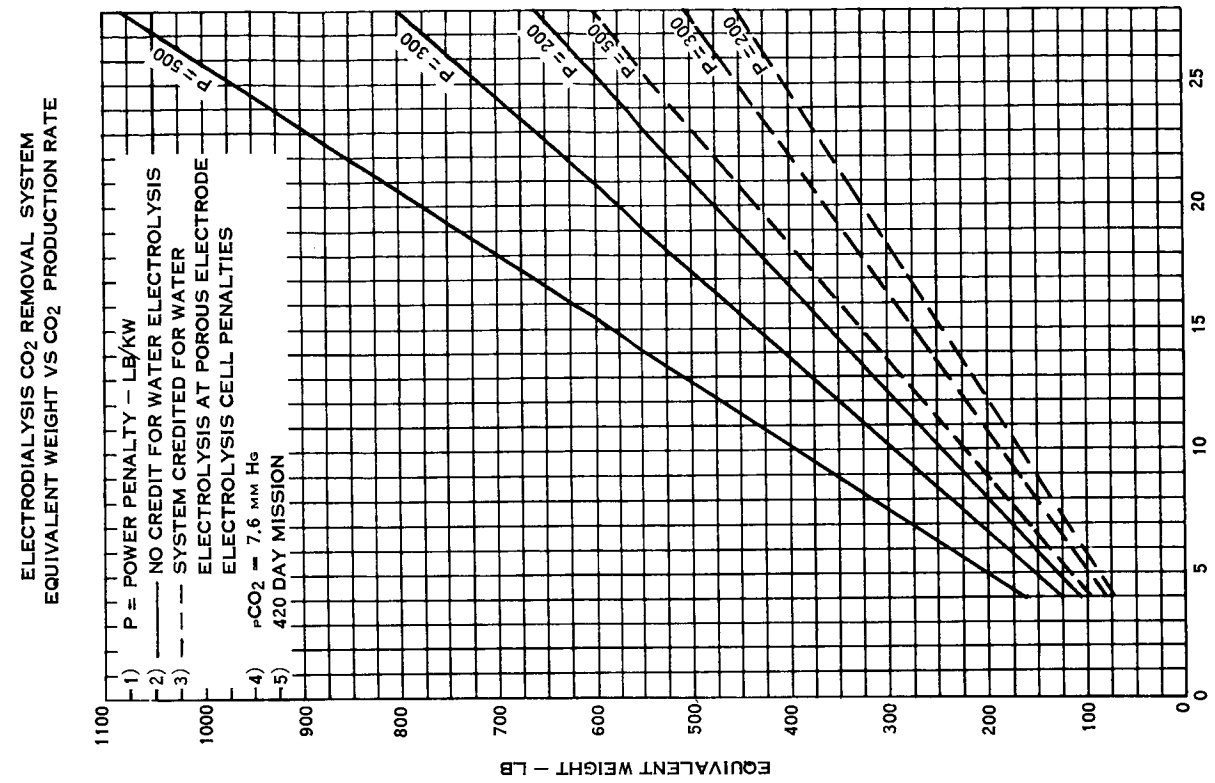


FIGURE 2-52

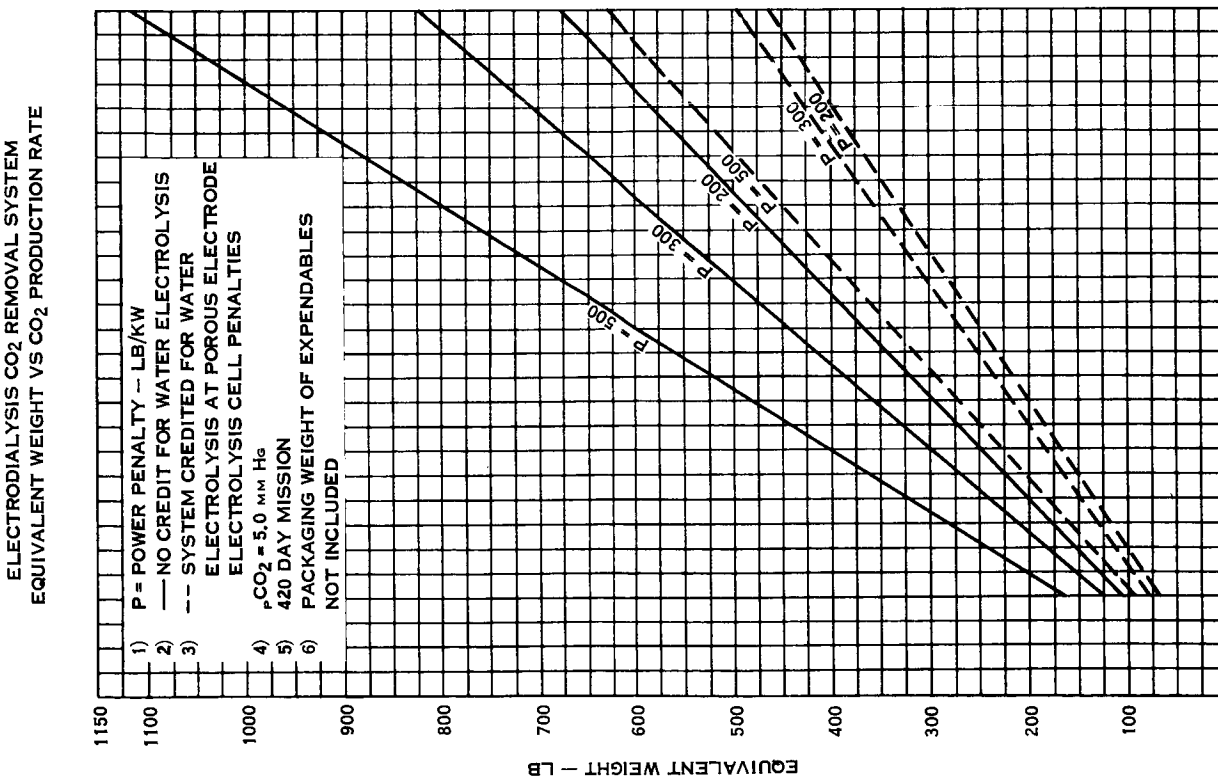


FIGURE 2-51

ELECTRODIALYSIS CO_2 REMOVAL
WEIGHT VS MISSION TIME

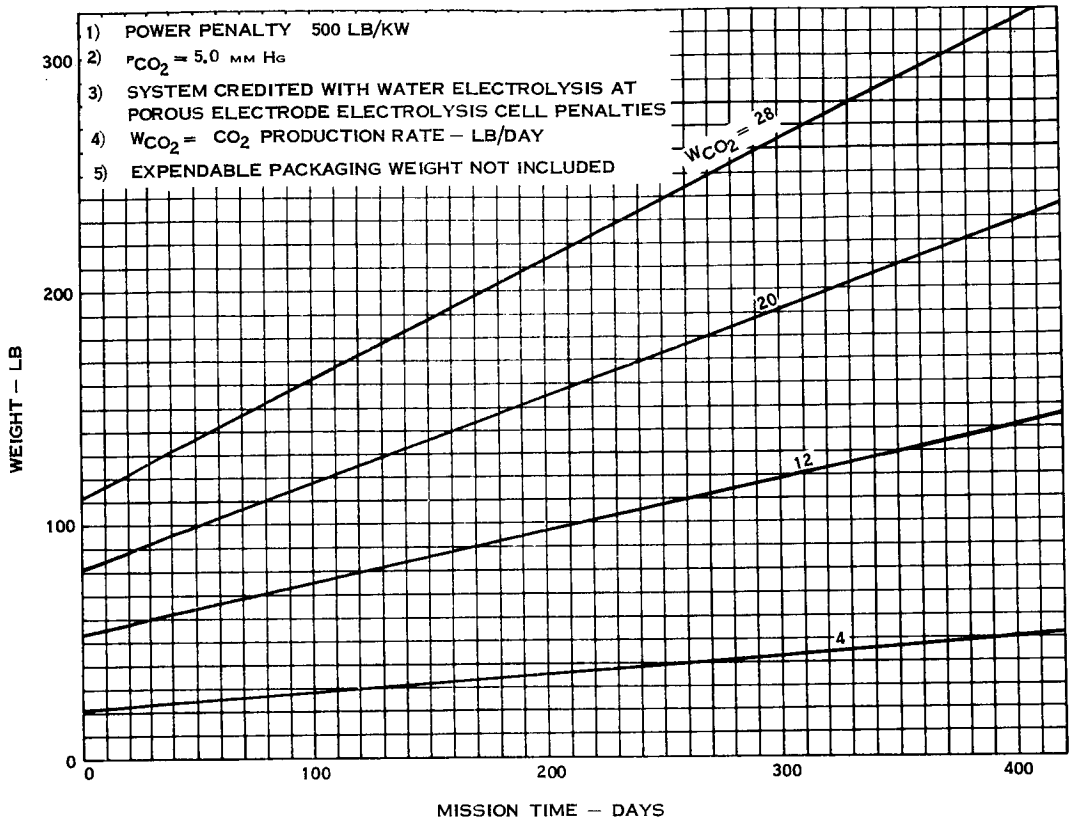


FIGURE 2–53

ELECTRODIALYSIS CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

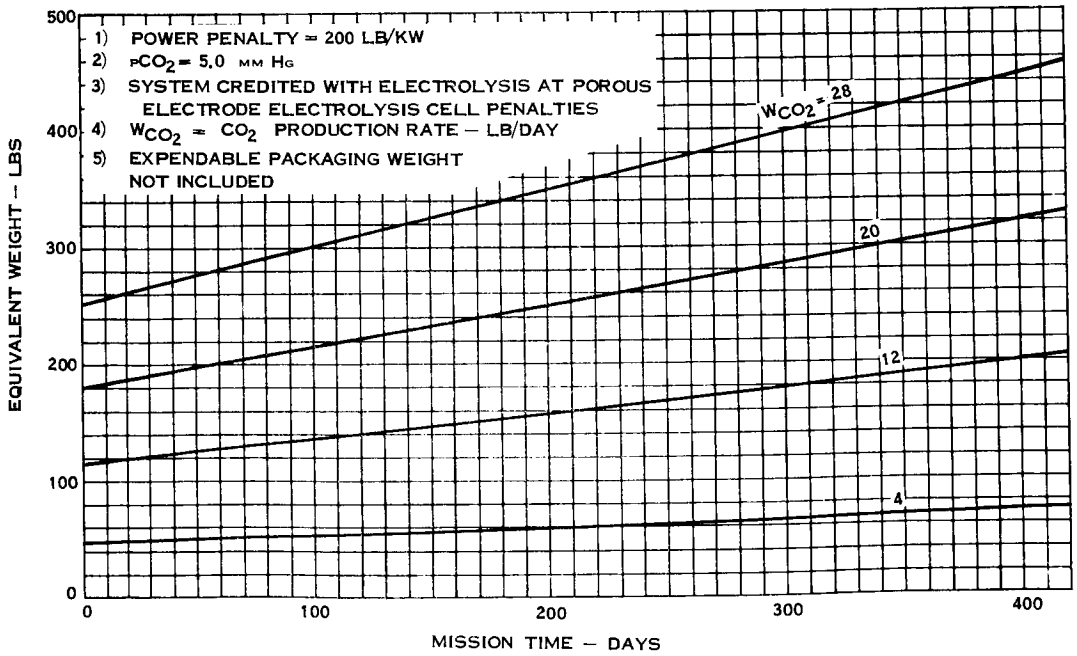


FIGURE 2–54

ELECTRODIALYSIS CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

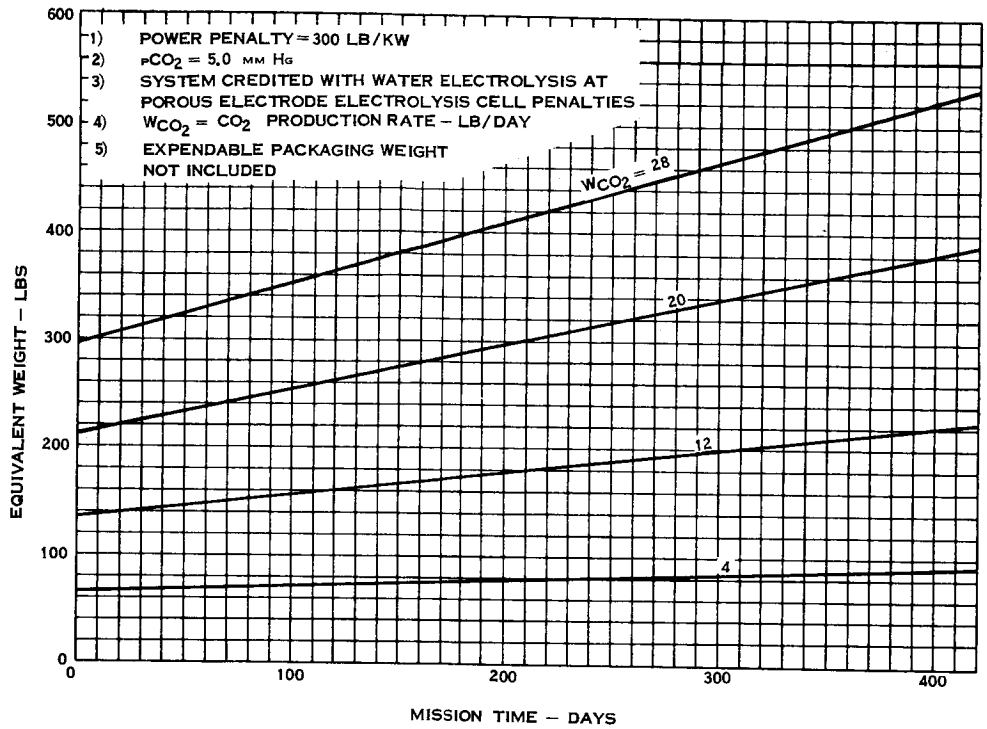


FIGURE 2–55

ELECTRODIALYSIS CO_2 REMOVAL
EQUIVALENT WEIGHT VS MISSION TIME

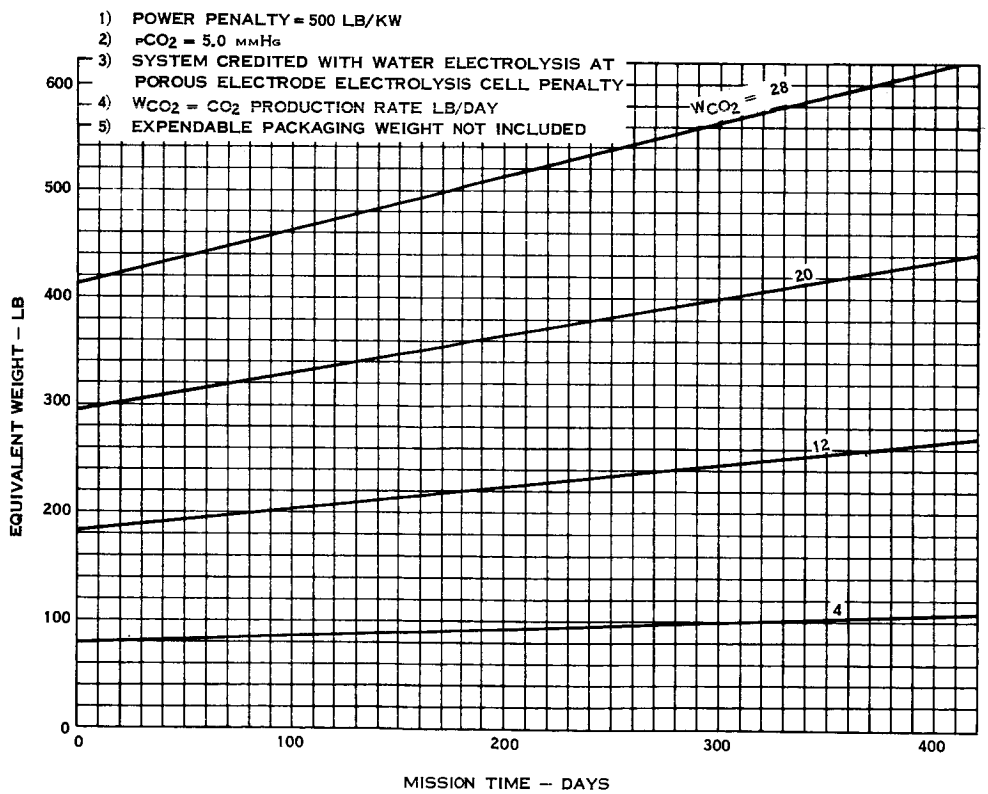


FIGURE 2–56

2.7.4 (Continued)

problems for long duration missions. The addition of three liquid gas separators reduces system reliability to some extent and presents some problems not yet solved by presently developed zero "g" liquid gas separators. The high water sweep stream required to wash the gas bubbles from the electrodes results in an outlet mixture which is essentially liquid, thus making gas separation more difficult. No separator has been tested to date for this application.

The system should operate well in zero gravity application if the separators can be built. If the predicted performance improvements by 1973 which were used in this study can be achieved, the system looks worthy of further consideration as a removal and transfer device. The exhaust of CO_2 at elevated pressures improves integration potential with many CO_2 reduction systems.

2.8 Miscellaneous Chemical Absorbents

2.8.1 General

In addition to the previous CO_2 removal systems, several other methods of removing and recovering CO_2 have been considered. These include removal by absorption in silver oxide, absorption by alkali metals, and removal by several non-regenerable metallic oxides and hydroxides. The information available on these methods is presented in the following section.

2.8.2 CO_2 Removal by Silver Oxide

Silver oxide (Ag_2O) has been considered as a regenerable CO_2 removal agent. It reacts with carbon dioxide to form the carbonate as follows:

$$Ag_2O + CO_2 \longrightarrow Ag_2CO_3 \qquad (1)$$

The equilibrium ratio is 5.27 pounds Ag_2O/lb CO_2. This is much too high to allow silver oxide to be considered as a non-regenerable absorbent. However, the silver carbonate is decomposed to the oxide, liberating CO_2, at moderately high temperatures (400°F). For this reason, some theoretical studies have suggested the use of the silver oxide as a regenerable absorbent.

Unfortunately, the silver oxide has a tendency to decompose to silver and oxygen when heated. The decomposition reaction is as follows:

$$Ag_2O \longrightarrow 2Ag + 1/2\ O_2 \qquad (2)$$

2.8.2 (Continued)

The partial pressure of O_2 in this reaction at a given temperature is greater than the partial pressure of CO_2 in reaction (1). This means that when the silver carbonate is heated to convert it to silver oxide, the oxide thus formed will have a strong tendency to decompose to silver and oxygen. The silver, once formed, is stable and will not react further, so reaction (2) is essentially irreversible. The only thing that would permit this scheme to be used is a great difference in reaction rates, with reaction (1) proceeding much faster (by orders of magnitude) than reaction (2). While little is known about these rates, it is unlikely that such a large difference would exist. The use of silver oxide as a CO_2 removal agent must therefore be considered unfeasible.

2.8.3 Alkali Metal Superoxides

The superoxides are a class of chemicals which react with carbon dioxide to form the carbonate, releasing oxygen in the process. Potassium superoxide has been manufactured and used for many years, while sodium superoxide has just been developed. The reactions for both are the same, although sodium superoxide would be preferable because of its lighter weight. The basic reactions are:

1) $4\ MO_2 + 2H_2O \longrightarrow 4\ MOH + 3\ O_2$

2) $2\ CO_2 + 4\ MOH \longrightarrow 2\ H_2O + 2\ M_2\ CO_3$

This system has fallen out of favor in recent years owing to its high weight penalty and control problems. The utilization of KO_2 has not been above 80%, due to many side reactions which occur and to the residual KO_2 which must be maintained to keep up the reaction rate. The humidity of the entering air must be carefully controlled, as the superoxide becomes a slush if exposed to too much moisture. Also, it is difficult to match the input and output of the KO_2 bed with the metabolic requirements of man. The superoxide method was, therefore, not considered further and no parametric data was prepared for it.

2.8.4 Non-Regenerable Metallic Oxides and Hydroxides

Several metallic oxides and hydroxides have the ability to remove carbon dioxide from an air stream by converting it to the carbonate. Of these, lithium hydroxide has undergone considerable development work. The other compounds considered here (lithium oxide, calcium oxide, magnesium oxide) are mostly theoretical at this point. The information presented here is from Hamilton Standard research work done over the past several years.

2.8.4 (Continued)

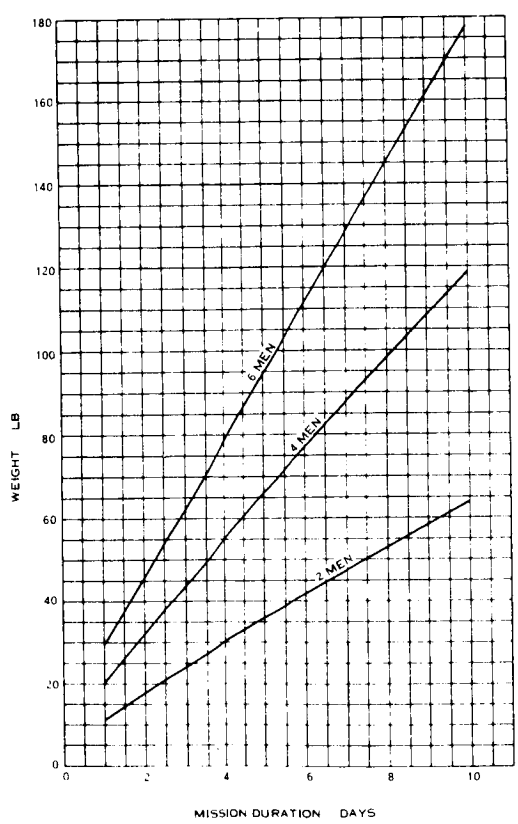
These non-regenerable CO_2 removal systems consist simply of a canister through which the recirculating breathing gas is passed and the CO_2 is absorbed. The cartridge is generally constructed so a replaceable cartridge can be replaced at about one day intervals. The used cartridge is not regenerable and must be discarded.

Lithium hydroxide is the most common of the metallic hydroxides and absorbs CO_2 according to the following reaction:

$$2\ LiOH + CO_2 \longrightarrow Li_2\ CO_3 + H_2O$$

The equilibrium ratio between the reactants is 1.09 pounds LiOH/lb CO_2.

Figure 2-57 shows the weight of LiOH required as a function of time and CO_2 production rate. This curve is based on Hamilton Standard test data. It can be seen that the use of LiOH is feasible only for short missions where the CO_2 will not be recovered.



LITHIUM HYDROXIDE CO_2 REMOVAL
WEIGHT VS MISSION TIME

FIGURE 2 - 57

NOTES

1. CO_2 GENERATION RATE = 2.5 LBS/MAN DAY.
2. EFFICIENCY RANGE = 0.42 (2 MEN 1 DAY) TO 0.85 (6 MEN 10 DAYS).
3. EFFICIENCY = LBS CO_2/LB LIOH.

2.8.4 (Continued)

Another such chemical, lithium oxide, reacts with CO_2 as follows:

$$Li_2O + CO_2 \longrightarrow Li_2CO_3$$

For the reaction as written, the equilibrium ratio is 0.68 pounds Li_2O/lb CO_2. This is considerably more favorable than the LiOH. However, there are many problems connected with the operation of a lithium oxide system. The reaction only takes place in the presence of water vapor, and it probably is a two-step process with the hydroxide as an intermediate as follows:

1) $Li_2O + H_2O \longrightarrow 2\ LiOH$
2) $2\ LiOH + CO_2 \longrightarrow Li_2CO_3 + H_2O$

Therefore, water must be present at all times in order for this reaction to take place.

The lithium oxide bed in practice is only usable at very low gas velocities and high relative humidities. The bed is also subject to clogging due to the formation of the hydroxide. For these reasons, and at the present stage of development, Li_2O must be considered less desirable than LiOH for CO_2 removal.

Another non-regenerable chemical, magnesium oxide, absorbs CO_2 as follows:

$$MgO + CO_2 \longrightarrow MgCO_3$$

The equilibrium ratio is 0.91 lbs MgO/lb CO_2. This is slightly better than the equilibrium figure for LiOH. However, the reaction rate for magnesium oxide is extremely slow (except at high temperatures) and the system is less desirable than lithium hydroxide for this reason.

The last such chemical to be considered is calcium oxide, which reacts with CO_2 as follows:

$$CaO + CO_2 \longrightarrow CaCO_3$$

The equilibrium ratio is 1.27 lbs CaO/lb CO_2. This is worse than that for LiOH and the reaction rate is very slow except at elevated temperatures. This absorbent should not be considered further.

2.8.5 Conclusions

The chemical CO_2 absorbents were considered primarily for the short duration portions of the mission such as earth blast-off and rendezvous with the Mission

2.8.5 (Continued)

Module, short time extravehicular excursions in deep space, Mars blast-off and rendezvous with the Mission Module, and Earth Re-entry Module. Of the absorbents considered, only LiOH and Li_2O show much promise. LiOH has the advantage of a much more advanced development status than Li_2O. However, it is possible that future work with Li_2O may solve the problems associated with Li_2O, resulting in a slightly lighter weight than that associated with LiOH.

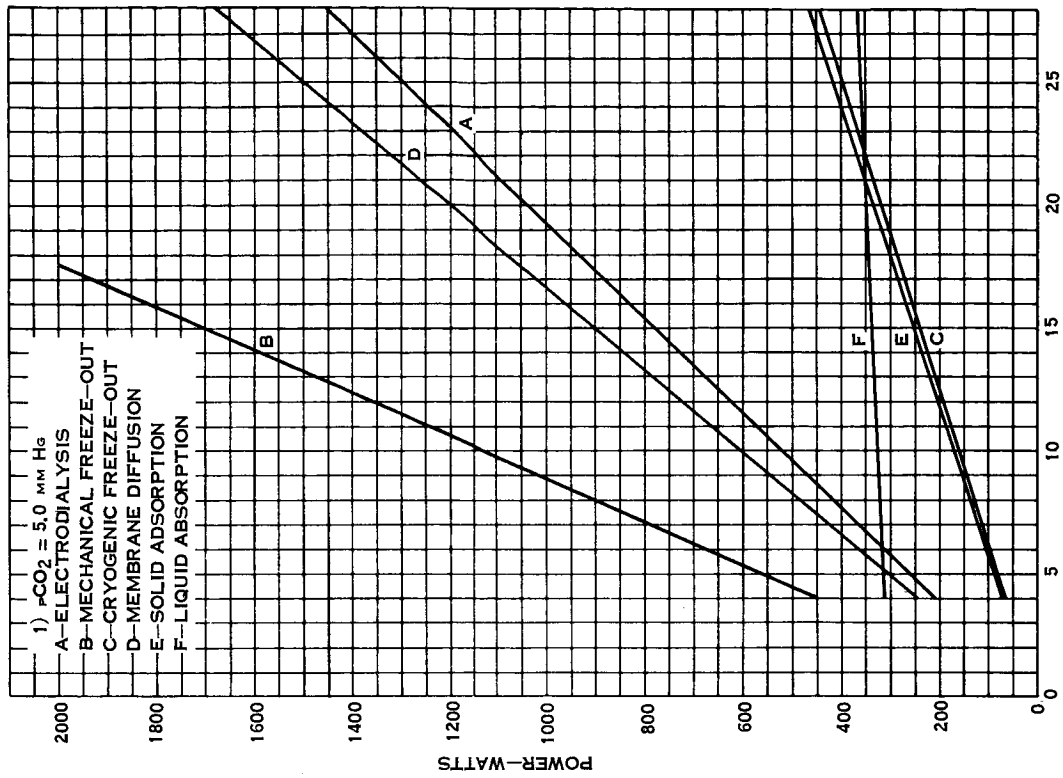
2.9 Comparative Discussion

To permit proper evaluation of the various methods of CO_2 removal, comparison plots have been made. Figure 2-58 shows the comparison of the fixed weight of the various systems. This curve is of little value by itself because for long missions, the additional expendables must be considered the same as fixed weight. However, it is included here to permit evaluation of future developments such as reductions in the rate of expendable use. The power required by each of these systems is shown in Figure 2-59. This curve illustrates that solid adsorption and cryogenic freeze-out are the most competitive systems from a power requirement basis, in that they are about 100 watts under the nearest competitor -- liquid absorption. The previous fixed weight competitors, mechanical freeze-out and membrane diffusion, require substantial amounts of power, thus making them unattractive for a CO_2 removal aspect alone. As mentioned in the individual discussion, however, the electrodialysis approach utilizes a portion of this power to generate oxygen from the circulating water. Thus, although an attempt has been made to credit the system with this power to establish it on a removal basis alone, it cannot be truly considered as solely a removal system.

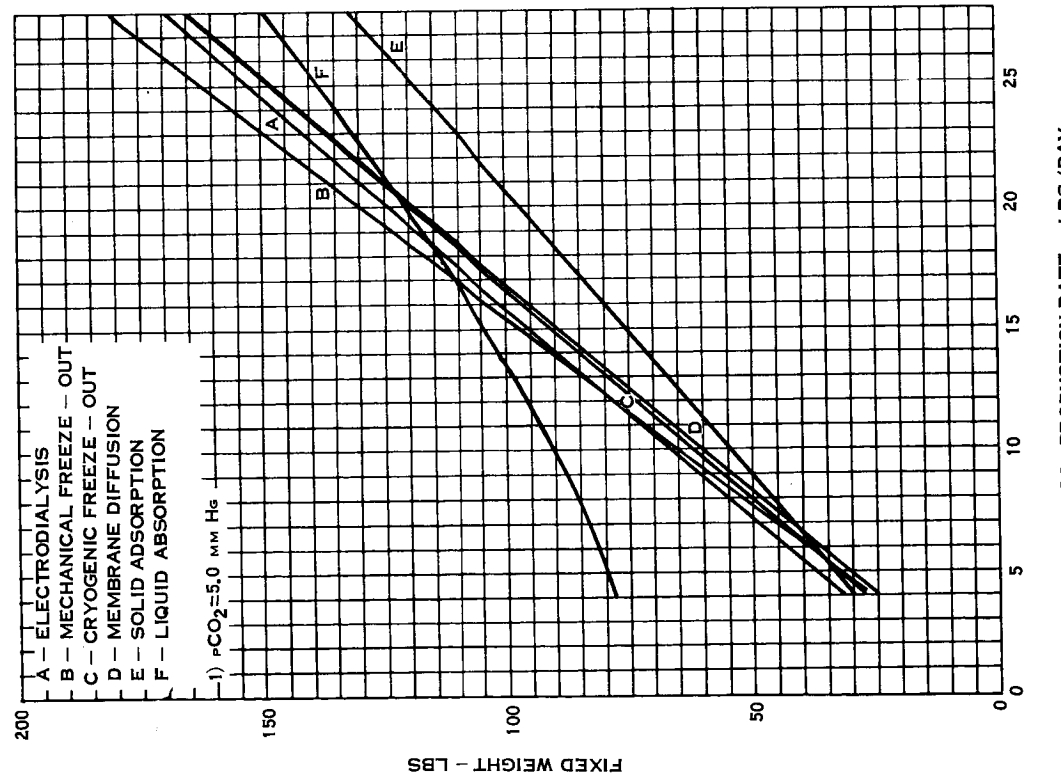
Figures 2-60 through 2-62 present a comparison of the total equivalent weights of all systems for a 420 day mission as a function of CO_2 production rate for power penalties of 200, 300, and 500 pounds per kilowatt. It can be seen that the most competitive systems for the 420 day 6 man mission with a 500 pound per kilowatt power penalty are solid adsorption, liquid absorption and cryogenic freeze-out. Final selection of one of these approaches is dependent on integration with the rest of the system and is covered in Section 6.0 of this report.

To permit evaluation of the various systems for mission times other than 420 days, Figures 2-63 through 2-65 are presented. It can be seen that for a 500 pound per kilowatt power penalty, solid adsorption and cryogenic freeze-out are competitive over the entire range from zero to 420 days, and that liquid absorption becomes more competitive with longer mission durations.

Other factors which must be considered in the selection of a system are reliability and development status. From this standpoint, the solid adsorption system has the advantage of a rather advanced development status, whereas the development status



CO_2 PRODUCTION RATE–LBS/DAY
FIGURE 2–59



CO_2 PRODUCTION RATE – LBS/DAY
FIGURE 2–58

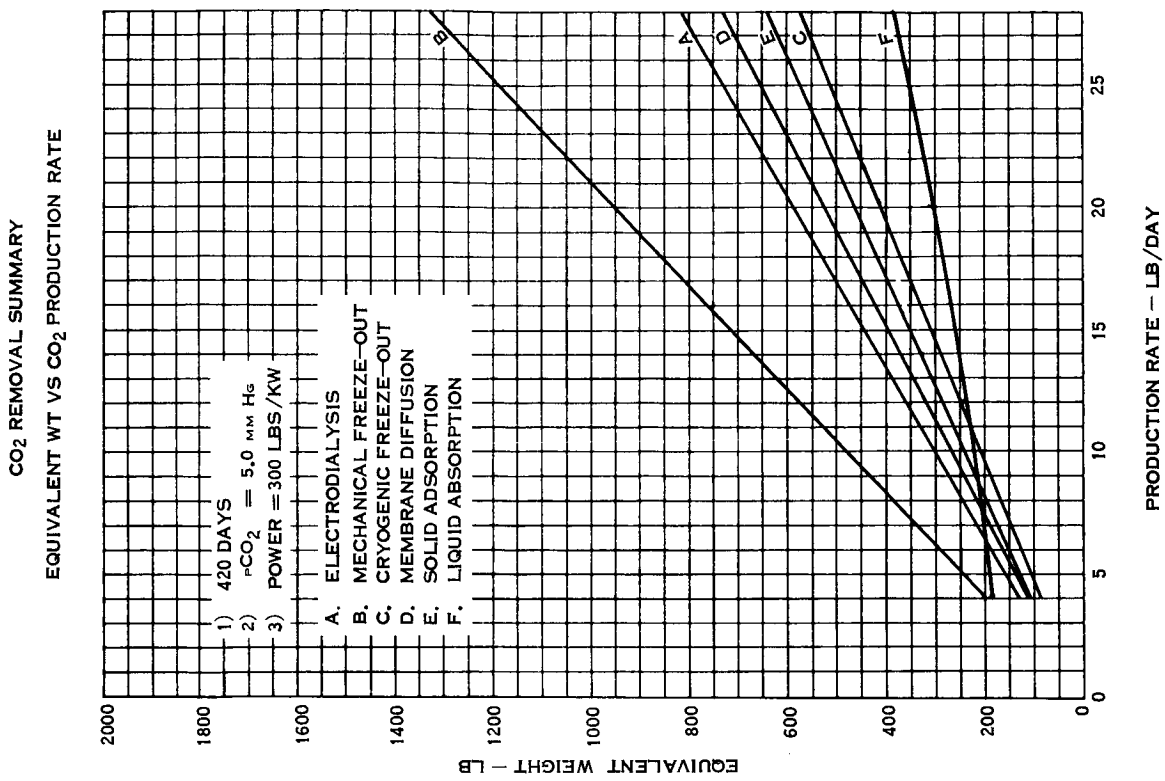


FIGURE 2–61

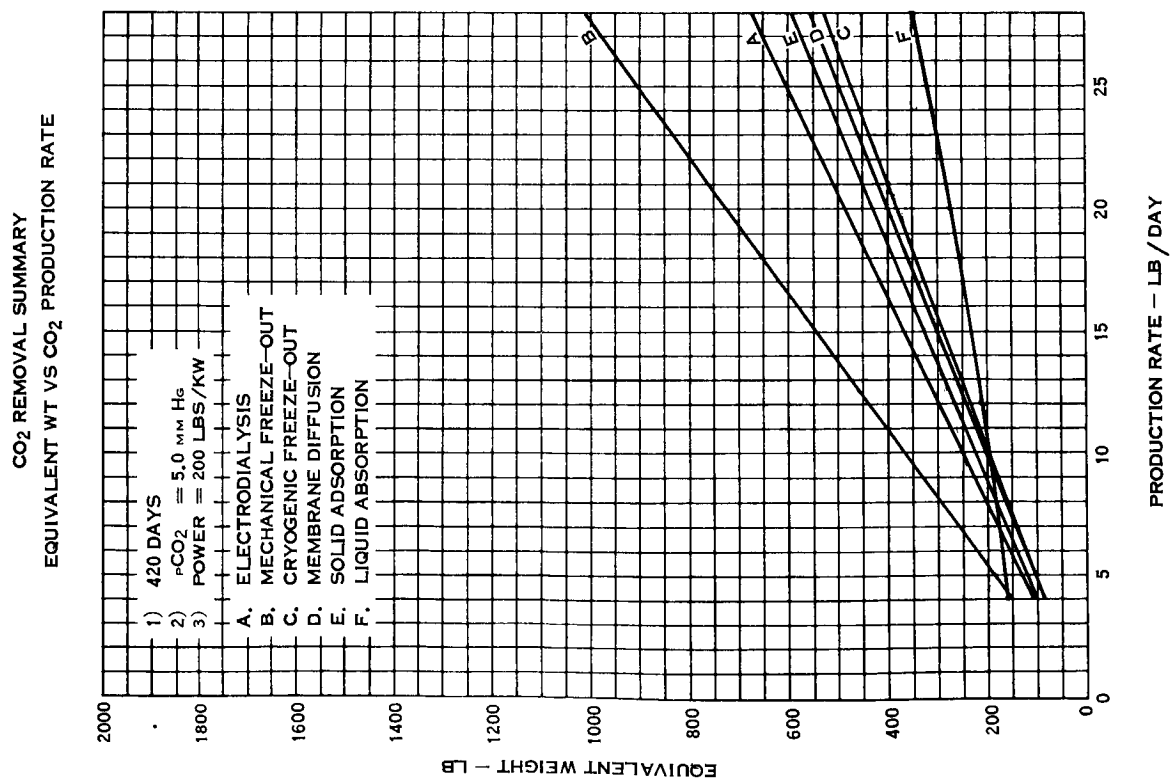


FIGURE 2–60

CO_2 REMOVAL SUMMARY

EQUIVALENT WT VS CO_2 PRODUCTION RATE

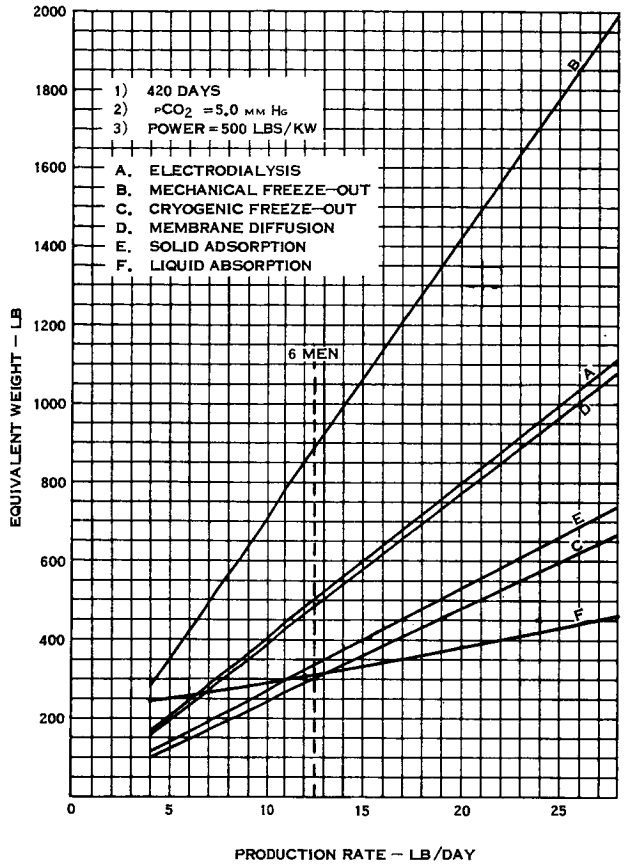


FIGURE 2–62

CO_2 REMOVAL SUMMARY

EQUIVALENT WEIGHT VS MISSION TIME

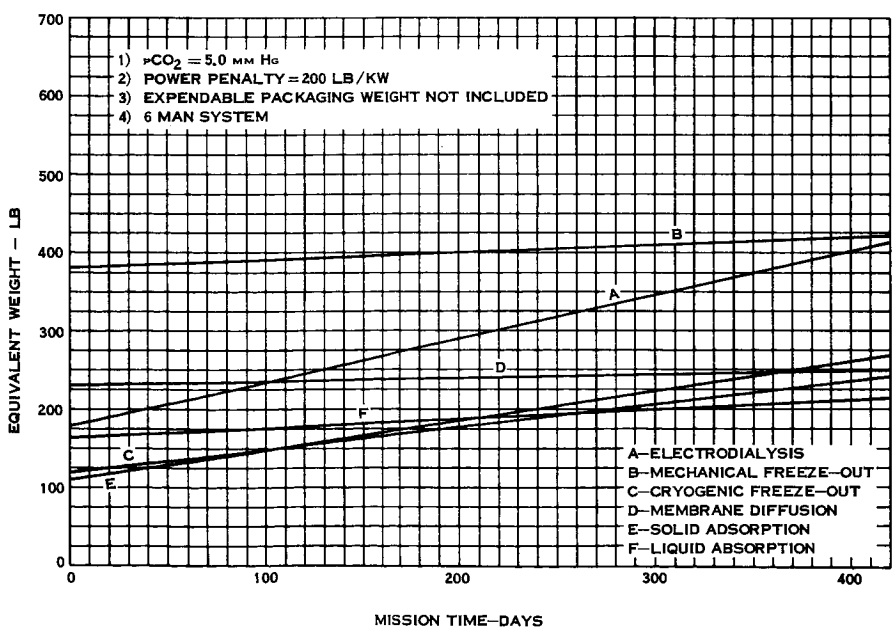


FIGURE 2–63

CO_2 REMOVAL SUMMARY
EQUIVALENT WEIGHT VS MISSION TIME

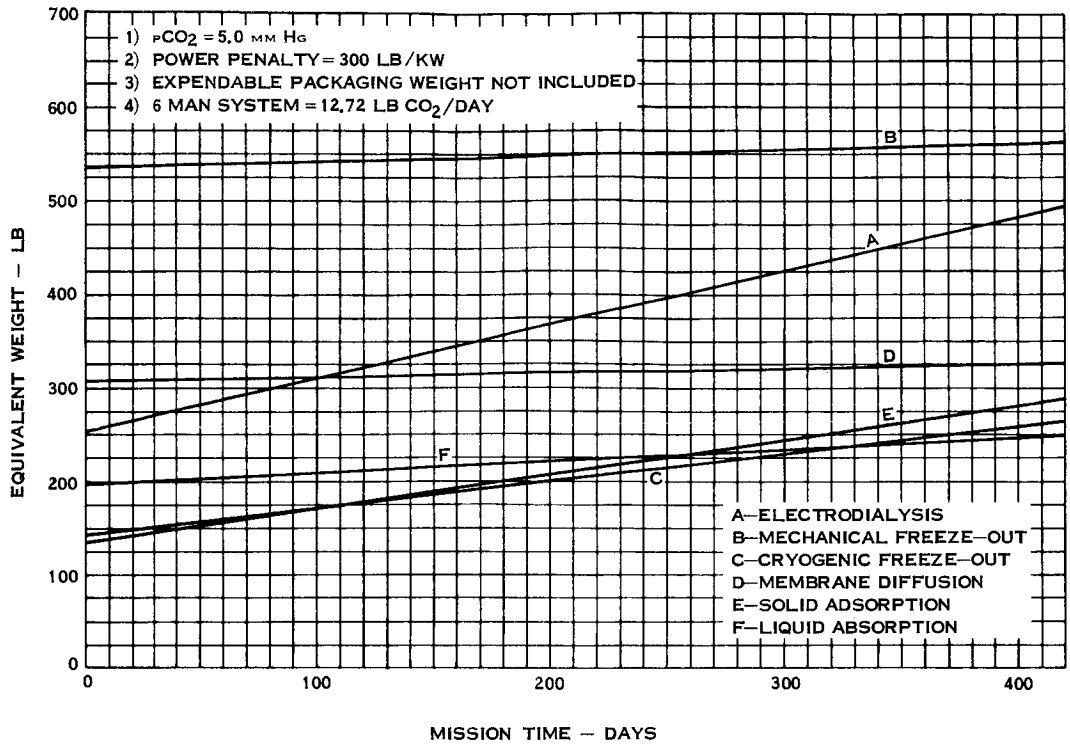


FIGURE 2—64

CO_2 REMOVAL SUMMARY
EQUIVALENT WEIGHT VS MISSION TIME

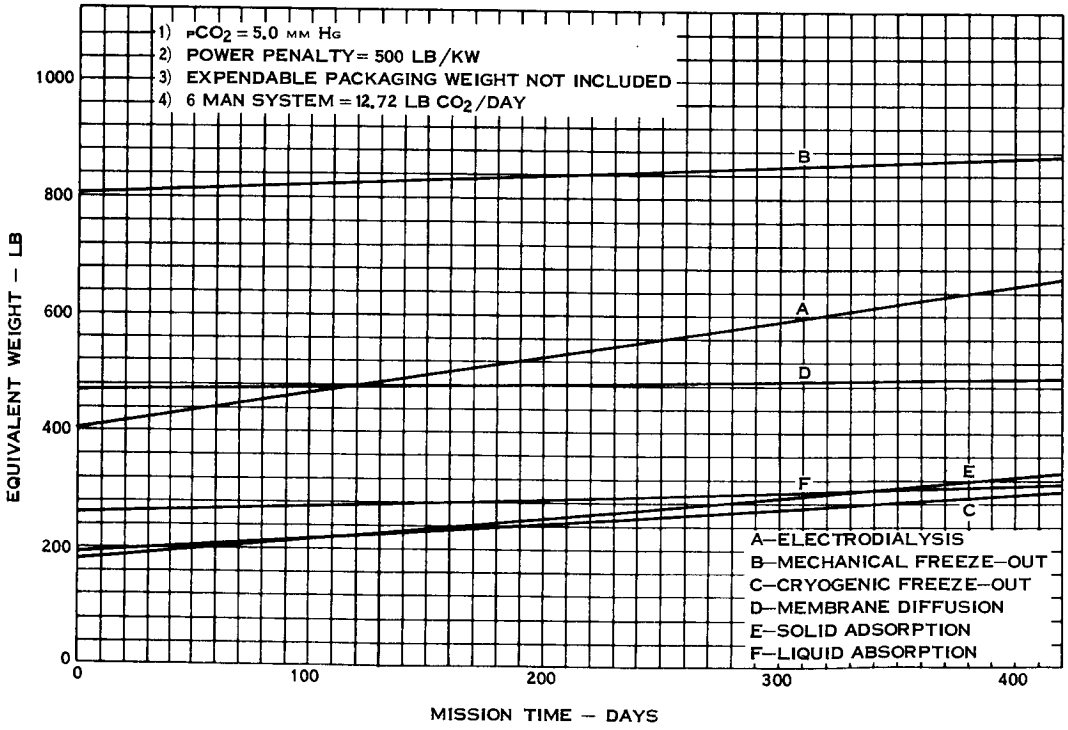


FIGURE 2—65

2.9 (Continued)

of the cryogenic freeze-out is very poor. Cryogenic freeze-out can be considered only for systems which do not reclaim the oxygen from the CO_2 and which have adequate cryogenic stores on board.

2.10 References

1. Hougan and Marshall, "Adsorption Rates on Solid Desiccants," Perry's Chemical Engineers' Handbook, 1950.

2. "Dehydration of Air and Gas with Davison Silica Gel," W. R. Grace & Co., Davison Chemical Division, Baltimore, Maryland, Technical Bulletin 202, 1958.

3. "Molecular Sieve Equilibrium Curves" furnished by both W. R. Grace & Co., Davison Chemical Division, Baltimore, Maryland; and Union Carbide Corp., Linde Division, Tonawanda, New York.

4. McRae, W. A. "Carbon Dioxide Removal and Water Electrolysis Subsystems for Manned Vehicles Having Extended Missions," Ionics Incorporated, Cambridge, Massachusetts, Report 11-P-63-26, August 1963.

5. Greatorex, J. L. "Four Man Prototype Atmospheric Control Subsystems," Contract No. NAS-9-1308 Progress Reports 1-4, Ionics Incorporated, Cambridge, Massachusetts, February - August 1963.

6. Major, C. V. "Investigation of Unique Gas Permeability Cell System to Remove CO_2 and Other Noxious Gases from Spacecraft Cabins," Contract No. NASr-73 Progress Reports 1-6, Dept. of Chemical Engineering, State University of Iowa, December 1961 - March 1963.

7. Meetings and phone conversations with personnel from Ionics Incorporated.

SECTION 3.0

CARBON DIOXIDE REMOVAL AND TRANSFER

3.0 CO_2 REMOVAL AND TRANSFER SYSTEMS

3.1 Introduction

In order to arrive at a more complete picture of the weight and power penalties associated with a carbon dioxide reduction system, the sum of the collection, transfer, and actual reduction process penalties must be considered. Section 2.0 presented studies of CO_2 removal systems without CO_2 transfer and storage. Some additions or modifications must be considered, however, so that the CO_2 transfer function can be effected. This section supplements Section 2.0 and completes the basic study of CO_2 collection and transfer. This work, done as part of the major subsystem integration phase, is included at this point to allow the reader more flexibility in CO_2 removal subsystem definition. Section 6.0 presents the comparison of integrated CO_2 collection, transfer, and reduction systems. Only the candidate systems determined by Section 2.0 are considered here, and the discussion centers around the changes required by the transfer requirements.

3.2 Transfer Systems Sizing

The evaluation of the six CO_2 removal systems discussed in Section 2.0 showed only solid adsorption, liquid absorption, and electrodialysis to be competitive for integration with systems employing oxygen recovery. Cryogenic freeze-out was eliminated since it is very unlikely that sufficient make-up oxygen will be stored cryogenically for long duration missions to meet the flow requirements of that system in the Mars Excursion Module, on the other hand, the fuel cell used as a source of power provides an ample source of oxygen (which makes cryogenic freezeout feasible for that system). Mechanical freeze-out has non-competitive weight and power characteristics along with reliability problems inherent with rotating equipment. The development status of membrane diffusion systems and the unattractive equivalent weight characteristics ruled this approach out at this time.

3.2.1 Solid Adsorption CO_2 Removal and Transfer

The first removal system to be discussed is the solid adsorption system. CO_2 can be collected from the solid adsorbent zeolite material by three primary methods:

1. Vacuum desorption through use of a vacuum pump.
2. Heated desorption by electrical power or circulating fluid.
3. A combination of heat and low pressure.

Each of these methods was evaluated to provide an indication of its relative merits for the Mars Mission application.

ROTARY PISTON VACUUM PUMP
PERFORMANCE CHARACTERISTICS

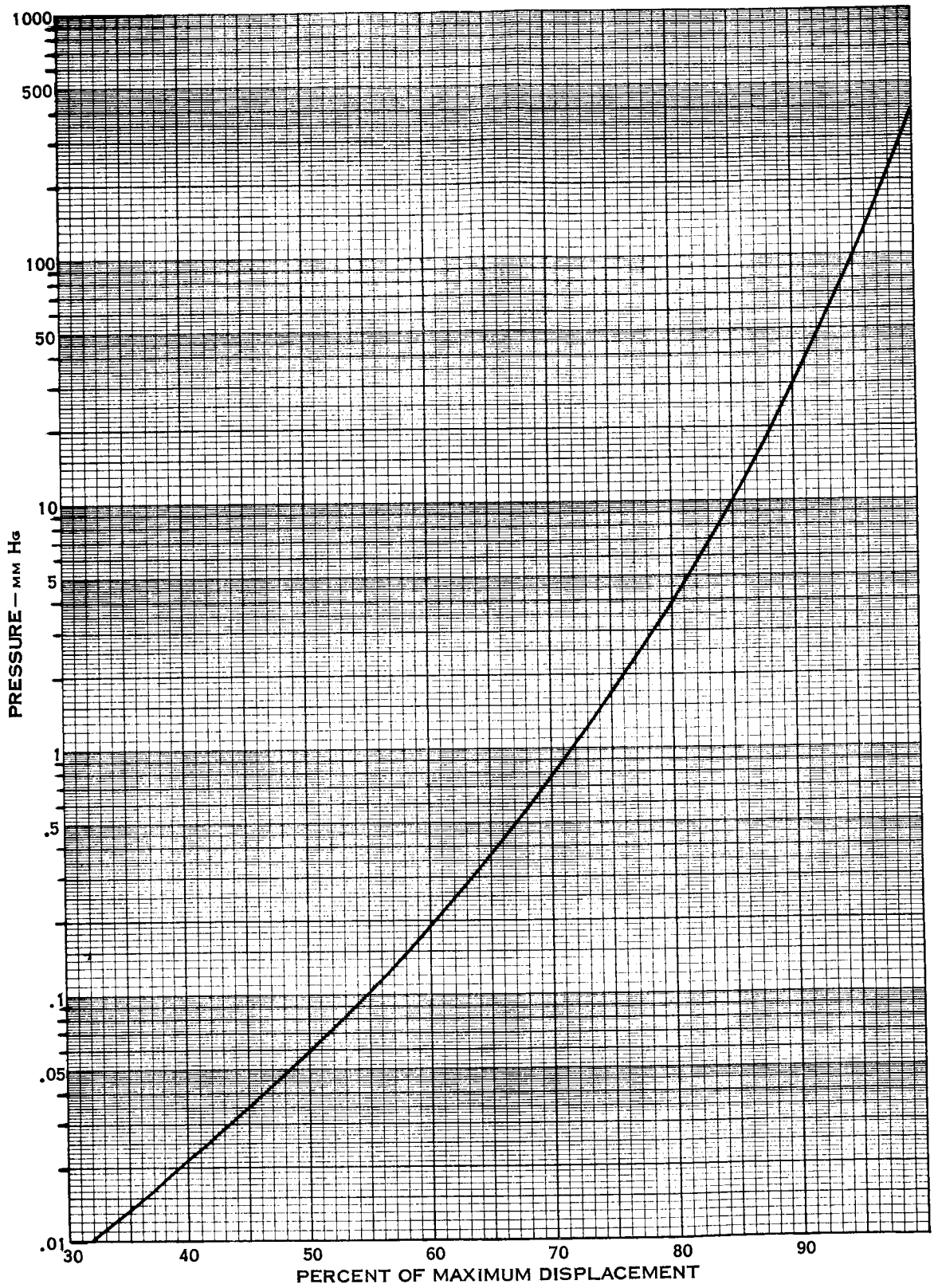


FIGURE 3—1

3.2.1 (Continued)

In the consideration of a total vacuum desorption method, an extensive review was made of vacuum pump characteristics in order to evaluate the compatibility of present day vacuum technology with the solid adsorption system requirements. The ultimate pressure required for canister desorption with no supplementary heat falls at 0.2 mm. Hg. in the medium vacuum range. For this vacuum range and the capacities required for this CO_2 transfer system, a rotary positive displacement piston pump was found to have the most attractive characteristics.

In order to permit a simple characterization of the pumps with respect to their pumping speed, a standard pressure is taken as the basis for specifying the displacement, with this pressure being atmospheric for rotary pumps. Figure 3-1 shows a typical variation of displacement with pump suction pressure for a rotary piston pump. The adiabatic efficiency of compression is mainly a function of pump capacity and suction pressure as illustrated by Figures 3-2 and 3-3. The theoretical adiabatic work for CO_2 compression per unit capacity as a function of pump suction pressure for a constant delivery pressure is shown in Figure 3-4.

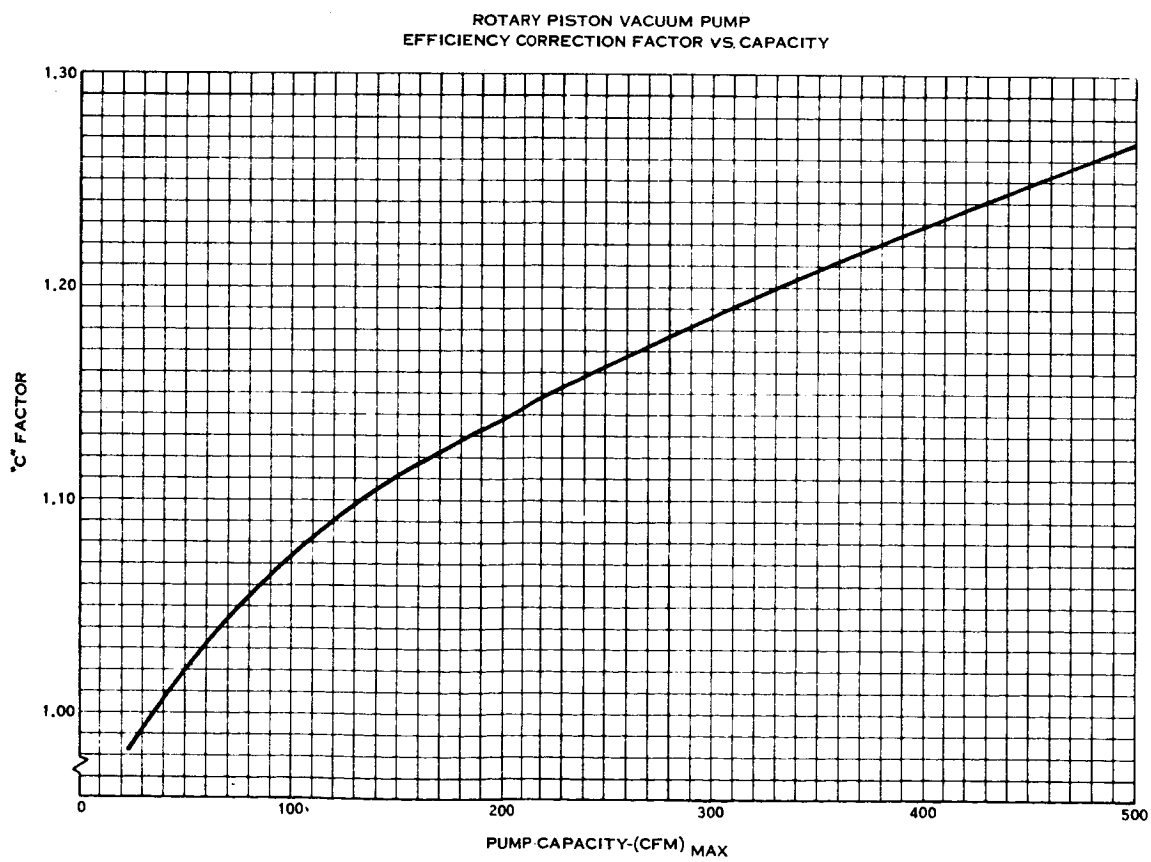


FIGURE 3-2

ROTARY PISTON VACUUM PUMP
EFFICIENCY VS SUCTION PRESSURE

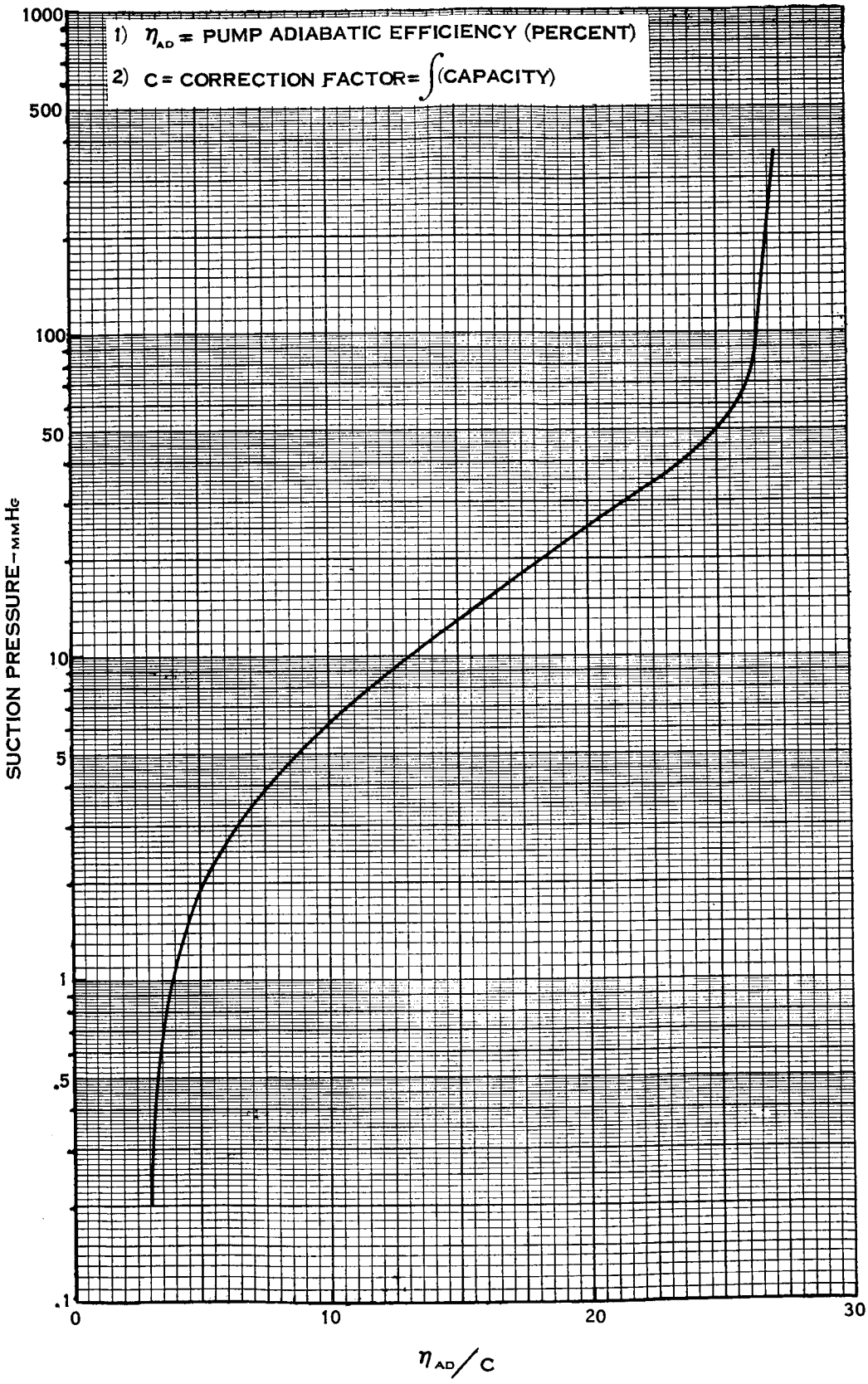


FIGURE 3–3

CARBON DIOXIDE

ADIABATIC WORK OF COMPRESSION VS SUCTION PRESSURE

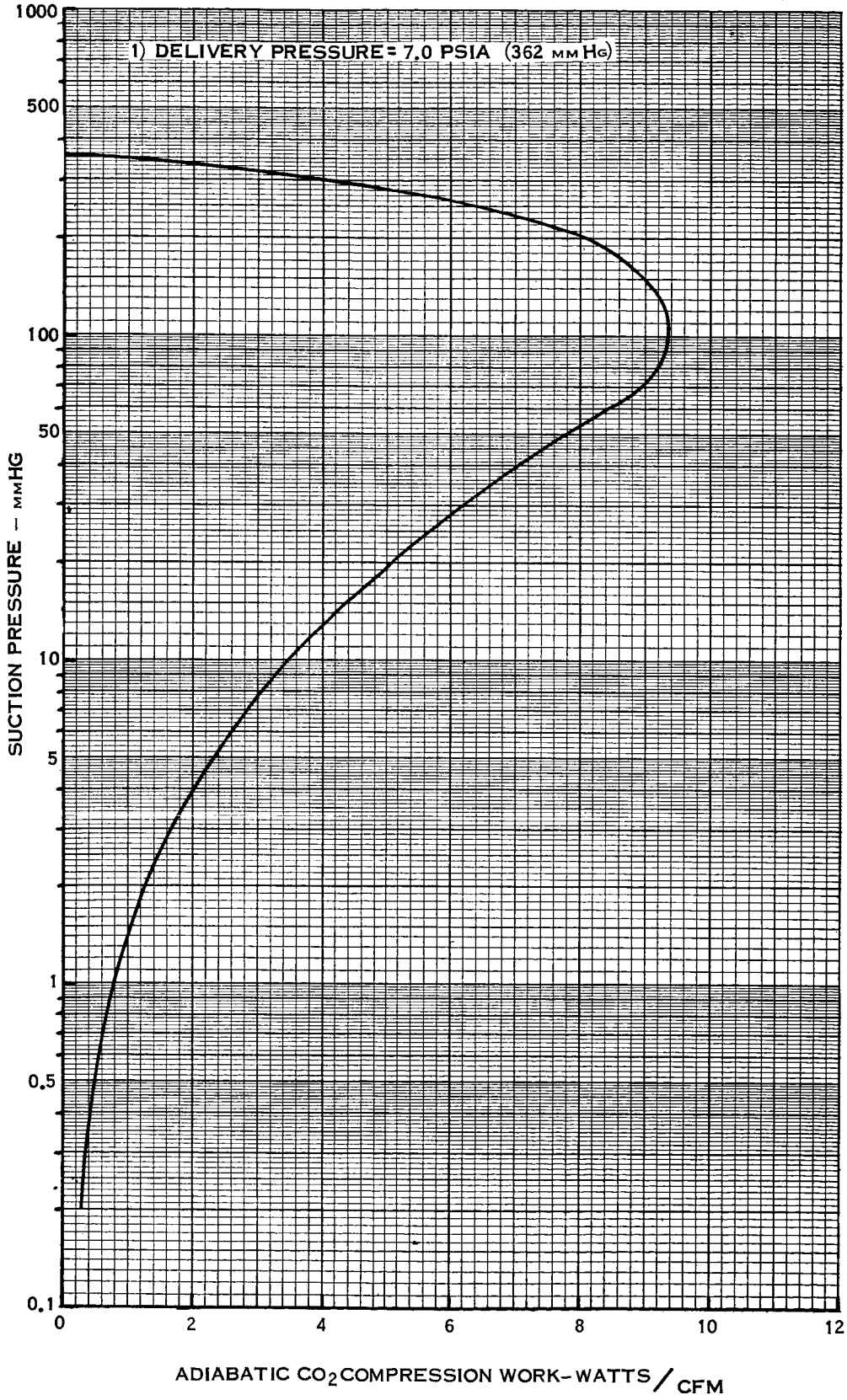


FIGURE 3–4

3.2.1 (Continued)

It was noted that pumps having the capacity required for this application have, on the whole, been developed only for industrial applications and therefore exhibit high weight characteristics. Figure 3-5 shows this variation with pump rated capacity. The information on present state-of-the-art pump capabilities came from a survey of catalogs of the leading manufacturers, including Leybold, Stokes, Consolidated Vacuum, Kinney, Veeco, and Beach-Russ. Super-imposed is a plot showing a reasonable predicted weight for spacecraft quality pumps. These figures illustrate the overall characteristics of vacuum pumps used in evaluating system performance for the study.

It is desirable during the initial portion of the CO_2 canister desorption cycle to discharge the pump to the cabin environment, since the initial pump discharge during canister pump-down is mostly cabin air which appears as canister ullage at the completion of the previous adsorption cycle. After the canister is drawn down, pump discharge is directed to the CO_2 accumulator, thus providing relatively pure CO_2. Figure 3-6 shows the pump-down characteristics for various capacity pumps and can be used in establishing cycle sequence times.

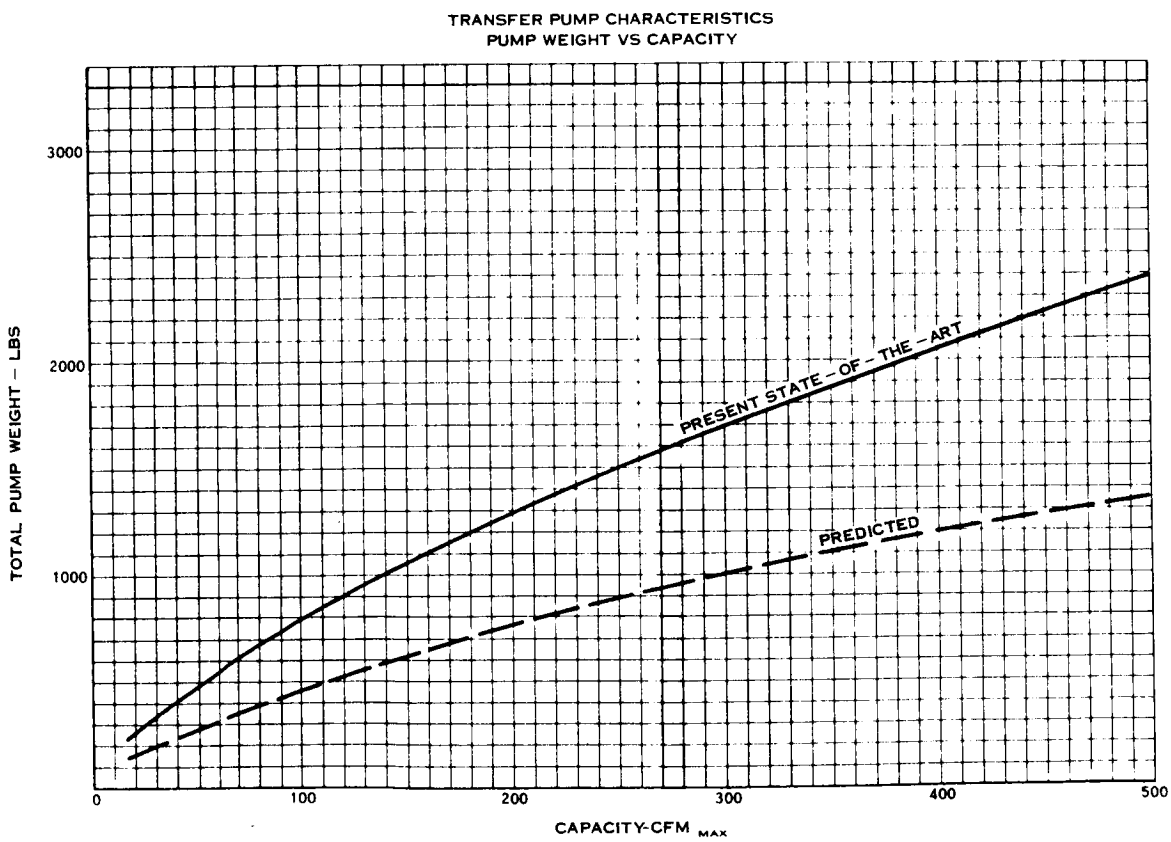


FIGURE 3–5

PUMP-DOWN CHARACTERISTICS

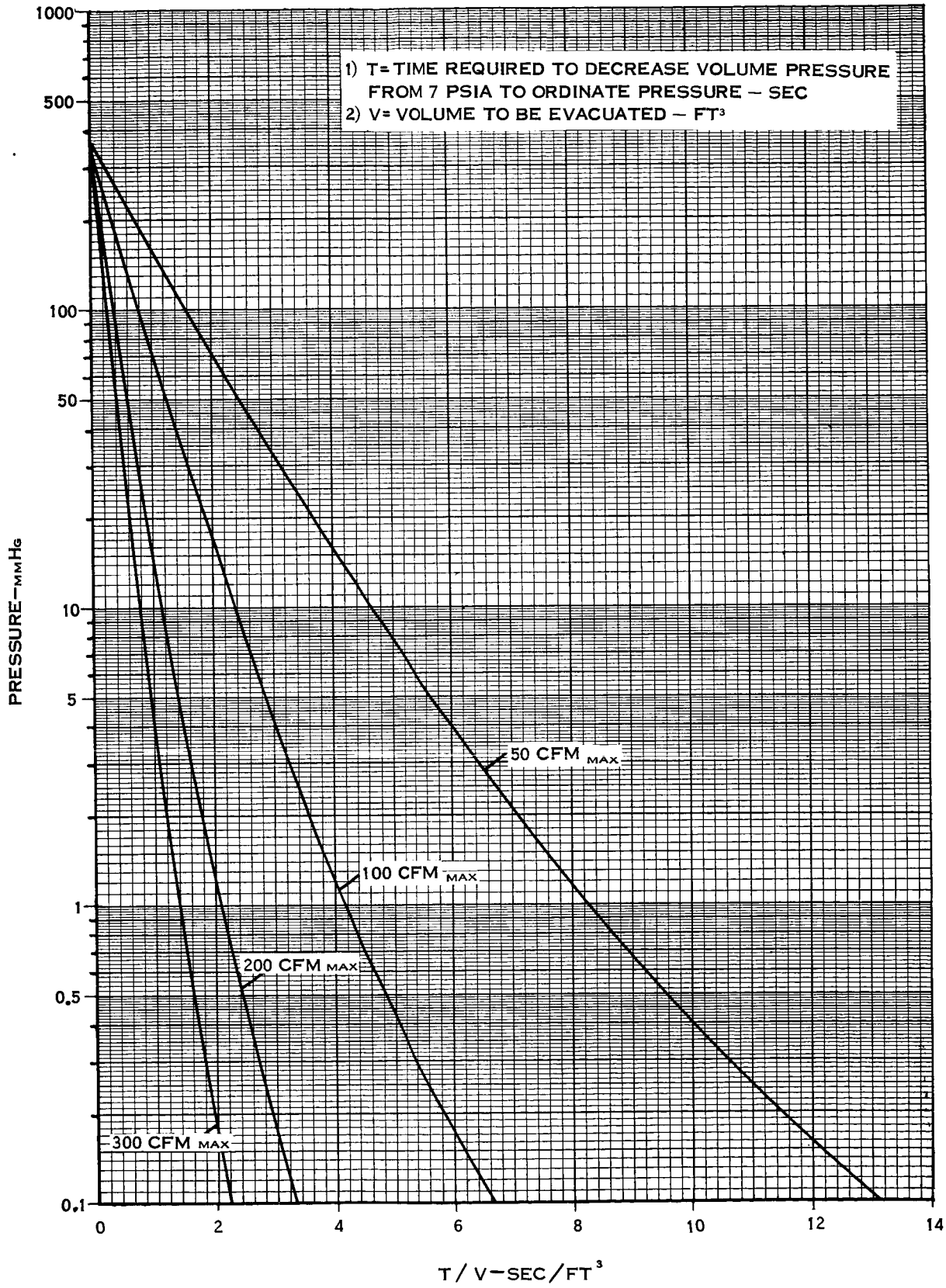


FIGURE 3–6

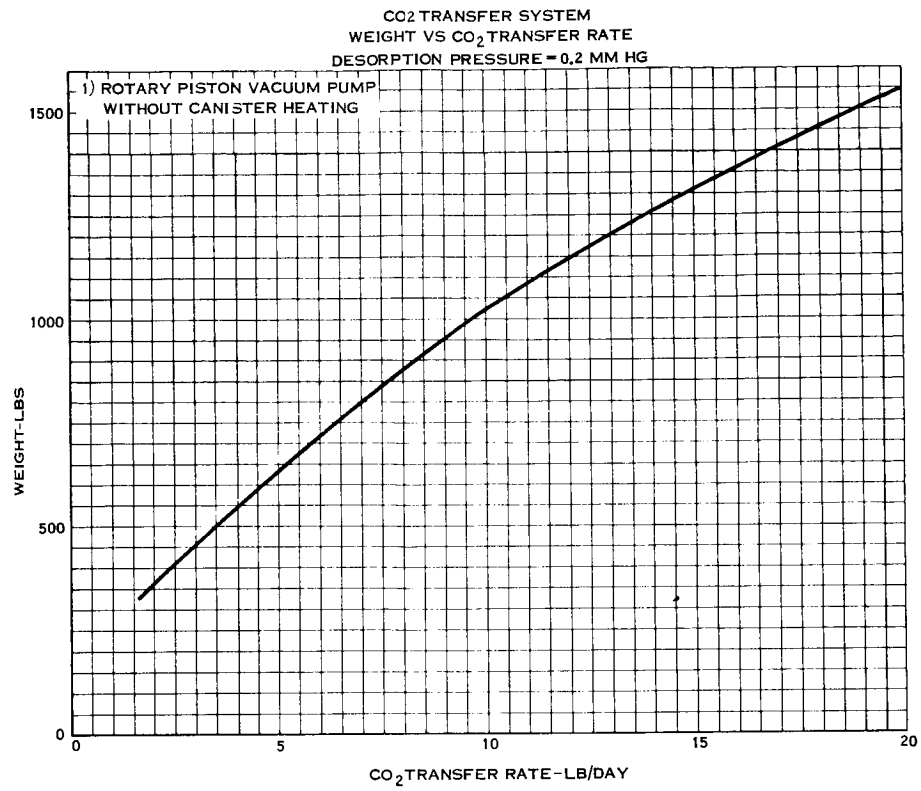


FIGURE 3–7

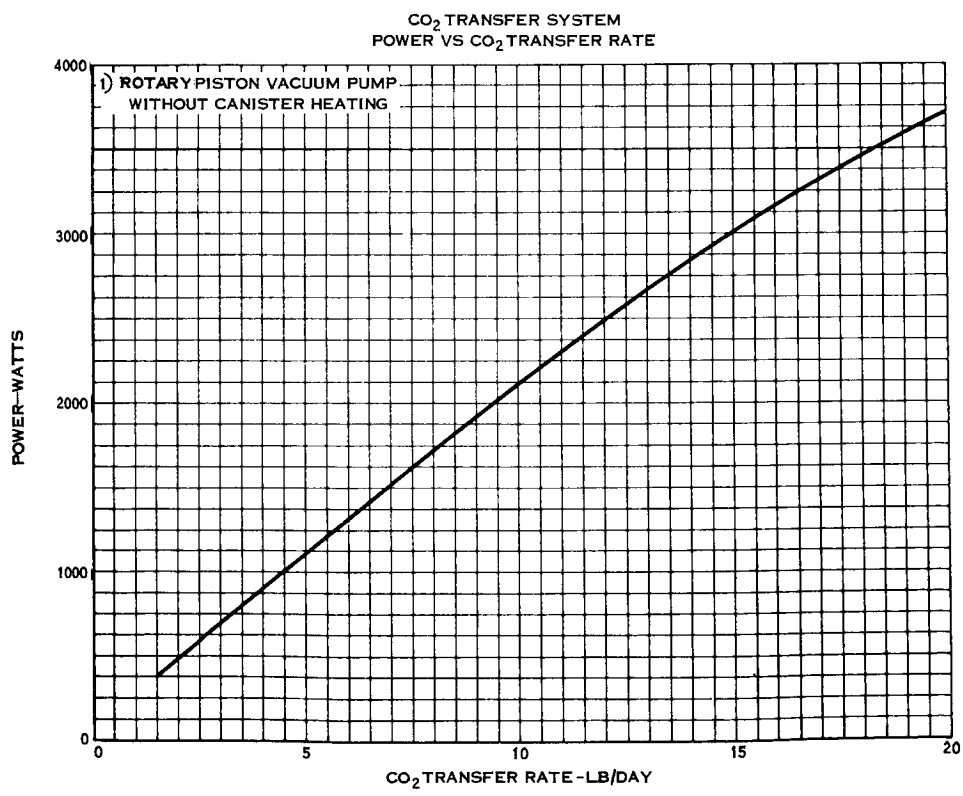


FIGURE 3–8

3.2.1 (Continued)

The results of the study of total vacuum desorption of the canisters are illustrated in Figures 3-7, 3-8, and 3-9. A review of these figures rapidly illustrates that this method is totally unacceptable for an optimum system. Fixed weight, as shown in Figure 3-7, is about 1200 pounds for a 6 man system (12.72 lbs CO_2/day). Further, the corresponding power requirement (Figure 3-8) is 2600 watts, thus yielding a total equivalent weight for 6 men between approximately 1700 and 2500 pounds, dependent upon the power supply, as shown in Figure 3-9.

The next area investigated was that of partial pumping accompanied by heated desorption.

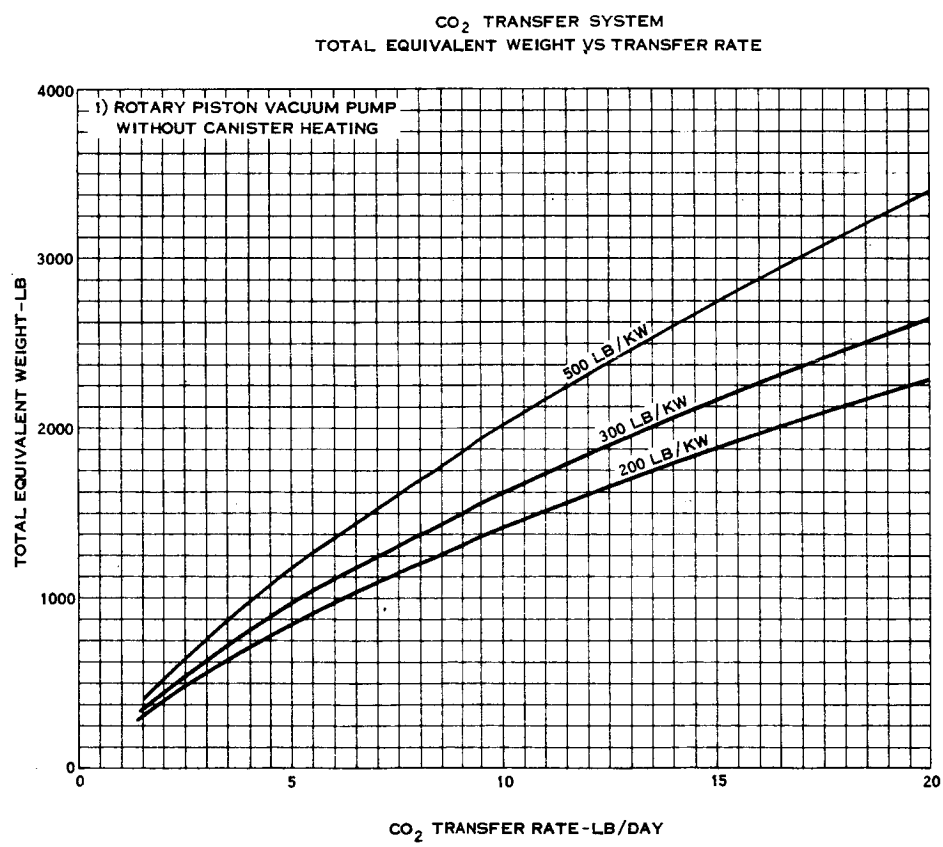


FIGURE 3 – 9

3.2.1 (Continued)

By using heat addition to the CO_2 canister during desorption, the desorption can be accomplished at a higher pressure, thus reducing pumping power but increasing heating requirements. As the desorption pressure is raised, less pumping power and lower capacity is required; therefore, a smaller weight pump can be used. Counter-acting these factors is the increase in power required to raise the bed to higher temperatures. Therefore, a trade-off can be performed to determine the optimum desorption pressure and temperature combination. Since the thermal mass of the canister is involved, the transfer system must be mated to the solid adsorption removal system to evaluate overall optimum desorption temperature and system cycle times. In the integrated systems, a portion of the pump input power is removed from the CO_2 delivery stream in the form of heat and used to aid in desorbing the silica gel canister. The optimum point of operation, of course, depends on the heating power and electrical power equivalent weight penalties.

The results of the optimization for the Mars Mission Module conditions are shown in Figures 3-10, 3-11, and 3-12 and are much more acceptable than the total pumping method. These figures illustrate the total penalties for both CO_2 removal and transfer using partial heated desorption. The method of heating was electrical only, and heating power therefore cost as much as pumping power. It was assumed that 120°F heat was available from the electronics equipment. Waste heat from the nuclear reactor was not employed in this method. The total fixed weight of removal system and pump for a 6 man system is approximately 220 pounds, which is a considerable improvement over the full pumping system. Power, as shown in Figure 3-11, is under 700 watts, of which 300 is required for electrical heating. Both of these curves yield an equivalent weight range from 340 to 575 pounds, dependent upon the power supply.

A second optimization was performed assuming that heat will be available at no power penalty in the Mars Mission. The heat source in this case would be waste heat from the nuclear reactor. Results of the optimization indicate that under these conditions, the best method of accomplishing the transfer system is that of total heated desorption with no pumping requirements.

Figures 3-13, 3-14, and 3-15 present the results of the total heating analysis from a weight, power, and equivalent weight basis (based on zero penalty for waste heat). As expected, this is the lightest weight method. The total fixed weight of the collection and transfer system is reduced to under 110 lbs. for the 6 man system. The power required is all electrical and requires a total of 95 watts. The elimination of the vacuum pump and the lower power cost presents a savings in equivalent weight of 72% to a figure of approximately 158 pounds (Figure 3-15). Thus, with heated desorption using reactor waste heat, the combined CO_2 removal and transfer penalty is less than the penalty for CO_2 removal alone shown in Section 2.0 for electrical power.

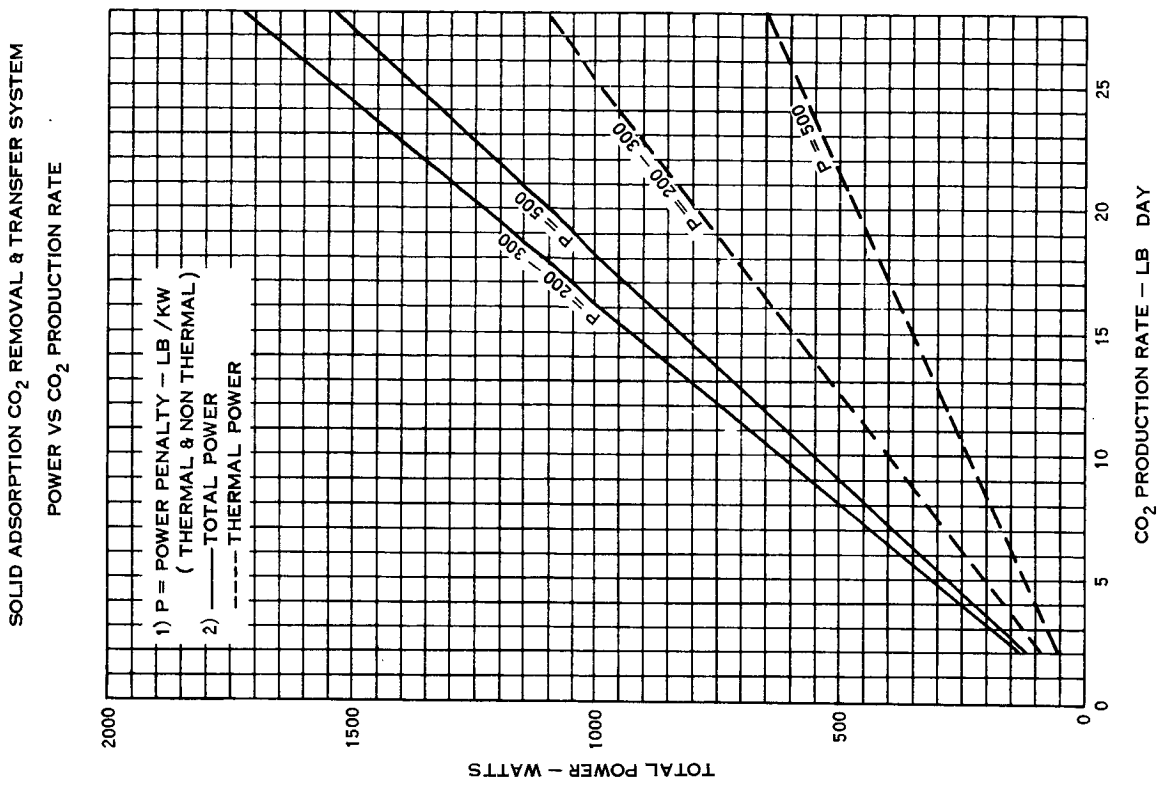


FIGURE 3–11

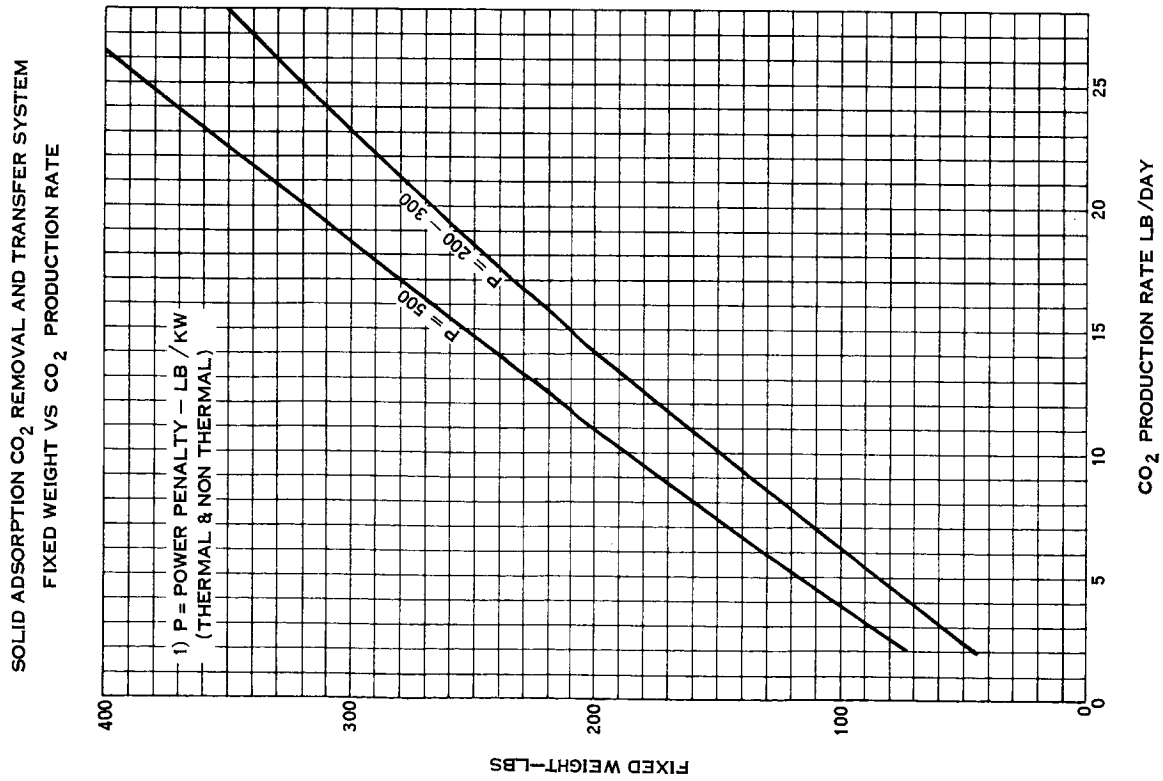


FIGURE 3–10

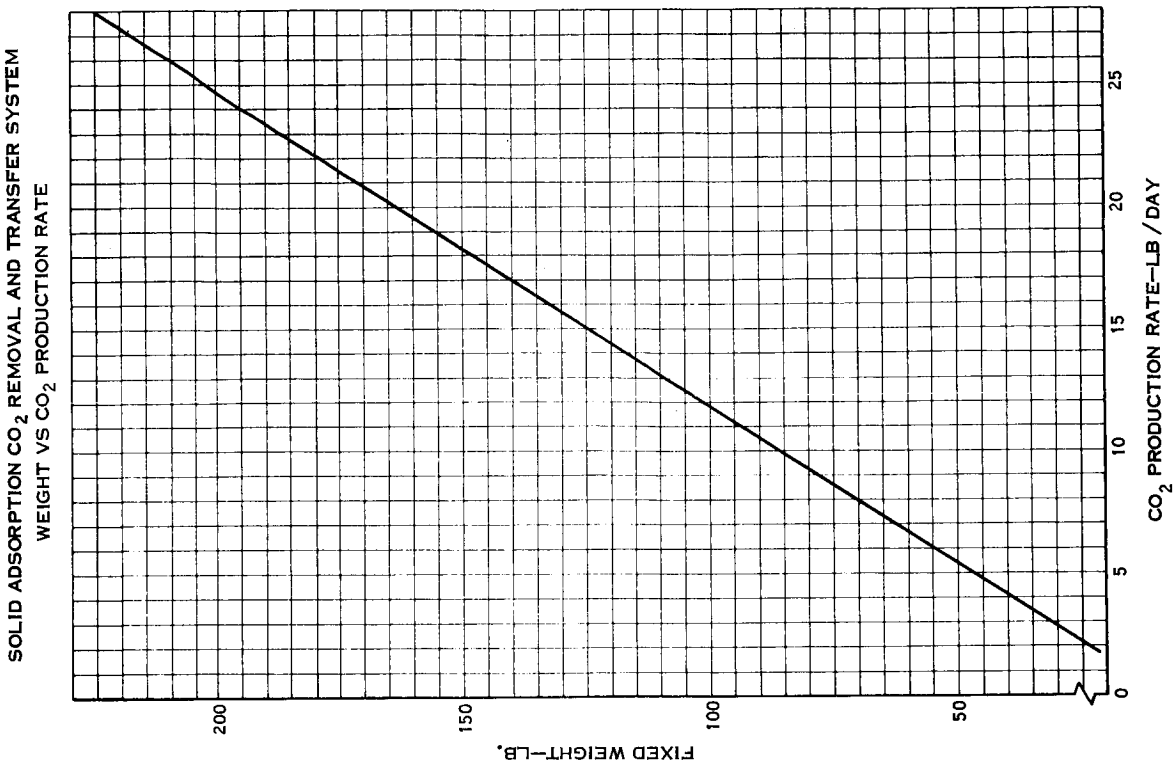


FIGURE 3-13

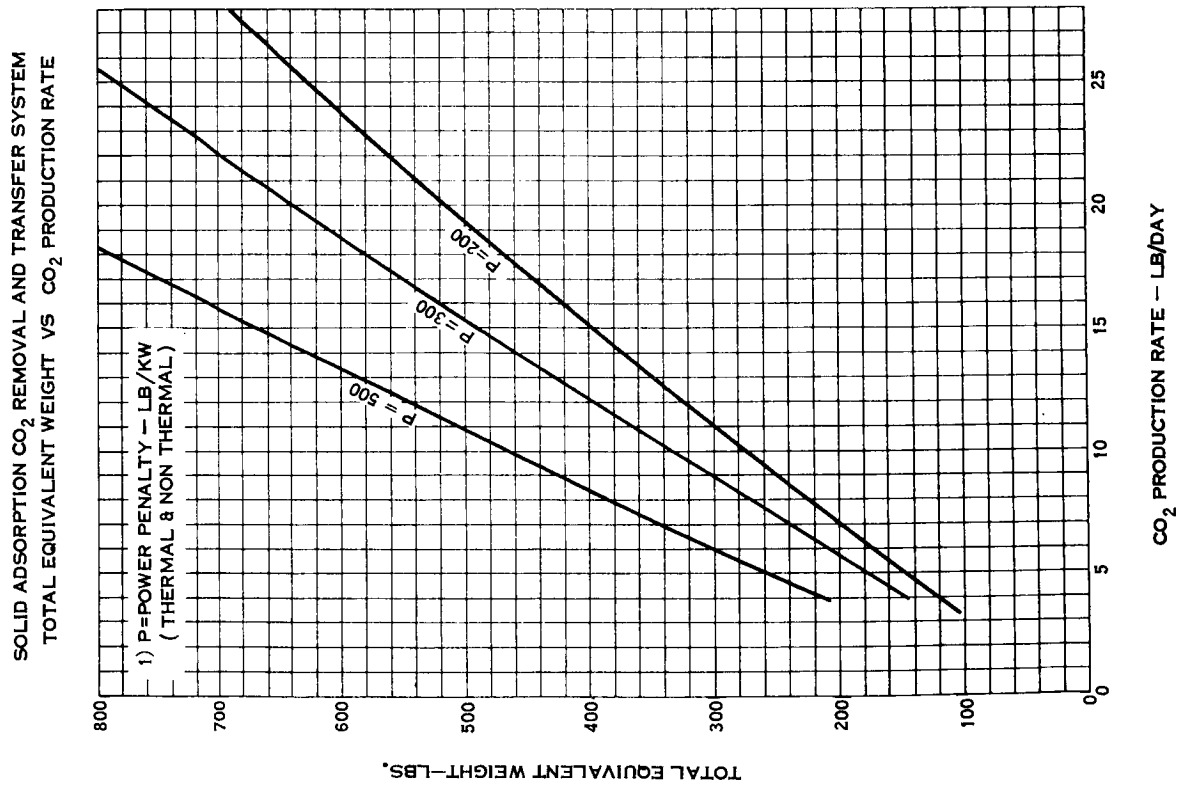


FIGURE 3-12

SOLID ADSORPTION CO_2 REMOVAL AND TRANSFER SYSTEM
TOTAL EQUIVALENT WEIGHT VS CO_2 PRODUCTION RATE

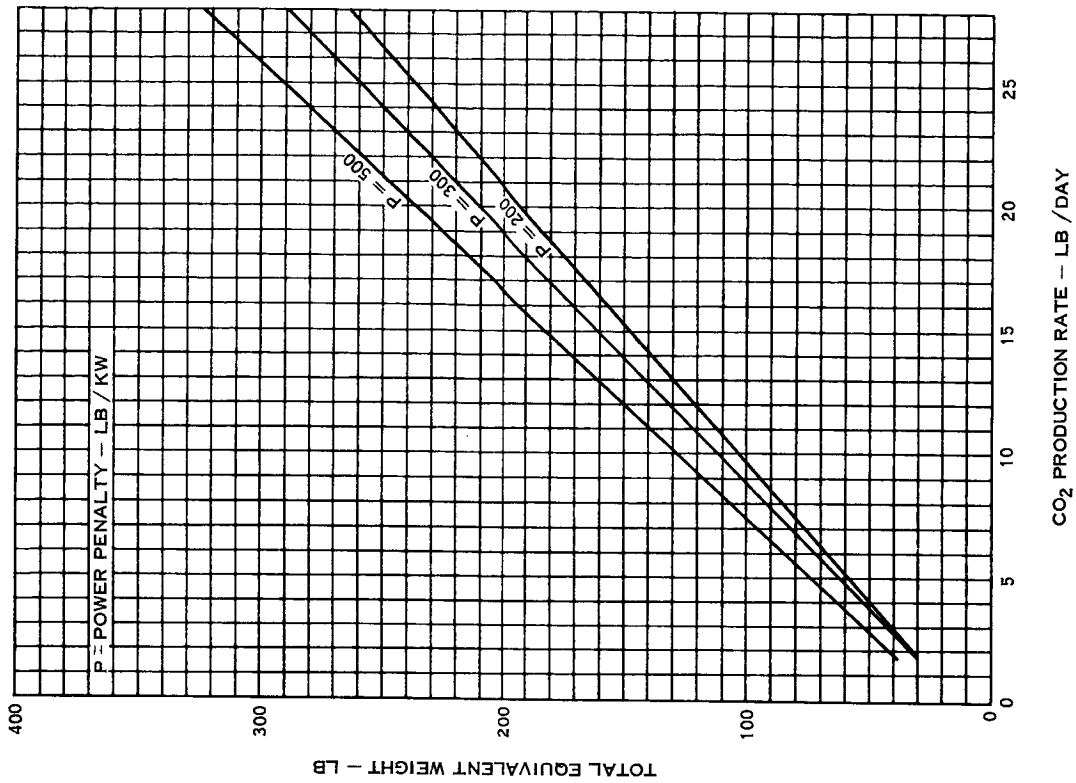


FIGURE 3–15

SOLID ADSORPTION CO_2 REMOVAL AND TRANSFER SYSTEM
POWER VS CO_2 PRODUCTION RATE

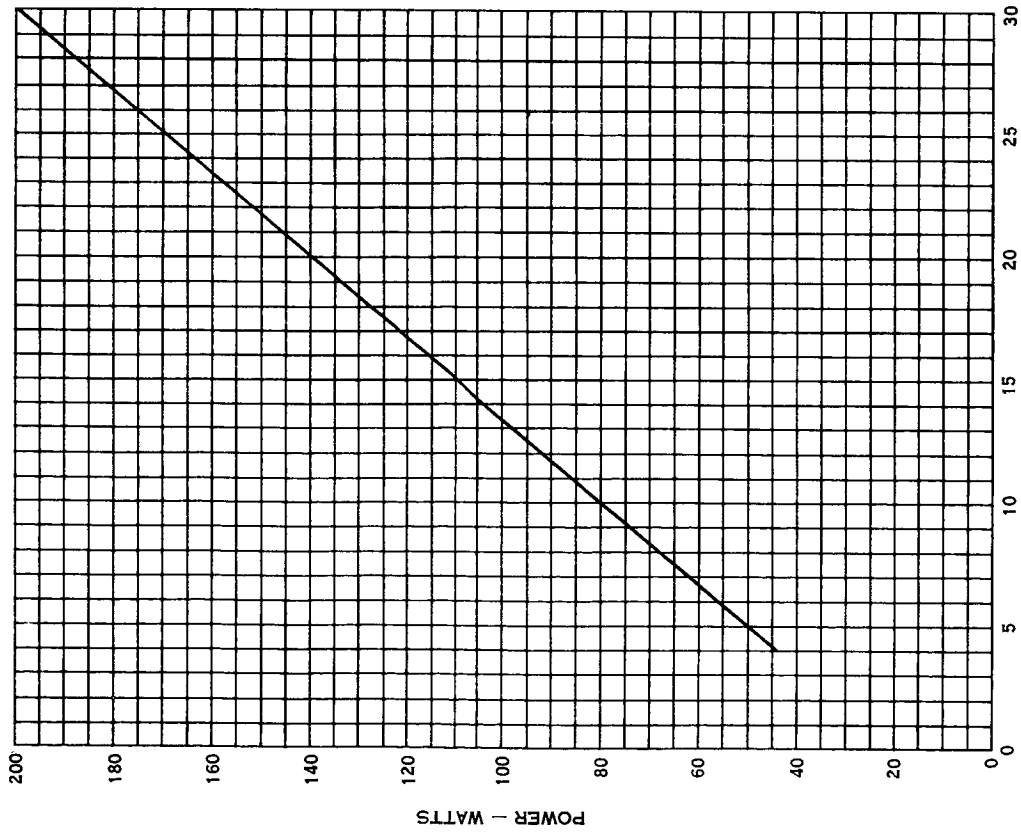


FIGURE 3–14

3.2.2 Liquid Absorption

The liquid absorption system required no complex transfer system since CO_2 is desorbed by heating the absorption fluid at essentially ambient pressure. The flow schematic is similar to that shown in Section 2.0, with the water saturated CO_2 now directed to the CO_2 reduction system. Should the reduction system require a dry delivery gas for efficient operation, a parallel pair of desiccant beds alternately cycled can be employed to dry the CO_2 stream. The heat necessary for regenerating the absorption fluid is supplied by reactor heat at zero cost.

The results of the system optimization for the Mars Mission Module conditions are shown in Figures 3-16 through 3-18. The fixed weight curve shows a relatively small increase with CO_2 process rate since the absorption liquid flow is kept constant. The weight increase can be attributed to an increase in contactor length and process air flow rate. The regenerable heat exchanger, contactor, and liquid inventory make up approximately two-thirds of the total system fixed weight. The combination of low fixed weight and relatively low electrical power penalties make the total equivalent weight attractively low, as shown in Figure 3-18.

3.2.3 Electrodialysis

The electrodialysis removal system also provides for CO_2 transfer at system pressure. The flow schematic is similar to that shown in Section 2.0. However, if the hydrogen is used in the CO_2 reduction system (Bosch & Methoxy systems), the cell effluent CO_2 and hydrogen flow can be combined and passed through a single liquid gas separator. CO_2 delivered to the reduction system is saturated with water. Should drying be required for efficient reduction system operation, a pair of desiccant beds in a parallel flow arrangement can be alternately cycled

The fixed weight, power, and total equivalent weight are shown in Figures 3-19 through 3-21. The equivalent weight is quite high relative to other methods of CO_2 management. However, as has been previously noted in Section 2.0, the electrolysis of water is an integral function of system operation. Therefore, when the system is integrated into an overall environmental control system requiring a water electrolysis capability, a credit penalty reduction can be applied to the electrodialysis unit. This is shown in the aforementioned figures for porous electrode electrolysis cell penalties. In the optimization procedure, it was noted that the optimum electrodialysis cell current density for minimum total equivalent weight was approximately the same for the three power penalties (200, 300, and 500 lbs/KW) considered. However, in applying credit for water electrolysis, the porous electrode electrolysis cell optimum current density was found to be quite sensitive to varying power penalty. This is reflected in the curves, which show the credit for the three power penalties.

LIQUID ABSORPTION CO_2 REMOVAL AND TRANSFER SYSTEM
POWER VS CO_2 PRODUCTION RATE

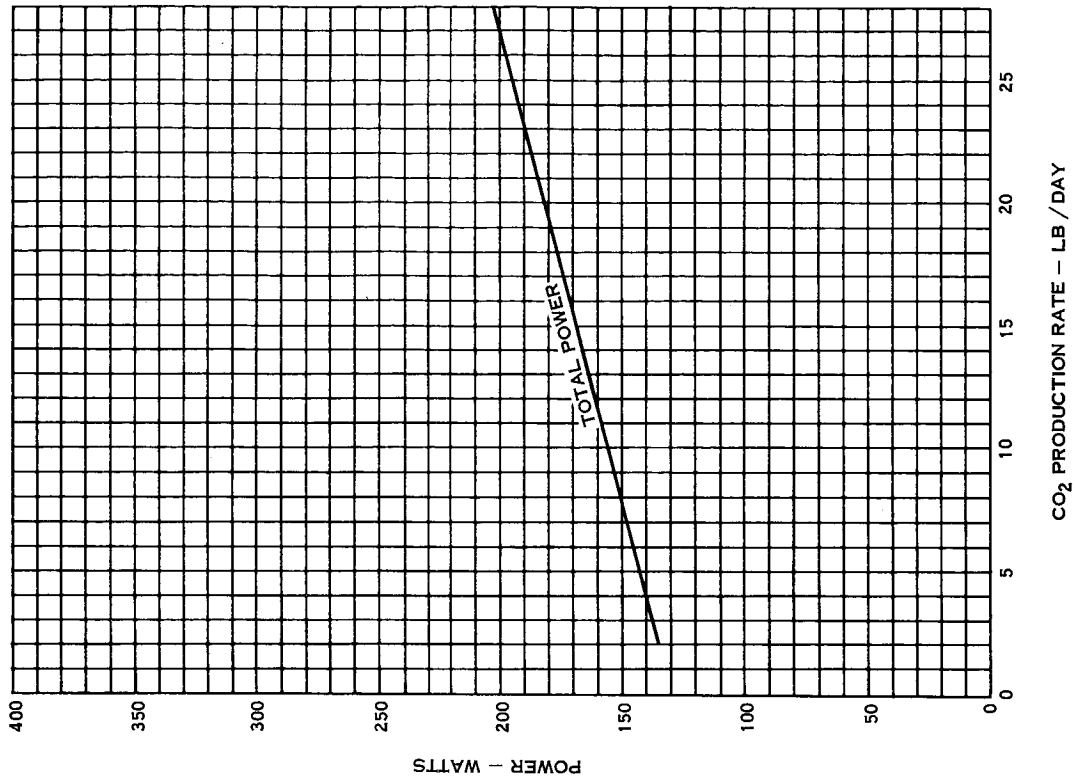


FIGURE 3–17

LIQUID ABSORPTION CO_2 REMOVAL AND TRANSFER SYSTEM
WEIGHT VS. CO_2 PRODUCTION RATE

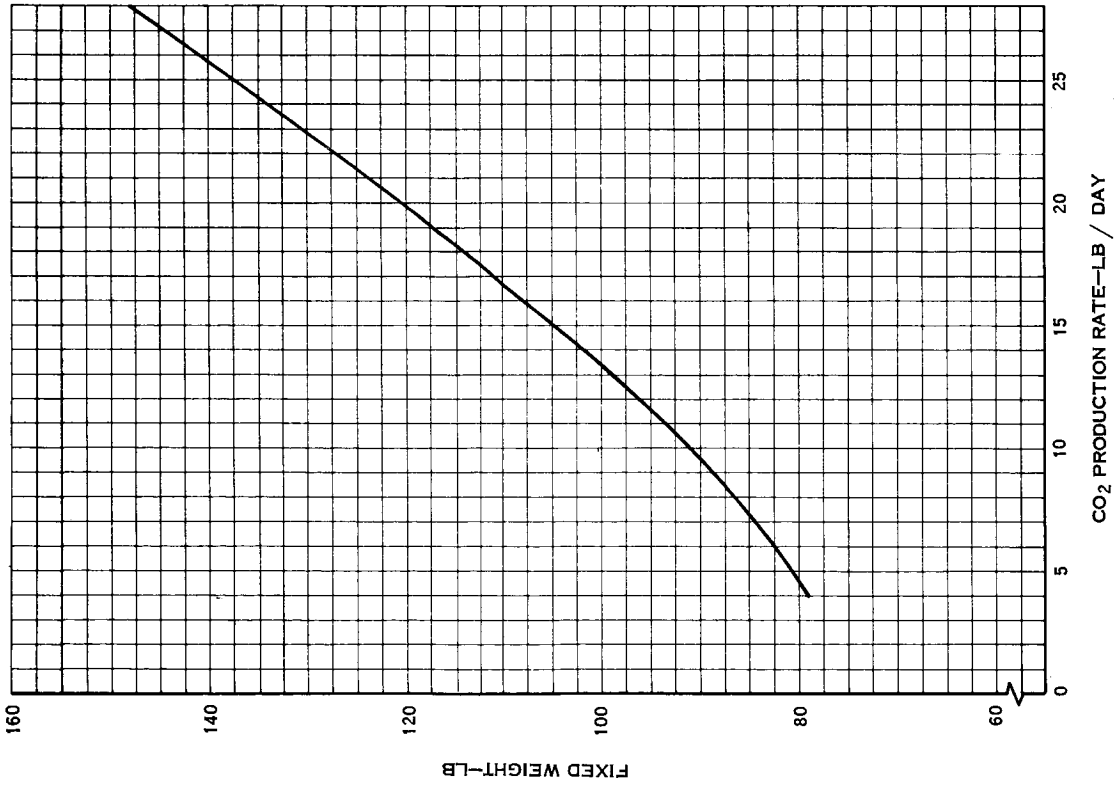


FIGURE 3–16

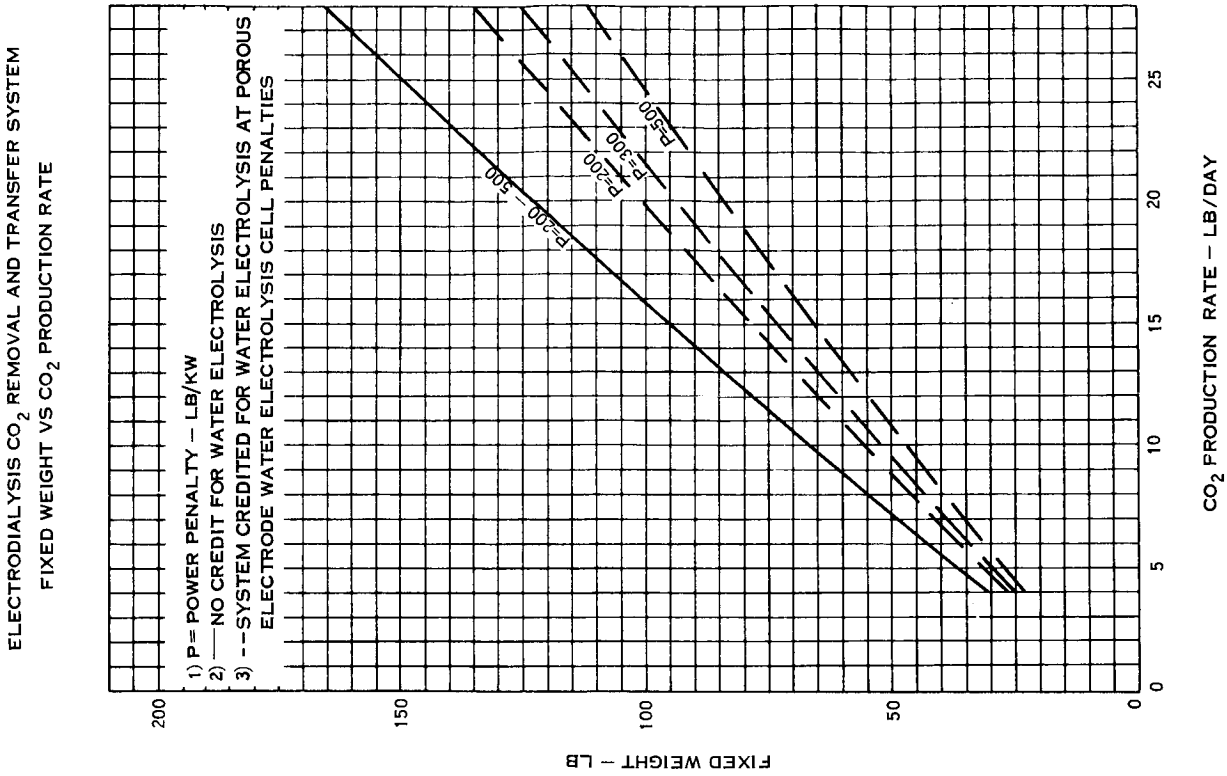


FIGURE 3–19

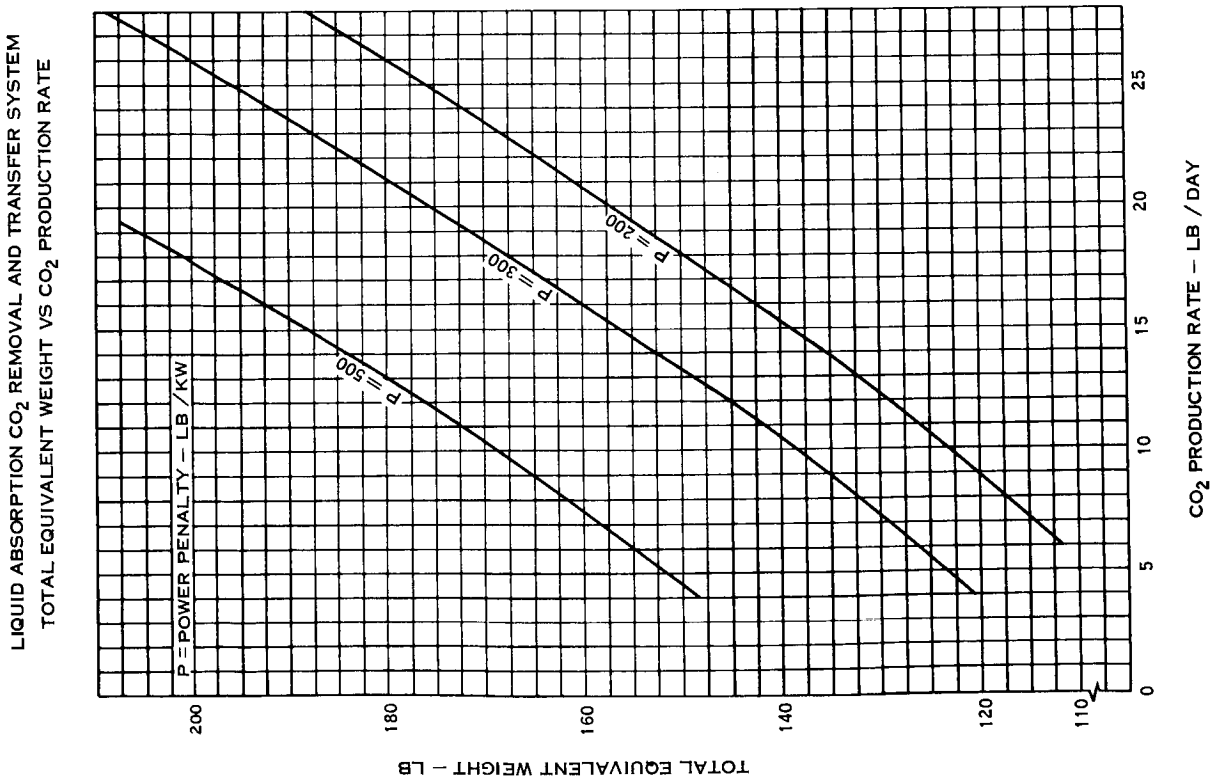


FIGURE 3–18

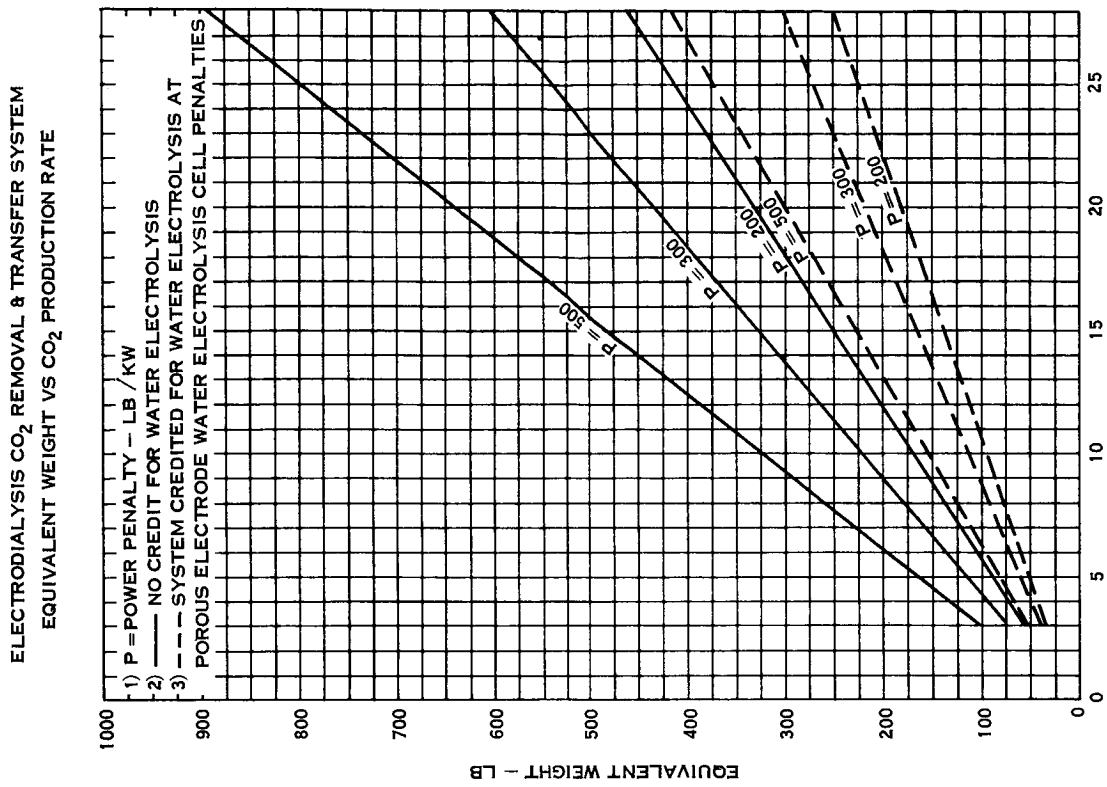


FIGURE 3–21

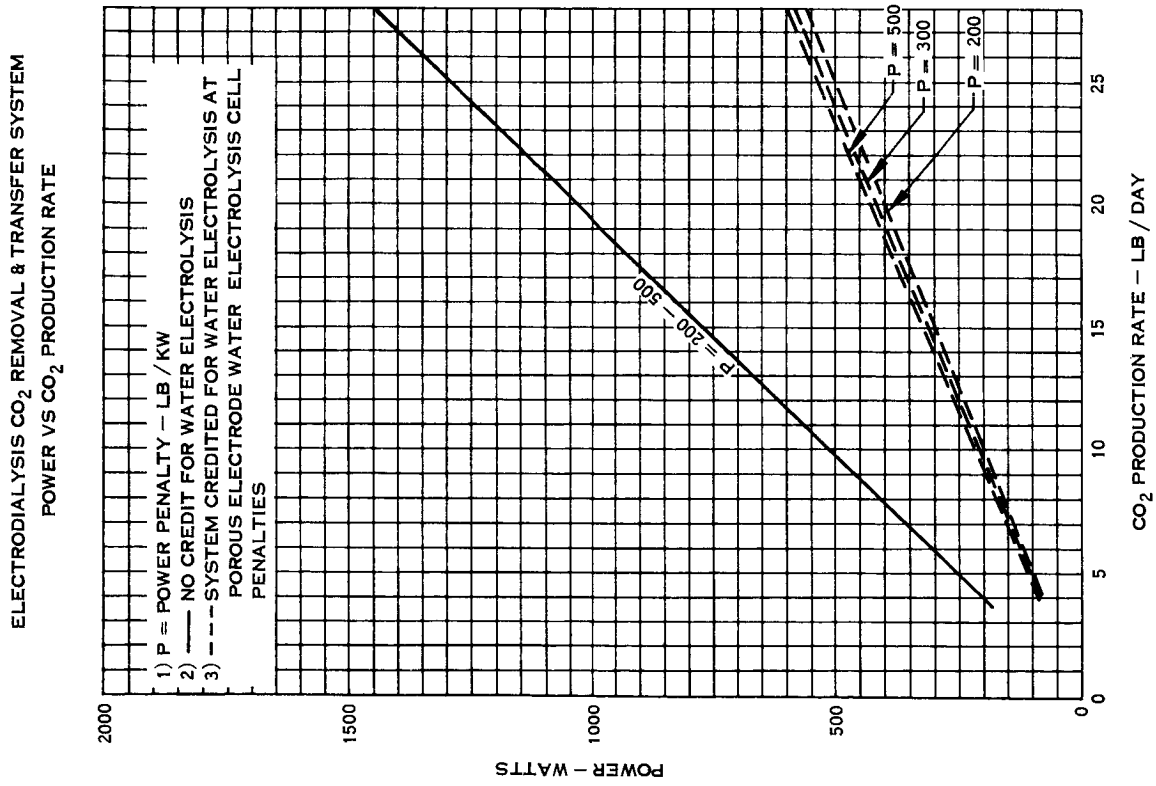


FIGURE 3–20

3.2.3 (Continued)

The fixed weight, power, and total equivalent weight are shown in Figures 3-19 through 3-21. The equivalent weight is quite high relative to other methods of CO_2 management. However, as has been previously noted in Section 2.0, the electrolysis of water is an integral function of system operation. Therefore, when the system is integrated into an overall environmental control system requiring a water electrolysis capability, a credit penalty reduction can be applied to the electrodialysis unit. This is shown in the aforementioned figures for porous electrode electrolysis cell penalties. In the optimization procedure, it was noted that the optimum electrodialysis cell current density for minimum total equivalent weight was approximately the same for the three power penalties (200, 300, and 500 lbs/KW) considered. However, in applying credit for water electrolysis, the porous electrode electrolysis cell optimum current density was found to be quite sensitive to varying power penalty. This is reflected in the curves, which show the credit for the three power penalties.

3.3 CO_2 Collection and Transfer System Comparison

Figures 3-22 through 3-24 present a comparison of the candidate removal and transfer systems with waste heat desorption. Comparison of the three systems (liquid absorption, solid adsorption, and electrodialysis with credit for the water electrolyzed), show that, at the 6 man design process rate of 12.72 pounds per day, the equivalent weights are within 20 pounds. In the case of the liquid absorption system, however, a flatter slope of total equivalent weight with CO_2 process rate exists. The result of this is a 70 pound reduction of total equivalent weight over the solid adsorbent at a 28 pound per day CO_2 process rate.

In order to obtain a more complete perspective of available CO_2 collection and transfer systems, other factors such as development status and delivery condition of the CO_2 must be considered. Since the reduction systems are sensitive to quantities of moisture and cabin air in the transported CO_2, these quantities can be used as a point of comparison. This is discussed in Section 6.0 on CO_2 management.

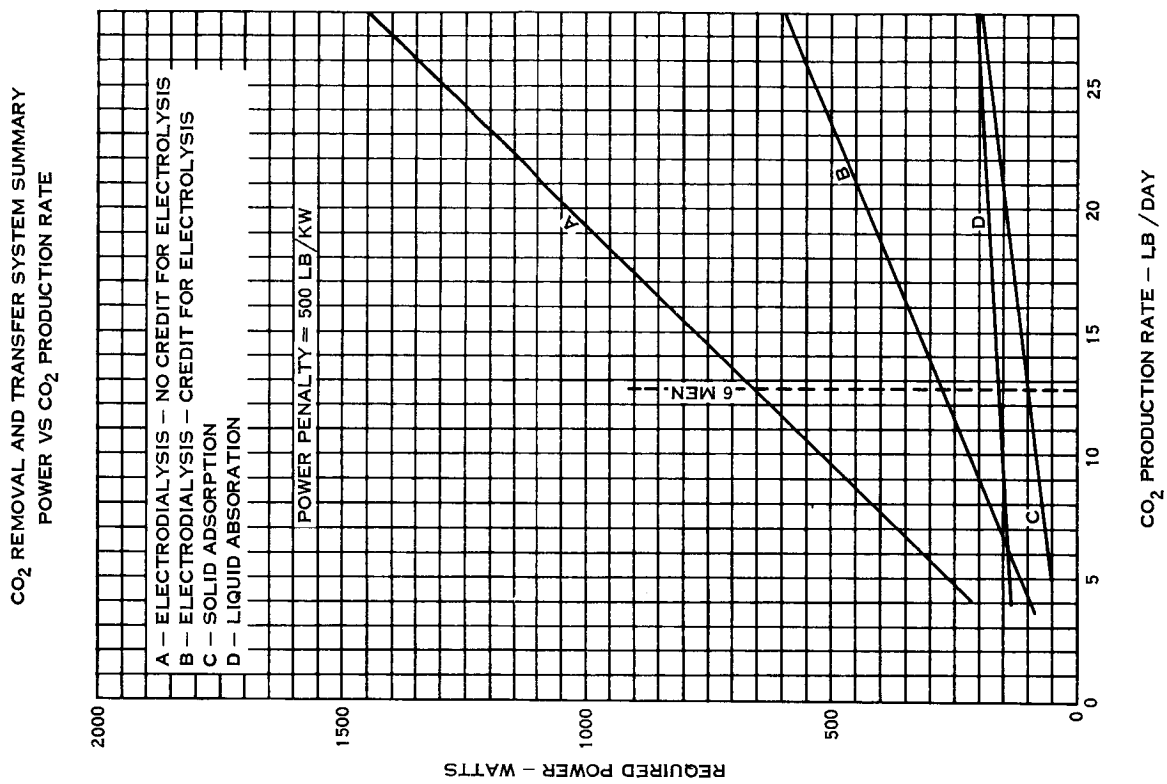


FIGURE 3–23

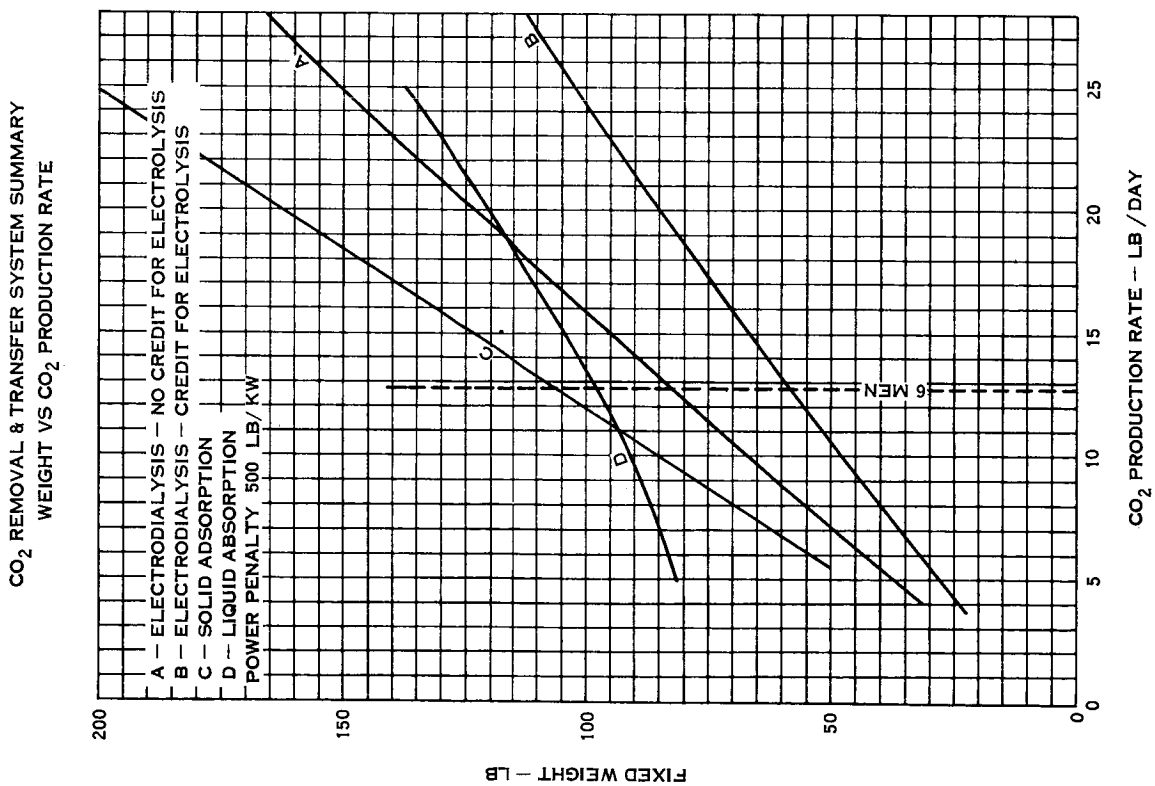


FIGURE 3–22

CO_2 REMOVAL AND TRANSFER SYSTEM
TOTAL EQUIVALENT WEIGHT VS CO_2 PRODUCTION RATE

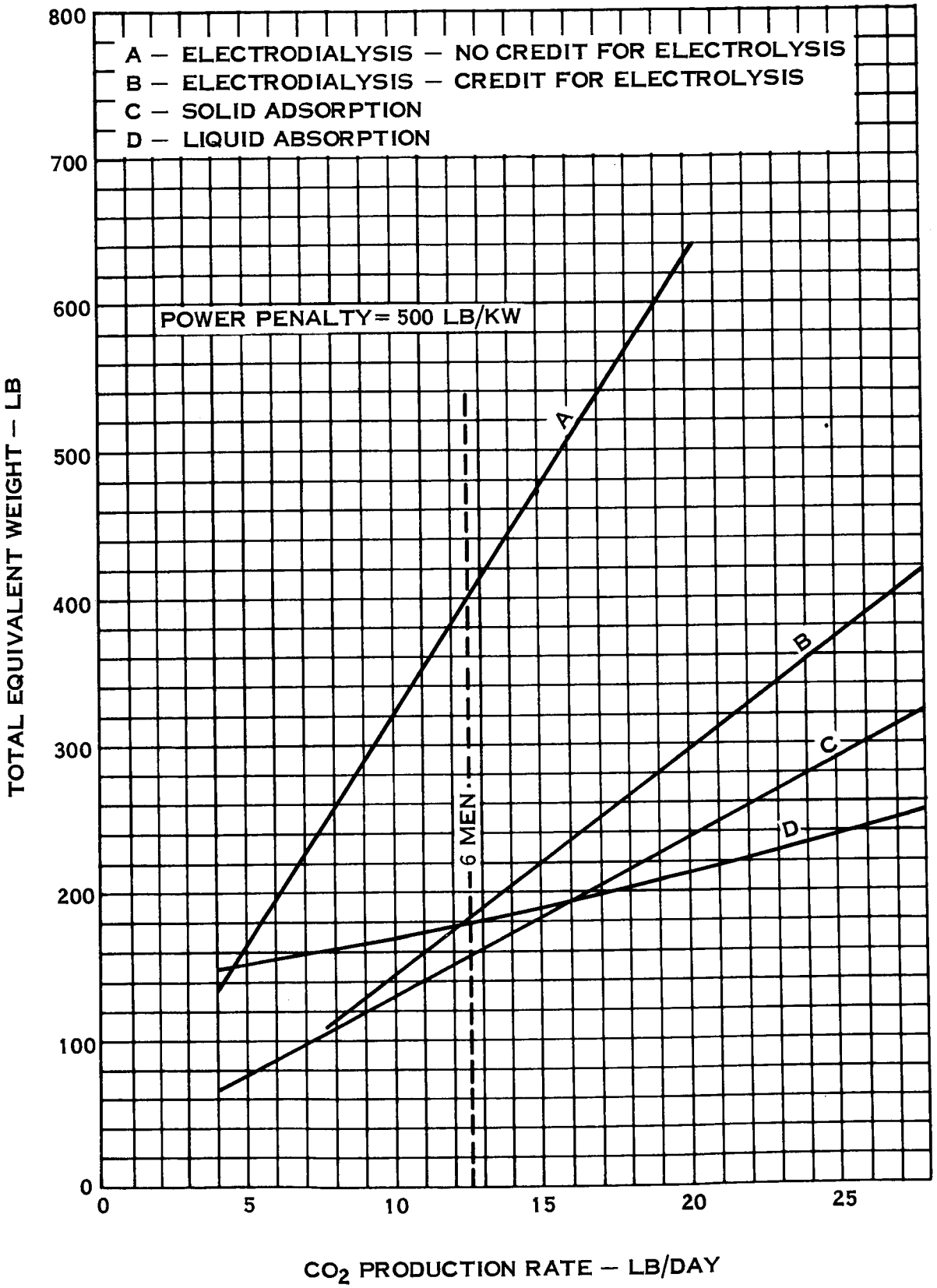


FIGURE 3–24

SECTION 4.0

WATER ELECTROLYSIS

4.0 WATER ELECTROLYSIS

4.1 General

4.2 Objectives

The study of water electrolysis systems takes a different approach than that of many of the other subsystem investigations. Water electrolysis is, in principle, one approach (that of dissociating water into hydrogen and oxygen), and cannot readily be examined using many different principles or theories. The basic problem is the determination of a best approach to the electrolysis problem of the many variations being considered throughout industry.

Electrolysis systems are of primary interest for this study for two applications. The first application is as a potential oxygen generation device replacing the more conventional stored oxygen thus allowing water to be stored rather than cryogenic or gaseous oxygen at elevated pressures. The second area of interest for water electrolysis systems is as a portion of certain CO_2 reduction systems. CO_2 reduction equipment using hydrogenation processes produces water as an intermediate product. Thus, it becomes necessary to dissociate the water to provide oxygen and also to regenerate the hydrogen for recycling within the system.

For purposes of this study, a review of the various electrolysis approaches being taken throughout industry was necessary to determine the potential weight, power, and equivalent weight characteristics of electrolysis systems to be used in further system integration work. An analysis presents an optimization of each of the approaches to determine minimum weight points and then selection of a representative approach for amplification into working data for the rest of the system integration study. By pursuing the study in this fashion, the output of this subsystem phase is sufficient design data for integration in open system oxygen supply equipment or closed system CO_2 reclamation equipment.

4.1.2 Discussion of Data Presentation

The organization of this section is somewhat different from other sections in that a basic description of electrolysis processes precedes the discussion of the various approaches considered. This is possible due to the similarity of all the processes in basic principles.

For each electrolysis method considered, an optimization of system equivalent weight is presented to allow determination of the minimum point for current state-of-the-art equipment and, in many cases, for predicted performance of improved equipment in the future. Each variation is accompanied by a brief description of its particular processes and a simplified schematic approach to system operation

4.1.2 (Continued)

to allow understanding of the differences.

The final data presentation to be utilized for further subsystem integration work takes two forms. The first form is an illustration of the weight and power requirements as a function of the metabolic requirements for the crew. This will illustrate the weight penalties for the open system approach. Secondly, the data is presented to illustrate the fixed weight, power, and equivalent weight as a function of the amount of water processed by the system. Presentation of the data in this manner is more general and allows more flexibility of use in integration with CO_2 reduction systems. The usage of both sets of data allows consideration of water electrolysis for both major applications.

4.1.3 General Discussion of Process

Electrolysis is an electrochemical process by which water can be dissociated into its basic elements, hydrogen and oxygen. The gross process may be written on a mole basis as $H_2O \rightarrow H_2 + 1/2\ O_2$, or on a weight basis as $H_2O \longrightarrow .111\ H_2 + .889\ O_2$.

To allow the electrolysis process to proceed, the water must be ionized to form an electrolyte. This is normally accomplished by the addition of an acid or base such as sulfuric acid or potassium hydroxide. In the latter case, reaction is as follows: $H_2O + KOH \rightarrow 2OH^- + H^+ + K^+$. In the electrolysis cell, reactions occur at an anode and cathode. At the cathode, the hydrogen ions combine with free electrons to form hydrogen whereas at the anode the hydroxyl ion loses an electron to form gaseous oxygen and water.

The potential difference required between the anode and cathode is a function of the electrode material and shape, the electrolyte itself, the electrolyte temperature and pressure, and the electrode current density. The theoretical potential difference based on free energy considerations is 1.225 volts at 14.7 psia and 72°F, and varies with pressure and temperature as indicated in the Figures 4-1 and 4-2. In actual practice, the voltage required is in the range from 1.5 to 3 volts dependent upon the previously mentioned parameters. The actual voltage will decrease with an increase in temperature or an increase in pressure. This is true since bubble size is decreased with increased pressure and the electrical resistance of the electrolyte is thereby decreased. This is in contrast to the fact that theoretical voltage shows an increase with pressure.

The basic problem in operating a conventional electrolysis unit under zero gravity conditions is the separation of the evolved gas from the electrolyte. This is the main area of difference between the various systems being developed in industry today for space application. The schemes utilized range from liquid-gas separation through an

H_2O ELECTROLYSIS SYSTEM
REVERSIBLE CELL POTENTIAL CHARGE VS. PRESSURE

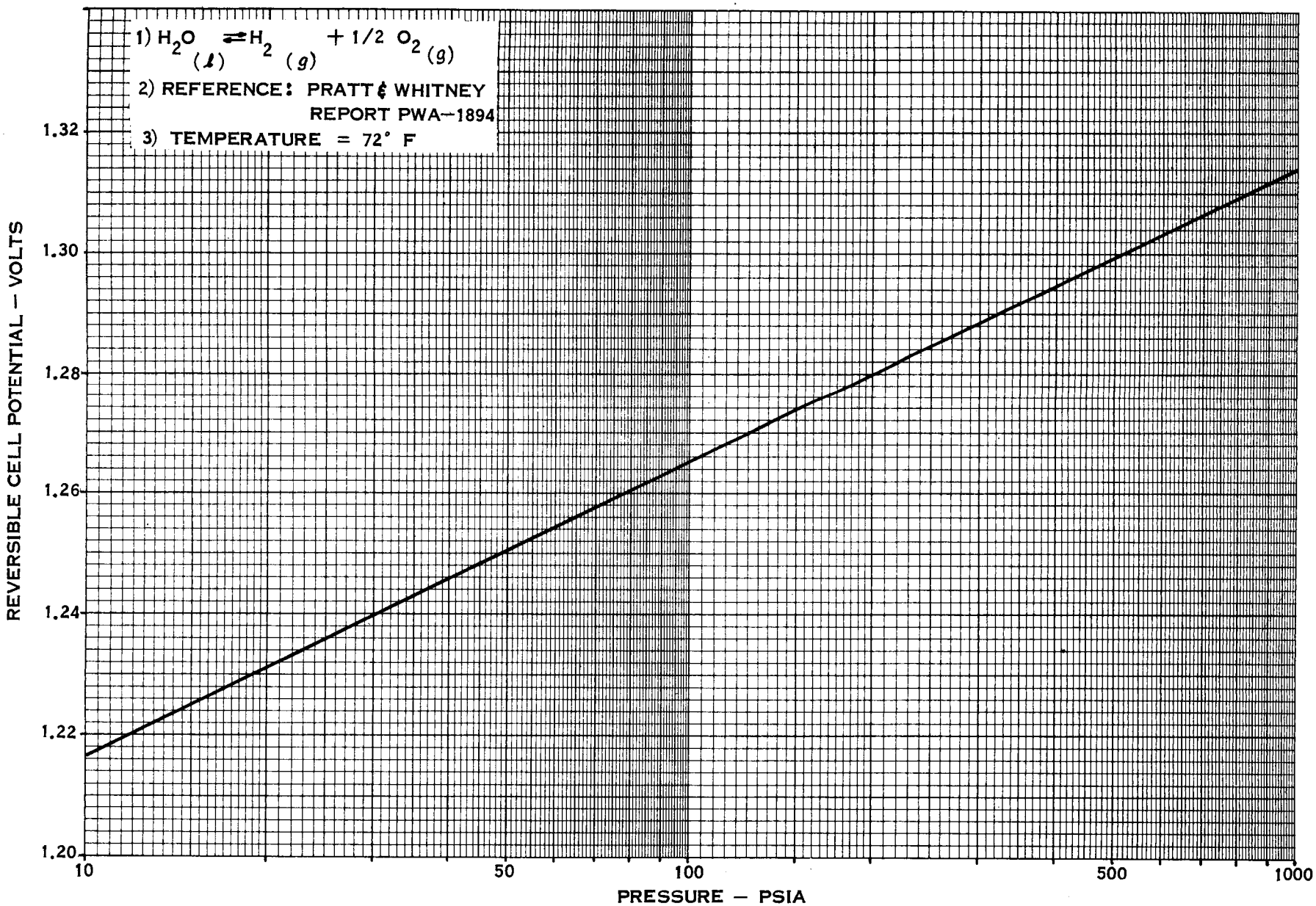


FIGURE 4–1

H_2O ELECTROLYSIS SYSTEM
REVERSIBLE CELL POTENTIAL VS. TEMPERATURE

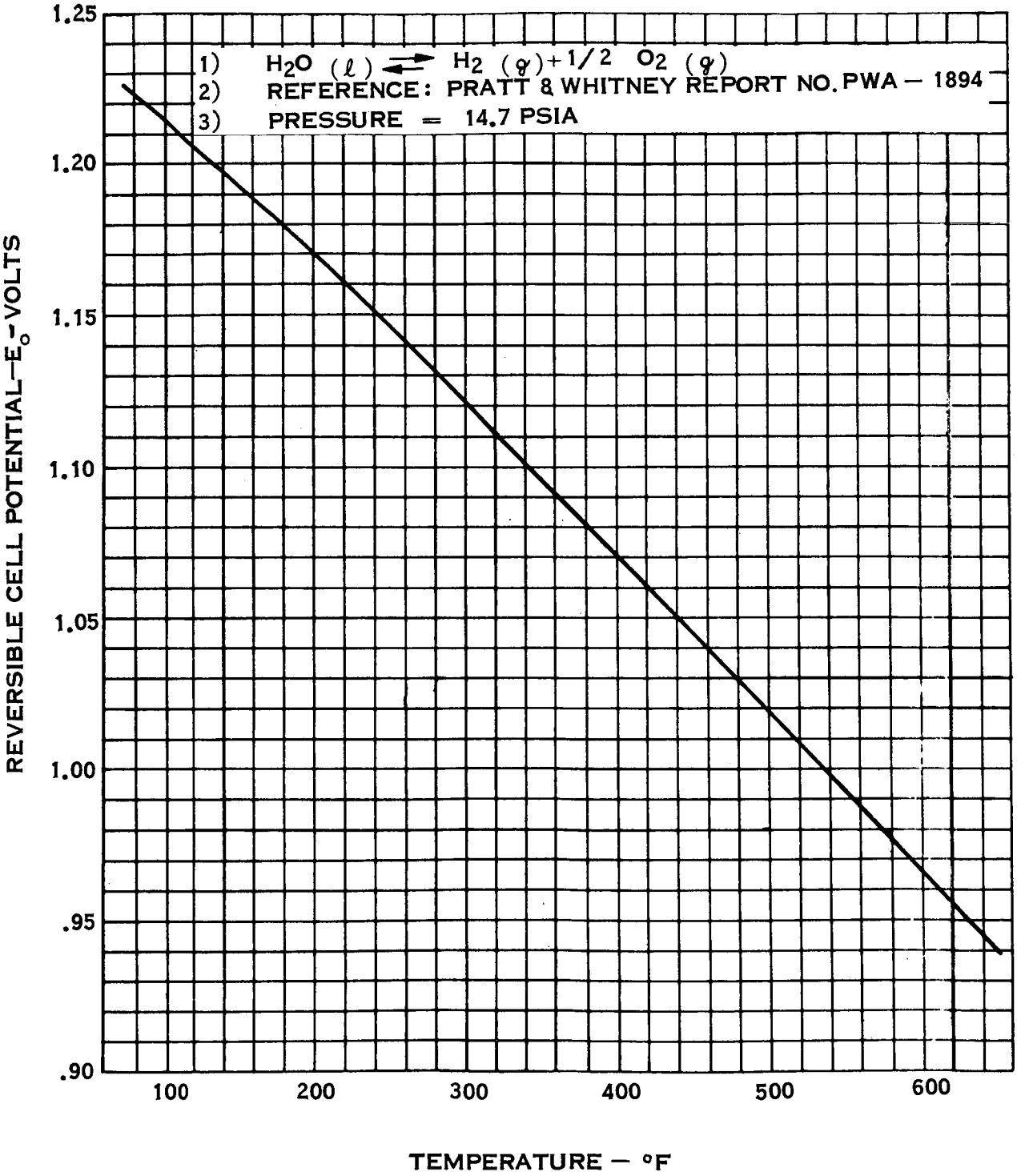


FIGURE 4—2

4.1.3 (Continued)

artificial gravity field to the use of selective ion transfer membranes. Operation of these systems in a one "g" environment indicates potential adaptability to zero gravity operation. However, none of the current units have been run for a long enough period, or under simulated spacecraft installation conditions to demonstrate satisfactory reliability for long missions.

To arrive at a selection of a typical system approach, the initial comparison was made on the basis of equivalent weight over a range of power penalties and subsystem availability. For this phase of the study, weight penalties for the water storage equipment have not been included since the amount of stored water required is dependent upon the system into which the electrolysis unit is eventually integrated. This allows more flexibility of use in later applications.

The current or faradayic efficiency for the systems investigated is between 99 and 100%. Therefore, the relationship between water consumed and oxygen produced may be calculated from the chemical equation for the reaction. The electrode potential difference increases with current density for all the cells investigated and is the cause of the increase in power equivalent weight with current density. The only variation of the equivalent weight with extended mission duration may be brought about by reliability requirements, leading to sturdier construction for longer missions.

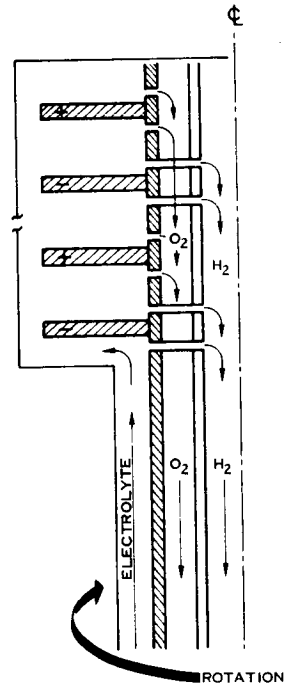
4.2 Rotating Electrolysis Cell with Conventional Electrodes

The analysis of this particular electrolysis approach is based upon two Air Force contracts performed by Battelle Memorial Institute and the AiResearch Manufacturing Co. The reports "Research on the Electrolysis of Water Under Weightless Conditions" Report No. MRL-TDR-62-44 by Battelle and "Analytical Methods for Space Vehicles Atmospheric Control Processes" Report No. ASD-TR-61-162 by AiResearch provided the basic data utilized in analysis of this approach.

The unit is a conventional type electrolysis cell, which is rotated as illustrated in Figure 4-3 to provide a hydrostatic pressure gradient in the electrolyte, so that the oxygen and hydrogen bubbles will flow toward the center of rotation and thus separate from the electrolyte. The electrolyte considered is a 28% (By Weight) solution of potassium hydroxide in water. This solution provides maximum conductance. The laboratory model design current density is 36.6 amp/ft^2 and the maximum current density that was obtained during testing is 59 amp/ft^2.

Figure 4-4 illustrates the optimization of this system approach to determine the lowest equivalent weight operating parameter. As seen in the figure, the optimum

4.2 (Continued)



ROTATING H_2O ELECTROLYSIS CELL

FIGURE 4-3

equivalent weight occurs at a density of 195 amp/ft.^{2} at the power penalty under consideration (500 lbs/KW). Since no indication of polarization at 59 amps/ft.^{2} was noted and other similar electrolysis cells have been successfully operated at higher current densities, it was assumed that the system would be capable of successful operation at the higher (optimum) current density. If cell cooling causes a problem, this could potentially be overcome by the addition of a cell cooling system. Figure 4-5 presents an estimate of the potential performance of the system with added development effort and modification. As illustrated by comparison of Figures 4-4 and 4-5, the optimum equivalent weight at a power penalty of 500 lbs/KW could be reduced from 1020 to 940 lbs. by further development work in the opinion of Battelle. The particular approach is well established in industrial application and upon successful solution of the zero gravity separation problems could prove a reliable concept for space utilization.

4.3 Porous Electrode Electrolysis System

This system under development by the TAPCO Div. of Thompson Ramo Wooldridge,

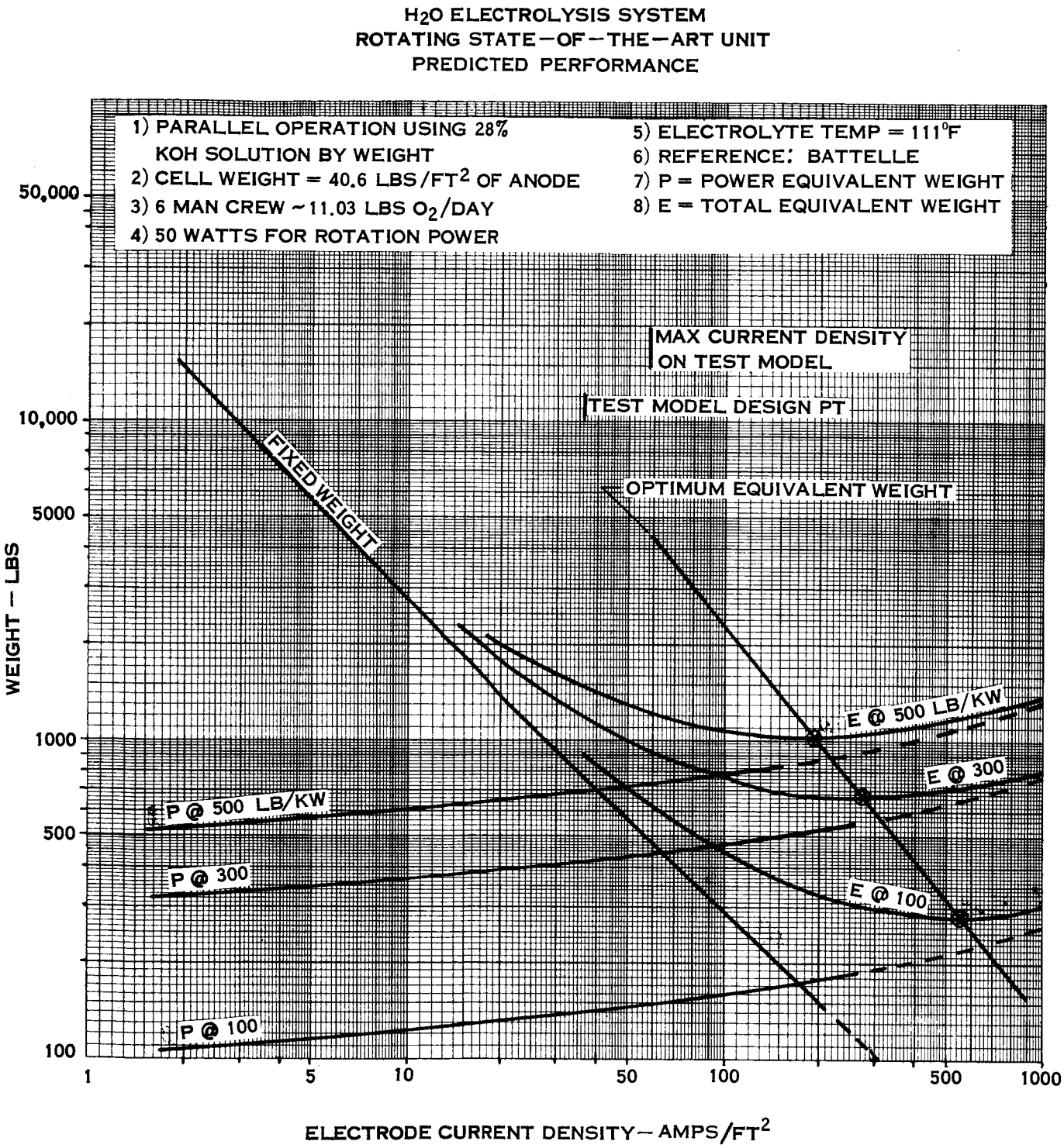

H2O ELECTROLYSIS SYSTEM
ROTATING STATE—OF—THE—ART UNIT
PREDICTED PERFORMANCE
1) PARALLEL OPERATION USING 28% KOH SOLUTION BY WEIGHT
2) CELL WEIGHT = 40.6 LBS/FT2 OF ANODE
3) 6 MAN CREW ~11.03 LBS O2/DAY
4) 50 WATTS FOR ROTATION POWER
5) ELECTROLYTE TEMP = 111°F
6) REFERENCE: BATTELLE
7) P = POWER EQUIVALENT WEIGHT
8) E = TOTAL EQUIVALENT WEIGHT
MAX CURRENT DENSITY ON TEST MODEL
TEST MODEL DESIGN PT
OPTIMUM EQUIVALENT WEIGHT
FIXED WEIGHT
E @ 500 LB/KW
E @ 300
E @ 100
P @ 500 LB/KW
P @ 300
P @ 100
WEIGHT — LBS
50,000
10,000
5000
1000
500
100
1
5
10
50
100
500
1000
ELECTRODE CURRENT DENSITY — AMPS/FT2

FIGURE 4—4

H_2O ELECTROLYSIS SYSTEM
PREDICTED PERFORMANCE—ROTATING UNIT

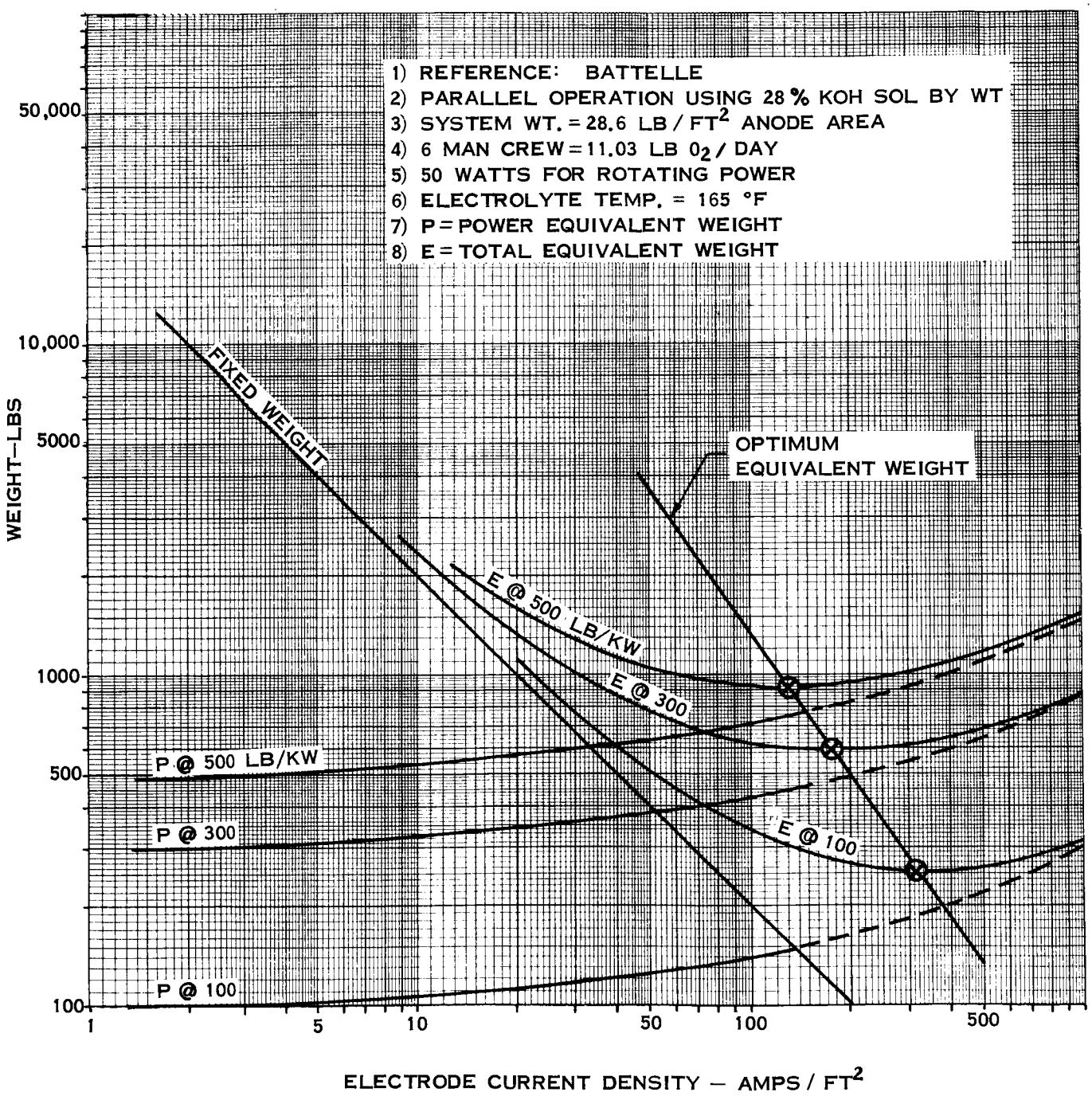


FIGURE 4–5

4.3 (Continued)

Inc., has been analyzed utilizing TAPCO Report No. ER-5482 "MOSS and MARS Environmental System Studies" supplemented by discussions with TAPCO personnel. A similar approach is also under investigation by Pratt and Whitney Division of United Aircraft Corporation.

The system under development by TAPCO appears to provide operation independent of gravity. The basic cell construction as illustrated in Figure 4-6 utilizes a 28% solution of potassium hydroxide by weight as the electrolyte. The electrolyte is transported from a sump to the electrodes by a nylon wick material. An asbestos divider is placed between the wick and the anode to prevent oxygen bubbles from passing back into the electrolyte due to the positive pressure gradient in the direction of gas flow. Asbestos is not required on the cathode side. The generated gases flow through the porous electrode by capillarity, then out of the cell between the electrode and the cell parting sheets which are separated by a monel screen which also serves as a current distribution device.

H_2O ELECTROLYSIS SYSTEM
POROUS ELECTRODE CELL

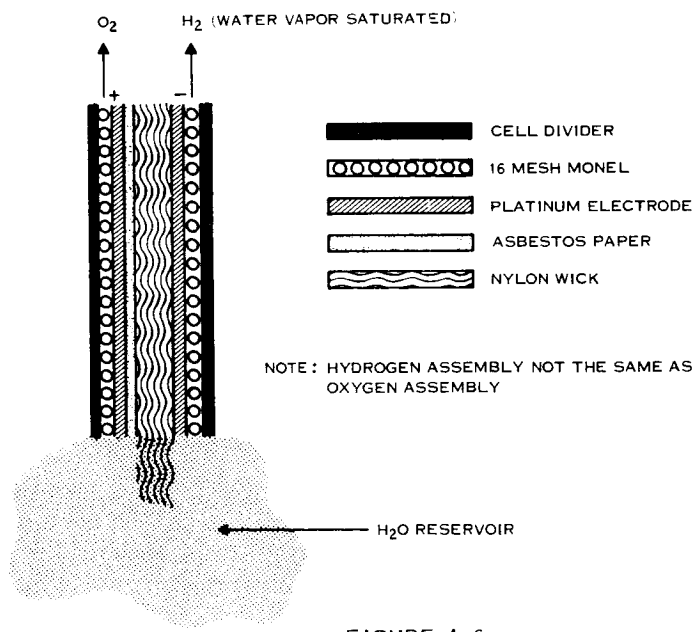


FIGURE 4-6

4.3 (Continued)

Water carry-over is limited to vapor with which the gases are saturated. The cell presently developed has been run at a current density of 165 amps/ft^2 with good results. Further discussions with TAPCO personnel brought out the fact that use of current densities up to about 500 amps/ft^2 should present no problem other than cell cooling, which could be overcome by incorporating a cooling system. Although zero gravity operation of the cell has not been fully established, the only problem to be anticipated is a change in the electrolyte film characteristics on the screen side to the electrodes. This may affect water carry-over. However, it is believed that this problem may be solved by proper feed water regulation. Figures 4-7 and 4-8 illustrate the optimum configuration under current thinking and as predicted for future operation. The comparison of both figures at the power penalty of 500 lbs/kw indicated an expected reduction in equivalent weight from 1100 to 695 lbs, which is a considerable change if the anticipated development improvements can be accomplished.

4.4 Rotating Electrolysis Cell with a Hydrogen Diffusion Cathode

This system, as explained in Air Force Report AMRL-TDR-62-94 "Research on Electrolysis of Water with a Hydrogen Diffusion Cathode to be Used in a Rotating Cell" was investigated by Battelle Memorial Institute. The distinguishing feature of this electrolysis cell is the cathode. Centrifugal force produced by the cell rotation is used to establish a hydrostatic pressure gradient in the electrolyte, so that evolved O_2 bubbles will flow toward the center of rotation, thus separating from the electrolyte. Separation of the gaseous hydrogen and oxygen is accomplished by a Palladium foil hydrogen diffusion cathode that will permit generation of hydrogen into a gaseous phase on the side of the cathode opposite the side on which hydrogen is deposited by electrolysis of water. Since the cathode operation is by diffusion, it is independent of gravity. Figure 4-9 illustrates a possible method of constructing this particular electrolysis cell.

Battelle data indicates successful cathode operation has been established at current densities up to 265 amps/ft^2 with 100% hydrogen transmission. An optimistic prediction of cell performance by Battelle indicates that an equivalent weight of approximately 650 lbs may be achieved after further development for a power penalty of 500 lbs/kw. This is illustrated in Figure 4-10. If the fixed weight predicted can be achieved, the optimum weight for a power penalty of 500 lbs/kw will occur at a current density of 100 amps/ft^2. All of this data must be considered very optimistic at this time due to the very early stages of development for this particular approach.

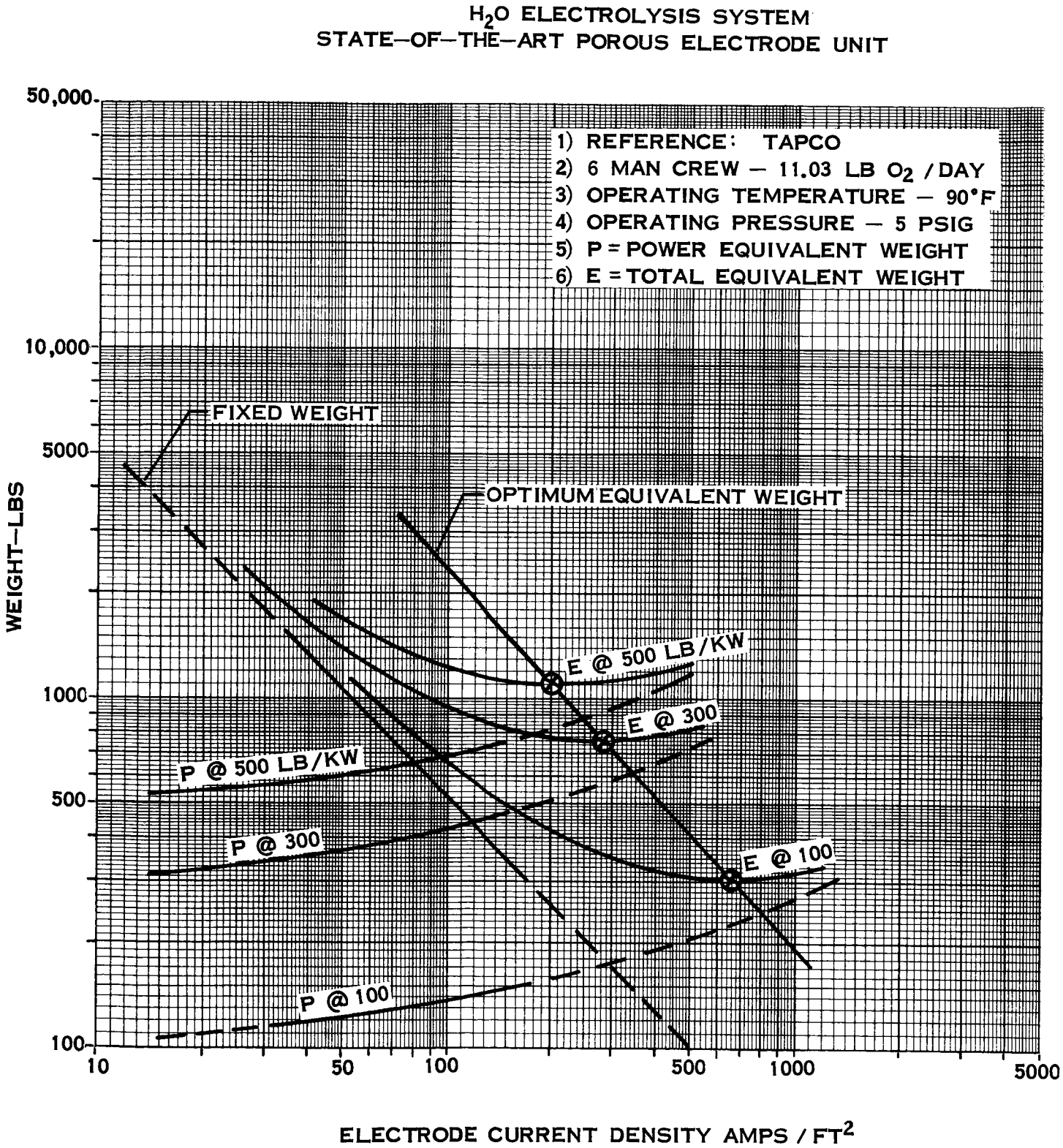

H_2O ELECTROLYSIS SYSTEM
STATE-OF-THE-ART POROUS ELECTRODE UNIT
1) REFERENCE: TAPCO
2) 6 MAN CREW – 11.03 LB O_2 / DAY
3) OPERATING TEMPERATURE – 90°F
4) OPERATING PRESSURE – 5 PSIG
5) P = POWER EQUIVALENT WEIGHT
6) E = TOTAL EQUIVALENT WEIGHT
FIXED WEIGHT
OPTIMUM EQUIVALENT WEIGHT
E @ 500 LB/KW
E @ 300
E @ 100
P @ 500 LB/KW
P @ 300
P @ 100
WEIGHT–LBS
50,000
10,000
5000
1000
500
100
10
50
100
500
1000
5000
ELECTRODE CURRENT DENSITY AMPS / FT^2

FIGURE 4-7

H_2O ELECTROLYSIS SYSTEM
PREDICTED PERFORMANCE — POROUS ELECTRODE UNIT

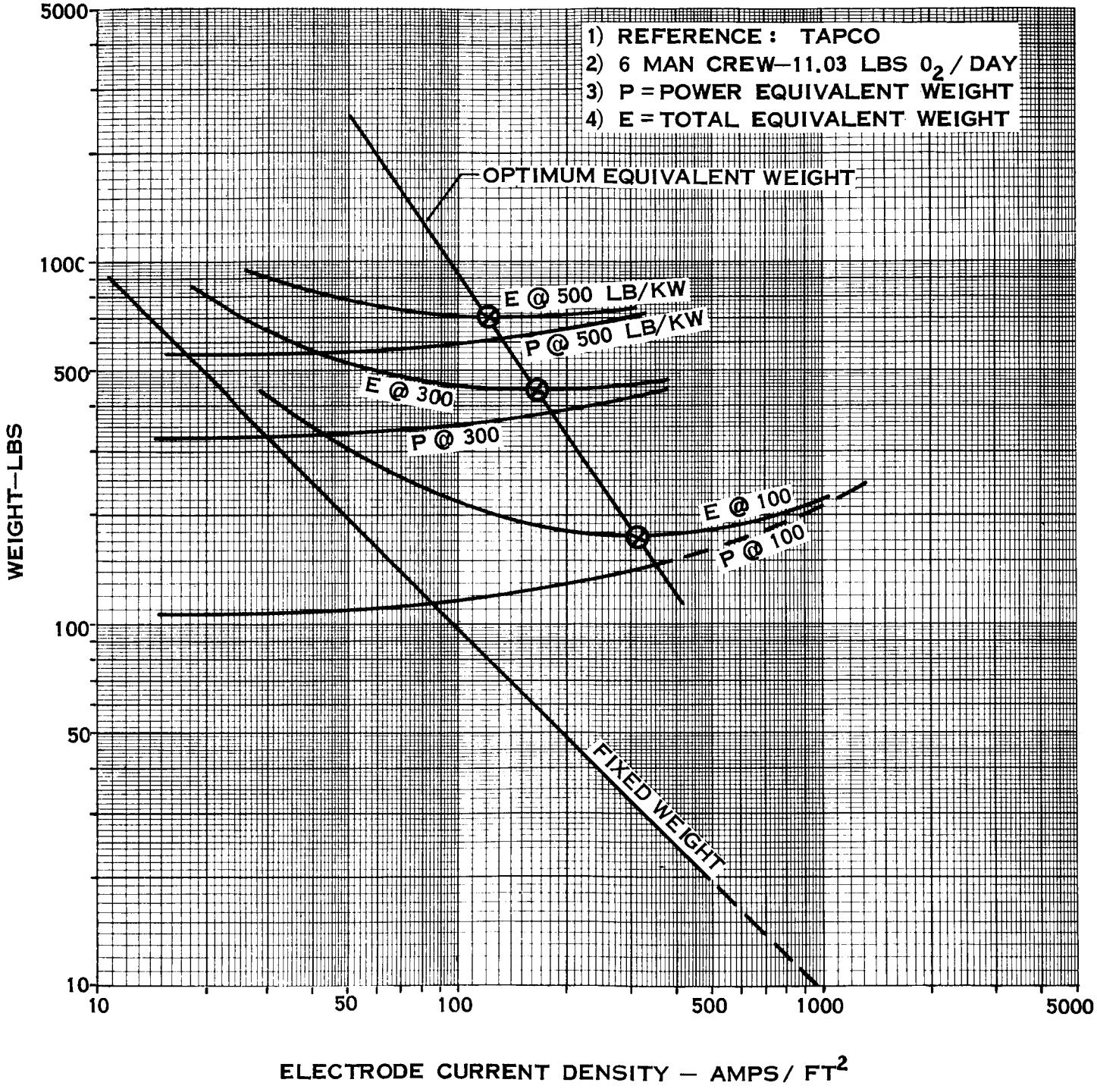


FIGURE 4—8

4.4 (Continued)

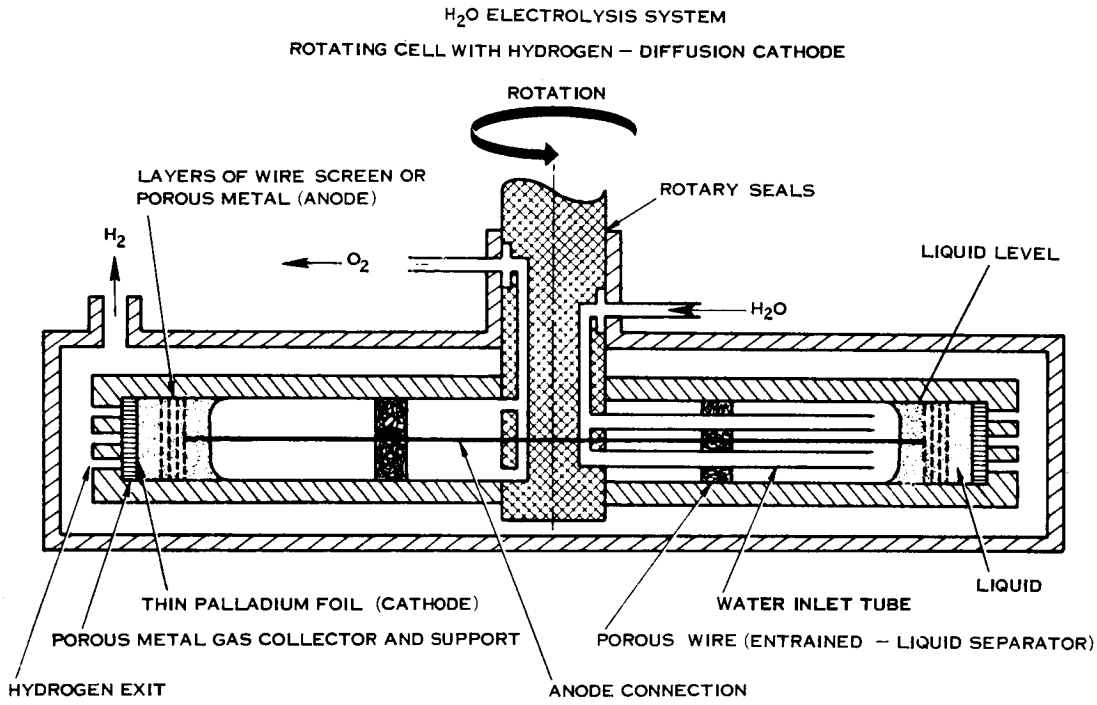


FIGURE 4 – 9

4.5 Combined Electrolysis Vortex Separator Cell

The Pratt & Whitney Aircraft Division of United Aircraft Corporation has performed preliminary testing toward the development of a 500 watt solar regenerative hydrogen-oxygen fuel cell power supply system designed to operate in an equatorial orbit. This work was done under contract No. DA 36-039-SC 85259 and is reported in Pratt and Whitney Report No. PWA 1894 (Research on a 500 Watt Solar Regenerative H_2 - O_2 Fuel Cell Power Supply System). The electrolysis portion of this unit consists of a pair of contoured wall vortex separators mounted axially on either side of a diaphragm. Electrolysis is carried out across this diaphragm as indicated in Figure 4-11.

H_2O ELECTROLYSIS SYSTEM
ROTATING CELL — HYDROGEN DIFFUSION CATHODE
PREDICTED PERFORMANCE

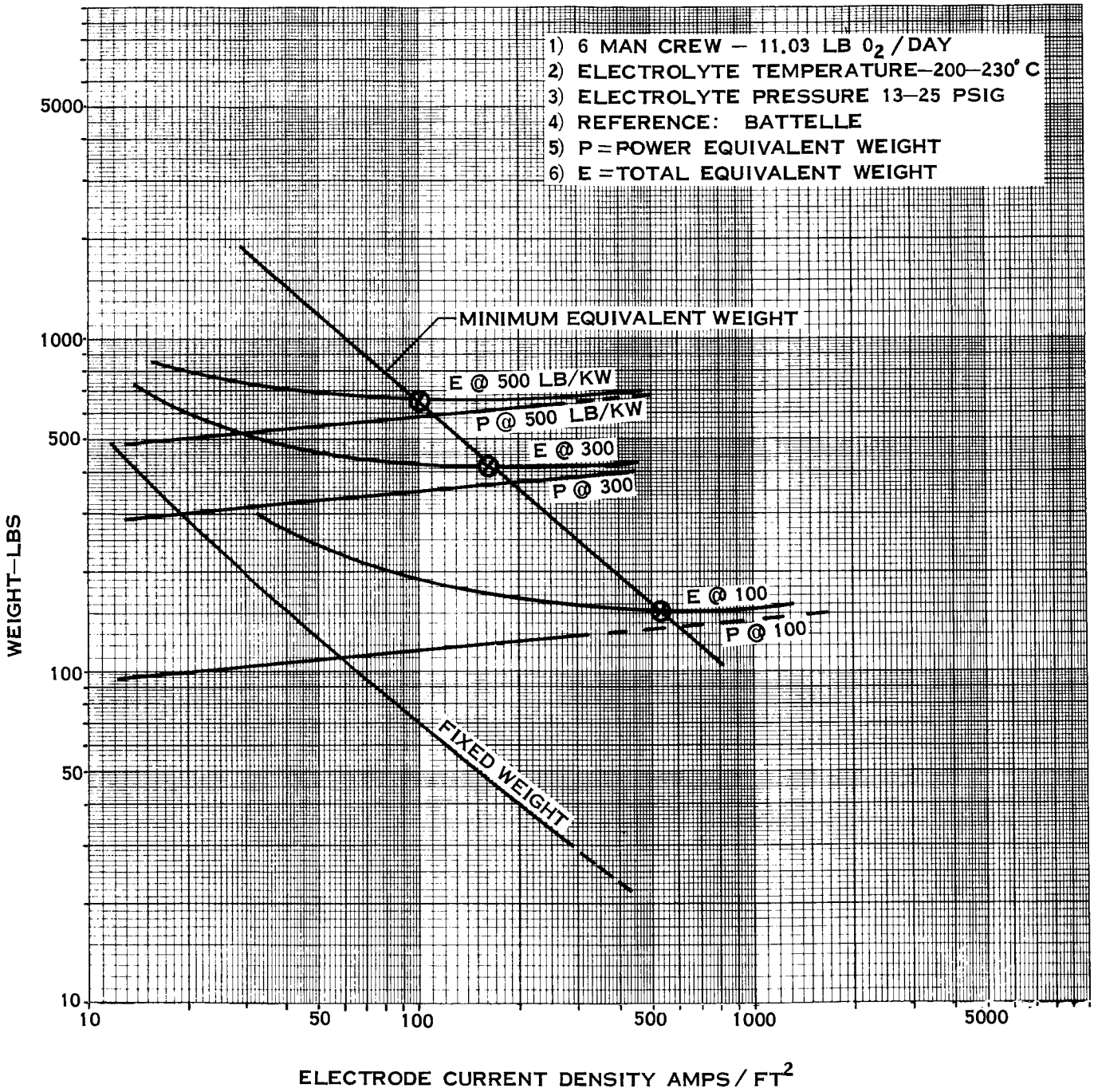
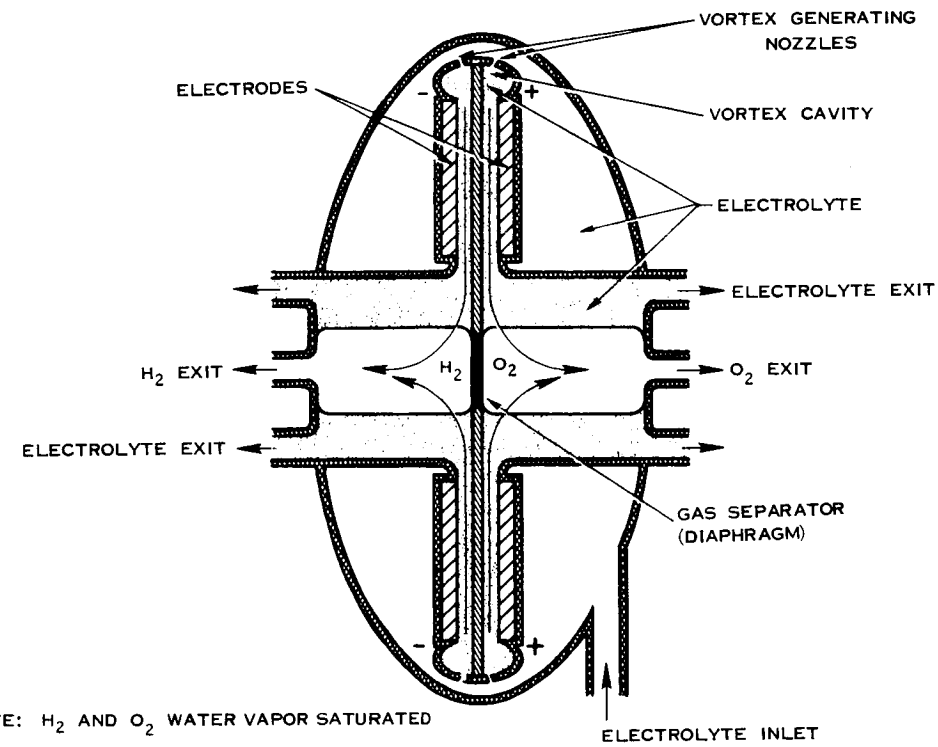


FIGURE 4—10

4.5 (Continued)

In this unit the electrolyte is pumped into a pressurized chamber surrounding the cell. The electrolyte flows from this chamber into the vortex cavity through vortex generating nozzles. In the vortex cavity the gas is generated at the face of the electrodes and flows toward the center of the cell with the electrolyte. At this point the gas and liquid are separated, the gas flowing to the storage area and the liquid being returned to the pump and recirculated to the cell. This cell has run at current densitites of 700 amps/ft^2 with good results. At this current density for a power penalty of 500 lbs/KW, the cell does not reach its minimum equivalent weight; however, the equivalent weight is of the same magnitude with other units of similar development status. Figure 4-12 illustrates the optimum weight consideration for this particular approach.

H_2O ELECTROLYSIS SYSTEM
COMBINED ELECTROLYSIS – VORTEX GAS LIQUID SEPARATOR UNIT



NOTE: H_2 AND O_2 WATER VAPOR SATURATED

FIGURE 4-11

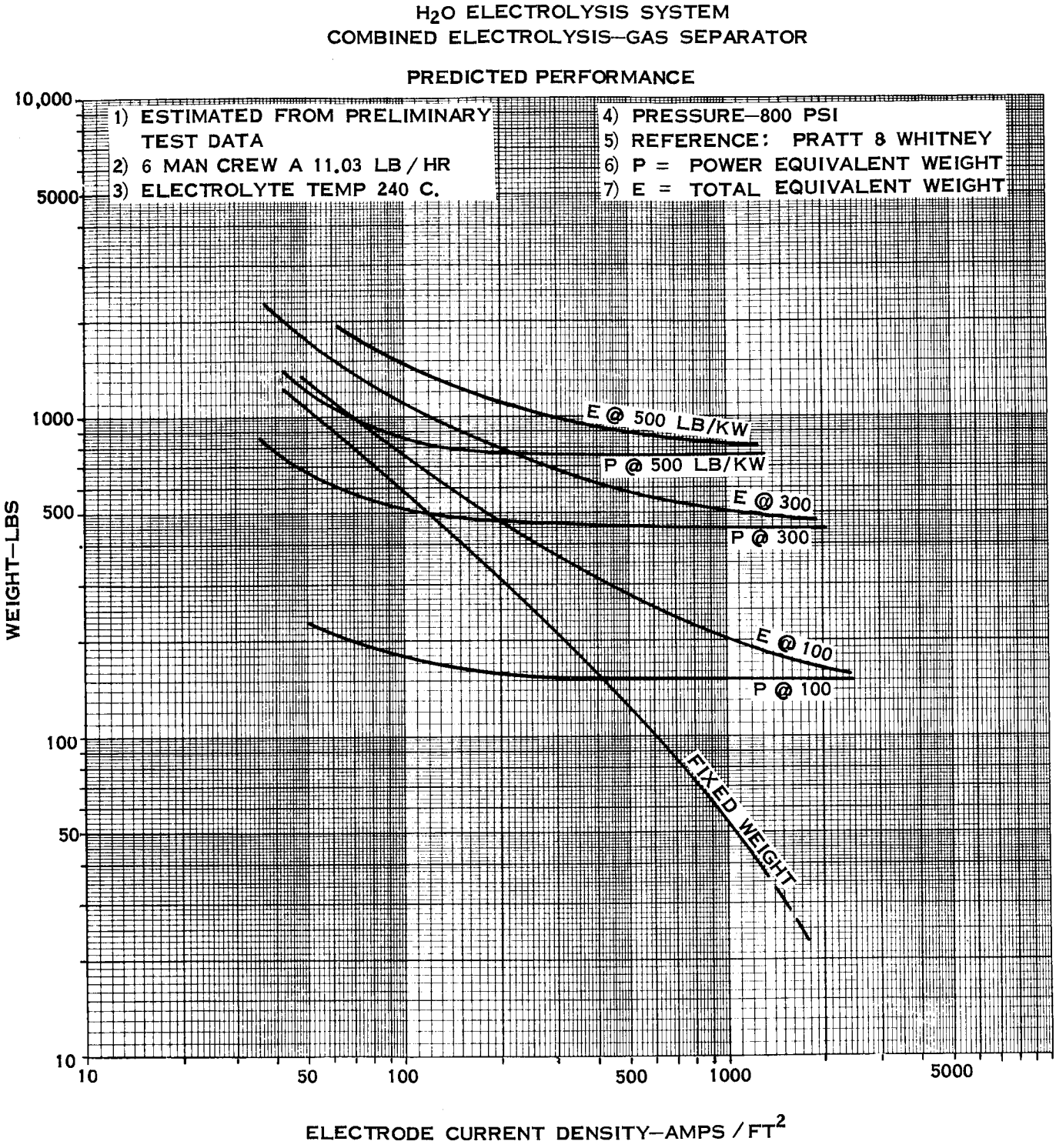

H_2O ELECTROLYSIS SYSTEM
COMBINED ELECTROLYSIS–GAS SEPARATOR
PREDICTED PERFORMANCE
1) ESTIMATED FROM PRELIMINARY TEST DATA
2) 6 MAN CREW A 11.03 LB / HR
3) ELECTROLYTE TEMP 240 C.
4) PRESSURE–800 PSI
5) REFERENCE: PRATT & WHITNEY
6) P = POWER EQUIVALENT WEIGHT
7) E = TOTAL EQUIVALENT WEIGHT
E @ 500 LB/KW
P @ 500 LB/KW
E @ 300
P @ 300
E @ 100
P @ 100
FIXED WEIGHT
WEIGHT–LBS
10,000
5000
1000
500
100
50
10
10
50
100
500
1000
5000
ELECTRODE CURRENT DENSITY–AMPS / FT^2

FIGURE 4–12

4.6 Organic Membrane Electrolysis Cell

This system approach, under development by Ionics, Inc., utilizes organic membranes for the basic media. The system, as described in Ionics Report No. 11-P-63-26 (Carbon Dioxide Removal and Water Electrolysis Subsystems for Manned Vehicles Having Extended Missions),has been the subject of independent research by Ionics as well as a current NASA contract.

The unique feature of this system approach is the utilization of an organic cation perm-selection membrane, which permits the passage of the hydrogen ion only as illustrated in Figure 4-13. Oxygen is liberated at the anode and hydrogen at the cathode. The gas water mixture is then passed through a passive gas liquid separator as shown in Figure 4-14.

Figure 4-15 illustrates the current state-of-the-art performance of the Ionics cell. As indicated by this figure, the current density for minimum equivalent weight is in the order of 6.2 amps/ft^2 for a power penalty of 500 lbs/KW. Ionics has done considerable testing with an electrode current density of 10 amps/ft^2 with good results. As illustrated in Figure 4-15, the equivalent weight at the 500 lbs/KW penalty is about 1090 lbs. Predicted performance estimates by Ionics indicate a reduction of equivalent weight to the order of 850 lbs. by 1973. This is illustrated in Figure 4-16. This particular system approach looks very promising for further spacecraft utilization.

4.7 Ion Exchange Membrane Electrolysis Cell

Another system which may prove very competitive is the inorganic ion exchange membrane cell. Its operation is similar to the organic membrane cell previously discussed. Figure 4-17 illustrates the basic cell operation. Water enters at the oxygen electrode and penetrates the cationic exchange membrane through the porous anode into the membrane. Hydrogen ions from the ionization of water traverse the membrane to the cathode where each receives an electron and is discharged as hydrogen gas. Simultaneously, the hydroxyl ions give up their electrons to the anode and are dissociated to oxygen gas and liquid water. The water is then electrolyzed while the oxygen leaves the compartment. Indications are that the equivalent weight of this system is in the same magnitude as the organic membrane system being developed by Ionics Inc. Insufficient data was available during the study to size this system although Illinois Institute of Technology is actively working on this approach.

4.8 Comparative Discussion

The selection of a typical system approach for inclusion in further system integration studies is not clear cut at this time due to the predicted potentials of all the systems

H_2O ELECTROLYSIS SYSTEM

ORGANIC MEMBRANE FLOW DIAGRAM

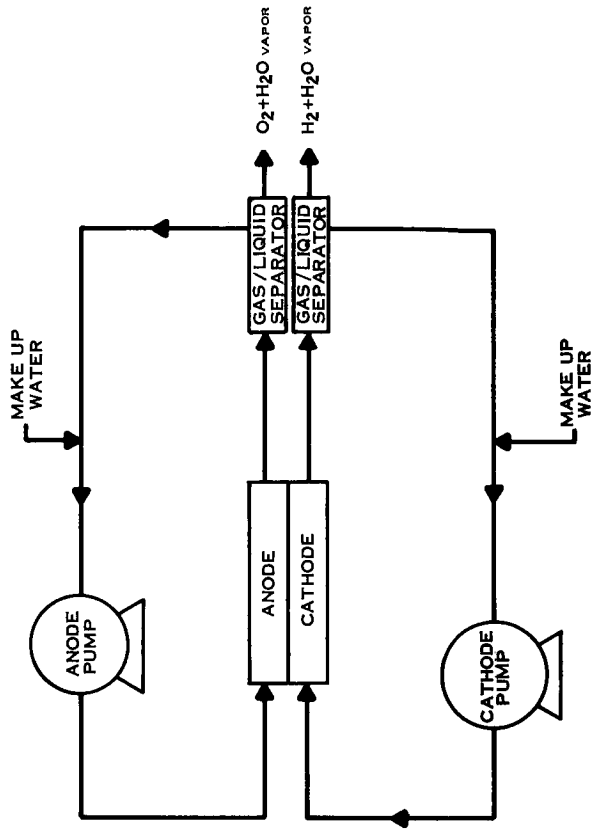


FIGURE 4-14

H_2O ELECTROLYSIS SYSTEM

ORGANIC MEMBRANE CELL OPERATION

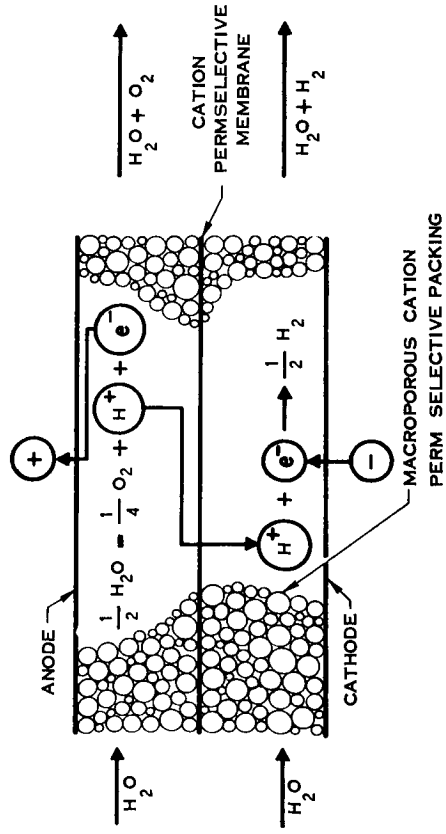


FIGURE 4-13

H O ELECTROLYSIS SYSTEM
2
STATE-OF-THE-ART-ORGANIC MEMBRANES

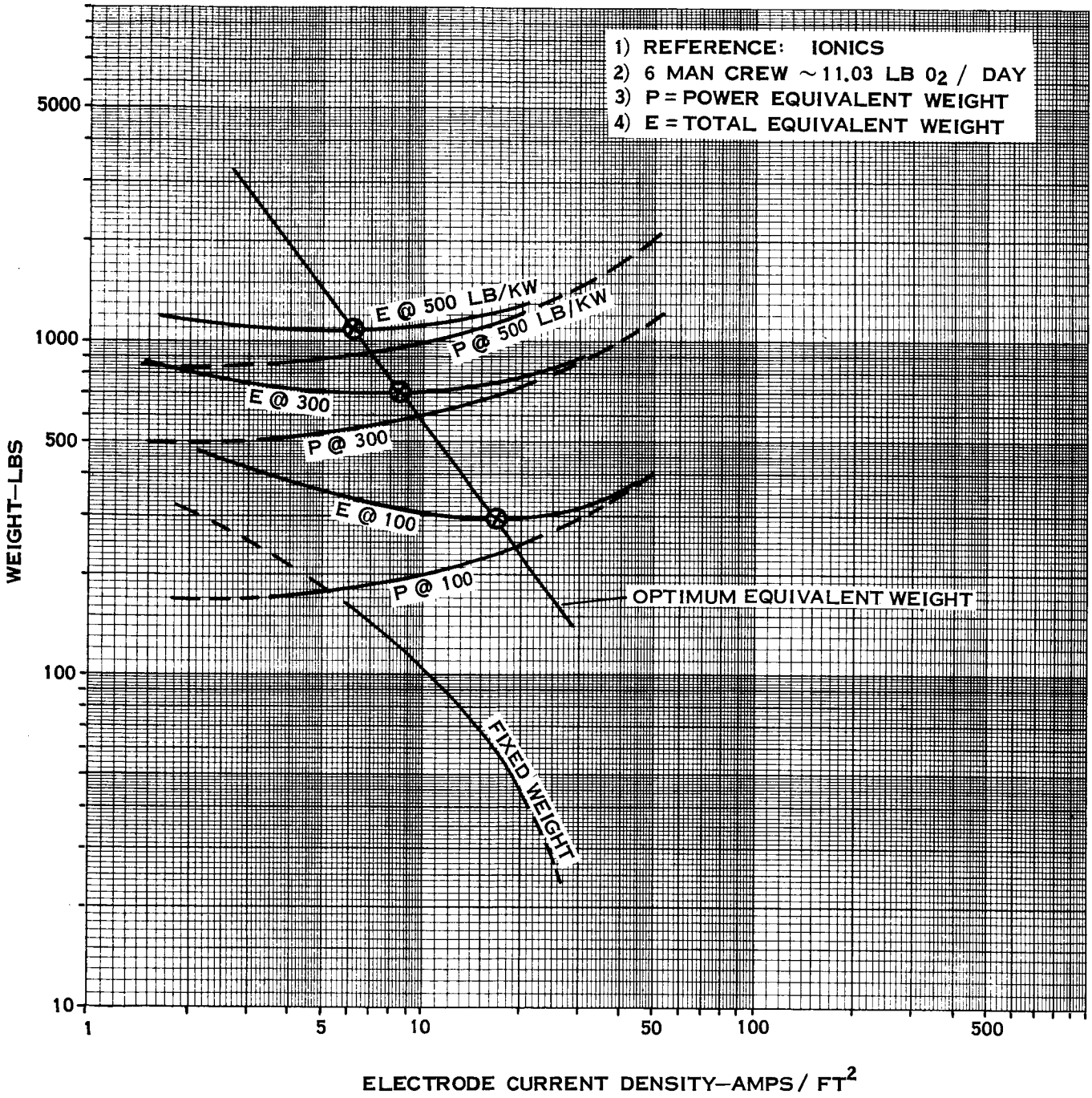


FIGURE 4-15

H_2O ELECTROLYSIS SYSTEM
PREDICTED PERFORMANCE — ORGANIC MEMBRANES

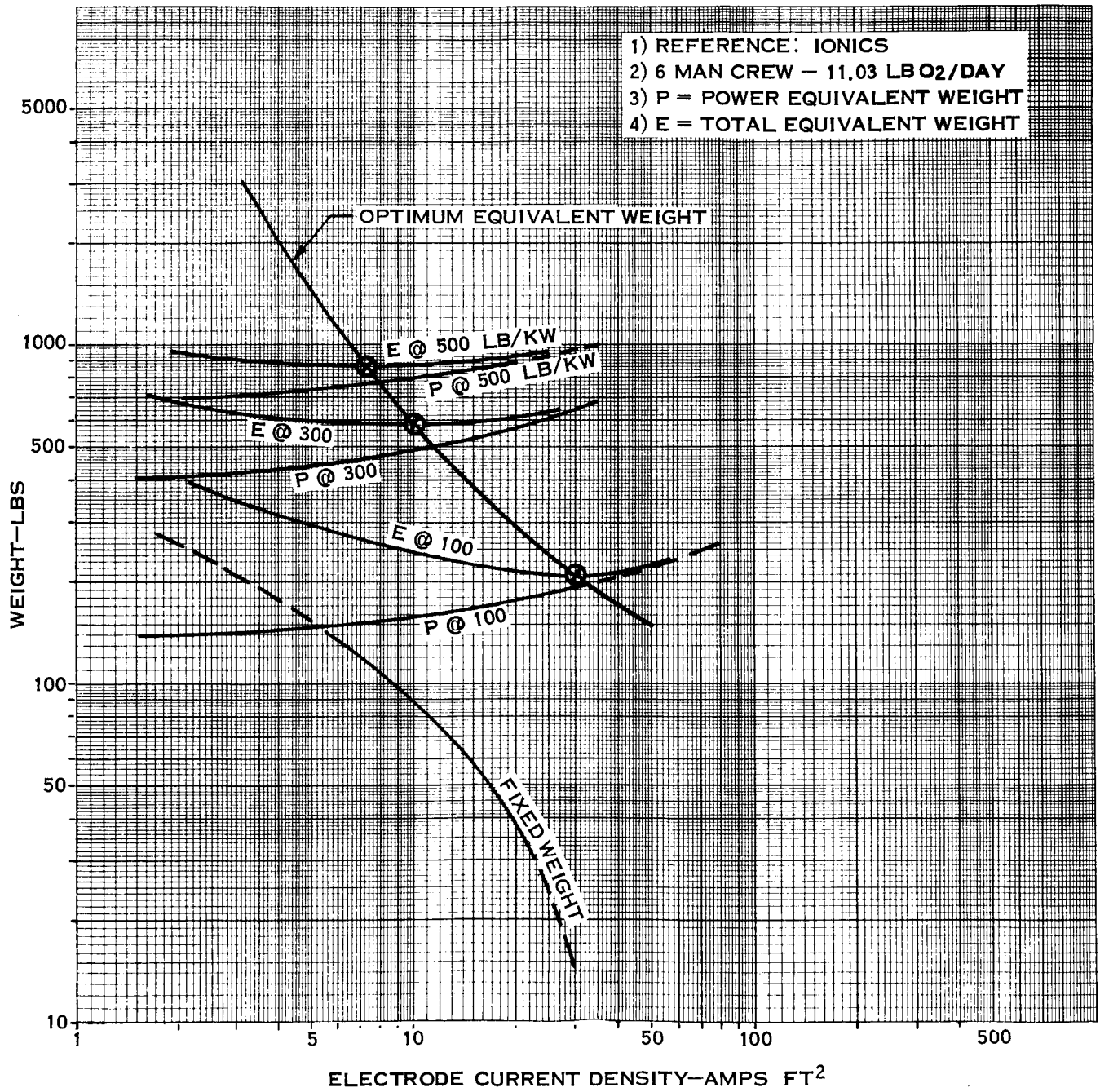


FIGURE 4—16

4.8 (Continued)

H_2O ELECTROLYSIS SYSTEM
ION EXCHANGE MEMBRANE ELECTROLYSIS CELL

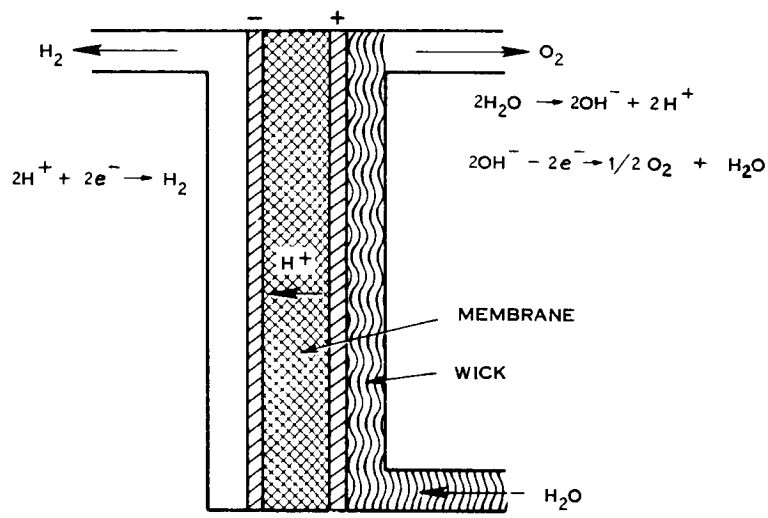


FIGURE 4-17

investigated to-date. However, to provide a representative set of data for further analysis, one system was selected as a representative candidate. Figure 4-18 illustrates the comparative weights of each approach for an 11.03 lb/day O_2 generation rate.

Of the systems investigated, the porous electrode system cell being developed by TAPCO and Pratt and Whitney was selected for integration with other subsystems. If the predicted development can be realistically attained, this cell offers the best potential performance characteristics by the expected use period. Although the organic and inorganic cells cannot be completely ruled out at this point in system development, experimental successes with small porous electrode units tend to indicate future success, thus leading to its selection as the model to be used in further system analysis. For system integration purposes, it is usually possible to consider

H_{20} ELECTROLYSIS
CELL EQUIVALENT WEIGHT COMPARISON
(6 MEN – 11.03 LB O_2 / DAY)

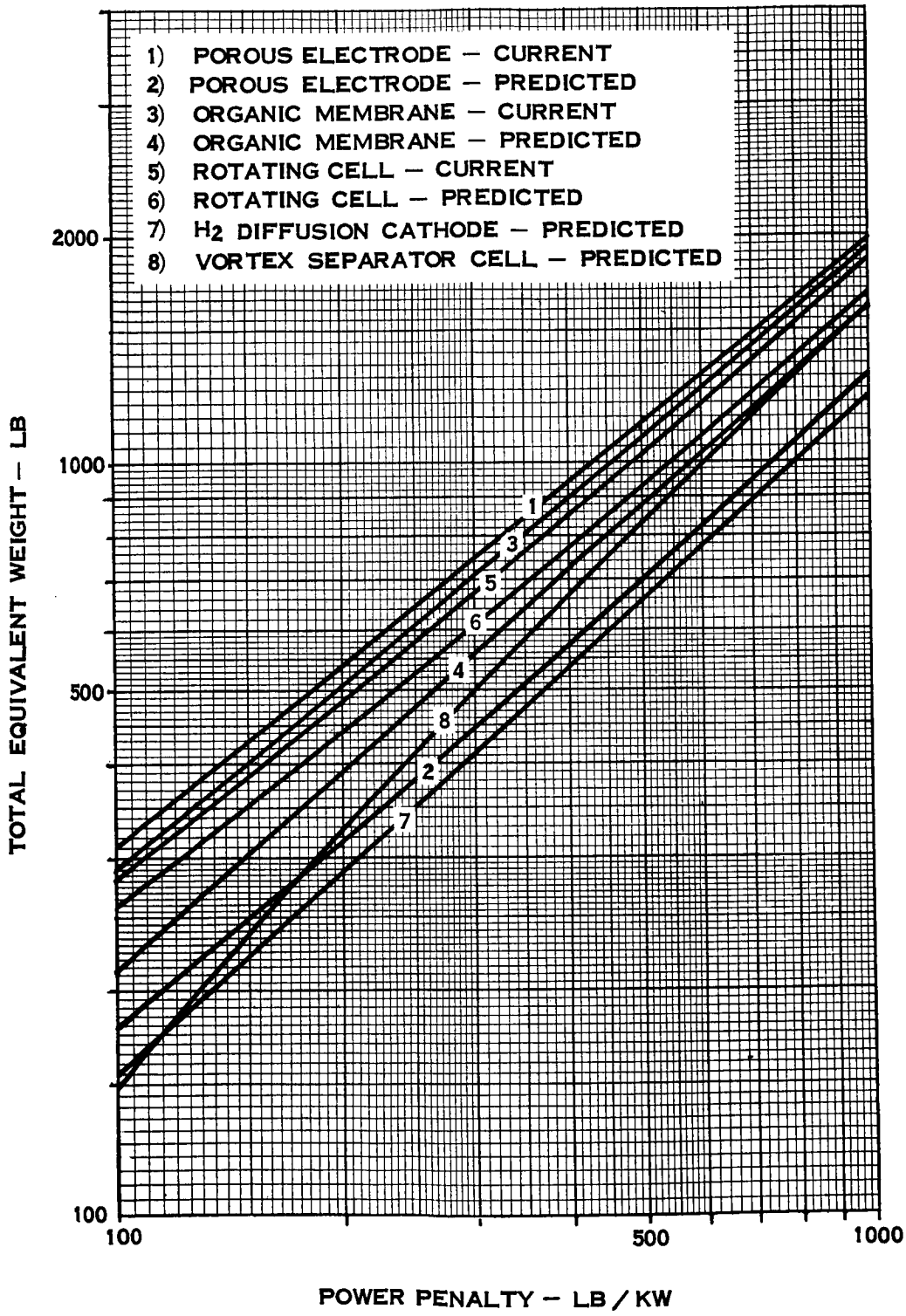


FIGURE 4–18

4.8 (Continued)

the electrolysis system as a "black box" which takes in water and electrical energy and evolves gaseous oxygen and hydrogen. This flexibility will allow insertion of another system approach with minimum effort during later integration studies if another approach proves more feasible than that being considered.

To allow utilization of the data for further system integration, it has taken two distinct forms. Figures 4-19 and 4-20 illustrate the power and equivalent weight requirements as a function of the crew size considered. These figures are based on the metabolic oxygen requirements of the crew and illustrate the variations with power penalty which may be required by a change in the eventual weight of the power supply system. These curves were presented to allow rapid comparison with oxygen storage curves of the open system oxygen supply method.

Figures 4-21, 4-22 and 4-23 illustrate the optimum fixed weight, power and equivalent weight of the electrolysis system as a function of the water electrolysis rate. These figures were prepared to allow integration with CO_2 reduction systems where the electrolysis requirements are determined by the water flow rate from the CO_2 reduction system. Thus, for integration, once the water flow rate is determined, the weight, power and equivalent weight for electrolyzing this water into hydrogen and oxygen can be obtained from these figures.

H_2O ELECTROLYSIS SYSTEM
OPTIMUM POWER REQUIREMENTS

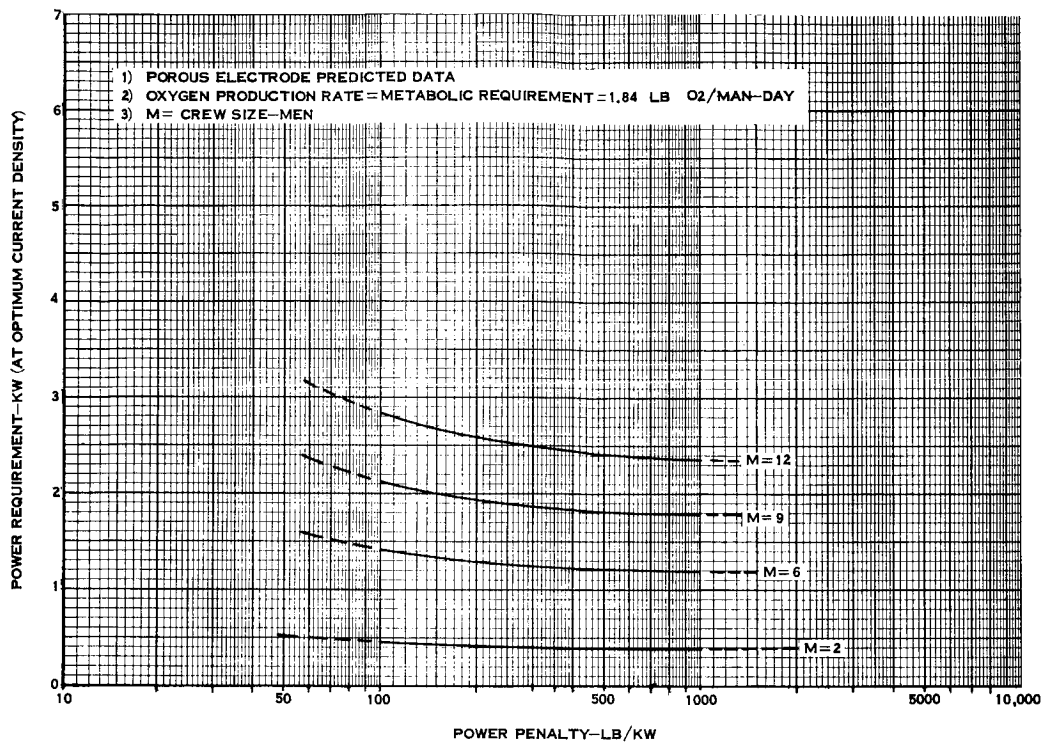


FIGURE 4-19

H_2O ELECTROLYSIS SYSTEM
OPTIMUM EQUIVALENT WEIGHT DETERMINATION

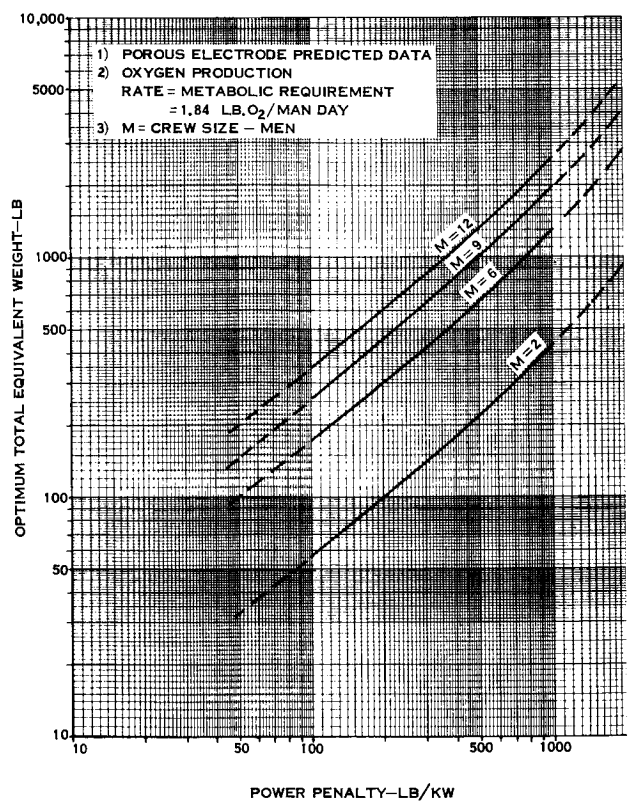


FIGURE 4-20

H_2O ELECTROLYSIS SYSTEM
FIXED WEIGHT VS WATER PROCESS RATE

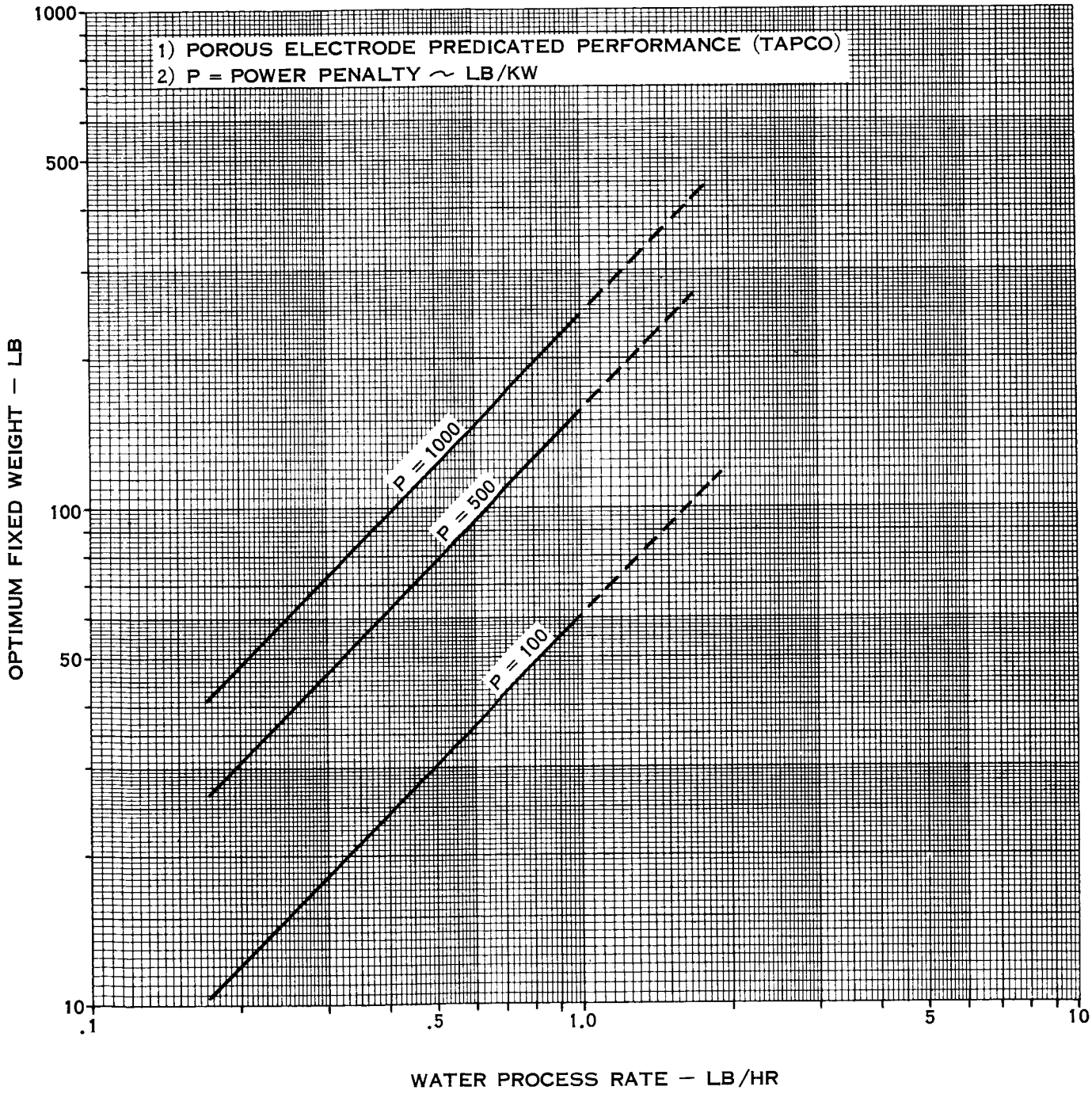


FIGURE 4 — 21

H_2O ELECTROLYSIS SYSTEM
POWER VS WATER PROCESS RATE

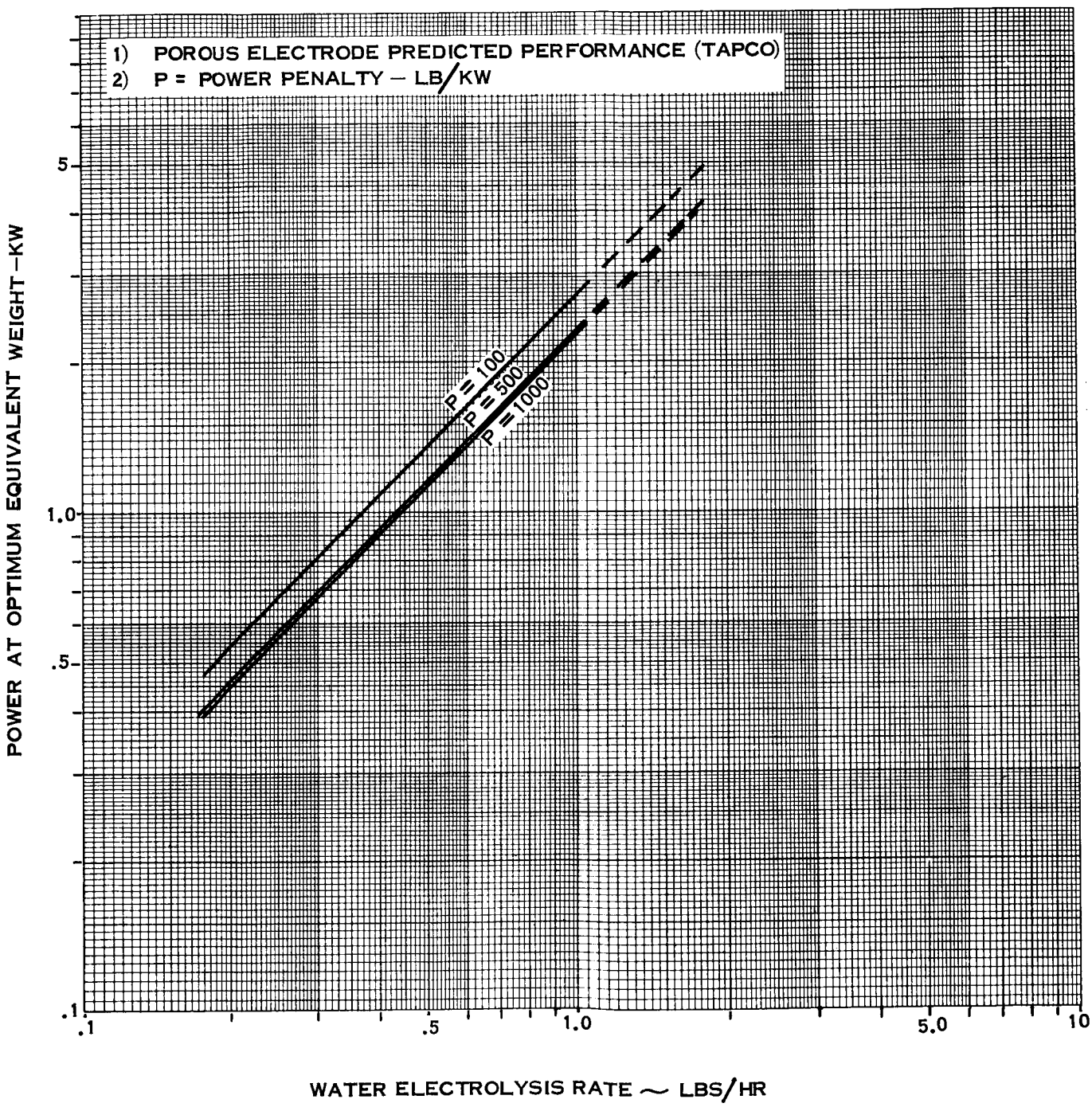


FIGURE 4 — 22

H_2O ELECTROLYSIS SYSTEM
EQUIVALENT WEIGHT VS. WATER PROCESS RATE

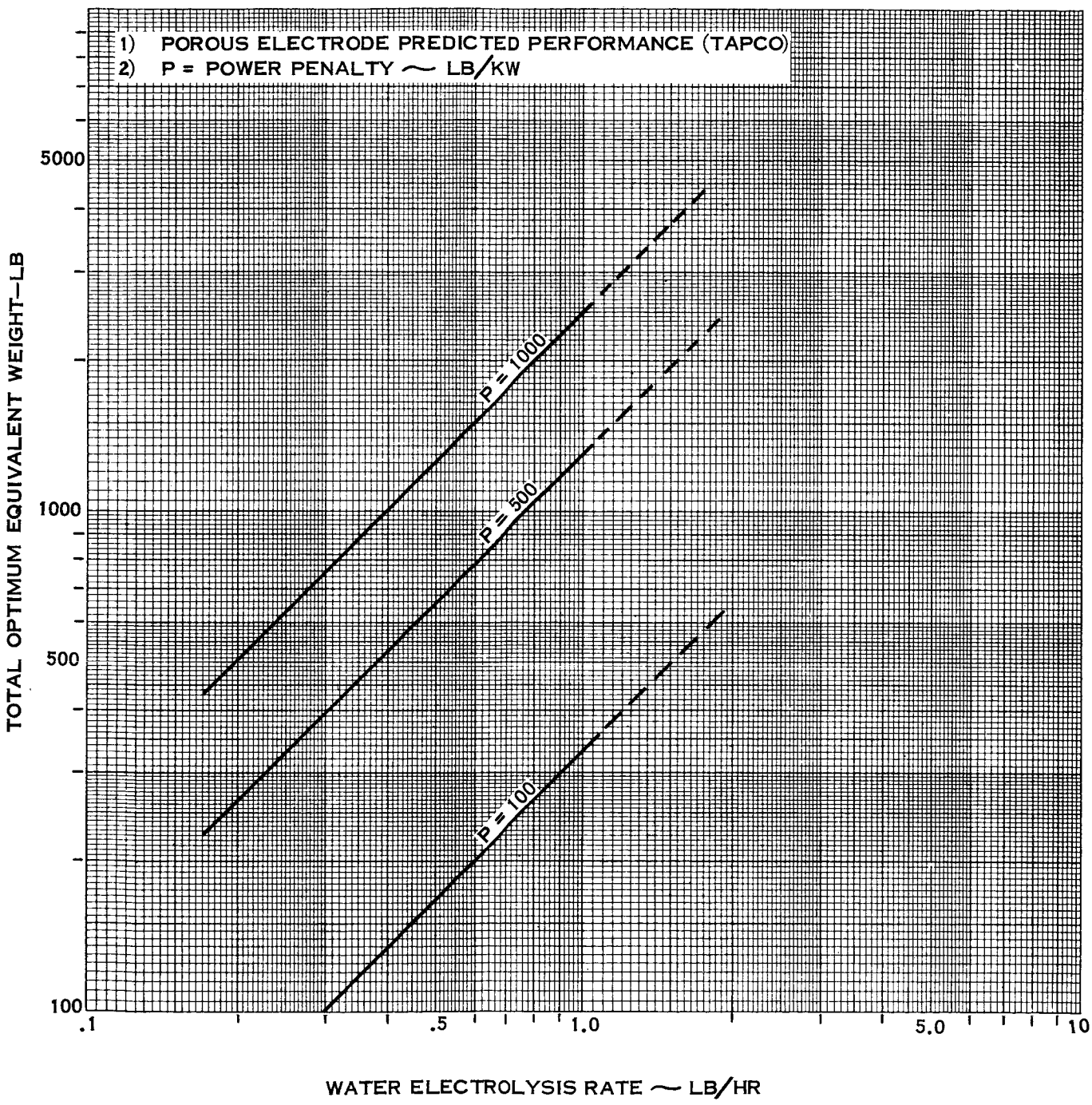


FIGURE 4— 23

4.9 References

1. "Research on a 500 Watt Solar Regenerative H_2-O_2 Fuel Cell Power Supply System," Eng. Report No. PWA-1894 by Pratt & Whitney Aircraft Division, United Aircraft Corporation.

2. "Research on the Electrolysis of Water Under Weightless Conditions," Report No. MRL-TDR-62-44 by Battelle Memorial Institute.

3. "Carbon Dioxide Removal and Water Electrolysis Sub-systems for Manned Vehicles Having Extended Missions," Eng. Report No. 11-P-63-26, by Ionics, Inc. Also communication with Dan Brown of Ionics, Inc.

4. "Analytical Methods for Space Vehicle Atmospheric Control Process," ASD-TR-61-162, prepared by AiResearch Manufacturing Co.

5. "Research on Electrolysis of Water with a Hydrogen-Diffusion Cathode to be Used in a Rotating Cell," AMRL-TDR-62-94 by Battelle Memorial Institute.

6. "MOSS and Mars Environmental System Studies," Eng. Report No. ER-5482 by TAPCO Division of Thompson Ramo Wooldridge, Inc.

7. Performance of a cell now being developed by TAPCO (Fig. 8-9). Communication with Martin Macklin of TAPCO.

SECTION 5.0

CARBON DIOXIDE REDUCTION

5.0 CO_2 Reduction

5.1 General

5.1.1 Objectives

Various methods have been studied for recovering oxygen from the CO_2 collected in the space vehicle. In this section of the report these various methods will be compared. This does not present the entire study, however, because each of these systems must be integrated with a CO_2 removal device to form a complete regenerative system. However, to allow a comparison on an equal basis, the CO_2 reduction systems will be considered separately, and the integration with removal devices will be reported in the major subsystem integration phase.

Several of these systems utilize the electrolysis of water in an intermediate step. The details of this particular process are discussed separately in Section 4.0 of this report.

The consideration of reduction system reliability, maintainability, and development status has not been fully covered at the subsystem level since this phase of the study does not provide a true indication of the candidate approaches. An evaluation of the weight penalties attributed to spares and redundancy will have to be made during the system definition phase to provide a full evaluation of system feasibility.

5.1.2 Discussion of Data Presentation

In this section each CO_2 reduction system considered will be discussed and a basic operational schematic presented to facilitate better understanding of the process. In addition, curves of weight, power, and expendables will be presented comparing all the methods to indicate the lowest weight method. The consideration of further system integration and reliability effects may change the schematic somewhat, but the basic process will be the same.

The expendable weights indicated do not include the packaging weight associated with storage in the vehicle.

5.2 Miscellaneous CO_2 Decomposition Systems

A brief review of the state-of-the-art for several advanced methods of decomposing CO_2 was conducted to determine applicability to Mars requirements. These methods included decomposition by nuclear radiation, photosynthesis, photochemical decomposition, and direct thermal decomposition. There is not enough

5.2 (Continued)

data available to allow a parametric presentation of these approaches, and they do not appear to have enough advantages to justify performing a theoretical analysis. However, a brief description of potential system approach is included for illustrative purposes.

5.2.1 CO_2 Decomposition Using Nuclear Radiation

One approach considered is that of decomposition using nuclear radiation. With this system approach, the exposure of CO_2 to radiation decomposes the CO_2 to carbon monoxide and nascent oxygen. Experience has shown that the nascent oxygen formed in this process is very active and recombines to form CO_2 again very rapidly. To combat this, a technique which uses NO_2 as an inhibitor to prevent the nascent oxygen formed by radiation from recombining has been partially developed. Using the NO_2, the process is as follows:

$$\text{radiation} + 2\,CO_2 \longrightarrow 2\,CO + 2O \qquad (1)$$

$$2NO_2 + 2O \longrightarrow 2\,NO + 2O_2 \qquad (2)$$

$$2NO + O_2 \longrightarrow 2\,NO_2 \qquad (3)$$

The sum of the above equations then yields:

$$2CO_2 + \text{radiation} \longrightarrow 2CO + O_2 \qquad (4)$$

It appears that the diatomic oxygen formed from this chain of reactions is much more stable than the nascent oxygen and not as prone to react with the CO. Another inhibitor which may be used is iodine which appears to be useful over a wider range of operating conditions, but it is less developed than the NO_2 approach. In actual operating experience, some carbon suboxide (i.e. C_xO_y) is formed along with the CO. This suboxide forms as a yellow-brown precipitate on the walls of the system which are exposed to radiation. In a typical flow system, oxygen concentrations in the neighborhood of 1 to 2% might be expected out of the reducer.

The radiation efficiency in this process can be stated in terms of the G value (or molecules reacted per 100 ev of incident radiation). For the reaction which forms CO from CO_2, the maximum theoretical G value is 34. However, in practice the actual G values vary from about 4 in a gamma field to an upper limit of about 9 or 10 in a field of alpha radiation with the use of inhibitors to raise the value.

5.2.1 (Continued)

The most optimum source of radiation would be an isotope or nuclear reactor power supply if one is included on the vehicle as the main power source. If an isotope is considered as the source of radiation, the production of .08 lb. of O_2 per hour with a G value of 5 would require a Co^{60} source of 73 kilocuries. In actuality, it is desirable to use some other isotope which would deliver radiation in the form of particles, but even with the higher G values obtained in this case, the use of isotopes seems impractical because of the severe shielding problems, cooling problems due to the inefficiency of the process, and the necessary decontamination problem would still exist, possibly to an even larger extent. An additional penalty of such a system would be the problem of transporting the material to and from a reactor which would most likely be located remotely. On the basis of the difficult reactor integration problem alone, this method can be disqualified. If it is possible to solve the problems, such as shielding, decontamination, and cooling associated with the radiation source and reduction unit, the problem of removing the small percentage of oxygen from the product stream still remains.

In conclusion, carbon dioxide can be reduced using radiation, however, it is not recommended at the present time due to the shielding required, the decontamination problems with the product stream, the reactor integration problem, and the potential danger of releasing a large amount of CO to the cabin in the event of some component failure.

5.2.2 Carbon Dioxide Removal by Photosynthesis

The problem of removing carbon dioxide from the air and converting it to oxygen is solved quite readily by green plants. These plants use CO_2 in their metabolic process, reacting it with water to form oxygen, carbohydrates, and many other compounds. The reaction is actually a photochemical one in which chlorophyll absorbs light energy and uses it to cause chemical reactions to take place. However, the reactions involved are extremely complex and thus far have not been duplicated by man. Photosynthesis would then be placed in a different category from the simple photochemical reactions.

In recent years there have been a number of papers published and studies made concerning the use of photosynthesis to remove CO_2 and provide O_2 in a space cabin. Generally, algae have been considered the most suitable plants for this application. These simple one celled plants have a rapid multiplication rate. All of the cells are involved in converting CO_2 (as opposed to a more complex plant which has roots, branches, etc.) so the algae should have a higher efficiency in CO_2 converted per pound than the higher plants.

5.2.2 (Continued)

The use of algae could theoretically lead to a completely closed ecological system. In such a system, both the oxygen and the food would cycle between man and algae. The algae would use CO_2 produced by the man and produce oxygen to be breathed by the man. Similarly, the algae would use the human waste products as food and would be eaten by the man. Unfortunately, such a system would be very difficult to attain in practice. For both physiological and psychological reasons, it is unlikely that the crew of a space vehicle could subsist exclusively on algae for any extended period of time. Studies on the palatability and nutritional value of algae are in an early stage and have had mixed results. It is also unlikely that the algae would live on raw human waste, and pretreatment of some kind would presunably be needed. Whether man could live on algae which live on human wastes has not really been determined as yet.

A comparison of photosynthesis with other methods of CO_2 removal reveals severe drawbacks to the photosynthesis system. Weight and power penalties are very high for several reasons. The algae live in water, and their optimum concentration is about 1%. This means that for every pound of algae needed there would be roughly 100 pounds of water. The solution must be continually agitated to provide good mass transfer rates and assure that the individual algae cells each receive about the same amount of illumination (too much or too little light is harmful to the algae). Also, the conversion of light energy to chemical energy is extremely inefficient, with values as low as 3% reported in the literature (the light needed will probably have to be supplied internally, as the use of natural sunlight would require a large illuminated area and would present severe design problems). For these reasons, algae do not begin to appear attractive until very long missions are considered. A study by the RAND Corporation, comparing an algae system with an inorganic CO_2 recovery system, puts the "cross-over point" at about 3 1/2 years, assuming that algae makes up half the food supply. If algae is not used as food, the cross-over point moves out to eight years.

Several other points should be mentioned in connection with the algae system. The algae have a tendency to stick to the walls of the container. They must be harvested frequently to maintain a constant density, and after harvesting they will decompose unless dried. They are subject to contamination by bacteria or protozoa. Also, the temperature of the solution must be carefully controlled.

5.2.3 Photochemical Decomposition of CO_2

When radiant energy is absorbed by a substance, the increased energy state of the molecules in that substance may cause chemical changes to take place. The subject of photochemistry deals with the chemical effects caused by radiant energy in the visible or ultraviolet range. Energy of longer wave lengths (infrared, etc.)

5.2.3 (Continued)

generally is not powerful enough to cause chemical changes, while shorter wave lengths (x-rays, etc.) often lead to changes in the nucleus and belong to the field of radiochemistry.

The formula which relates energy to wavelengths is:

$$E = hc/\lambda$$

where E is the energy of a photon, h is Planck's constant, c is the velocity of light, and λ is the wavelength. The energy of a beam of light therefore increases as the wavelength decreases. In order to effect a chemical change, the radiant energy must be capable of breaking a chemical bond in the molecule being subjected to radiation. Ultraviolet light, which has a shorter wavelength than visible light, has a greater chance of causing a chemical reaction to take place.

In the case of carbon dioxide, the radiant energy could be used to break one of the carbon-oxygen bonds in the CO_2 molecule and cause the following reaction to take place:

$$CO_2 \longrightarrow CO + 1/2\ O_2$$

The oxygen atoms stripped from the CO_2 molecule will combine with each other to form an oxygen molecule. It would of course be more desirable to form carbon and oxygen instead of carbon monoxide and oxygen, since this would double the amount of oxygen recovered and eliminate the serious toxicity problem of carbon monoxide. However, it is very difficult to do this as the binding force holding the CO molecule together is much stronger than that in the CO_2 molecule.

Very little has been done experimentally to investigate photochemical decomposition of carbon dioxide. The International Critical Tables lists the following results for an experiment in which CO_2 was subjected to ultraviolet irradiation:

λ (wavelength of light source) = 2200-2540 A°
T = 240°C

pCO_2 (mm Hg.)	1397	818	325	94.7
% of CO_2 decomposed	6.06	17.06	27.39	31.60

5.2.3 (Continued)

These results indicate that CO_2 can be decomposed photochemically. The reaction is aided by lower pressures, and probably also by elevated temperatures. No information was given on the time required to effect this decomposition or the energy expended.

5.2.4 Thermal Decomposition of CO_2

Like any other chemical compound, carbon dioxide can be broken up into its constituent atoms by heating. As in the case of photochemical decomposition, the CO_2 first reacts to become carbon monoxide and oxygen, and the carbon monoxide is broken into carbon and oxygen only with greater difficulty. Carbon monoxide can also react with itself to form CO_2 and carbon, so there are three reactions as follows:

1) $2\ CO_2 \longrightarrow 2CO + O_2$
2) $2\ CO \longrightarrow 2C + O_2$
3) $2\ CO \longrightarrow CO_2 + C$

At atmospheric pressure, the equilibrium for reaction (1) becomes favorable only above 3000°K (~ 4900°F). Reaction (2) does not become favorable until very much higher temperatures. Reaction (3) is an inverse function of temperature, and the equilibrium for this reaction becomes favorable below 1000°K (1340°F). By using two reactors in series, with the first at 5000°F and the second at roughly 1000°F, it is theoretically possible to use reactions (1) and (3) to decompose CO_2 into carbon and oxygen. Pressure effects could also be used, as reaction (1) would be aided by low pressure and reaction (3) by high pressure.

Design problems associated with this approach would include the difficulty of providing the very high temperatures needed, and of building a reactor to withstand these temperatures. Also, the oxygen must be removed from the mixture of gases without allowing it to recombine, as reaction (1) will proceed backwards very readily once the temperature is lowered.

5.3 Bosch CO_2 Reduction System

5.3.1 Introduction and Data Source

This reaction is of interest primarily due to its ability to produce water from CO_2 in one step. Subsequent electrolysis of the water produces the desired O_2. In the basic reaction, CO_2 and hydrogen are reacted at temperatures above 1000°F to

5.3.1 (Continued)

form water and carbon as follows:

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

Water is removed from a recirculating gas flow by condensation and separation. In the recirculation stream an equilibrium concentration of CH_4, CO, CO_2, H_2, and H_2O exists. Because of this recirculation, a 100% conversion of the processed CO_2 is anticipated. Carbon formed in the reaction is deposited on an expendable catalyst. Present data on catalyst usage indicates a range of carbon to catalyst ratios varing from 10:1 to 200:1. For the purpose of this study a 50:1 ratio has been established as a feasible ratio. The primary engineering problem to be solved for this system approach is the removal of the carbon.

The work of the Mechanics Research Division of General American Transportation Co. and the TAPCO Division of Thompson Ramo Wooldridge has been utilized in analyzing this system approach. Each concern approaches the problem somewhat differently, but the basic process is similar and the resultant analysis is a combination of the two approaches.

5.3.2 System Description

Figure 5-1 illustrates the MRD approach to this system and Figure 5-2 is the TAPCO system. Comparison of the two indicates that the basic components are similar but TAPCO includes carbon removal equipment to obtain high catalyst usage rates.

In the system, recirculation gases (CH_4, CO, CO_2, H_2, and H_2O) are mixed with the CO_2 feed and H_2 returning from the electrolysis cell and flow into a regenerative heat exchanger, which is used to bring the gas flow up to reaction temperature. The reaction temperature is maintained above 1300°F by use of electrical heaters in the reactor which make up for losses due to heat leaks. Some heat is generated in the reaction, but, due to the small quantity of CO_2 reacting, this must be supplemented by electrical heating. Heater power is determined by optimizing the penalty for heater power and insulation weight. An iron catalyst on which the carbon forms is used in the reactor.

The recirculated gases plus the newly reacted components leave the reactor and are cooled in the regenerator by the cold flow entering the regenerator.

Further cooling of the gases to 50-55°F results in condensation of the water formed in the reactor. This water is then removed from the recirculation stream by a

BOSCH REACTION CO_2 REDUCTION SYSTEM

(REFERENCE: MECHANICS RESEARCH DIVISION – GENERAL AMERICAN TRANSPORTATION CO.)

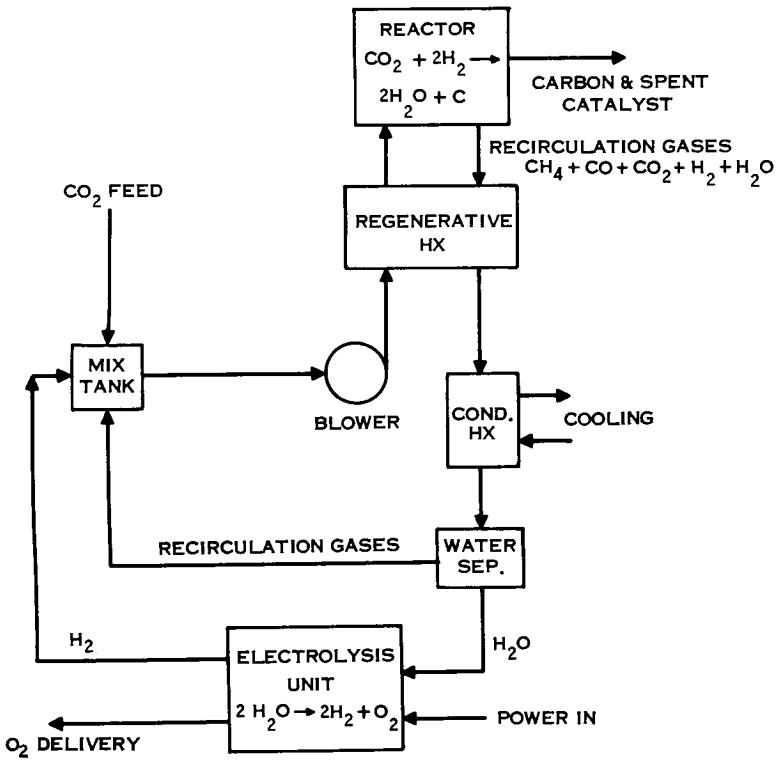


FIGURE 5–1

HYDROGENATION CO_2 REDUCTION SYSTEM

REFERENCE: (TAPCO DIVISION – THOMPSON RAMO WOOLRIDGE)

NOTE: RECIRCULATION GASES ARE CH_4, CO, CO_2, H_2 & H_2O

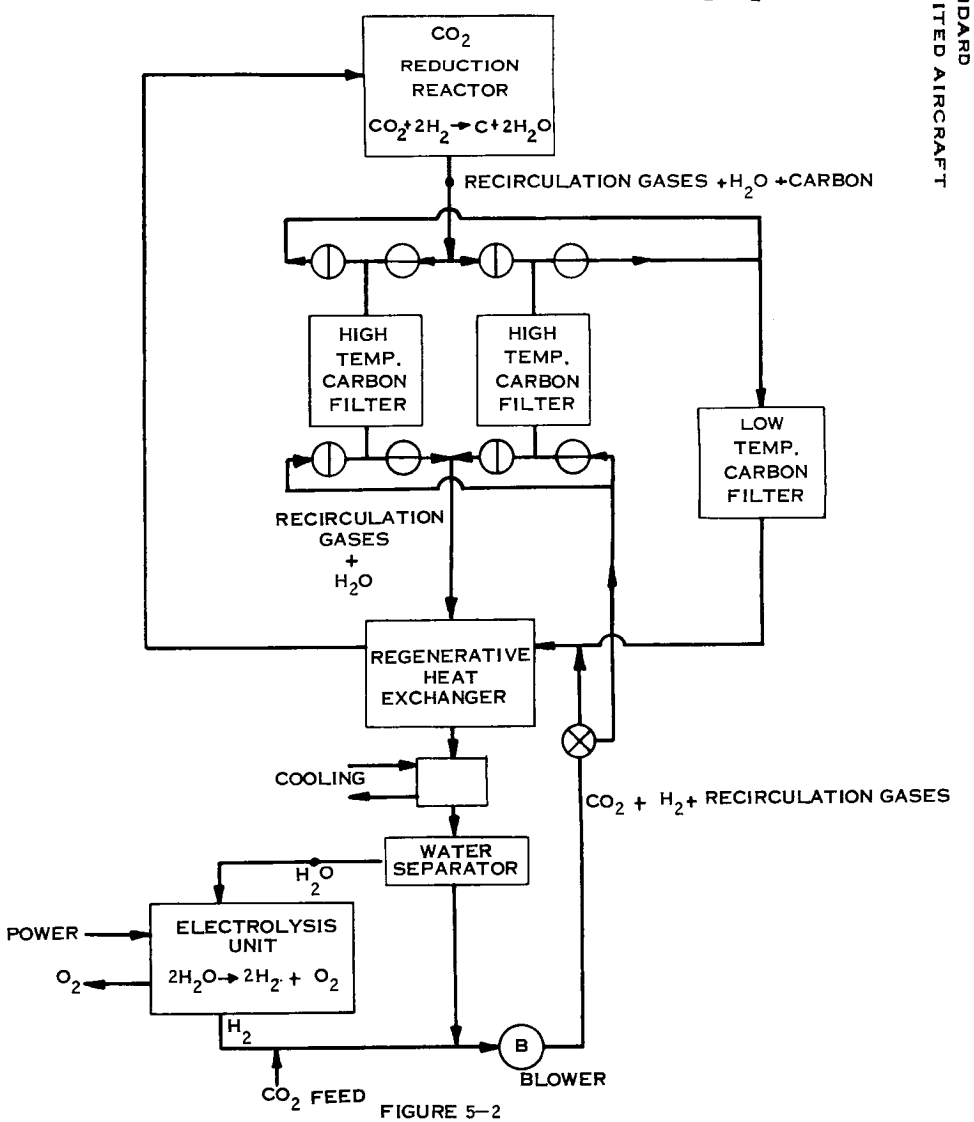


FIGURE 5–2

5.3.2 (Continued)

water separator and directed to an electrolysis cell which dissociates the H_2O into H_2 and O_2. The O_2 is then delivered to the cabin and the H_2 is recycled through the reactor with the remaining recirculated gases.

Carbon formation on and removal of the iron catalyst in the reactor presents a development problem in this type of system. Some of the proposed solutions (a few of which have been reduced to hardware) are presented below:

1. Carbon accumulation on the reactor catalyst with periodic removal or cleaning (possibly use throw away catalyst canisters).

2. Carbon collection on the catalyst with periodic high velocity gas purge overboard.

3. Carbon collection on the catalyst with periodic gas purge to a filter and collection system.

4. Use of dual reactor beds cycled when carbon deposit causes an excessive pressure drop.

5. A steady reactant flow system with continuous mechanical cleaning of carbon from the catalyst.

The TAPCO schematic (Figure 5-2) shows dual high temperature filter beds into which carbon is blown after being scraped off the catalyst in the reactor. Carbon is periodically blown into a low temperature filter bed for storage or removal.

5.3.3 Results

Weight, power, and equivalent weight curves for a Bosch reaction system are presented in Figures 5-3 to 5-6. The electrolysis system adds considerably to the system weight and power. For a 6 man system (12.72 pounds per day CO_2 process rate) at a power penalty of 500 pounds per kilowatt, the water electrolysis cell represents about 25% of the fixed weight and 78% of the power requirement.

Use of a hydrogen purge for cleaning carbon off the catalyst would result in an increased expendable weight. The primary expendable for this process is the catalyst. Although carbon to catalyst loading is dependent on many factors, it is felt that a 50 to 1 carbon to catalyst loading is attainable.

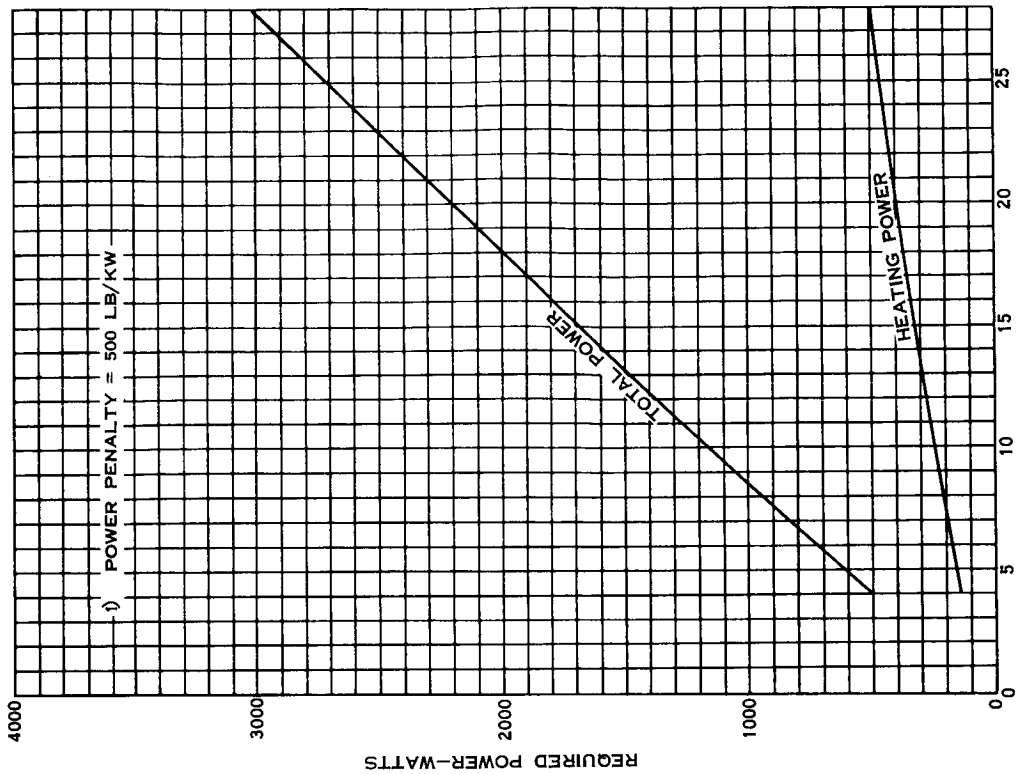


FIGURE 5–4

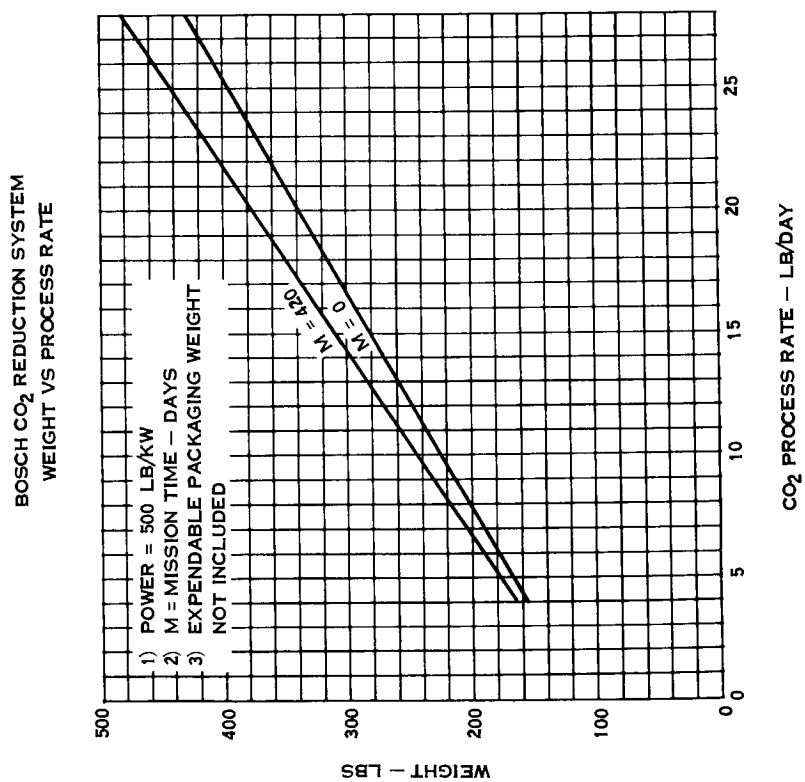


FIGURE 5 – 3

BOSCH CO_2 REDUCTION SYSTEM
EQUIVALENT WEIGHT VS CO_2 PROCESS RATE

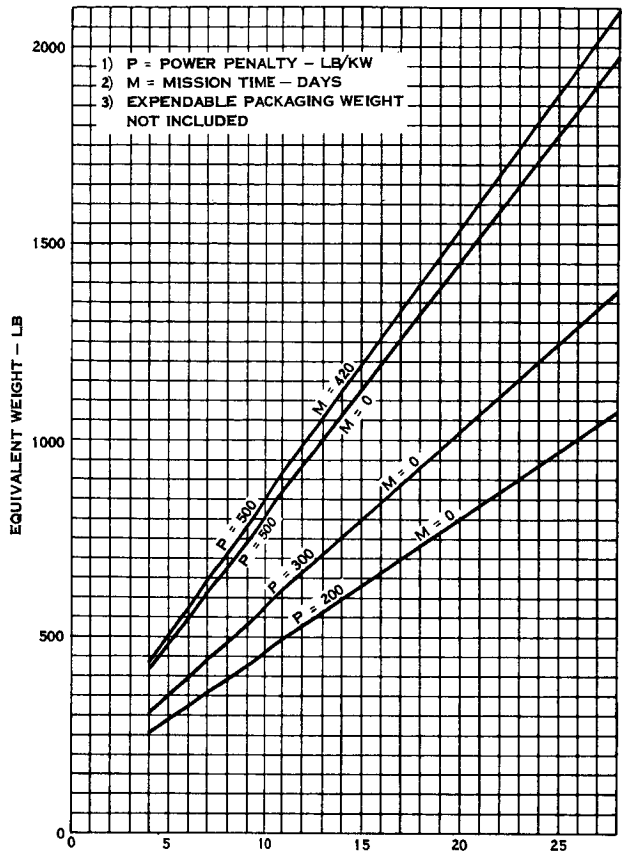


FIGURE 5 – 5

BOSCH CO_2 REDUCTION
EQUIVALENT WEIGHT VS MISSION TIME

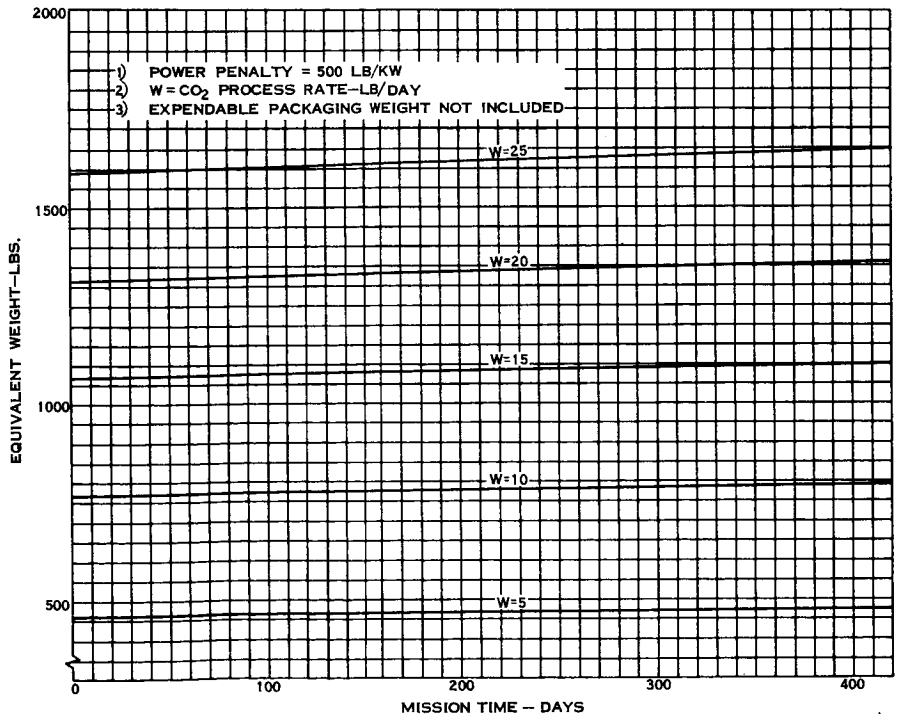


FIGURE 5–6

5.3.4 Conclusions

Although the Bosch reaction system is not the lightest of the candidate systems, it remains of interest since the reaction producing water may be accomplished in one step. In addition, it enjoys a good "state-of-the-art" status having been proved feasible in experimental tests. There exists a potential savings in weight and power consumption to be gained through system development since:

a. The carbon collection is an engineering problem, thus making weight reduction dependent upon the extent of detailed design and development employed.

b. The chemical reaction is actually exothermic so that heater power may be reduced by optimizing reactor insulation.

5.4 Methoxy CO_2 Reduction System

5.4.1 Introduction and Data Source

The Sabatier chemical reaction, also called methanization, and the methoxy reaction by the Isomet Corporation, can be described by the equation:

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

A supply of four moles of H_2 per mole of CO_2 is required for the reaction which occurs at high conversion efficiencies at temperatures in the 200 to 300°C range. Emperical data from both Reference 1 and Reference 2 demonstrate conversion efficiencies as high as 95% using a nickel catalyst. The water produced in the reaction is electrolyzed to form oxygen and hydrogen which can be recycled to help satisfy the hydrogen input requirement for the methanization reaction. Methane produced in the basic reaction may be:

1. Further reacted in a methane decomposer ($CH_4 \longrightarrow C + 2\ H_2$) for reclamation of all the hydrogen.

2. Dumped to space after the water is removed for electrolysis.

3. Converted to acetylene (C_2H_2) in an electric arc ($2\ CH_4 \longrightarrow C_2H_2 + 3H_2$) with H_2 filtration and C_2H_2 dump.

4. Further reacted with CO_2 at low temperature ($CH_4 + CO_2 \longrightarrow 2C + 2H_2O$)

5.4.1 (Continued)

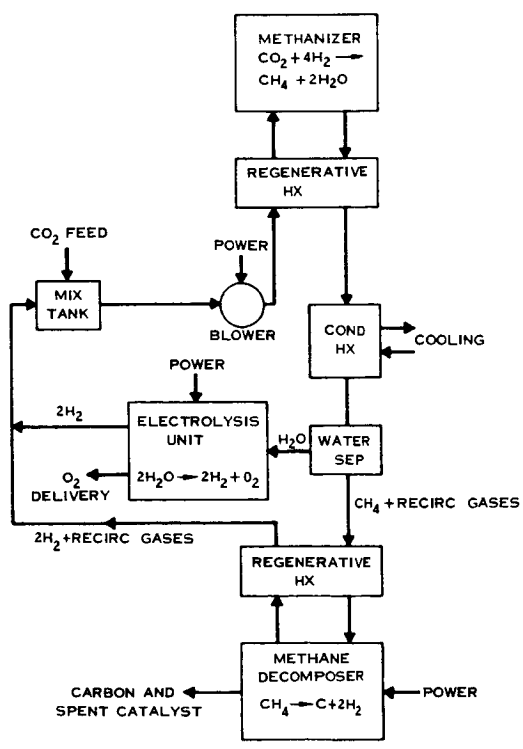
With the formation of acetylene (Method 3), theoretically 75% of the hydrogen in the methane may be recovered for subsequent recycling to the methanization reactor. The acetylene formation reaction is performed at about 700°F in the presence of an electric arc. One pass conversion is poor and it is necessary to recycle the gas stream through this reactor. A problem exists in separating the hydrogen from the acetylene and other recirculation gases occurring due to reactor inefficiencies. Although palladium-silver membranes have been mentioned for separating hydrogen, no testing has been conducted with such membranes integrated into a methoxy CO_2 reduction system. In addition there remains the problem of separating the recirculation gases from the acetylene.

Due to the preliminary research status of Method 4, insufficient data were availabe to evaluate this process for this study.

In light of their qualitative attractiveness, an analytical evaluation was made of two methoxy CO_2 reduction systems employing methods 1 and 2 respectively.

5.4.2 System Description

The schematic of the system using Method 1 is shown in Figure 5-7. Carbon dioxide



METHOXY CO_2 REDUCTION SYSTEM

FIGURE 5-7

5.4.2 (Continued)

and hydrogen from the electrolysis unit and methane decomposer along with the recirculation gases are directed into the methoxy reactor by the blower. The reactor is preceded by a regenerative heat exchanger to minimize power requirements.

Although high conversion occurs at temperatures such as 390°F, it is actually desirable to have a greater part of the reaction occurring at 570°F to 660°F in the high temperature portion of the catalyst bed. This arrangement takes advantage of the high kinetic rates in the high temperature portion and the high conversion but low reaction rate in the low temperature zone for "polishing" the reactor.

A combination of the high and low temperature regions of the reactor results in a small reactor volume with a high overall conversion efficiency. Energy input driving the regenerative function as well as providing for heat leak is supplied by the reaction itself which is exothermic. Flow leaving the reactor is cooled by the inlet flow in the regenerative heat exchanger. The flow is further cooled in a condensing heat exchanger in which the water formed in the Sabatier reaction is condensed at about a 50 to 55°F dew point. The gas and liquid condensate then enters a liquid-vapor water separator and the removed water is passed into the electrolysis unit for further reduction to H_2 and O_2. The moisture free gas is directed to the methane decomposer where hydrogen and carbon are formed. The hydrogen formed in the electrolysis cell and methane decomposer is recycled to the methanizer reactor along with the remaining recirculation gases. The methane can be decomposed with acceptable yields above 1100°F but higher temperatures are often used to obtain more dense carbon deposits.

In a system employing overboard discharge of methane, the methane decomposer is eliminated and make-up hydrogen must be supplied at the methanizer inlet.

A fair amount of empirical data has been accumulated concerning the Sabatier reaction. In addition the Isomet Corporation has conducted tests to evaluate methane decomposition. Unfortunately there has been no literature published on integrated reduction system tests employing the Sabatier and methane decomposition reactions. Such tests are essential to determine required recirculation rates due to the interplay of individual reactor inefficiencies. Although chemical equilibrium data can be used to obtain qualitative information, experience has shown it to be insufficient for supplying quantitative data due to the complex inter-reactions of actual operation. Therefore an analysis was undertaken to optimize a reduction system for different recirculation rates by determining optimum reactor insulation thickness. The recirculation rate range covered varies from a minimum rate of

5.4.2 (Continued)

one which is associated with ideal reactors having 100% conversion efficiencies to a maximum value of 24 which is that of the Bosch system reactor based on empirical data.

5.4.3 Results

Figures 5-8 through 5-12 show the methoxy reduction system (with methane decomposition) weight, power, and total equivalent weight as a function of CO_2 process rate over a range of recycle rates. The water electrolysis cell accounts for a large portion of the required power particularly at the low recycle rates. It is noted that for the same recycle rate, the methoxy system has a total equivalent weight approximately 25% greater than the Bosch system over the range of process rates. This can be attributed to the higher operating temperature of the methane decomposer which dictates more power to bring up the reactants to temperature as well as to make up for heat leak. In addition the methane decomposition process is endothermic thereby requiring added power.

Analysis of the methoxy system with methane dumped overboard showed the expendable weight to be prohibitively high for the Mars mission duration. Figure 5-13 shows the total equivalent weight breakeven time of this system when compared with both the previously mentioned methoxy system and the Bosch reduction system over a range of CO_2 process rates.

5.4.4 Conclusions

The methanization CO_2 reduction system is noted to have performance characteristics which span those of the Bosch system for the range of recycle flow rates. Until integrated tests are conducted to determine the required rate, no accurate comparison can be made with other systems. The development status of the methoxy system is not as good as that of the Bosch system.

The methoxy system is flexible enough for integration with several types of CO_2 collection and transfer systems since water is formed in the CO_2 reduction reaction.

It is felt that the slight shift in equilibrium resulting from a CO_2 feed saturated with water vapor will have a minor effect. As a result, collection and transfer systems delivering CO_2 saturated with water vapor, such as the electrolytic CO_2 scrubber or liquid absorption systems, may be used without any additional penalties.

METHOXY CO_2 REDUCTION
POWER VS. CO_2 PROCESS RATE

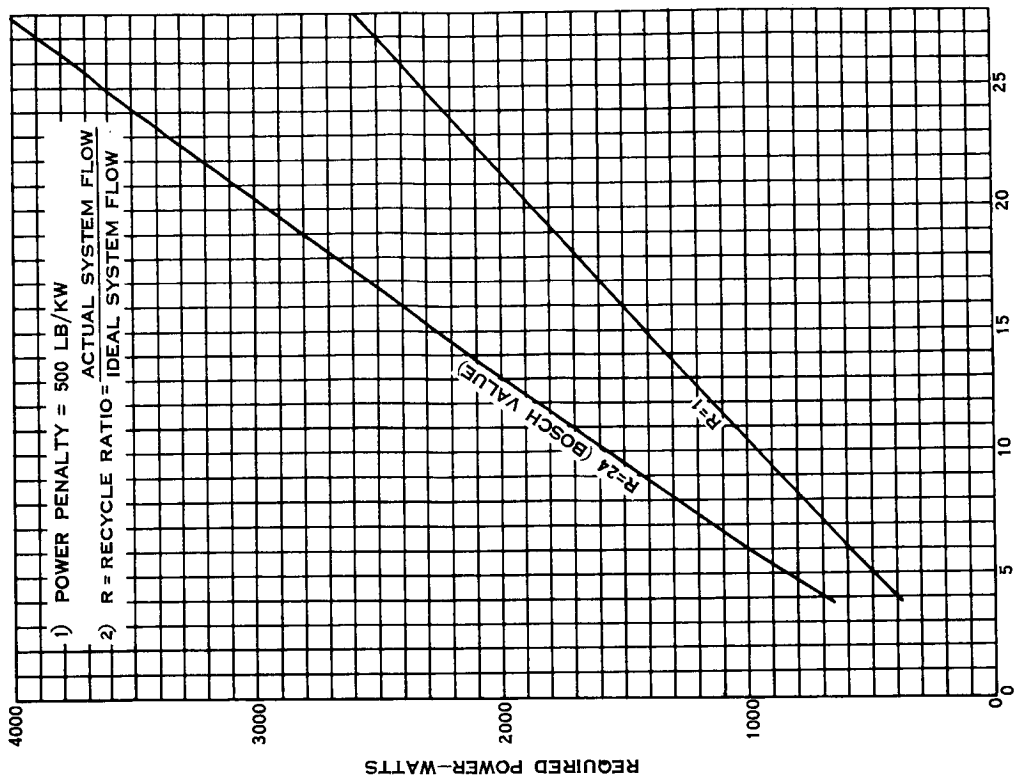


FIGURE 5-9

METHOXY CO_2 REDUCTION
WEIGHT VS. CO_2 PROCESS RATE

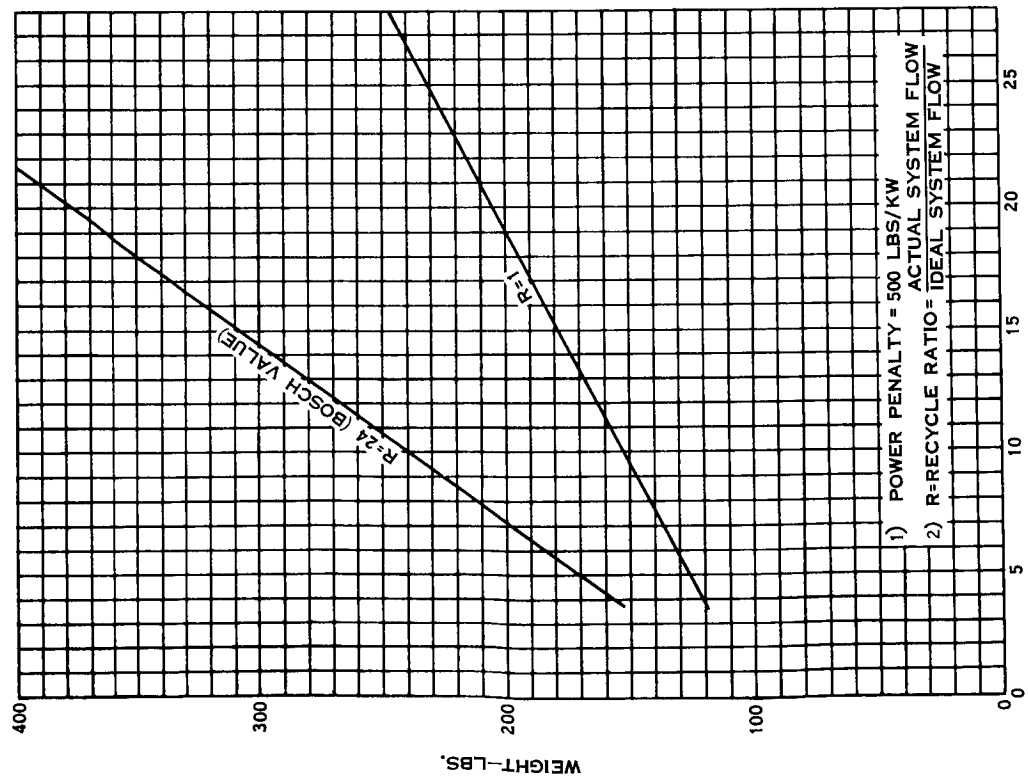


FIGURE 5-8

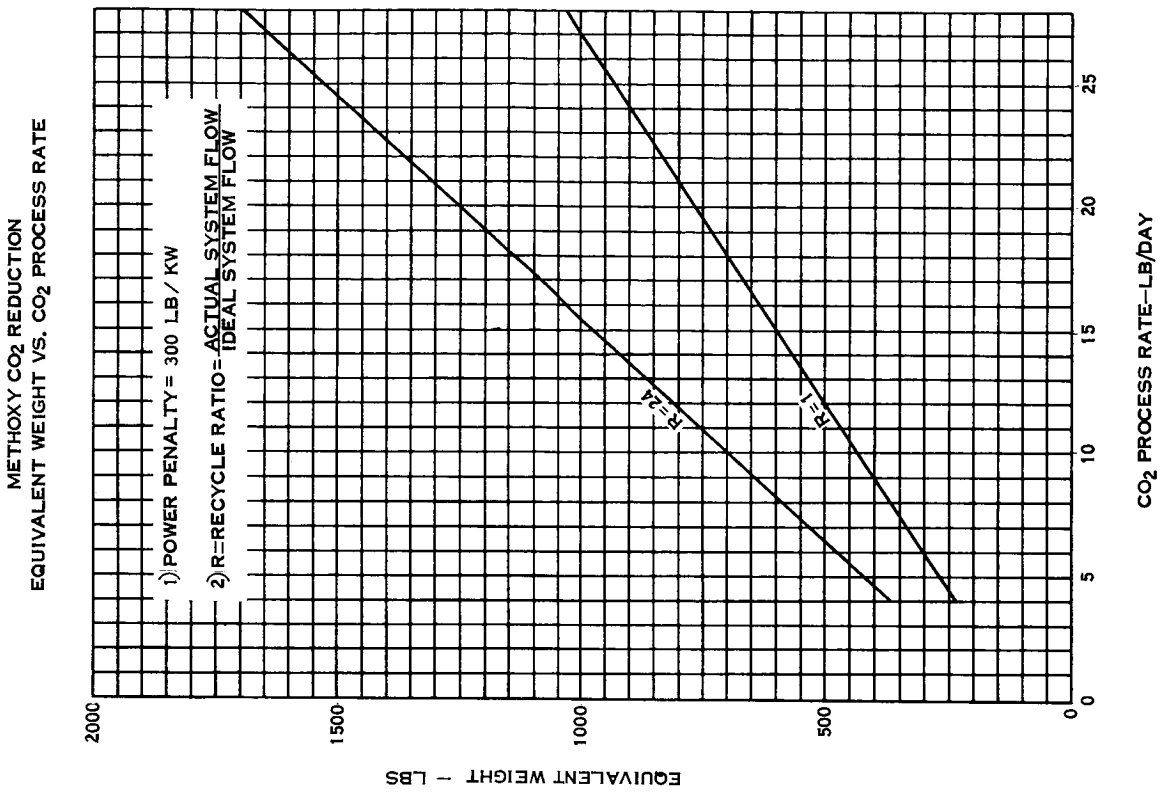


FIGURE 5–11

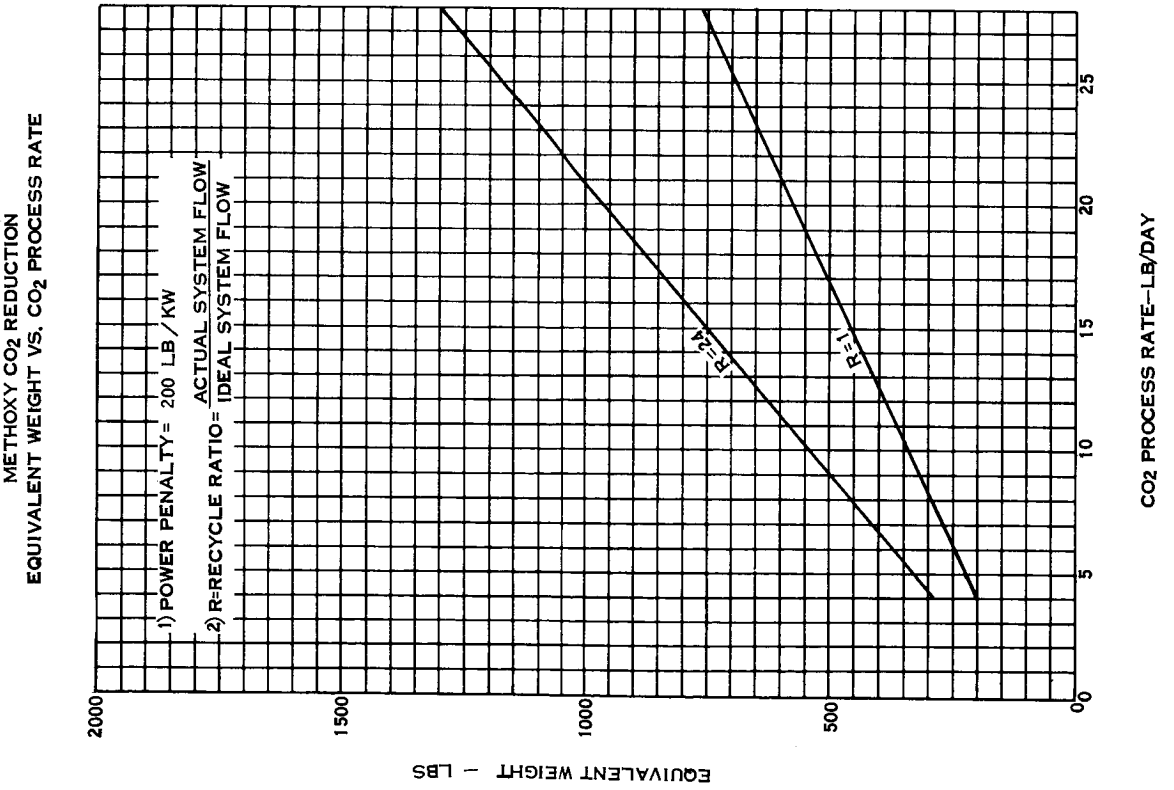


FIGURE 5–10

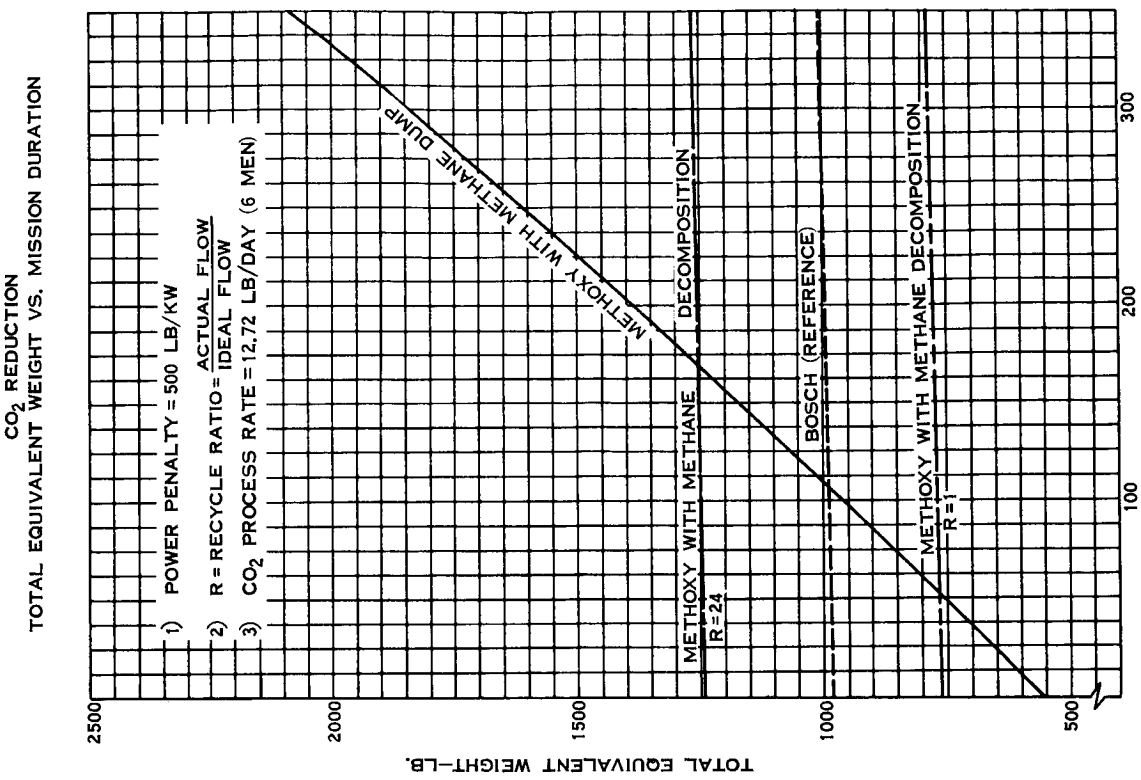


FIGURE 5–13

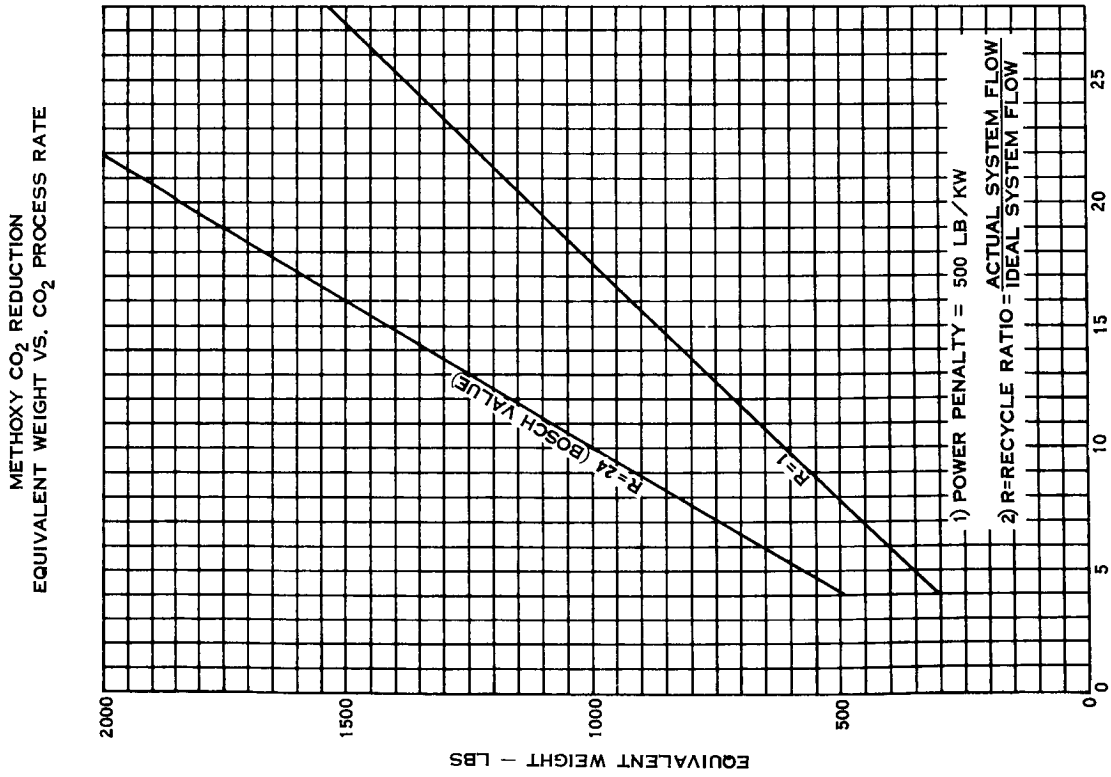


FIGURE 5–12

5.5 Solid Electrolyte CO_2 Reduction

5.5.1 Introduction and Data Source

The solid electrolyte system being developed by Isomet Corporation presents a direct approach to the problem with a minimum number of components. Isomet test data has been utilized as the major input to this analysis.

The process converts CO_2 to carbon and oxygen without producing water as an intermediate step, thus eliminating the zero gravity vapor-liquid separation problem. As is the case with most electro-chemical systems, a large increase in cell output is possible at only a small sacrifice in unit efficiency. The main requirement, under overload operation, is for additional cooling which can be provided with very little penalty to the system.

5.5.2 System Description

Figure 5-14 presents the basic schematic for the solid electrolyte system. The primary component is the solid electrolyte reactor which consists of ceramic tubes

SOLID ELECTROLYTE CO_2 REDUCTION SYSTEM
(REFERENCE: ISOMET CORPORATION)

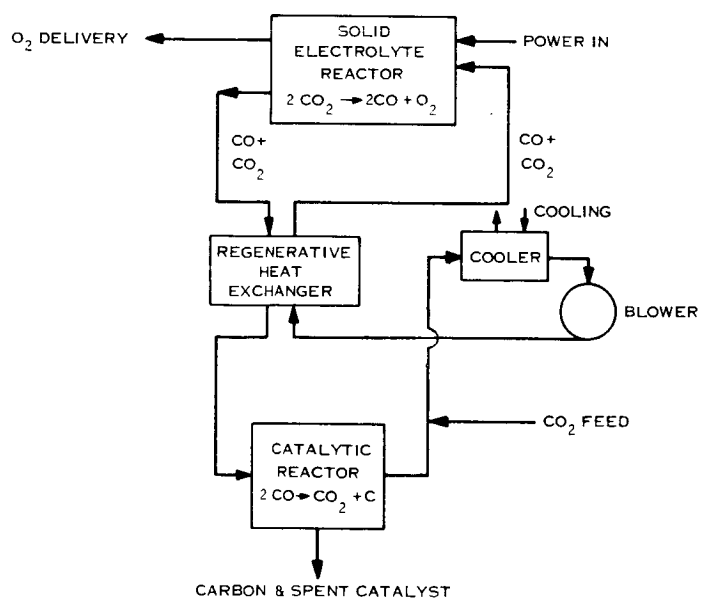


FIGURE 5-14

5.5.2 (Continued)

of a special mixed oxide composition. Electrodes are applied to the inner and outer surfaces of the tube walls and the tubes are heated internally by an auxiliary heating coil. CO_2 flows around the outside of the tube and the O_2 is liberated inside the tube. It is felt that the oxygen comes from a thermal decomposition of CO_2 to CO and nascent oxygen at the cathode surface where the oxygen atom is ionized. This oxygen ion then migrates under the influence of a potential field through vacancies in the crystal lattice of the solid electrolyte material. Upon reaching the anode, the oxygen ion is converted back to an oxygen atom.

A mixture of CO_2 and CO containing about 80-90% CO_2 is fed to the cell and oxygen is generated. The composition of the circulating gas varies with time as the catalyst in the catalytic reactor declines in activity. The gas flow to the cells, which are arranged in parallel, is evenly distributed. A composition sensor on the cell gas effluent determines the composition of the effluent recycle gas, and, when the concentration of CO in this effluent rises above 70%, automatically shuts down the cell. If the concentration of the CO is allowed to rise above this level, there is a possibility that the electrolyte will decompose. This switch then acts to protect the cell.

The power consumption in the cell is split between energy required to decompose the CO_2 and I^2R heating of the solid electrolyte material. The circulating gas stream will be cooled to provide temperature control in the loop. As the predicted cell efficiency is thought to be good and the operations temperature high, this unit must be well insulated to prevent excessive heat leak which would decrease unit performance. The auxiliary heaters, one in each tube, can be designed to bring the system to temperature (1830°F) in 4 hours with the normal operating power. No expendable weight is required for the operation of the solid electrolyte cells.

Upon leaving the electrolytic cell, the gases pass through a regenerative heat exchanger where the temperature is reduced to 932°F which is the operation temperature of the catalytic reactor. In the catalytic reactor, the carbon monoxide formed in the reduction cell is combined to form carbon and carbon dioxide over a nickel catalyst which is deposited on a light fibrous substrate. When the carbon has built up to high level, a pressure switch will sense the increasing ΔP and signal for a change of catalyst bed. The reaction occurring is exothermic in nature and no heating of this unit is necessary once the system has reached operating temperature. The gases leave the catalytic reactor and go to a cooler where the excess power put into the system in the electrolytic cell is removed.

5.5.3 Results

Figures 5-15 through 5-20 present the weight, power, and equivalent weight of the solid electrolyte CO_2 reduction system operating alone without regard to the type of CO_2 removal system. These curves are based on predictions of what can be achieved by 1973 rather than presently achieved results as in the mid-term report of this study.

The improvements required to attain this performance are:

(1) A reduction in the unit fixed weight by design of spacecraft type hardware rather than the presently existing breadboard type unit.

(2) Improvement of carbon to catalyst weight ratio to 50:1 instead of 10:1

(3) More efficient electrical design to result in an operating voltage of 2 volts instead of the present 3 volts.

Test results with the present unit indicate that these improvements are feasible.

5.5.4 Conclusion

Solid electrolyte system feasibility has already been proven and the major chemical and physical problems solved. However, prior to reaching a flight-worthy system, several remaining design problems must be solved such as the development of a high temperature fan and motor; lowering of the internal cell resistance; improvement of the cells resistance to shock, acceleration, and vibration loads; development of a simple method of carbon removal; and development of a system for delivering pure CO_2.

5.6 Molten Carbonate CO_2 Reduction

5.6.1 Introduction and Data Source

Reduction of CO_2 using molten carbonate electrolytic cells has been the subject of many research programs in the recent past. The system discussed in this report is an outgrowth of an internal Hamilton Standard research program, and the performance estimates are based on the results of that program. It should be noted that the results reported here are different from those in the mid-term report of this study because the results of recent testing have been included here.

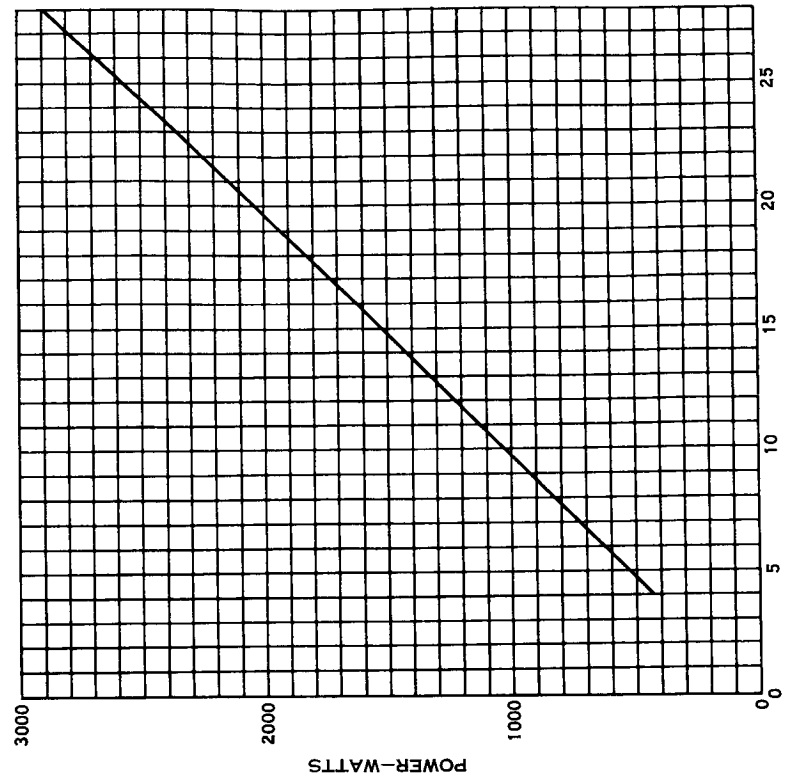


FIGURE 5–16

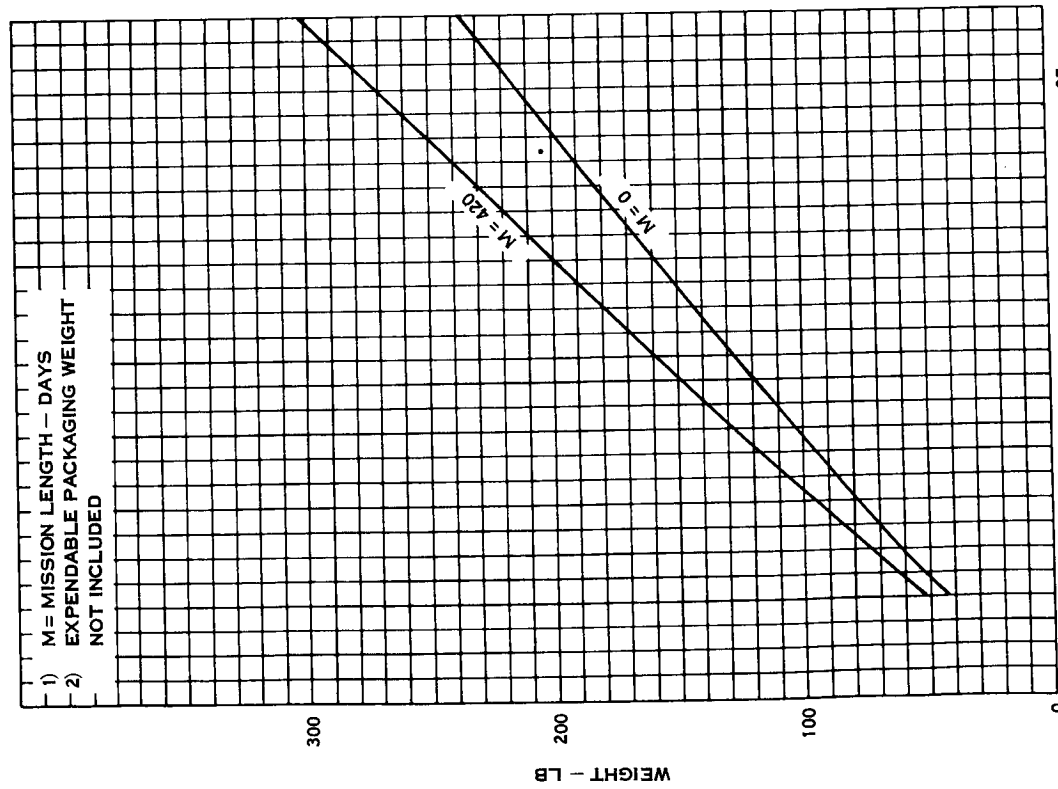


FIGURE 5–15

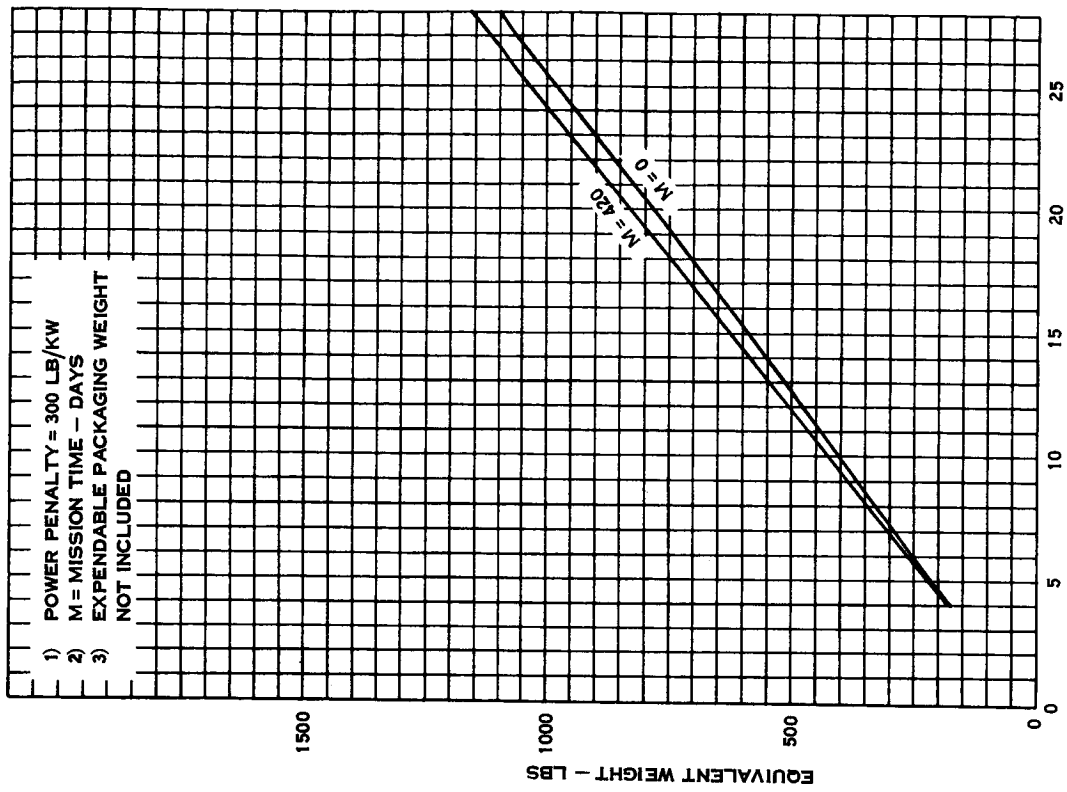


FIGURE 5–17

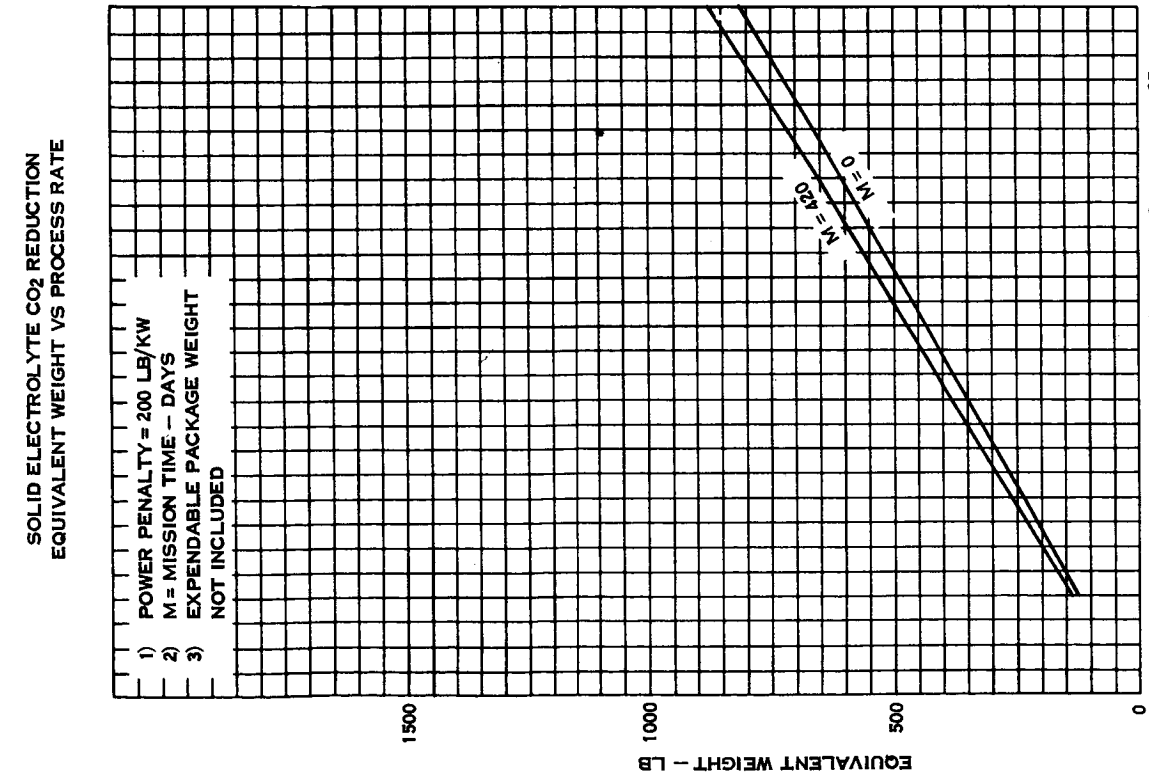


FIGURE 5–18

SOLID ELECTROLYTE CO_2 REDUCTION
EQUIVALENT WEIGHT VS PROCESS RATE

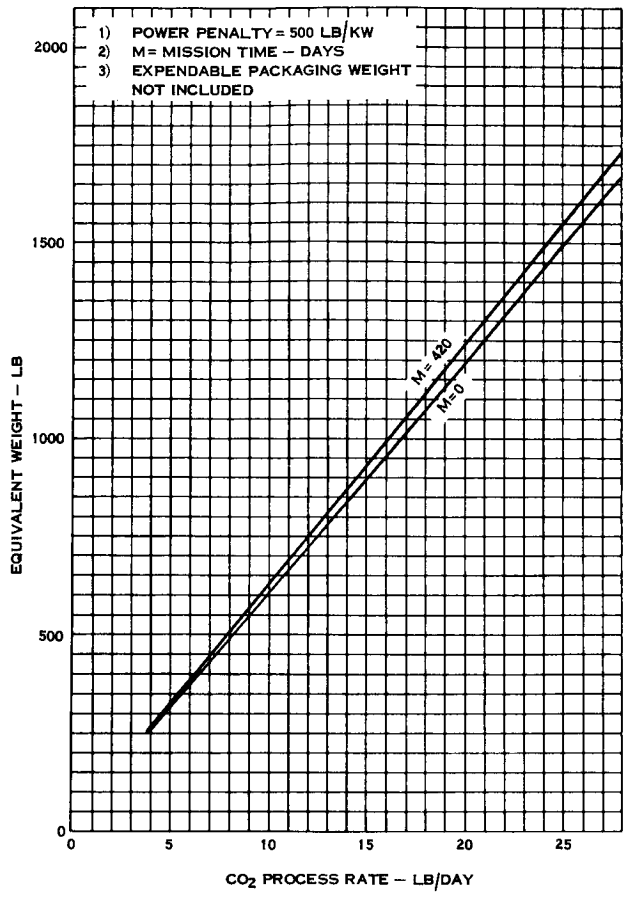


FIGURE 5–19

CO_2 REDUCTION SYSTEM
SOLID ELECTROLYTE
EQUIVALENT WEIGHT VS MISSION TIME

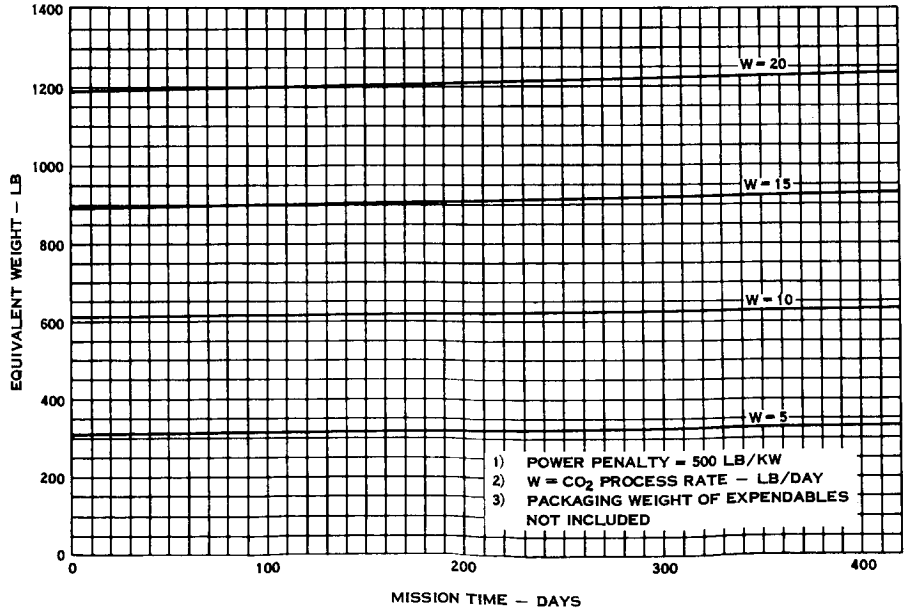


FIGURE 5–20

5.6.2 System Description

Figure 5-21 presents a simplified schematic of a molten carbonate system. The cabin air passes through a blower which supplies the pressure required to move the air through the heat exchanger and the melt. From there, it passes through a regenerative heat exchanger where it picks up heat from the leaving air stream. This heat exchanger must be of high effectiveness to prevent an excessive loss of heat to the air stream. The hot air stream then goes to the electrolysis cell. The concept of this cell is that a molten alkali carbonate may be electrolyzed so as to produce oxygen at the anode, and carbon and an alkali oxide at the cathode. The alkali oxide reacts with the CO_2 formed at the anode and removes CO_2 from the air stream which is bubbled through the melt. The result of this action is the replenishment of the carbonate, removal of CO_2 from the cabin air stream, and the addition of the manufactured oxygen to the air. This basic concept appears to be valid from experimental demonstration; however, the true process is far more complicated, and many conditions need to be met for successful accomplishment.

Oxygen liberation at the anode takes place in accord with Faraday's principle, but carbon dioxide from dissociation of the carbonate ion is also released, in the proportion of two moles per mole of oxygen. Since 33% oxygen purity is undesirable in terms of increased gas processing requirements, re-absorption of CO_2 at the anode is an important requirement. Experimentally, it has been shown that re-absorption of anode CO_2 can be obtained, thus allowing final release of high purity oxygen.

The locally increased concentration of the alkali oxide results in a local rise in melting point, tending toward the formation of a low density, porous structure of carbon including significant quantities of trapped salts, presumably high in alkali content. From an engineering point of view, it is preferable to extract a low-porosity (high density) form of carbon from the cell in order to avoid any necessity for further processing before discard as waste material, and to reduce the size of the cell since its size is determined partly by the volume required for carbon build-up on the electrodes. Development of the process has led to the point where the melt entrained in the carbon can be expected to be slightly less than ten percent.

The establishment of a design point for any given set of conditions (i.e., CO_2 flow, mission time, power penalty) must include a trade-off between fixed weight and unit efficiency. This is caused by the steep nature of the current density vs. voltage characteristic curve for units of this type. As might be expected, system size and weight will vary as the anode area. If a series of units are designed to

SCHEMATIC OF MOLTEN CARBONATE CO_2 SCRUBBER-REDUCTION SYSTEM

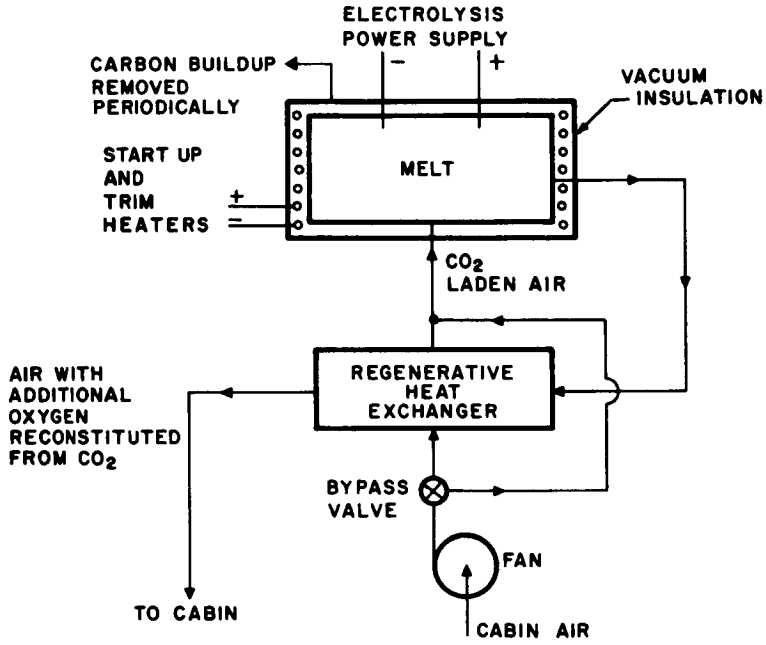


FIGURE 5—21

5.6.2 (Continued)

several levels of operating voltages (i.e. efficiency), the more efficient units will be larger. When system weight and power penalty are then combined to yield the equivalent weight, a minimum equivalent weight is observed at some voltage.

Thus, for every power penalty, there will be some optimum operating voltage. If voltage is decreased, unit weight will increase faster than power savings, and if voltage is increased, the unit weight savings will not match increase in power penalty.

The problem of zero gravity operation may be solved by rotating the melt chamber and providing for cathode assembly removal. In a system which uses molten carbonate electrolysis, dual units are recommended. This approach will increase system fixed weight a small amount but will substantially increase reliability. In the event of the failure of one of the units, the steep voltage current characteristics coupled with the large latitude of operating current densities possible with these units will permit full operation of one unit at a small increase in power. This means that for short periods one unit may be shut down for repairs and maintenance without sacrificing performance. Further, the failure of one of the units will not mean mission failure, only an increase of power consumption.

5.6.3 Results

Figure 5-22 through 5-27 present the weight, power, and equivalent weight of the molten carbonate reduction system. These curves are predictions of the performance capabilities of a spacecraft type unit which could be available by 1973. They are based on test results obtained from a present breadboard type unit.

Figure 5-22 illustrates the fixed weight of system and fixed weight plus expendables for 420 days as a function of CO_2 process rate. Figure 5-23 illustrates the power required as a function of CO_2 process rate. Figures 5-24, 5-25, and 5-26 illustrate the combined effect of power and weight as a total equivalent weight for 200, 300, and 500 pounds per kilowatt power penalties. The equivalent weight is also shown as a function of mission time in Figure 5-27. The expendables for this system are electrode weight for the removable electrodes and chemicals to replace that lost by entrainment in the discarded carbon.

5.6.4 Conclusions

The molten carbonate process is attractive in that it removes CO_2 from the air stream and reduces the CO_2 to O_2 in one step eliminating the need for additional

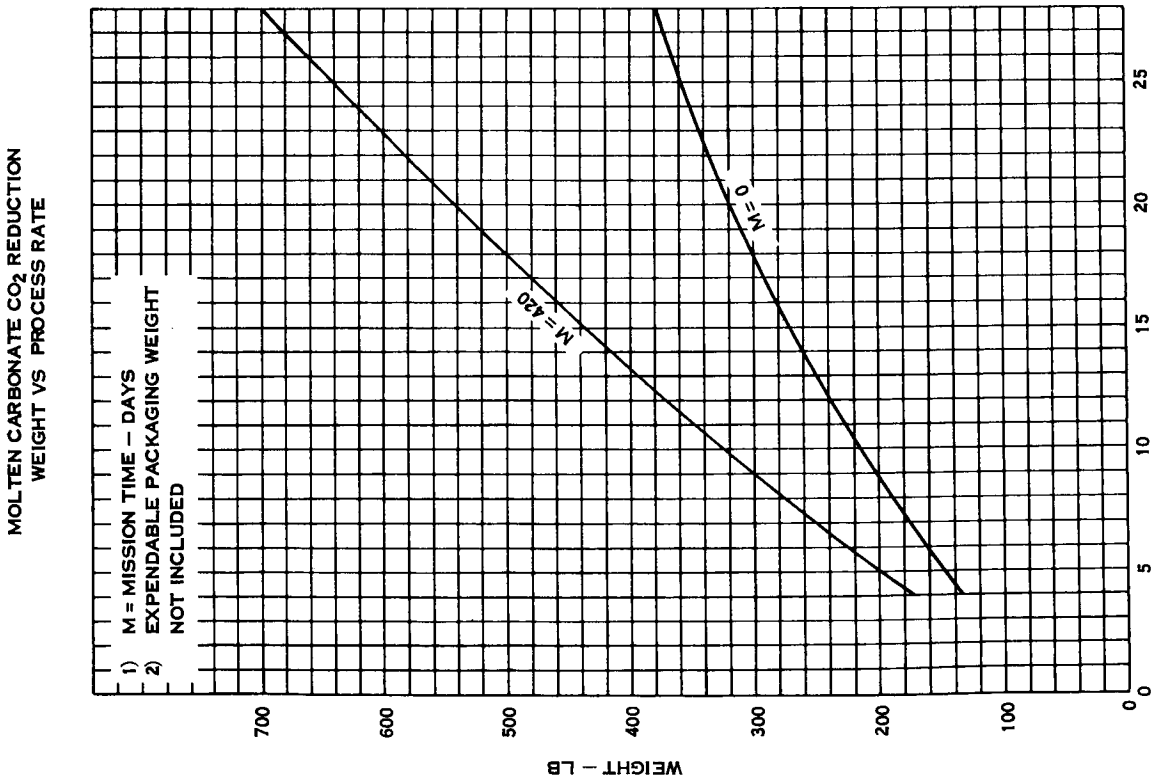


FIGURE 5–22

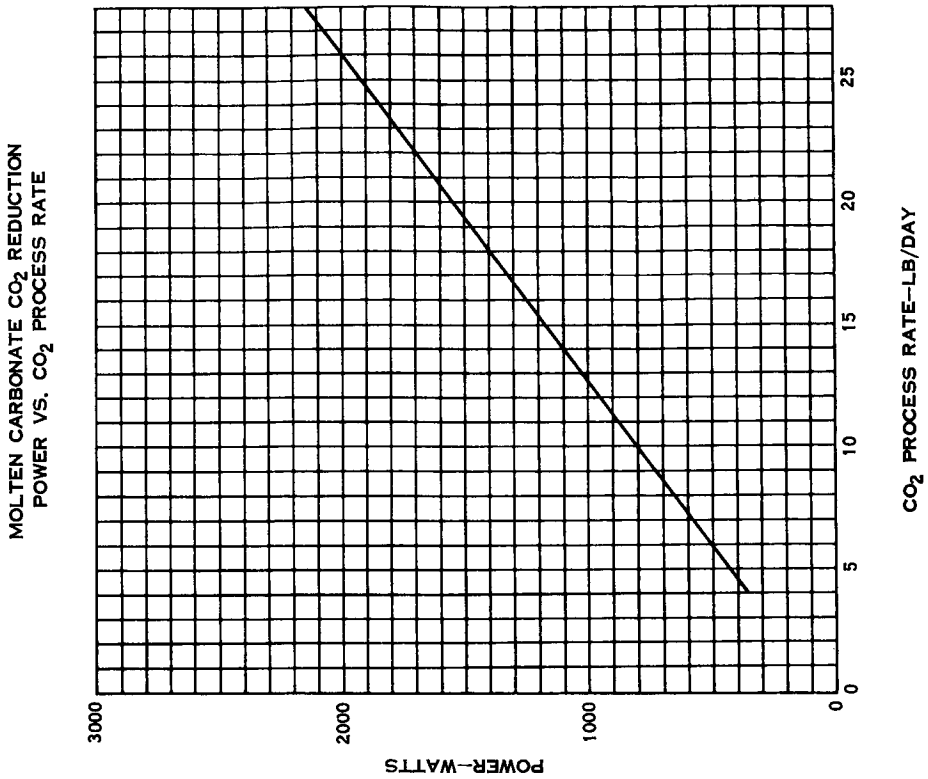


FIGURE 5 – 23

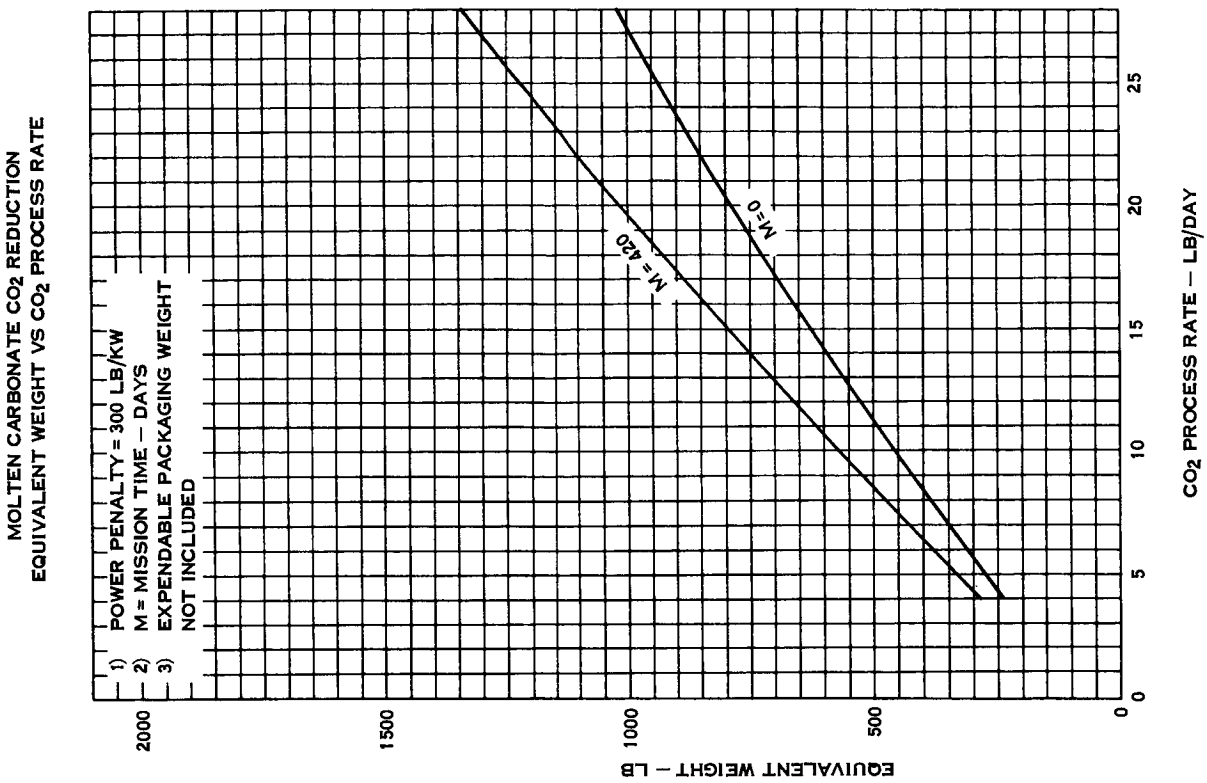


FIGURE 5–25

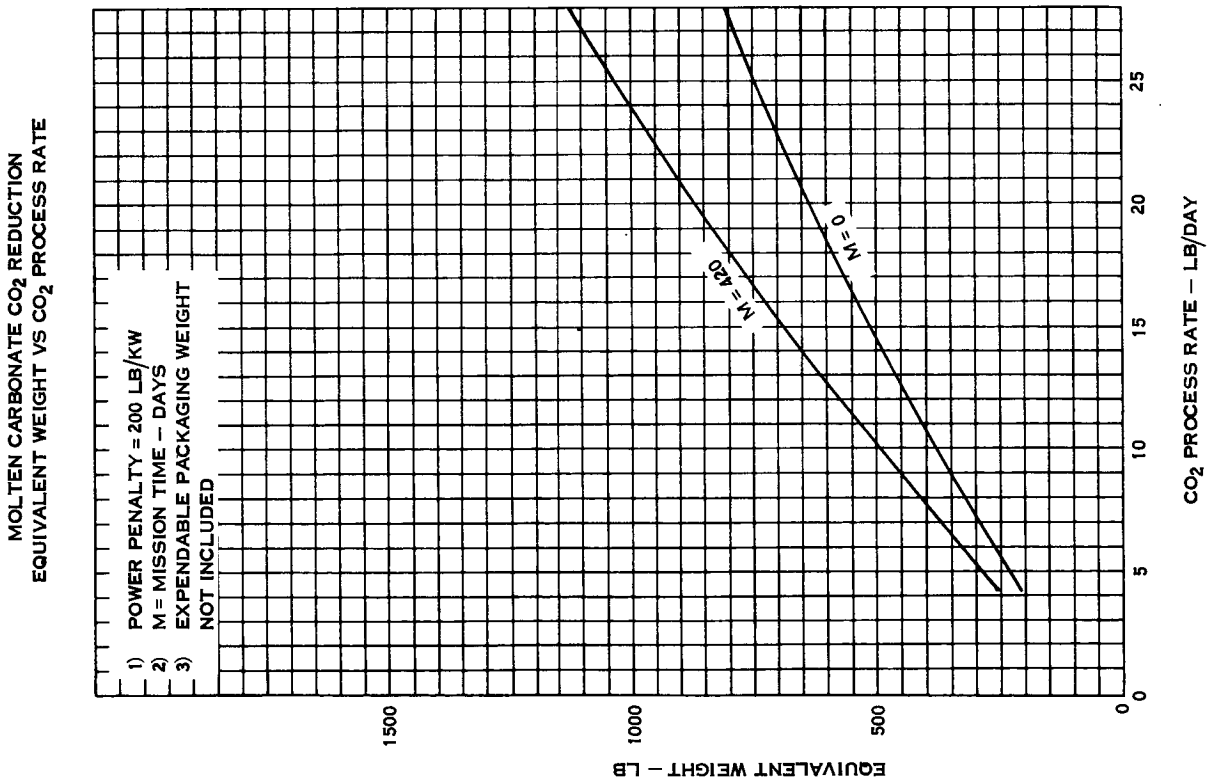


FIGURE 5–24

MOLTEN CARBONATE CO_2 REDUCTION
EQUIVALENT WEIGHT VS CO_2 PROCESS RATE

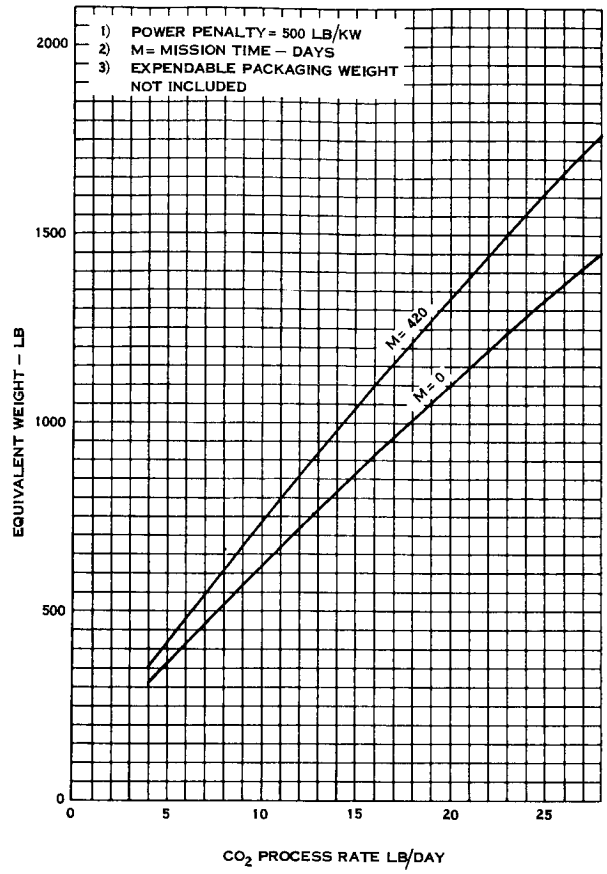


FIGURE 5–26

CO_2 REDUCTION SYSTEM
MOLTEN CARBONATE
EQUIVALENT WEIGHT VS MISSION TIME

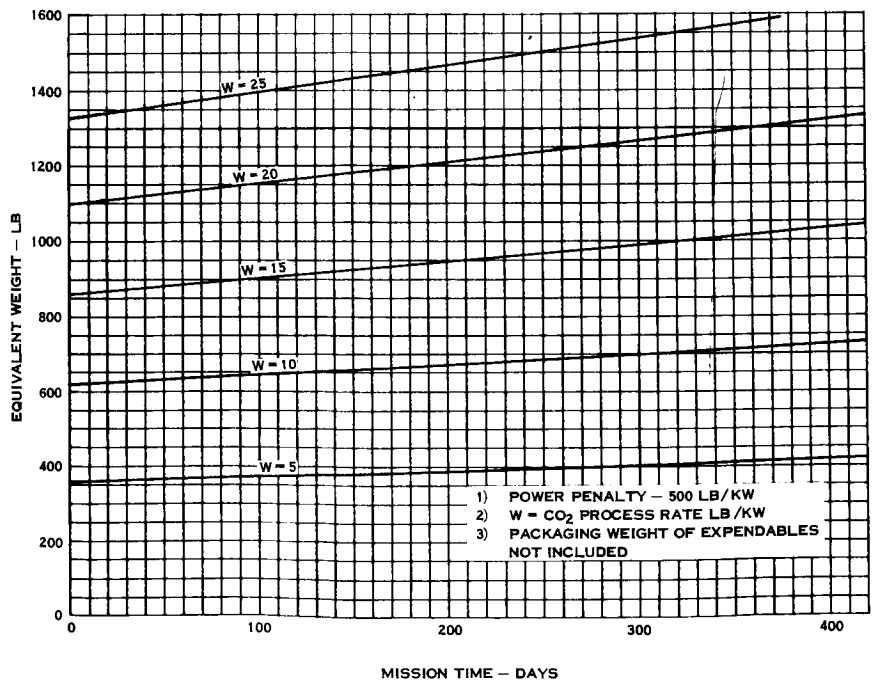


FIGURE 5–27

5.6.4 (Continued)

equipment. The primary problem areas seem to be adequate carbon deposit and removal and adaptability to zero "g" operation. At present the approach is still in the research stage and the zero gravity problem has not been fully considered. The basic approach is attractive enough to warrant further research and development work. The primary effort should be directed toward decreasing the expendable weight required for long duration missions.

5.7 Comparative Discussion

A comparison of CO_2 reduction systems is valid only if the method of CO_2 removal from the air stream and transfer to the reduction is considered. Therefore, a comparison will not be made in this section, but is shown in Section 6.0 of this report. There the various combinations of CO_2 removal and reduction systems are compared and parametric curves are presented.

5.8 References

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2. Ames, R.K. "Development of the Sabatier Life Support System," Boeing Co., Seattle, Washington, Proceedings of Institute of Environmental Sciences, 1963.

3. Chandler, H.W., Burghardt, S.I., Walden, G., Taylor, T.I. "Carbon Dioxide Reduction Systems," Isomet Corporation, Palisades Park, New Jersey, Report No. 5007-PR4-61, May, 1961.

4. Telephone conversation between Dr. H. Chandler of Isomet Corporation, Palisades Park, New Jersey, and R. Lamparter and J. Mattavi of HSD, December 4, 1963.

5. Telephone conversation between Dr. H. Chandler of Isomet Corporation, Palisades Park, New Jersey, and J. Mattavi of HSD, March 4, 1964.

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7. Babinsky, A. D. "MOSS and Mars Environmental System Studies," TAPCO Division of Thompson Ramo Wooldridge Inc., Cleveland, Ohio, ER-5482, August 1963.

8. Babinsky, A. D. "CO_2 Reduction System Atmospheric Regeneration System for the Life Support System for Space Flights of Extended Time Periods," TAPCO, ER-5233, February 1963.

9. Telephone conversation between M. Macklin of TAPCO Division of Thompson Ramo Wooldridge Inc., Cleveland, Ohio and J. Mattavi of HSD, March 4, 1964.

10. Archer, D. H. Sverdruys, E. F. "Solid Electrolyte Fuel Cells," Westinghouse Electric Corporation, Pittsburgh, Pa., Paper given at 16th Annual Proceedings Power Sources Conference, May 1962.

11. "The Sabatier Reaction for Inorganic Recovery of Oxygen in Manned Space Capsules," S.H. Cole and A.R. Tamplin, the RAND Corporation, 1960.

SECTION 6.0

CARBON DIOXIDE MANAGEMENT

6.0 CARBON DIOXIDE MANAGEMENT

6.1 Introduction

This section presents an analysis of integrated CO_2 management systems comprising removal, transfer, and reduction subsystems covered in Sections 2, 3, and 5 respectively. For those system approaches having water as an intermediate product, the electrolysis performance is based on the results of the subsystem study presented in Section 4.

The following is a list of combinations of CO_2 removal and reduction methods which were considered here as integrated systems:

System Designation	CO_2 Reduction Method	CO_2 Removal Method
A	Hydrogenation	Solid Adsorption - Waste Heat Purge
B	Hydrogenation	Solid Adsorption - Electrical Heat & Vacuum Purge
C	Hydrogenation	Electrodialysis
D	Hydrogenation	Liquid Absorption
E	Solid Electrolyte	Solid Adsorption - Waste Heat Purge
F	Solid Electrolyte	Solid Adsorption - Electrical Heat & Vacuum Purge
G	Solid Electrolyte	Electrodialysis
H	Solid Electrolyte	Liquid Absorption
J	Molten Carbonate	

The hydrogenation method of CO_2 reduction selected for consideration here is the Bosch system. This was chosen over the methoxy method as the best hydrogenation scheme in terms of total equivalent weight and development status. Section 5 contains a more detailed discussion of the selection of CO_2 reduction systems to be considered here.

The CO_2 removal methods are discussed in more detail in Sections 2 and 3. Two alternative solid adsorption schemes are presented, with one using waste heat for desorption and the other using a combination of electrical heat and vacuum desorption. These two schemes are based on two different optimizations, with reactor waste heat available in the first scheme and unavailable in the second. If waste heat is available, the optimum desorption method does not require the application of vacuum. However, with no waste heat available, the optimum method uses a combination of electrical heating and vacuum desorption.

6.1 (Continued)

A system description is presented along with schematics for each system. The results are presented in the form of weight, total power, thermal power, and total equivalent weight as a function of CO_2 process rate. A thermal inventory is given showing heat sink loads as a function of CO_2 process rate. The performance characteristics for a six man design condition are presented in tabular form. System reliability and development status is covered in a discussion of the results. A detailed description pertaining to each CO_2 removal, transfer, and reduction system by itself is given in Sections 2, 3 and 5 respectively. This is supplemented in this section with a brief description of the integrated management systems. The properties of the management system gaseous and liquid entering flows are defined at the interface stations to allow analysis concerning integration of the management systems with the overall environmental control system.

6.2 Hydrogenation (Bosch) Management Systems

6.2.1 System A - Hydrogenation with Solid Adsorption (Figure 6-1)

CO_2 removal is accomplished with a solid adsorption CO_2 removal system. The process air is drawn into the solid adsorption CO_2 removal system from the environmental control system recirculation stream at a point downstream of the water separator where the minimum moisture concentration exists. The CO_2 is desorbed and delivered to the Bosch reduction system by heating up the zeolite canister, thus driving off the CO_2 at a higher partial pressure than that at which it was adsorbed. A heat transfer fluid receives this heat from the waste heat source and delivers it to the bed through imbedded coils. The CO_2 is delivered to an accumulator and stored at a pressure slightly above the removal system pressure level. Just prior to desorption, a back flush from the accumulator through the bed to be desorbed and on to the CO_2 removal system inlet provides for minimum carry-over of nitrogen and oxygen to the reduction system. The desorbed gases are returned to the system inlet because the zeolite works more efficiently at higher CO_2 concentrations, and the concentration of CO_2 in the system is higher than that in the cabin air. Coolant flow to both sets of canisters is required at a temperature of 60°F or lower in order to cool the beds down at the conclusion of desorption. The coolant flow to the Bosch system condenser should be at a temperature of 50°F or lower. This system offers a competitive equivalent weight with a good development status. Although the power is high, more than 50% is thermal power which is obtained from a waste heat source at a very low penalty. The solid-adsorption principle for CO_2 removal has been applied and incorporated into prototype hardware by Hamilton Standard as well as other companies.

SYSTEM A
SOLID ADSORPTION CO_2 REMOVAL SYSTEM (WASTE HEAT PURGE)
BOSCH CO_2 REDUCTION SYSTEM

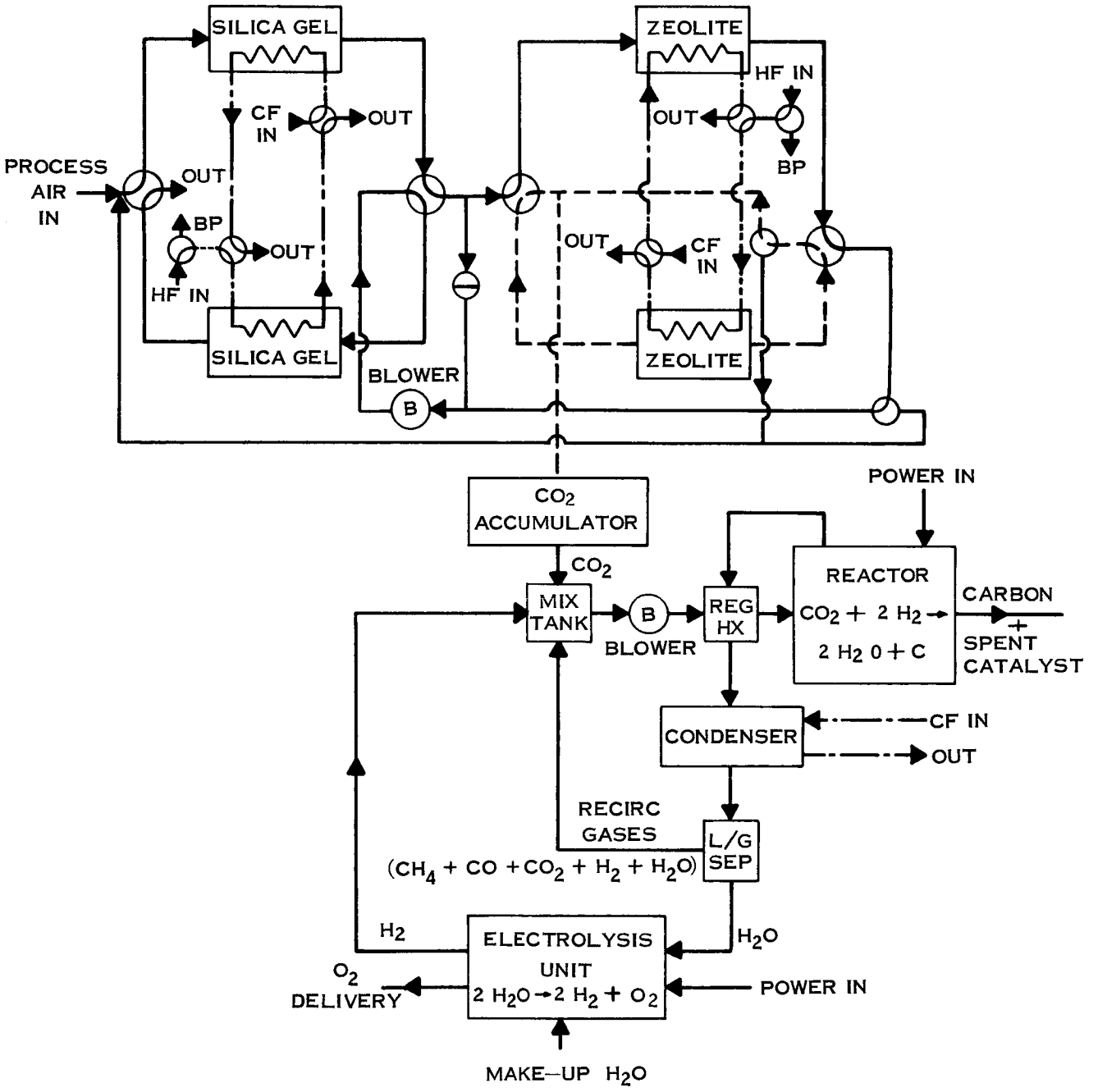


FIGURE 6–1

6.2.1 (Continued)

The major development areas are desorption techniques and reduction system optimization. Development work remains to be conducted to determine the optimum cycling times and amount of input energy. Predicted reduction system performance can be achieved by optimizing the reactor for minimum power by using proper insulation. The reduction portion has been successfully built and run to insure feasibility by MRD and Tapco. System reliability has been assessed as generally good. Although cycling operation is a characteristic of the removal system, tests have been conducted at Hamilton Standard with 30 days continuous running followed by a 14 day continuous run with no degradation in system performance. In the event of a heat transport fluid system failure (i.e., a radiator penetration, pump failure, etc.) or a reduction in available power, both the moisture and CO_2 adsorption canisters can be vented to the vacuum of space thereby allowing CO_2 removal capability to be maintained until the failure problem is eliminated. The reduction system with one-step reduction appears to be a reliable way of coping with side chemical reactions which could prove hard to control in segregated multi-step reactors. There is also a potential of converting the Bosch reaction to the Sabatier with overboard methane dump thereby reducing power during emergency situations.

6.2.2 System B - Hydrogenation with Solid Adsorption (Figure 6-2)

CO_2 is again removed with a solid adsorption system and delivered to a Bosch reduction system for oxygen recovery. However, CO_2 desorption is accomplished by using a combination of electrical heating and a vacuum pump. Heat removed from the CO_2 delivery stream during intercooling is used to aid in desorbing the silica gel canister of moisture. At the start of desorption, the canister mixture gas ullage is directed to the cabin as the canister pressure is pulled down after which the now relatively pure CO_2 is directed to the reduction system. The coolant flow to both sets of canisters should be at 60°F or lower while that coolant flow to the pump intercooler and Bosch system condenser should be no higher than 50°F. This system has the largest fixed weight due to the transfer system pump. This fixed weight along with a large electrical power requirement obtained at a high weight penalty make the total equivalent weight uncompetitive with the other management systems. The major development areas are the transfer pumps, desorption techniques, and reduction system optimization. A literature survey has revealed a lack of aerospace quality pumps having the necessary performance characteristics for CO_2 transfer. Presently available commercial vacuum pumps are much too heavy and inefficient (power consuming). Zero gravity lubrication and sealing are potential problem areas. In addition, lubricant vapors must be compatible with the reduction system.

This system has only fair to poor reliability due to inherent unreliable factors associated with rotating equipment (bearing life, dynamic seals, etc.). Evaluation

SYSTEM B
SOLID ADSORPTION CO_2 REMOVAL SYSTEM (ELECT HEAT & VAC PURGE)
BOSCH CO_2 REDUCTION SYSTEM

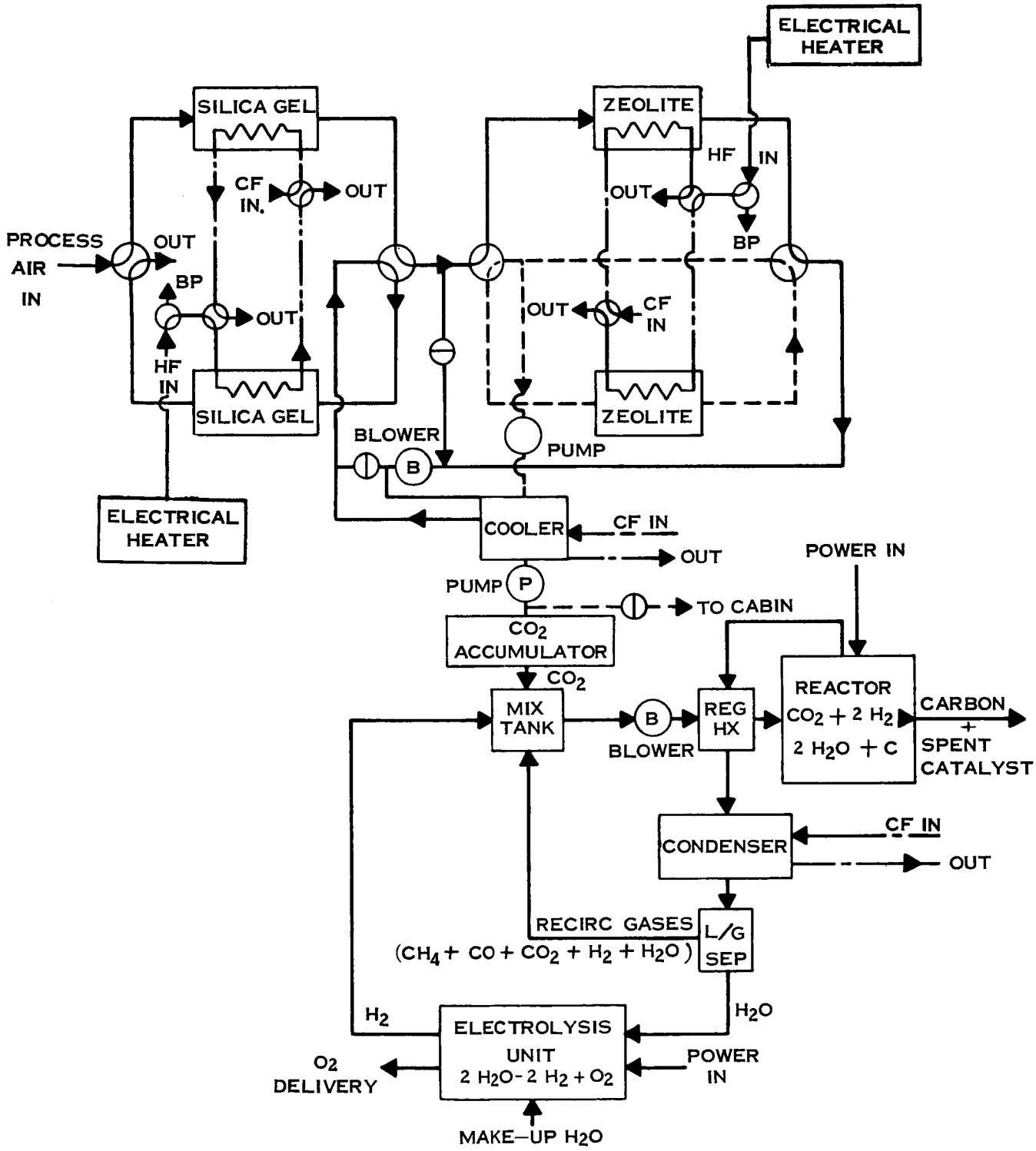


FIGURE 6–2

6.2.2 (Continued)

pertaining specifically to the reduction system is covered under the System A section. In conclusion, this system is presently unattractive and lacks the potential for being competitive with other systems.

6.2.3 System C - Hydrogenation - Electrodialysis (Figure 6-3)

Electrodialysis is used for CO_2 removal with delivery to the Bosch reduction system. The effluent CO_2 and hydrogen streams are combined and passed through a passive liquid gas separator where the water is removed and returned to the water reservoir. The CO_2 and hydrogen mixture proceed to the reduction system. Since the electrodialysis system requires water electrolysis for operation, a portion of the Bosch product water is directed to it, thereby reducing the size and power requirements of the reduction system water electrolysis unit. Coolant flow to the Bosch system condenser and electrodialysis cell water reservoir should be no higher than 50°F to keep the water vapor buildup in the system down to a reasonable level. This system has an equivalent weight which is the same as System A. Although it has a lower fixed weight, it consumes more electrical power, which dictates a large equivalent weight penalty. A prototype electrodialysis CO_2 removal system has been successfully built and run by Ionics, Inc. The major development areas are electrodialysis cell power, zero gravity liquid-gas separators, and reduction system optimization. Electrode technology and membrane arrangement (influences electrical resistance and consequently power) must be improved to reduce cell voltages approximately one-third below present state-of-the-art values in order to obtain the quoted performance based on Ionics predicted performance. Passive liquid gas separators are an area requiring much development in order to separate the cell effluent gaseous streams from the large liquid flow sweep streams providing gas transport from the cell electrodes. Reduction system performance can be achieved by insulation to minimize heat losses. System reliability should be good with both the removal and reduction system having continuous operation. although membrane life is an area offering questionable reliability. Again, evaluation pertaining specifically to the reduction system is covered under the System A section.

6.2.4 System D - Hydrogenation - Liquid Absorption (Figure 6-4)

CO_2 removal is accomplished using liquid absorption with the Bosch process used for reduction. The CO_2 is removed from the circulation absorption fluid by applying thermal energy at a temperature of 160°F derived from the waste heat source and delivered to an accumulator. The accumulator provides for a small storage in order to provide more steady state operation in the reeuction system during transient metabolic conditions. Make-up water is supplied to the electrolysis cell. The coolant should be provided to both system condensers at a temperature of 50°F or lower in order to minimize the amount of water vapor in the system.

SYSTEM C
ELECTRODIALYSIS CO_2 REMOVAL SYSTEM
BOSCH CO_2 REDUCTION SYSTEM

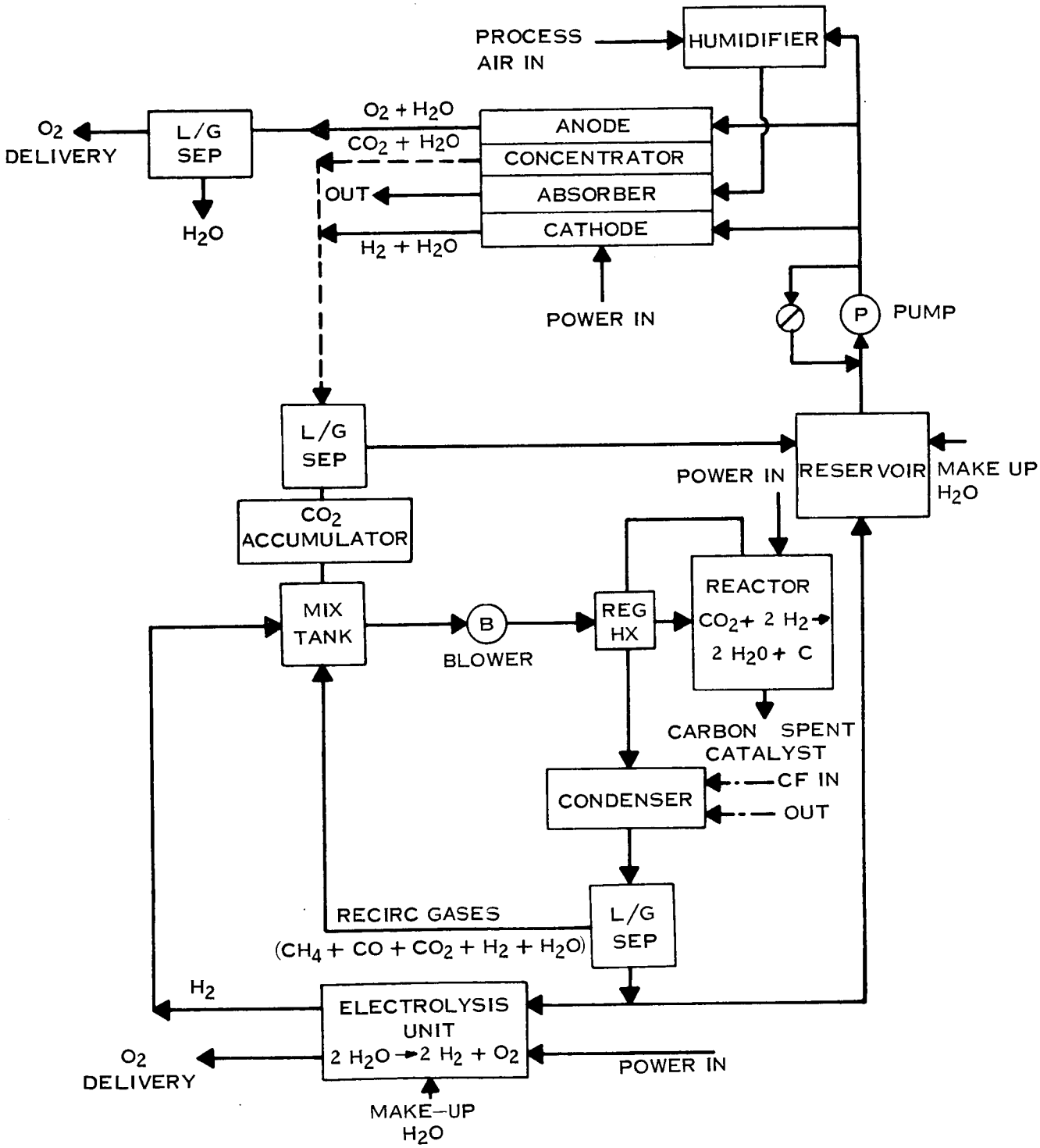


FIGURE 6-3

SYSTEM D
LIQUID ABSORPTION CO_2 REMOVAL SYSTEM
BOSCH CO_2 REDUCTION SYSTEM

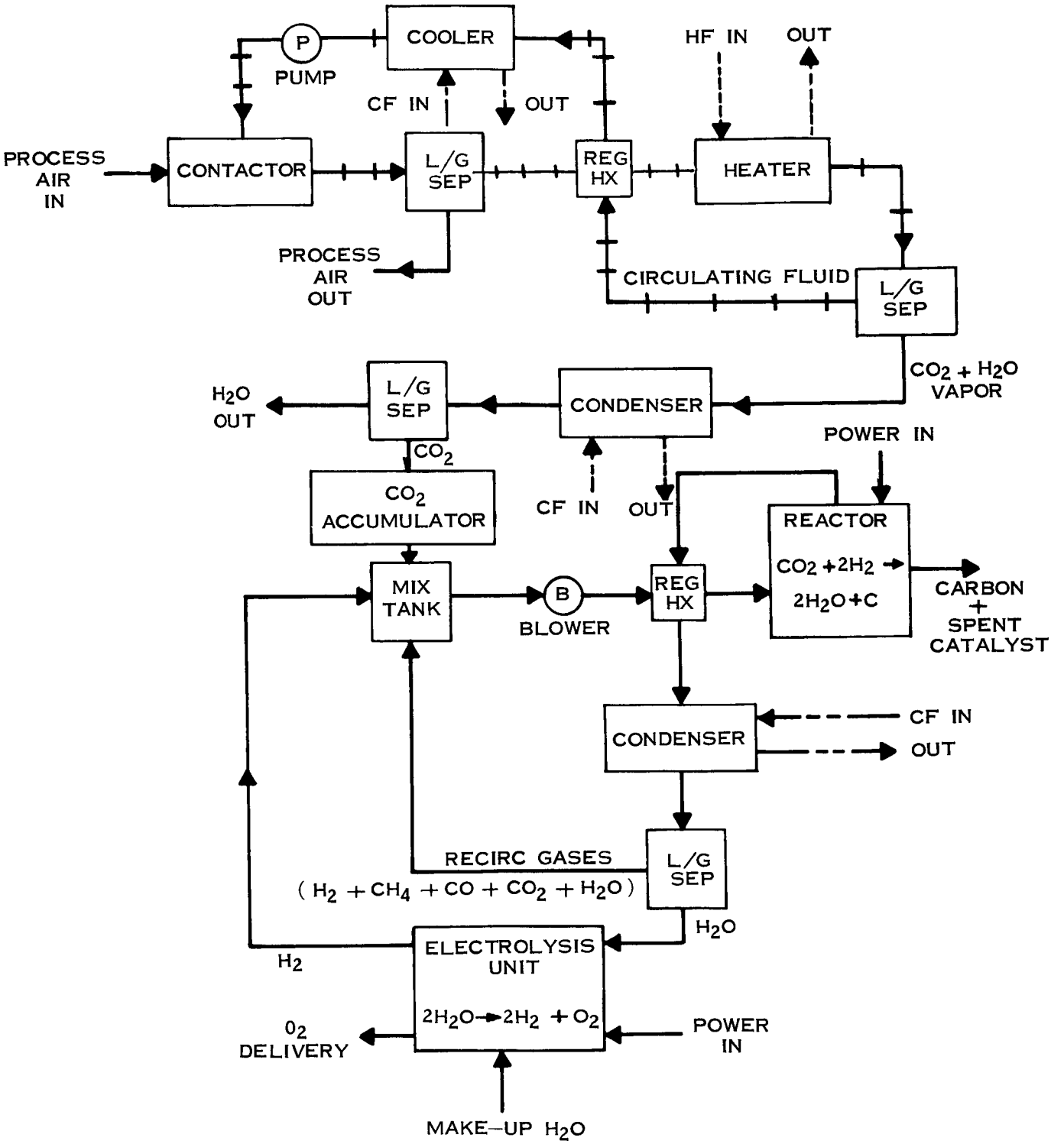


FIGURE 6-4

6.2.4 (Continued)

This system has a total equivalent weight similar to that of System A and C with the Bosch reactor accounting for a large portion of the fixed weight. The largest percentage of the input electrical power is associated with the water electrolysis cell in the reduction system. The major development area of the removal system is the liquid-gas contactor. The contactor represents an area which requires much development before predicted performance is achievable. Although marine systems have been operative, no space hardware has been tested. In addition, the marine system contactor operates by bubbling the process gas through the liquid absorption pool thereby taking advantage of gravity. The contactor envisioned in the proposed spacecraft system operates according to a different principle of dispersing the liquid absorption fluid through the process air in the form of atomized droplets. The reduction system development involves the use of insulation to minimize power losses. The overall system development has been rated as fair to poor. Reliability should be generally good with continuous operation possible. In conclusion System D offers competitive performance but lacks general attractiveness due to an inferior development status.

6.2.5 Results

Figure 6-5 shows the fixed weight of the studied CO_2 management system as a function of CO_2 process rate for the 5 mm of Hg CO_2 cabin concentration. The total peak power is presented in Figure 6-6. That portion of the total power which is introduced to the system as thermal energy is shown in Figure 6-7 for various CO_2 process rates. The fixed weight and power at its equivalent weight penalty are combined and presented in Figure 6-8. A thermal inventory was prepared to evaluate the required cooling rates and methods for each system to be used in integrating the management system with the overall environmental control system. The results are presented in Figures 6-9 through 6-12. The total thermal load is broken down to liquid coolant, ambient air, and process air loads. The liquid coolant represents the net thermal energy absorbed by the heat transport fluid and delivered directly to the radiator heat sink. The ambient air load is that thermal energy radiated and converted to the environment surrounding the CO_2 unit. The heat absorbed by the process air stream passing through the removal system is shown as the process air load. It is noted that the process and ambient air load require intermediate handling by the cabin heat exchanger before being radiated to space via the heat sink radiator. In addition, the ambient air load has an effect on the required ventilation rate in that compartment housing the CO_2 unit. The expendables are shown in Figure 6-25 as a function of mission duration and CO_2 process rate thereby completing the quantitative description of each system. These expendables are considered to come entirely from the CO_2 reduction part of the system, since all material leaving the CO_2 removal system was considered to be passed on to the reduction system. The expendable rate for CO_2 reduction systems using hydrogenation and solid electrolyte methods was roughly the same.

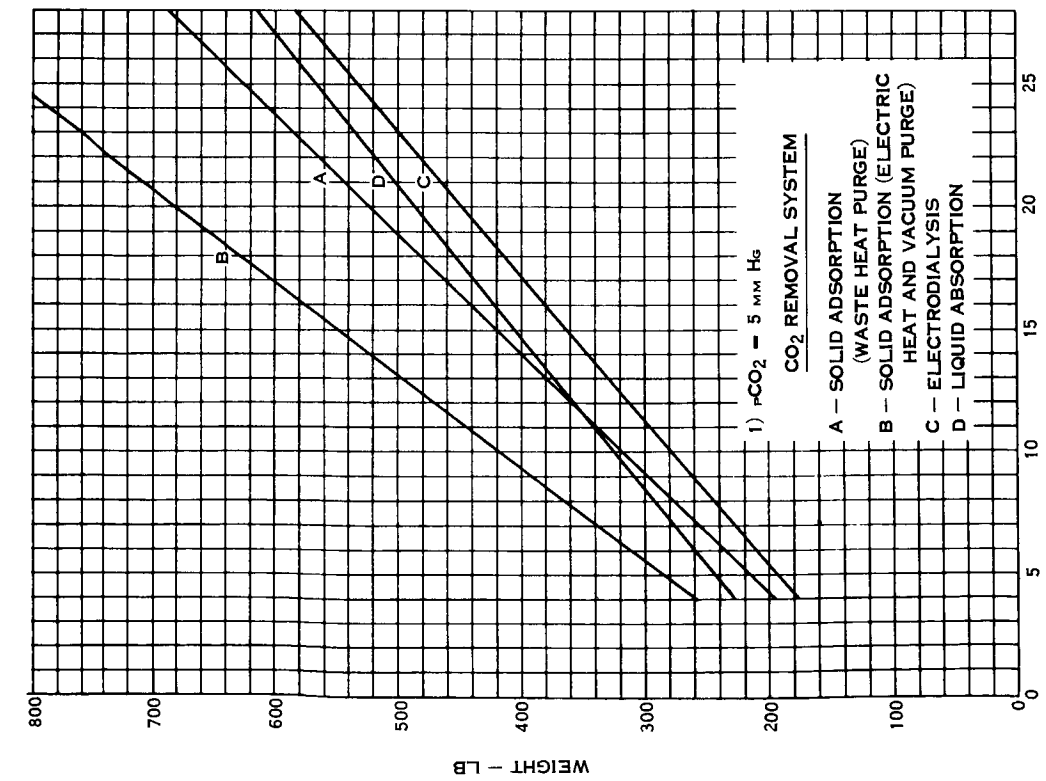


FIGURE 6–5

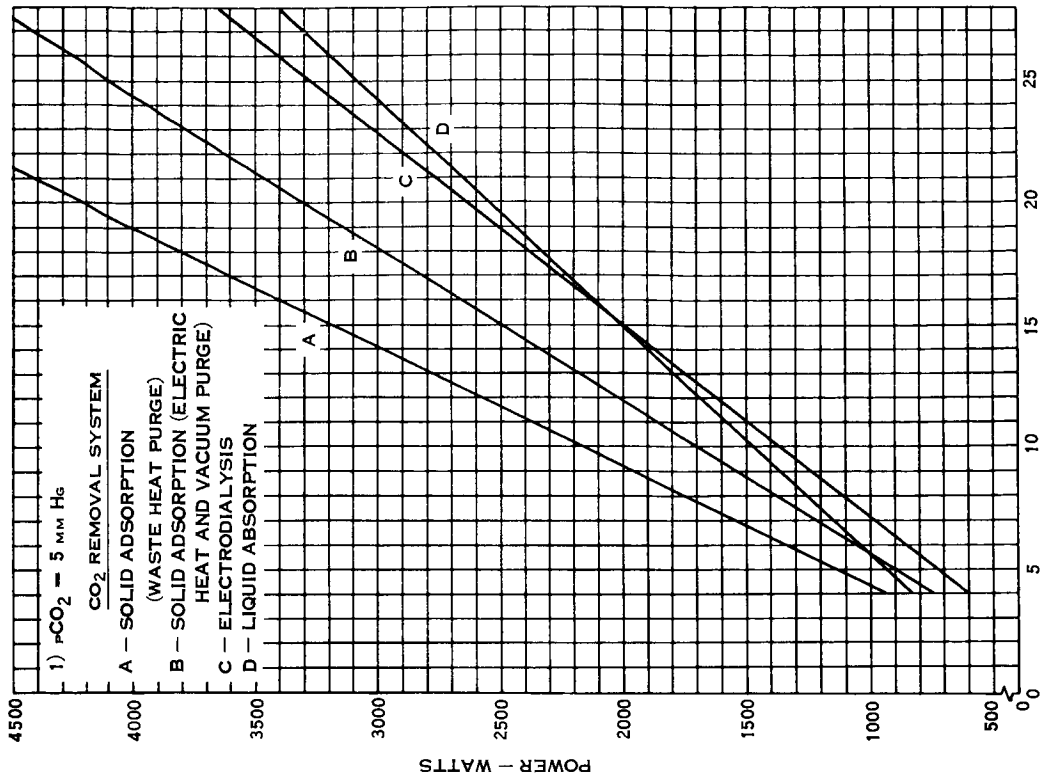


FIGURE 6–6

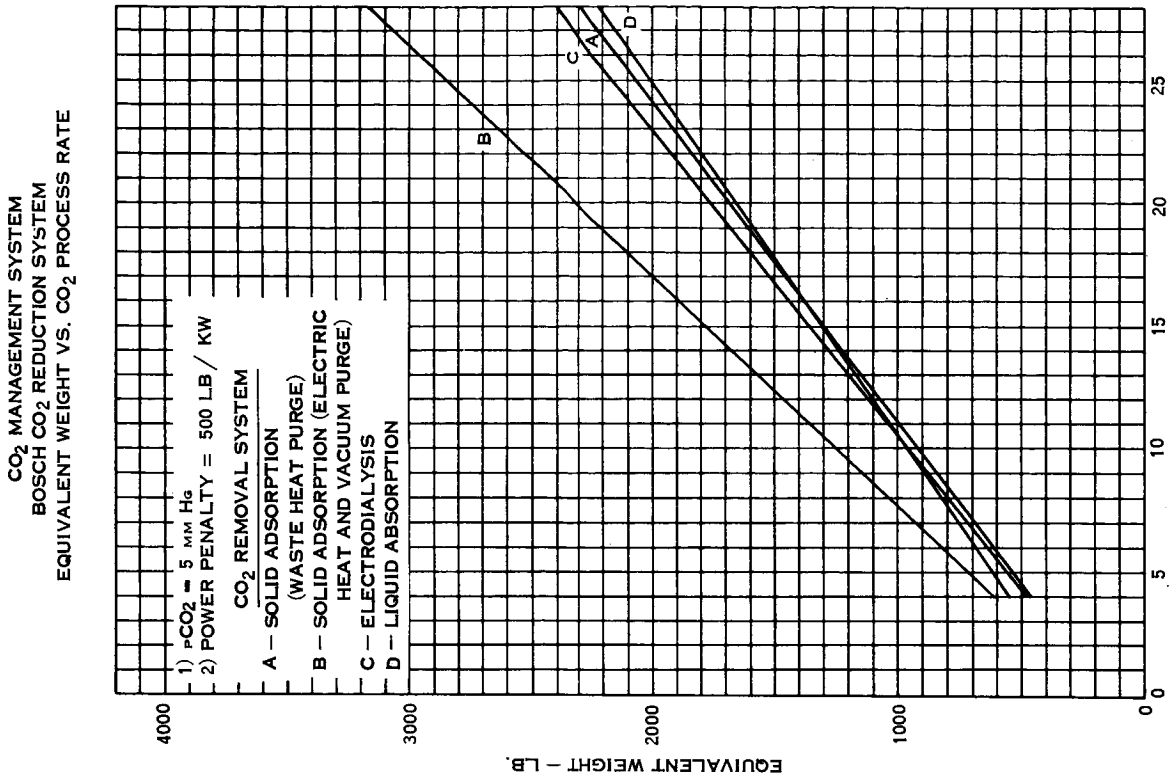


FIGURE 6-8

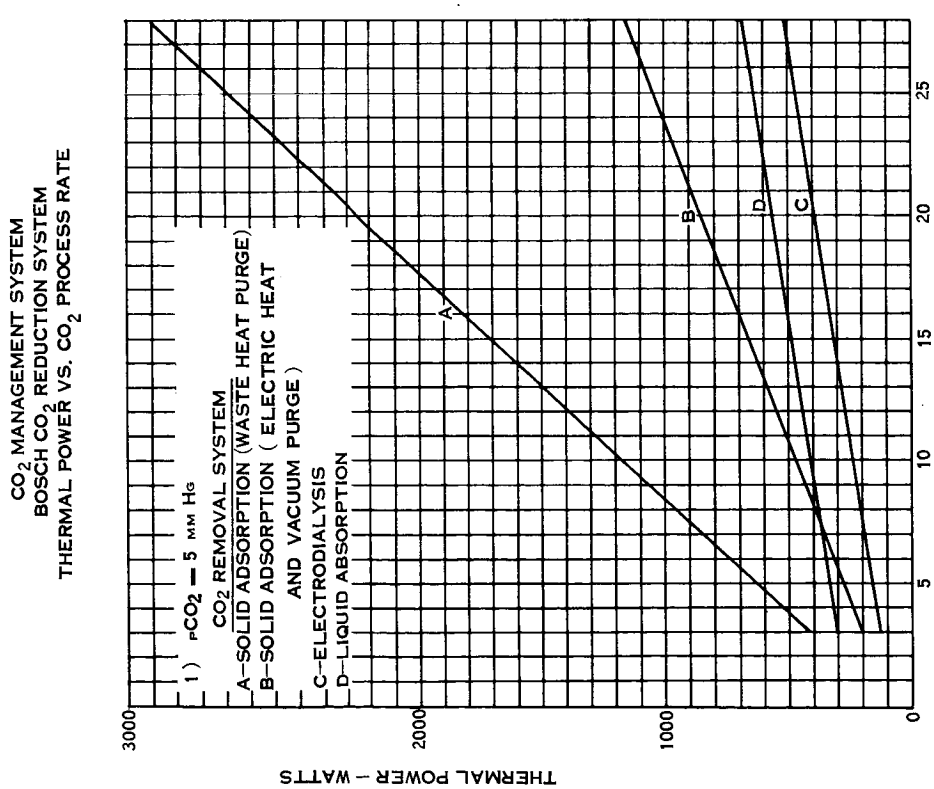


FIGURE 6-7

CO_2 MANAGEMENT SYSTEM
BOSCH CO_2 REDUCTION SYSTEM
THERMAL LOAD VS. CO_2 PROCESS RATE

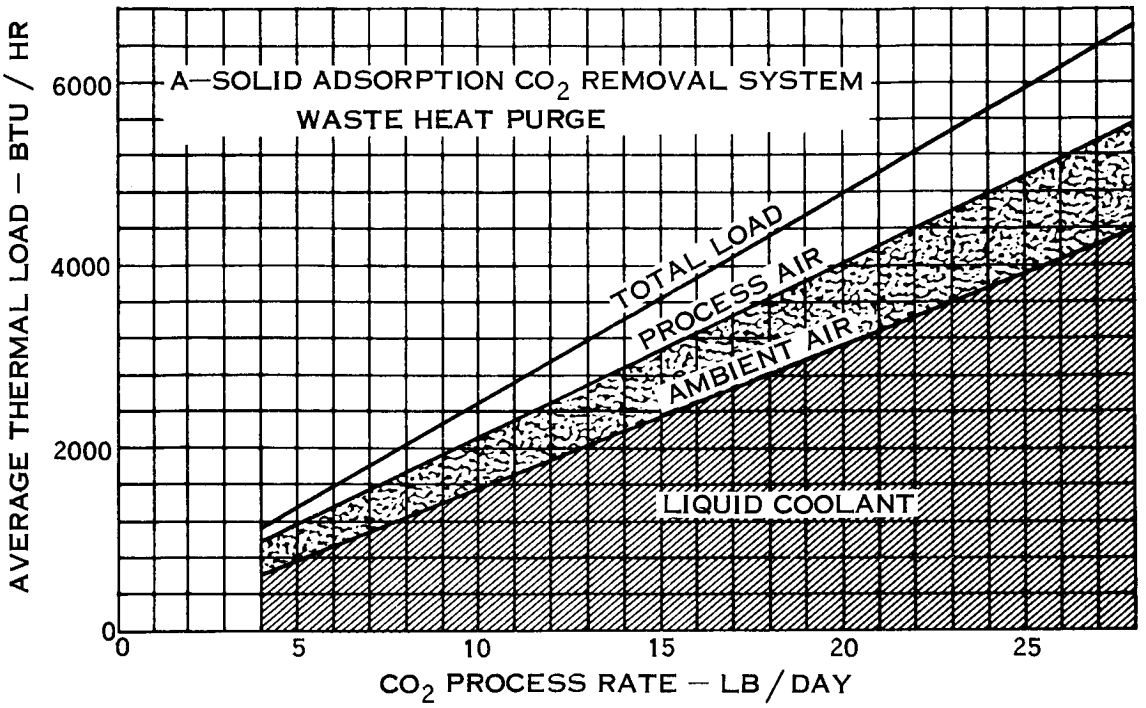


FIGURE 6—9

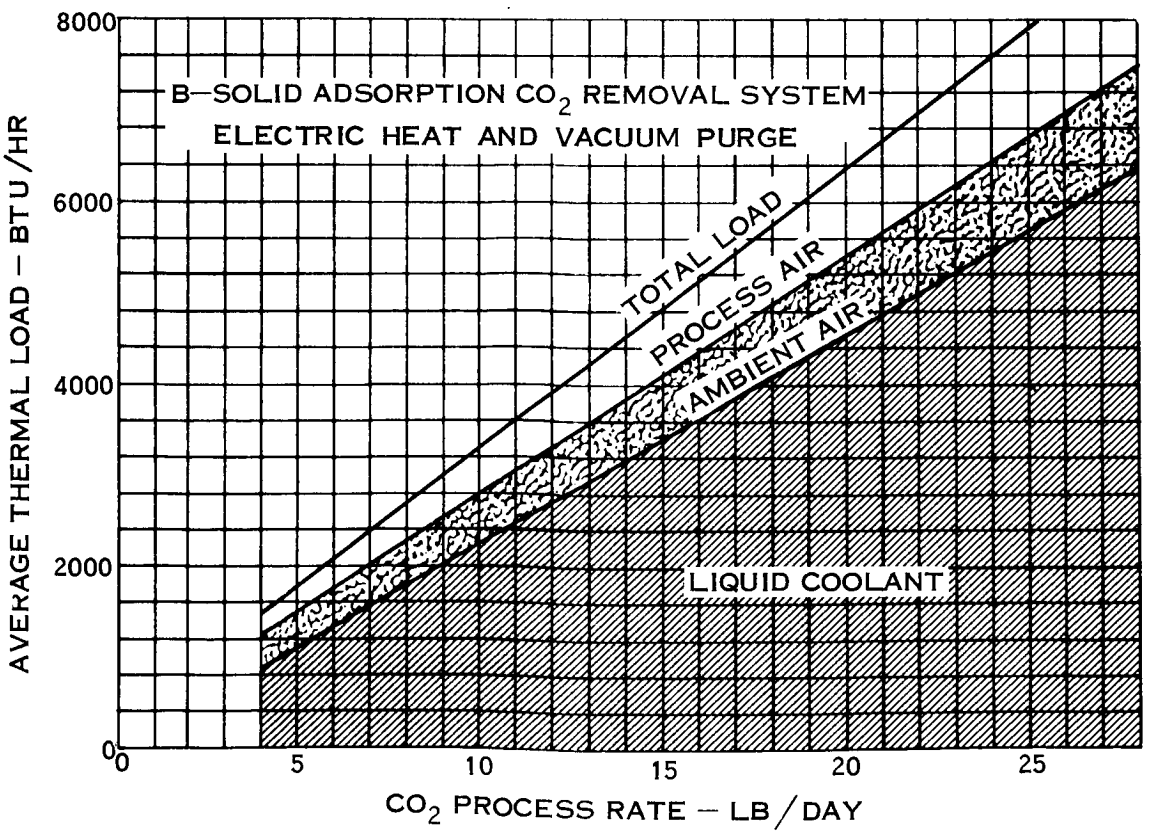


FIGURE 6—10

CO_2 MANAGEMENT
BOSCH CO_2 REDUCTION SYSTEM
THERMAL LOAD VS. CO_2 PROCESS RATE

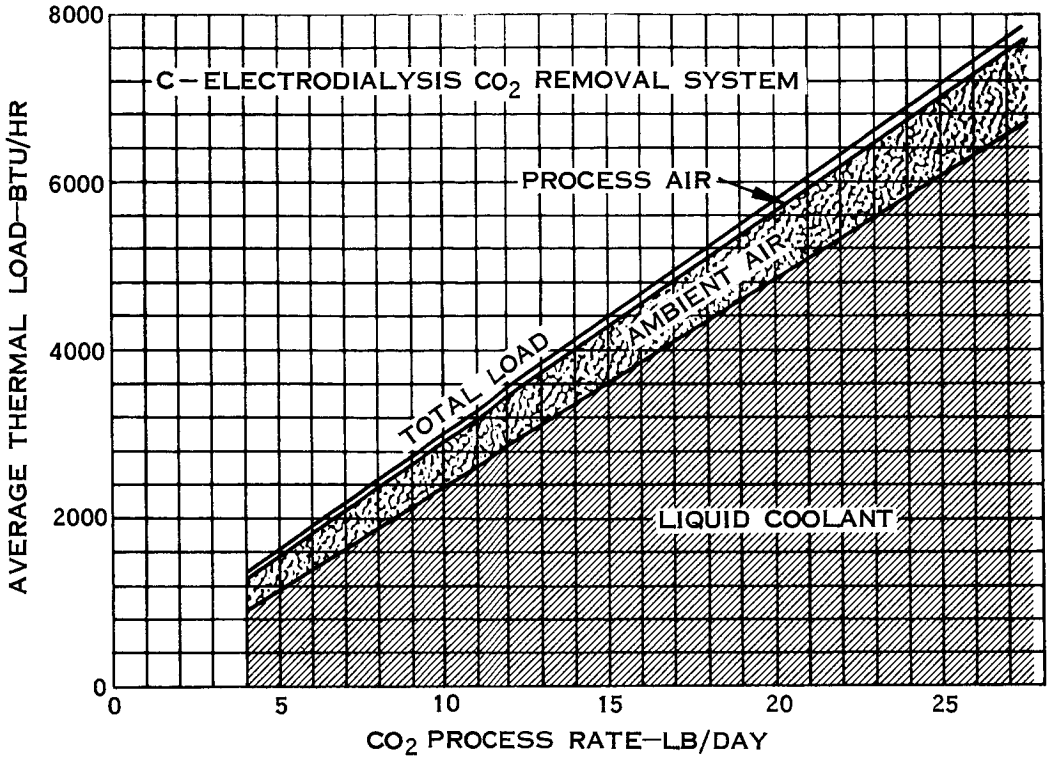


FIGURE 6–11

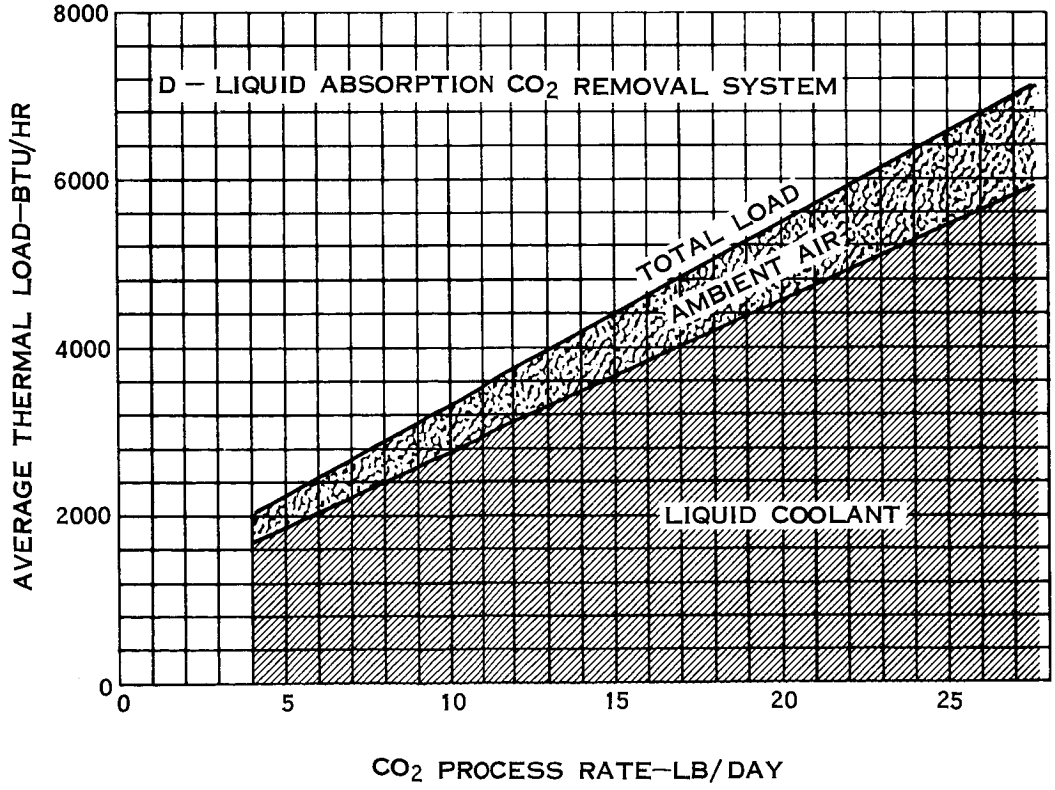


FIGURE 6–12

6.3 Solid Electrolyte Management Systems

6.3.1 System E - Soild Electrolyte - Solid Adsorption (Figure 6-13)

Solid adsorption with waste heat purge is used for removal and the solid electrolyte system is used for CO_2 reduction. Heat required for CO_2 desorption is supplied at 350°F-400°F by a transport fluid circulated through coils embedded in the canister and returned to the waste heat source. The CO_2 is delivered to an accumulator where it is stored at a slight positive pressure. A backflush is provided prior to desorption in order to purge the O_2 - N_2 ullage mixture present in the canister and provided a pure CO_2 flow during desorption. The coolant flow to the cooler in the solid electrolyte system should be at a temperature of 70°F or lower to provide a sufficiently low temperature to the blower, and the coolant flow to the zeolite and silica gel canisters should be 60°F or lower in order to provide a proper adsorptivity. Hot fluid should be delivered to the silica gel canister at 200°F or higher to provide sufficient moisture desorption. Provision is made to dump CO_2 overboard for short times in the event of reduction system breakdown or system overload.

This system has a very low total equivalent weight. Although requiring a fair amount of power, most of it is thermal energy which is obtained from a waste heat source at a low penalty. The major areas requiring development are the CO_2 thermal desorption and the reduction system power reduction. The first area is associated with the removal portion of the management system, which, in turn, is discussed under System A. The power requirements quoted by Isomet for solid electrolyte CO_2 reduction would require considerable development effort for attainment. For this reason, the overall management system development status has been assessed as good to fair. It is felt that reliability of this system is also in the good to fair category. There appears to be some apprehension concerning the mechanical properties of the ceramic electrolyte material which will require resolution during system development. The concentration of carbon monoxide in the electrolyte cell must be constantly monitored since a high concentration might cause the electrolyte to decompose. In conclusion, this system is potentially attractive but requires much development.

6.3.2 System F - Solid Electrolyte - Solid Adsorption (Figure 6-14)

Solid adsorption is used for removal with the solid electrolyte system for reduction. The solid adsorption CO_2 canister is desorbed by applying a combination of electrically supplied heat and low pressure obtained with a vacuum pump. The process air stream receives heat from the pump intercooler which contributes in desorbing the moisture from the silica gel canister. Canister mixture gas ullage is directed to the cabin at the start of desorption in order to provide a pure CO_2 flow to the reduction

SYSTEM E
SOLID ADSORPTION CO_2 REMOVAL SYSTEM (WASTE HEAT PURGE)
SOLID ELECTROLYTE CO_2 REDUCTION SYSTEM

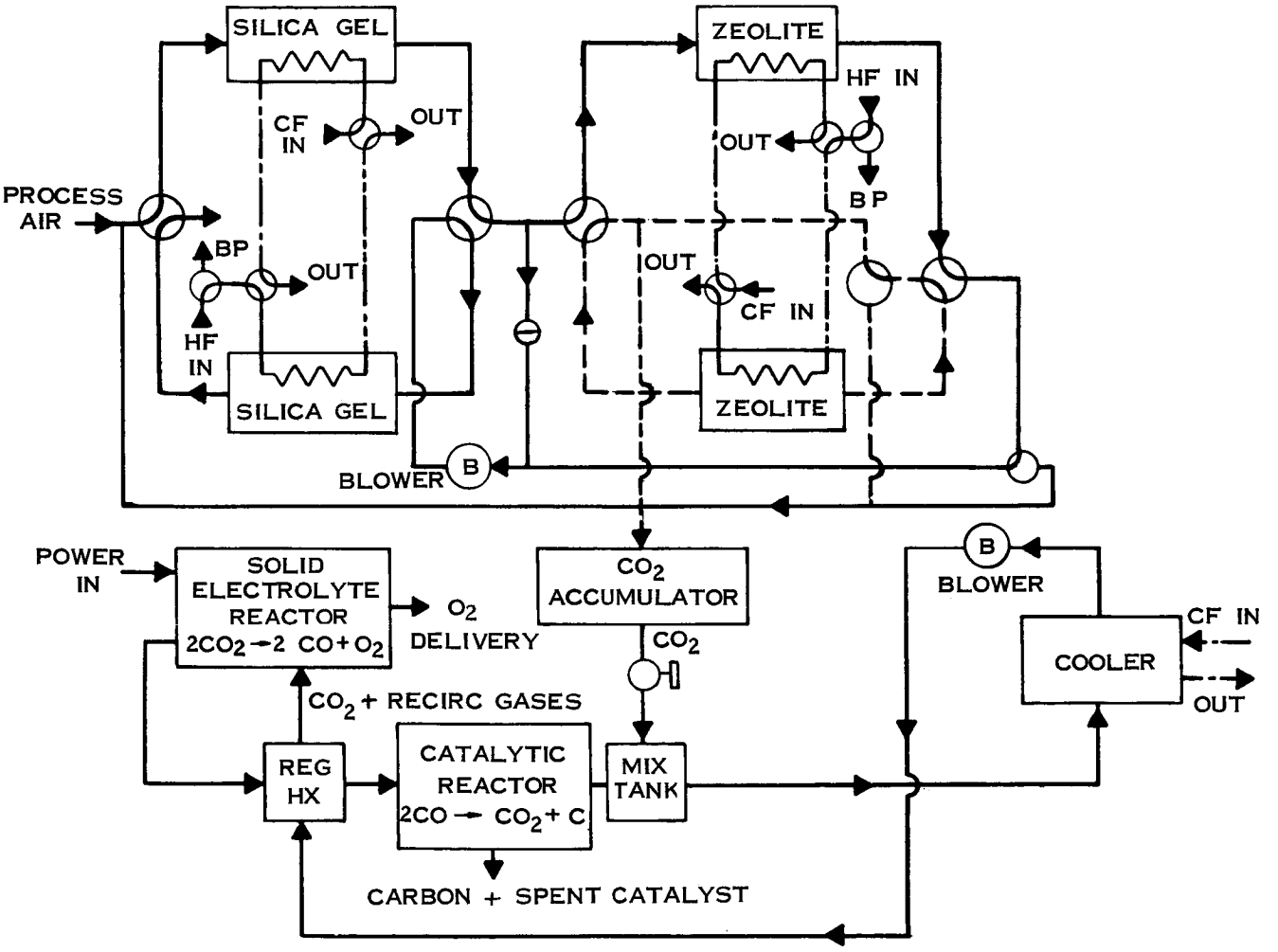


FIGURE 6–13

SYSTEM F
SOLID ADSORPTION CO_2 REMOVAL SYSTEM (ELECT. HEAT & VAC. PURGE)
SOLID ELECTROLYTE CO_2 REDUCTION SYSTEM

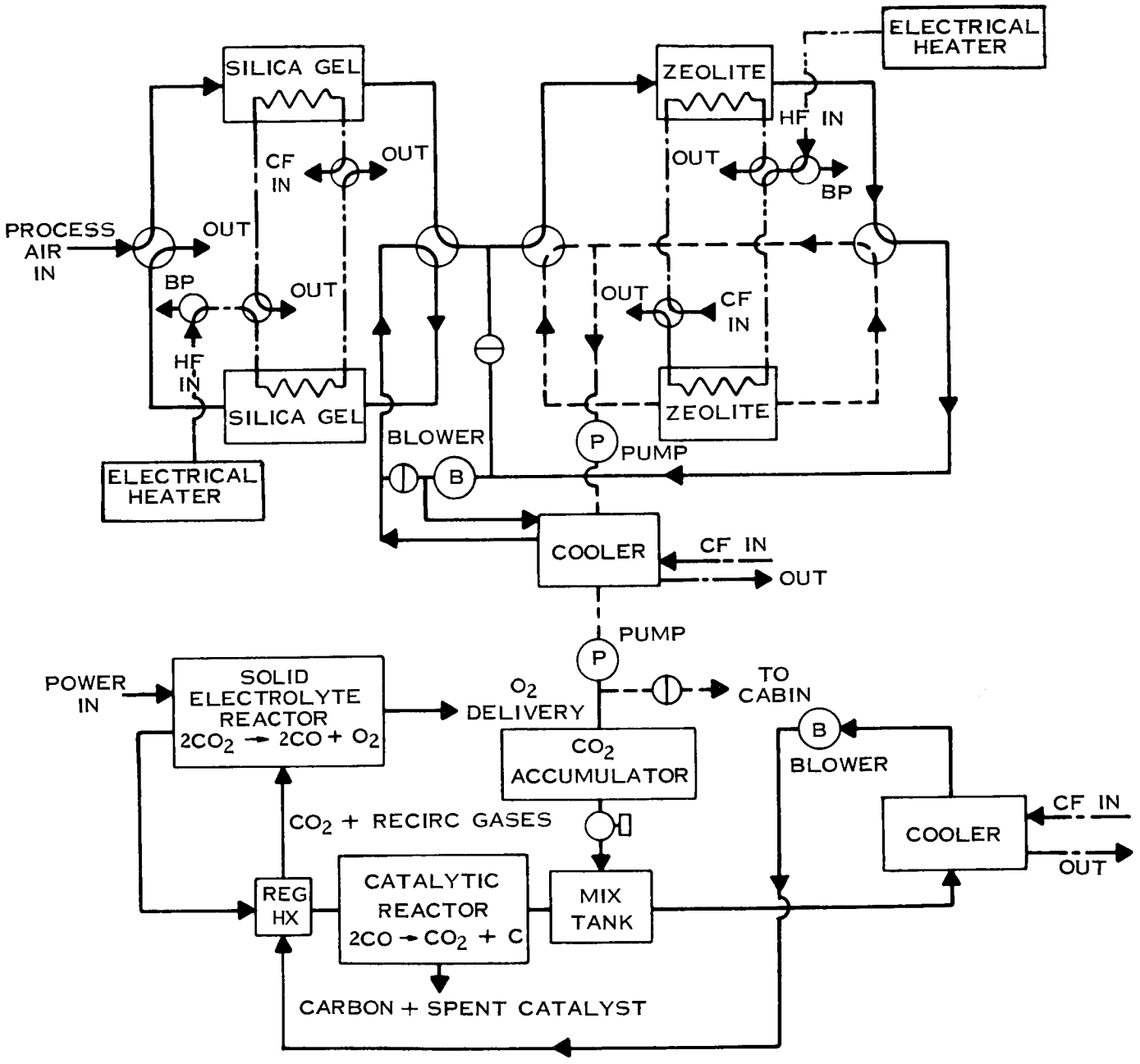


FIGURE 6–14

6.3.2 (Continued)

system when the flow is redirected there. The coolant flow to the cooler in the solid electrolyte system should be at a temperature of 70°F or lower to reduce the recirculation gas to an acceptable level for the blower, and pump intercooler temperature should be on the order of 50°F.

This system has a large equivalent weight due to the fixed weight and power consumption of the transfer system pump. The major development areas are the transfer pump, desorption techniques, and reduction system power reduction. The first two areas which are associated with the removal system are discussed in more detail under System B. Likewise the solid electrolyte reduction system is discussed under the previous system. The overall system development status is felt to be in the fair to poor category and reliability has also been evaluated as fair to poor with the major problem areas being the rotating pump and the electrolyte material. In conclusion this system appears to be relatively unattractive.

6.3.3 System G Solid Electrolyte - Electrodialysis (Figure 6-15)

Electrodialysis is used for CO_2 removal with delivery to the solid electrolyte reduction system. The removal system delivers CO_2 in a moisture saturated condition. This moisture must be removed since the solid electrolyte system requires a dry CO_2 delivery. Any moisture entering the reactor will be reduced to hydrogen and oxygen. The hydrogen will dilute the recycle stream and require periodic purges. Further, the power to reduce the water will show up as an inefficiency. Therefore, dry CO_2 delivery is required and this is accomplished by using two silica gel beds which are placed in parallel and alternately cycled. The hot and dry oxygen effluent flow from the solid electrolyte reactor is used to purge the canister of moisture. Silica gel beds are cooled with a 60°F or lower coolant circulated through coils embedded in the canister. The cooler flow upstream of the blower in the reduction system loop is supplied with 70°F fluid. Make-up water is provided to the electrolysis cell to replace moisture carryover by the oxygen, hydrogen, and process air flow streams which leave the system in a saturated condition. The hydrogen can be passed through a set of dehydrator beds similar to those shown for the CO_2 stream to recover moisture prior to discharge overboard (not shown on schematic).

System G has an equivalent weight which is high relative to the other methods of CO_2 management. However, the electrolysis of water is an integral function of system operation. Therefore should water electrolysis be required in the overall environment control system, a credit can be given to the removal system which brings it in line with System E on an equivalent weight basis. Development status is fair with zero-gravity liquid gas separators, and reduction system power reduction the major areas requiring development. The removal system effluent CO_2 stream is moisture saturated. Since the solid electrolyte reduction system requires a dry delivery gas, a pair of desiccant beds must be employed for drying the gas. Therefore, any

SYSTEM G
ELECTRODIALYSIS CO_2 REMOVAL SYSTEM
SOLID ELECTROLYTE CO_2 REDUCTION SYSTEM

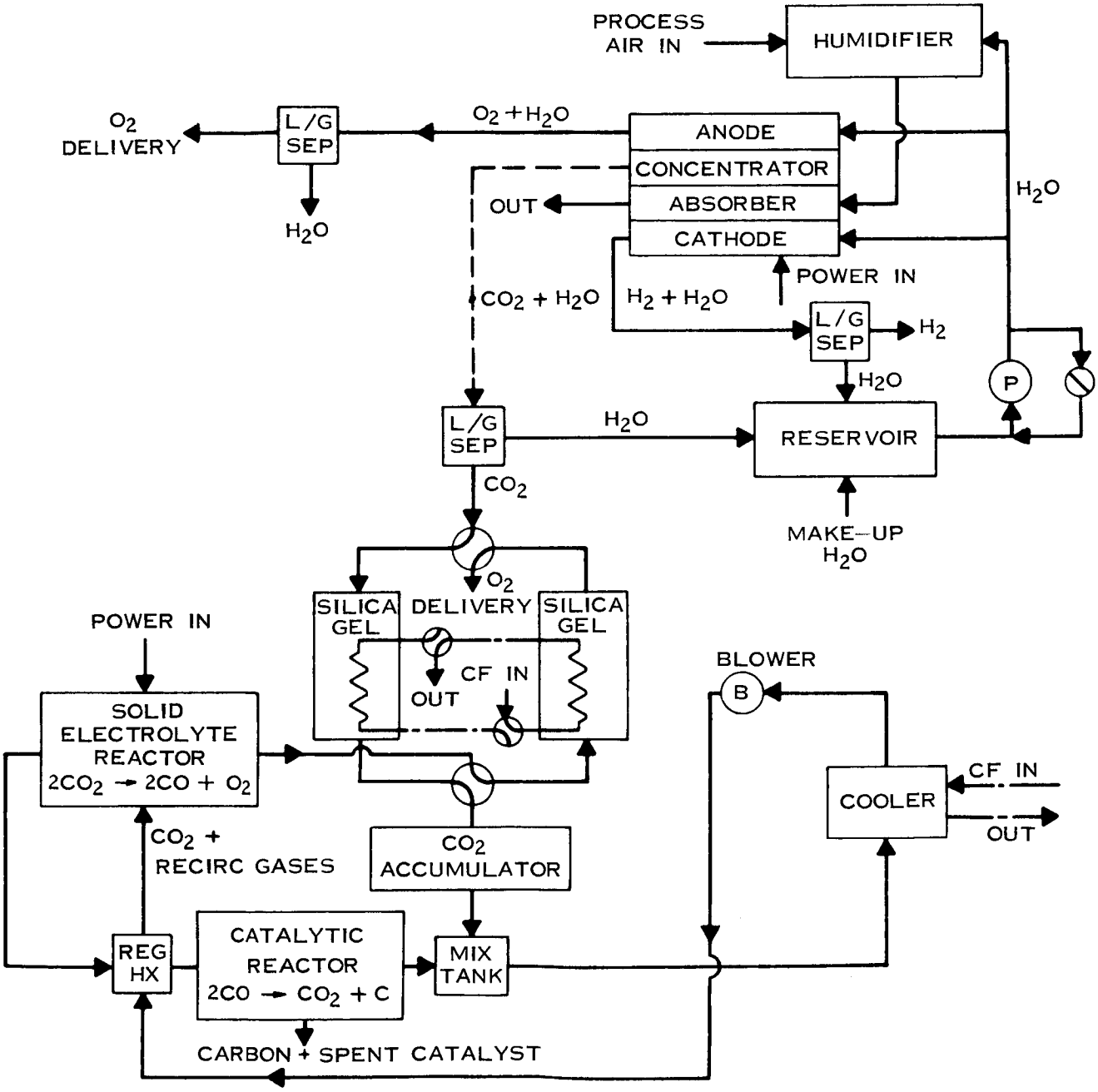


FIGURE 6-15

6.3.3 (Continued)

possible advantage of continuous operation associated with the removal and reduction system is eliminated by the required desiccant bed cycling operation. The system overall reliability is felt to be good to fair. Additional details pertaining to the removal and the reduction system are covered under System C and System E respectively.

6.3.4 System H Solid Electrolyte - Liquid Absorption (Figure 6-16)

Liquid absorption is used for CO_2 removal with the solid electrolyte system for CO_2 reduction. This removal system also delivers the CO_2 in a moisture saturated condition. Thus a set of alternately cycled desiccant beds are used to dry the CO_2 stream before delivery to the reduction system. Temperature of the coolant flow to the cooler in the reduction system loop as well as the CO_2 absorption fluid stream should be 70°F or lower. The condenser coolant stream should provide a flow at 45° to 50°F while the heater flow from the waste heat source should be at 160° or higher. Air is taken off the main system flow stream at a temperature of 70-80°F.

System H has an equivalent weight which is similar to that of System E and G with water credit. The major development areas are the contactor and the reduction system power reduction. The development status has been assessed as poor. As with System G, a parallel pair of alternately cycled dehydrator beds must be used to remove the moisture from the removal system effluent stream prior to delivery to the reduction system. System reliability is good to fair. Overall, this system appears potentially attractive but has an inferior development status.

6.3.5 Results

The results for the solid electrolyte CO_2 management systems are presented in Figures 6-17 through 6-24 in the same form as previously presented for the hydrogenation systems. Figure 6-25 presents the expendable rate for both solid electrolyte and hydrogenation approaches.

6.4 Molten Carbonate Management System (Figure 6-26) - System J

The molten carbonate system offers the largest potential of all the management systems due to its ability to remove the CO_2 from the process air stream as well as reducing the CO_2 to O_2 and carbon. System operation has been previously discussed in Section 5.7 and will not be repeated in detail in this section. Referring to Figure 6-26, the process air is introduced to the rotating melt chamber, the CO_2 is removed, and the air returned to the cabin. The CO_2 is then electrolytically decomposed to carbon and oxygen with the carbon plating out on the electrode.

SYSTEM H
LIQUID ABSORPTION CO_2 REMOVAL SYSTEM
SOLID ELECTROLYTE CO_2 REDUCTION SYSTEM

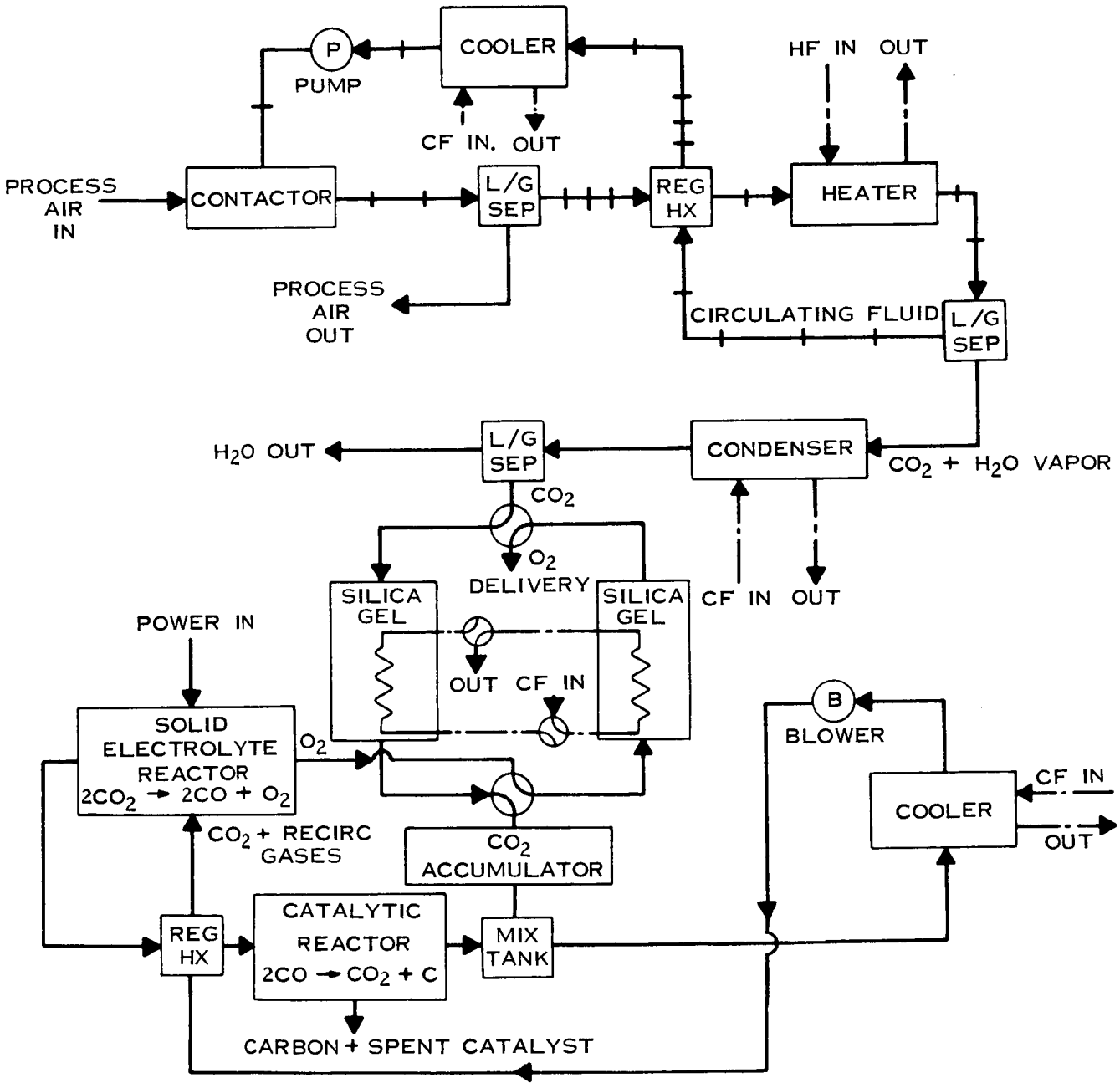


FIGURE 6–16

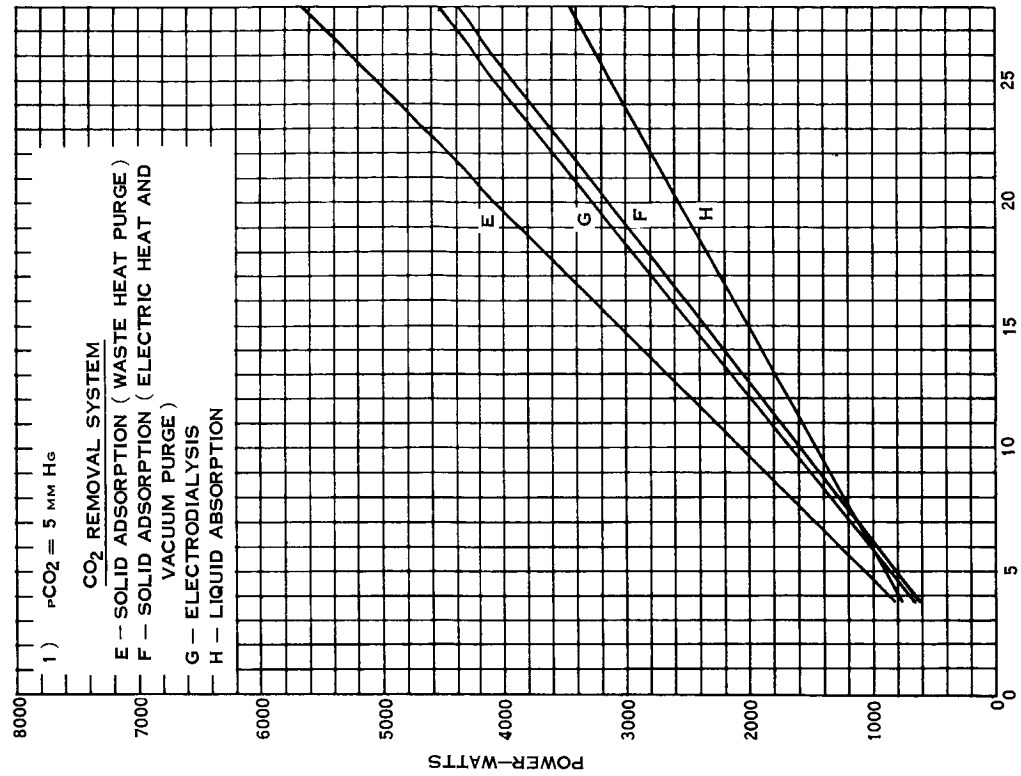


FIGURE 6–18

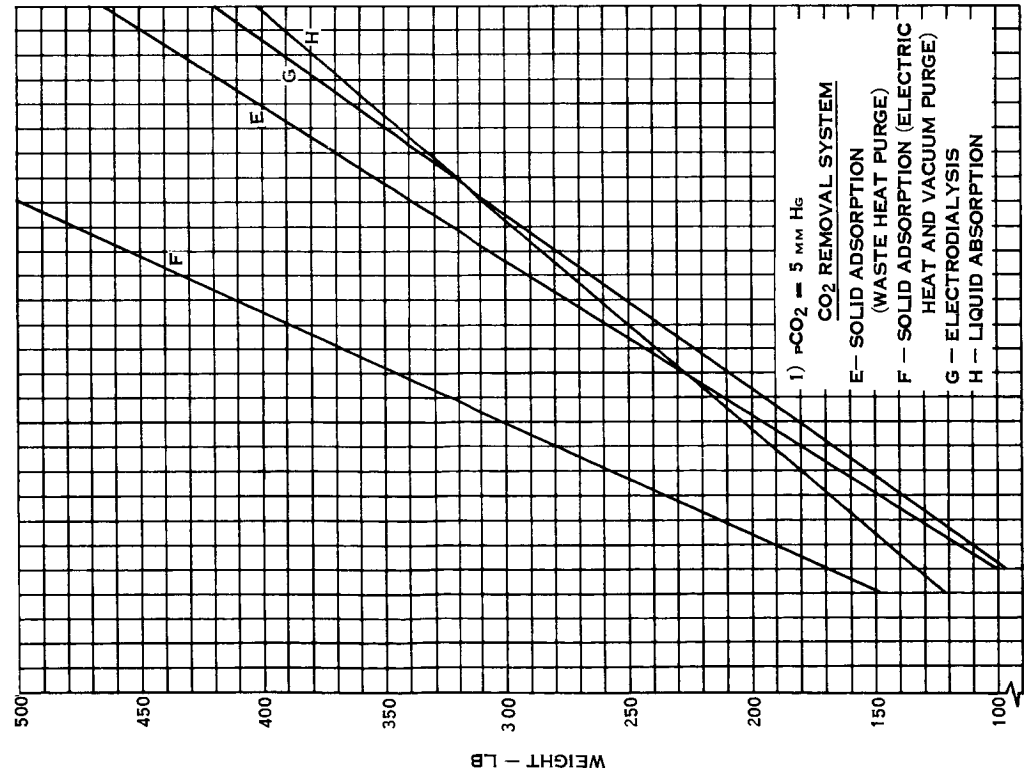


FIGURE 6–17

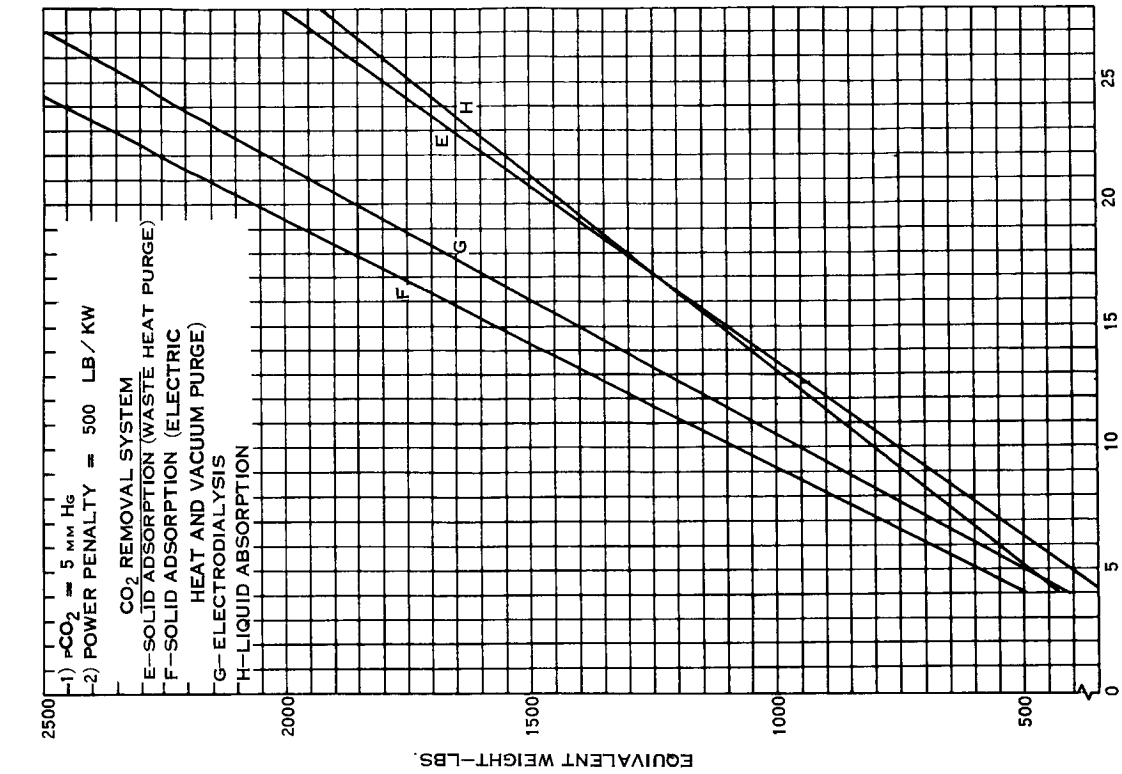


FIGURE 6–20

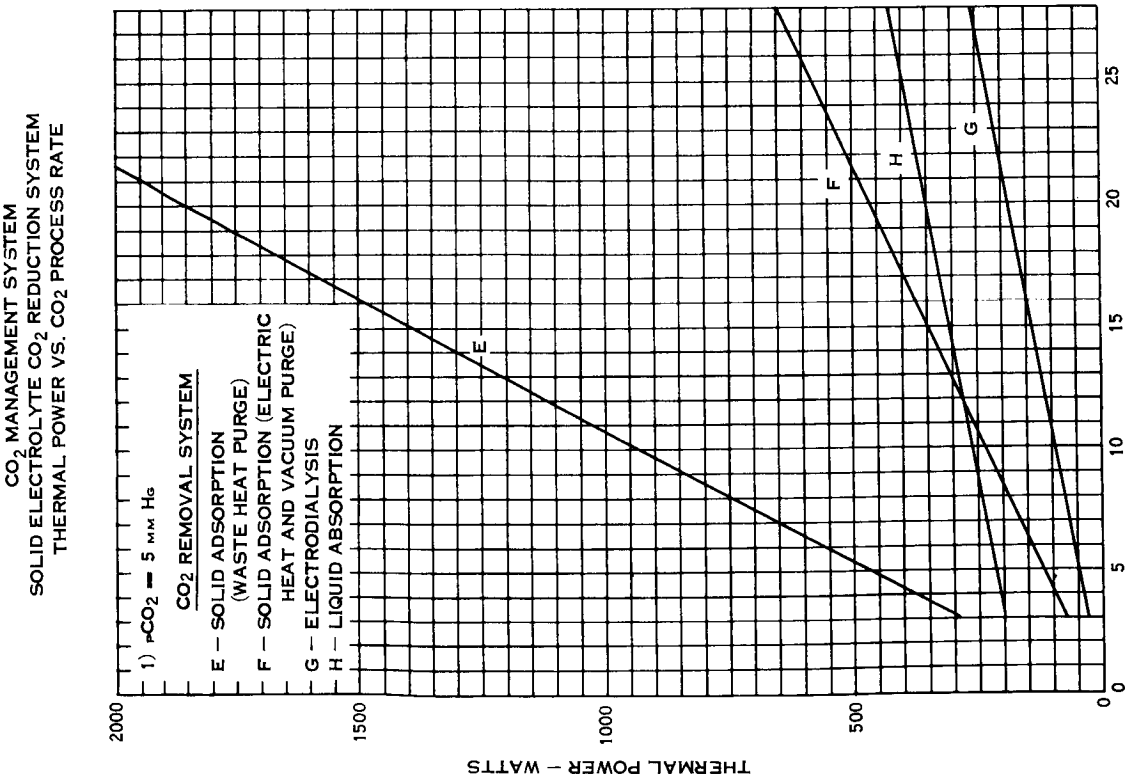


FIGURE 6–19

CO_2 MANAGEMENT SYSTEM
SOLID ELECTROLYTE CO_2 REDUCTION SYSTEM
THERMAL LOAD VS. CO_2 PROCESS RATE

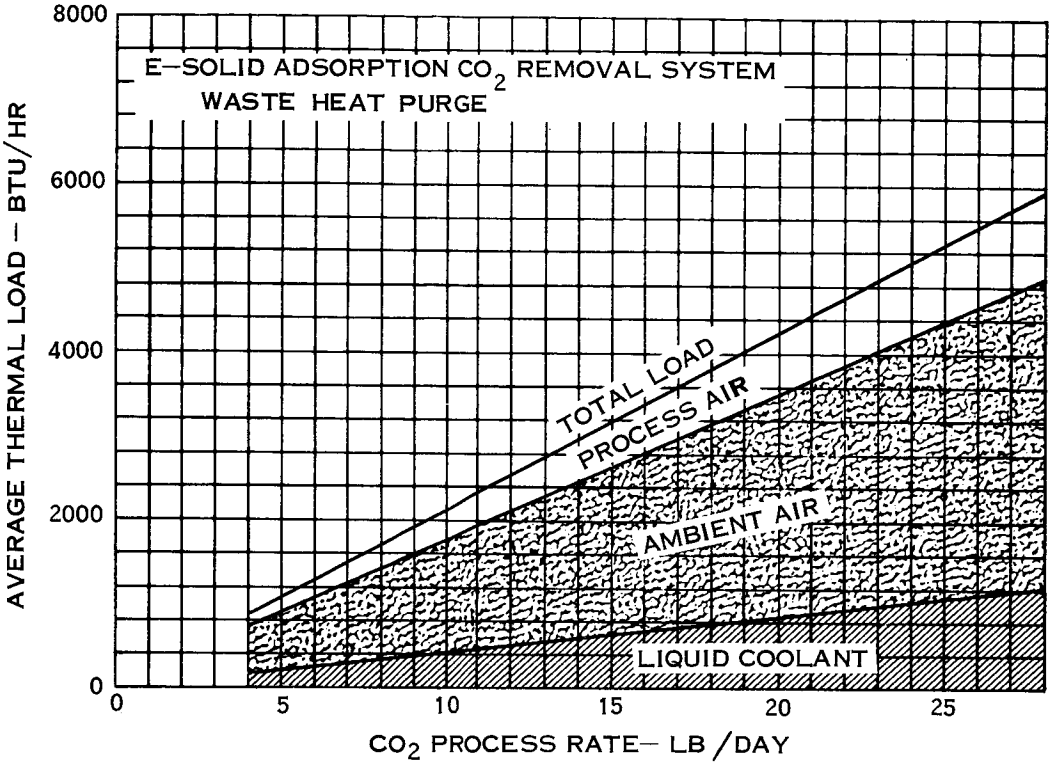


FIGURE 6–21

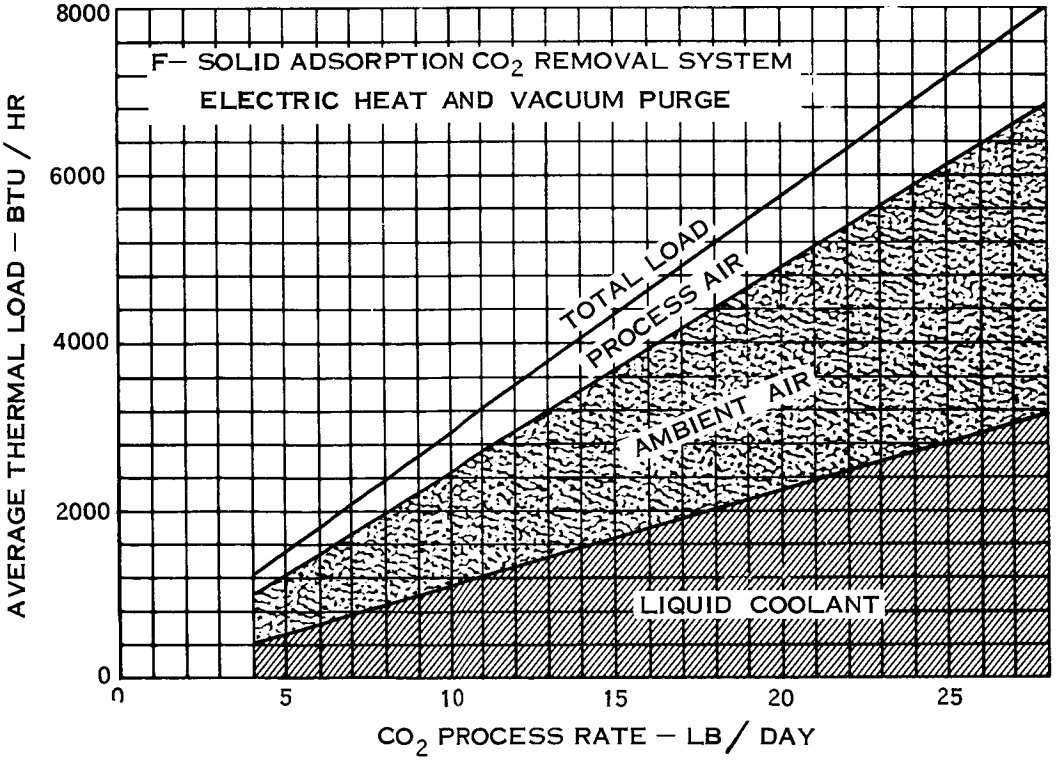


FIGURE 6–22

CO_2 MANAGEMENT
SOLID ELECTROLTYE CO_2 REDUCTION SYSTEM
THERMAL LOAD VS. CO_2 PROCESS RATE

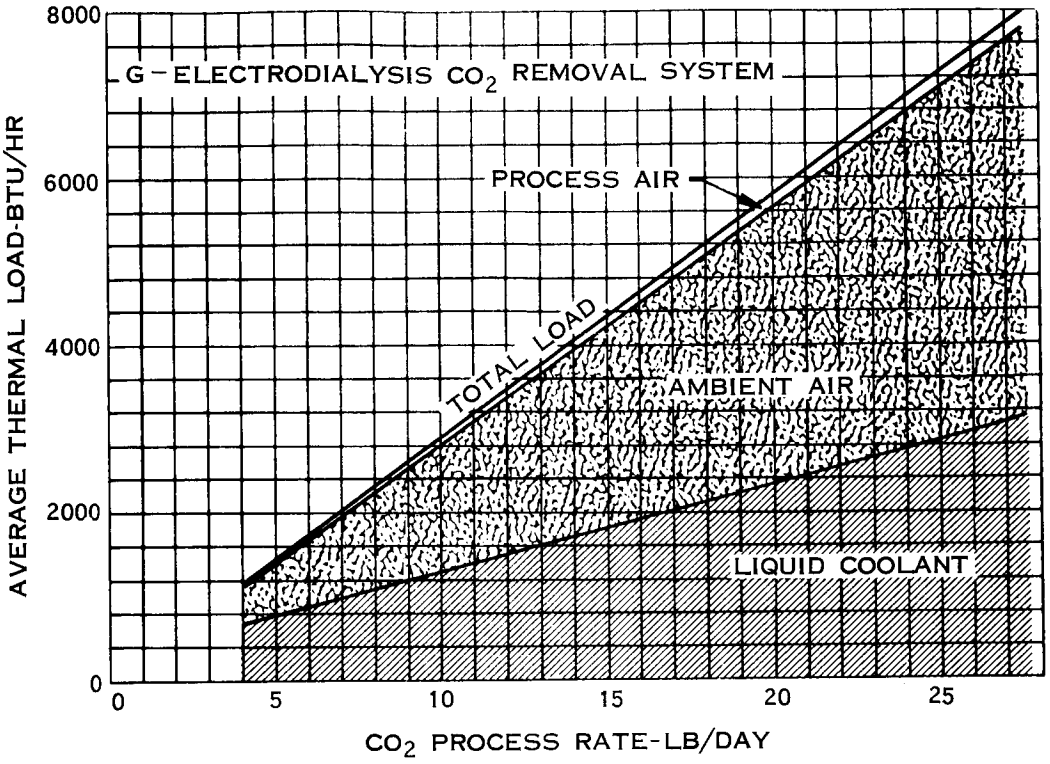


FIGURE 6–23

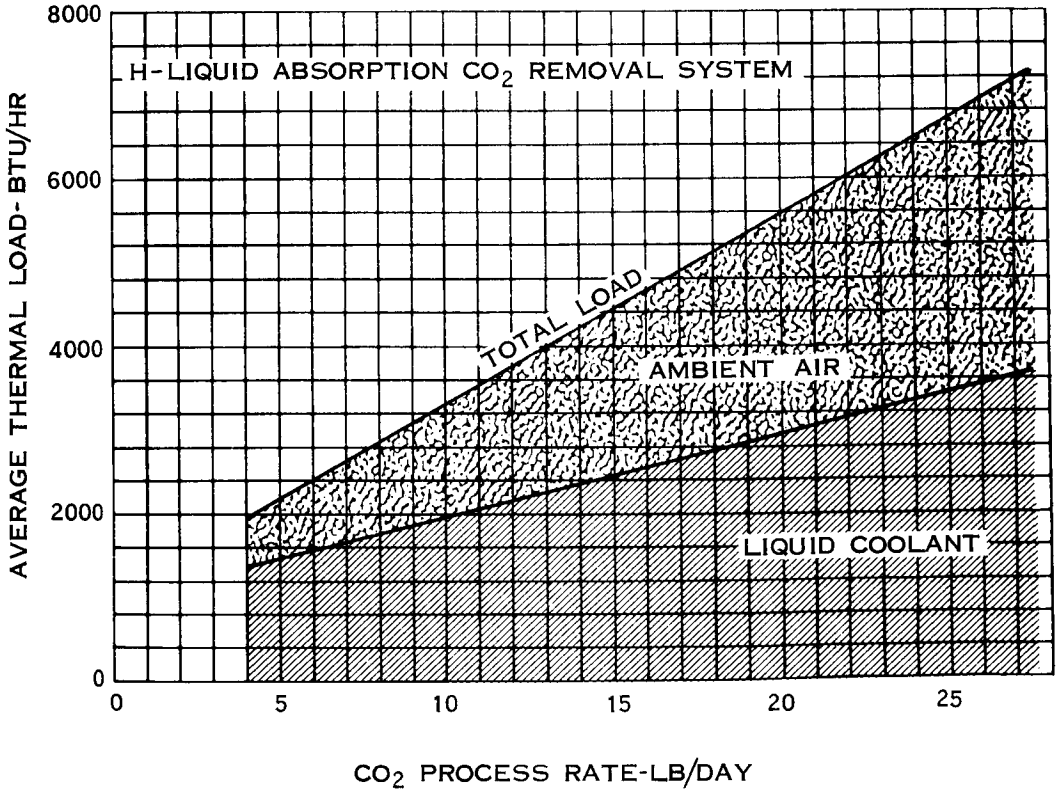


FIGURE 6–24

CO_2 MANAGEMENT SYSTEM (A–H)
EXPENDABLE WEIGHT VS. MISSION TIME

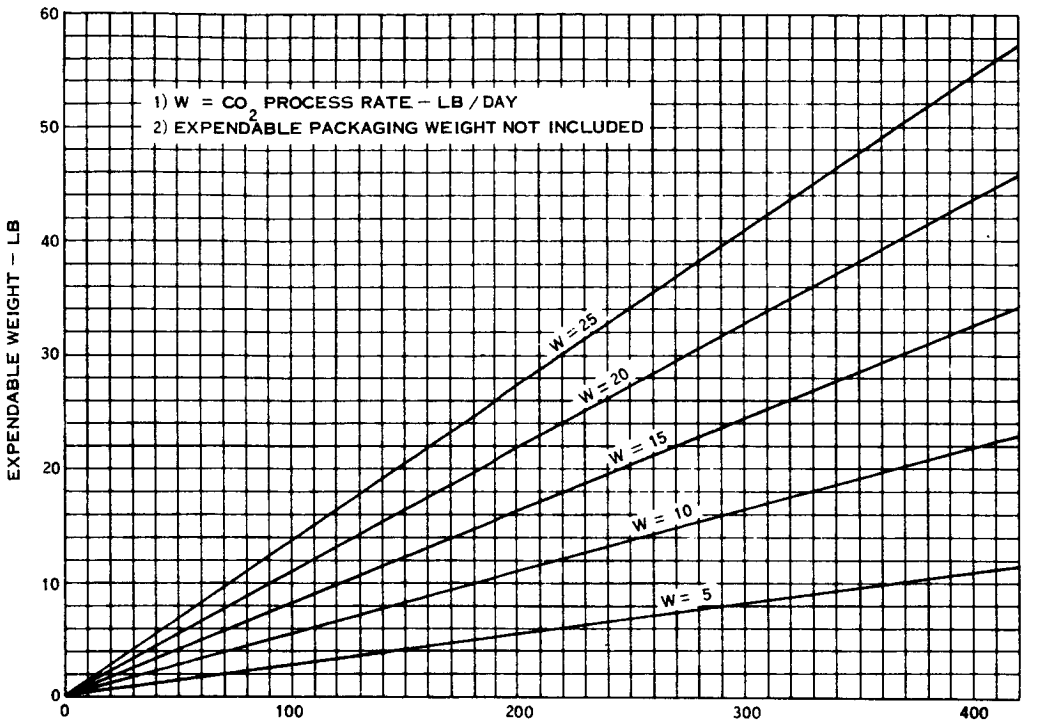
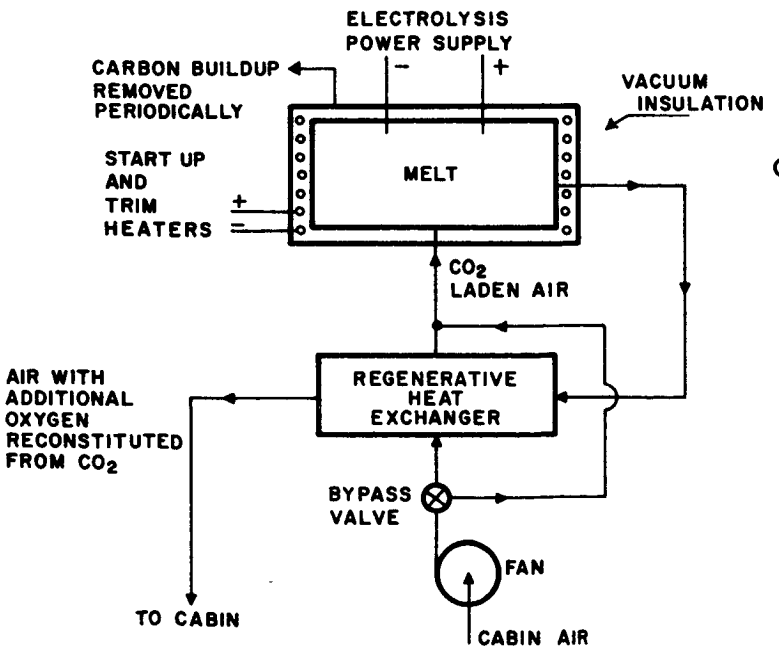


FIGURE 6–25



SYSTEM J
MOLTEN CARBONATE
CO_2 SCRUBBER–REDUCTION
SYSTEM SCHEMATIC

FIGURE 6–26

6.4 (Continued)

This system has the lowest equivalent weight of those considered, but is also in an early development stage. Feasibility of the process has been verified in research testing at Hamilton Standard but more effort is required on the optimum melt selection and zero "g" operation prior to full evaluation of the potential of this system. Once these are determined better estimates of overall expendable requirements for the system can be made.

Present estimates consider that a portion of the melt is trapped in the carbon plated on the electrode although ideally this can be eliminated. The electrode itself is considered an expendable at this point in the development cycle but methods of carbon removal can be studied to allow re-use of the electrodes.

The results for the molten carbonate CO_2 management system are presented in Figures 6-27 through 6-31. The fixed weight and power estimates for this system are presented in Figures 6-27 and 6-28 respectively. Figure 6-29 illustrates the net thermal energy absorbed by the temperature control system and rejected by the space radiator. Figure 6-30 presents the total equivalent weight estimate for this system. Figure 6-31 presents a preliminary estimate of the expendable requirements for this subsystem based upon current data. It must be repeated here that further development effort on this system could reduce the expendable requirements to zero, thus this figure allows only a first approximation of this penalty.

6.5 Comparative Discussion

A summary of carbon dioxide management systems is shown in Figures 6-32 and 6-33. The actual selection process is left to the system integration discussion. However, a preliminary examination of these figures indicated that for a six man system for a 420 day mission the molten carbonate system posesses a slight weight. advantage over the solid electrolyte-solid adsorption system. However, this advantage decreases with increases in mission time, but increases with increasing CO_2 production rate. The more rapid increase in molten carbonate system weight with increasing mission time is a result of the high expendable rate associated with the molten carbonate system. As mentioned previously, there is a potential to decrease this expendable rate to nearly zero, which would result in a large weight advantage for molten carbonate. The solid electrolyte-solid adsorption indicates a considerable weight advantage over the other systems and currently enjoys a somewhat better development status than the molten carbonate.

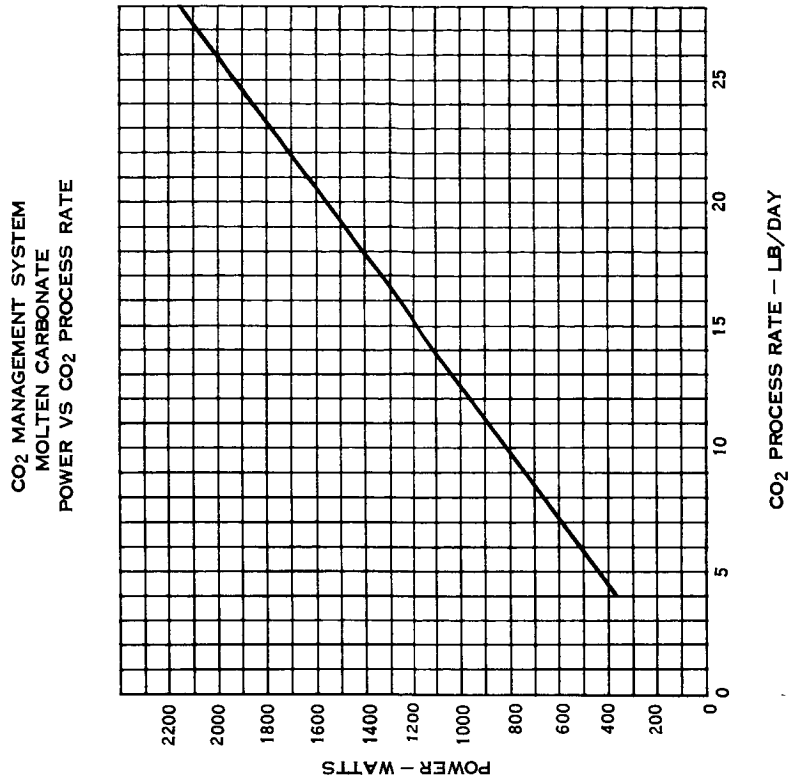


FIGURE 6–28

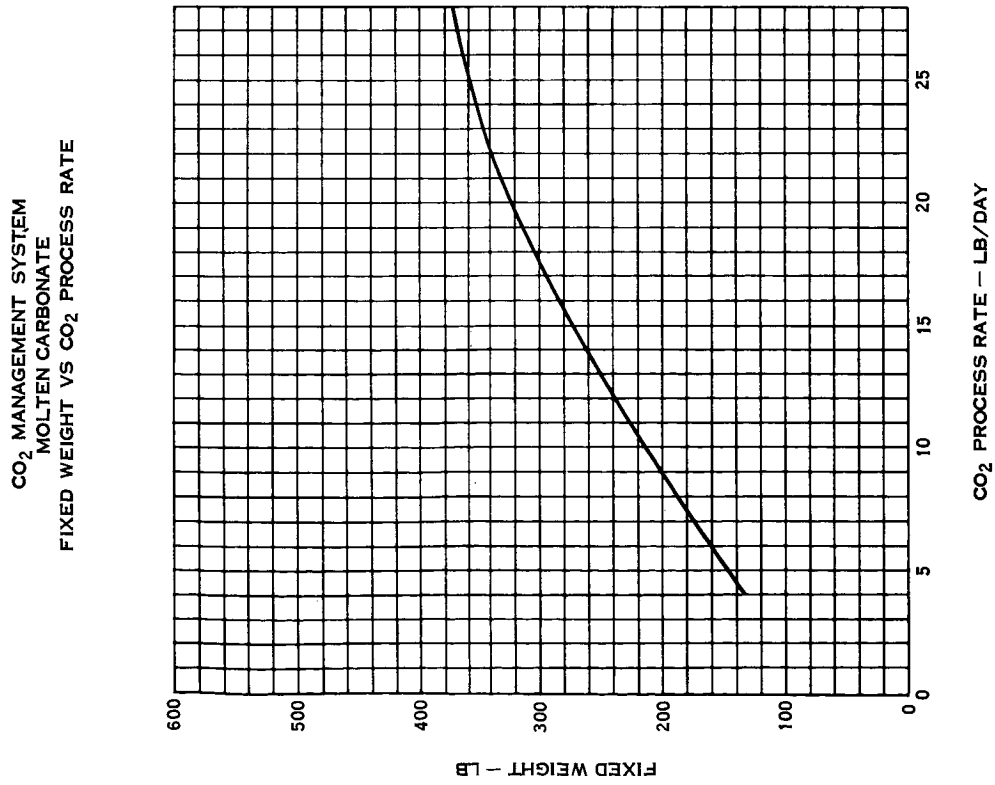


FIGURE 6–27

CO_2 MANAGEMENT SYSTEM
MOLTEN CARBONATE
THERMAL LOAD VS CO_2 PROCESS RATE

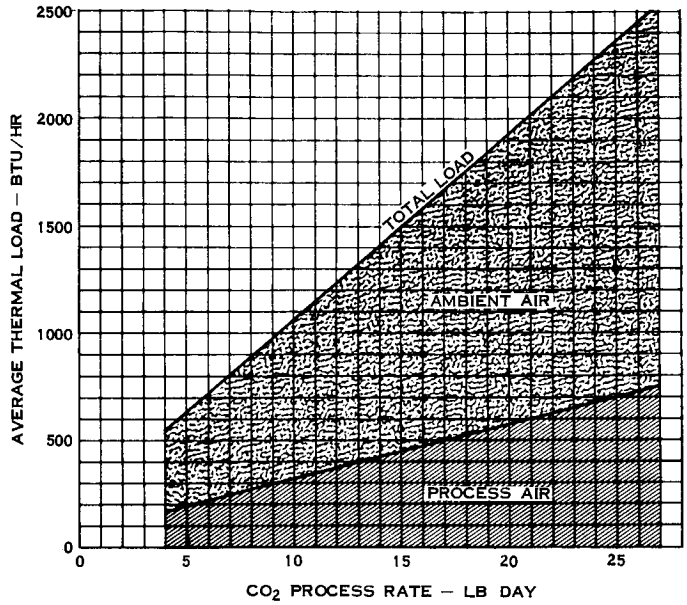


FIGURE 6–29

CO_2 MANAGEMENT SYSTEM
MOLTEN CARBONATE
EQUIVALENT WEIGHT VS CO_2 PROCESS RATE

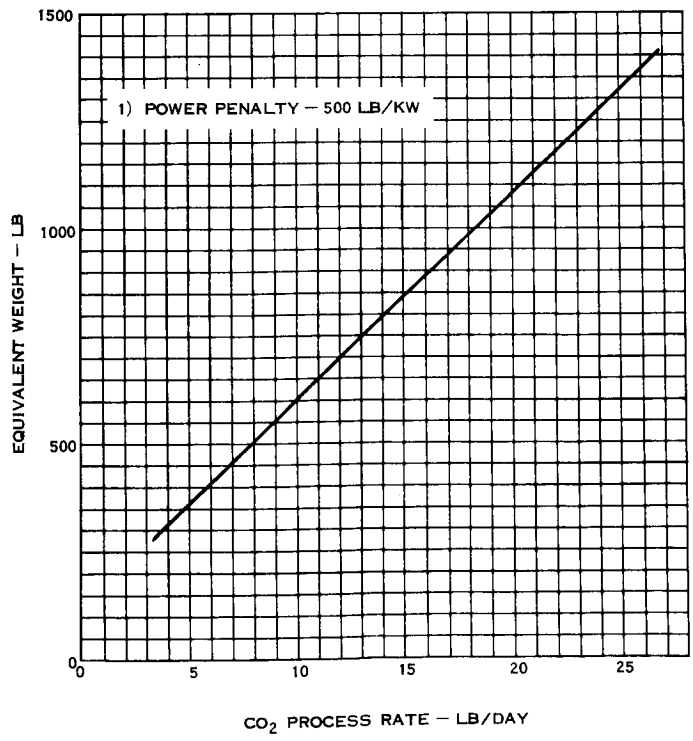


FIGURE 6–30

CO_2 MANAGEMENT
MOLTEN CARBONATE
EXPENDABLE WEIGHT VS MISSION TIME

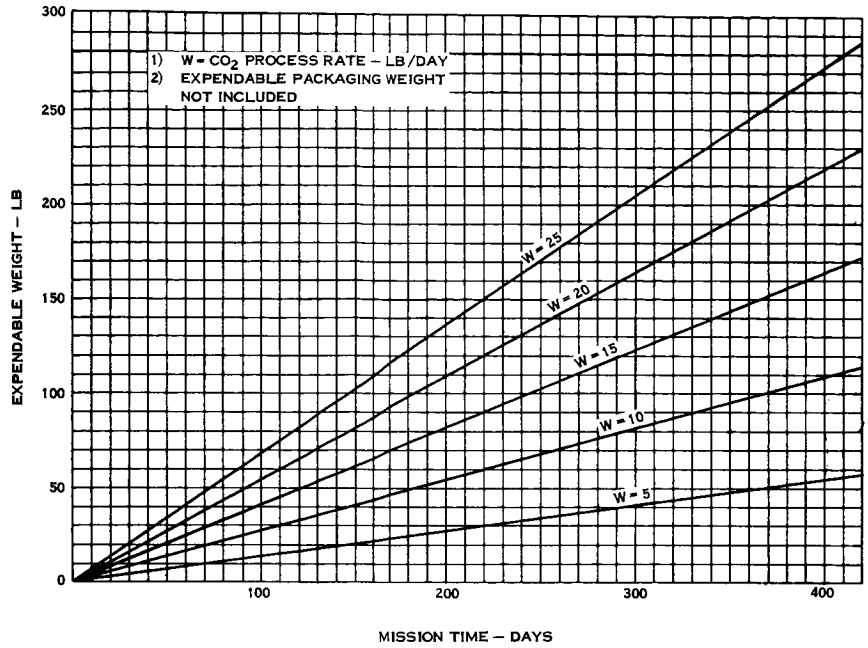


FIGURE 6–31

CO_2 MANAGEMENT SUMMARY
TOTAL EQUIVALENT WEIGHT VS CO_2 PROCESS RATE
420 DAY MISSION

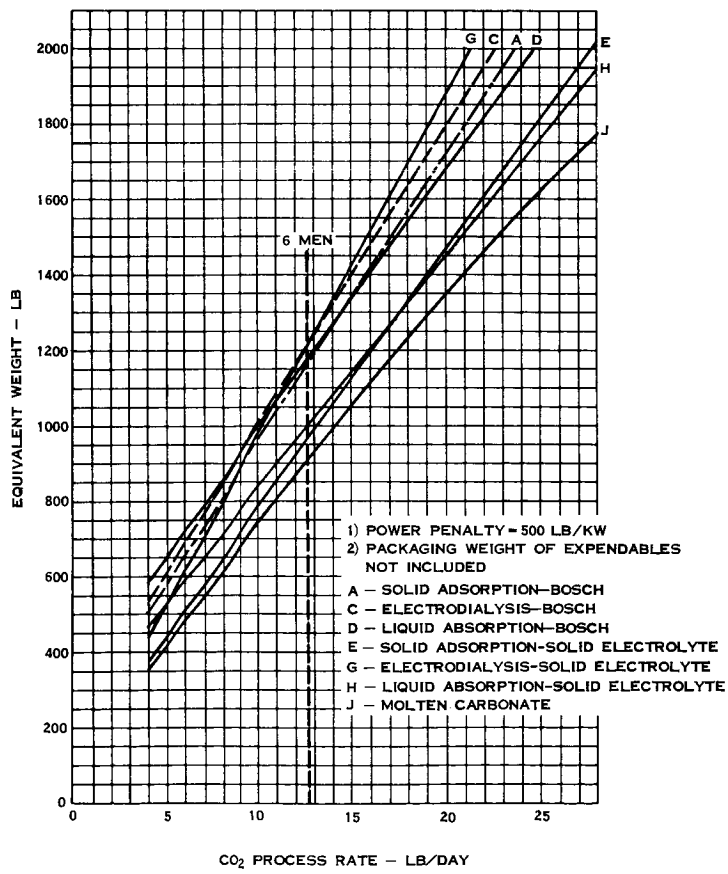


FIGURE 6–32

CO_2 MANAGEMENT SUMMARY
TOTAL EQUIVALENT WEIGHT VS MISSION TIME

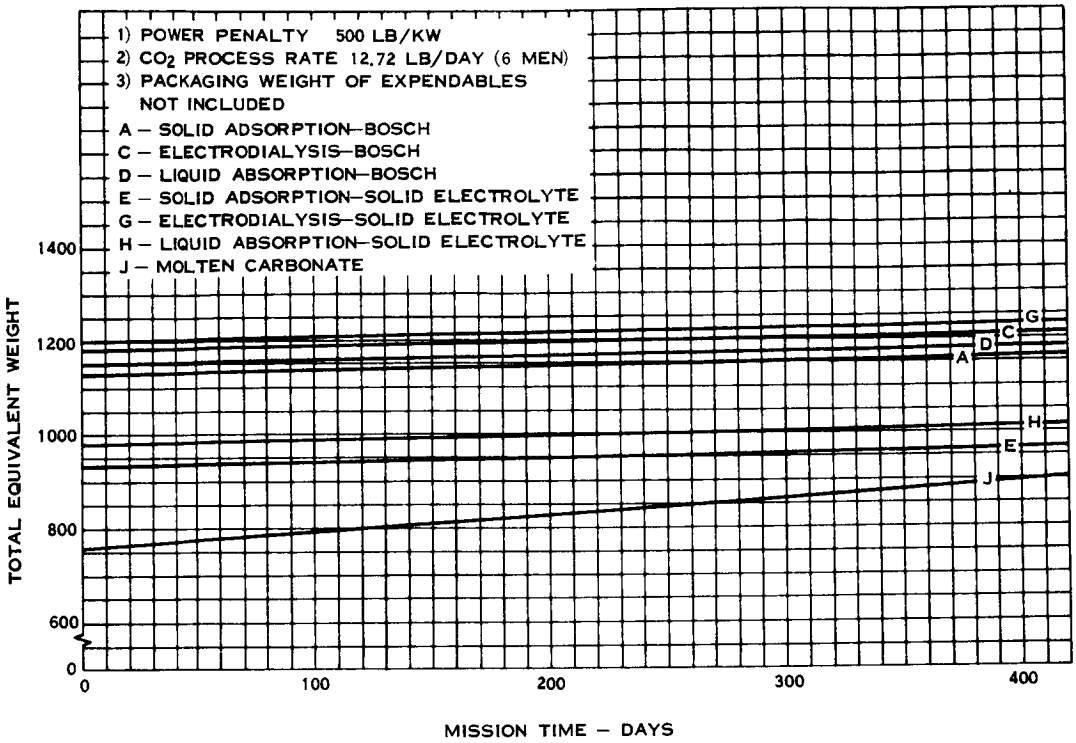


FIGURE 6–33

SECTION 7.0

ATMOSPHERIC SUPPLY

7.0 ATMOSPHERIC SUPPLY

7.1 General

7.1.1 Objectives

The subsystem analysis of atmospheric storage methods was conducted to provide sufficient data for use in the system integration phase of the study, when the carbon dioxide removal and reduction systems will be combined with storage tanks to provide the required atmospheric constituents. Since the amount of stored atmospheric constituents required depends upon mission duration, leakage rate, and oxygen recovered, the storage data is presented in a readily usable form to eliminate the need for sizing calculations for each step in the later integration studies. Thus, the information is presented as stored fluid tankage weights as a function of the useful weight, and the effects of fluid use rates and standby time of the system prior to actual use.

A considerable variety of storage methods are available for analysis as potential candidate systems. This study has included cryogenic storage in supercritical form and subcritical form, as well as gaseous storage and a brief treatment of mixed gas storage. All of these were investigated in detail relative to their overall merit to the final system design. The cryogenic storage systems received considerably more detail than gaseous storage, since their peculiar nature makes the effect of various changes in parameters much more critical than that of gaseous storage, where a constant pressure is maintained during standby and essentially instantaneous supply is available.

This portion of the overall study was not intended to present a final design for any gaseous or cryogenic storage requirements. This will be a subject for the system integration phase once final storage quantity requirements are determined. It is possible from the data presented to roughly approximate the overall weight associated with storage of any quantity of fluid, thus allowing rapid resizing of storage system requirements with changes in system design point or mission duration.

7.1.2 Use of Data

The data presented for atmospheric storage system approaches is entirely parametric in nature, in that major variables have been considered in the sizing study. As previously mentioned, the objectives behind the presentation of this data are allowance of rapid resizing of gross storage system requirements and easy determination of gross system weight changes with a change in the overall quantity stored.

In the case of supercritical, subcritical, and gaseous storage, the curves take the form of a determination of total weight as a function of useful fluid weight. Thus,

7.1.2 (Continued)

upon determination of the desired fluid quantity to be stored, the tankage or storage weight associated with this can be determined.

Also included are basic schematic approaches for the storage systems considered, as well as a description of system operation in each case from initial filling through use of the fluid. The discussion also illustrates the potential methods of maintaining operating pressure within cryogenic storage systems.

7.2 Cryogenic Storage

7.2.1 Supercritical Storage with Thermal Pressurization

The supercritical cryogenic storage system is not a new concept in the space life support industry. Systems of this type are presently being developed for use on the Gemini, Apollo and Lunar Excursion Module spacecraft, thus making considerable data available in this area. For the analysis presented in this study, the primary data inputs were previous in-house Hamilton Standard cryogenic programs, with supplementary data provided by the Bendix Corporation - Pioneer Central Division. Many other competent suppliers exist in this field; however, generalized design data does not vary substantially between suppliers. The National Bureau of Standards has provided much of their latest data on liquid nitrogen and oxygen properties. This data has been very valuable in the performance of this study.

Supercritical storage offers many potential advantages in space use, the more obvious of which are the adaptability to zero "g" operation and the lower tankage weights as compared to gaseous storage systems. The supercritical fluid, as such, is a homogeneous fluid and thus does not involve the problems of liquid-gas metering in zero "g".

Figure 7-1 illustrates a typical operation of a supercritical storage system on a pressure-enthalpy diagram. Spherical tanks, as shown in Figure 7-2, were utilized in this study and the discussion revolves about this configuration. The tank is filled or partially filled with liquid at a pressure of one atmosphere and is sealed at point 1 on the diagram. Heat is then added to the system with the fluid at constant average density. Heat may be added by a circulating transport fluid via a heat exchanger, by electrical heaters, or by heat leakage through the tank walls and supports. In either of the three cases, the heat addition is continued until state two is reached. At this point, no phase distinction exists between portions of fluid. These gradients may be controlled and maintained within a given tolerance band by proper design of the heat exchanger surface, thus avoiding any system complications due to their presence. Fluid delivery is then accomplished at constant pressure by adding heat at the proper rate until point 3 is reached. This method avoids a two phase situation within the fluid up to that point.

SUPERCRITICAL STORAGE TANK CONFIGURATION

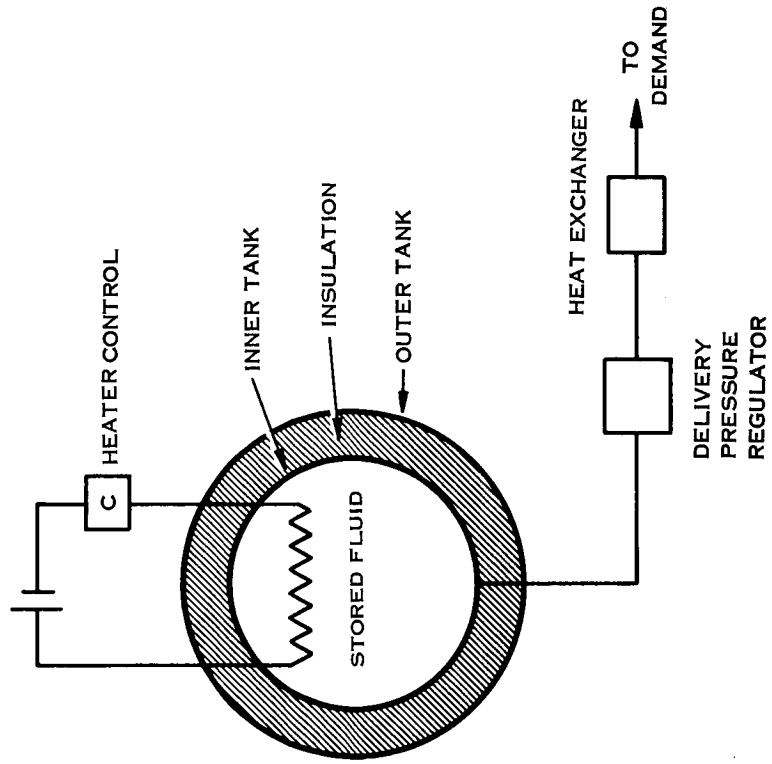


FIGURE 7–2

SUPERCRITICAL STORAGE
AVERAGE PATH FOLLOWED BY THE FLUID

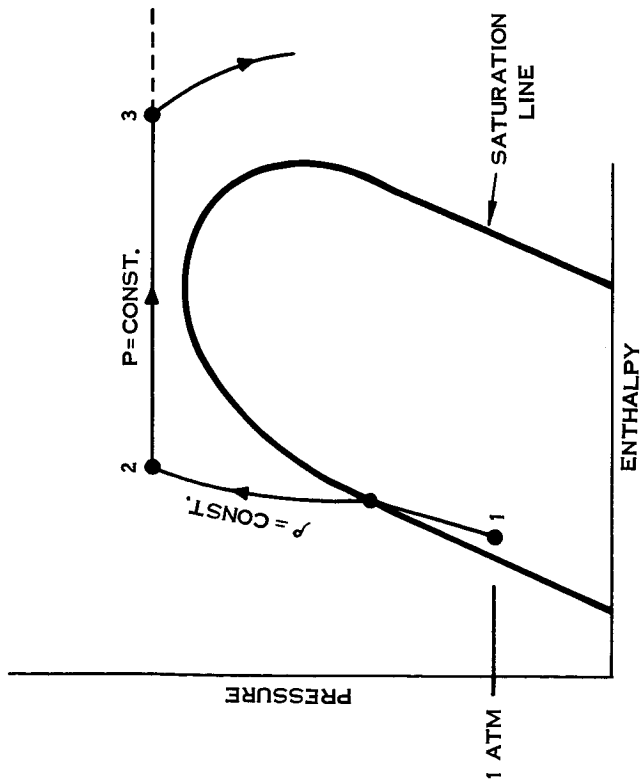


FIGURE 7–1

7.2.1 (Continued)

Two methods of limiting the pressure in a cryogenic tank during stand-by period were considered. One method is to initially underfill the tank such that the heat leakage will expand the stored fluid with increasing temperature to fill the tank, and then pressurize to the required value by the end of the stand-by period. Another scheme is to completely fill the tank with liquid initially and vent fluid during stand-by as required to limit the tank pressure.

An investigation of the two methods indicates that the former will yield minimum storage subsystem weight for the range of stand-by (0-360 hours) and the range of usable fluid weight (200-1200 lbs.) under consideration for leakage and metabolic requirements. The latter method is applicable to long stand-by periods in the order of several months or years.

Figure 7-3 illustrates the proper rate of heat addition for oxygen storage as a function of the storage pressure level and the amount of fluid remaining in the tank. Thus, when the use rate is determined, the heat addition requirements can be selected from this figure at the desired operating pressure. Figure 7-4 presents the same data for the case of nitrogen storage. If a tank pressure decay is permissible, heat addition may be avoided after point 3 in the pressure-enthalpy diagram is reached and an energy savings may be realized. At some time past this point, it actually becomes impractical to attempt to maintain the initial pressure by heat addition.

The schematic presents the storage system only to the point of the initial pressure regulating valve. In actuality, atmospheric storage is controlled by a demand system within the overall life support system pressure control equipment. Upon demand from this equipment and its associated sensors, the fluid is withdrawn from the tank, passes through the initial pressure regulating valve to the demand valve which admits it to the cabin or main system as required. In many cases, the exit temperature of the fluid may be lower than desired system inlet temperature and supplemental heating will be required upstream of the demand valve. This system has not been illustrated during this analysis since it is a function of final system integration and need not be finally determined until that time. The penalty for the demand system will be essentially the same for all atmospheric storage systems, thus the weight penalty has been omitted from the data presentation in this section and must be an added factor in overall system design.

In summary, supercritical storage provides the desired fluid in a high density form within small, relatively lightweight containers. The system reliability may be somewhat lower than a simple gas system with an inflow valve, however, weight savings are considered for this approach, making it a desirable candidate. Secondly, the single phase storage aspect of the fluid minimizes flow control and metering problems as well as the overall operational aspects in zero "g".

SUPERCRITICAL O_2 STORAGE
SPECIFIC HEAT INPUT REQUIRED TO MAINTAIN CONSTANT PRESSURE
VS
FLUID DENSITY AND TANK PRESSURE

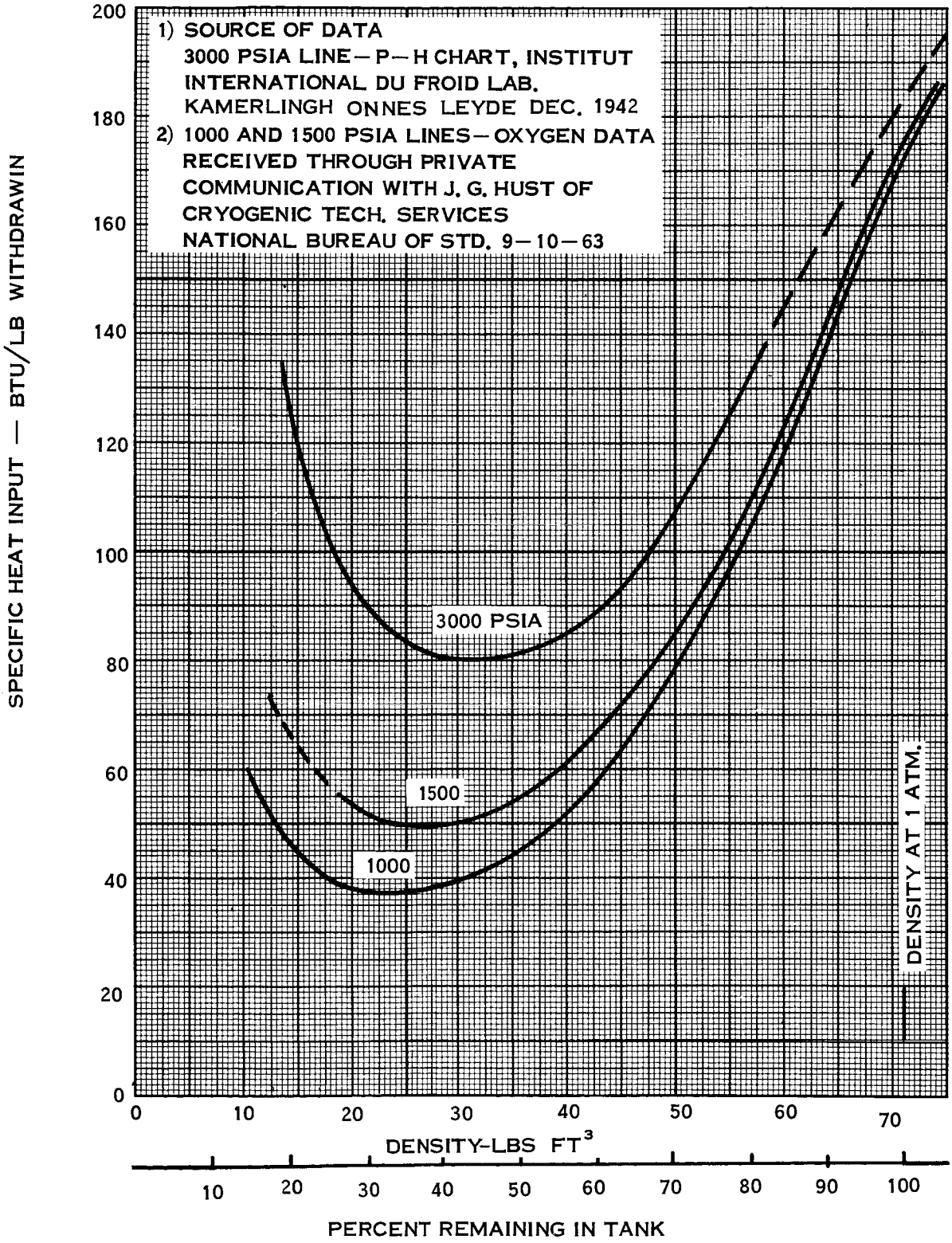


FIGURE 7—3

SUPERCRITICAL N_2 STORAGE
SPECIFIC HEAT INPUT REQUIRED TO MAINTAIN CONSTANT PRESSURE
VS
FLUID DENSITY AND TANK PRESSURE

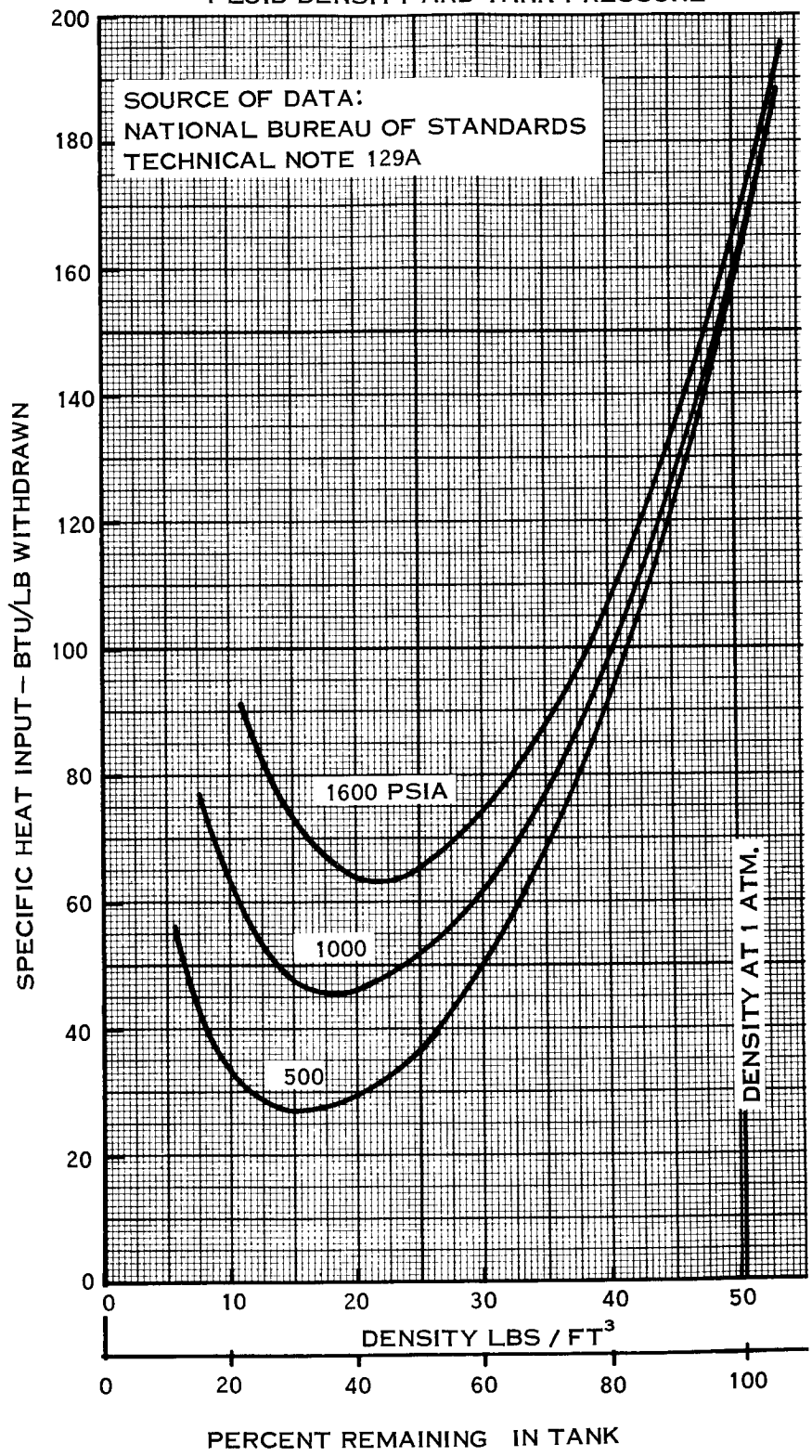


FIGURE 7 – 4

7.2.2 Subcritical Storage with Thermal Pressurization

The subcritical cryogenic storage system is essentially two phase storage during the entire storage period. The two phase storage aspect brings with it the associated liquid vapor metering problems in zero "g" which makes system control somewhat more difficult than that for supercritical storage. Potential weight advantages of this approach, however, make its investigation desirable. The operation of the subcritical storage system discussed in this report is illustrated in Figure 7-5, a pressure-enthalpy diagram. In this case the tank may be of any convenient shape and is more adaptable to vehicle packaging problems than the normal spherical tankage required for supercritical storage.

The storage tank is partially filled at a pressure of one atmosphere and sealed at point 1 in the diagram. Heat is then added by methods similar to that outlined for supercritical storage until the desired operating pressure is reached at point 2. Fluid delivery occurs with the system maintained at a constant pressure between points 2 to 3. Constant pressure maintenance is accomplished by the addition of heat to balance the outflow from the system. This heat requirement to maintain a constant pressure within the storage container as well as providing gaseous delivery of the fluid is approximately equal to the latent heat of vaporization of the fluid upstream of the delivery pressure regulating valve.

As previously mentioned, the major problem associated with two phase subcritical storage is the metering of the fluid upon demand. This is caused by the amorphous presence of vapor and liquid within the tank in a zero gravity environment and subsequently a random withdrawal of either or both. Figure 7-6 presents the basic system schematic utilized in this study. As shown in this schematic, the fluid leaving the tank is passed through a controlled restriction to provide a constant mass flow with a constant pressure drop. Preliminary testing on this type of restrictor at Hamilton Standard has indicated a variation of liquid to vapor mass flow rate of only 6 to 1 with a fixed pressure drop and a restrictor with fixed flow resistance. This preliminary test data indicates that the metering problem associated with two phase storage is less than might be anticipated; due partly to the fact that the laminar flow characteristics are primarily dependent upon the ratio of density to viscosity. This ratio changes far less than does the density as the phase changes from liquid to gas.

Another potential solution to the metering problem is to construct the internal surfaces of the tank such that the surface tension forces between liquid, vapor, and tank wall will cause the liquid to be gathered in one particular portion of the tank in zero "g". By thus separating liquid and vapor, either one or the other can be metered separately.

Upon leaving the restrictor, the fluid is then passed through the heat exchanger in which the heat is transferred from the tank fluid and the tank ambient to the leaving

SUBCRITICAL STORAGE SYSTEM SCHEMATIC

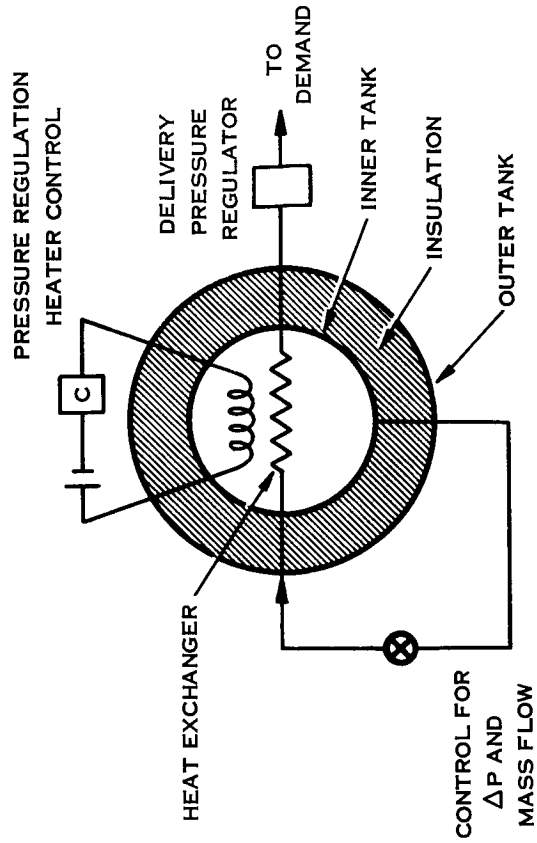


FIGURE 7–6

SUBCRITICAL STORAGE
AVERAGE PATH FOLLOWED BY THE FLUID

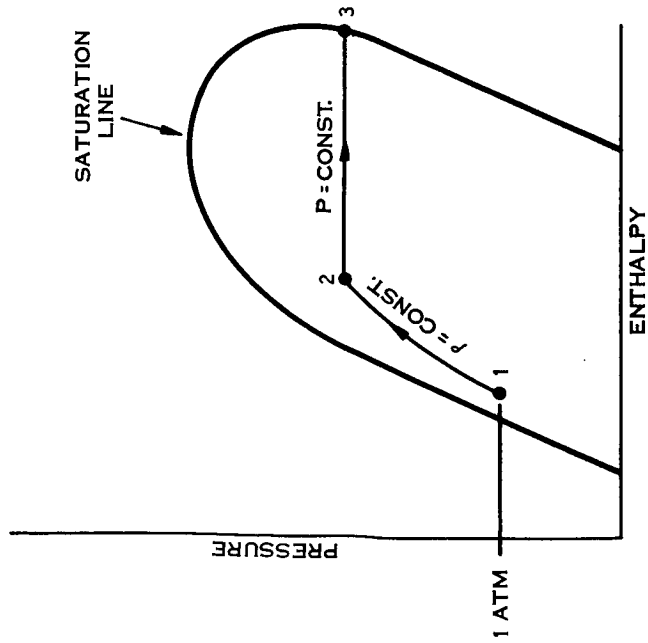


FIGURE 7–5

7.2.2 (Continued)

fluid to vaporize it. With this approach, the heat leaking into the storage vessel is used to vaporize the delivered fluid thus reducing system insulation requirements. In order to obtain a temperature difference between the leaving fluid and the fluid within the tank itself that was considered sufficient for adequate operation, a storage pressure of 100 psia was selected for this analysis.

Subcritical storage, although initially unattractive due to the two phase metering problems in zero "g" offers many potential advantages over supercritical storage. The low storage pressure permits utilization of tankage in essentially any convenient shape without necessitating thick walled vessels, thus allowing more flexibility of overall tankage design than that available with supercritical storage. The minimum heat input requirements for subcritical storage offers other potential advantages. Since a minimum heat input equal to the heat of vaporization of the fluid is required, the minimum heat capacitance of the fluid in the tank is considerably greater (from 2.4 to 2.9 times as great for nitrogen and oxygen respectively). The insulation requirements of a subcritical storage system are then considerably less in cases where the use rate is low.

The two phase storage minimizes the problems encountered in supplying heat to the stored fluid for pressure control. Heat transferred from the heating element to the fluid appears to be adequate because the boiling phenomena gives good heat transfer coefficients at low gravity conditions and it is expected that this will be the case in zero gravity as well.

7.2.3 Cryogenic Storage Using a Positive Expulsion

The third cryogenic storage scheme investigated was liquid storage with positive expulsion of the liquid from the container by a bladder or piston arrangement. This system was devised to avoid the two phase metering problem inherent in low pressure storage when using fixed volume containers. The utilization of the bladder or piston arrangement maintains the stored fluid in the liquid form thus assuring a liquid delivery to the demand system. A bladder type container as indicated in Figure 7-7 will probably prove to be the most practical approach, however, at present no suitable material seems available to satisfactorily perform the task of flexing as a bladder in cryogenic liquids. This has been substantiated in a report by Beech Aircraft Corporation. This bladder design problem will be the major development task associated with obtaining a system of this type.

Another problem associated with this storage system approach is that of accurately controlling system heat leakages from the external environment. In order to maintain a liquid within the bladder, the heat leakage into the contained fluid must be essentially eliminated. This may be accomplished by expanding the pressurized

POSITIVE EXPULSION CRYOGENIC STORAGE
AVERAGE PATH FOLLOWED BY FLUID LEAVING TANK

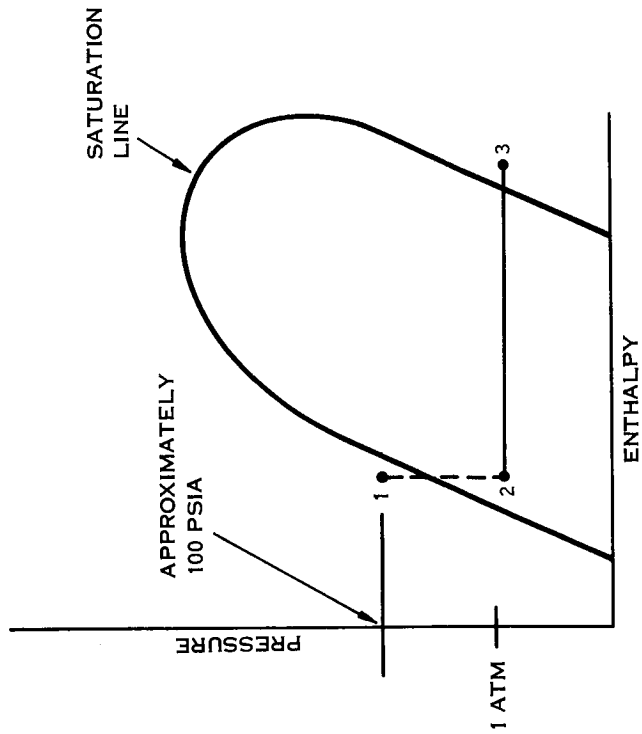


FIGURE 7–8

POSITIVE EXPULSION CRYOGENIC STORAGE SYSTEM SCHEMATIC

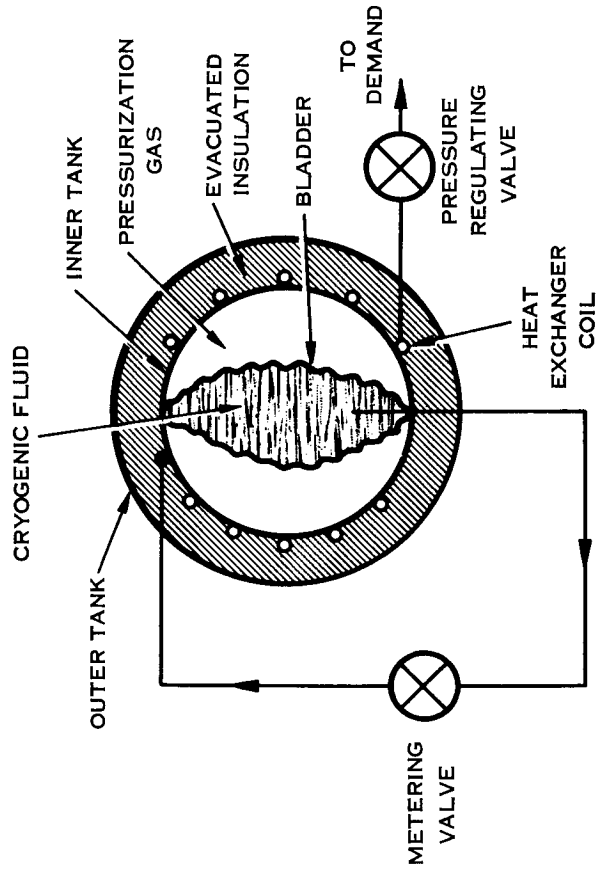


FIGURE 7–7

7.2.3 (Continued)

effluent cryogenic fluid through a metering valve, thus reducing temperature, then by proper insulation and heat exchanger design all the heat leak through the insulation will be transferred to the leaving fluid. Figure 7-8 illustrates the path followed by the fluid within the system. Sub-cooled liquid at point 1 in the diagram is expanded to state 2. Heat is transferred to the efflux fluid at constant pressure thus vaporizing it.

The weight of this subcritical positive expulsion approach will be approximately the same as a two phase storage system using thermal pressurization. The primary advantage of this system over a thermally pressurized two phase system is the relative ease of metering the efflux fluid. This may not prove to be a significant enough point to require development of this system and its associated bladder design in comparison with other more promising, more potentially available system approaches.

Since the system weight is quite similar to that of the subcritical system discussed in the preceding section, no parametric data presentation has been made for this approach and it is considered essentially non-competitive at this time in view of the other system capabilities which are available.

7.3 Gaseous Storage

Gaseous storage was considered primarily for supplementary oxygen requirements and repressurization requirements since for large storage systems its weight and volume are prohibitive. However, it does present potential advantages for long term storage prior to use such as that of repressurization and is thus worth considering in the initial analysis. Since pressure decay and boiling vent losses do not occur with a gaseous storage system, and the storage is at higher pressure allowing instantaneous and rapid use, repressurization requirements could be accomplished by gaseous storage.

Gaseous storage is also being considered for the Earth Re-entry Module. In this case the quantity of gas to be stored is not large and the added reliability may offset the weight disadvantage of the storage technique.

Figure 7-9 presents a comparison of potential storage containers for gaseous nitrogen over a range of pressures. This figure illustrates the storage weight and volume requirements as a function of the quantity of nitrogen stored. From this figure the optimum storage system for the point of interest can be determined quite readily. The figure allows selection of a storage pressure on the basis of minimum weight, minimum volume or some intermediate point between the two, dependent upon the relative importances placed upon each. Also the effect of a material change can be readily determined. Figure 7-10 presents the same com-

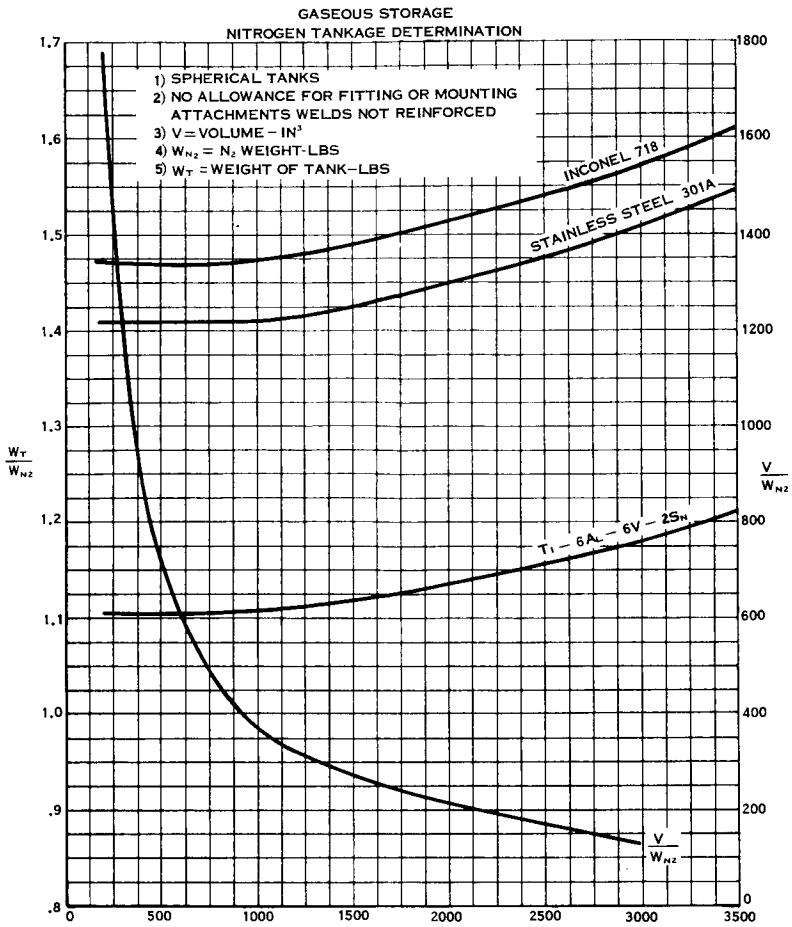


FIGURE 7–9

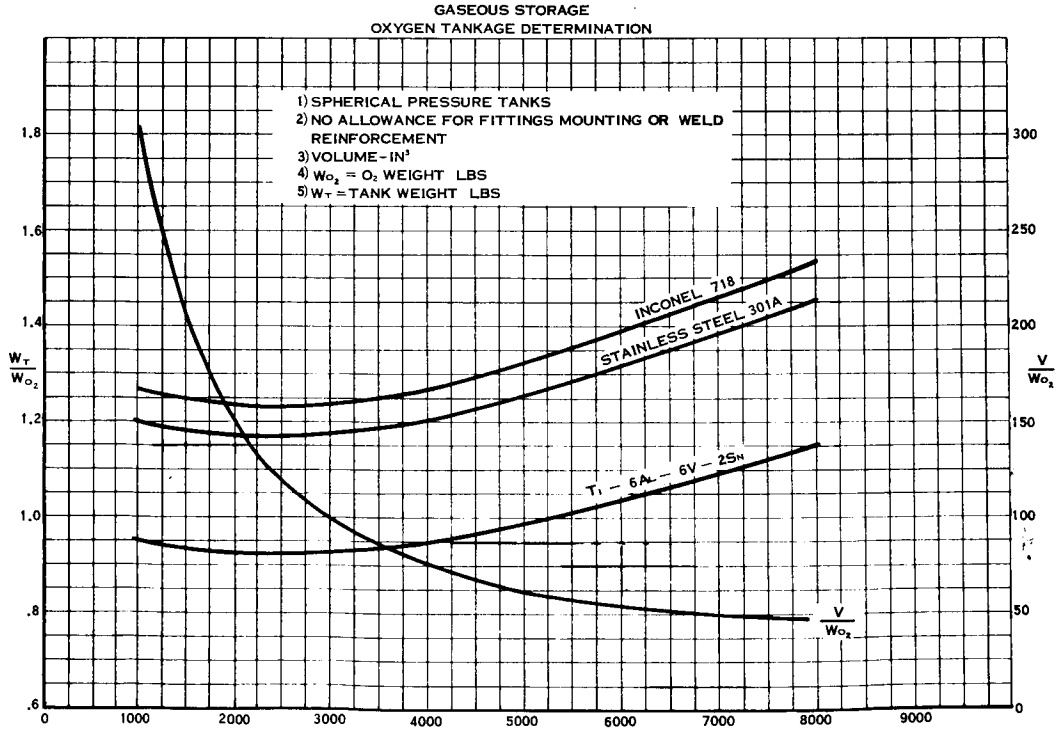


FIGURE 7–10

7.3 (Continued)

parison for the case of oxygen storage. One point must be made about this figure. The stainless steel curve is for a tank cryogenically stretched by the Ardeform process. This process, developed by the Arde-Portland Company provides a method of obtaining high strength to weight ratios with stainless steel at low weight penalties.

While titanium is shown in this curve for comparison purposes, it will not be considered further because there is serious question about the compatibility of titanium and high pressure oxygen.

Figures 7-11 and 7-12 present system sizing curves for nitrogen and oxygen at one specific pressure. If this pressure proves optimum, the weight of the tankage system associated with any stored fluid weight can be easily obtained from these two curves. The curves themselves are somewhat self-explanatory and if a different pressure level is desired, similar curves can be prepared quite easily from the data in Figures 7-9 and 7-10.

7.4 Mixed Gas Storage

A mixed gas storage system was briefly considered for this requirement, but was ruled out due to its great dependence upon stable use rates of both constituents. This system, which stores both oxygen and nitrogen within the same container and feeds them at a predicted use rate is very attractive for vehicles where leakage is relatively constant and crew activity and crew occupancy variations are minor or of short duration. In the case of the Mars vehicle, where crew variations may range from 2 to 6 men, the system is unattractive due to its constant mixture delivery.

The system holds some attractiveness in the case of vehicle repressurization requirements in that the constant mixture fluid can be stored and delivered to the cabin without major monitoring and inflow metering requirements. For the case of a completely voided module, the system can be opened and allowed to fill the module to the desired total pressure without fear of the resultant constituent imbalance.

7.5 Chemical Storage

Chemical Storage of atmospheric components has the advantage of long storage life without boil-off or venting losses. These systems in general are characterized by weights which are higher than corresponding cryogenic system weights for mission which have moderate to high minimum use rates and all but the longest hold times. The main advantage of these chemical storage systems lies in very

GASEOUS N_2 STORAGE
TANKAGE WEIGHT VS FLUID WEIGHT

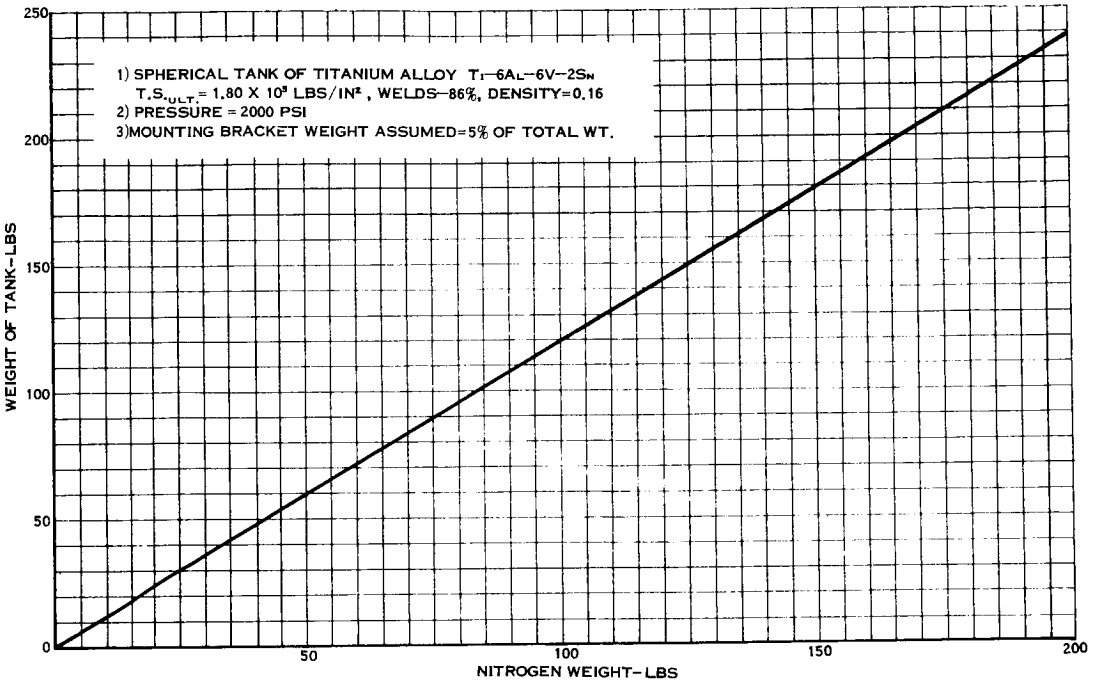


FIGURE 7–11

GASEOUS O_2 STORAGE
TANKAGE WEIGHT VS FLUID WEIGHT

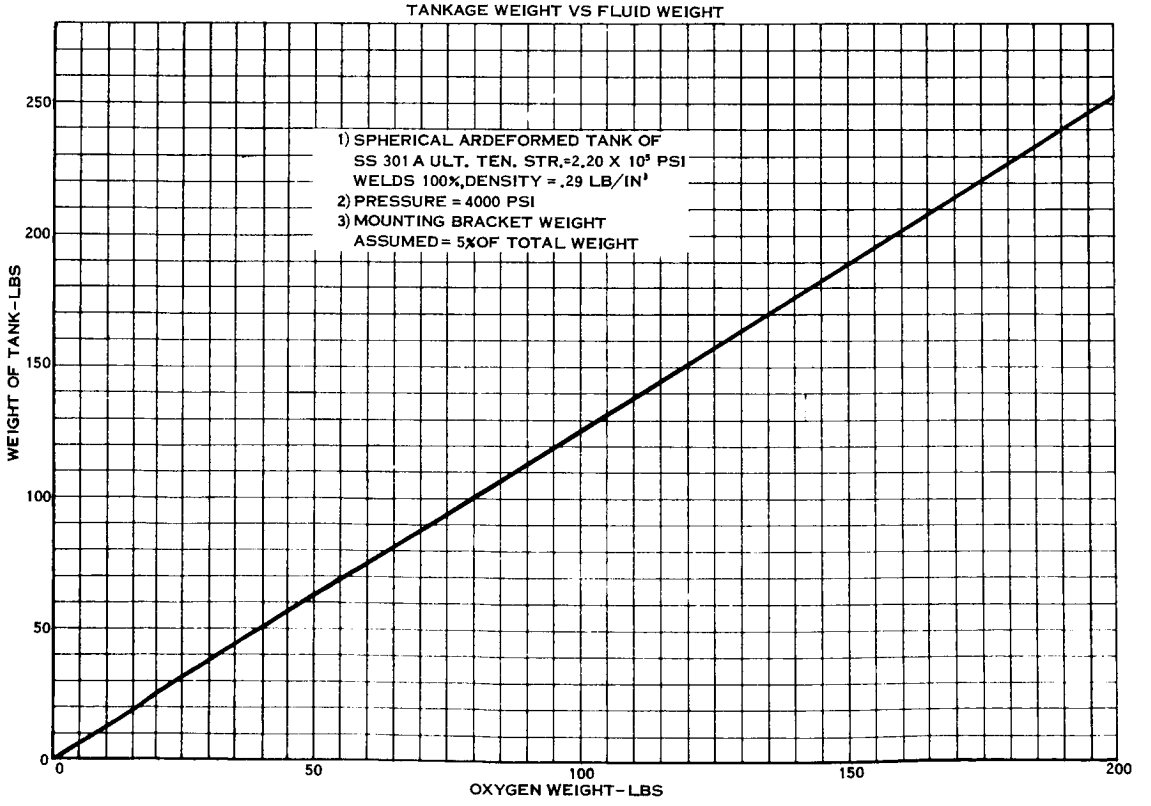


FIGURE 7–12

7.5 (Continued)

long mission times with use rates which are very low or intermittent. For the purposes of this disucssion only those chemicals which exhibit a minimum weight potential in their class will be examined. Further, those chemicals which perform dual functions such as the superoxides which both remove CO_2 and supply O_2 will not be discussed on a subsystem level as they depend on integration into a complete system to such a large extent.

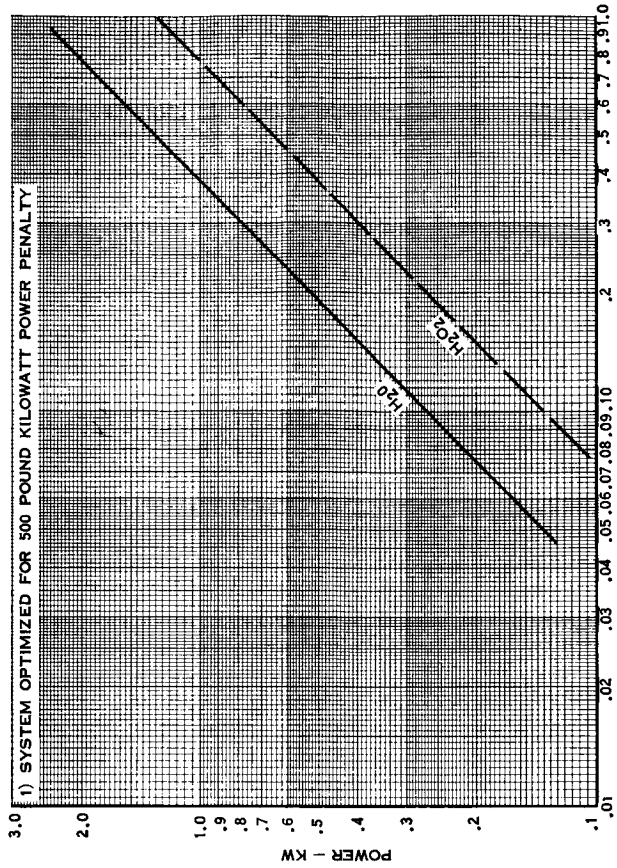
The chemicals which can be used for the storage of oxygen can be classifed as the alkali earth peroxides, superoxides, ozinides, chlorates, perchlorates, and water. Of the above, the various orders of oxides do not contain enough recoverable oxygen to be considered on this basis alone. However, they may be competitive in some systems when they can be given credit for their CO_2 absorption capabilities. The chlorates and perchlorates are similar except that the perchlorates contain an extra usable oxygen atom per molecule. Of the perchlorates the chemical lithium perchlorate ($LiClO_4$) yields the highest quantity of pure oxygen. The reaction this chemical undergoes to produce oxygen is as follows:

$$Li\,Cl\,O_4 \longrightarrow Li\,Cl + 2O_2$$

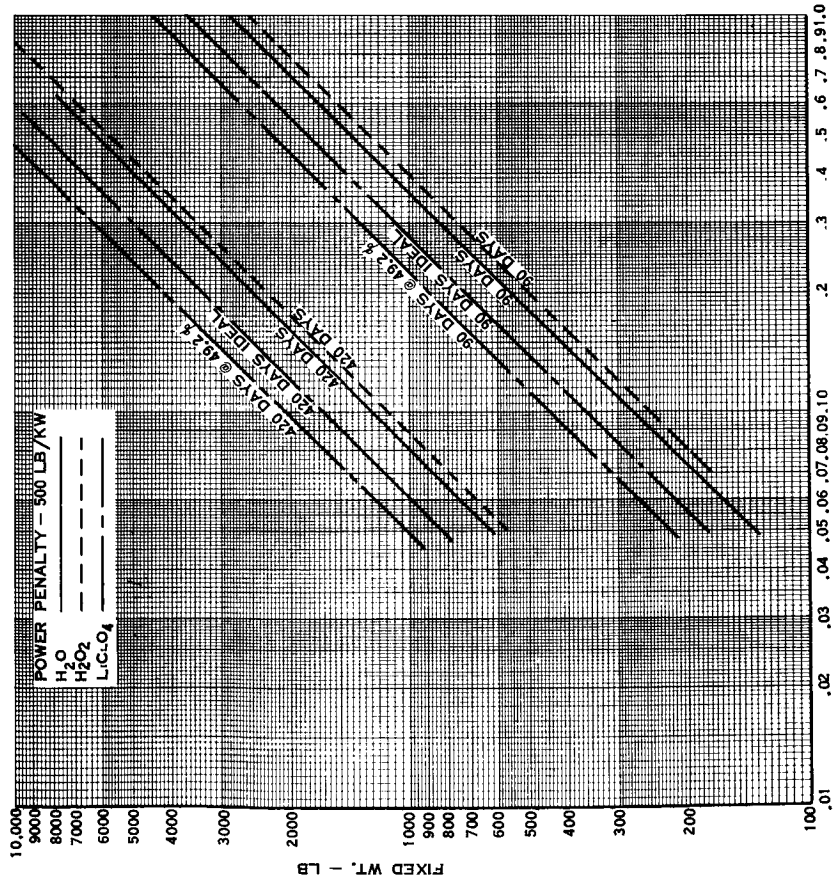
Foote Mineral Co. has developed a candle using this chemical under an Air Force contract which yields 49.2% usable oxygen by weight. A curve of system weight vs. oxygen flow for 90 and 420 day missions for this chemical candle and the ideal output for this chemical is included in Figure 7-13. This is the only chemical not requiring water electrolysis for which data is presented as it is the lightest and has a good development status. The main disadvantage of this candle is the difficulty in obtaining a variable oxygen supply.

Two other chemicals were considered as an oxygen supply medium. These are water and hydrogen peroxide. In evaluating these two chemical sources, which require the electrolysis of water, the data presented in the electrolysis subsection was used and water tankage weights were obtained from the LEM ECS system. In this case of the hydrogen perioxide, a catalyst unit would first decompose the peroxide to oxygen and water and the water would be subsequently reduced. Fixed weight, power, and total equivalent weight at 500 lbs per KW vs. oxygen flow are presented in Figures 7-13 through 7-15 for these two chemicals.

Chemical storage of nitrogen usually revolves around the azide chemicals. The only azide which gives a reasonable nitrogen yield is Lithium Azide. However, after talking with Foote Mineral Co. this chemical was not evaluated in detail due to its extreme instability and, as a result, safety hazard.



O_2 FLOW RATE ~ LB/HR
FIGURE 7-14



O_2 FLOW RATE ~ LB/HR
FIGURE 7-13

CHEMICAL OXYGEN STORAGE
TOTAL EQUIVALENT WEIGHT
VS
O_2 FLOW RATE

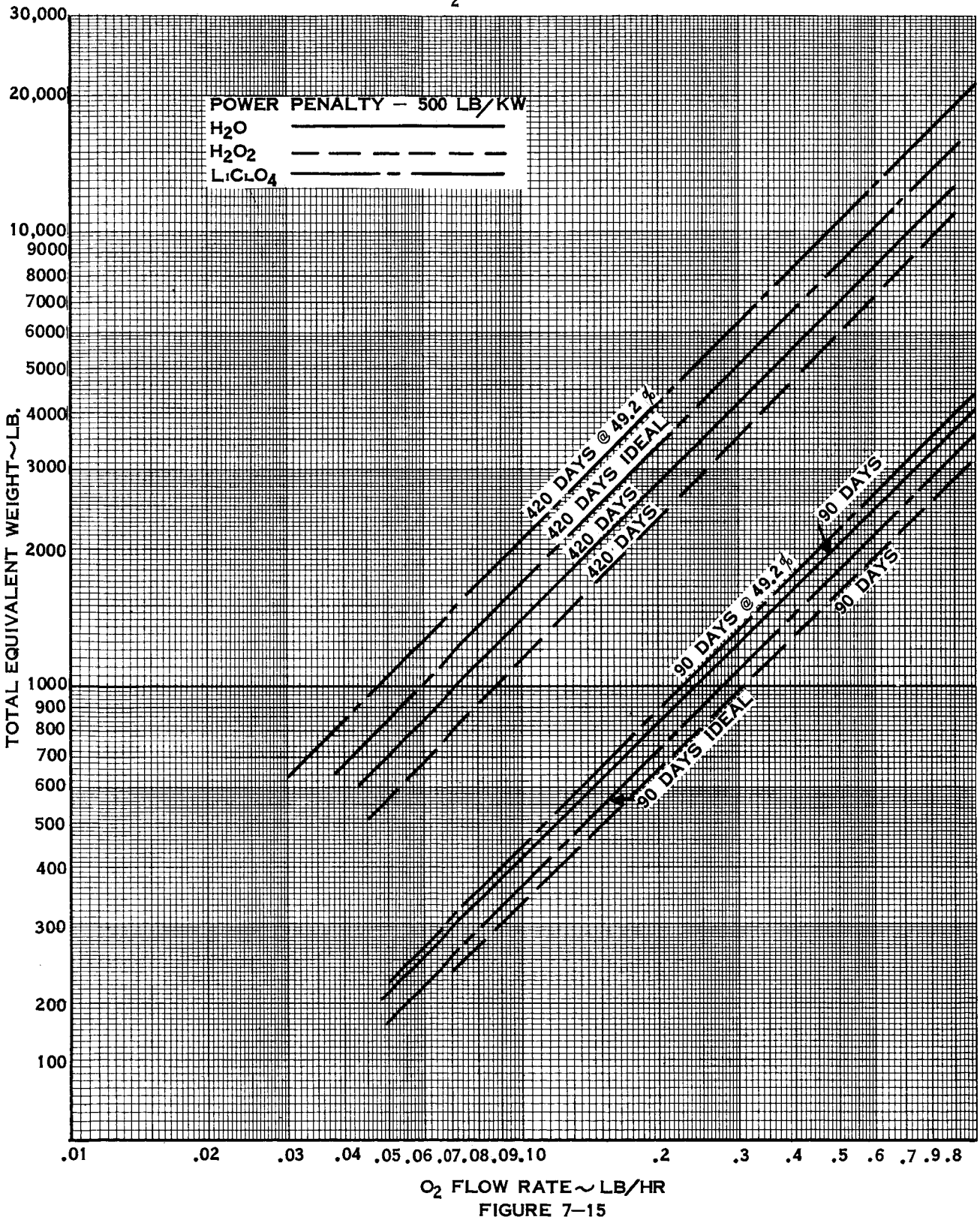


FIGURE 7–15

7.6 Comparative Discussion

The data associated with the supercritical, subcritical, gaseous, and chemical storage systems is presented in the following pages. Certain major assumptions associated with the preparation of the data apply to most of the curves, and are repeated here for better overall understanding of the curves.

1. Cryogenic system tankage will be designed to eliminate venting for pressure control except in those cases where venting results in a weight advantage.

2. The cryogenic oxygen tankage system was considered as consisting of an inner tank of Inconel with an outer shell of aluminum. Insulation design was based on laminations of .008 inch of glass paper and .00023 inch aluminum foil with 55 shields per inch. The conductivity of this insulation is 3.5×10^{-5} BTU per ft. degree Rankin.

3. The cryogenic nitrogen tankage system was designed to the same basic ground rules as that of oxygen except that the inner shell was taken as titanium.

4. To provide a consistent basis for comparison all tankage systems were considered spherical in shape.

5. The configurations considered for each of the systems are those previously discussed and presented in Figures 7-2 and 7-6.

Considering the analysis in this manner, the primary parameters affecting system weight become the fluid payload, the minimum usage rate of the fluid, and the standby time required before any fluid is withdrawn. In cases where a very low minimum use rate exists, use rate is the determining factor of overall system weight. As the minimum use rate increases, the lowest system weight must be determined by a trade-off of weight due to initial ullage and insulation weight for a particular standby time.

Figure 7-16 presents a comparison of gaseous, supercritical and subcritical storage for the oxygen supply for the Mars Mission Module. It can be seen that subcritical storage has a weight advantage throughout the entire range of storage weights considered.

The hydrogen peroxide storage technique which uses a water electrolysis cell, as presented in Figure 7-15, exhibits the same penalty as the subcritical storage method for a 420 day mission time and a power penalty of 500 lb/KW. A final choice between these two methods must ultimately depend on system considerations, such as reliability, good module refill response, and spare part considerations.

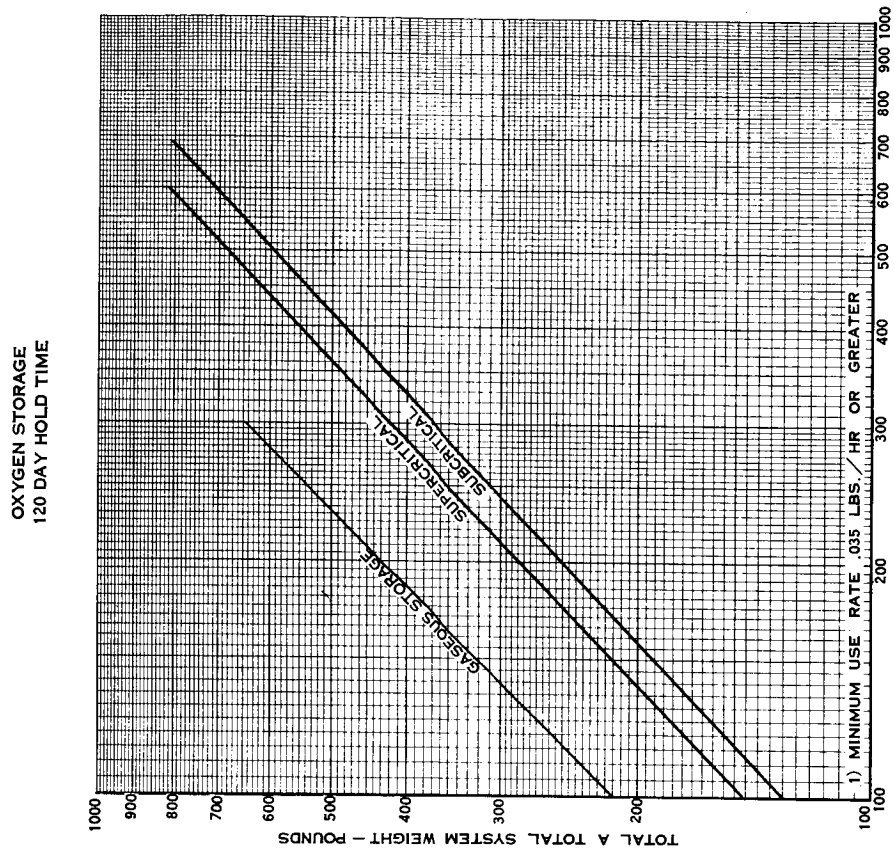


FIGURE 7 – 17

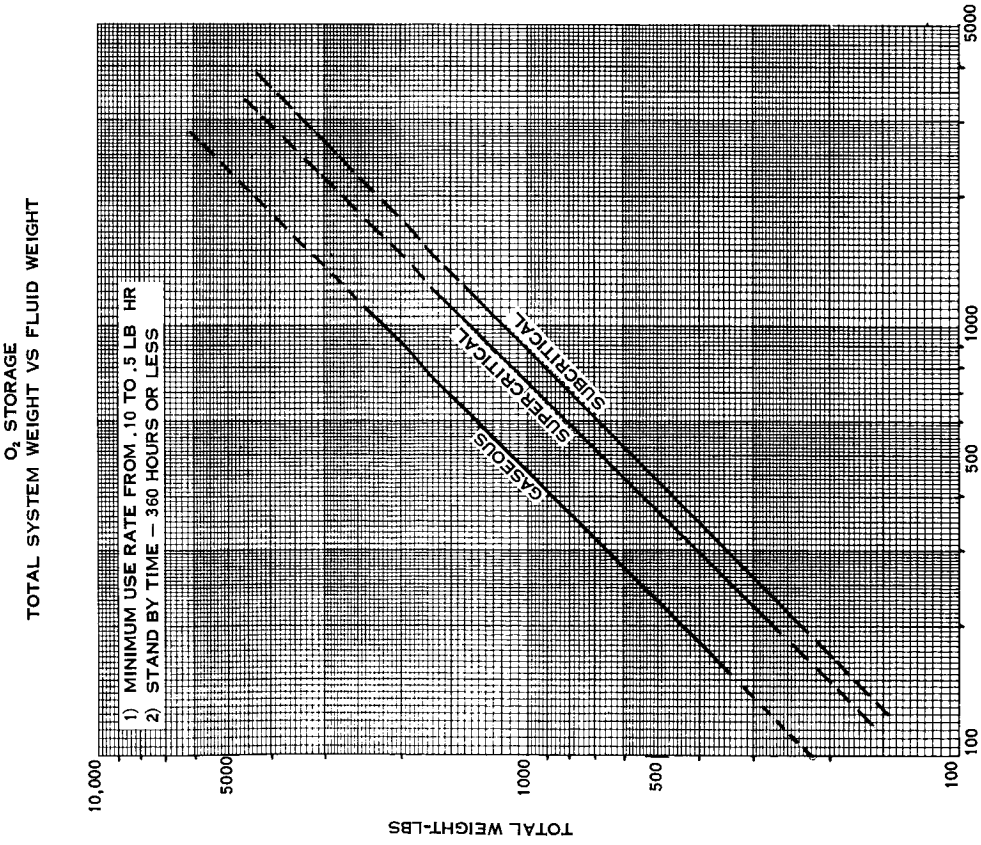


FIGURE 7 – 16

7.6 (Continued)

No clear choice is possible at this subsystem level. Further, differences in power penalty and mission time can drastically effect this trade-off.

Figure 7-17 presents the same comparison for a storage tank for the Mars Excursion Module where there will be a period of 120 days between filling and use. Subcritical storage indicates a weight advantage for this vehicle also.

A comparison of oxygen storage methods for the Earth Re-entry Module is shown in Figure 7-18. In this case, there is a period of 420 days between filling and use. In the range of interest for the ERM the total weight of the system is about the same for either subcritical or supercritical storage and is only 15 to 20 pounds lighter than gaseous storage. Therefore, the added reliability possible with gaseous storage may indicate gaseous rather than supercritical storage.

Figures 7-19 and 7-20 present the weight of supercritical and subcritical storage systems for atmospheric nitrogen as a function of fluid weight and use rate. Figure 7-21 has been drawn from these curves for a minimum use rate of .05 pounds per hour and compared with gaseous storage. It can be seen that again subcritical storage is the preferred method for the Mars Mission Module.

Figures 7-22 and 7-23 present comparisons of nitrogen storage methods for the Mars Excursion Module and Earth Re-entry Module respectively. It can be seen that the subcritical storage is the preferred storage for the MEM, but gaseous storage is clearly indicated for the ERM.

The preceding curves did not include the equivalent weight of power required to maintain pressurization of the cryogenic tanks. Figure 7-24 presents the equivalent weight of power required as a function of use rate and power penalty. Electrical heating has been assumed because the penalty is small and the simplicity may be worth a small weight disadvantage compared to the use of waste heat. The power charged as a weight penalty in this figure includes that required for thermal pressurization and that required to raise the efflux fluid to 70°F. Although the pressurization heating requirement is somewhat less for nitrogen than oxygen, the total power to bring both fluids to 70°F is essentially the same. Therefore, one curve has been provided for both oxygen and nitrogen.

SUPERCRITICAL N_2 STORAGE
TOTAL SYSTEM WEIGHT VS FLUID WEIGHT

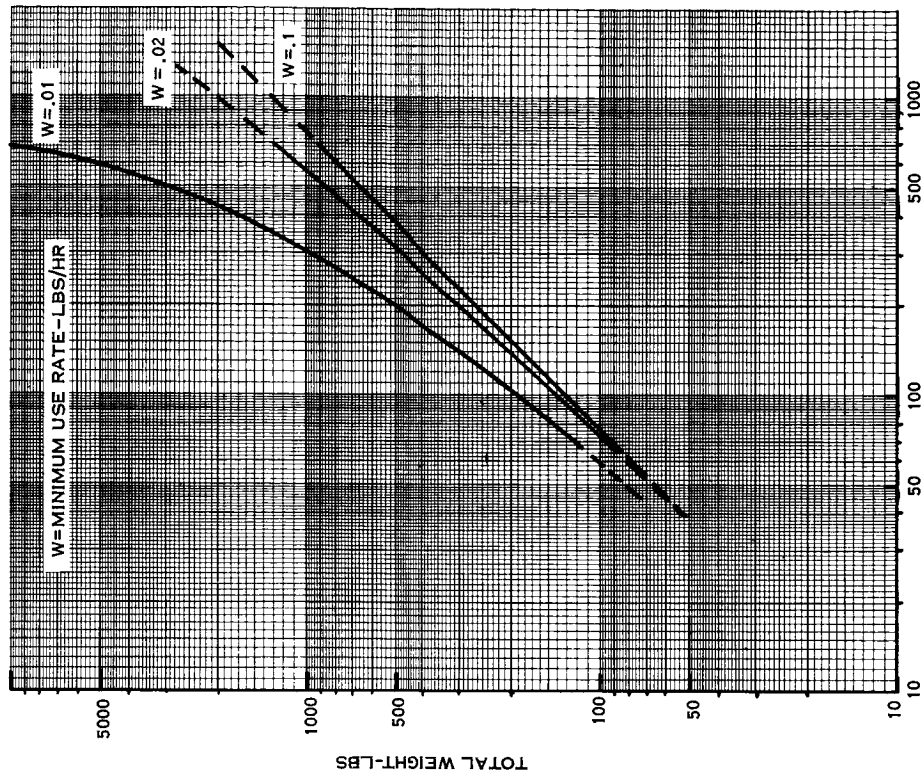


FIGURE 7 — 19

OXYGEN STORAGE
TOTAL SYSTEM WEIGHT VS USEFUL OXYGEN WEIGHT
420 DAY HOLD TIME

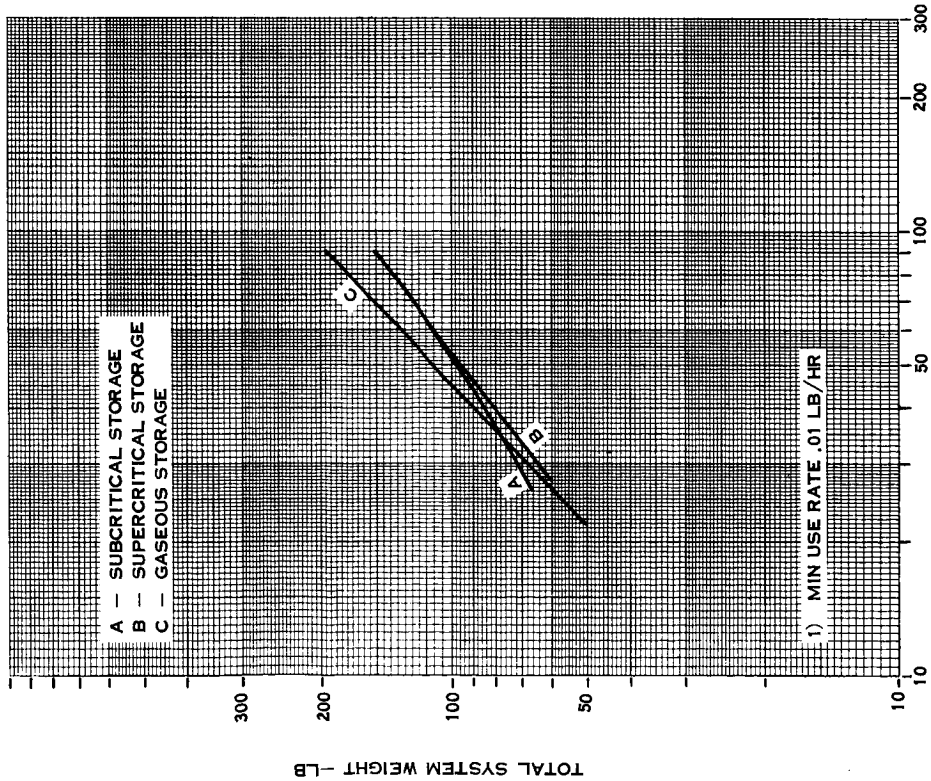
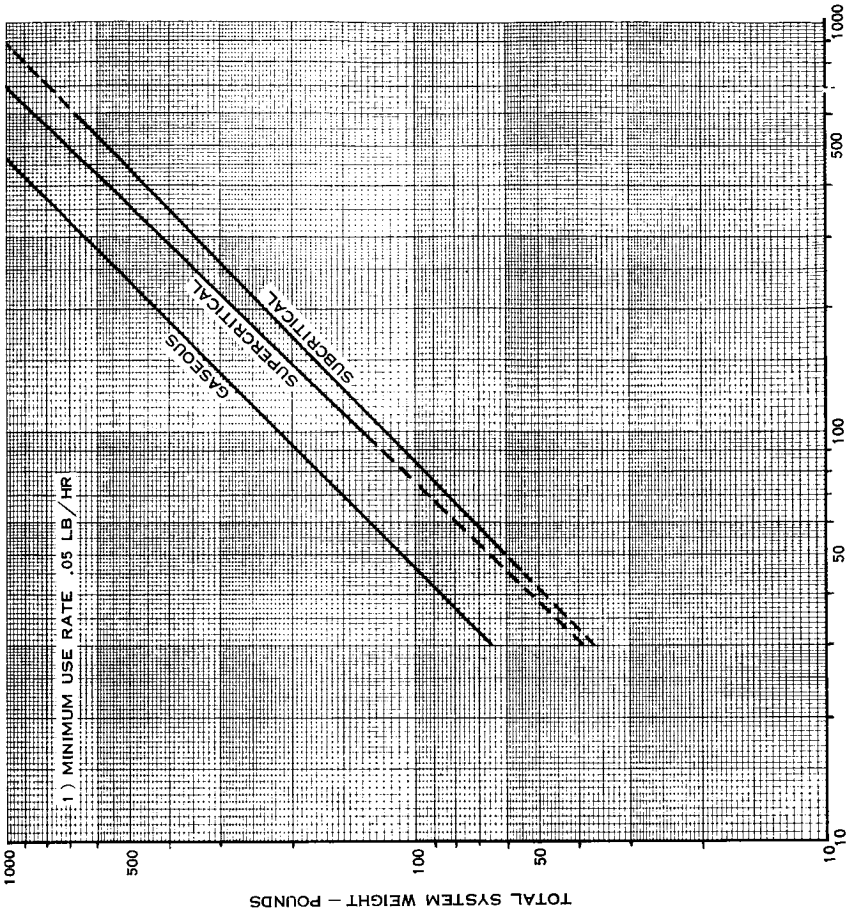
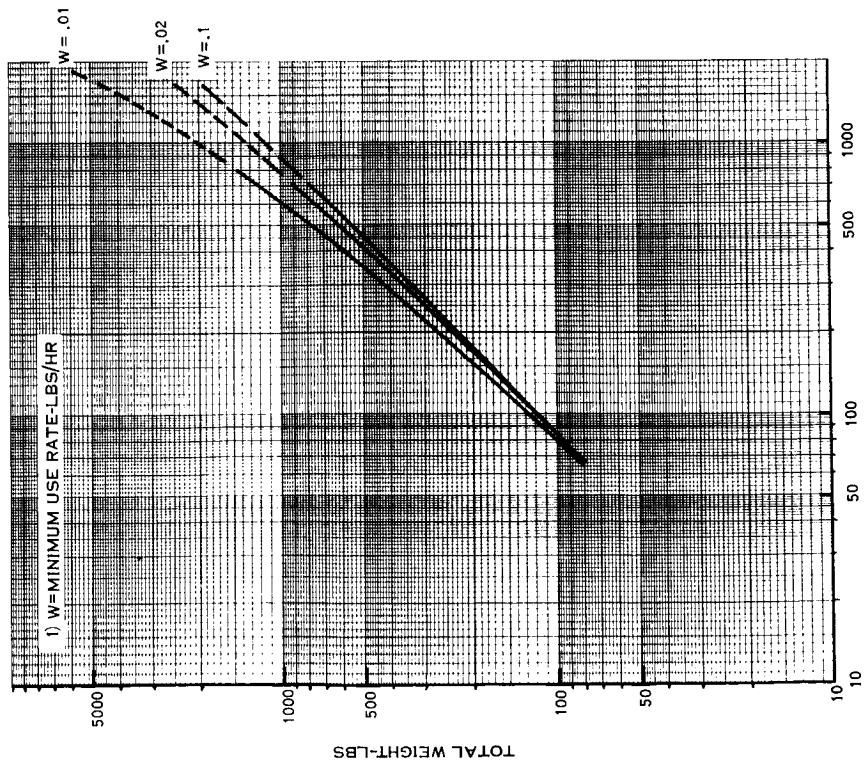


FIGURE 7 — 18



N_2 STORAGE
TOTAL SYSTEM WEIGHT
VS
USEFUL FLUID WEIGHT

FIGURE 7 – 21



SUBCRITICAL N_2 STORAGE
TOTAL SYSTEM WEIGHT VS FLUID WEIGHT

FIGURE 7 – 20

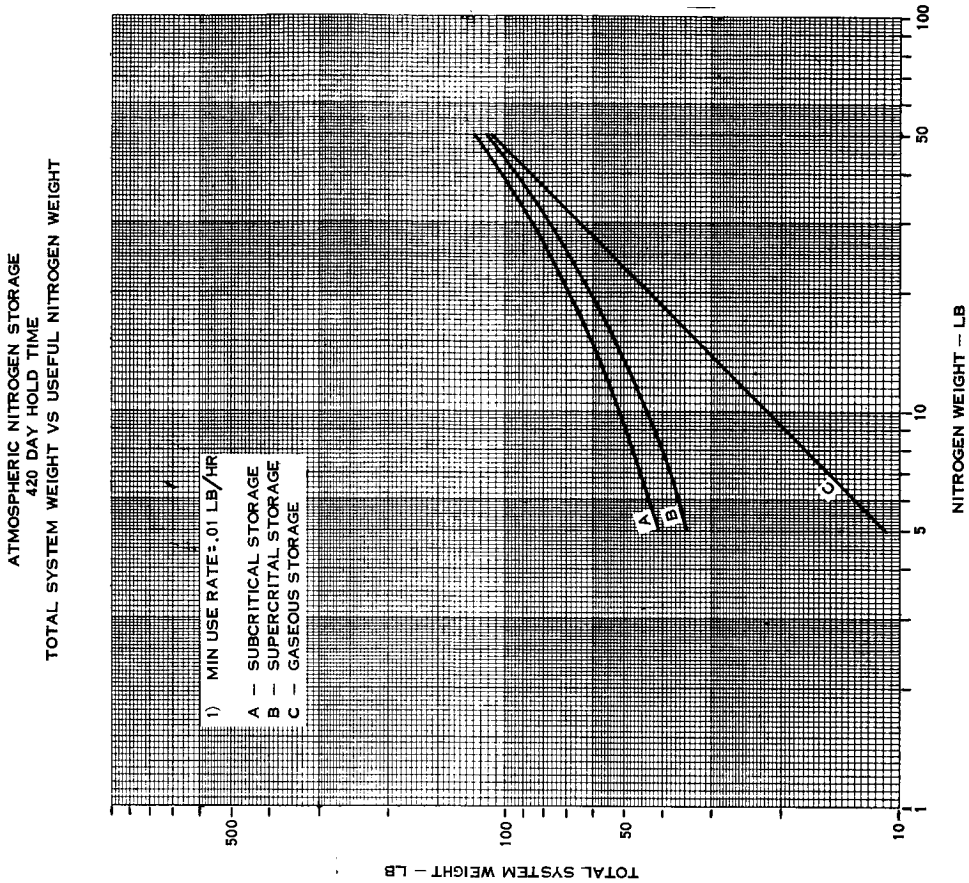


FIGURE 7 – 23

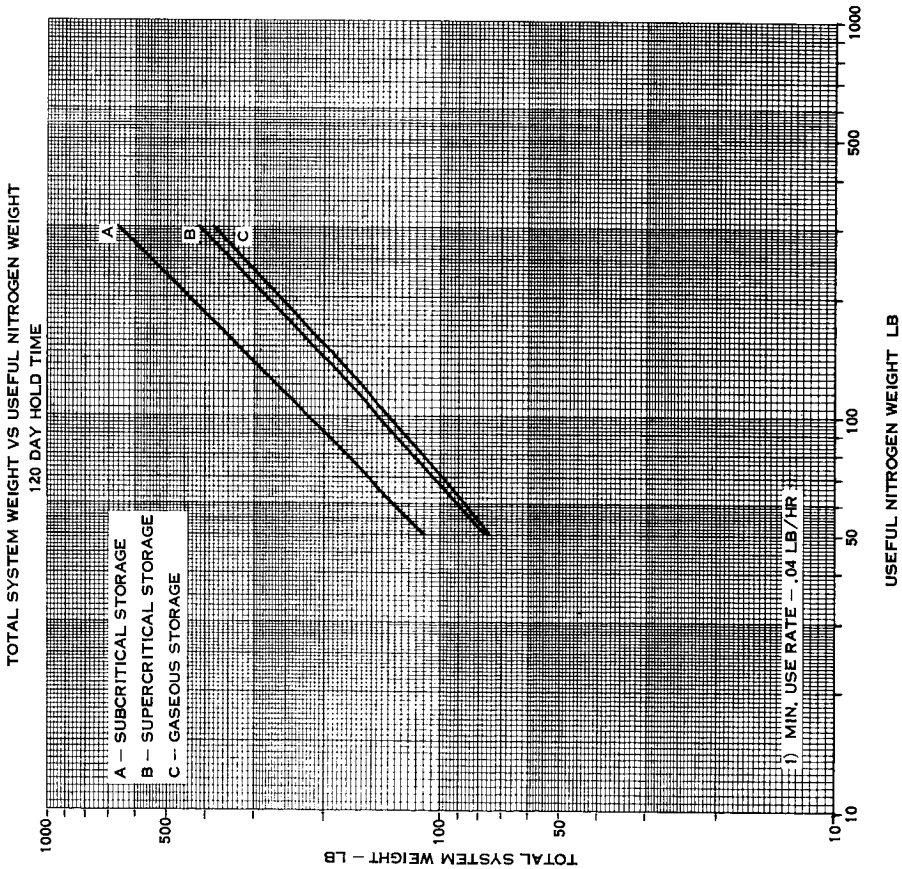


FIGURE 7 – 22

7.7 References

1. Oxygen Chart, Enthalpy Vs. Pressure, by Institute International Du Froid Laboratoire Kamerlingh Onnes, Leyde 1 December 1942.

2. "Preliminary Data" on the properties of oxygen at low temperatures received through private communication with J. G. Hust of NBS on August 17, 1964.

3. "Interim Thermodynamic Properties for Gaseous and Liquid Oxygen at Temperatures from 55 to 300°K and Pressures to 300 Atm." by R. B. Stewart, J. G. Hust and R. P. McCarty, NBS 7922. Received through private communication with the authors.

4. "The Thermodynamic Properties of Nitrogen from 114 to 540°R Between 1.0 and 3000 psia" by T. A. Strobridge, NBS Technical Note 129A.

5. "Analytical Methods for Space Vehicle Atmospheric Control Processes," prepared by AiRésearch Manufacturing Co. ASD-TR-61-162.

6. "Positive Expulsion of Cryogenic Liquids," Beech Eng. Report No. 14180.

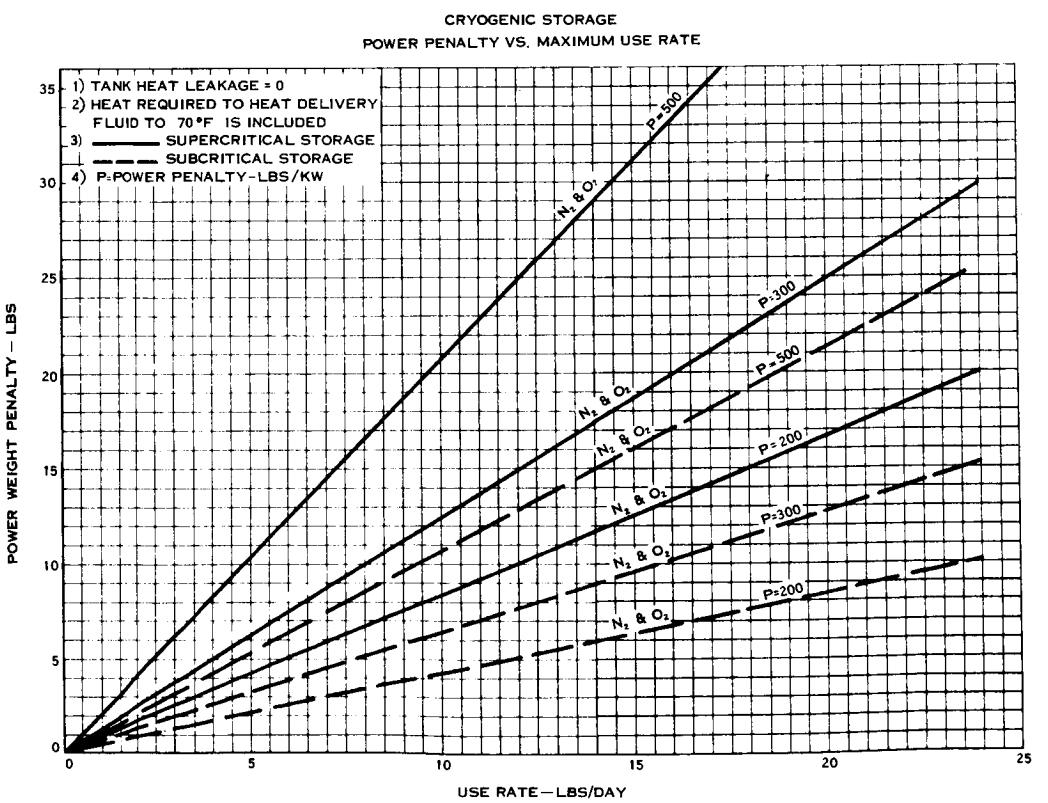


FIGURE 7 – 24

SECTION 8.0

WATER RECLAMATION

8.0 WATER MANAGEMENT

8.1 General

During the Mars mission the crew will require water for drinking, food preparation and bathing. Since the journey to and from Mars will last for 420 days, it will be necessary to recover and reuse the available water supply repeatedly.

The water requirements utilized in this study are presented below. These values as shown are based on assumed realistic values within the range of specified water requirements presented in Section 3.0 of Volume 1.

	M. E. M.	M. E. M. and E. R. M.	Extra-Vehicular
Intake (lb/man-day)			
Food and drink	6.17	7.94	20.10
Water of Oxidation	.77	.77	.77
Output (lb/man-day)			
Urine (Water Content)	3.31	3.34	2.64
Respiration	2.86	4.60	5.29
Perspiration	.44	.44	12.61
Fecal Water	.33	.33	.33

Examination of the water requirements reveals that with highly efficient water recovery the metabolic needs can be satisfied without the use of fecal water. For this reason, water recovered from feces will not be used for drinking, but will instead be used to produce oxygen by electrolysis if required.

8.1.1 Objectives

The analysis of water reclamation considered each source of contaminated water separately rather than investigating one piece of equipment to handle contaminated water from all sources. Urine, wash water, and humidity water were treated as separate sources. The initial analysis was for urine reclamation since this presents the most difficult contaminant removal problem. The contaminants in

8.1.1 (Continued)

urine are more severe in their effect on subsystem operation than those in either wash water or the water recovered from the atmospheric control system. This section discusses the result of the analysis.

The primary objective of the initial analysis was selection of candidate system approaches for urine reclamation. To accomplish this in an optimum fashion with each system penalized equally, certain basic assumptions were made. The primary assumption was that each system should basically stand alone without assistance from potential integration parameters from the rest of the life support equipment. For some approaches investigated, this was not completely feasible, however, consideration was given to this in the final comparative discussions.

The primary reason for reclaiming water from the three sources above is to satisfy the metabolic requirements, and consequently the subsystems will be evaluated mainly on this basis. However, it can be seen that complete water recovery will provide an excess beyond the metabolic needs, and this may be useful for additional purposes depending on other subsystems. The most obvious use of excess water is to provide a source of oxygen by means of electrolysis. There will always be some cabin leakage, and on a long mission this can amount to substantial weights of oxygen required. If the system power penalty is low enough to make electrolysis of water more attractive than storage of oxygen, then any excess water can lead to a weight saving for the atmospheric supply system.

However, the production of excess water will not be a major factor in the comparison of these water reclamation systems, since it is primarily of interest during system integration.

A second item of importance in the discussion is that of reliability and maintainability considerations. The main purpose of the analysis to-date is presentation of system sizing parameters for each approach considered and selection of candidate approaches worthy of further studies. Thus, weight penalties with time do not include penalties attributable to spares or maintenance requirements. It was felt that, in general, this is a low penalty for all candidate systems and would be handled qualitatively. With this in mind, a system with inherently poor reliability which would seem to require excessive spares or maintenance is penalized qualitatively at this time.

8.1.2 Discussion of Data Presentation

The primary data required for full utilization of the results are weight, power, and expendable requirements over the range of interest. However, to more clearly

8.1.2 (Continued)

define the system, additional cross plots have been prepared to illustrate overall penalties on a cumulative basis.

In addition to this data, a basic system schematic is illustrated for each approach. These schematics must be tempered by the comments on reliability and individual operation since the effects of system integration and reliability may alter the system. However, for basic discussion purposes, the schematics are complete.

It should be pointed out here that where a penalty for expendables is included, this penalty is the weight of the expendables alone and does not include any packaging associated with initial storage. This philosophy has been taken to allow more universal usage of the data at a later date when storage methods are selected for the overall system. Not including those penalties at this time allows simpler utilization of the data in the system integration phase. A second point to be considered is the fact that system integration is not considered in this phase of the study. Although system integration may benefit some of these system approaches by providing waste heat (thus reducing electrical power requirements), consideration of the overall system may also penalize some of the water reclamation approaches due to the temperature levels associated with the system. For example, a system which utilizes waste heat from the main thermal control system does so at a decrease in power but at an increase in radiator weight penalty due to the lower inlet temperature available to the radiator. It was felt that these factors should be considered in the final integration phase rather than during the initial subsystem studies.

8.2 Urine Reclamation by Electrodialysis

8.2.1 Introduction and Data Source

The analysis of electrodialysis urine reclamation systems was based on information provided by Ionics Inc. in Cambridge, Mass. This data presented in reports from Ionics to Hamilton Standard as well as previous contract reports allowed consideration of this approach in sufficient detail for this study.

This approach to urine reclamation has received considerable interest throughout the industry due to its apparent simplicity, low weight, and power requirements. Ionics has extended their experience in commercial brackish water purification into the urine reclamation field thus offering a system with considerable previous experience in general terms although somewhat limited in specific application. Some work is being pursued on this approach by others in the industry, however, the Ionics data was considered sufficient and completely typical for this approach and has been used as the primary input.

8.2.2 System Description

Figure 8-1 presents the basic schematic for the electrodialysis process. The primary component of the electrodialysis system is the stack itself. This electrodialysis stack consists of alternate pairs of anion and cation permeable membranes with a potential difference maintained across the membranes with electrodes. This allows removal of electrolytes from the circulating solution thus purifying the water. Non-electrolytes cannot be removed by the membrane stack and must be removed prior to or subsequent to processing by the membranes.

This means that the only major contaminant that will be removed from urine by the electrodialysis stack is sodium chloride. Since urea, which is a non-electrolyte, is the main contaminant present in urine, the process must include some alternate means of removing urea. In the proposed system, the urea is removed prior to the membrane stack by charcoal filtration after having been treated with a complexing agent. A suitable complexing agent, which precipitates the urea and allows it to be filtered out by the charcoal, has been developed by Ionics Inc.

ELECTRODIALYSIS H_2O RECLAMATION

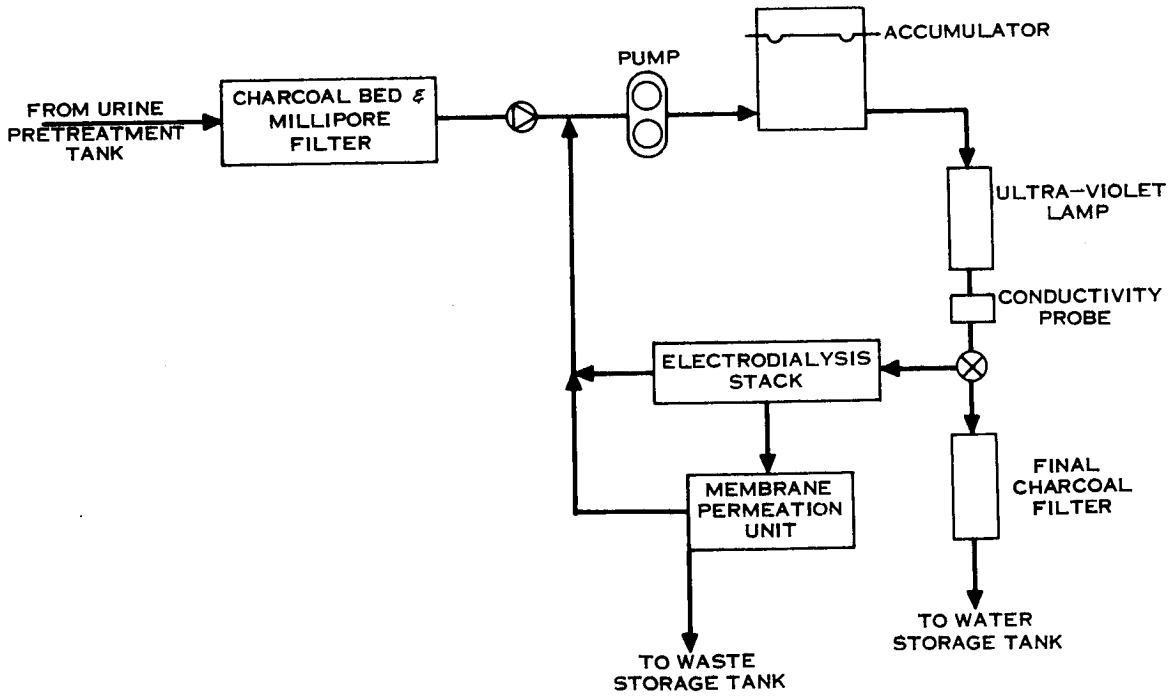


FIGURE 8-1

8.2.2 (Continued)

After filtration the treated urine is passed to the electrodialysis stack where the ions are evenly distributed at the inlet. However, upon coming in contact with the potential difference across the membranes, separation does initiate. The positively charged ions pass through the cation permeable membranes under the influence of the applied potential but are unable to pass the anion permeable membranes. A similar action is imposed on the negatively charged ions by the anion permeable membranes thus removing both types of ions from the main process stream. By alternating cells throughout the electrodialysis stack and passing the process water through every other cell, purification can be achieved. The alternate cells which pass the water become depleted of ions with the other cells becoming more concentrated by the removed ions. The process is continually repeated and the process water recycled until the required degree of desalination is achieved. The concentrate stream contains a certain quantity of endosmotic water that has dissolved in it all the salts and represents a fraction of the original water that canot be recovered by this process. After completion of desalination in the electrodialysis cell, the processed water is final treated by charcoal filtration and irradiation with ultraviolet light prior to storage or final usage. Some problems may exist in the basic electrodialysis stack in separating trace quantities of oxygen and hydrogen which appear at the electrodes. Basically the process is quite adaptable to zero gravity operation if these trace gases produced can be minimized or suitably removed. This remains as a design and development problem, which must be solved prior to utilization of this approach, however it is not considered a major problem since it is primarily a gas-liquid separation problem which has received considerable attention for other applications.

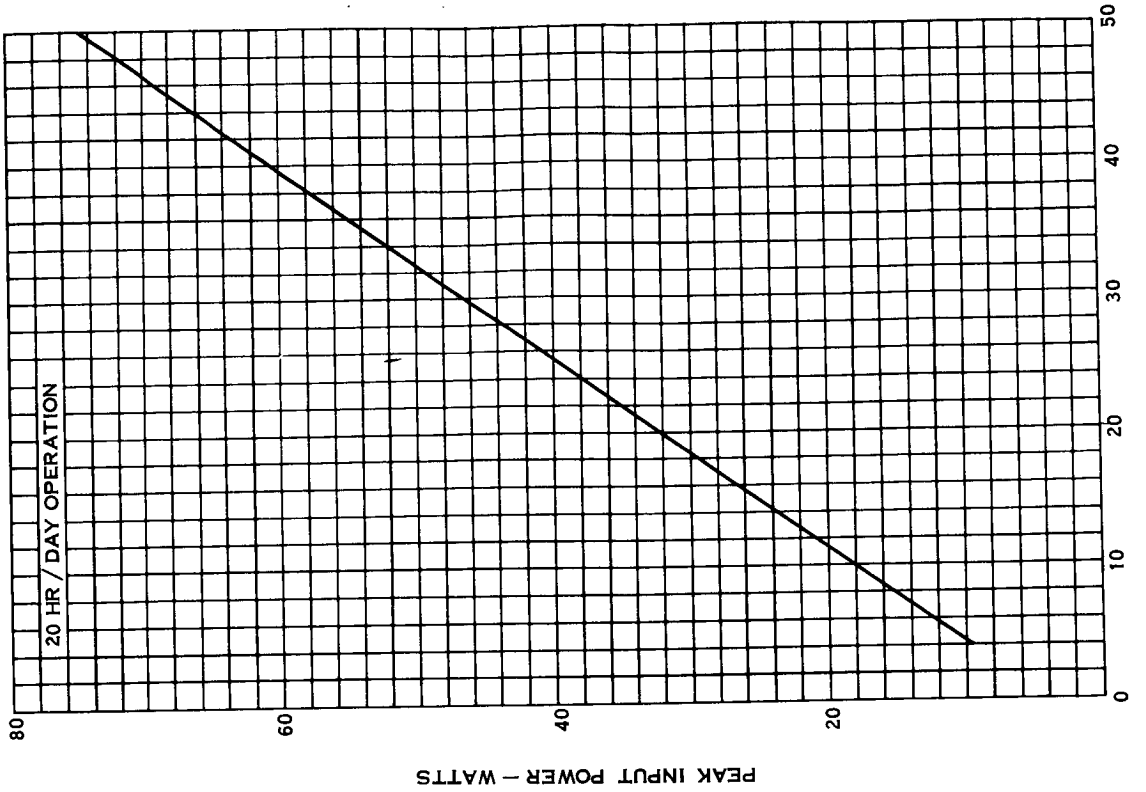
In the electrodialysis process some water, called endosmotic water, is transferred into the concentrate stream along with the ions. This limits the amount of water that can be recovered from urine by the electrodialysis stack to 95%. In an effort to increase the yield still further, Ionics Inc. has proposed the addition of a membrane permeation unit. This will extract water from the concentrate stream and raise the overall system recovery to 96.8%.

The membrane permeation unit extracts water from the concentrate stream by distilling water through a perm-selective membrane that will pass water vapor but not salt ions. While this additional unit increases the yield it also increases the system complexity.

8.2.3 Results

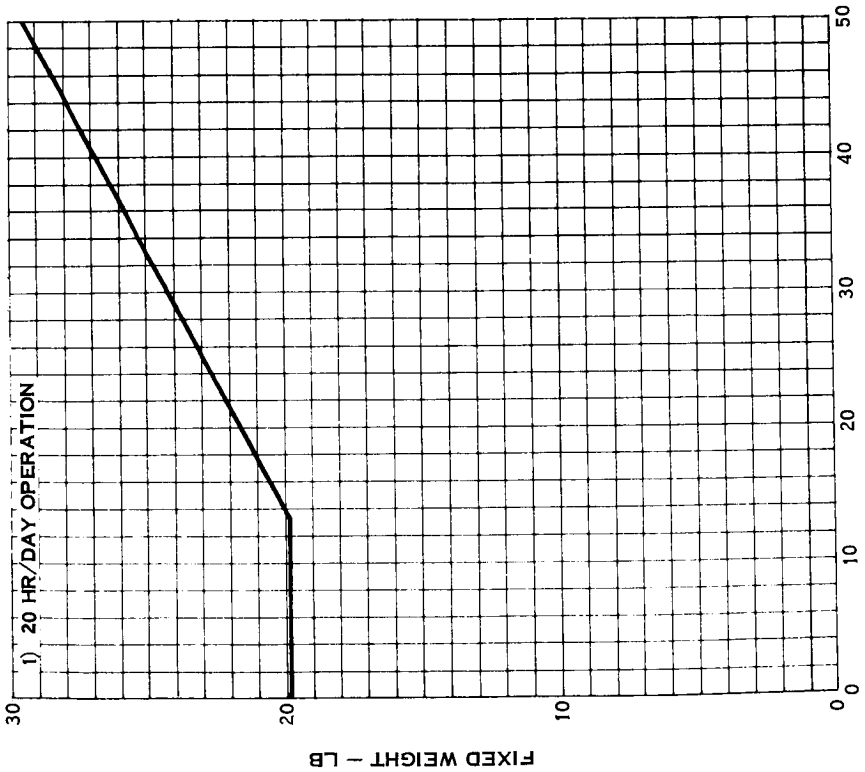
Figure 8-2 presents the results of the analysis of system fixed weight variation with changes in urine process rate. The process rate is shown over a range of 0 to 50 lbs. per day which covers a design point range up to 14 men.

ELECTRODIALYSIS URINE RECLAMATION
PEAK INPUT POWER VS. URINE PROCESS RATE



URINE PROCESS RATE–LB / DAY
FIGURE 8-3

ELECTRODIALYSIS URINE RECLAMATION
FIXED WEIGHT VS. URINE PROCESS RATE



URINE PROCESS RATE – LBS/DAY
FIGURE 8–2

8.2.3 (Continued)

From this curve, the basic weight of the system may be determined. The curve is flat over the low range since a limiting value of stack size is reached. The storage tanks required for the raw urine and the potable water on the outlet have not been included in the weight consideration since the effect of these is relatively equal for all system approaches and need not increase the complexity of the data presentation. Figure 8-3 presents the system power requirements as a function of urine process rate to allow sizing of the overall system. It can be noted from each of these figures that initial fixed weight and initial power requirements for the system are quite low thus making it an attractive approach.

Figure 8-4 illustrates the equivalent weight of the system as a function of the urine process weight for a 420 day mission. The primary penalty associated with the system is the high amount of pre-treatment charcoal required per lb. of urine processed. This use rate (.242 lbs. per man day) detracts from the otherwise attractive features of the overall system. Considerable discussion has taken place as to the feasibility of regenerating this charcoal to make it usable continuously thus eliminating a great percentage of this expendable weight requirement. This has not yet been proven, however, and still remains as a problem area to be solved before adequate appraisal of this approach can be made. The regeneration of charcoal that has been saturated with urea cannot be predicted theoretically at this time, although it appears an important area to be evaluated experimentally, if electrodialysis is considered worthy from other aspects.

Figure 8-5 illustrates this point somewhat more clearly by presenting the equivalent launch weight of the electrodialysis system as a function of the mission duration. It can be seen that changing the mission period from 0 to 420 days offers a considerable change in the equivalent weight of the system at launch. Looking at the zero ordinate, it is apparent that the fixed weight and weight of power for electrodialysis are quite low. However, the expendable rate mounts quite rapidly with increase in mission duration if the charcoal is not regenerated.

8.2.4 Conclusions

The electrodialysis process has many problem areas which must be resolved prior to its suitability for manned space vehicle applications. The previously mentioned problem of heavy expendable weights due to charcoal is perhaps the greatest of these problems. However, other problems which have become apparent are those of functional operation of the membrane permeation unit and demonstration of membrane reliability in use with urine over an extended period of time. Ionics has been quite successful with membrane life in brackish water plants, however, the problems

ELECTRODIALYSIS URINE RECLAMATION SYSTEM
EQUIVALENT WEIGHT VS URINE PROCESS RATE
420 DAY MISSION

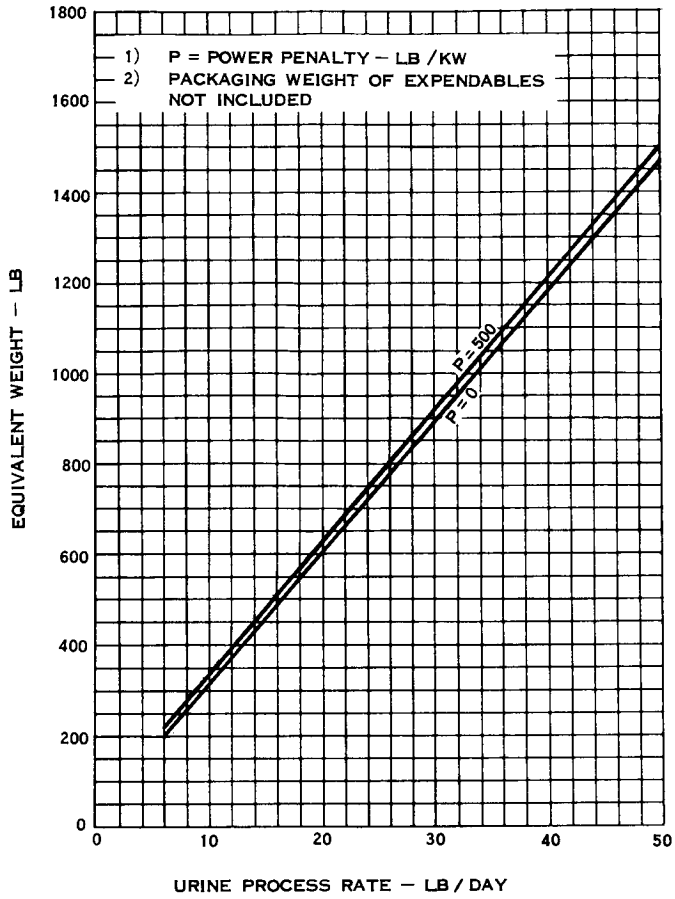


FIGURE 8–4

ELECTRODIALYSIS URINE RECLAMATION
EQUIVALENT WEIGHT VS MISSION TIME

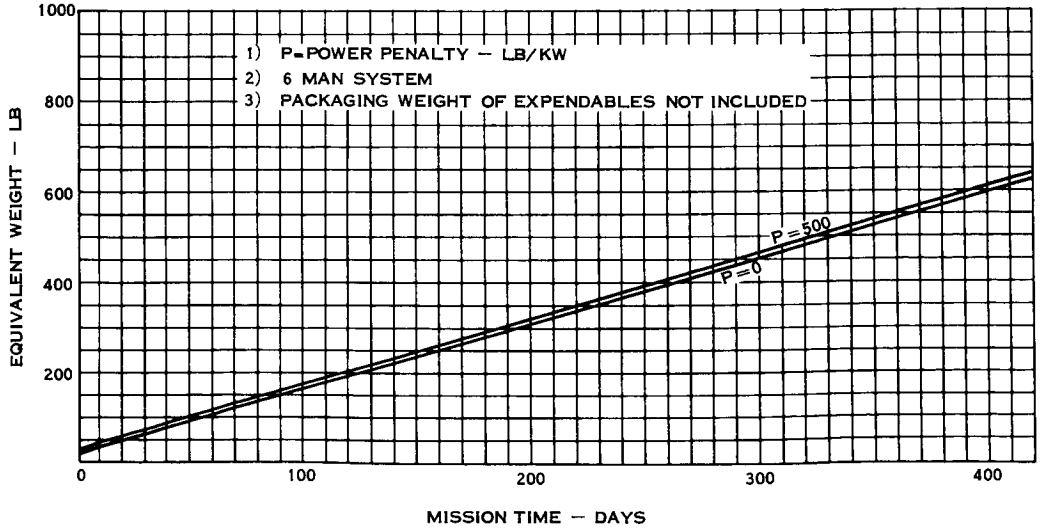


FIGURE 8–5

8.2.4 (Continued)

may be significantly different and can best be proved by extended duration testing. Electric Boat (A Study of Water Reclamation for Space Stations, Contract NAS 1-2208) has indicated that the membrane pore size is so small as to inhibit the passage of large ions. This means that any large ions present in the urine would remain in the effluent stream and could lead to progressive build up of contaminants within the astronaut's system. This area should also be more fully evaluated experimentally prior to system selection. There exists the possibility that in a urine solution, organic membranes may serve as sites for bacterial growth.

If extended testing proves that high purity water is repeatedly attainable, and if the membrane problems can be overcome, then electrodialysis can be considered a very promising approach. Among its advantages are that it requires a minimum of moving parts, low weight, volume, and power requirements, and predictions of long life. The system approach itself is competitive enough to be considered further in the system integration phase and many of these points will be given more attention during this portion of the study.

8.3 Air Evaporation Urine Reclamation

8.3.1 Introduction and Data Source

Urine reclamation by direct evaporation into a circulating air stream is the simplest urine reclamation approach which can be considered. This approach, which has been the subject of considerable Hamilton Standard research work in the past year, has been analyzed somewhat arbitrarily here due to its full dependence on final system integration parameters, however, reasonable estimates of system operation have been made to allow parametric sizing of the system. Main source of data for this analysis has been the Hamilton Standard test work to-date.

8.3.2 System Description

Figure 8-6 presents a schematic of the air evaporation system considered in this analysis. The system presented in this schematic is a closed system (air is constantly re-circulated throughout a closed loop). Air evaporation may also be used in an open system approach where the circulating cabin air is the process media, however, development testing on the problem of odor carry-over into the cabin is required before full evaluation of this method can be completed.

In the closed system operation the circulating air is normal cabin atmosphere at normal cabin pressure so that there is no pressure loading on the system ducting.

8.3.2 (Continued)

AIR EVAPORATION H_2O RECLAMATION

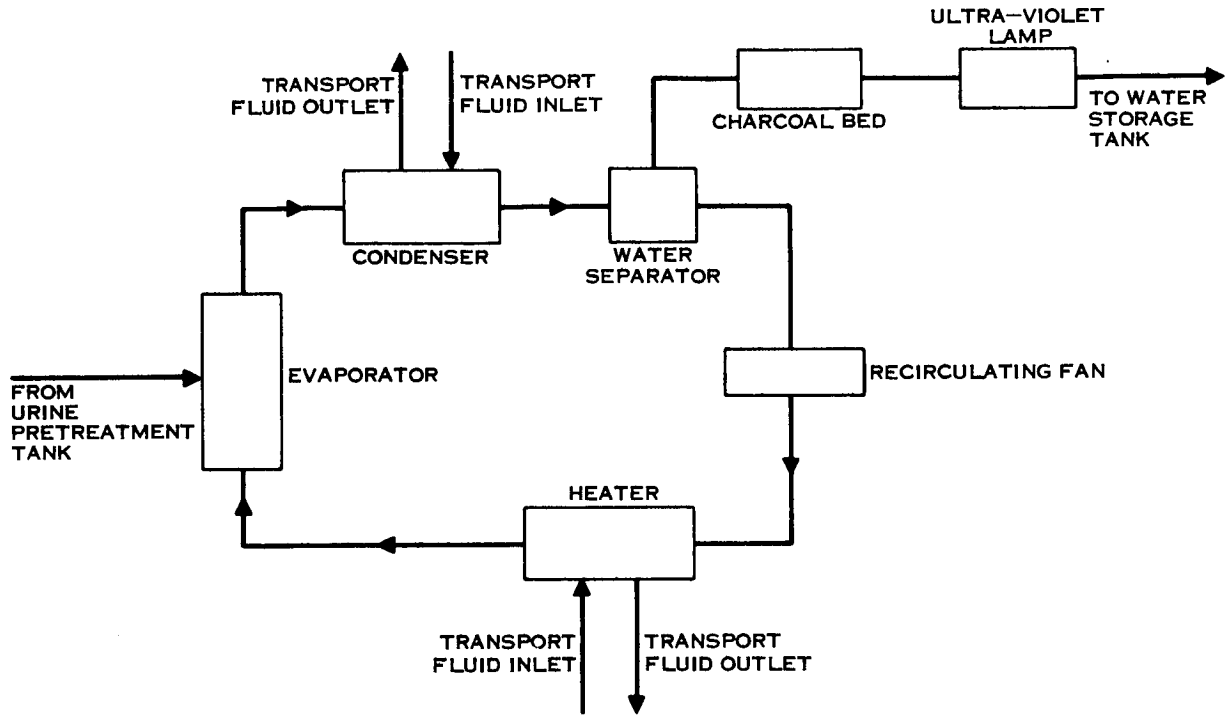


FIGURE 8-6

The system consists of an evaporator, a condenser, a fan, a water separator, and a heater. The process urine is brought into the wick evaporator after a series of pre-treatment and filtration processes and distributed through wicks in the evaporator where the hot air evaporates the water leaving the solids in the wicks. From this point, the vapor is condensed to water droplets similar to the condensation process taking place in the main thermal control system and is then removed by a water separator similar to or identical to (depending upon size requirements) the one in the main system. The cool air then passes through a heater where the heat required for evaporation is returned to the air by a circulating heat transport fluid in the case of a closed system, or by the cabin heat load in the case of an open system. The hot air then re-enters the air evaporator to close the cycle and complete the process. The condensed moisture separated by the water separator is pumped out

8.3.2 (Continued)

of the system to storage or post-treatment depending on its eventual use. One of the virtues of this system is the ability to recover one hundred per cent of the water. This is achieved simply by operating the system till the wicks are dry.

In the pre-treatment process, a chemical is added which serves two purposes. First it disinfects the urine to retard bacterial growth and secondly, it complexes the ammonia ions so that they will not be distilled as free ammonia along with the water vapor. This treatment is important since the urine soaked wicks can only retain contaminants that are non-volatile.

One other element may be applicable in the overall system and that is an odor control device within the circulating air stream. It is desirable to include one in the system to hold down the potential odor generation by the evaporating urine to preclude any immediate problems which could be caused by a leak in the system. The amount of charcoal required for this odor protection is small in comparison to the rest of the expendables and is deemed a good investment.

The primary expendable requirements for an air evaporation system are the wicks in the evaporator, pretreatment chemicals and charcoal filters. Since the solids in the urine remain in the wicks, they must be changed periodically to maintain their capacity and efficiency. This wick replacement problem must be the subject of system development to assure an optimum method of replacement from a weight and ease of maintainability point of view but is considered minor in its affect on overall development status of the system. The evaporators may provide some problem in wick distribution but this is also considered a development problem and is not a severe design drawback.

State-of-the-art equipment exists for all other components and should not require any severe development problems since the primary requirement is adequate sizing of equipment rather than extending its performance requirements or capabilities.

8.3.3 Results

Since the air evaporation system must be integrated with the entire life support system due to dependency upon the circulating coolant loop for heat addition and condensation, it is impossible to make a specific design of a system applicable to all conditions. As system heat loads, flows, and temperature change, the optimum weight and power of the air evaporation system will change. Since the purpose of this phase was determination of parametric data to allow rapid calculation of system weight and power at the later phase, this system was studied to provide

8.3.3 (Continued)

design data requirements initially, and then an estimate of final system heat loads, flows, and temperatures was made to provide comparative data on this approach.

Since the heat of evaporation and the sensible heat of the air are equal in the evaporator, and if the air leaving the evaporator is assumed saturated, basic design data may be generated to allow sizing of the system at a later date. Figure 8-7, 8-8 and 8-9 were prepared for evaporator performance from these assumptions. These figures illustrate the amount of moisture that can be picked up by a pound of air with the entering hot air temperature and the entering saturation temperature specified on the graphs. For flexibility, the figures were prepared at the design pressure and the extremes of the operating pressure range. By using these curves, the required air weight flow to process urine at any rate can be quickly determined.

The next area of interest in sizing is that of the heat exchanger weight requirements. If one assumes that the fin geometry and air side pressure drop are fixed, the heat exchanger weight is then proportional to UA. Picking a transport fluid for illustration purposes (in this case, glycol) and setting a pressure drop and fin geometry, calculations were made indicating that core weight is approximately equal to 1.4 x UA. Figure 8-10 presents the core weight per unit air mass flow vs. the mass flow ratio and heat exchanger effectiveness, thus allowing approximation of heat exchanger core weight. This can be used for both condenser and heat exchanger weight calculations; however, the ΔP should be doubled to account for the increase in pressure drop due to condensation in the condenser. Although this offers a conservative design, it is adequate for initial sizing purposes. The fins selected and the ΔP of the core are considered to be within the range of interest for this application.

The evaporator weight varies with the inlet temperature and humidity as well as with the number of men. No presentation of evaporator weight variation has been made; however, it will be a relatively light component and should have a small effect on overall system weight.

Figure 8-11 allows determination of system input power requirements. This figure presents the power requirements as a function of total system airflow and the air pressure drop throughout the system in inches of water. Three specific pressure drops are illustrated in this figure to allow comparison of power requirements over the range of interest. Thus, this figure and the preceding figures permit initial system sizing once final life support system temperature limits are established.

To allow an evaluation of this approach with other candidate water reclamation approaches, it became necessary to attempt reasonable assumptions of final system temperature levels to provide an early indication of the air evaporation weight and power requirements in the final configuration. The selected system input parameters

AIR EVAPORATION URINE RECLAMATION
AIR MOISTURE CAPACITY IN EVAPORATOR
PRESSURE = 3.5 PSIA

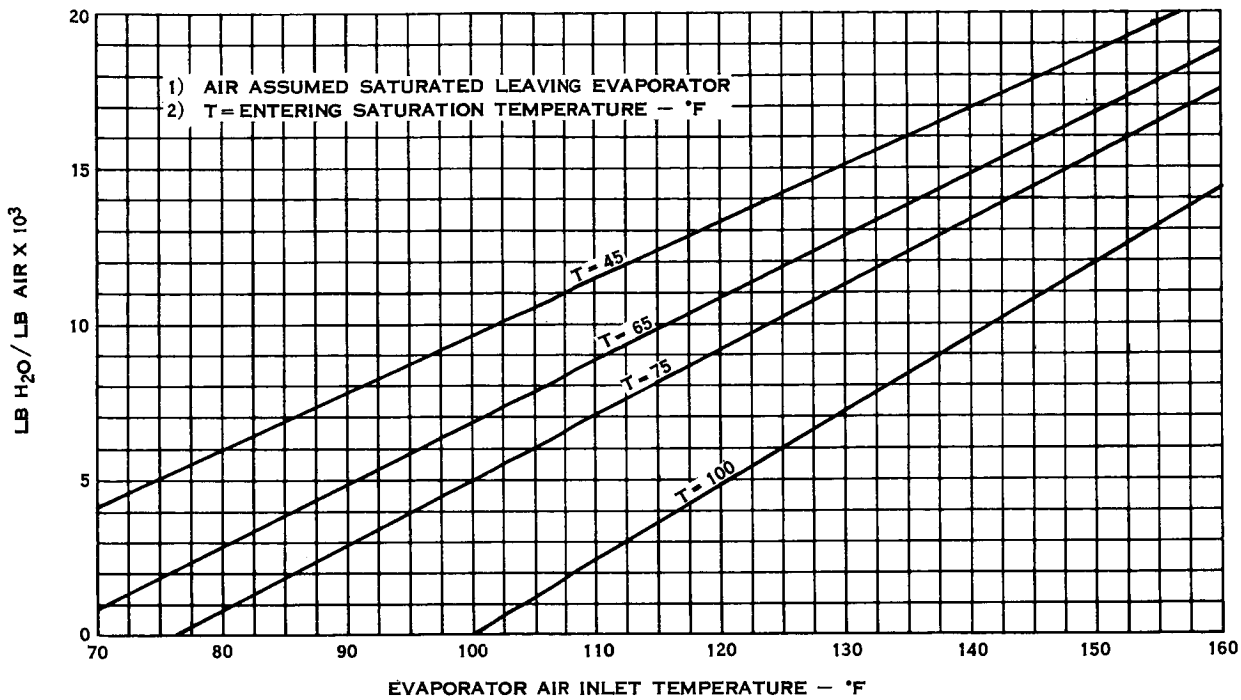


FIGURE 8—7

AIR EVAPORATION URINE RECLAMATION
AIR MOISTURE CAPACITY IN EVAPORATOR
PRESSURE = 7.0 PSIA

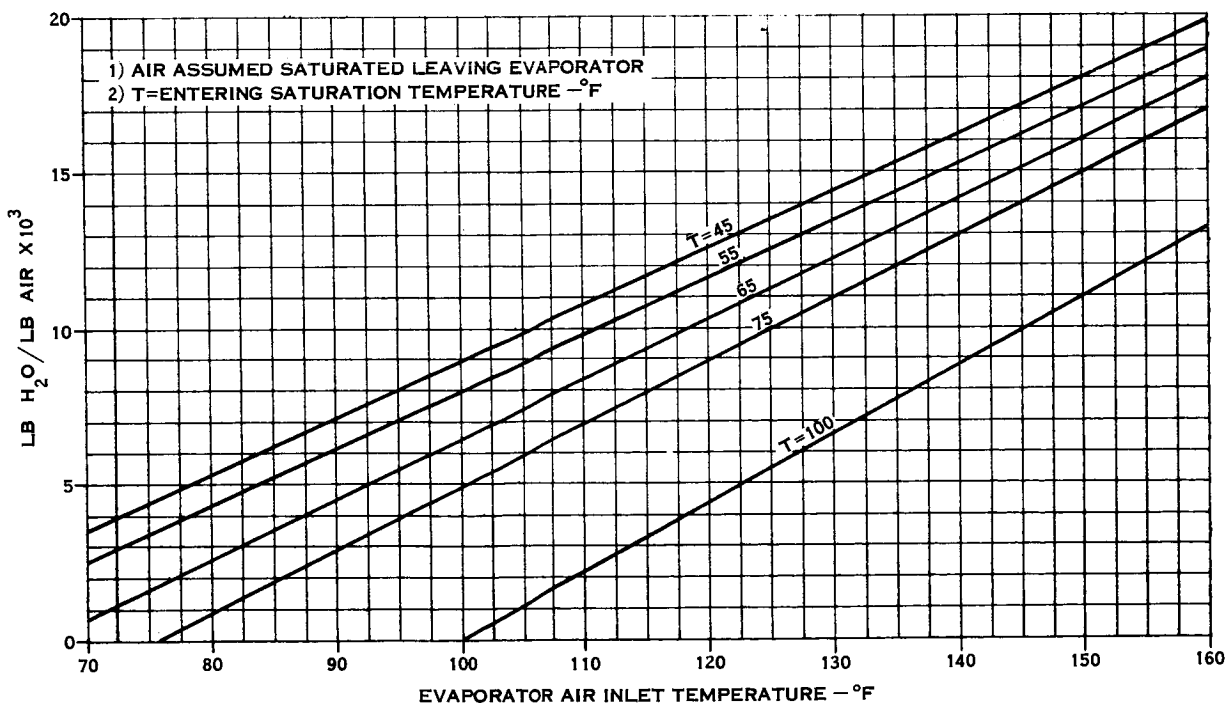


FIGURE 8—8

AIR EVAPORATION URINE RECLAMATION
AIR MOISTURE CAPACITY IN EVAPORATOR
PRESSURE=14.7 PSIA

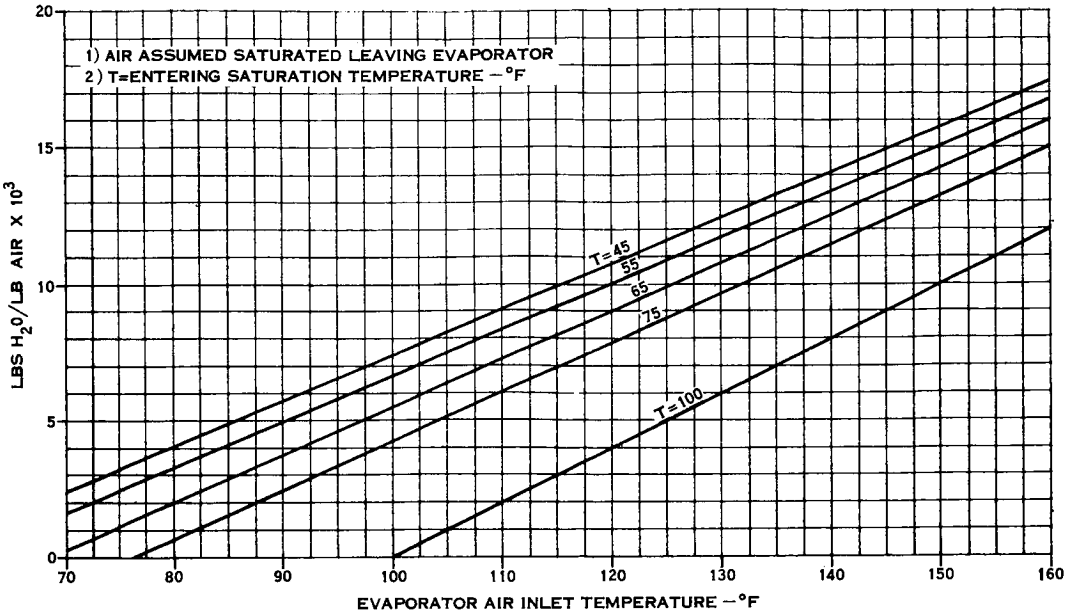


FIGURE 8–9

AIR EVAPORATION WATER RECLAMATION
HEAT EXCHANGER CORE SIZE REQUIREMENTS

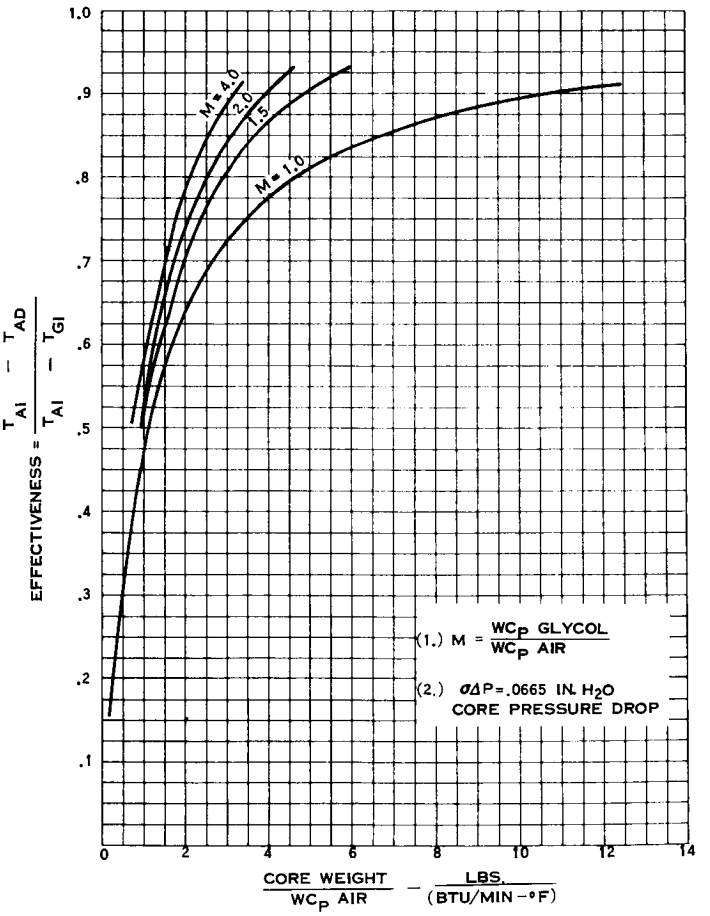


FIGURE 8 – 10

AIR EVAPORATION URINE RECLAMATION
FAN POWER REQUIREMENTS

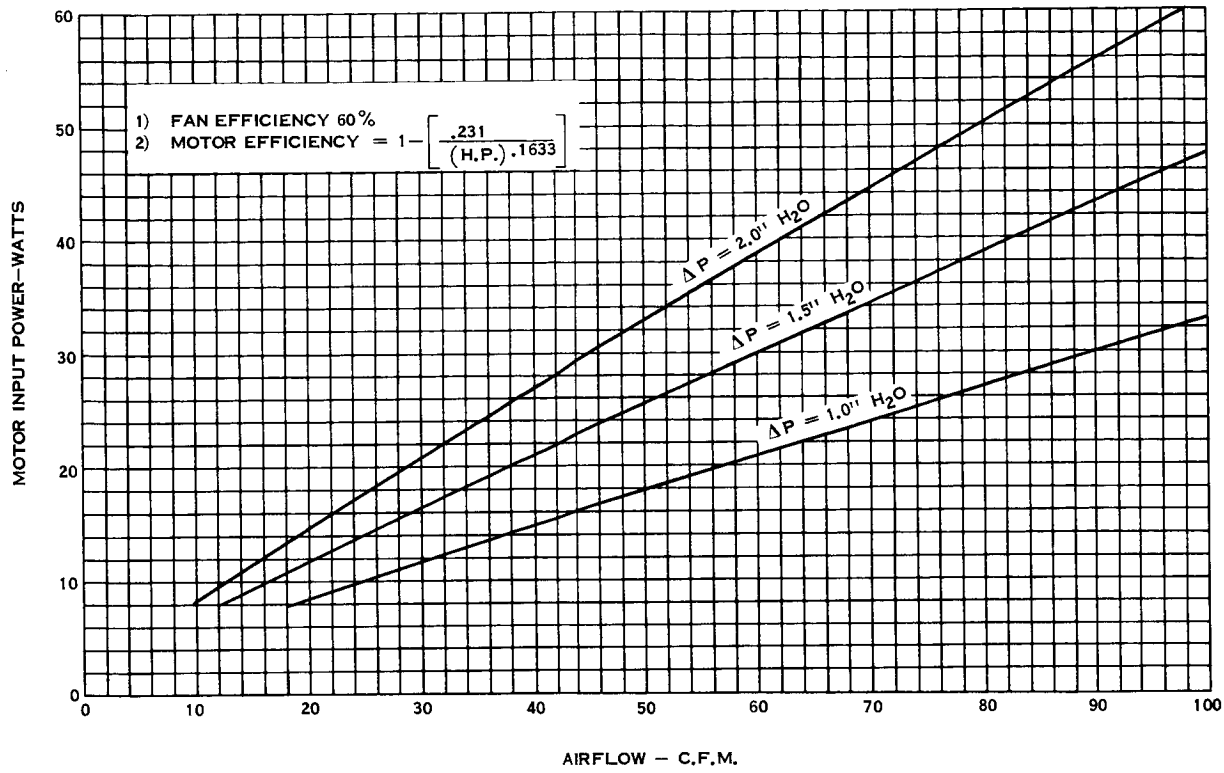


FIGURE 8–11

AIR EVAPORATION URINE RECLAMATION
FIXED WEIGHT VS URINE PROCESS RATE

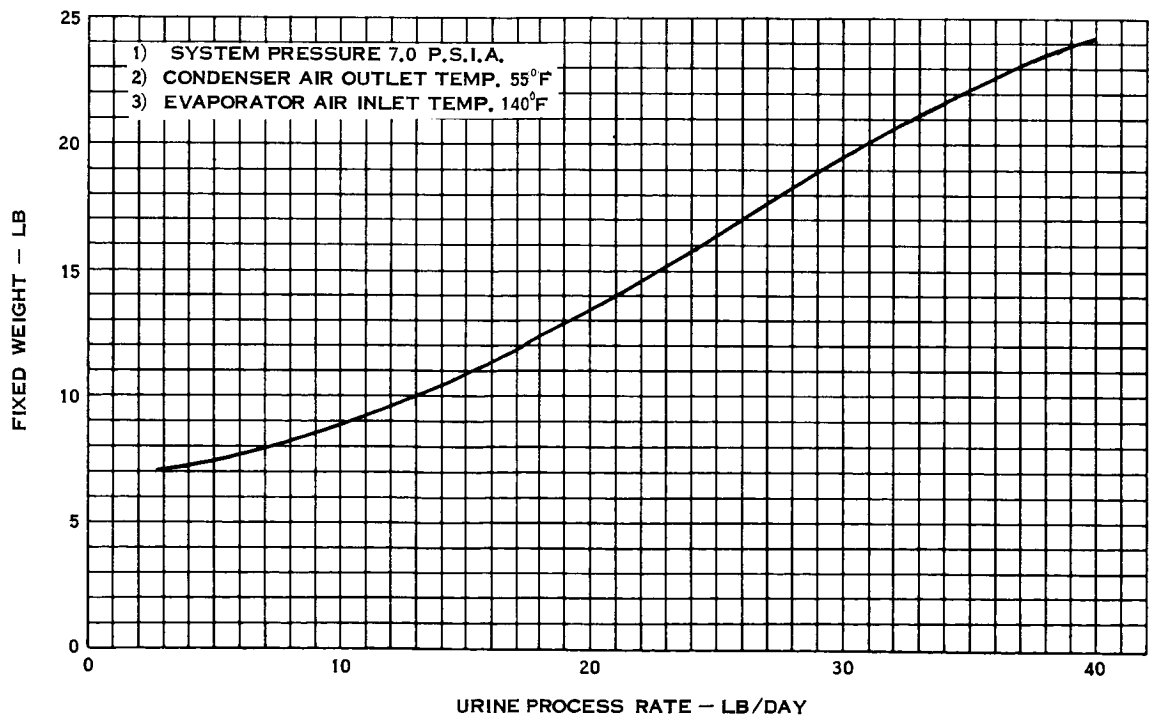


FIGURE 8–12

8.3.3 (Continued)

are within the final range of interest, thus allowing an accurate preliminary comparison of this system's applicability and its candidacy for further study. For this analysis the system was assumed to operate at 7.0 psia as specified for the Mars Mission vehicles. The circulating air dry bulb temperature at the evaporator inlet was 140°F, and the dew point at the condenser outlet was 55°F. The total system pressure loss was set at 2.0" H_2O and the system power consumption was the associated fan power plus 5 watts for an ultraviolet lamp.

Figure 8-12 illustrates the estimated fixed weight evaluation as a function of the urine process rate. This curve has a leveling off point at the lower system sizes due to the fact that component weights reach a minimum practical value below which a linear relationship with flow requirements does not hold thus reaching a limiting factor in system weight. Figure 8-13 presents the estimated input power requirements for this system in final application. A simplifying assumption of a constant fan efficiency was made to allow the data to be presented in parametric fashion. This assumption is quite reasonable for this type of equipment and should not affect determination of power requirements.

Figure 8-14 illustrates the system equivalent weight as a function of the urine process rate for a 420 day mission. Figure 8-15 presents the system weight variation as a function of mission duration. The effect of power is negligible as illustrated in Figure 8-14 which presents the equivalent weight at power penalties of 0 and 500 lbs./kilowatt. The small difference between these two lines is readily noticed.

8.3.4 Conclusions

The air evaporation urine reclamation approach is a promising contender for final system selection due to its extremely low fixed weight and power penalty and overall simplicity. The achievement of complete water recovery is very significant and means that useful water beyond metabolic needs may be provided for other purposes such as electrolysis.

Reliability is enhanced due to the fact that the heat transfer to the urine occurs at a gas to liquid interface rather than across a metallic surface where scaling and corrosion could be troublesome.

In this system the urine residue is deposited on the wicks in the evaporator and, when saturated, the wicks are dried out by simply operating the system without the addition of urine. When the residue is in this dry solid form, handling and storage presents no problem. Another interesting factor is the potential ease of application within the main thermal control system. If development testing illustrates that an open approach can be taken to air evaporation, a further reduction in system fixed

AIR EVAPORATION URINE RECLAMATION
POWER VS URINE PROCESS RATE

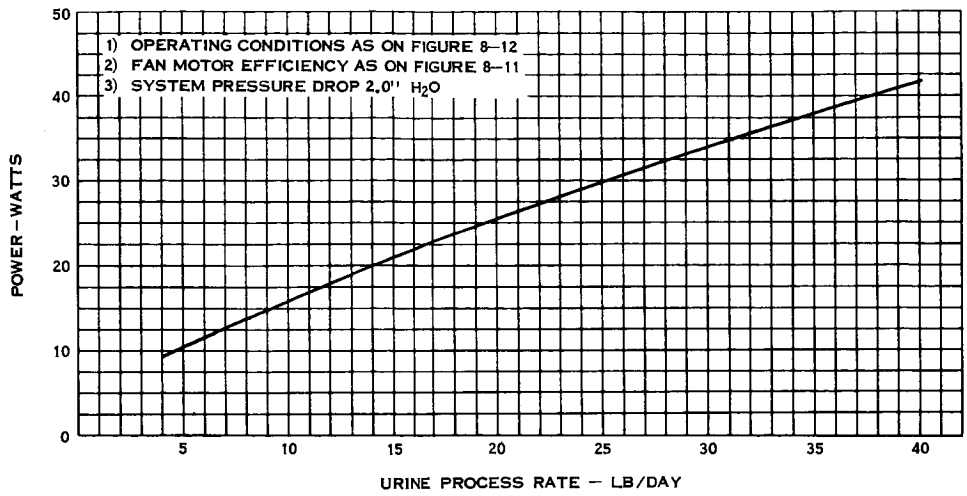


FIGURE 8–13

AIR EVAPORATION URINE RECLAMATION SYSTEM
EQUIVALENT WEIGHT VS PROCESS RATE
420 DAY MISSION

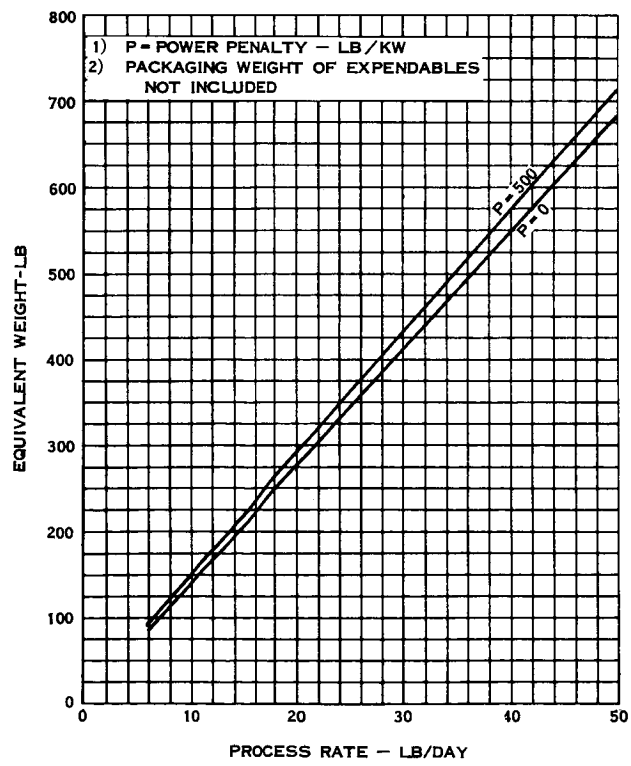


FIGURE 8–14

8.3.4 (Continued)

weight is probable since condenser, water separator, fan, and heater weight can be eliminated, except for the slight increase in main thermal control system size due to the added capability required.

The system requires expendables for pre-treatment and post-treatment as well as continual changing of the wicks in the evaporator. However, the rate of utilization of these expendables (in the order of 3% by weight of the urine processed) is reasonable for consideration in the final system approach.

AIR EVAPORATION URINE RECLAMATION
EQUIVALENT WEIGHT VS MISSION DURATION

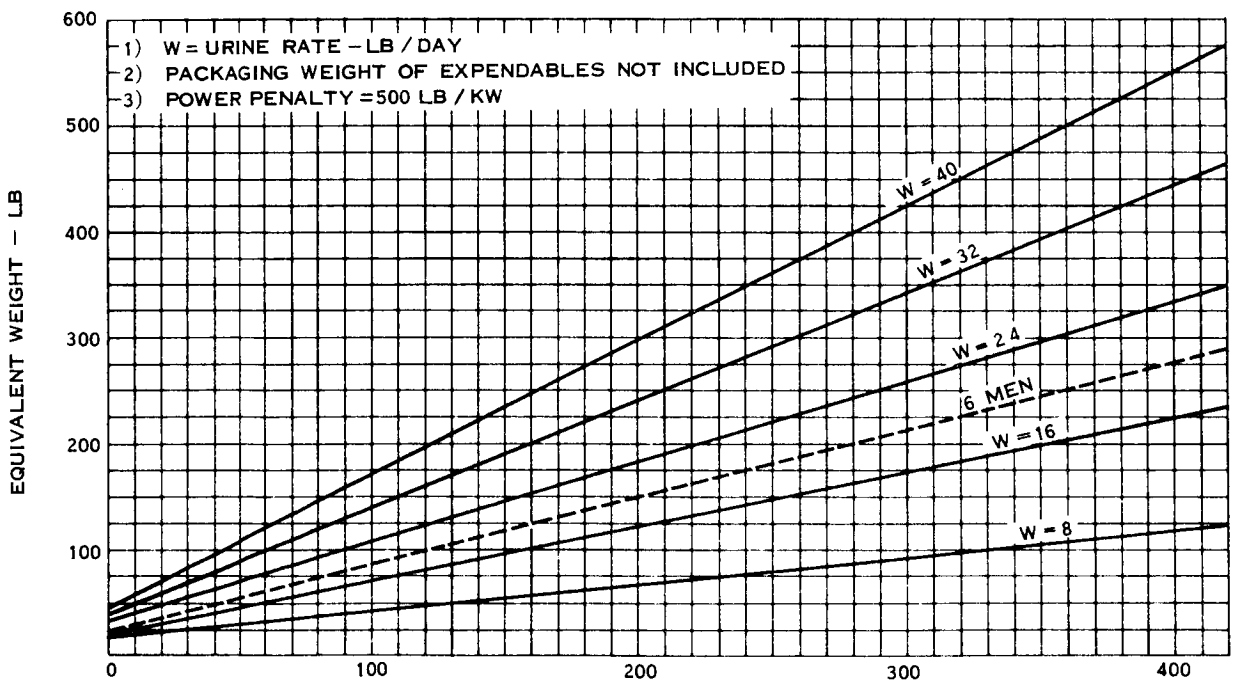


FIGURE 8–15

8.4 ELF Water Reclamation

8.4.1 Introduction and Data Source

The ELF water reclamation system (electrolysis cell-fuel cell system) is a concept of the General Electric Co. which has undergone preliminary development testing under an Air Force contract, as reported in U.S. Air Force Report AMRL-TDR-63-32 dated April, 1963.

This technique combines ion exchange membrane electrolysis cells with ion exchange membrane fuel cells so that oxygen and hydrogen, which are electrolyzed from urine, recombine in the fuel cell to produce potable water. The system description and data presented in this report are based largely on the results of that contract and to a certain extent include extrapolations of test results and data to provide the required parametric presentation for this report.

8.4.2 System Description

Figure 8-16 presents a simplified schematic approach to the ELF system. Operation is quite simple with no major moving parts and success is mainly dependent upon the reliability of the electrolysis cell and fuel cell. Raw urine is fed into the electrolysis cell where it is disassociated into hydrogen and oxygen. The two gases are then utilized as the input fuel for the fuel cell, where recombination occurs as part of the process and potable water is an end product. The power generated by the fuel cell contributes to reducing the high power requirement of the electrolysis cell.

Development work on this system has been essentially limited to the work described in this report and certain long term mission hesitancies arise from the analysis. A membrane life problem occurred during initial testing at a period of approximately 800 hours in duration. General Electric recommends consideration of membrane replacement at approximately 60 day intervals and believes that membrane replacement will be a low weight penalty to the overall vehicle.

Another area of concern with this approach is the apparent lack of expendable requirements for membrane protection in the electrolysis cell itself. The introduction of raw urine directly to the electrolysis cell may create problems for long life operation due to the urea and other contaminants which remain within the cell as the hydrogen and oxygen are given off. These questions make systems application perhaps more complex than that illustrated in the schematic of Figure 8-16. If an ELF system were to be operated for a period as long as 420 days the cell electrolyte would have to be replaced. In this study an expendable weight penalty was determined assuming the replacement of electrolyte at sixty day intervals.

8.4.2 (Continued)

ELF WATER RECLAMATION SYSTEM
SIMPLIFIED SCHEMATIC

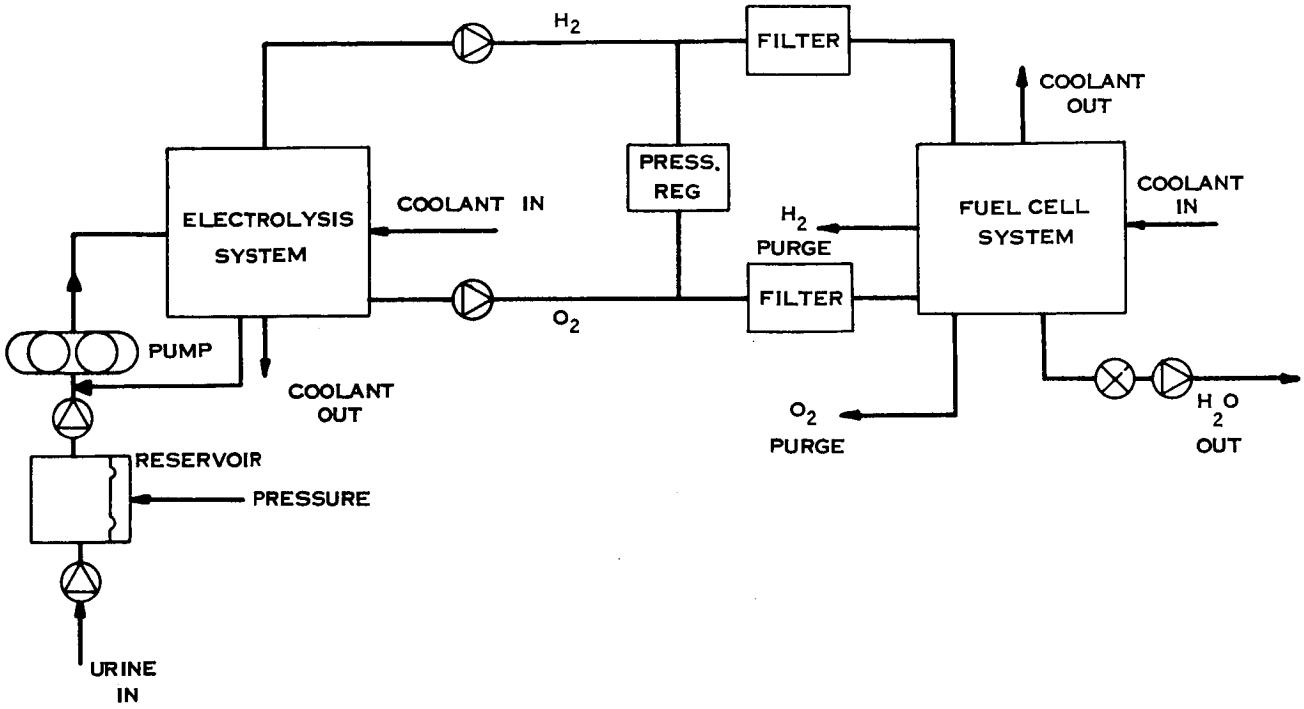


FIGURE 8 – 16

8.4.3 Results

A limited analysis was done on this system approach to determine the weight, power, and equivalent weight requirements of the system to allow comparison with other system approaches investigated. Although this application was not initially considered as part of the overall study work statement, its uniqueness and potential long term mission application made its limited inclusion desirable.

Figure 8-17 illustrates the system fixed weight requirements as a function of the urine process rate. It can be noted from earlier system discussions for water reclamation, that this weight is relatively high in comparison to other approaches. Figure 8-18 presents the power requirement as a function of the urine process rate. At the main point of interest (6 men, 20.8 lbs. of urine per day) the inlet power requirements for this system are in the order of 1300 watts or better than 200 watts per man which is a considerable penalty to pay compared to alternate methods of urine reclamation. The effect of this power is illustrated in Figure 8-19 which

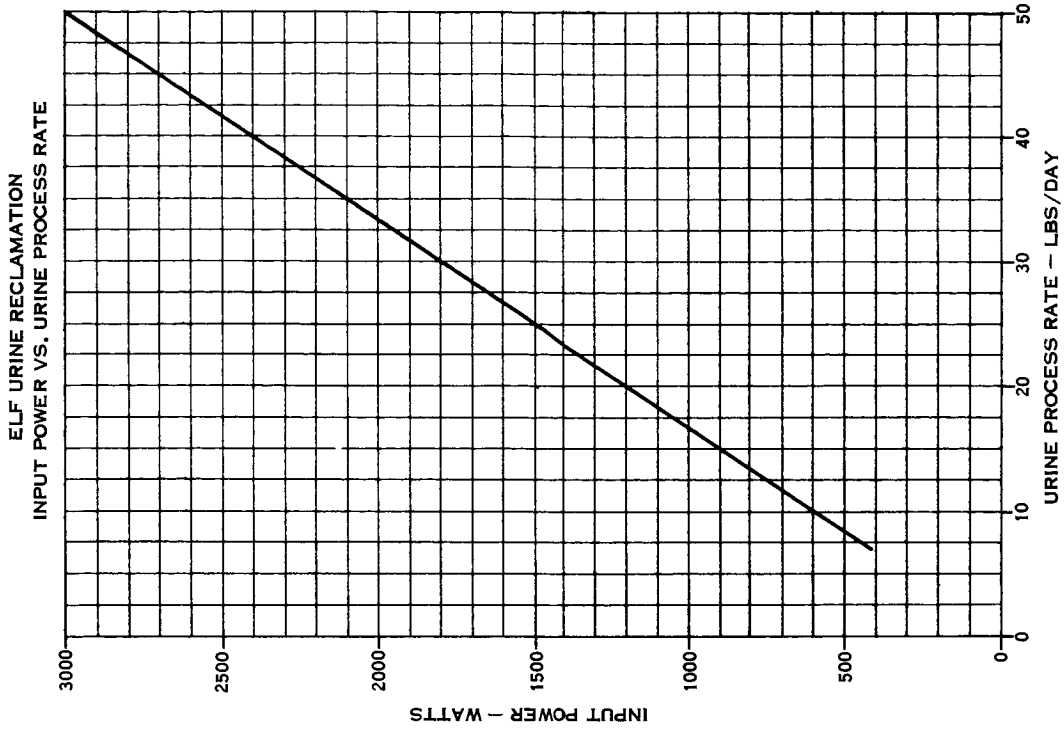


FIGURE 8–18

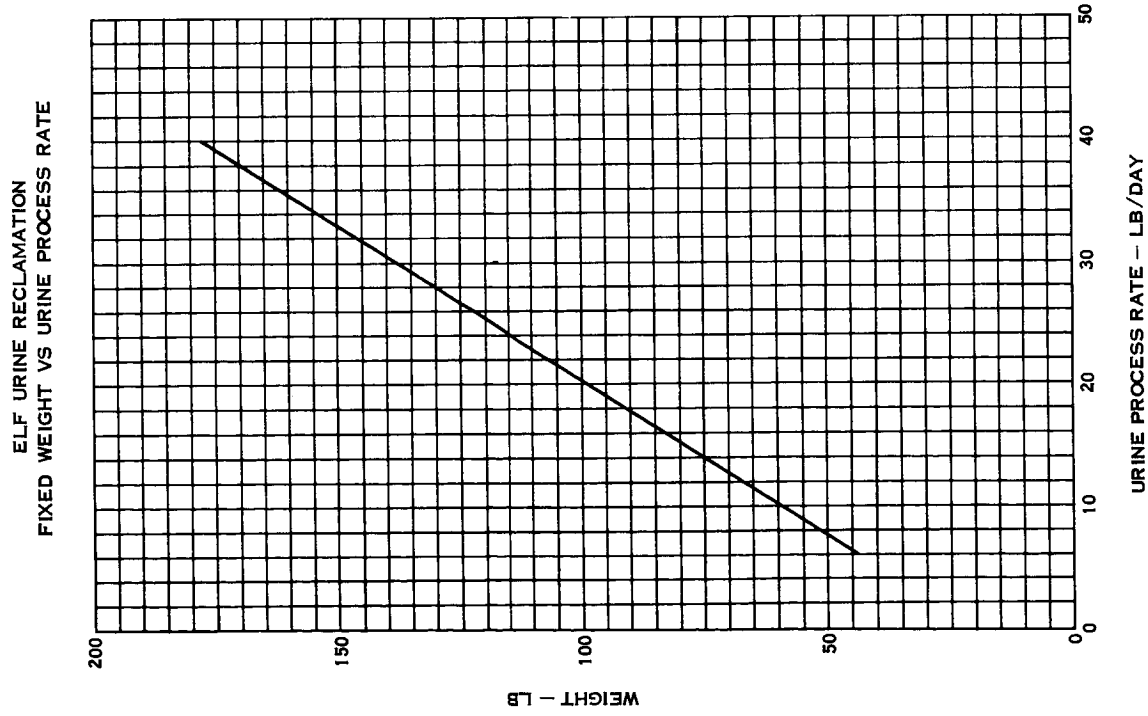


FIGURE 8–17

ELF URINE RECLAMATION
EQUIVALENT WEIGHT VS URINE PROCESS RATE
420 DAY MISSION

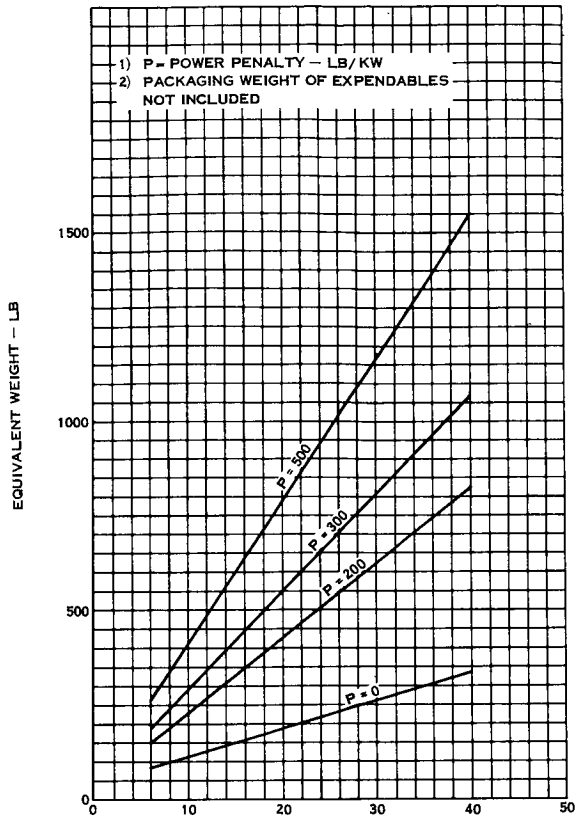


FIGURE 8–19

ELF URINE RECLAMATION
EQUIVALENT WEIGHT VS MISSION TIME

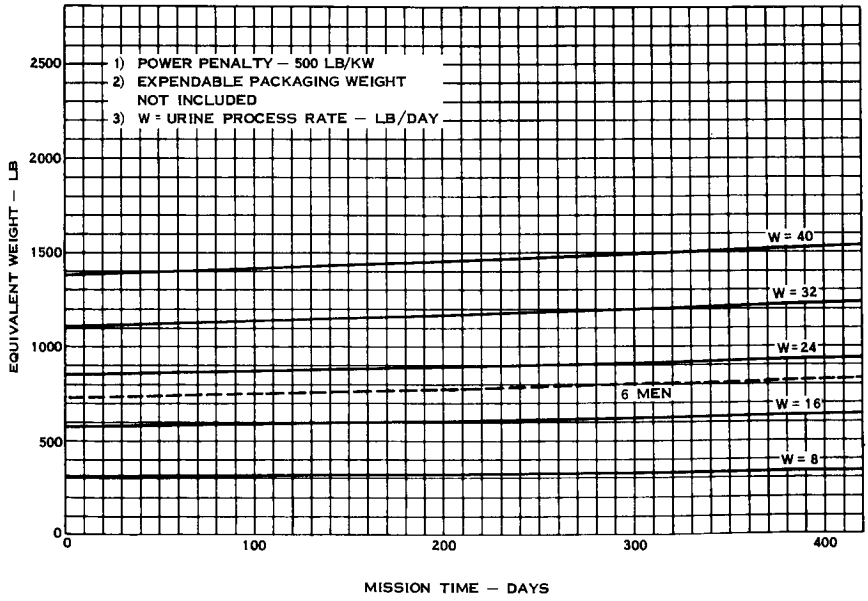


FIGURE 8–20

8.4.3 (Continued)

presents the equivalent weight of the system as a function of the process rate. Figure 8-20 illustrates the system equivalent weight as a function of mission duration. General Electric data indicates that the expendable requirements are quite low, however, a better evaluation of the replacement parts, system life, and potential pre- and post-treatment requirements will be necessary prior to full validation of this particular assumption and the estimate used for this study.

8.4.4 Conclusions

In conclusion, the ELF urine reclamation system has as its main potential advantage a simplified stop-start procedure in comparison with many other water reclamation systems. However, the extremely high power requirements coupled with the membrane life problem may make the system non-competitive for the Mars Vehicles. Later system applications, where the cost of power and the launch capacity of the initial booster are more favorable, could evolve the ELF system as a definite candidate depending upon the final expendable utilization rates. Qualitatively, the system reliability should be considerably less than that of some of its counterparts due to the comparatively exotic processes utilized and the considerable amount of valving required for actual system operation which is not shown in the simplified schematic. This feature would have to be evaluated further prior to utilization of the approach.

Water has been tested and appears potable from the results of system operation to-date. A reclamation efficiency of approximately 90% has been exhibited which is low by comparative standards and would require some improvement for both the case where urine is used solely to equal the metabolic water balance and especially for the case where the excess water generated by the crew is utilized as a partial oxygen make-up. On a mission of 420 days, a small percentage deficiency in water reclamation amounts to a large total weight.

8.5 Vapor Compression Water Reclamation

8.5.1 Introduction and Data Source

A vapor compression system is presently being evaluated by the Langley Research Center of the National Aeronautics and Space Administration. This system which was provided to the Langley Research Center under contract by the Mechanics Research Div. of General American Transportation Co. has been evaluated for this study. Other areas of industry are also involved in vapor compression water reclamation, however, the data on hand to-date indicates that the Mechanics Research approach is the most attractive.

8.5.1 (Continued)

This study analysis has been based upon information in Mechanics Research Div. reports on the system numbered MR1186-30 and MR5614-0. These reports present results of a design study and preliminary testing on two versions of the vapor compression system. This has been supplemented by a performance prediction from the Langley Research Center on actual system performance after development and qualification. Data presented in this study is based on this Langley Research Center information.

8.5.2 System Description

Figure 8-21 presents a simplified schematic approach to the vapor compression system considered in this study. The system consists essentially of a urine evaporator,

VAPOR COMPRESSION H_2O RECLAMATION

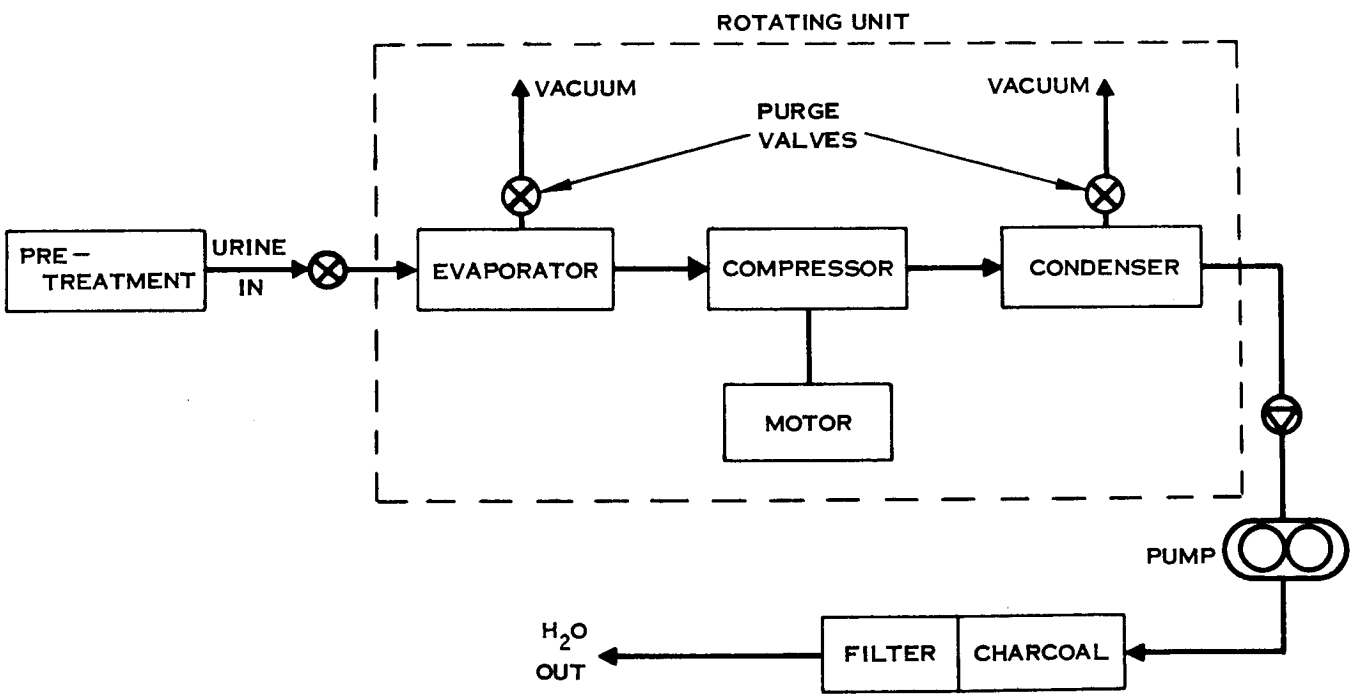


FIGURE 8 – 21

8.5.2 (Continued)

compressor, and condenser. For adequate operation, the urine must be treated prior to introduction to the evaporator and subjected to a certain amount of post-treatment after condensation to assure potability. The schematic indicates that the problem of gas-liquid separation in zero "g" is solved for this approach by rotation of the evaporator and condenser. In actuality, the evaporator and condenser are regenerative in nature with evaporation occurring in the center cylinder of a rotating set of concentric cylinders and condensation occurring between the walls of the two cylinders providing regenerative heat exchange through the condenser wall to the evaporator. The compressor is included in this rotating configuration and provides the energy input to the system. The process operates at low pressures which are maintained by periodic purging of the system to space vacuum.

System operation may be traced simply as follows: urine is pre-treated and evaporated after introduction to the system. The compressor raises the vapor pressure of the steam and the condenser condenses the vapor to water. The compression allows the latent heat of condensation to be used to evaporate the water from the urine. Condensate is drawn off of the condenser, post-treated and then passed to storage tanks for eventual use.

This system has the primary problem of scale formation on the evaporator heat transfer surfaces. This formation, if allowed to continue for an appreciable period of time, degrades the heat transfer process to a point where system efficiency is below desirable limits. The system in question eliminates this problem by operating as a semi-batch type process and periodically cleaning the evaporator by removing a plastic liner which clings to the evaporator walls. Thus, the scale is formed on the liner and can be removed easily. This method of scale removal presents a slight initial degradation to the heat transfer surface due to the presence of the plastic liner, but allows the complete cleaning of the surface. A disadvantage of this approach, however, is somewhat complex operating procedure required for plastic liner removal. Development work will be required in this area prior to acceptance of this system for long duration missions with minimum maintenance.

8.5.3 Results

The data utilized in the study for the vapor compression system was expanded somewhat by in-house Hamilton Standard experience to provide the required range of interest for this study. This was necessary since most of the work done to-date on this system approach has evolved about a single design point.

8.5.3 (Continued)

Figure 8-22 presents the variation in system fixed weight as a function of the urine process rate and Figure 8-23 illustrates the system power requirements as a function of the process rate. The actual input power illustrated here is quite low in comparison with other system approaches and is quite attractive. A simplified assumption of constant compressor efficiency was made in preparation of this curve which might affect the accuracy of the data at the extremes of the range. The percentage effect of this assumption however is low enough to allow its utilization as a good approximation.

Figures 8-24 and 8-25 illustrate the variation in total system equivalent weight as a function of the process rate and mission duration. In this case the assumption of 20 hours per day system operation has been utilized as a reasonable value. Figure 8-24 presents the equivalent weight against urine process rate for a 420 day mission. Figure 8-25 shows equivalent weight against mission duration. The equivalent weight includes expendables which consist of pre- and post-treatment chemicals, evaporator liner, and water and air lost during purging.

The weight evaluation of the vapor compression system makes it a very attractive system for further study as a potential candidate in the overall life support system approach. The system has received considerable early development attention both in industry and in the work of the Langley Research Center and the basic principles are proven. Estimated future recovery efficiency is quite good with approximately 95% of the water recovered from the urine. Three problems exist however which must be solved prior to utilization of this system in the final space station configuration. The first of these problems, the scaling of the evaporator heat transfer surfaces, has been previously mentioned in the discussion of the plastic liners utilized in the evaporator. The second problem, that of separation of the liquid vapor phase in the evaporator and condenser for zero "g" operation, has not been fully evaluated for zero "g" conditions and may require more development work prior to satisfactory operation. The present method of rotating the evaporator and condenser and creating an artificial gravity field seems the most direct solution to this problem. However, rotational speeds and equipment sizes may require considerable optimization prior to final system qualifications. The third area of concern, which must be investigated further during development aspects, is that of potential presence of non-condensibles in the condenser. The present design utilizes a purge to vacuum to rid the condenser of these non-condensibles which inhibit condensation. This approach is satisfactory for adequate condensation, however start-up and periodic purging of the condenser creates a penalty for the air lost over a long period of time. The primary disadvantages of the system are the unadaptability to intermittent operation, the reliability problems associated with rotation of the evaporator and condenser, and the reduced pressure operation of the entire system. All of these require further analysis and evaluative testing.

VAPOR COMPRESSION URINE RECLAMATION
INPUT POWER VS PROCESS RATE

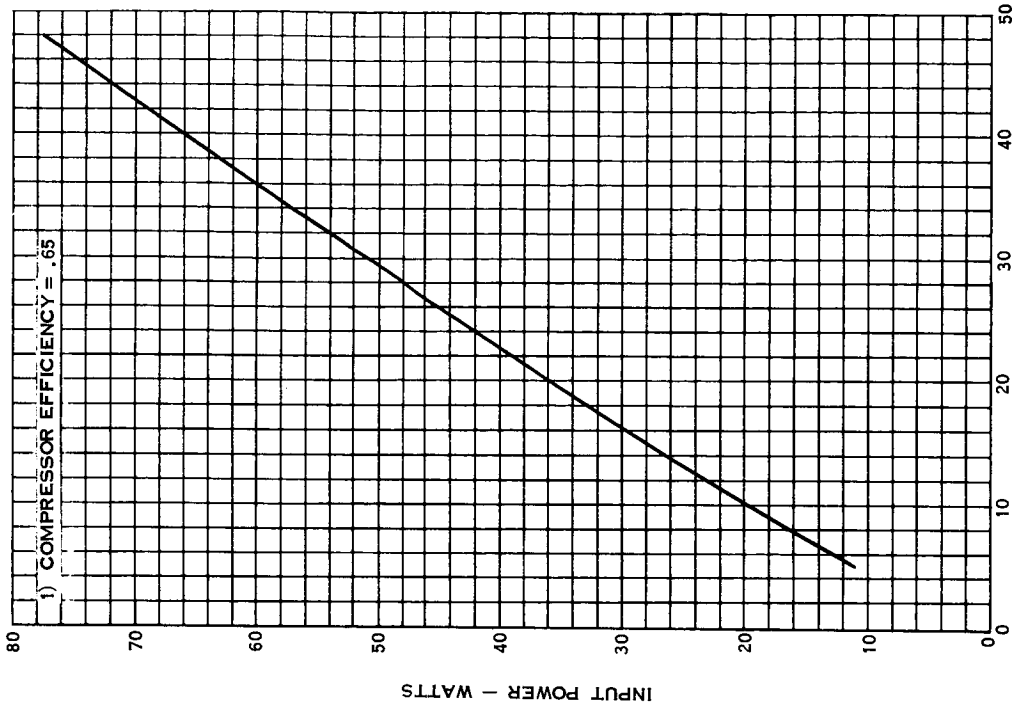


FIGURE 8–23

VAPOR COMPRESSION URINE RECLAMATION
FIXED WEIGHT VS URINE PROCESS RATE

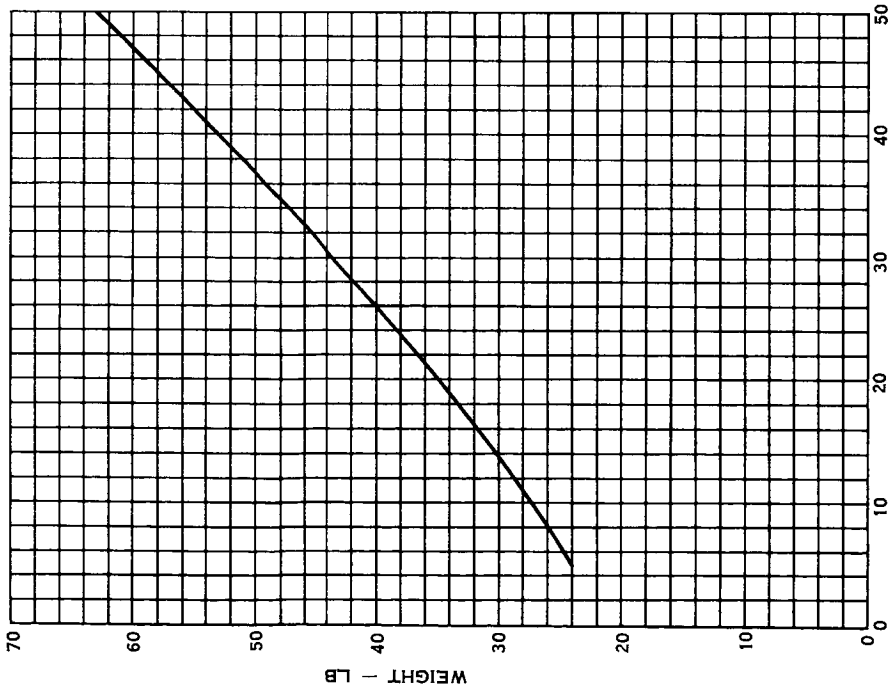


FIGURE 8–22

VAPOR COMPRESSION URINE RECLAMATION
EQUIVALENT WEIGHT VS PROCESS RATE
420 DAY MISSION

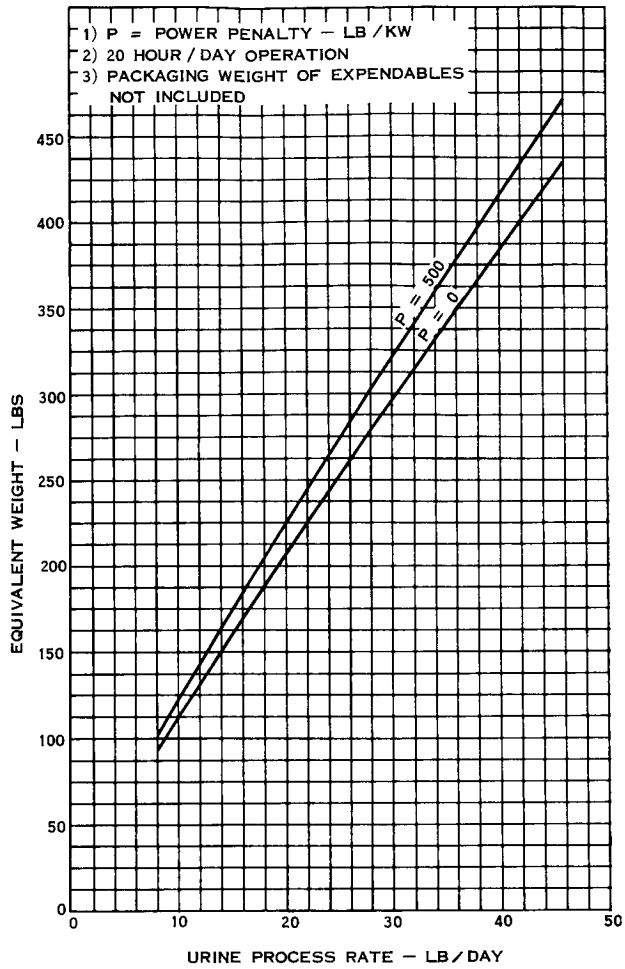


FIGURE 8–24

VAPOR COMPRESSION URINE RECLAMATION
EQUIVALENT WEIGHT VS. MISSION TIME

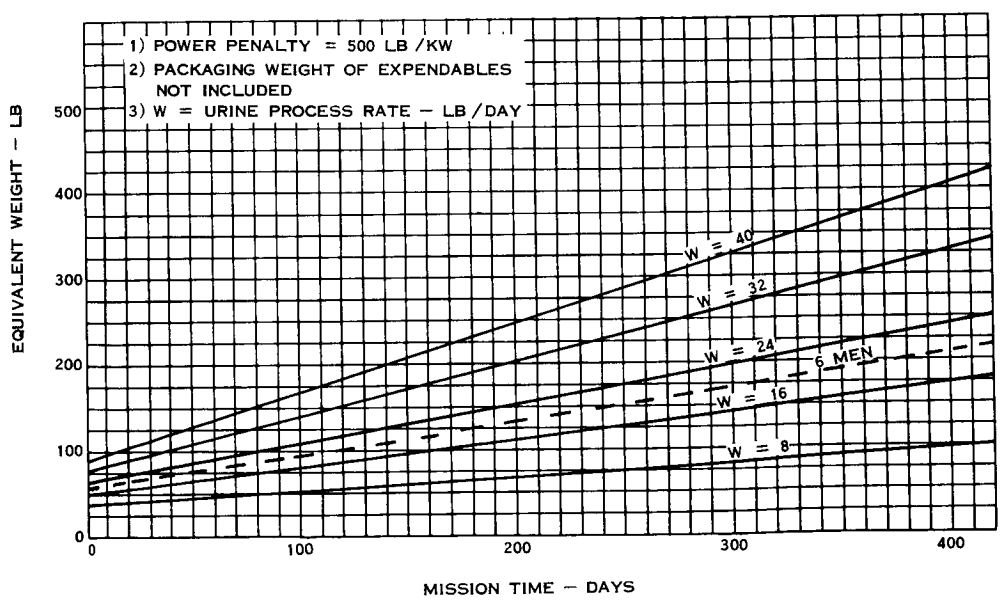


FIGURE 8–25

8.6 Oil Jet Evaporation Water Reclamation

8.6.1 Introduction and Data Source

The oil jet evaporator system is essentially a vapor compression water reclamation system. This system was the subject of a research program by Hamilton Standard in the recent past. Its potential attractiveness in some areas and overall difference in approach warranted its inclusion in this study as a potential candidate water reclamation system.

The data presented is based essentially on research data with the system approach as yet to be demonstrated in its entirety. The research data accumulated to-date has been primarily concerned with establishment of component feasibility rather than overall system demonstration. Development status is very poor in general, although some potential advantages may make it a competitive system for longer duration missions if certain improvements can be made.

8.6.2 System Description

Figure 8-26 illustrates the oil jet evaporator system considered in this study. As

OIL JET WATER RECLAMATION SYSTEM

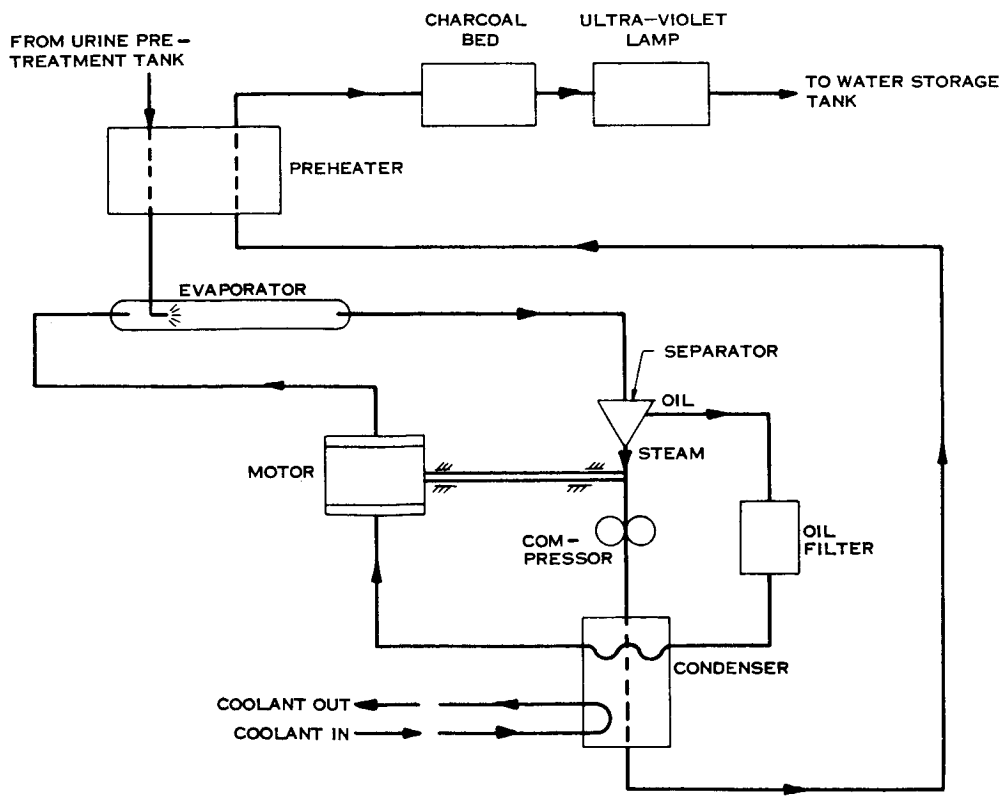


FIGURE 8 — 26

8.6.2 (Continued)

previously mentioned, the system is essentially a vapor compression system in that reclamation occurs by evaporating the urine and condensing and recovering the distillate. The primary difference from the standard thinking for vapor compression systems is the inclusion of a circulating oil transport loop to eliminate the scaling and heat exchange fouling problems in the evaporation portion of the cycle. The raw urine is fed into the system through an ejector type nozzle and evaporation occurs at this nozzle, thus presenting a vapor formation within the circulating oil. A separator installed downstream of the evaporator is utilized to remove the water vapor from the circulating oil leaving the solids to be carried off by the circulating oil stream. The separated vapor is then compressed and condensed. The heat of condensation is rejected to the oil which then returns to the evaporator inlet to complete the cycle.

The circulating oil carries off the urine solids from the evaporator and the heat transfer area and gives them up to a filtration system within the oil loop. Thus, removal of solids from the system can be accomplished simply and directly by changing the filter media periodically, rather than by cleaning the evaporator as has been recommended for other vapor compression approaches. Tests in Hamilton Standard's research laboratory illustrate that the oil will act as a washing solution and remove the scale from the evaporator. The urine inlet nozzle feasibility has been demonstrated using research equipment but no prototype test work has been accomplished.

A potential replacement for the circulating oil loop is raw urine itself. This exchange should reduce system weight substantially by eliminating the complexities of dual fluids. In this case, a portion of the raw urine would be circulated through the system to provide the transport media for the evaporated urine and the urine contaminants. This concept has not been established sufficiently to allow its recommendation at this point in time.

8.6.3 Results

The anlaysis of the oil jet system and of vapor compression in general is simplified during initial calculations by the establishment of Figure 8-27. This figure illustrates the compressor power requirements as a function of condenser saturation temperature. This figure allows a rapid initial determination of the power penalty for the system when the operating temperatures are established.

Figure 8-28 illustrates the fixed weight variation of the oil jet system as a function of the urine process rate. The power requirements are illustrated by Figure 8-29. The design point case of six men or 20.8 lbs. of urine per day requires approximately 46 watts for total system operation, which is a reasonable figure for this type of equipment.

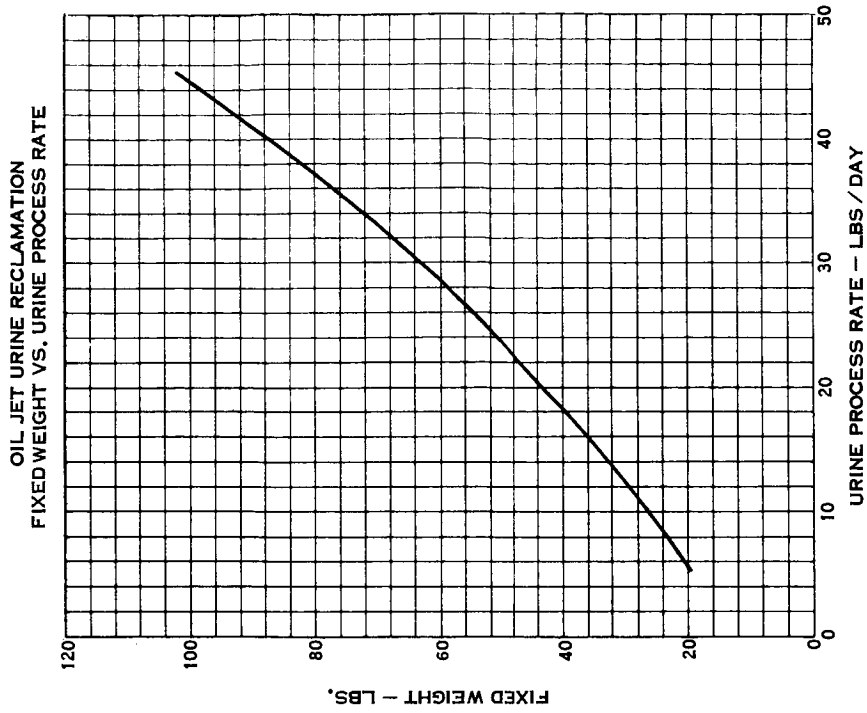


FIGURE 8–28

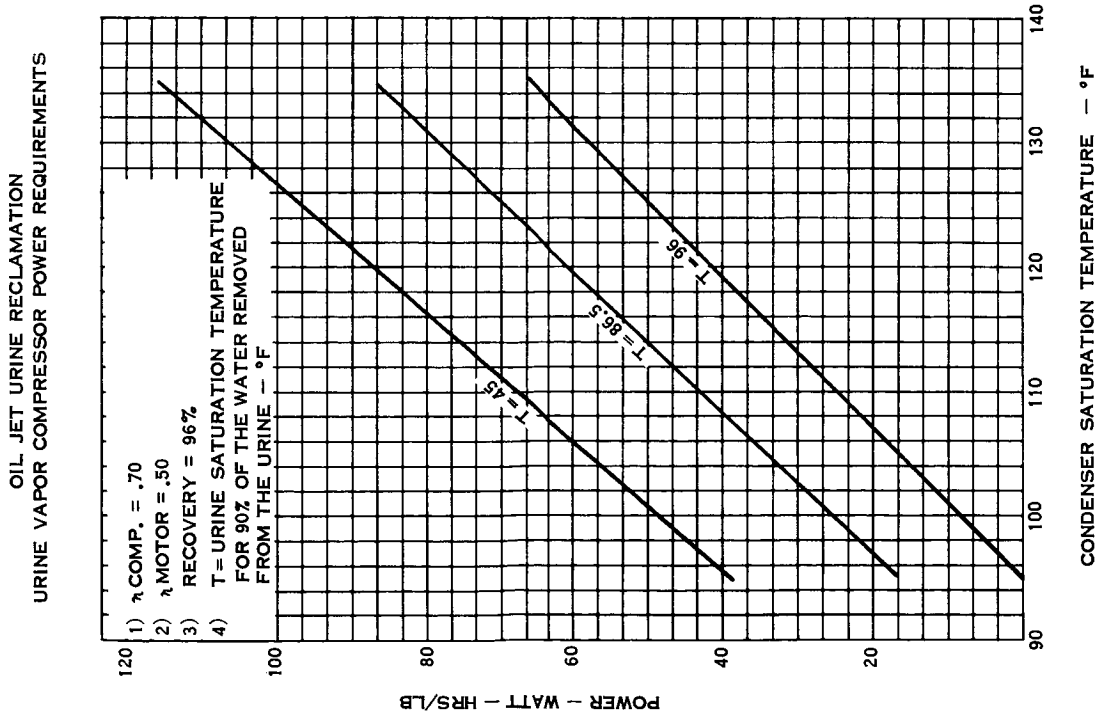


FIGURE 8 – 27

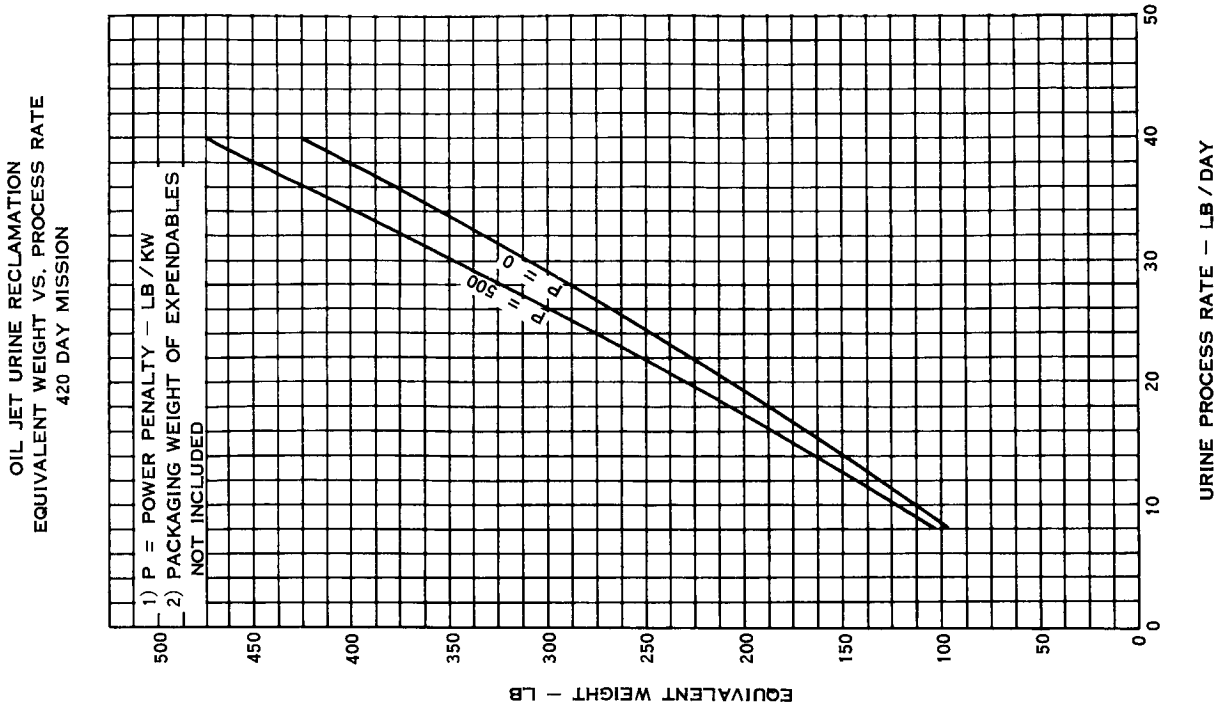


FIGURE 8–30

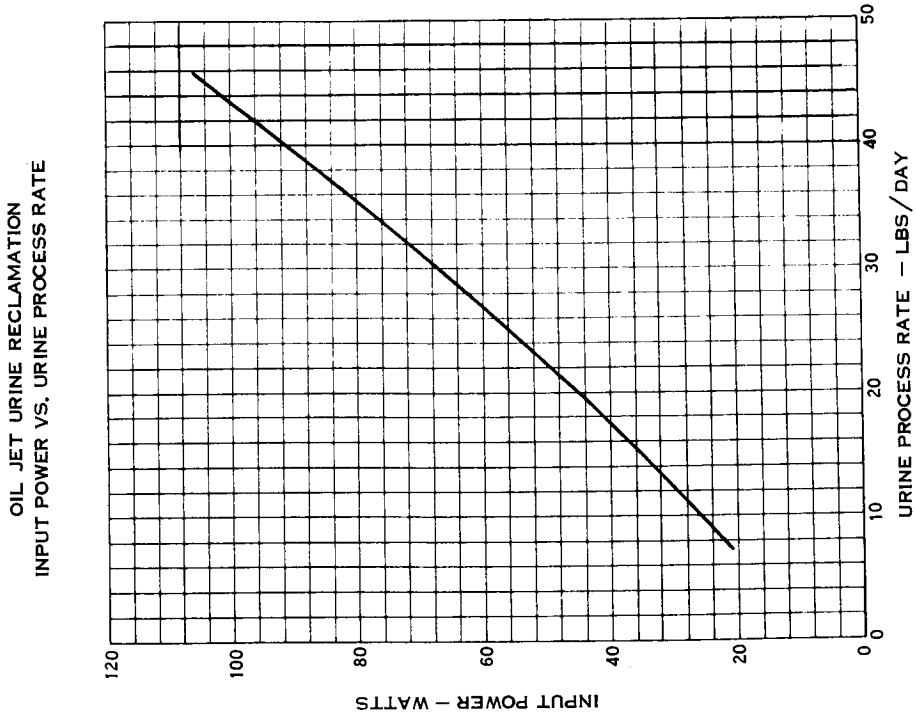


FIGURE 8 – 29

8.6.3 (Continued)

To illustrate the overall system penalties as a function of the urine process rate (crew size) Figures 8-30 and 8-31 have been prepared. Figure 8-30 presents this comparison as equivalent weight against urine process rate for a 420 day mission and Figure 8-31 shows equivalent weight against mission duration over the range of interest. It should be mentioned again that the expendable penalties are for pre- and post-treatment chemicals alone, and do not include packaging requirements.

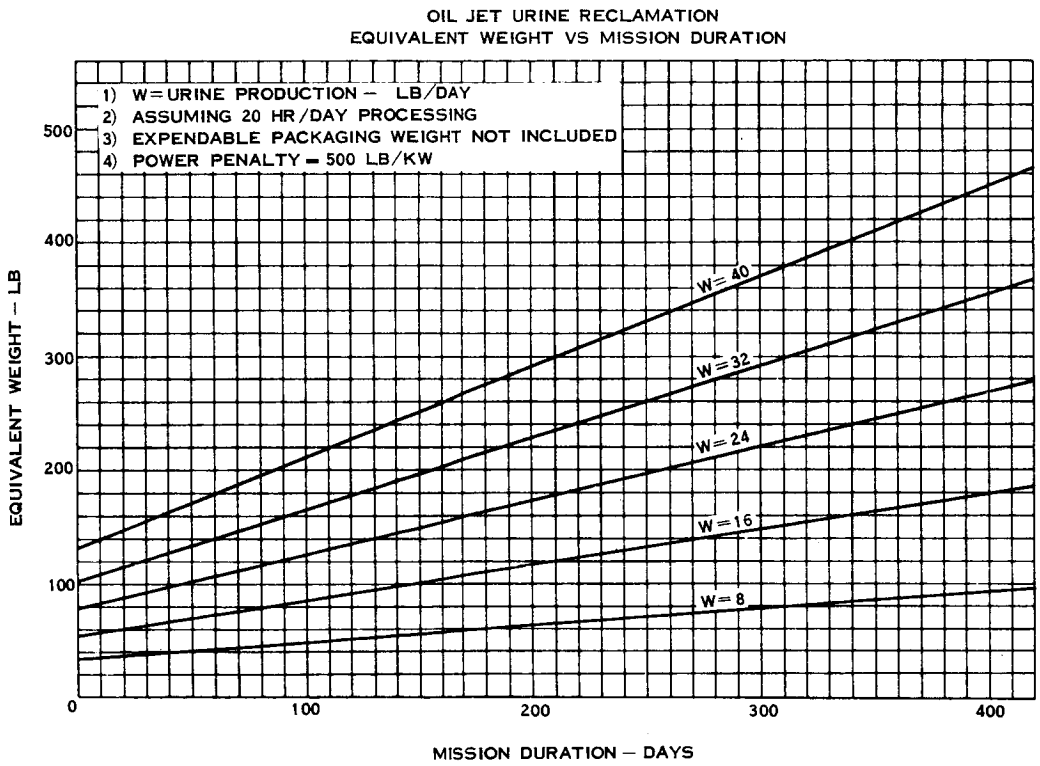


FIGURE 8 – 31

8.6.4 Conclusions

The oil jet urine reclamation system is attractive due to the simplification of the evaporator scale removal problem and its high urine reclamation efficiency which approaches 100%. These two factors are desirable in any water reclamation system and make this approach worthy of consideration upon initial evaluation.

8.6.4 (Continued)

Many problems exist, however, in development of a system of this type. The most significant is the design of the condenser for zero "g" operation. If a condenser were available with an operating effectiveness in the order of those utilized in aircraft systems, power requirements for this approach could be reduced in the order of 14%. Hamilton Standard has run considerable test evaluations of zero "g" condensers in the past, but condenser effectiveness has not reached the standards known in previous aircraft equipment. Thus, effectiveness utilized in this analysis had to be a reasonable estimate rather than that which could be reached by extensive and exhaustive development testing. The condenser is the major unattractive point of the system application.

Other areas of concern in design of a system of this type are potential clogging of the pitot pump which could foul system operation and extensive problems in start-up. The start-up requires a lengthy check list and established procedure for accurate system operation.

In summary, the system cannot be considered fully competitive at this time and although its weight, power, and expendable requirements are attractive, other systems with similar or better requirements for the same range of interest which also exhibit a more advanced development status tend to eliminate this system from further consideration.

8.7 Vacuum Distillation

8.7.1 Introduction and Data Source

The investigation of vacuum distillation as a potential means of water reclamation for the Mars Mission utilized an approach developed by the General Electric Co. known as a vapor pyrolysis. This approach utilizes the addition of a high temperature catalyst to a more conventional vacuum distillation system.

The primary sources of data for this analysis are U. S. Air Force Technical Documentary Report No. AMRL-TDR-63-32 and General Electric Report R62SD39. The former is primarily concerned with General Electric's test work on the ELF water reclamation system previously discussed, however, recent estimates of weight and power associated with vacuum pyrolysis are also presented. The second reference is a study of the purification of water from biological waste, which describes the system approach in more detail. Vacuum distillation is a potentially attractive method due to the lack of major moving parts in the system application. For this reason, it was investigated as a part of the study program.

8.7.2 System Description

Figure 8-32 presents a simplified schematic of the vapor pyrolysis system analyzed for this study. The system has three primary components: the urine boiler, the catalyst and the condenser. The urine is vaporized in the boiler and the vapor passed over the catalyst which is at a temperature of approximately 1000° centigrade. The catalyst oxidizes the trace gas contaminants present in the vapor and

VACUUM DISTILLATION WATER RECLAMATION SYSTEM
SIMPLIFIED SCHEMATIC

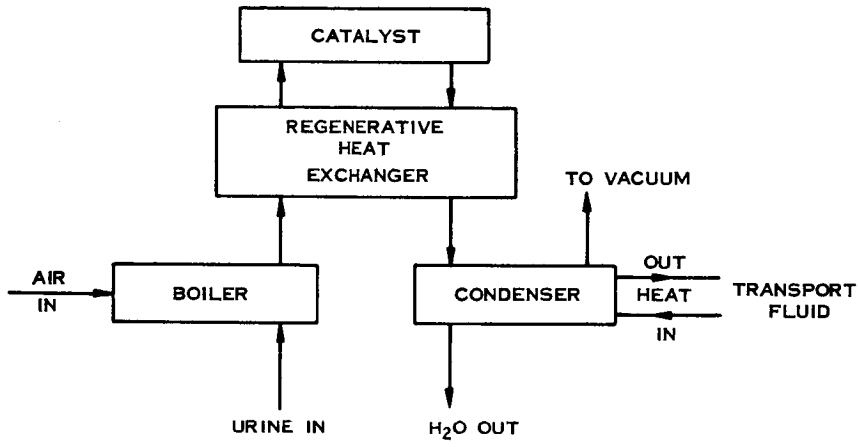


FIGURE 8 – 32

they are eliminated from the system by venting to space vacuum. The vapor itself is condensed and the condensate drawn off to water storage. The distillation is carried out at low pressure and temperature (1.10 psi and 105°F). The exhaust to space vacuum maintains the desired low pressure so that the vapor boils at 105°F and the catalyst is utilized to destroy any carry-over contaminants including bacteria in the vapor. A potential disadvantage of this method of achieving the operating pressure is that some air or oxygen is lost in the process of oxidation of the potential contaminants as well as during the venting to space. These, however, are the primary expendable requirements associated with the system.

8.7.2 (Continued)

The major problem with the design of this particular approach is its dependency upon a highly effective zero "g" condenser. This problem, the same found in the oil jet evaporator system, may reduce performance expectancy of the present system in terms of weight and power. Present recovery percentage is about 90% of the water in the urine which is low in comparison to other system approaches.

8.7.3 Results and Conclusions

The initial analysis of the vapor pyrolysis system coupled with the small amount of research work eliminated it as a potential candidate system for the Mars Mission. Present work in this area has not progressed much past the initial research stage in test equipment, thus, estimates of weight and power cannot be accurately predicted. The General Electric report on the subject assumes that the condenser will be developed as the result of other space usage requirements and their efforts in solution of this problem have not been applied to any great degree. The advanced development stages of the other systems in comparison with this approach makes vacuum distillation not particularly attractive at this time. For this reason, no effort was made to do a theoretical analysis on system performance or to provide weight and power estimates.

The major advantage of this system is the minimization of expendables which makes its development for a long term mission such as the Mars Mission an area worth investigation prior to final system design. The elimination of major moving parts such as a compressor fan, or internal water pumps increases inherent reliability of the system as indicated by the simplicity of the schematic. However, the disadvantages inherent in the system far outnumber the potential advantages to be gained by its utilization.

As in the case with vapor compression systems, the evaporative area must be provided with some method of scale removal to assure adequate heat transfer capacity during extended operation. No method of scale removal or plastic liner similar to the vapor compression approach seems to have been investigated at this time. The previously mentioned zero "g" condenser problem is also a development problem which must be solved prior to utilization of vapor pyrolysis. Another major problem area is a requirement for separation of the vapor and liquid prior to the catalyst bed to prevent the liquid entering the catalyst. This could probably be accomplished by the use of membranes or by spinning part of the apparatus but would result in increased system complexity. Finally, the vapor flow to the catalyst and the catalyst operating temperature might prove to be a control problem not

8.7.3 (Continued)

presently anticipated. The laboratory testing to-date has indicated that if the reaction temperature is too low, the pH of the product water becomes unacceptably high. Thus, the power input to the catalyst would have to be closely controlled as would be the vapor flow across the catalyst.

Due to the lack of accurate answers to many of these questions, as well as the limited testing performed on the system to-date, this approach was not deemed desirable and will not be considered during system integration. However, it is an area in which future development effort could be devoted.

8.8 Freezing

8.8.1 Introduction and Data Source

Some investigation was made into the possibility of recovering potable water from urine by freezing. When contaminated water is frozen, the ice crystals which precipitate will be relatively pure water. There are various methods of recovering this water and three of them are discussed here, freeze crystallization, reiterative freezing and freeze sublimation.

The following documents were used as references for this study.

WADC Technical Report 60-243 by Wallman and Barnett; Office of Saline Water, Progress Report No. 7 by Rose and Hoover; and Journal of American Rocket Society, December 1962 by Hendel were used for freeze crystallization.

The Transactions of the Seventh Symposium on Ballistic Missile and Space Technology by J. Beutel was used as reference for reiterative freezing.

Journal of the American Rocket Society, December 1962 by Hendel, and "Water Reclamation Systems Study for Manned Orbital Space Vehicles" by Ionics Inc. were used as reference for freeze sublimation.

8.8.2 System Description

(a) Freeze Crystallization. This method is a change of phase process, liquid to solid, and is simply the freezing of ice crystals in urine, extraction of the crystals and remelting. The chief obstacle appears to be that "mother liquor" adheres to the ice crystals produced and is trapped between aggregates of fine crystals. This means that the dissolved product water contains a high percentage of impurities. To overcome this, the freezing process can be repeated to successively

8.8.2 (Continued)

reduce the concentration of contaminants, or the ice crystals can be washed with pure water prior to melting and the wash water itself purified by freezing. It has been estimated by Wallman and Barnett (WADC Tech Report 60-243) that when processing urine, at least three stages of freezing would be required to produce a potable product water with a concentration of solids no greater than 500 ppm.

As further evidence of the difficulty of separating pure ice crystals from the concentrated liquid, Rose and Hoover (O.S.W. Progress Report No. 7) made the following comment:

"Ice made from a saline solution always consists of crystals of minute size, and a mass of such crystals necessarily retains in its interstices a comparatively great volume of mother liquor which cannot be separated by ordinary draining, filtering, centrifuging or washing."

It will be difficult to obtain high yields with this type of process. It has been reported by Hendel (Journal ARS, December 1962) that approximately 75% of the water can be recovered from urine by this means. For an extended mission, this is not satisfactory recovery.

(b) Reiterative Freezing. The water recovery process using reiterative freezing has been investigated and described by J. Beutel (Transaction of the Seventh Symposium on Ballistic Missile and Space Technology).

In the reiterative freezing process, a column of urine is slowly frozen with the solid to liquid interface starting at one end and proceeding along the axis of the cylinder. Since the solubility of the solute is lower in the solid phase than in the liquid phase, a concentration gradient is established along the axis of the tube.

This process can be repeated by slowly moving a heating element along the axis of the tube. This causes a molten zone to slowly proceed along the axis, and with each cycle, the solute becomes more concentrated in the direction of motion of the molten zone. When this cycle has been repeated a sufficient number of times, the desired purification will have been attained at the first end of the cylinder. This ice may then be separated and melted in order to produce potable water.

The major disadvantage of this process is the large number of cycles required. The experimental work showed that 13 to 15 freezing cycles were needed to produce water with a purity of 400 PPM. This of course will result in a large expenditure of energy as well as time. The process may be exceedingly slow since the experimental freezing rates were 10^{-3} to 5×10^{-5} cm/sec. Such a slow processing

8.8.2 (Continued)

rate would result in equipment too large and heavy for a space vehicle.

The maximum yield mentioned in the experimental report was 80% and this is low for an extended space mission. Although the reiterative process reduced the bacteria count in the processed water, some additional post-treatment would still be required to achieve fully potable water.

(c) Freeze Sublimation. Freeze sublimation or freeze drying is a phase change process from solid to vapor. It can be used to recover water from urine by freezing and then subliming off the water vapor. This requires operation below the triple point which is 3 mm Hg and 20°F for urine. The vapor is condensed out as pure water.

This system can recover 80% of the available water according to Hendel (Journal ARS, December 1962). Other authors have reported even higher recoveries (Ionics - Water Reclamation Systems Study for Manned Orbited Space Vehicles). The product water is of high quality.

The chief disadvantage of this process is its size due to the low operating pressure of 3 mm Hg and to the large area of space radiator required to reject the condenser heat at 20°F. It has been estimated that the required heat of sublimation can be readily obtained from cabin waste heat but there will be a requirement for precise thermal control to supply only the exact quantity of heat required for sublimation.

Since the condenser must operate in zero "g" there will have to be some means of directing the vapor flow to the cooling surface and then removing the pure water crystals.

When the water vapor is sublimed from the frozen urine, the residue will be left behind as a dry solid. This may present problems of heat transfer on the evaporator surfaces.

8.8.3 Results and Conclusions

Due to a lack of quantitative data no attempt has been made to size a freezing type water recovery system for a space vehicle. From the qualitative discussions above, however, it does not appear that freezing is a competitive or attractive method for water recovery.

8.8.3 (Continued)

Foremost among the disadvantages are the relatively poor recovery and the large size of the systems that would be required. In addition, it appears that the development status of these systems is poor. For these reasons it is not recommended that further consideration be given to freezing methods for water reclamation.

8.9 Chemical Treatments

8.9.1 Introduction and Data Source

This section discusses the removal of detergent from wash water by filtration through anionic resins. The only information on this subject was provided in phone calls to Rohm and Haas, and Winthrop Laboratories, manufacturers of anionic resins.

8.9.2 Discussion and Conclusions

An attempt was made to find chemical treatments of a general type that would be useful in reclaiming water. Nothing was found that would be suitable for urine processing, but it appeared that anionic resins might be very useful in reclaiming wash water.

Wash water, while technically contaminated, is very dilute, especially if generous quantities have been used for washing. It was felt that used wash water could be made suitable for drinking if the detergent or soap could be removed. If a detergent of the type such as "Phisohex" is used for washing, it could probably be removed by filtration through an anionic resin.

At the present time no specific resin has been developed for this purpose, but the two vendors listed above were optimistic that the required resins could be made. In order to limit the amount of resin required to the minimum value, it will be necessary to use a specific resin with a specific detergent. Anionic resins have a capacity for removing contaminants on the basis of one to two milliequivalents of contaminant per ml of resin. Since the synthetic detergent such as "Phisohex" possesses an extremely large molecule, the weight of resin required for removal is quite modest.

Although no resins have been developed for the specific removal of "Phisohex," it is understood that research work is being carried out for the removal of household detergents from municipal water supplies.

8.9.2 (Continued)

In conclusion it can be said that the removal of detergents from wash water by anionic resins is a process that looks attractive due to simplicity and low expendable weight. Since suitable resins are not available at this time further development should be encouraged.

8.10 Comparative Discussion of Urine Processing

To summarize the discussion of urine reclamation systems, the primary parameters for each of the systems have been plotted in this section to provide ready comparative data on all of the systems, dependent upon the actual specification requirements being considered. Figure 8-33 presents the comparison of system fixed weight as a function of the urine process rate. Reference to this figure indicates that the most attractive system from a fixed weight basis, is the air evaporation approach with the electrodialysis system a close competitor. Air evaporation, as mentioned in the discussion of that particular approach, is based on an estimate of final system operating temperature levels. However, it should not change appreciably from this point in fixed weight determination for other operating temperature levels, and thus can be considered the lightest potential fixed weight system for water reclamation. The differences between the four lower systems, the oil jet evaporator, vapor compression, electrodialysis and air evaporation is not of enough significance to rule out any candidate if fixed weight is an important parameter.

Figure 8-34 illustrates the input power requirements for each of the systems as a function of the urine process rate. In this case, the air evaporation approach offers the minimum power requirement of all systems investigated. The electrodialysis, vapor compression, and oil jet evaporator systems are also quite competitive from a power requirement point of view. Although the higher power of the oil jet evaporator approach coupled with its development status may not make it as attractive as the other applications, the difference between air evaporation and vapor compression is primarily due to the zero "g" condenser problems mentioned in the detail discussion and could be improved.

This summary comparison makes apparent the extremely high power requirement of the ELF system. If the weight penalty for power is not extremely low, this would make the ELF system completely uncompetitive.

In a similar fashion, Figure 8-35 shows the system expendable weights against process rate. This indicates that the expendable rate for electrodialysis is extremely high due to the great quantities of charcoal required for the removal of urea. This would appear to make electrodialysis uncompetitive unless substantial

URINE RECLAMATION SUMMARY
FIXED WEIGHT VS URINE PROCESSED

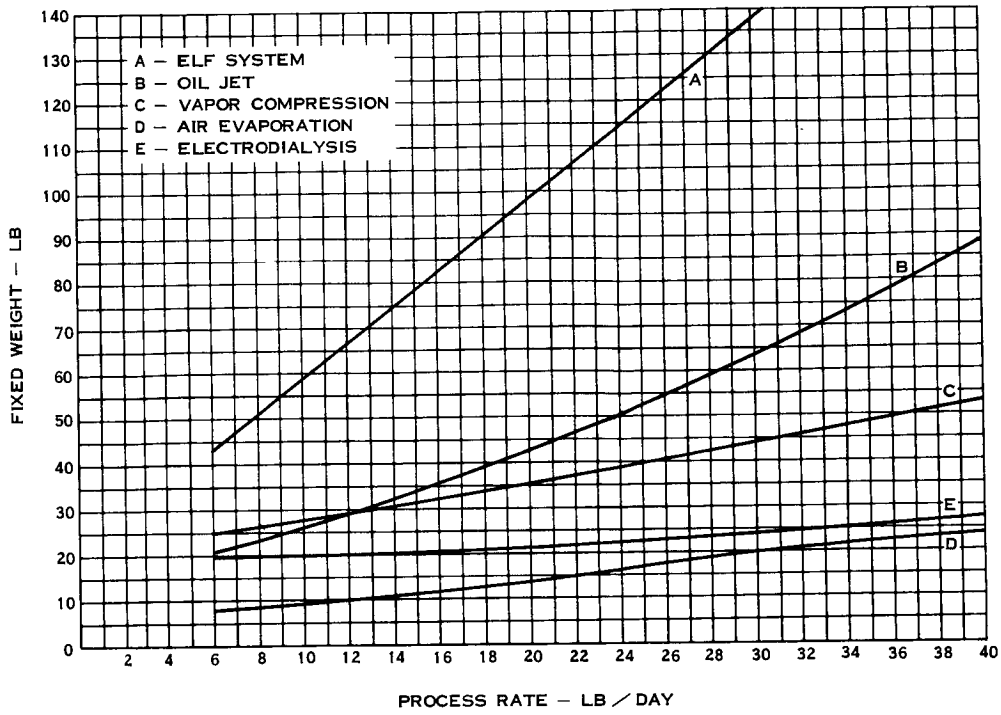


FIGURE 8–33

URINE RECLAMATION SUMMARY
POWER VS PROCESS RATE

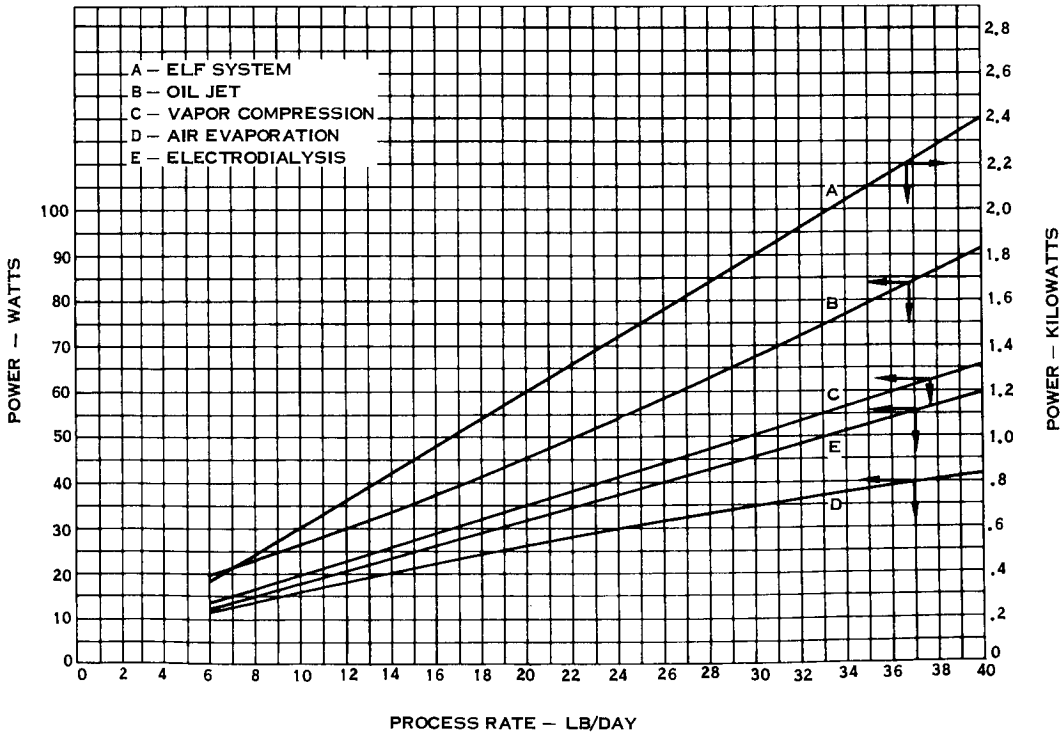


FIGURE 8–34

URINE RECLAMATION SUMMARY
EXPENDABLES VS PROCESS RATE
420 DAY MISSION

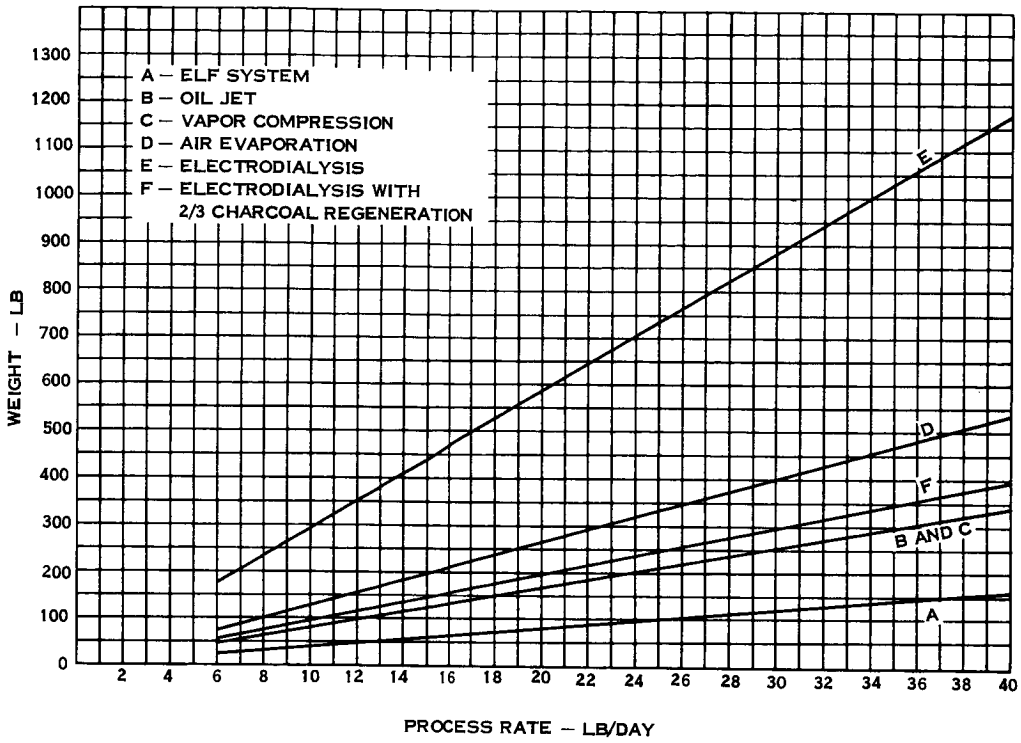


FIGURE 8–35

URINE RECLAMATION SUMMARY
EQUIVALENT WEIGHT VS PRODUCTION RATE

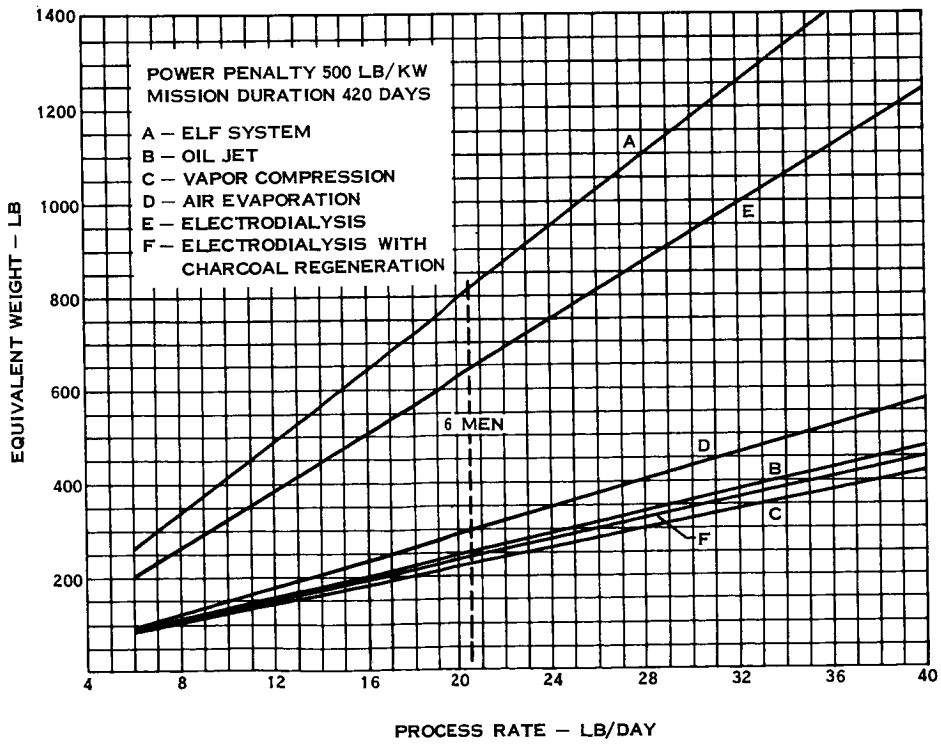


FIGURE 8–36

8.10 (Continued)

regeneration of charcoal could be achieved. Curve F shows that to be competitive, the regeneration would need to reduce the charcoal requirements by two thirds. A the present time, this is not considered feasible and may be extremely difficult to achieve.

The data from these three figures have been combined in Figures 8-36 and 8-37 to show equivalent weight against process rate and mission duration, respectively. For this comparison, a power penalty of 500 lb/KW has been used.

Both of these figures show that the ELF system and electrodialysis without charcoal regeneration are uncompetitive on an equivalent weight basis.

At the main point of interest for this study, a six man crew for 420 days, four systems are competitive on a weight basis; air evaporation, vapor compression, oil jet and electrodialysis with charcoal regeneration. The oil jet system is not recommended at this time due to the complexity and poor development status, and the electrodialysis is not recommended due to the unresolved problem of charcoal regeneration.

Thus, air evaporation and vapor compression are considered worthy of further study and are of interest in the system integration phase. One point must be restated in this particular application and that is the philosophy of equivalent weight determination. In the discussion of urine reclamation alone, no penalties have been attached to any system for a reclamation efficiency of less than 100%. This was based on the decision that for initial analysis, a system would be considered satisfactory if its reclamation efficiency was sufficient to balance the metabolic water requirements of the crew. In cases where a use is found for this excess water such as with an electrolysis cell to make up a portion of the oxygen requirements, the higher reclamation efficiency systems will become more attractive and relative penalties must be established. With this in mind a final curve, Figure 8-38, was prepared to show the weight of water that was not recovered from urine for each of the systems studied. For a short mission of a few weeks the unrecovered water from an inefficient system is not of much consequence, but when the mission extends to 420 days, the unrecovered water amounts to a few hundred pounds and warrants serious consideration for alternate use beyond the metabolic requirements.

8.11 Comparative Discussion of Wash Water

8.11.1 Introduction

On a long duration mission such as the journey to and from Mars, consideration must be given to the provision of bathing for the crew and to reclamation of the

URINE RECLAMATION SUMMARY
EQUIVALENT WEIGHT VS MISSION DURATION

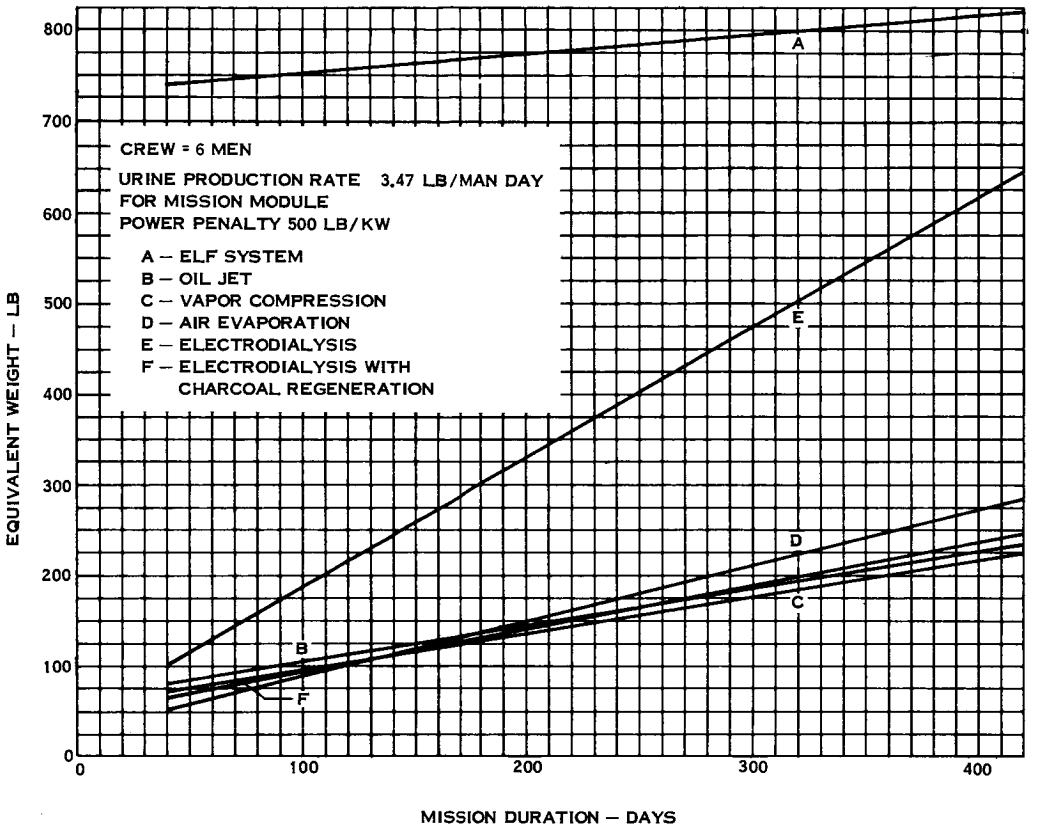


FIGURE 8–37

URINE RECLAMATION SUMMARY
WEIGHT OF UNRECOVERED WATER VS MISSION DURATION

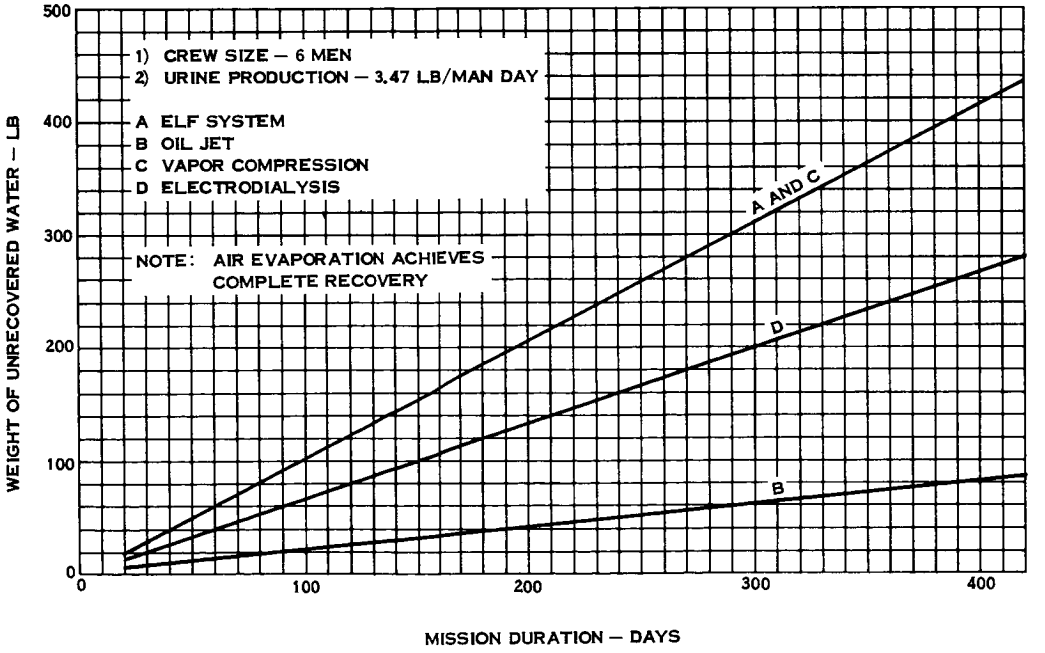


FIGURE 8–38

8.11.1 (Continued)

used wash water. It was considered desirable to reclaim the water to a potable level in order to provide the maximum reliability to the overall water supply system.

At this time the optimum quantity of wash water to be used by each astronaut has not been established. For this reason wash water processing was examined for two different use rates, 14 and 40 lb. per man day. The contaminants present in used wash water were assumed to be that specified in the NASA Life Sciences Data Book, .00704 lb. of material removed from the body per man day. It was also assumed that a synthetic detergent such as "Phisohex" would be used for skin cleaning.

Three fundamental water processing methods were evaluated for wash water recovery: liquid to vapor phase change, electrodialysis and ionic resin filtration. A total of five variations and combinations of these methods were considered.

A. Air Evaporation Closed Loop
B. Air Evaporation Open Loop
C. Vapor Compression
D. Electrodialysis
E. Electrodialysis with Charcoal Regeneration

The ionic resin filtration was used only in conjunction with methods A, B, and C above when the water use rate was 40 lb. per man day. This resin was used as discussed in Section 8.9 to remove the detergent used for skin cleaning. When 40 lbs. of water per man day was used, only 14 lbs. was processed by method A, B or C and the remaining 26 lbs. was filtered through the ionic resin. With the contaminant rate specified earlier of .00704 lb. per man day, if 14 lb. was completely processed in a phase change process the remaining 26 lb. would have a contaminant level less than 500 ppm. If the detergent was removed by an anionic resin, then the water could be considered suitable for consumption. It was felt that this approach which combined Methods A, B or C with ionic resin filtration for reclaiming wash water would result in the lowest overall weight when the use rate was 40 lb. per man day.

This approach was not employed with electrodialysis however, and all the wash water was passed through the stack whether the use rate was 14 or 40 lb. per man day.

8.11.2 System Description

Air Evaporation - Air evaporation was evaluated for wash water reclamation due to its simplicity and low power and weight. Since wash water has a very low level

8.11.2 (Continued)

of contaminants with almost negligible odor, it was considered feasible to reduce the overall weight and power by employing an "open loop" air evaporation system. This system has already been described under the appropriate urine reclamation section. For the sake of comparison, both open and closed loop systems have been evaluated in the following section, 8.11.3.

These systems have been sized to process wash water at the usage rates of 14 lb. per man day. If the higher usage rate of 40 lb. per man day is desired, it is proposed that the air evaporation be combined with an anionic resin filtration to avoid an excessive increase in size of the distillation unit. In this case the used water supply would be divided into two parallel streams with the first, of 14 lb. per day per man being processed by air evaporation, and the remainder, of 26 lb. per day per man being processed by ionic filtration.

Vapor Compression - A Vapor Compression system was also considered for wash water reclamation. This was done in a similar manner to the air evaporation method in that the basic system was sized to handle a usage rate of 14 lb. per man day, and then combined with an ionic resin treatment for a total 40 lb. per man day usage rate.

Electrodialysis - For the recovery of wash water, electrodialysis was considered a promising system due to its low fixed weight and power consumption. When used with wash water, which is fairly dilute in terms of contamination, the electrodialysis stack will only run as long as required to maintain a predetermined level of salinity and will be monitored by a conductivity probe. The system will be similar to that proposed for urine reclamation but due to the nature of the used water, it will be designed to achieve complete reclamation with a single pass through the stack.

8.11.3 Results

The following set of curves present the system weights as a function of process rate and mission duration. Figures 8-39 to 8-43 are applicable where the water use rate is to be 14 lb. per man day. The actual use rate is significant as well as the process rate because the amount of expendables used is a function of the contaminant or the dirt removed from the skin rather than the amount of water used.

The set of curves Figures 8-44 to 8-48 are applicable where the water use rate is 40 lb. per man day. These equivalent weight curves represent the air evaporation and vapor compression systems combined with ionic resin filtration.

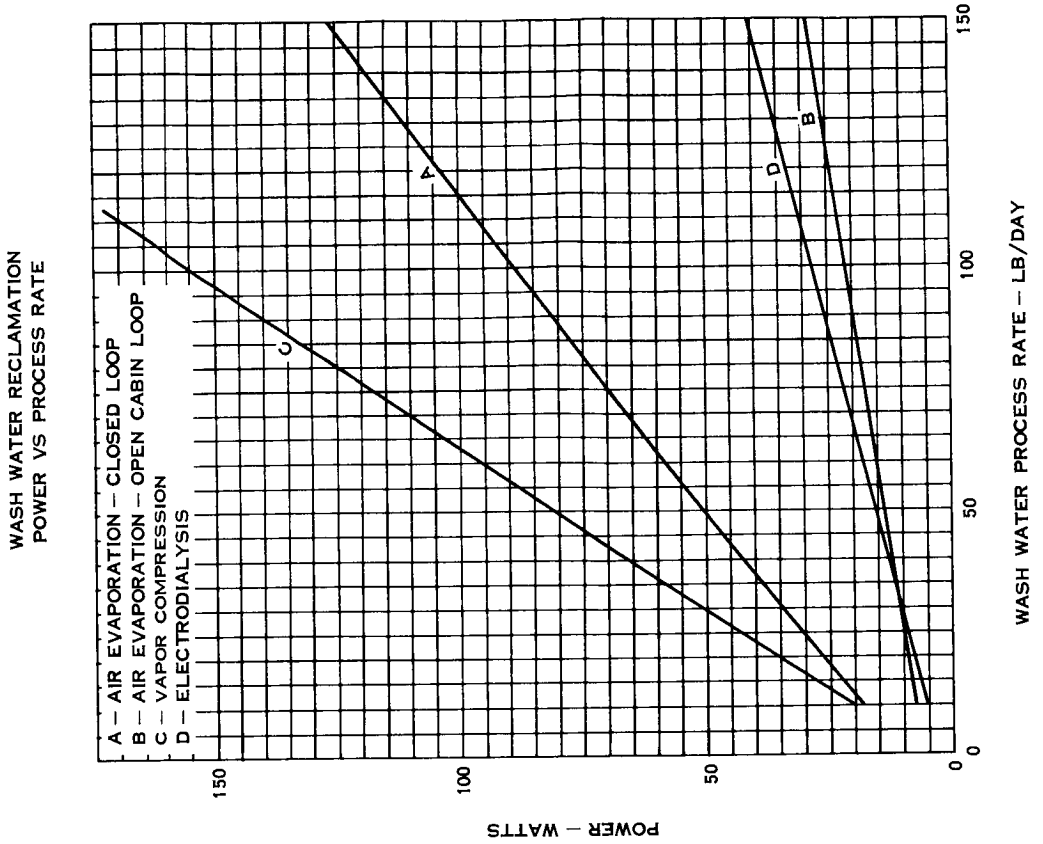


FIGURE 8 – 40

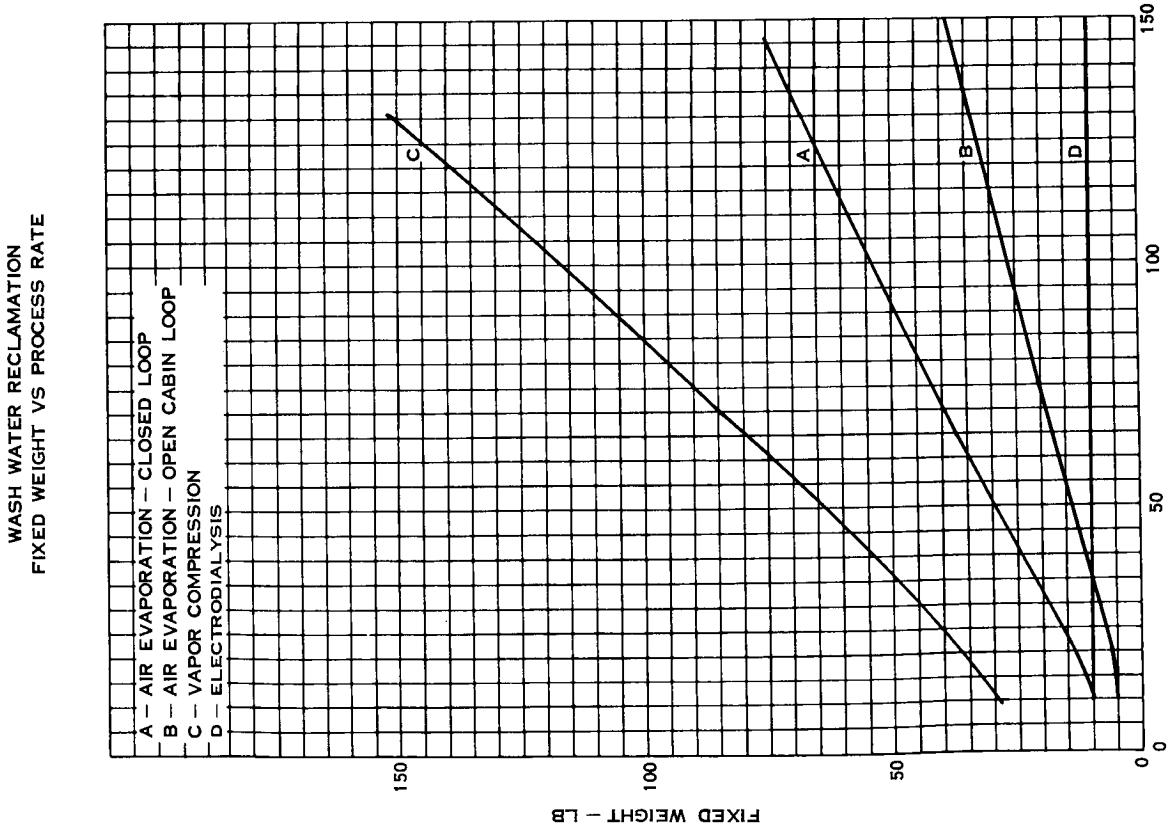


FIGURE 8 – 39

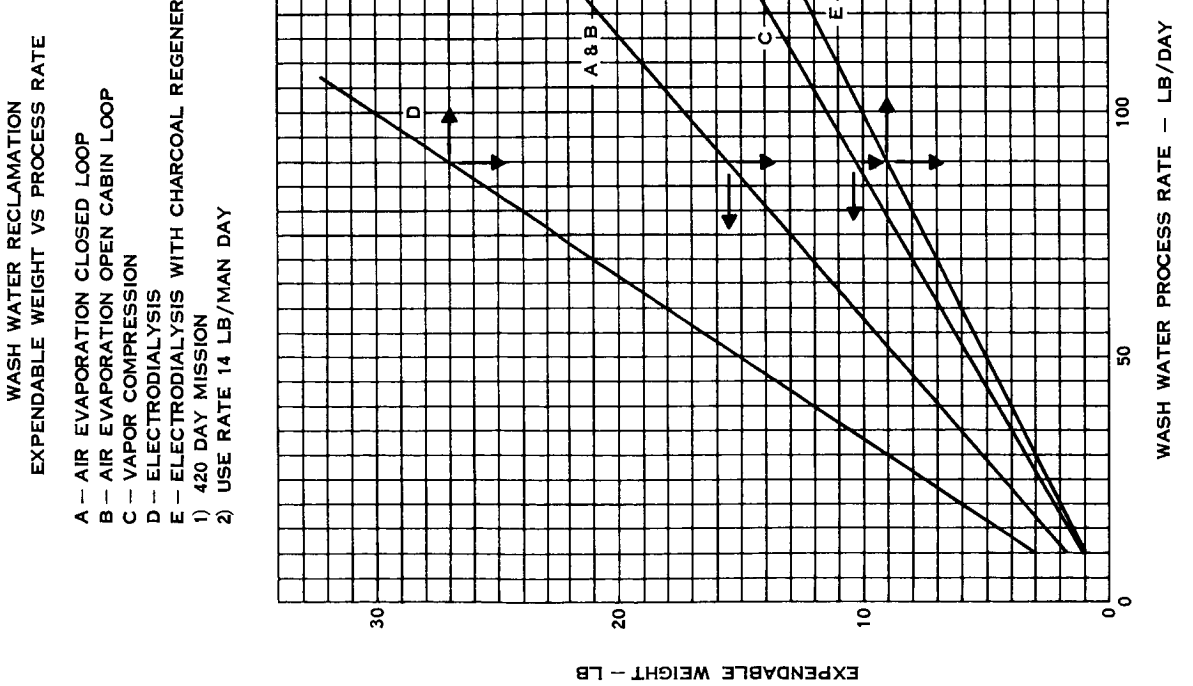


FIGURE 8 – 41

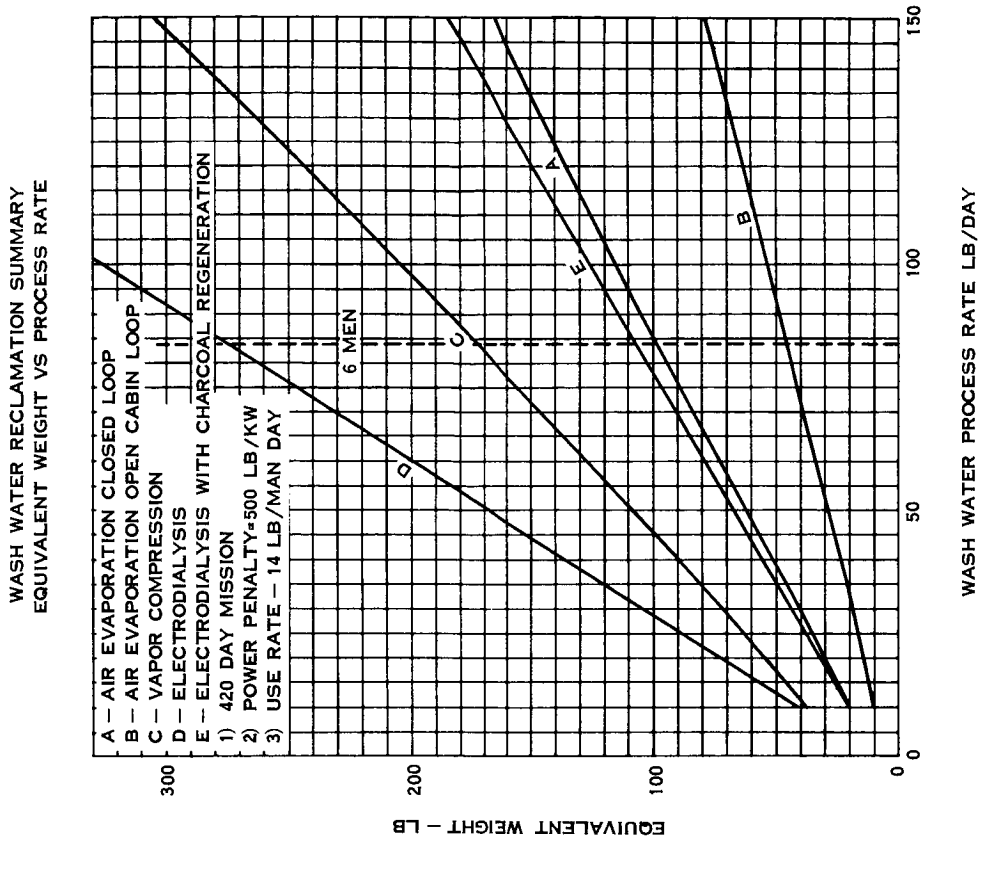


FIGURE 8 – 42

WASH WATER RECLAMATION SUMMARY
EQUIVALENT WEIGHT VS MISSION DURATION

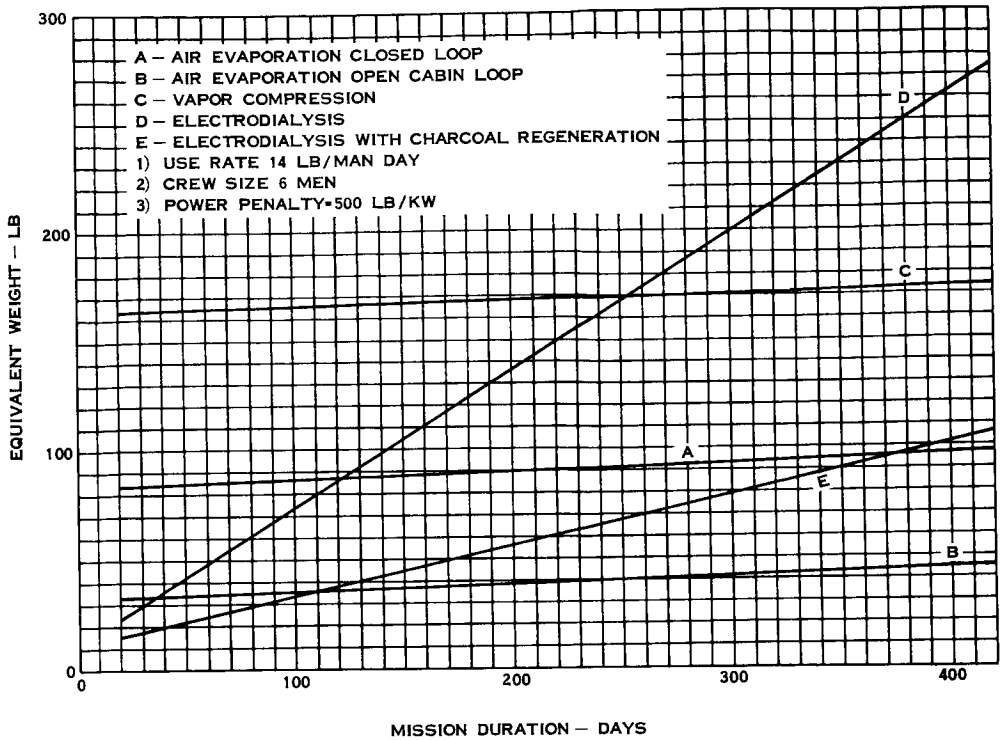


FIGURE 8 – 43

WASH WATER RECLAMATION
FIXED WEIGHT VS PROCESS RATE

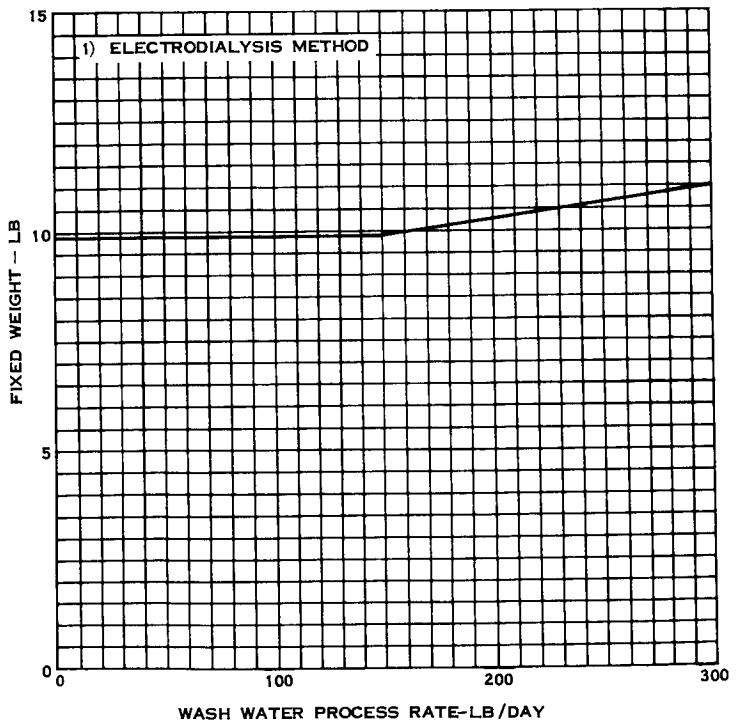


FIGURE 8 – 44

WASH WATER RECLAMATION
EXPENDABLE WEIGHT VS PROCESS RATE

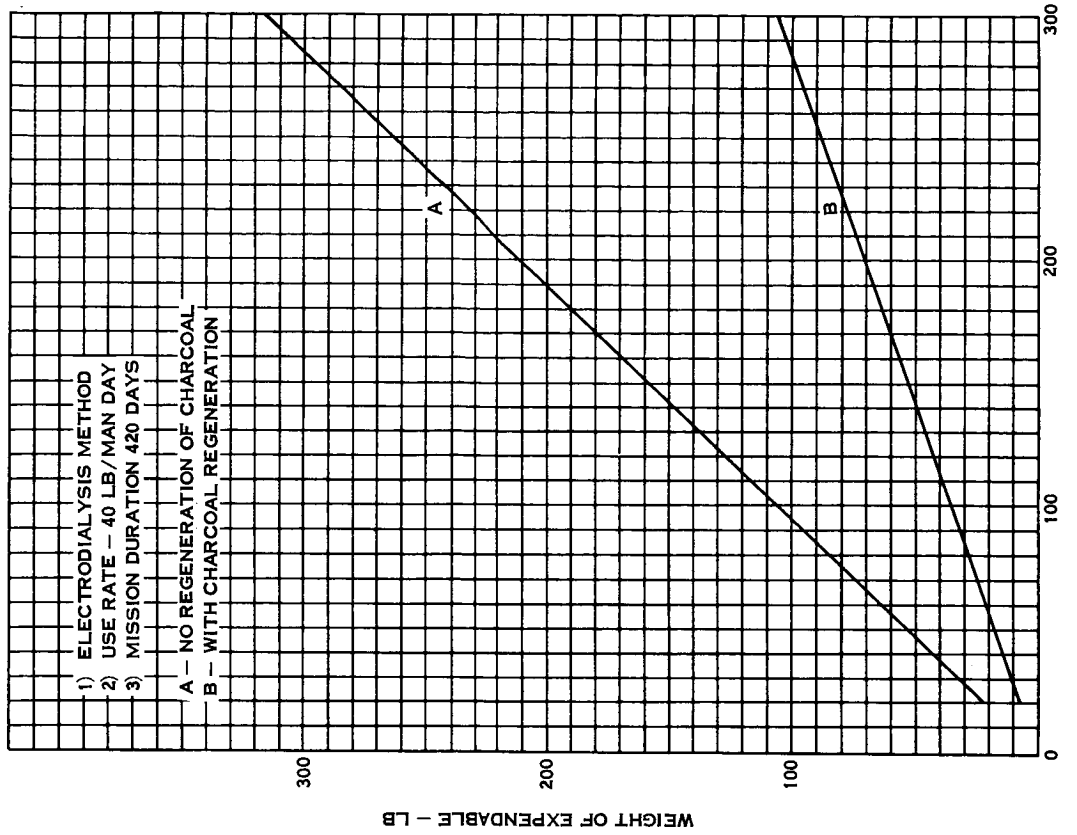


FIGURE 8–46

WASH WATER RECLAMATION
POWER CONSUMPTION VS PROCESS RATE

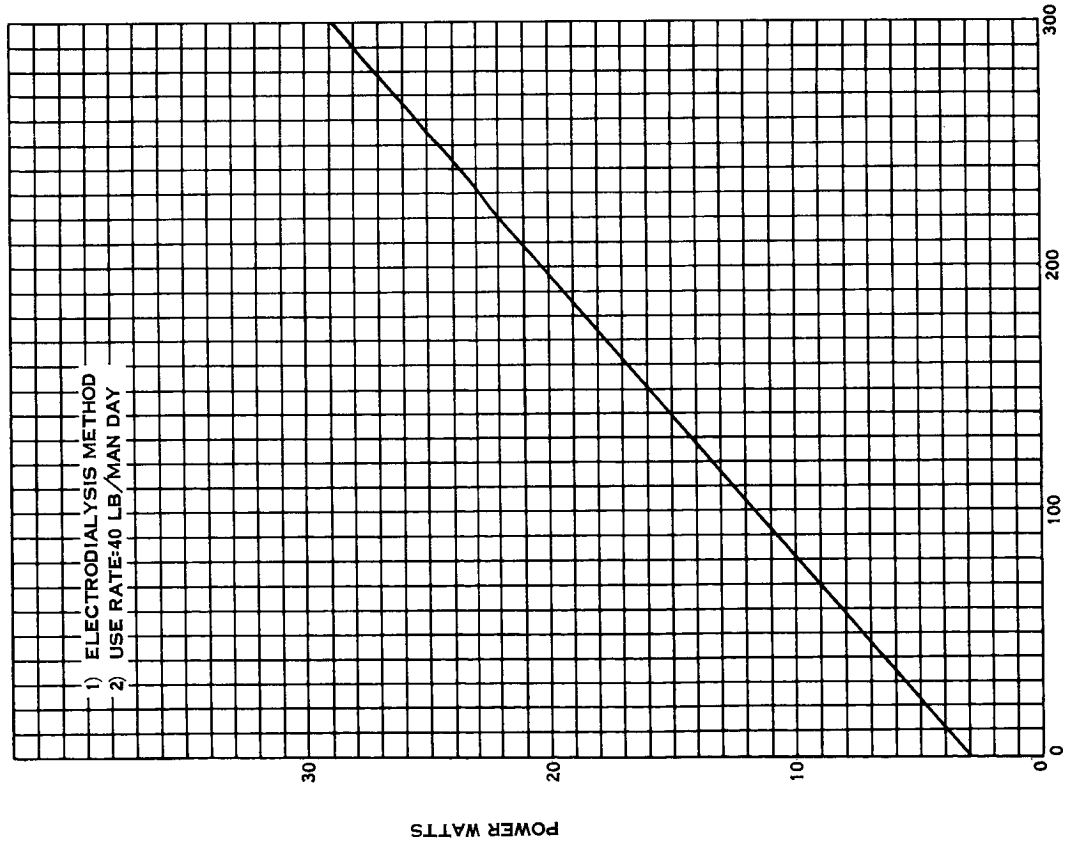


FIGURE 8–45

WASH WATER RECLAMATION SUMMARY
EQUIVALENT WEIGHT VS PROCESS RATE

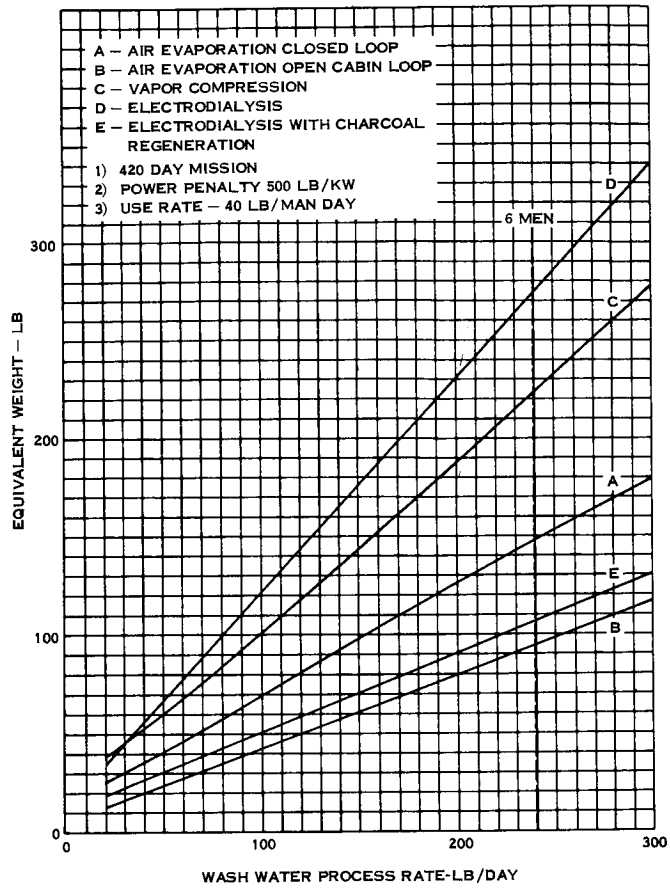


FIGURE 8–47

WASH WATER RECLAMATION SUMMARY
EQUIVALENT WEIGHT VS MISSION DURATION

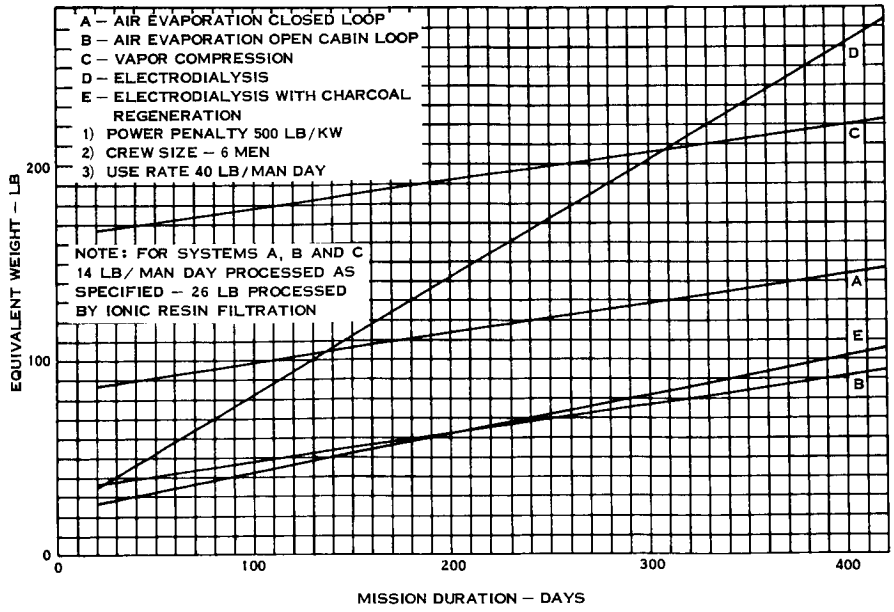


FIGURE 8 – 48

8.11.4 Conclusions

It can be seen from Figure 8-47 and 8-48 that electrodialysis is too heavy when used without charcoal regeneration, but is very competitive if charcoal regeneration is considered. As has been mentioned in connection with urine systems, however, the successful regeneration of charcoal may present formidable problems.

Vapor compression presents a high equivalent weight due to the relatively high fixed weight of the system.

It can be seen from the equivalent weight summaries, 8-42, 43, 47 and 48, that air evaporation is very competitive on a weight basis, especially when the open loop arrangement is employed.

As a conclusion from these comparisons, it is recommended that efforts be continued to further develop an open loop air evaporation system for the recovery of wash water.

8.12 Humidity Water Reclamation

The humidity control system constantly removes water from the cabin atmosphere in order to maintain a comfortable relative humidity. The actual mechanics of this water removal are described under the section on humidity control.

It can be seen from examination of the water requirements that humidity water is needed to complete the metabolic balance. This section considers the treatment of this water.

It is anticipated that humidity water will be basically pure with a minimum of processing required. The environmental control system will contain a contaminant control subsystem to purify the atmosphere which should inhibit the build up of contaminants in the humidity water.

Humidity water treatment should consist of filtration for particulate removal and filtration through charcoal and ion exchange resins for control of odor and taste.

At this time, there is no certainty concerning the condition of water recovered from a humidity control system due to the large number of variables involved. There is a need for more experimental evidence from simulated space capsule operation to verify the exact water processing requirements. Tests of water recovered from the humidity control system of a "clean room" at Hamilton Standard showed that it was potable with no bacteria, low solids content, and very slight odor.

8.13 Potability Testing of Water

8.13.1 Introduction

A complete water management system must include an inspection process to guarantee that the recovered water is potable. If a contaminant is detected, the faulty subsystem will be isolated and repaired and the contaminated water can then be reprocessed.

8.13.2 General Testing

The testing proposed here covers general methods that would be considered suitable for any water recovery system. The spacecraft environment is basically clean without many of the contaminants that would be found on earth.

Water potability testing would include the following contaminant areas:

1. Salts, minerals and other inorganic compounds.
2. Non-living organic materials.
3. Bacteria, fungus or mold.

The anticipated sources of contamination are carryover of raw urine from the urine processing system or failure of charcoal filters due to overloading.

8.13.2.1 Tests for Inorganic Materials

A sample of the recovered water will be tested with a conductivity cell. This will be capable of detecting ionic constituents down to 3 ppm. Through careful attention to material selection in the space cabin design, it should be possible to eliminate substances that would be harmful in concentrations below 3 ppm.

8.13.2.2 Tests for Non-Living Organic Materials

A sample of water would be evaporated and the residue heated with oxygen. The exhaust gas could then be examined for the presence of carbon dioxide.

8.13.2.3 Tests for Bacteria, Fungus or Mold

If it is considered undesirable to spend the time required to grow culture, a direct examination for bacteria is possible. A sample would be passed through a millipore filter and the residue treated with a bacterial stain. This would be examined under

8.13.2.3 (Continued)

a microscope and a bacterial count carried out. If, however, a positive identification of bacterial types is required, then a culture must be grown over a twenty-four hour period or longer.

8.13.3 Bacterial Control by Hot Storage

It is proposed that the water management system include hot storage as a final means of bacterial control. The water used for food preparation, warm drinks and bathing will require heating before use, so it is proposed that all water storage tanks be maintained at 140 to 160°F. At this temperature, non-sporulating types such as enteric or coliform bacteria would be killed and any remaining spore types such as bacillus would be greatly inhibited. In addition, water boils at 177°F in a 7.0 psia atmosphere; therefore, to provide a margin of safety 160°F was selected as the maximum storage temperature.

In tests at Hamilton Standard, pure potable water was first exposed to the atmosphere until air-born bacteria had raised the bacteria count to a high level. Then the water was heated to various temperatures (170, 165 and 140°F) for varying periods of time up to four weeks. At 165°F the bacteria counts made were all zero per ml, whereas at the lower temperature (140°F), a maximum count of 40 per ml was obtained. For comparison purposes: Grade "A" milk has a maximum bacteria count of 30,000 per ml and certified milk has a maximum count of 500 per ml. Consequently, even the lower temperature processing is an order of magnitude lower than the most stringent requirements for milk. In addition, this water was fed to a primate for a period of 60 days with no ill effects. From the results of these tests, the lower temperature limit of hot water storage was selected at 140°F.

Because of the effectiveness of hot storage in maintaining bacteria free water, it is recommended as part of the water management system.

8.14 References

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3. Water Reclamation Subsystem for Manned Vehicles Having Extended Missions, Ionics Incorporated, No. 11-P-63-25.

8.14 (Continued)

4. Electrolysis Fuel Cell System, General Electric Co., Report AMRL-TDR-63-32.

5. A Study of Water Reclamation Systems for Space Stations, General Dynamics Corporation, Electric Boat Division, U 413-62-208.

6. Recovery of Water During Space Missions, F. J. Hendel, ARS Journal, December 1962.

7. Vacuum Distillation With Pyrolysis, General Electric Co., R 62 SD 39.

8. Vapor Compressor Water Reclamation System, General American Transportation Co., Mechanics Research Divison, MR 1186-30, MR 5614-0.

SECTION 9.0

WASTE MANAGEMENT

9.0 WASTE MANAGEMENT

9.1 Introduction

The subsystem survey of waste management was concerned primarily with treatment and processing of feces although many other items must be considered when a better overall vehicle waste analysis is available. Other items such as paper, food wastes, other personal wastes and equipment waste are not well defined at this phase of the Mar's mission analysis. The waste materials present two basic problems in a closed environment. Primarily, the potential presence of pathogenic organisms which could be detrimental to crew health must be considered and secondly, any water trapped in the wastes should be recovered if possible. This discussion will concern itself with fecal processing since it presents the most severe technical problem due to the high bacteria content.

9.2 Processing

9.2.1 General

Four general methods of feces processing were considered in this study.

1. Storage
   a. Simple storage
   b. Storage preceded by germicide treatment
2. Distillation and Pyrolysis
3. Incineration
4. Microbiological Treatment

Methods 2, 3, and 4 result in recovery of the fecal water while Method 1 does not.

The study was based on the assumption that fecal production rate was 0.50 lb./man day of which 0.33 lb. was water. Briefly, this means that 6 men on a 420 day mission would produce 1260 lb. of feces containing 840 lbs. of water.

9.2.2 Processing Without Water Recovery

9.2.2.1 Storage

A brief review showed that mere collection and storage of untreated feces was unacceptable for the following reasons:

9.2.2.1 (Continued)

a) The feces contain pathogenic bacteria that would multiply rapidly at normal room temperature and the presence of such material on the spacecraft would constitute an unacceptable hazard to the health and safety of the crew.

b) It has been estimated that untreated feces will generate 5 ml STP of gases per gram. Since some of these gases are extremely unpleasant or odorous a storage system would have to be pressurized and leakproof or the system would have to be carefully designed to vent to the contaminant control equipment.

c) The containers and storage system would have to be strong enough to resist any possibility of bursting under conditions of rapid cabin depressurization.

d) If any failure of the containers should occur such as burst or leakage, the contaminated matter could be spread throughout the space cabin.

9.2.2.2 Storage with Germicide Treatment

The most straight forward treatment deemed suitable for space flight is simple storage of the feces following thorough mixing with a germicide. This system has many advantages in simplicity and safety. By virtue of chemical treatment immediately after collection there is minimum danger from pathogenic organisms. The following is quoted from reference 7:

"Most important is the fail-safe potential of a chemical system. Once the waste materials are properly treated with an effective broad-spectrum antimicrobichemical, they cannot putrefy regardless of what happens to the equipment. Aseptic storage would be unnecessary since any contaminating organisms that enter the stored waste would be killed or inhibited by the chemical contained in the waste".

The chemicals suitable for bacterial treatment fall into two classes, gas and liquid. The use of gas, such as ethylene oxide, is rejected for safety reasons. Any leaks due to failures of any sort would introduce these gases directly into the cabin atmosphere. It has been stated that "Use of sterilizing gases would probably result in greater hazards than those from putrefaction, as an equipment failure in a closed system could prove fatal to the astronauts."

A very suitable chemical preservative is Weladyne, prepared by West Chemical Products, Inc. This is a type known as iodophor, consisting of a complex formed by attachment of iodine to large, surface active organic molecules. This provides positive killing action against all types of bacteria including spores. It has been estimated that if the germicide is used in a concentrated form, a weight equivalent to 2% of the weight of feces will be sufficient.

9.2.2.2 (Continued)

An important aspect of the disinfecting of feces is the method of mixing with the germicide. For very short duration missions, the feces could be collected in plastic bags, sealed and manually kneaded to thoroughly mix the disinfectant chemical. However, this process would be too tedious to repeat regularly during a long mission and some forms of mechanical mixing must be developed. There are a variety of methods that might be used and development of a suitable device is one element in this system that requires further work. Some possible methods are discussed below.

The feces could be placed in a flexible plastic container and the contents kneaded by an external mechanical device. In this approach, a mechanical "kneading machine" merely replaces and duplicates the action performed by the astronaut on a short mission. The next most obvious approach is to use direct mechanical mixing. In a number of studies, a device resembling a household blender has been recommended. In a report by General Electric, they have tested devices resembling blenders, household meat grinders with screw feed, and centrifugal impellers that force the waste matter through screens. In many industrial processes, mixing of semi-solid substances is required and some adaptation of these methods to miniaturized space hardware should be possible. One possible example is the bread making machines used for kneading dough. Another process that has considerable simplicity is the shaker used to mix paint when a tube of color is added to a base. It might be possible to collect the feces in a can, add germicides, seal the can lid and simply shake for a specific time period.

A suitable device for mixing germicide should be obtainable at a weight no greater than eight pounds. One factor which will aid the distribution of a chemical in liquid form is the fact that in zero "g", capillary forces become more significant than they are on earth, and this will increase the tendency for the germicide to diffuse throughout the feces.

The feces would be stored in small containers after the addition of germicide. These would have some form of sealing, probably a screw top and would be strong enough to withstand 7 psi pressure differential in case the cabin became depressurized. If manufactured of aluminum or plastic, the wall thickness would be determined by stiffness requirements for handling rather than bursting strength. Suitable containers would probably weigh less than 10% of the weight of feces contained.

A final method of treating feces is to store the waste in the frozen form. Without germicide treatment, however, this is not sufficiently safe, for any subsequent failure of the refrigeration system would render the waste susceptible to putrefaction. If germicide is added, the same system and expendables are required as for the system previously described, and the weight and power required for freezing have to be paid for without substantial additional benefit.

9.2.3 Processing of Feces with Water Removal

The next approach to feces control is to consider processes that remove and recover the water which accounts for approximately two thirds of the total weight.

The primary consideration here is whether or not the recovered water can be considered fit for use. If it is not to be used but merely allowed to leak overboard from a feces drying system there is not much advantage to be obtained over the simple storage and germicide system described previously. If the reclaimed water is not to be used the original capsule take-off weight is the same whether the feces is stored wet or dry. Since the wet processed feces will occupy less volume than that originally required for food, the additional volume attained by drying of the feces is not of great consequence. Once a space capsule is in orbit any small weight reduction achieved by ejecting fecal water overboard is of very small benefit and hardly worth the energy required to extract the water.

However due to the length of the mission the total weight of fecal water produced is 840 pounds and as such, very serious consideration must be given to any possible method of reclamation for use on the space capsule.

While it is recognized that there are serious technical and aesthetic problems to the use of fecal water for human consumption there is a possible alternative to wasting 840 lbs. of water. This is to reclaim the fecal water and use it in an electrolysis cell to produce oxygen.

If the cabin leakage on the Mars Mission Module is at the maximum allowable value of 0.1 lb./hr. then the total mission atmosphere loss will require approximately 500 lbs. of oxygen for make-up and this could well be supplied through electrolysis of fecal water. While the technical problems of odor removal and sterilization would still be severe the aesthetic objections to the use of fecal water would be largely overcome. As a consequence of this possible water use, consideration is given to the processing of feces to recover sterile water. The following methods have been considered.

9.2.3.1 Distillation and Pyrolysis

The moisture content of feces can be reclaimed by applying heat in a distillation process. The water distillate has been found to contain a distinct fecal odor and is therefore directed to a pyrolysis cell where passage over a catalyst bed at 1850°F has been found effective for destroying all bacteria and eliminating any odors. Figure 9-1 shows the schematic of a proposed water recovery system. A regenerative heat exchanger is located between the distillate chamber and pyrolysis unit to minimize the required input power. The pyrolysis cell effluent vapor is cooled by the regenerative heat exchanger and then directed to the condenser. After being condensed the water is held in a

9.2.3.1 (Continued)

storage tank until required by the electrolysis cell. The electrolysis cell can operate at or near cabin pressure and can produce make-up oxygen on demand. Figure 9-2 shows the fixed weight and total equivalent weight for various power penalties as a function of crew capacity and is based on the production shown in Figure 9-4. The required input power,which includes heating for distillation, pyrolysis and make up for leakage, is shown in Figure 9-3. A trade-off was performed between insulation weight and heat leakage equivalent weight penalty using Johns-Manville MIN K 503 superinsulation. No penalty has been charged for cooling (vapor condensation) since the penalty is determined by the heat sink performance characteristics which require a system integration analysis for definition. The required amount of cooling is equal to that of the power input.

WASTE PRODUCT
WATER RECOVERY SYSTEM

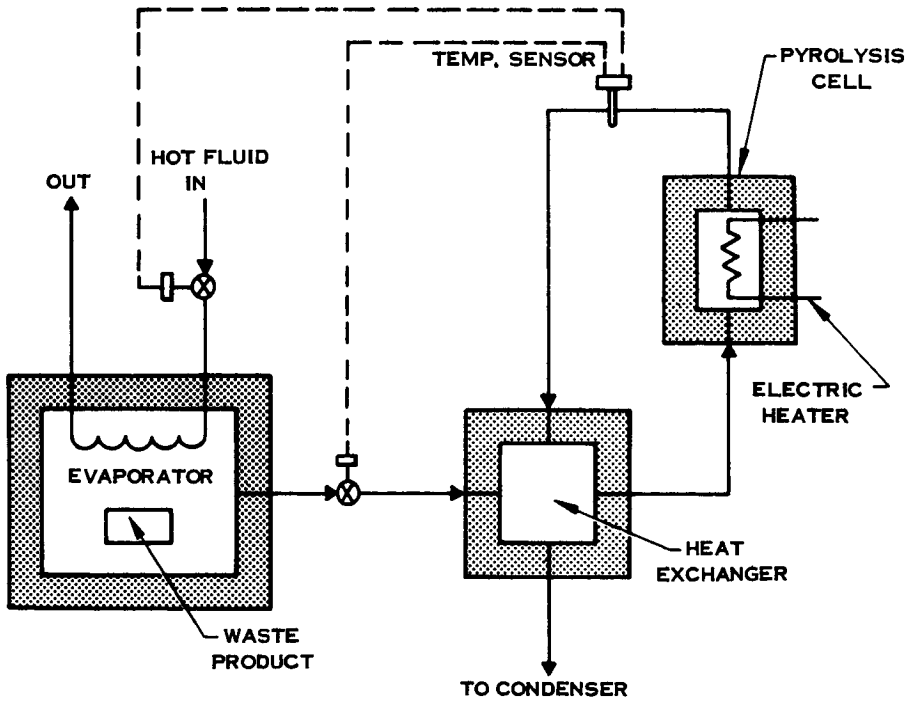


FIGURE 9-1

FECES WATER RECLAMATION SYSTEM
TOTAL EQUIVALENT WEIGHT VS CREW CAPACITY

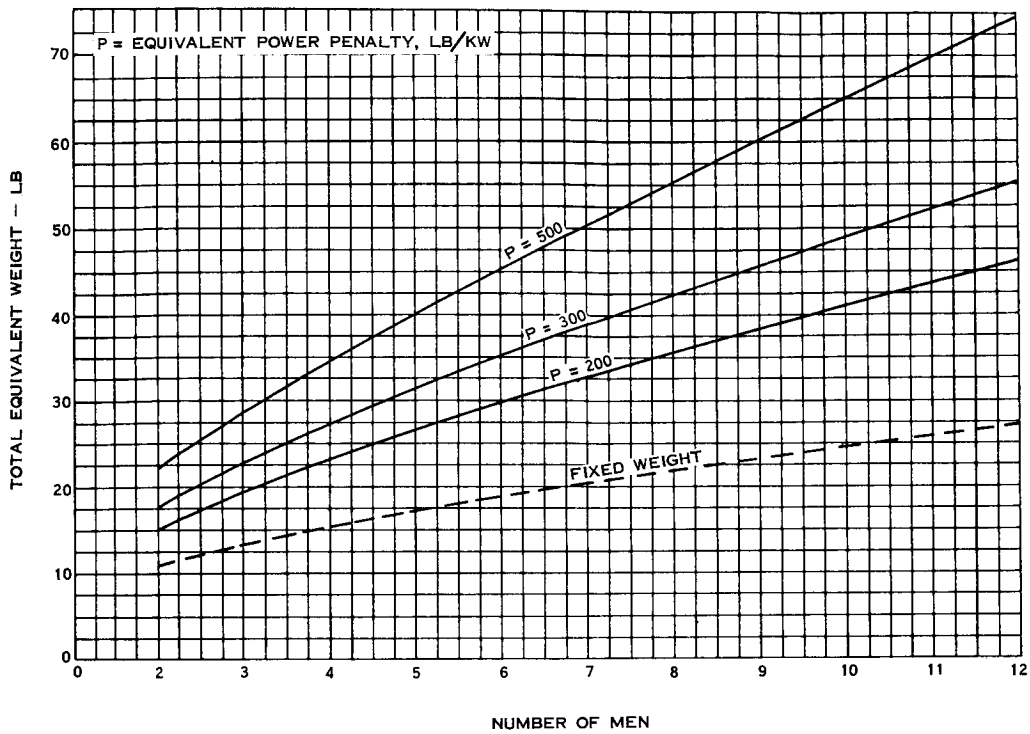


FIGURE 9–2

FECES WATER RECLAMATION SYSTEM
POWER VS CREW CAPACITY

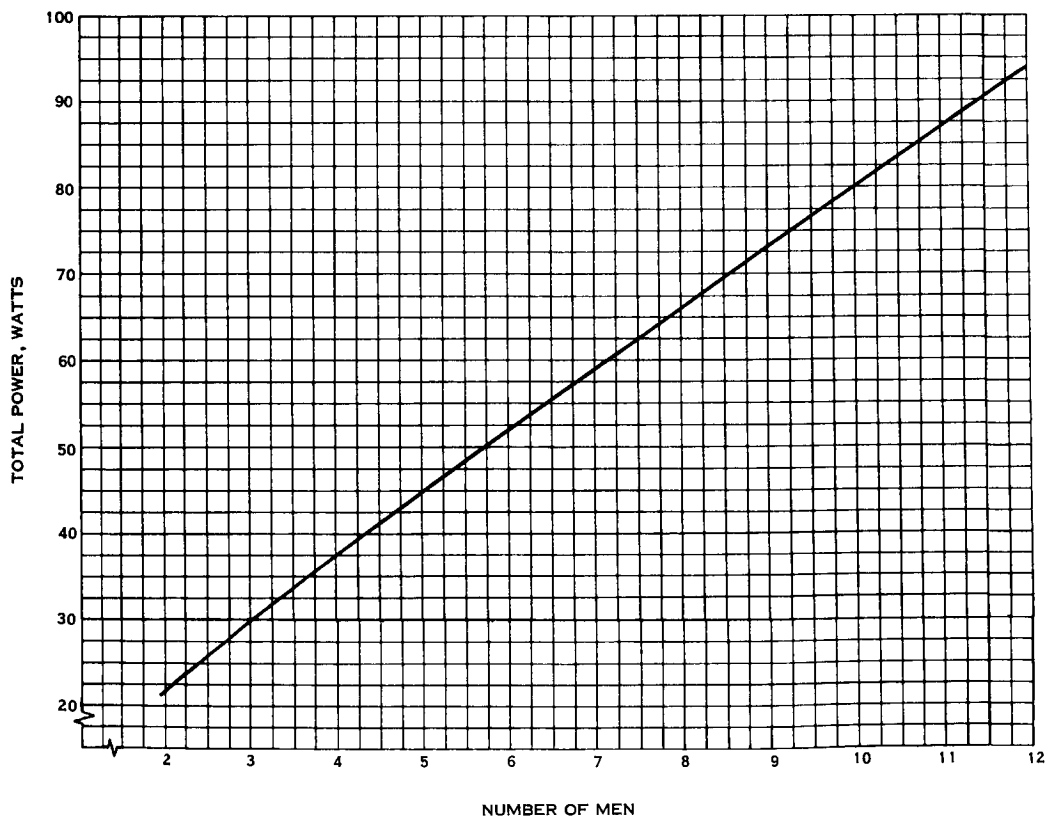
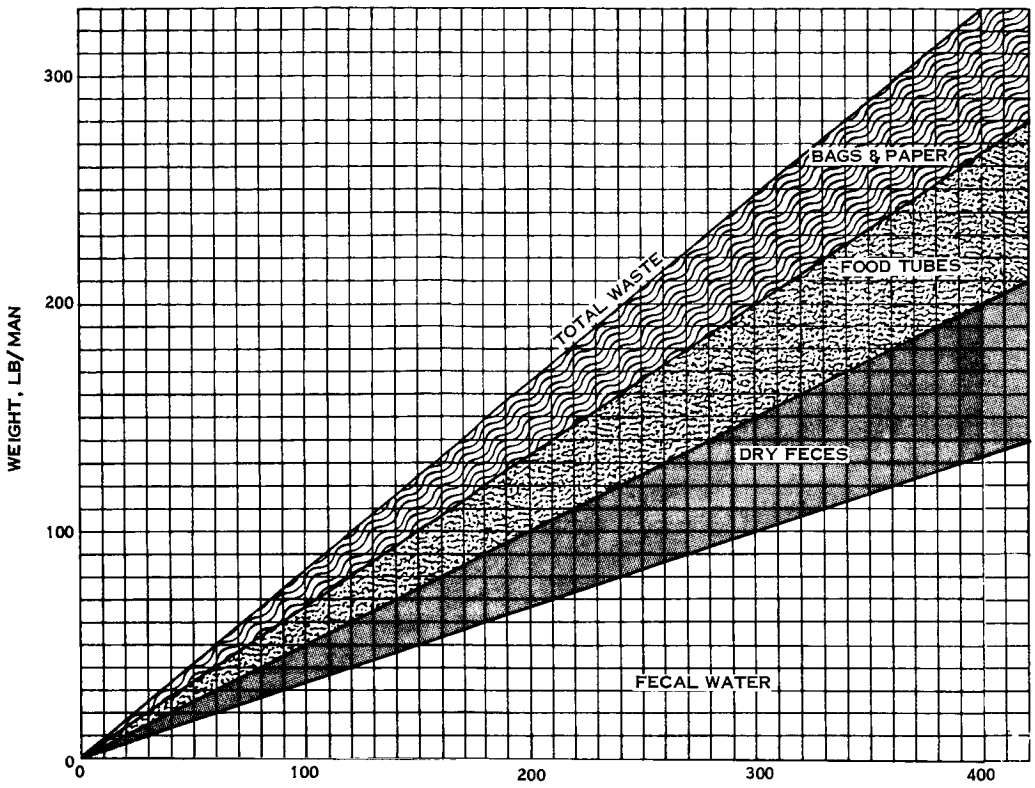


FIGURE 9–3

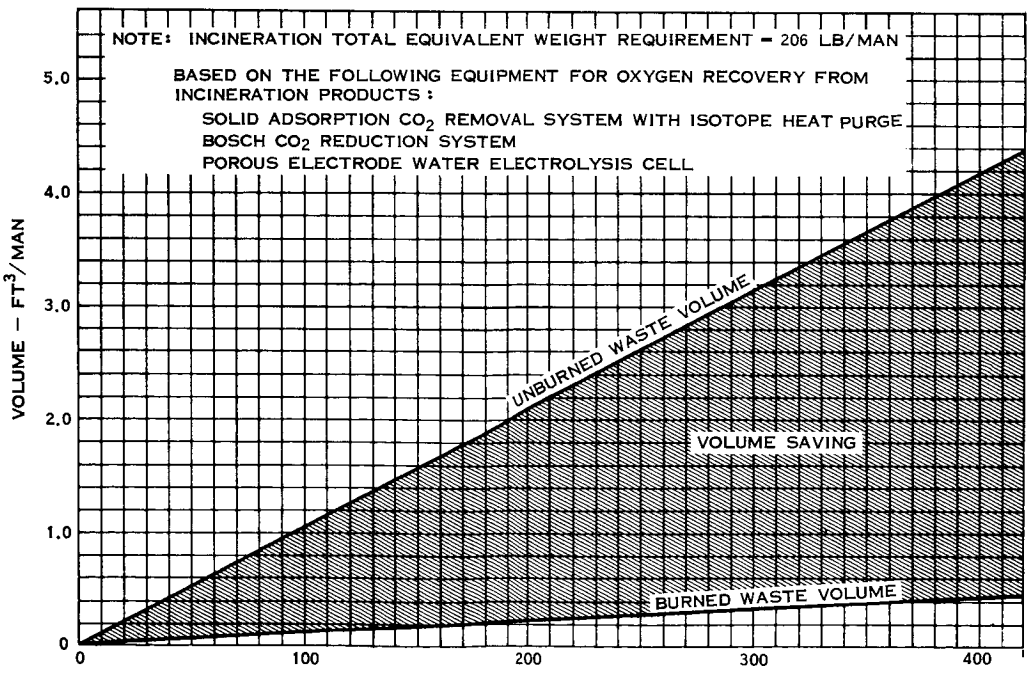
WASTE WEIGHT VS MISSION DURATION



MISSION DURATION, DAYS

FIGURE 9–4

WASTE INCINERATOR
VOLUME SAVING VS MISSION DURATION



MISSION DURATION DAYS

FIGURE 9–5

9.2.3.2 Incineration

Upon dehydration, the product residue can be incinerated if further reduction in waste products is desired. Incineration can be accomplished by admitting a controlled flow of oxygen which is regeneratively pre-heated by effluent products of combustion. The carbon and hydrogen present in the waste are oxidized to carbon dioxide and water vapor respectively. In order to provide efficient operation, the oxygen containing products of reaction are directed to reduction units where the oxygen is reclaimed for subsequent re-cycling to the incinerator. Analysis was performed for incineration of the dry waste products depicted graphically in Figure 9-4 as a function of mission duration. The total equivalent weight of an incineration system is shown in Figure 9-5 and includes the weight and power for the incinerator plus the products of combustion control systems along with the oxygen recovery system. Complete combustion has been assumed in the calculations. This has been found to occur during tests reported by MRD in "Waste Disposal for Aerospace Missions". The equivalent weight penalty is shown as directly proportional to crew capacity. Although a slight deviation from direct proportionality does exist, it was felt to be insignificantly small. Also shown on the curve is the volume saving as a function of mission duration which allows a trade-off between volume and total equivalent weight. It is noted that any volume saving requires a large amount of power and weight.

The possibility of incinerating in a closed non-flow volume was reviewed. Operation would be similar to that used in bomb calorimeter tests. Advantages would be the reduction of any danger of undesirable gaseous carryover as well as elimination of controls necessary for monitoring flow to the open incinerator system. However, it is felt these are outweighed by the disadvantages connected with a closed system. That is, the system must be operated at very high pressures with less control of the combustion process. In addition a regenerable heat input can no longer be used to minimize input power. Oxygen reclaimed from the combustion products would have to be pumped up to a high pressure for admittance to the combustion chamber.

9.2.3.3 Microbiological Treatment of Waste Products

Another method of handling waste products utilizes biological processes whereby organic waste compounds are used up by biota in supporting microbial metabolism either in the presence (aerobic biota) or absence (anaerobic biota) of free oxygen. The aerobic process is relatively rapid and produces end products (mostly CO_2) which are not noxious and do not support pathogens (virus). The anaerobic systems

9.2.3.3 (Continued)

eliminate the oxygen supply requirement since oxygen necessary for metabolism is derived from compounds in the waste. However, the waste digestion process is slow and results in such noxious gases as hydrogen sulfide, carbon monoxide, and pyrimidines. The main digestor gases are methane and carbon dioxide. Pathogens do tend to thrive in this type environment. For these reasons the aerobic process appears to be the more attractive of the two biological processes. There is substantial evidence that only a few of the necessary aerobic biota required to handle a broad spectrum of waste products are found in human discharges such as feces, perspiration and urine. It has been stated in "Microbiological Waste Treatment Processes in a Closed Ecology" that both replacement and replenishment would probably be required in a workable biological system. Mixed biota cultures would be carried in the frozen state until required.

The development status of aerospace equipment employing microbiological processes for waste disposal is relatively weak, and good quantitative performance characteristics are not available.

However, based on processes explored in the laboratory, the following numbers are offered indicating the minimum predicted power associated with the various processing equipment as defined in "Microbiological Waste Treatment Processes in a Closed Ecology".

Process	Power (watts/man)	Volume (ft^3/man)
Aerobic		
Activated Sludge	1000	2
Trickling Filter	200	.7
Anaerobic		
Mesophilic Digestion (20°C to 43°C)	100	.4
Thermophilic Digestion (43°C to 56°C)	200	.4

In lieu of the large penalty and the many problems of biological waste treatments, this process appears relatively unattractive for semi-closed ecological systems with interest in re-cycling the water product of feces only. This process increases in attractiveness for more completely closed systems associated with large crew capacity permanent outputs (i.e., lunar bases) where carbon will be re-cycled by integrating waste management with photosynthetic processes.

9.3 Summary

For the extended mission in the MMM it is recommended that the feces be first treated with a germicide immediately after collection to minimize the possibility of contamination. Following this it is recommended that the feces be dried and the vapors pyrolized and recovered for use in an electrolysis cell. For 6 men in the MMM Figure 9-6 shows the total stored weight without water extraction. This includes feces, germicide and containers. This can be contrasted with the following weight for a drying and pyrolysis system:

a) Without water extraction

Germicide, mixer and storage containers	175 lb
Wet feces	1260 lb
Total weight in system	1435 lb
Water contained in stored feces and unavailable for use	840 lb

b) Water extraction following germicide treatment and pyrolysis

Germicide, mixer and storage containers	175 lb
Dried feces residue	420 lb
Evaporator and pyrolysis unit	45 lb
Condenser	1 lb
Electrolysis unit (500 lb/KW Power Penalty)	100 lb
Total	741 lb
Water released for use	840 lb
Oxygen contained in water	746 lb

The above figures compare two systems of feces treatment, both with and without water extraction. It can be seen that by employing system (b) it is possible to extract 746 lb. of oxygen from the fecal water. This is accomplished by the use of an evaporator pyrolysis unit and electrolysis unit of 146 lb. equivalent weight.

In either case (a) or (b) above, the same weight is required for germicide treatment and storage of the feces or dried feces residue.

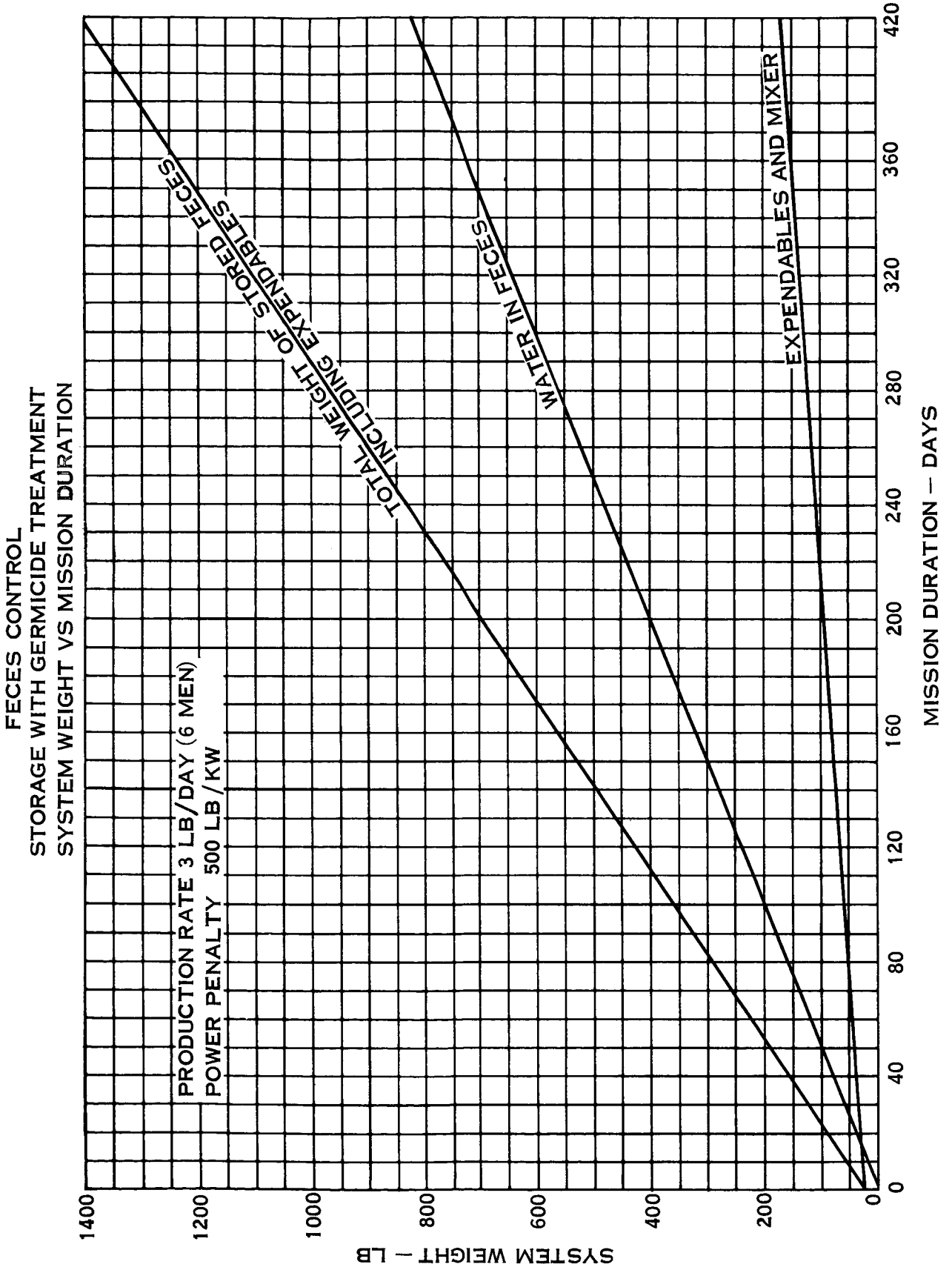

FECES CONTROL
STORAGE WITH GERMICIDE TREATMENT
SYSTEM WEIGHT VS MISSION DURATION
PRODUCTION RATE 3 LB/DAY (6 MEN)
POWER PENALTY 500 LB/KW
TOTAL WEIGHT OF STORED FECES INCLUDING EXPENDABLES
WATER IN FECES
EXPENDABLES AND MIXER
SYSTEM WEIGHT — LB
0
200
400
600
800
1000
1200
1400
MISSION DURATION — DAYS
0
40
80
120
160
200
240
280
320
360
420

FIGURE 9–6

9.4 References

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SECTION 10.0

THERMAL AND HUMIDITY CONTROL

10.0 THERMAL AND HUMIDITY CONTROL

10.1 Objectives

This section presents a general discussion of the requirements of the major components associated with the temperature and humidity control functions. Separate headings discuss fans, water separators, the space radiator, and heat exchangers. To more fully illustrate the effect of the overall system design point on these items, generalized sizing data is presented.

The actual design of any of this equipment is dependent upon the ultimate system sizing, thus a full parametric treatment is not possible on a subsystem basis. The data, therefore, may be used for generalized early studies but should not be loosely over-interpreted to any specific case without careful examination.

The discussion on space radiators presents background studies on coolant choice, meteoroid protection, etc. with the actual sizing procedure treated in the system volume of this report.

10.2 Coolant Survey

10.2.1 Discussion

The coolant survey for the space radiator consisted of a series of contacts with manufacturers of candidate fluids to determine the latest properties of the particular fluid. Initially, these properties were compiled for general reference as illustrated in Table 10-1. This table presents the important fluid properties over the general operating range. Reference to the table illustrates that considerable gaps appear in the data for several fluids due to either their limited usage to-date or lack of previous interest in the particular property at the temperature indicated.

Although this table is sufficient from a reference point of view, it does not provide a rapid indication of the more attractive fluids at any particular operating temperature. In an attempt to provide a rapid visual determination of the relative merits of each fluid, a fluid properties parameter based on overall system performance which is proportional to the ratio of pumping power to heat transfer conductance was derived for both laminar and turbulent flow.

The derivation of the parameter is based on the pipe pressure drop equation, friction factor equation for pipe flow, Nusselt number equation for flow in round tubes, and the normal heat exchanger or radiator heat balance equation. These expressions are as follows:

TABLE 10-1

COMPARISON OF THE PROPERTIES OF HEAT TRANSPORT FLUIDS

Property	Units	Ethylene Glycol Solution (60-40)	Coolanol 35 (Monsanto)	Coolanol 45 (Monsanto)	OS-45-IV (Monsanto)	OS-139 (Monsanto)	MC-198 (Monsanto)	FC-75 (3M)	Oronite 8200	QF-1-0077 (Dow Corning)
Boiling Temp. @ 1 ATM.	°F	> 234	> 600	> 500	> 700		460	210/224	> 500	> 600
Pour Point	°F	-80	< -120	< -85	< -85	< -100	< -120	< -80	-100	< -80
Flash Point	°F		370	370	370	340	170	None	390/405	405
Toxicity		NIL	NIL	NIL			Somewhat @ 300°F	NIL	NIL	Relatively Non-Toxic
Operating Temp. Range	°F	-65/250	-65/300	-65/400		-100/300	-	-80/441	-65/500	-80/600
Density @ -65°F	lb_m/ft^3	71.5	58.9	59.3		59.9	59.9	122.3	61.2	58 (*2)
Density @ 100°F	lb_m/ft^3	67.0	54.1	54.5	55.6 @ 77°F	55.2	55.5	107.5	56.4	54 (*1)
Viscosity @ -65°F	lb_m/ft-hr	3050	2100	5520		545	62.0	32	5430	2930 (*2)
Viscosity @ 100°F	lb_m/ft-hr	6.8	13.7	27.5	28 @ 77 (*2)	9.09	3.65	2.78	71.6	16 (*1)
Specific Heat @ -65°F	Btu/lb_m-°F	.588	.378	.377		.38 (*2)	.40	0.215	.29	.375
Specific Heat @ 100°F	Btu/lb_m-°F	.767	.467	.462	.45 @ 77°F	.46 (*1)	.45	0.252	.39	.446
Thermal Conductivity @ -65°F	Btu/hr-ft-°F	.230	.0505 (*1)	.0622 (*1)				0.088		
Thermal Conductivity @ 100°F	Btu/hr-ft-°F	0.221	.0706	.0753	.08 @ 77°F	.0763 (*1)	.058 (*1)	0.0775	.080	.076
Relative Laminar Pumping Power @ -65°F	Pump HP / Pump HP For Glycol @ 100°F	674	1650	4280		410		14.1	6700	
Relative Laminar Pumping Power @ 100°F	Pump HP / Pump HP For Glycol @ 100°F	1.0	8.4	17.0	17.3 @ 77°F	5.5	4.96 @ 30°F	1.47	57.6	16.8

Notes:

(*1) obtained by linear interpolation between two points
(*2) obtained by linear extrapolation beyond two points.

10.2.1 (Continued)

$$\Delta P = \frac{2f\, L_p W^2}{D_p\, g \rho A_p^2} \quad (1)$$

$$f = \frac{0.0791}{(Re_p)^{0.25}} = \frac{0.0791}{\left(\frac{W\ D_p}{A_p\, \mu}\right)^{0.25}} \qquad \text{Turbulent Flow (2)}$$

$$Nu = 0.027\ Re_h^{0.8}\ Pr^{0.33} \left(\frac{\mu_a}{\mu_s}\right)^{0.14} \qquad \text{Turbulent Flow (3)}$$

where: $Nu = \frac{h\ D_h}{k}$

$$Re_h = \frac{W\ D_h}{A_h\, \mu}$$

$$Pr = \frac{\mu C_p}{k}$$

$$Q = WC_p\ (T_{f_1} - T_{f_2}) \quad (4)$$

Equation (3) is the turbulent flow equation recommended by McAdams (1942) for highly viscous fluids. The

$$\left(\frac{\mu_a}{\mu_s}\right)^{.14}$$

term in equation (3) is the contribution of Sieder and Tate (1936), which makes the equation valid for both heating and cooling. This equation is only the last of a series of similar equations, all having 0.8 as the exponent of the Reynolds number, but with exponents of the Prandtl number varying from 0.3 to 0.4. Previous authors gave slightly different constant factors for the equation and exponents of the Prandtl number for cooling and heating, but no universal equation for both. However, since both heating and cooling of the transport fluid is taking place in the heat exchangers around the loop, this term will be greater than 1 when the fluid is being heated and less than 1 when the fluid is being cooled. The most serious variation from unity would occur near the freezing point of the fluid, where the slope of the viscosity curve versus temperature becomes very steep.

10.2.1 (Continued)

However, for the most part, the design of the system will be such that the selected heat transport fluid will not be operating near its freezing point for any significant period of time. For this reason and to provide a general equation of reasonable validity and accuracy for comparative evaluation of heat transport fluids within an overall system, the following assumption was made:

$$\left(\frac{\mu_a}{\mu_s}\right)^{0.14} \approx 1$$

In addition to these equations, it was assumed that the operating conditions and all of the transport loop dimensions, except the overall radiator and heat exchanger sizes, are the same for all fluids. This says that L_p, A_p, D_p, D_h, A_h, Q and $(T_{f_1} - T_{f_2})$ are essentially the same for all fluids.

The turbulent pumping power for a transport fluid loop was derived from the first two equations.

$$\text{Turbulent pumping power} = \frac{W\Delta P}{\rho} = \frac{0.1582\, L_p\, W^3}{D_p\, g\, \rho^2\, A_p^2 \left(\frac{W D_h}{A_p \mu}\right)^{0.25}} \qquad (5)$$

The assumptions reduce this equation to the following proportionality:

$$\text{Turbulent pumping power} \propto \frac{\mu^{0.25}\, W^{2.75}}{\rho^2} \qquad (6)$$

However, equation (4) and the assumptions imply that the fluid flow rate, W, is inversely proportional to the fluid specific heat, C_p.

$$\text{Turbulent pumping power} \propto \frac{\mu^{0.25}}{C_p^{2.75}\, \rho^2} \qquad (7)$$

By means of a similar procedure, the following proportionality can be derived for the fluid turbulent convection coefficient for the heat exchanger or space radiator.

$$h \propto \frac{k^{0.67}}{(C_p\, \mu)^{0.47}}$$

10.2.1 (Continued)

The convection coefficient is essentially a measure of the heat transfer conductance of a fluid. Thus, the ratio of the pumping power to the heat transfer conductance is proportional to a quantity which is exclusively a function of fluid properties. This proportionality is:

$$\frac{\text{Turbulent Pumping Power}}{\text{Turbulent Heat Transfer Conductance}} = \chi \propto \frac{\mu^{0.72}}{C_p^{2.28}\, k^{0.67}\, \rho^{2}} \qquad (9)$$

A similar analysis can be made for laminar flow through the pipes and over the heat transfer surfaces using the following equations:

$$Nu = 1.86\, Re^{1/3}\, Pr^{1/3} \left(\frac{D_h}{L}\right)^{1/3} \left(\frac{\mu_a}{\mu_s}\right)^{0.14} \qquad \text{Laminar Flow (10)}$$

where: $Nu = \dfrac{h\, D_h}{k}$

$Re = \dfrac{W\, D_h}{A_h\, \mu}$

$Pr = \dfrac{\mu\, C_p}{k}$

Again $\left(\dfrac{\mu_a}{\mu_s}\right)^{0.14} \approx 1$ was assumed as an average. This was defined on Page 10-4, within a loop doing both heating and cooling.

From this:

$$\frac{hD_h}{k} = \text{constant} \left(\frac{W\, D_h}{A_h\, \mu}\right)^{0.33} \left(\frac{\mu\, C_p}{k}\right)^{0.33} \qquad (11)$$

Equation (11) can be reduced to the following proportionality:

$$h \propto k^{0.67} \qquad (12)$$

For laminar flow, the pipe friction factor is as follows:

$$f = \frac{16}{Re_p} = \frac{16\, A_p\, \mu}{W\, D_p} \qquad (13)$$

10.2.1 (Continued)

This can be substituted into equation (1) to derive the laminar pumping power.

$$\text{Laminar Pumping Power} = \frac{W\Delta P}{\rho} = \frac{32\ L_p\ \mu\ W^2}{D_p^{\ 2}\ g\ A_p \rho^2} \qquad (14)$$

The assumptions reduce this equation to the following proportionality:

$$\text{Laminar Pumping Power} \propto \frac{\mu W^2}{\rho^2} \qquad (15)$$

Equation (4) and the assumptions imply that W is inversely proportional to C_p.

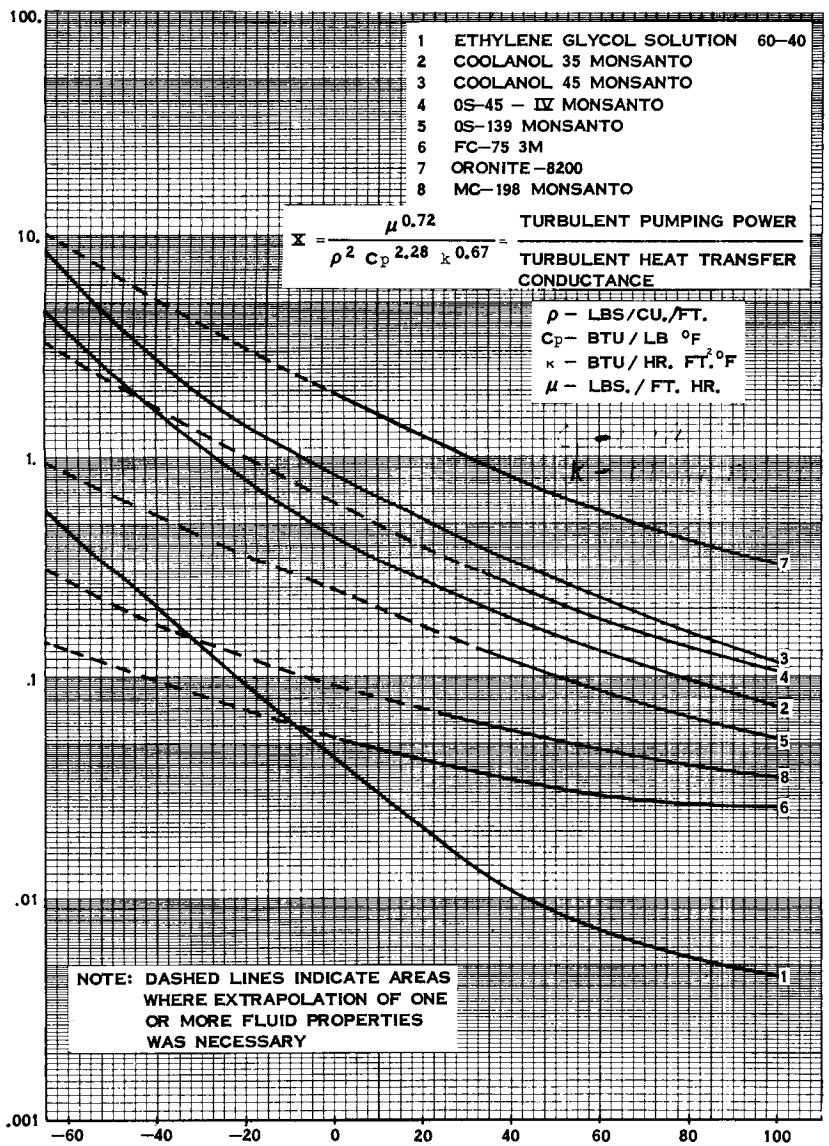
$$\text{Laminar Pumping Power} \propto \frac{\mu}{\rho^2\ C_p^{\ 2}} \qquad (16)$$

Therefore, for laminar flow over the heat transfer surfaces and through the interconnecting piping, the ratio of laminar pumping power to laminar heat transfer conductance, Υ, is as follows:

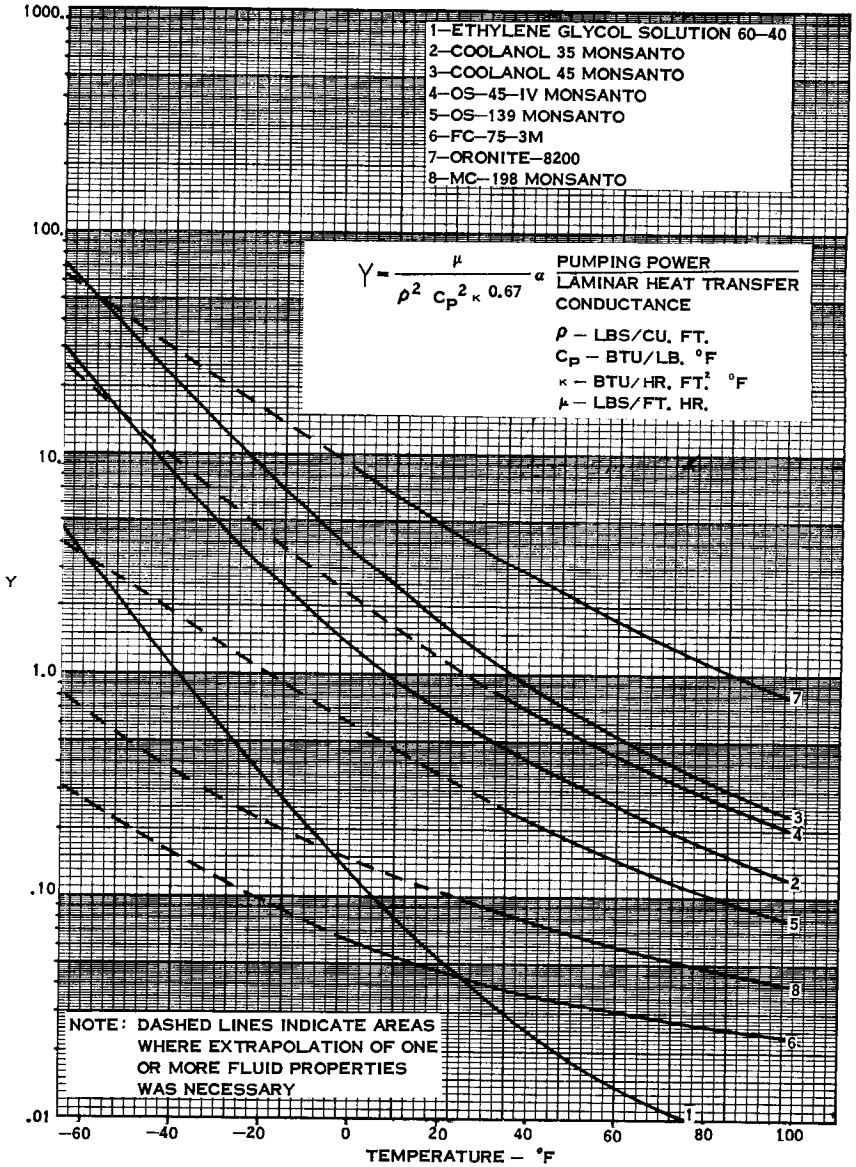
$$\frac{\text{Laminar Pumping Power}}{\text{Laminar Heat Transfer Conductance}} = \Upsilon \propto \frac{\mu}{\rho^2\ C_p^{\ 2}\ k^{\ 0.67}} \qquad (17)$$

In the selection of a transport fluid, minimum pumping power and heat transfer equipment weight (i.e. maximum heat transfer conductance) are major considerations. Thus, it appears that the fluid having the minimum value of the above parameter should require the lowest pumping power and the smallest heat exchangers and space radiator if it is acceptable on other bases such as toxicity, freezing point, stability, etc.

Figure 10-1 presents the comparison of fluids for this parameter with turbulent pressure drop and turbulent heat transfer, while Figure 10-2 presents this comparison for laminar heat transfer and laminar pressure drop. It was assumed in the analysis that the pressure drop in the heat exchangers can be represented by pipe friction factors, which is true for a space radiator or a tube bundle, but is only an approximation for a plate and fin type heat exchanger. In any system, four combinations of both turbulent and laminar pressure drop and heat transfer are possible, but the parameters involved differ only by a factor of μC_p to a power. This factor shifts the temperature at the intersection points of the curves and the magnitude of the parameter, but the overall order of the curves relative to each other remains substantially unchanged. Although a transport loop can have turbulent flow through the inter-connecting piping, and laminar pressure drop and heat transfer in the heat exchangers, it would be confusing to present the parameters for this mixed system



TURBULENT FLUID COMPARISON
FIGURE 10–1



LAMINAR FLUID COMPARISON
FIGURE 10 – 2

TRANSPORT FLUID COMPARISON

10.2.1 (Continued)

since either the pressure drop of the heat exchangers or the interconnecting piping would have to be neglected. Therefore, in order to be consistent, only the total laminar and total turbulent cases have been presented here. It can be seen from Figures 10-1 and 10-2 that FC-75 and (60-40) glycol offer the lowest pumping penalty per BTU rejected over portions of the range illustrated, but due to temperature limitations for (60-40) glycol, FC-75 has been selected as the most favorable transport fluid. Table 10-1 also shows that FC-75 has the lowest laminar pumping power of all the fluids investigated at -65°F, which would be favorable for low load space radiator operation. Actually pumping power may be the most significant factor rather than the ratio of pumping power to heat transfer conductance, but FC-75 would be the fluid selected by either criterion.

10.2.2 Coolant Survey Nomenclature

A_p	Pipe flow area
A_h	Heat exchanger or radiator fluid flow area
C_p	Fluid specific heat
D_p	Pipe diameter
D_h	Diameter of heat exchanger or radiator fluid passages
f	Friction factor
g	Acceleration of gravity
h	Heat transfer convection coefficient
k	Fluid thermal conductivity
L_p	Fluid loop pipe length
Nu	Nusselt number
Pr	Prandtl number
ΔP	Pressure drop of the fluid loop
Q	Heat exchanger or radiator heat load
Re_p	Pipe Reynolds number
Re_h	Heat exchanger or radiator Reynolds number
T_{f_1}	Heat exchanger or radiator inlet temperature
T_{f_2}	Heat exchanger or radiator outlet temperature
W	Fluid Flow Rate
μ	Fluid viscosity
ρ	Fluid density

10.3 Radiators

10.3.1 General

The space radiator study work during the subsystem definition phase was designed to provide meaningful general data which could be utilized during final system design. A space radiator is such an integral part of the thermal control system that an attempt at final definition at this point in the study would be useless. Thus, the work to-date has surveyed candidate items for the exterior coating and meteoroid protection. In addition, basic generalizations on the effect of vehicle orientation on radiator design were made to illustrate the relative penalties.

The coating study consisted of a review of available materials and their properties to provide an indication of the most desirable coating for the final design. It is impossible to consider all selection factors prior to final design, but the field can be narrowed considerably. In the meteoroid protection study, the goal was selection of a typical approach which would result in minimum overall weight penalties to the system. All schemes could not be considered due to practical limitations, but several representative approaches were analyzed for applicability.

The orientation analysis was designed to provide an estimate of the radiator size and weight of a radiator for an oriented vehicle as compared with one for a random oriented vehicle during transit from Earth to Mars. A study has been made of orientations during Mars orbit and on the Mars surface to aid in selecting the design points for the MMM and MEM radiators.

The results presented in this section will document the preliminary work done on the radiators and allow understanding of the reasons behind the selection of the final radiators. Care must be exercised in the interpretation of this data to avoid being overspecific on any particular point. The results presented in this section are designed to illustrate the overall trend in the design rather than providing a specific reference case. If this is kept in mind during the subsequent discussion a clearer understanding of the results should be possible.

10.3.2 Coating Survey

The coating survey for the Mars Vehicle radiators followed the same intent as the coolant survey; a collection of pertinent coating properties to establish applicability of materials for the final design. Metals for radiators are desirable because of thermal conductance and structural requirements, but they generally have optical properties unsuitable for efficient thermal radiation. Thus, it is necessary to coat the radiator surface with a material which selectively absorbs or emitts radiant energy as a function of wave length. For this application, the coating should be one which has a low absorptivity in the short wave length range (solar energy, $0<\lambda<3.0\mu$), and yet is highly emissive in the infrared or long wave length range ($3.0<\lambda<\infty\mu$). Space radiators require that the ratio of the solar absorptivity (α_s) to the long wave

10.3.2 (Continued)

length emissivity (ϵ) should be as low as possible, while the emissivity should be as high as possible. Furthermore, these coating characteristics should remain constant or degrade only slightly, after prolonged exposure to solar radiation, hard vacuum, and any other environmental conditions.

Table 10-2 is a listing and comparison of the coatings for which published data exists which are considered to be the best available at the present time. The majority of these coatings were tested under laboratory conditions only with the actual space simulation tests for determining the degradation of the coatings discussed in detail in the references. All of these coatings are capable of withstanding a 400°F ascent temperature for at least 10 minutes.

The coatings considered can be grouped into two basic types according to their method of providing a low solar absorptivity and a high thermal emissivity. These two types are referred to as "single surface" and "double surface" concepts and are described in Reference 1 as follows:

The "single surface" concept describes a homogeneous, opaque surface inherently highly reflective to solar radiation, and which possesses a high emissivity at ambient temperatures. Examples are white paint, "smoked" magnesium oxide, and certain vacuum-deposited materials.

The "double surface" concept describes a visually transparent coating over a highly polished metallic surface. The transparent coating transmits solar radiation to the metal, where it is reflected through the coating to space. Simultaneously, the coating is highly emissive in the long wave length range. Examples are transparent plastic or lacquer over polished aluminum.

A review of Table 10-2 indicates that all but two of the coatings (#6 and #8) are of the "double surface" concept.

The coatings can be further categorized according to the material components. Those presented here are either composed of all-inorganic components or a combination of organic and inorganic components. All but two of the coatings (#5 and #7) are composed of all-inorganic components. A comparison of the tabulated surface coating data indicates that, in general, minimum degradation occurs in a system composed of all-inorganic components.

The coating thickness is a very important factor in producing the characteristic optical properties. Too thin a coating will allow transmission of radiant energy to the subsurface, resulting in incorrect optical properties. A program conducted by Lockheed (Reference 3) indicates that the minimum thickness required for opacity of a "single surface" coating is approximately 0.003 of an inch. The range of thicknesses of the coatings listed in Table 10-2 was 0.003 to 0.006 of an inch.

TABLE 10-2 - SELECTIVE RADIATOR COATINGS

COATING NUMBER	SUPPLIER	REFERENCE	α_s		ϵ		α_s/ϵ	COATING COMPOSITION		SUB-SURFACE
			BEFORE	AFTER*	BEFORE	AFTER*	AFTER*	VEHICLE	PIGMENT	
1	1	1	0.147	0.159	0.925	0.925	0.172	Potassium Silicate	Zinc Oxide	Aluminum Alloy 7075-T6
2	2	1	0.142	0.156	0.878	0.875	0.178	Sodium Silicate	Synthetic Spodium	Aluminum Alloy 7075-T6
3	2	1	0.100	0.165	0.871	0.876	0.188	Potassium Silicate	Zirconium Zilicate	Aluminum Alloy 7075-T6
4	3	1	0.09	0.186	0.907	0.905	0.206	Potassium Silicate	Zirconium	Aluminum Alloy 7075-T6
5	4	1	0.158	0.184	0.888	0.878	0.210	Silicon Resin	Zinc Oxide	Aluminum Alloy 7075-T6
6	5	1	0.197	0.211	0.947	0.935	0.226	Phosphate Bonded Cr-Ni Spinel-sil-cate Sn O_2		Aluminum Alloy 7075-T6
7	2	1	0.129	0.181	0.862	0.873	0.207	Silicone	Titanium Dioxide	Aluminum Alloy 7075-T6
8	6	2	0.16	0.18	0.37	0.69	0.26	Anodized with Brytal Process		Polished aluminum alloy
9	6	3	0.19	**	0.76	**	**	Anodized with Alzak Process		Polished aluminum alloy

List of Suppliers:
1. Armour Research Foundation 2. Lockheed Missiles and Space Division 3. Space Technology Lab 4. Jet Propulsion Lab 5. North American Aviation, Los Angeles Division
6. Aluminum Company of America
* After simulated solar-vacuum exposure for 300 hours for coatings 1-7 and 96 hours for coatings 8 and 9
** No data found in the literature for this coating after solar-vacuum exposure, but the percentage degradation in properties is expected to be similar to coating number 8.

10.3.2 (Continued)

The percentage composition of pigment and vehicle making up the coating also has considerable effect on the radiant characteristics as shown in Table 10-3 for zinc oxide and potassium silicate. The values shown are for before and after exposure to the simulated space environment.

Table 10-3

Effect of Pigment to Vehicle Composition Ratio for Zinc Oxide-Potassium Silicate Coating

Composition Ratio Pigment Weight/Vehicle Weight	α_s Before	α_s After	ϵ Before	ϵ After
2.15/1	0.258	0.269	0.93	0.95
4.3/1	0.132	0.138	0.98	0.99

The simulated solar exposure for these tests was 268 hours.

After consideration of the factors required for coating selection, a preliminary choice of the zinc oxide-potassium silicate composition has been made based on the data currently available. This composition has the lowest α_s/ϵ ratio and is clearly the most stable which makes it very attractive for Mars Vehicle use.

The samples were irradiated by using several A-H-6 lamps, which have been widely accepted as the best available approximation of extra-terrestrial sunlight, and vacuum (about 10^{-6}mm. Hg.) was maintained by a suitably trapped oil diffusion pump (Reference 4).

10.3.3 Orientation Analysis

The weight and area of the space radiator are dependent on the heat to be dissipated and the radiation to which the radiator will be exposed. There are various possibilities for solar radiation, but there are two extremes which should be considered. The vehicle could be oriented such that the spin axis is radial to the sun. Therefore, the radiator can be positioned on the top or bottom of the mission module in a plane parallel to the spin axis and it will never be exposed to the direct rays of the sun. This will be described as a K = zero-influx radiator. The second case to be considered is that of a random oriented vehicle. If the orientation is random, it must be assumed that the vehicle could orient itself such that the spin axis would be perpendicular to a radial from the sun. Then the radiator would be in the direct rays of the sun during part of each revolution of the vehicle. If this is the case, the design point would occur at the highest solar radiation part of the mission.

10.3.3 (Continued)

Figure 10-3 illustrates the solar radiation that exists in space along the path traveled by the Mars Mission Module. The term solar radiation, as used herein, refers to the direct release of energy by the sun and varies inversely as the square of the distance from the sun. The term solar radiation was used in preference to the term solar constant which is only correct for a given radius from the sun. The word solar constant is a misnomer when applied to the solar system, because it is really a variable.

It can be seen in Figure 10-3, that the design point will be conditions on about the 350th day of the mission for a randomly oriented vehicle. If this solar radiation ($So = 1200$ Btu/hr ft^2) is assumed, along with the assumption that the radiator is flashing through the direct rays of the sun with a radiator absorbtivity of 0.15, integration of the rotating flat plate radiator through 360° yields an average absorbed influx of $K = \alpha So/\pi = 57.2$ Btu/hr ft^2 acting on the radiator. Figure 10-4 illustrates the resulting radiator weight and area for a constant load as the tube spacing is varied.

Although an orientated radiator will have a $K = 0$ absorbed influx, between the Earth and Mars, this influx will increase in the Mars orbit due to planetary emission and albedo. The optimum Mars orbit gives a maximum absorbed influx of $K = 10.5$ BTU/hr ft^2, and the resultant areas and weights are again shown as a function of tube spacing in Figure 10-5. Since the projected area of one side of the Mars Mission Module is approximately 947 ft^2, it can be seen that the orientated radiator gives a substantial savings in weight by being able to accommodate the area given for the optimum tube spacing which occurs at $\ell = 15$ inches.

10.3.4 Mars Orbit Radiator Influx

A study was made of a series of possible orientations of the Mission Module radiator with respect to Mars and the Sun at a height of 200 nautical miles. Figure 10-6 shows the radiator, which was considered a flat plate, always facing toward Mars in Case 1, facing away from Mars in Case 2, and vertical to the Mars surface in Case 3 (the method of calculating the absorbed influx was taken from Reference 5). Figure 10-7 shows Case 4 with the sun's rays always parallel to the plate. However, the most favorable orientation was found to be Case 5, which is shown in Figure 10-8. The influx in this case varies between $K = 10.5$ and 9.5 BTU/hr ft^2. The flat plate radiator is parallel to the plane containing the orbits of the planets around the sun so that the radiator is facing deep space. The direct solar absorbed influx is zero, but components of Mars planetary thermal radiation and albedo keep the influx from being zero on the radiator. For higher orbits the absorbed influx would decrease. Case 5 is for an equatorial orbit, which is the natural orbit for the MMM rather than a polar orbit. A polar orbit may involve a drastic change in the trajectory of the vehicle.

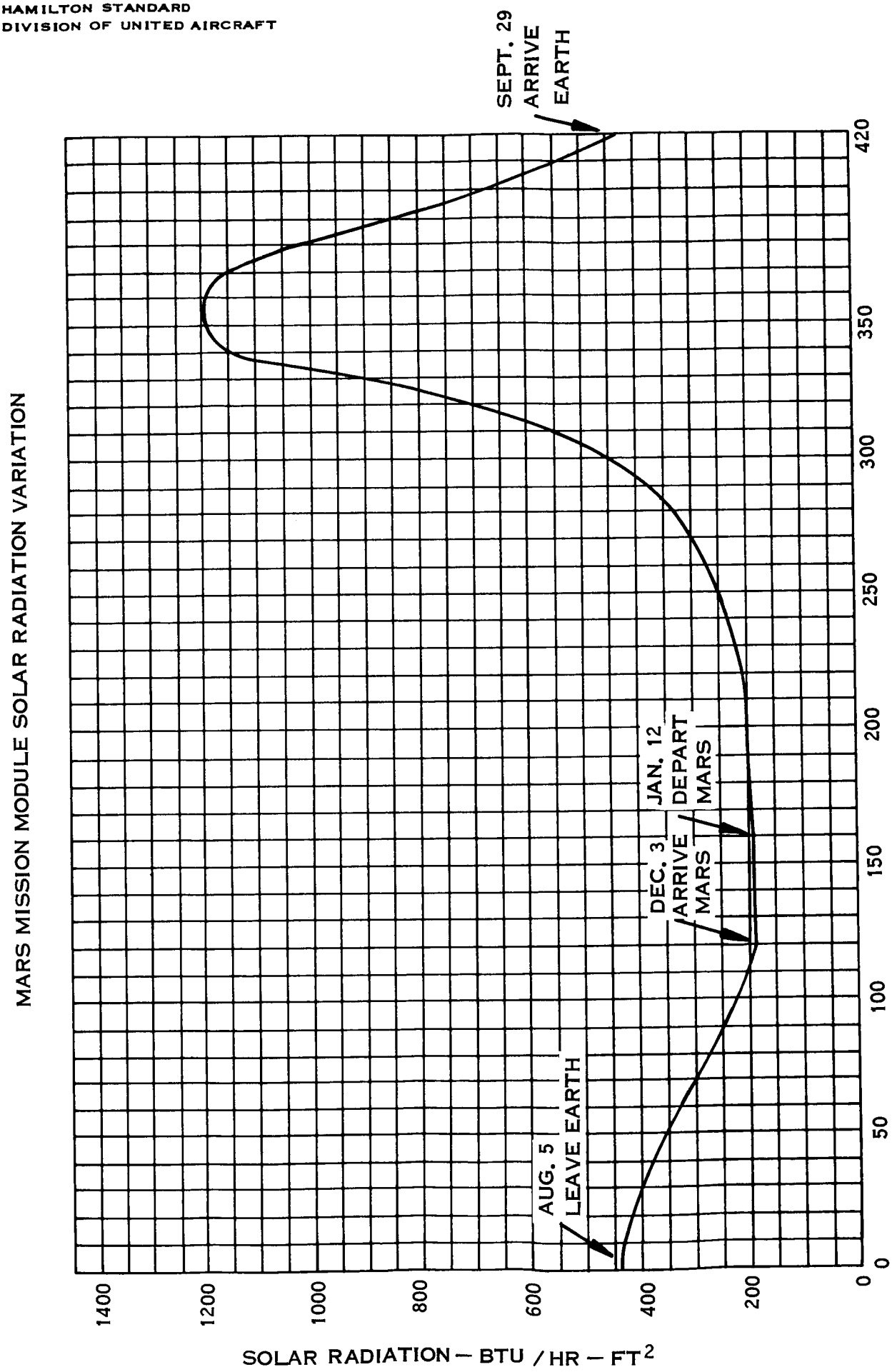

MARS MISSION MODULE SOLAR RADIATION VARIATION
SEPT. 29
ARRIVE
EARTH
JAN. 12
DEPART
MARS
DEC. 3
ARRIVE
MARS
AUG. 5
LEAVE EARTH
0
50
100
150
200
250
300
350
420
MISSION TIME — DAYS
0
200
400
600
800
1000
1200
1400
SOLAR RADIATION — BTU / HR — FT2

FIGURE 10-3

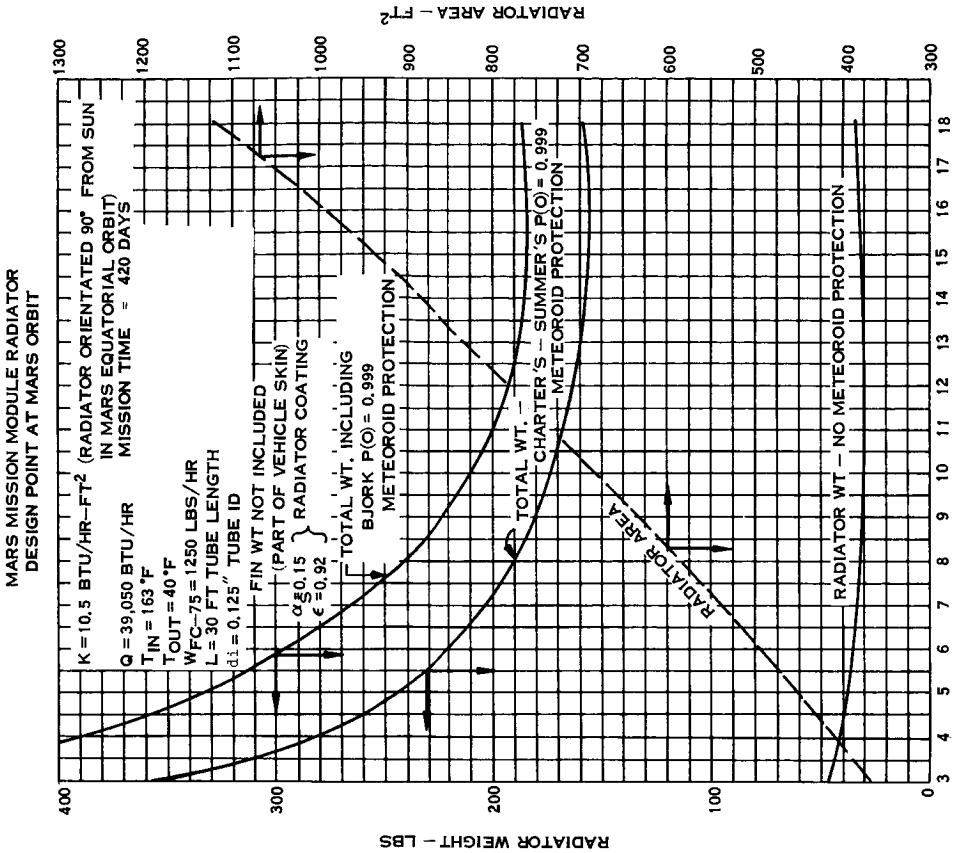


FIGURE 10-5

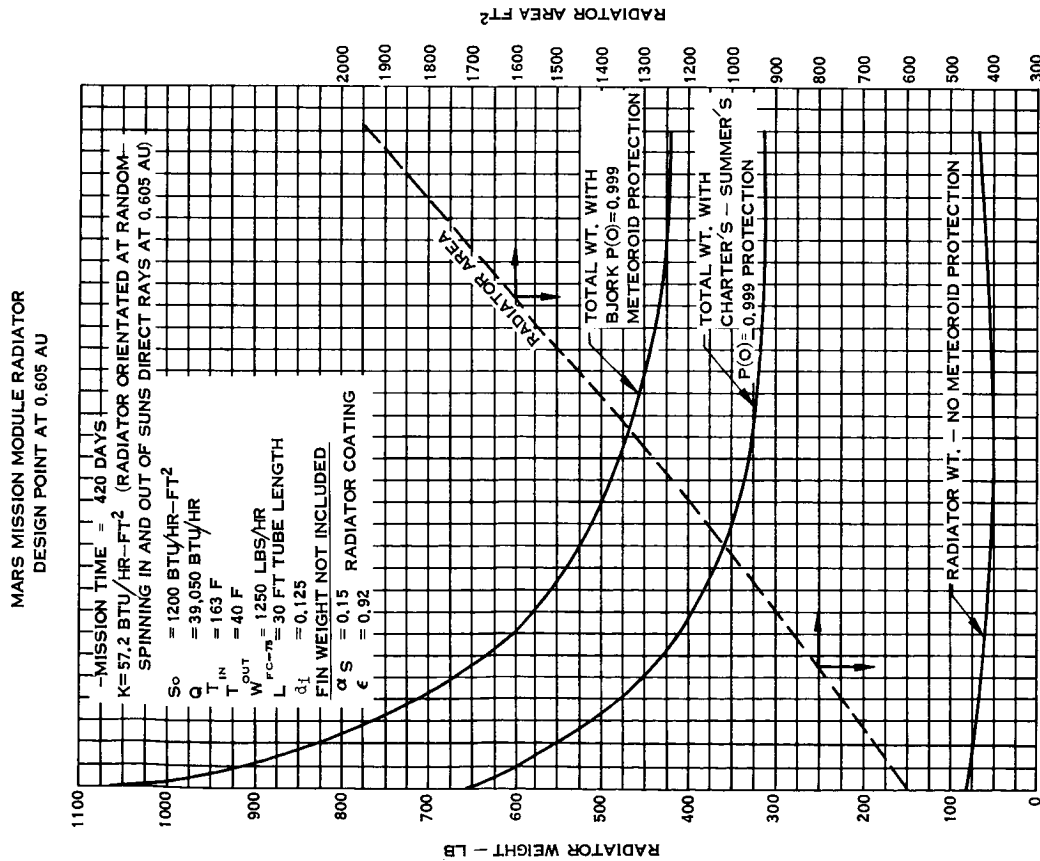


FIGURE 10-4

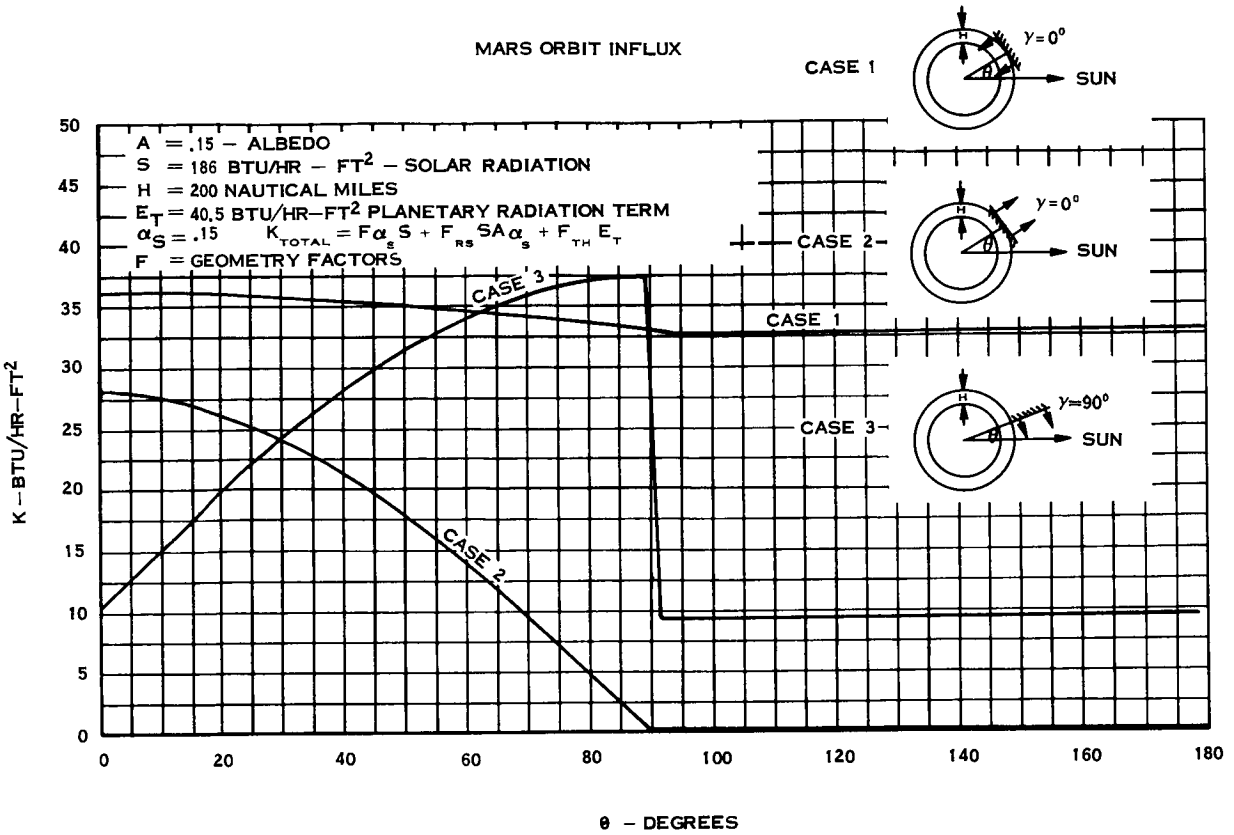


FIGURE 10-6

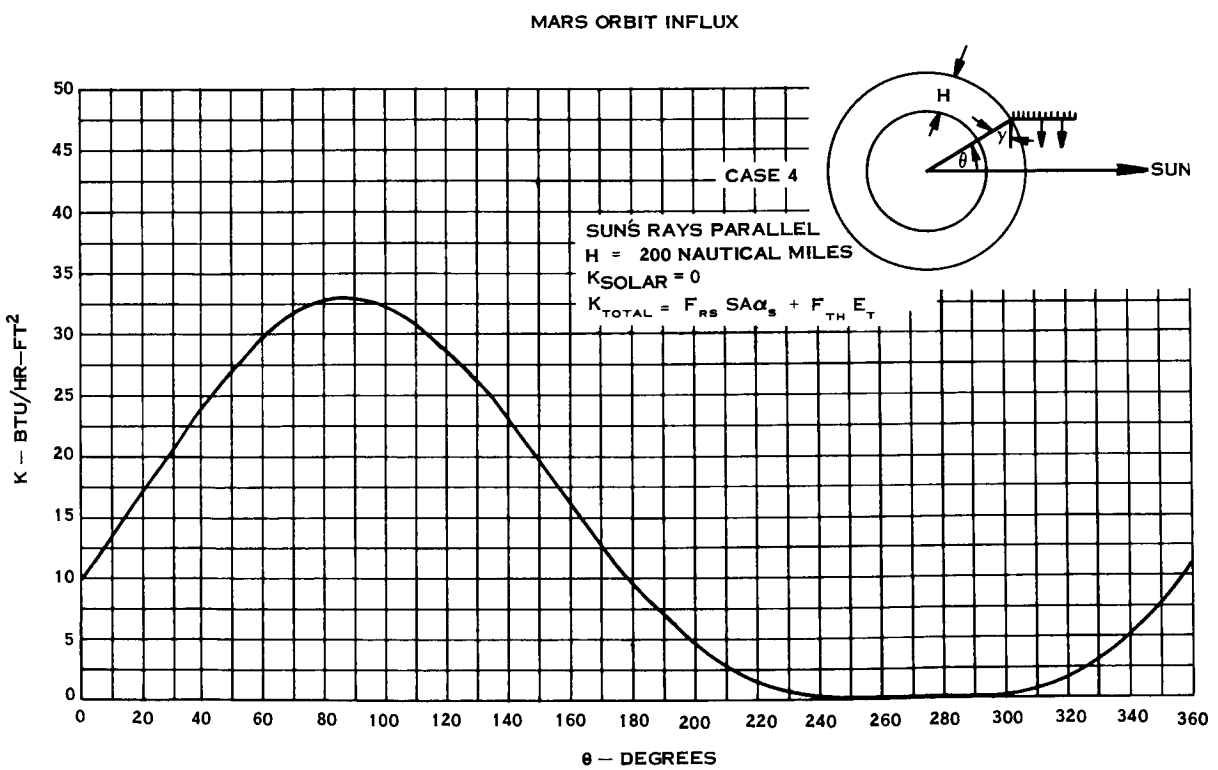


FIGURE 10-7

MARS ORBIT INFLUX

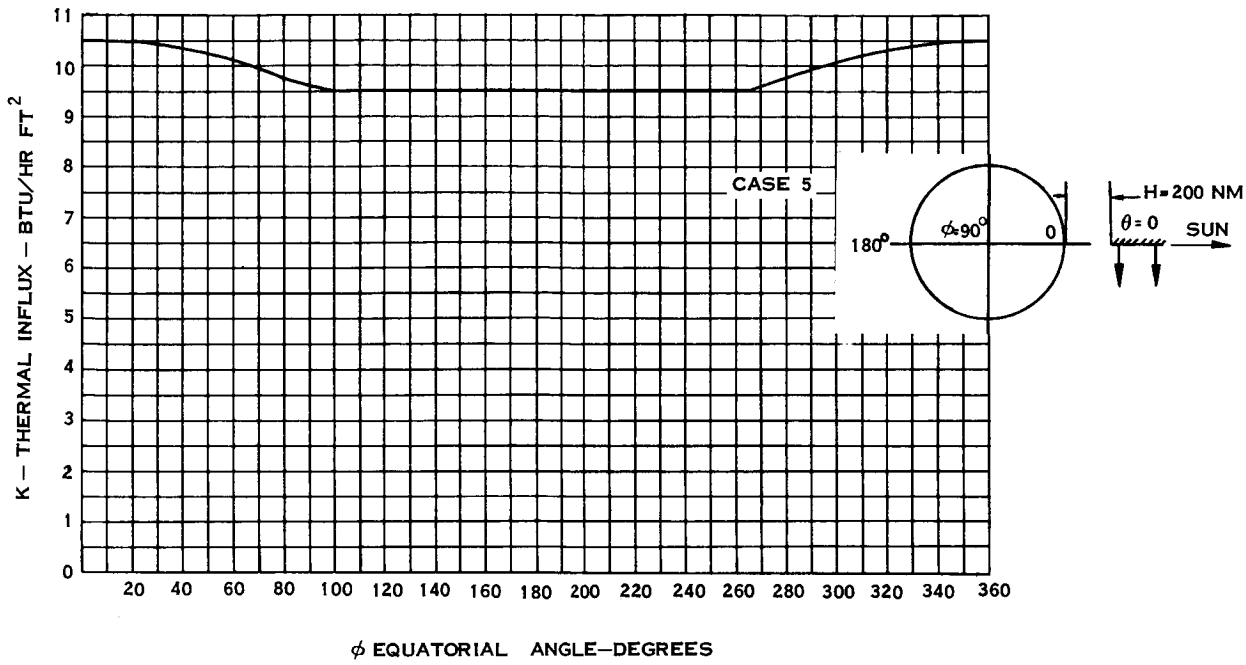


FIG. 10–8

MARS SURFACE FLAT PLATE RADIATOR INFLUX

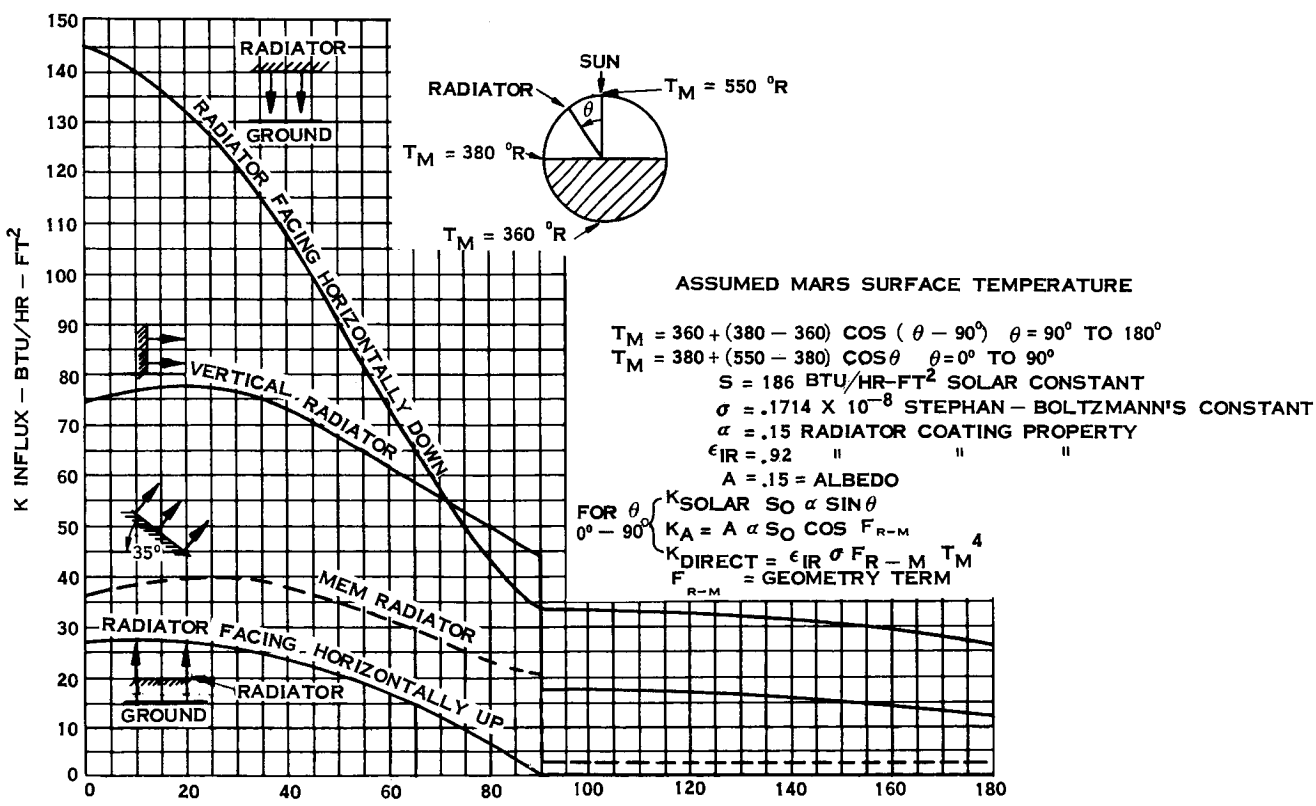


FIGURE 10–9

10.3.4 (Continued)

All the radiator orientations would require some power to initiate them, but no one appears more difficult than any other, so Case 5 was chosen for the design point of the MMM radiator. Since the influx is uniform for this case, temperature transients would be minimized.

10.3.5 MEM Radiator Orientation

A Mars surface temperature distribution was assumed based on equatorial midday, equatorial sunrise, and the polar region temperatures given in Reference 6. Flat Plate radiators were assumed as either vertical, horizontal-facing up, or horizontal-facing down relative to the surface of Mars, which was assumed to be flat.

Incident radiation consists of direct solar radiation from the sun, scattered and reflected sun radiation from a nearby planetary body (albedo), and radiation directly emitted by the planetary body (planetary emission). As shown in Reference 5, these components of the incident radiation can be transformed into the absorbed radiator influx by applying the radiator coating properties and geometric terms called shape factors and summing up the contribution of each component to obtain K, the average influx. Figure 10-9 shows the influx for various orientations of flat plate radiators versus location on the Mars surface. It was further assumed that the Mars atmosphere is perfectly transparent to radiation. Since the model atmosphere used in the study indicates that there is very little carbon dioxide and no water vapor in its composition, it was assumed that there is no gas radiation present. The radiators have an absorbtivity of 0.15 and an emissivity of 0.92. The horizontal-facing up radiator had the most favorable influx due to the elimination of the direct planetary emission, which is very high at midday at the equator, so the ideal design point for the MEM radiator would be $K = 28$ Btu/hr-ft^2 with a minimum influx of $K = 0$ at $\theta = 90°$ to $180°$. However, such a radiator could not be integral with the vehicle. Therefore, a radiator inclined at an angle of 35° to the horizontal was taken as the design point. Such a radiator could be located in the flat section of the MEM.

An isotope radiating section was included for the MEM since an isotope heater is needed to provide cabin comfort at night due to the high heat leakage out of the vehicle. This radiator can also be integral with the vehicle and inclined at an angle of 35° to the horizontal. The design point for the radiators was taken as $K = 36$ BTU/hr. - ft^2, the influx that occurs for a Mars location angle of $\theta = 0°$.

10.3.5.1 Radiator Nomenclature

α_S	Solar Absorptivity
ϵ	Emissivity
λ	Radiation Wave Length

10.3.5.1 (Continued)

μ	Micron = 10^{-6} meters
So	Solar Radiation (Solar Constant)
K	Absorbed Radiation
T	Temperature
W	Weight Flow
L	Tube Length
d_i	Tube Inside Diameter
P (o)	Zero Puncture Probability
ℓ	Tube Spacing
Q	Heat Load
H	Altitude
θ	Planet Location Angle
ϕ	Equatorial Angle
γ	Angle Between Radiator Normal and Planet
A	Albedo
E_T	Total Energy Rate Emitted Per Planet Unit Area
F	Geometry Factor
RS	Reflected Solar (Subscript)
TH	Thermal (Subscript)

10.3.6 Meteoroid Protection

10.3.6.1 Radiator Tube Configuratives

In the early part of the study, three radiator meteoroid protection schemes were considered. They were the bumper, shield, and heavy tube configurations as shown in Figure 10-10. At that time, the shield mode of protection gave the lowest weight penalty with the Whipple 1963 flux data. In addition, the modified Charter's - Summer's equation was used for both single and multi-sheet protection, but with the multi-sheet penetration factor, K' = 1 for both. This was unduly severe on the bumper or multi-tube configuration. More recent work on meteoroid protection methods has resulted in some simpler and more easily constructed schemes as shown in Figure 10-11.

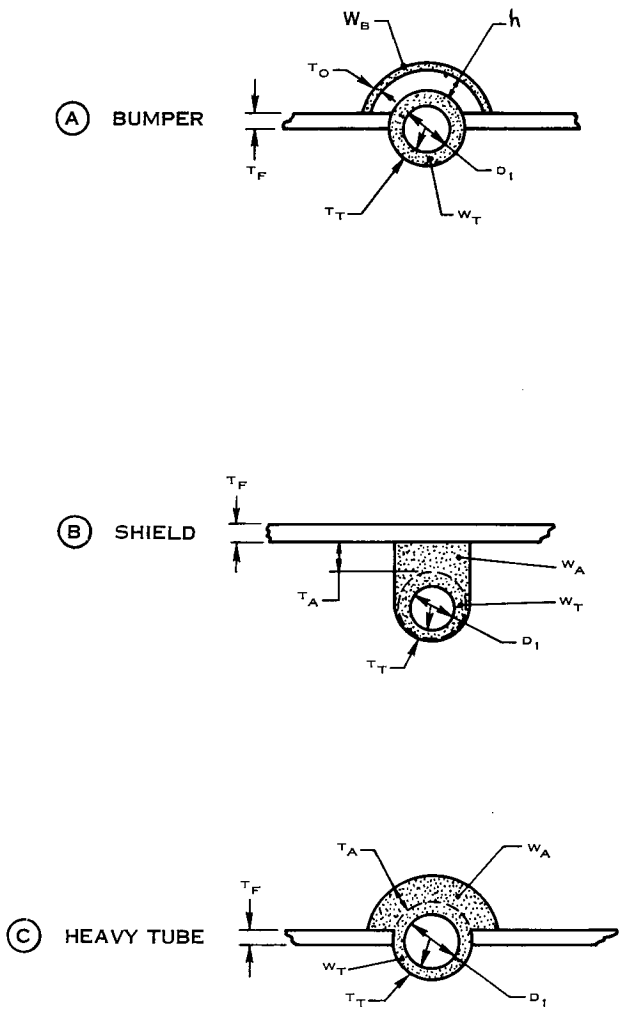
For the final phase of the study, the heavy tube protection was chosen to be used and was evaluated by the Bjork penetration criteria. The protection weight per foot of tube for any required meteoroid protection thickness is shown in Figure 10-12.

For the multi-sheet protection a "Tee Bar" arrangement was optimized by assuming tube stand-off distances or h's of 1, 1.5, and 2 inches for a tube protective area ($NT \times Lxd_i$) of 9.62 ft^2, which was the vulnerable area of an early MMM radiator. Each h has a K', as taken from Figure 10-14, which allowed the protection thickness to be calculated from the modified Charter's-Summer's equation, which in turn gave areas. The optimum area or lowest weight occurred for a distance of h = 2 inches, and K' = 0.2. Although in Figure 10-14, the curve of h versus K', blends into K' = 1 for a separation distance of zero inches, the curve is undefined for values of h greater than two inches so the optimization study was not carried beyond this point. Actually as h increased indefinitely, the conduction of the heat from the tube to the fin becomes more difficult, and the radiator size would have to be made larger to compensate for this effect. Figure 10-13 gives the multi-sheet armor weight as a function of the required thickness. The armor weight becomes constant for a thickness of .06 inches, which is the sum of the initial tube and fin dimensions. The weight then becomes just the separation strut. Physically, this means that thicknesses less than .06 inches are not structurally feasable, and that the separation distance, h, can now be reduced rather than the thickness.

10.3.6.2 Mars Radiator Meteoroid Protection

The field of meteoroid study is composed of three basic areas:

INITIAL RADIATOR METEOROID PROTECTION SCHEMES



NOTE SHADED SECTIONS REPRESENT WEIGHTS COMPUTED IN THE STUDY

FIGURE 10-10

RADIATOR TUBE CONFIGURATIONS

1 AND 4 USED IN FINAL STUDY

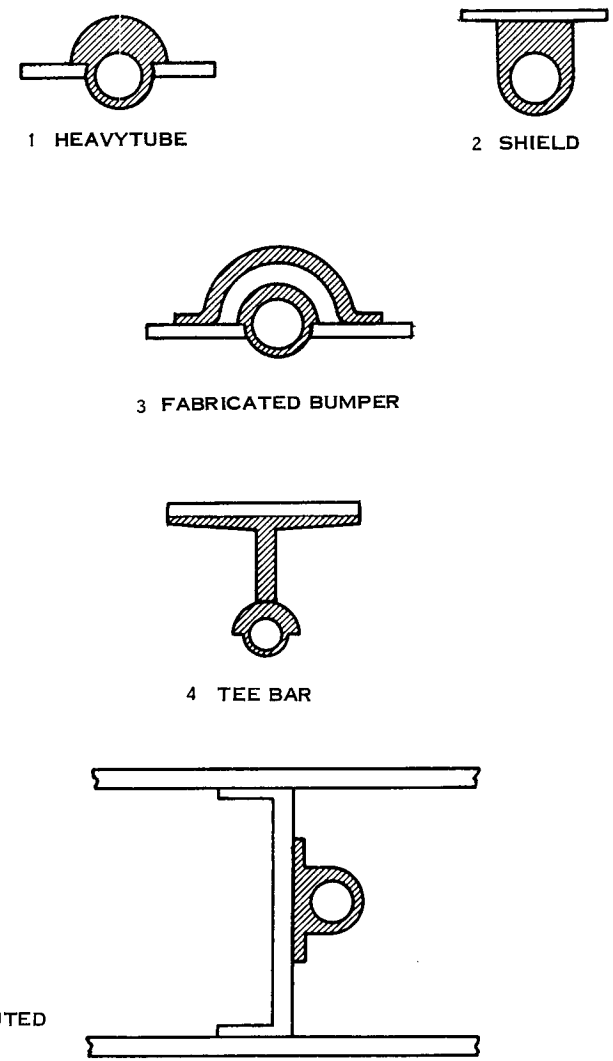


FIGURE 10-11

MULTI-SHEET WEIGHT VS. THICKNESS

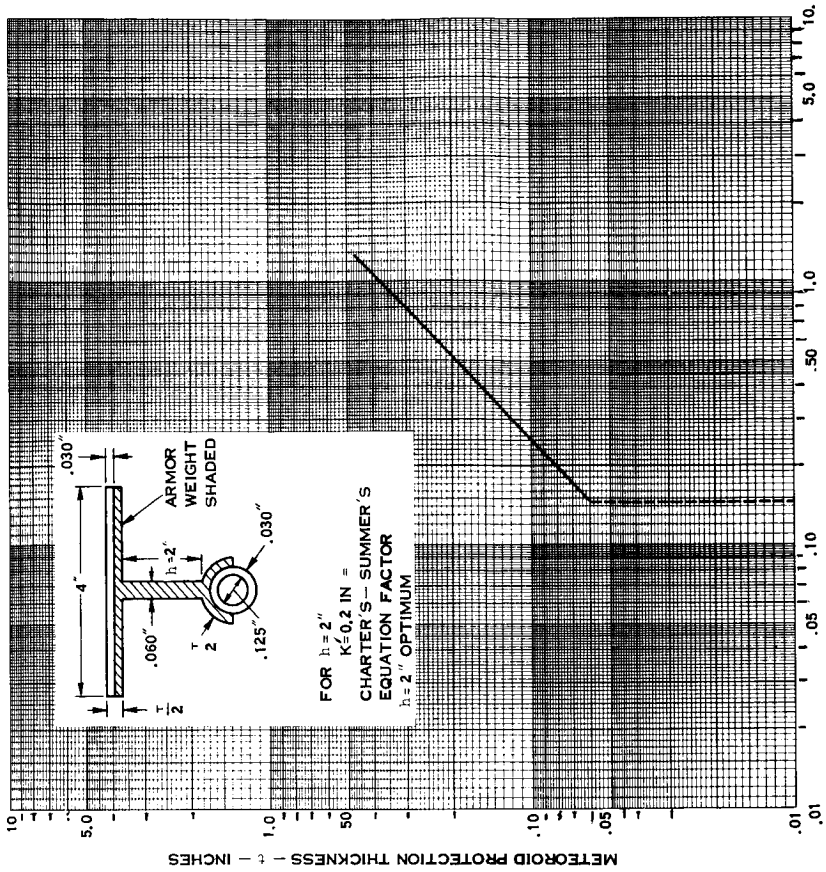


FIGURE 10-13

HEAVY TUBE ARMOR WEIGHT VS THICKNESS

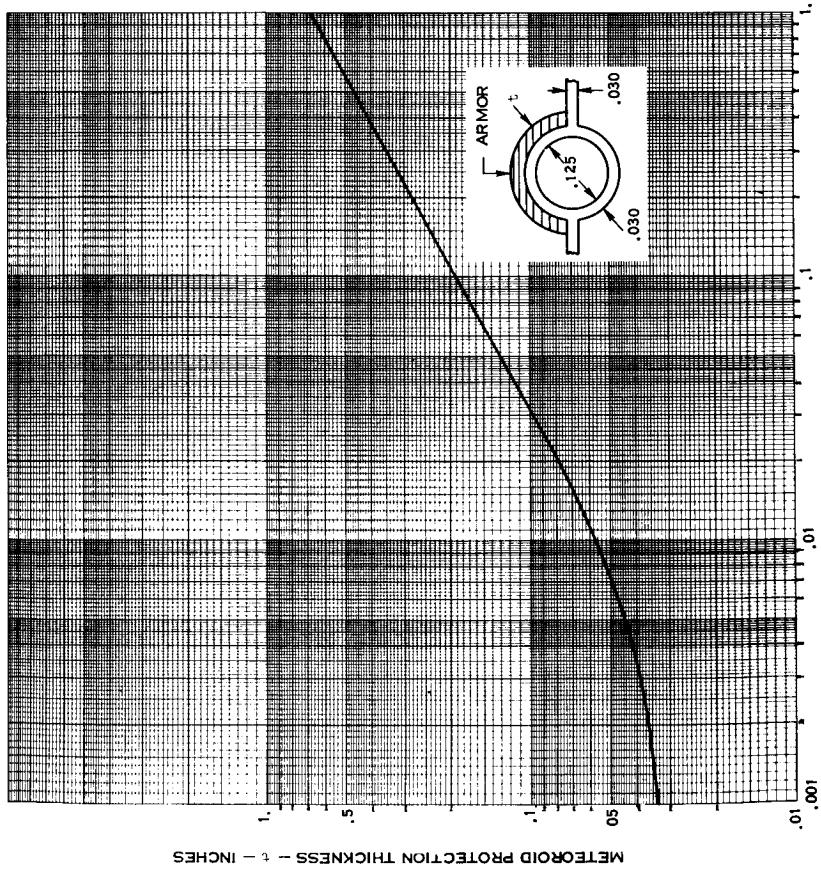


FIGURE 10-12

MULTI-SHEET SEPARATION DIST.
VS.
MULTI-SHEET PENETRATION FACTOR

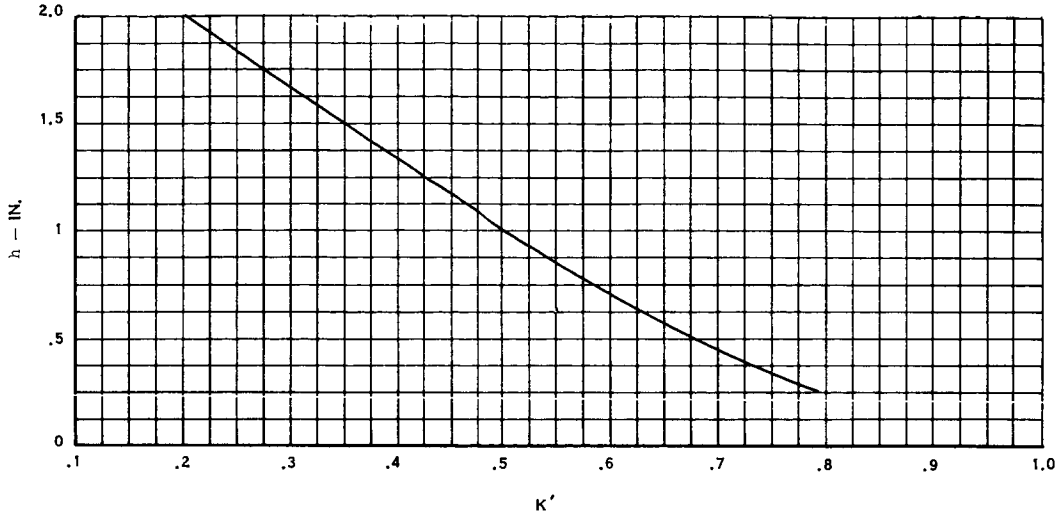


FIGURE 10-14

SPORADIC FLUX-MASS ENVELOPE
MARS MISSION

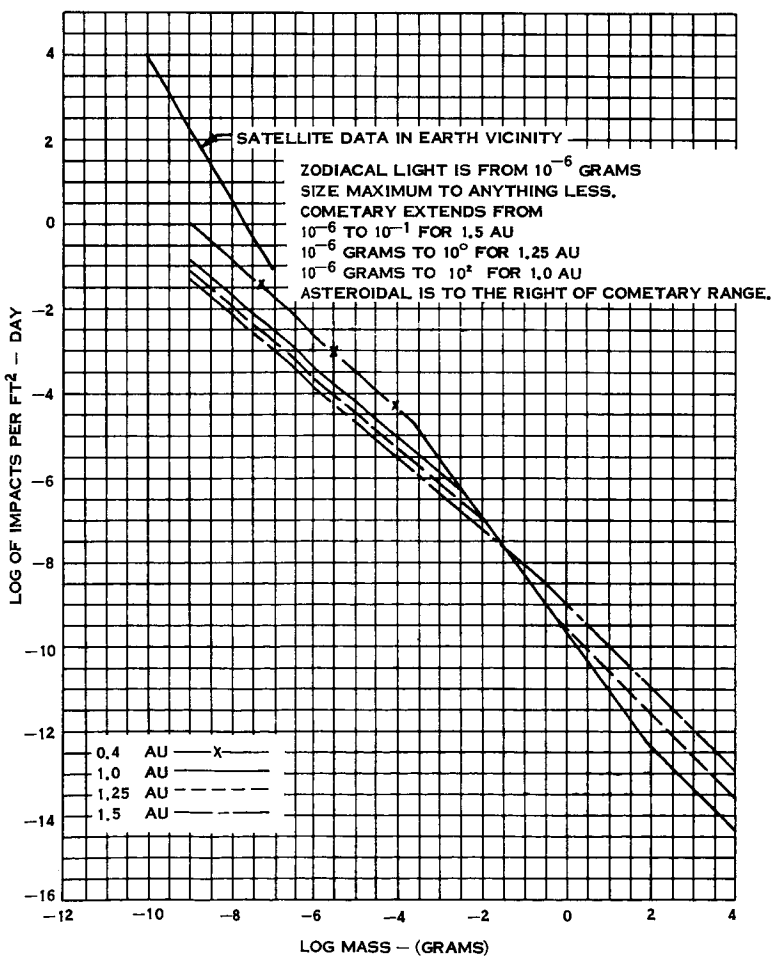


FIGURE 10-15

10.3.6.2 (Continued)

1. The determination and prediction of the sporadic meteoroid flux vs. mass distribution, as well as determining the physical properties of meteors (density, composition, etc.).

2. Various theories based on analytical and empirical reasoning, that describe the methods by which meteoroid penetration occurs in metallic targets in the various velocity regimes.

3. Methods of protecting against meteoroid penetration. This consists of both mechanical design, experimental work and theoretical analyses of the protection thickness required to prevent penetration.

A complete discussion of these areas is far beyond the scope of this report, but Reference 7 contains an excellent review of these areas. However, a brief review will be presented of work in these three areas pertinent to the discussion.

Various visual, radar, radio and direct impact techniques have been used to formulate a relationship between meteoroid flux (particles/area-time), mass, velocity, and density. The relationship between meteoroid flux and mass is a log-linear distribution of the form

$$\log(\psi) = \log \alpha + \beta \log(m) \qquad (1)$$

and is shown plotted in Figure 10-15 at various locations in the solar system. This is the NASA suggested Meteoroid Environmental Model that replaces the Whipple 1963 data used initially in the study.

The average meteoroid density is dependent upon the size and origin of the meteoroid. Meteoroids of Asteroidal origin, consisting of stone fragments, have an average density of 3.5 gm/cc. Meteoroids of Cometary origin are believed to have a porous fragile structure. Because of this porosity of the cometary meteoroids, their density is dependent upon their size. The average densities suggested by NASA for use in this study are given in Table 10-4.

The meteoroid velocity varies inversely as its mass and distance from the Sun. The relationship between average meteoroid velocity and location is shown in Figure 10-16.

As to the actual penetration criteria, many theories have been postulated as to how projectile penetration occurs in the range of high and hyper velocity impact. These include both hydrodynamic theories, and thermal vaporization models. As of now, laboratory experiments have been limited to velocities of less than 25,000 ft/sec., so experimental data must be cautiously extrapolated to the higher velocity regime.

DIST. FROM SUN
VS.
AVG. METEOROID VEL.

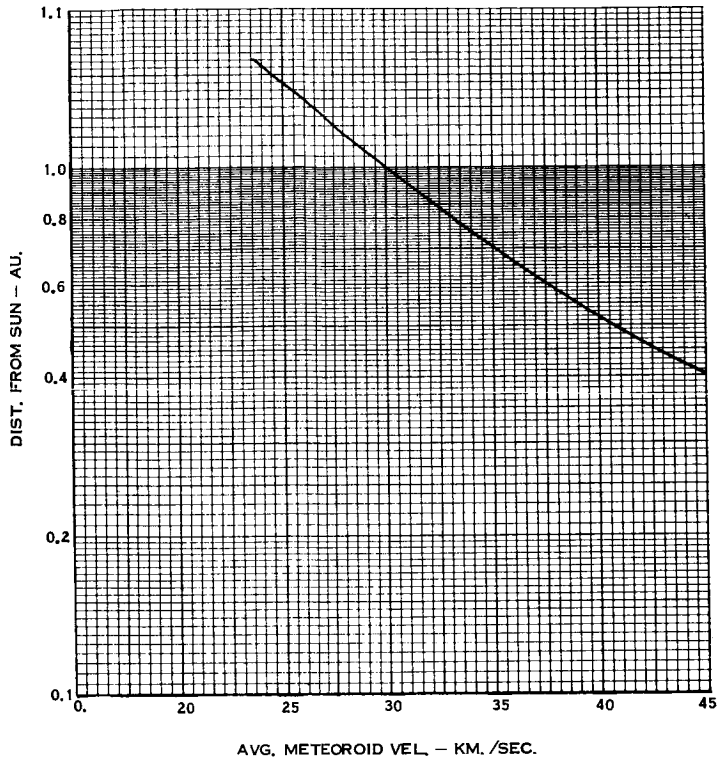


FIGURE 10-16

MULTI-SHEET RADIATOR
METEOROID PROTECTION
VS.
METEOROID FLUX

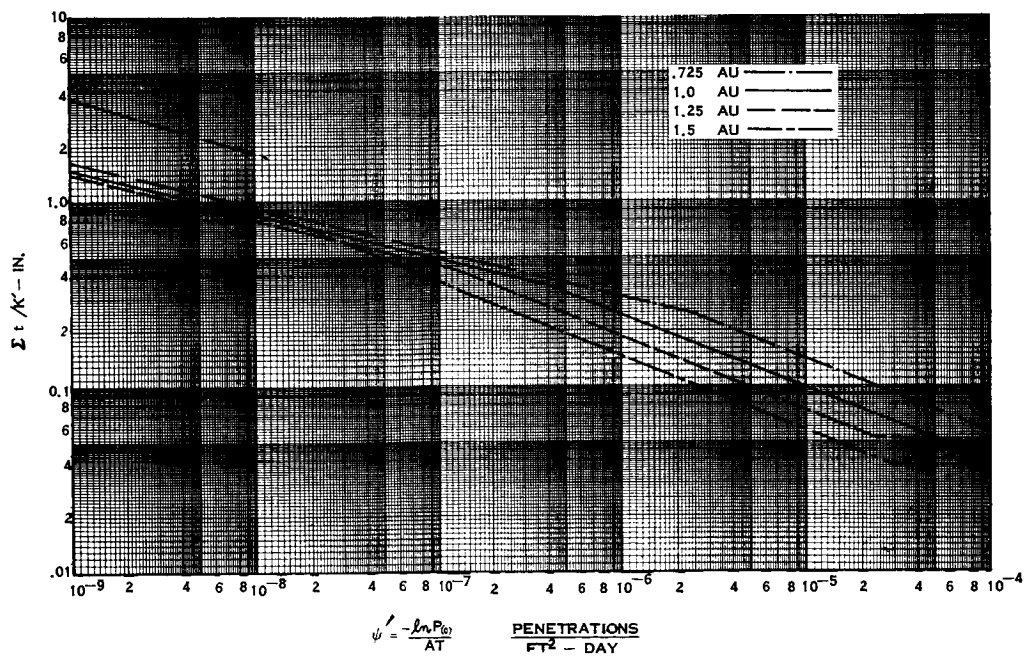


FIGURE 10-17

10.3.6.2 (Continued)

TABLE 10-4
METEOROID MASS AND DENSITY

Distance From Sun (AU)	Mass (gm)	Avg. Density (gm/cc)
Entire Solar System	10^{-9} to 10^{-6}	3.5
1	10^{-6} to 10^{2}	.5
1	10^{2} and greater	3.5
1.25	10^{-6} to 1	.5
1.25	1 and greater	3.5
1.5	10^{-6} to 10^{-1}	.5
1.5	1 and greater	3.5

By postulating that projectile kinetic energy is proportional to penetration depth, Charter's and Summer's derived a relationship between non-dimensional penetration depth and the physical properties of a spherical meteoroid. Experimental work showed that the penetration did not exactly follow the theoretical expression so the equation was modified as follows:

$$\frac{p}{d} = 2.28 \left(\frac{\rho_p}{\rho_t} \times \frac{V}{C} \right)^{2/3} \qquad (2)$$

It has been suggested by NASA that a further modification of this equation be used to calculate multi-sheet or double wall meteoroid protection.

$$\frac{\Sigma t}{d} = 3.42 \; K' \left(\frac{\rho_p}{\rho_t} \times \frac{V}{C} \right)^{2/3} \qquad (3)$$

10.3.6.2 (Continued)

The constant in this equation includes a factor of 1.5 to correct the crater depth (P) in a semi-infinite target to a finite thickness that will be just penetrated by the same projectile. A multi-sheet penetration factor K' has been included to account for the reduced protection required, because the bumper absorbs a portion of the meteoroid energy and causes the meteoroid to fragment into smaller pieces. Figure 10-14 shows the multi-sheet penetration factor as a function of sheet separation distance.

For calculating single-sheet meteoroid protection Bjork's penetration theory has been suggested by NASA.

$$t = 1.64\,(mV)^{1/3} \quad \text{- for aluminum targets} \tag{4}$$

This theory neglects the strength of the target material because it has been found that, at high impact velocities, the forces generated far exceed the strength of the target material.

In order to provide a certain radiator reliability against a penetration failure, it is assumed that the probability of having a certain number of penetrations occuring during a given mission time can be represented by a Poisson distribution,

$$P(n) = \frac{(\psi \quad A\,T)^n}{n!} \quad e^{-\psi A T} \tag{5}$$

where ψ is the meteoroid flux, A the exposed tube area, and T the total mission time.

Since, for a radiator zero penetrations can be tolerated,

$$P(o) = e^{-\psi A T} \tag{6}$$

Referring to Eq. 1, ψ is given by the expression,

$$\psi = \alpha \; m^{+\beta} \tag{7}$$

where for the assumption of spherical meteoroids,

$$m = \left[\frac{\pi}{6} \quad \rho_p \quad d^3 \right] \tag{8}$$

For a space radiator one of the design variables is usually total equivalent length, or (NT) × (L) . Thus, the total exposed area is (NT × L × d_i). This presents a good basis on which a parametric curve of meteoroid protection can be based, for inclusion in a radiator optimization study.

10.3.6.2 (Continued)

The Sporadic Flux-Mass Envelope for the Mars Mission shown in Figure 10-15 was taken as the starting point in the calculation. It was estimated from the study specification that the times to be spent at different distances from the sun are as follows:

@	1AU	T = 10 days	Earth and Vicinity
@	1.25 AU	270 days	In Transit
@	1.52 AU	50 days	Mars and Vicinity
@	0.725 AU	90 days	Vicinity of Venus Orbit
		420 day mission	

The 0.725 AU line was obtained by interpolation between the 0.4 AU and the 1.0 AU line in Figure 10-15. For multi-sheet protection, the modified Charter's - Summers equation, assumed spherical particles, and the Poisson flux distribution for zero hits yields the following equations:

$$\Sigma \frac{t}{d} = 3.42 K' \left(\frac{\rho_p \; V}{\rho_t \; C} \right)^{2/3}$$

$$d = \left(\frac{6}{\pi} \right)^{1/3} m^{1/3} \rho^{-1/3}$$

$$\psi = \frac{-\ln P(0)}{AT}$$

Using these three relationships and Figure 10-15, Σ t /K' was plotted against -ln P (o)/AT for each distance from the sun as shown in Figure 10-17. Values of ψ are read off at constant Σ t/K' at each AU. For a given vulnerable area, NTxLxd$_i$, a P (0) can be calculated. The actual P (0) for this Σ t/K' is now the multiple of the P's or the antilog of the sum of the logarithm of the P's.

$$P(0) = e^{-A(\psi_1 T_1 + \psi_2 T_2 \cdots \psi_n T_n)} = P_1(0) \, P_2(0) \ldots P_n(0)$$

Figure 10-18 shows Σt/K' versus - ln P (0) for a vulnerable area of 9.62 ft.^{2} Figure 10-19 shows Σt/K' versus mission reliability.

MULTI-SHEET RADIATOR
METEOROID PROTECTION
AS A FUNCTION OF
RELIABILITY

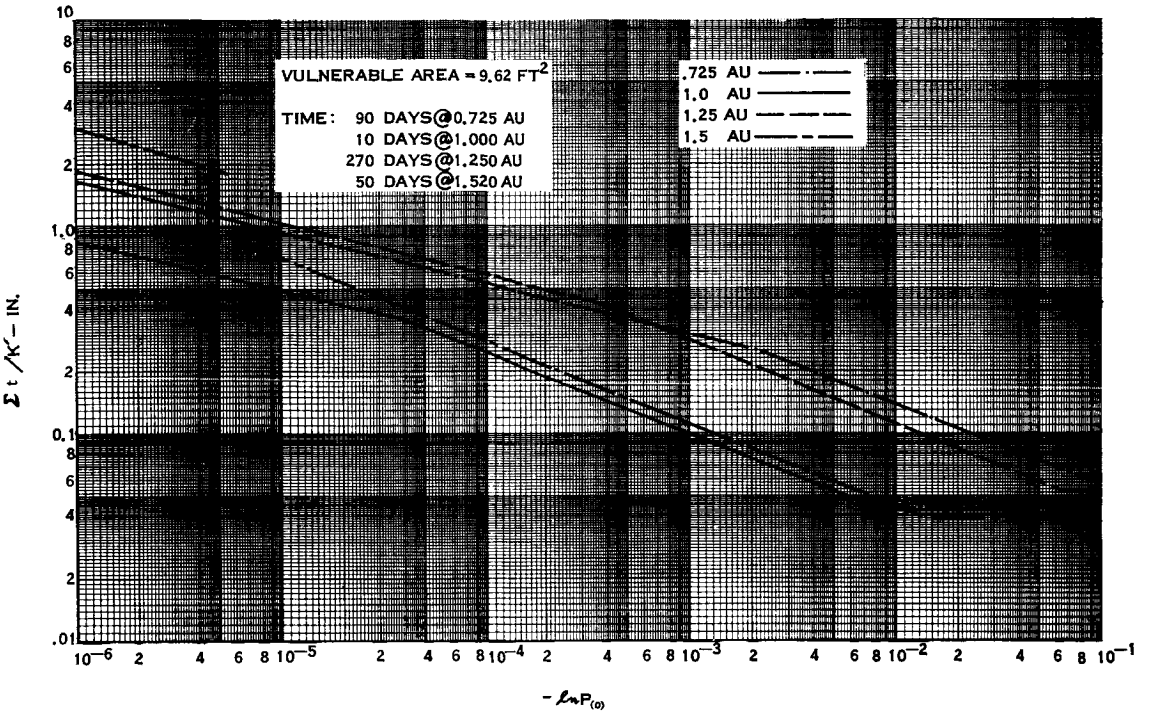


FIGURE 10-18

MULTI-SHEET RADIATOR
METEOROID PROTECTION
VS.
MISSION RELIABILITY

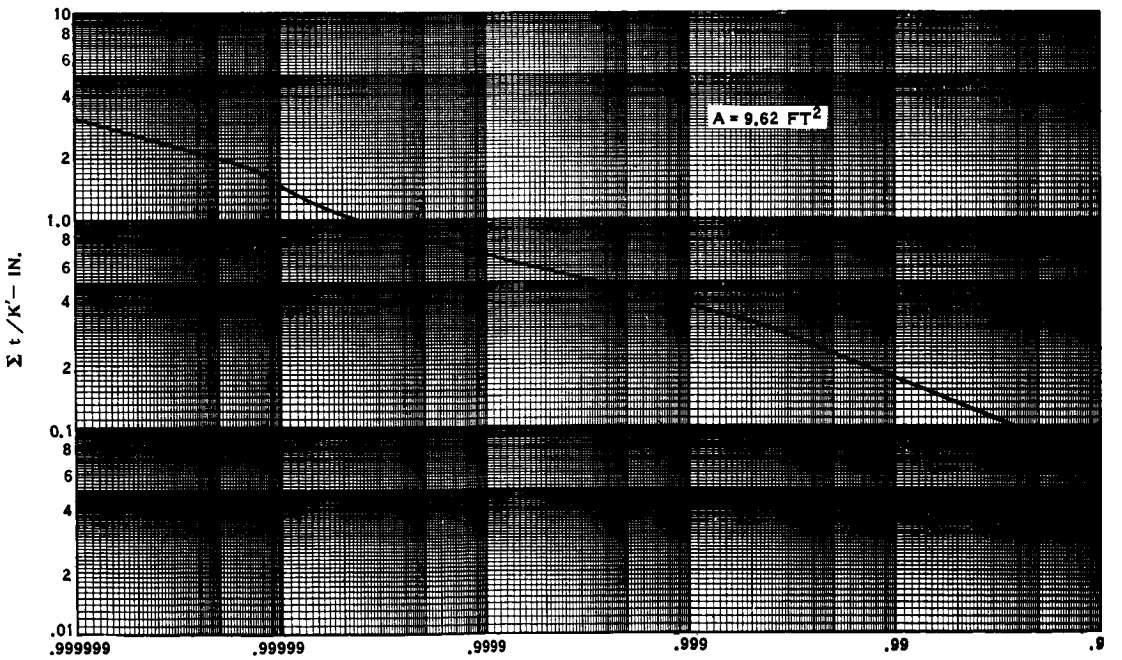


FIG. 10-19

10.3.6.2 (Continued)

By a like procedure, the single sheet meteoroid protection using the Bjork equation, $t = 1.64\ (MV)^{1/3}$ for aluminum, yields similar curves.

Figure 10-20 shows the Bjork thickness against -ln P (0)/AT. By using the sample area, 9.62 ft^2, and the respective times for each curve, Figure 10-21 was obtained. By assuming a thickness and reading off the -ln P (0) for each curve, the combined P (0) can be calculated as shown in Figure 10-22.

Due to the complexity involved in the multi-meteoroid flux curves, it is not possible to solve directly for the required thickness for an overall mission no puncture probability. It is easier to assume a thickness, work out the reliability for each portion of the mission, and then get the overall reliability for the total time the radiator is exposed.

Using the method described, and assuming various vulnerable areas, curves were generated at the agreed upon no puncture probabilities of P(0) = 0.99 and 0.999 for each penetration criteria. Figure 10-23 shows thickness as a function of the zero puncture probability and vulnerable area for the MMM radiator using the Bjork equation. The comparible curve of $\Sigma t/K'$ is shown for the modified Charter's-Summer's equation in Figure 10-24.

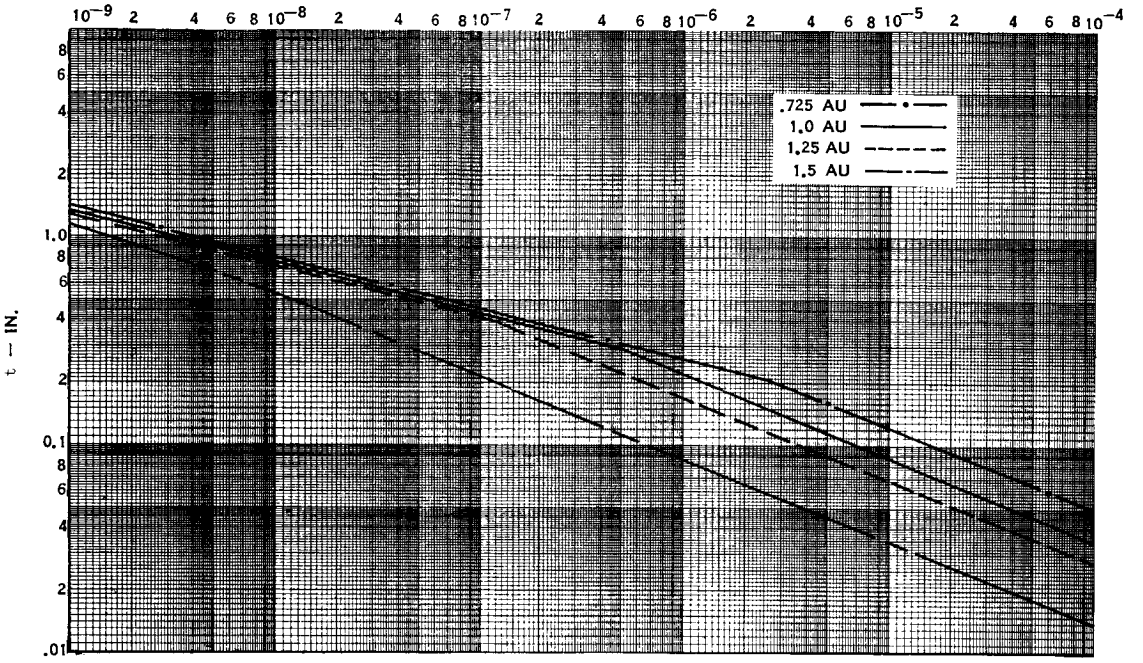
10.3.6.3 MEM Radiator Meteoroid Protection

It was assumed that the MEM radiators would have to be protected for 160 days, which would include the 120 day trip to Mars and the stay time of 40 days. The radiators would then be left behind, either on Mars or in a Mars orbit, prior to the departure of the MMM for Earth. In an effort to simplify the solution for protection thicknesses, the 1.25 AU curve was used with the total time of 160 days to obtain the two curves, Figures 10-25 and 10-26 for the Bjork and Charter's - Summer's thicknesses against radiator vulnerable area and zero puncture probability. A check on the accuracy of these curves was made by integrating the meteoroid environmental model using the following:

T = 5 days	@	1.0 AU Vicinity of Earth
110 days	@	1.25 AU Transit
5 days	@	1.5 AU Vicinity of Mars
40 days	@	1.5 AU Stay Time
160 days		

The spot check revealed no significant departure from the simplified curves.

SINGLE-SHEET RADIATOR
METEOROID PROTECTION
VS.
METEOROID FLUX



$$\psi = \frac{-\ln P(o)}{AT} \quad \frac{\text{PENETRATIONS}}{FT^2 - DAY}$$

FIG. 10-20

SINGLE-SHEET RADIATOR
METEOROID PROTECTION
AS A FUNCTION OF
RELIABILITY

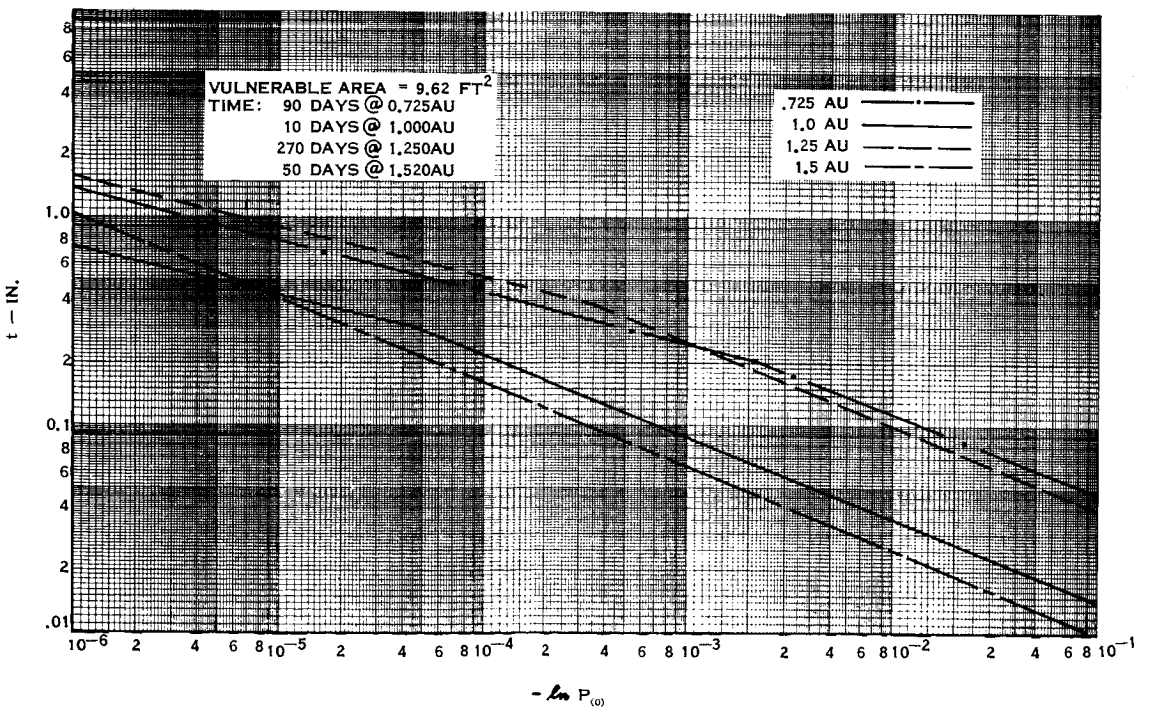


FIG 10-21

SINGLE–SHEET RADIATOR
METEOROID PROTECTION
VS.
MISSION RELIABILITY

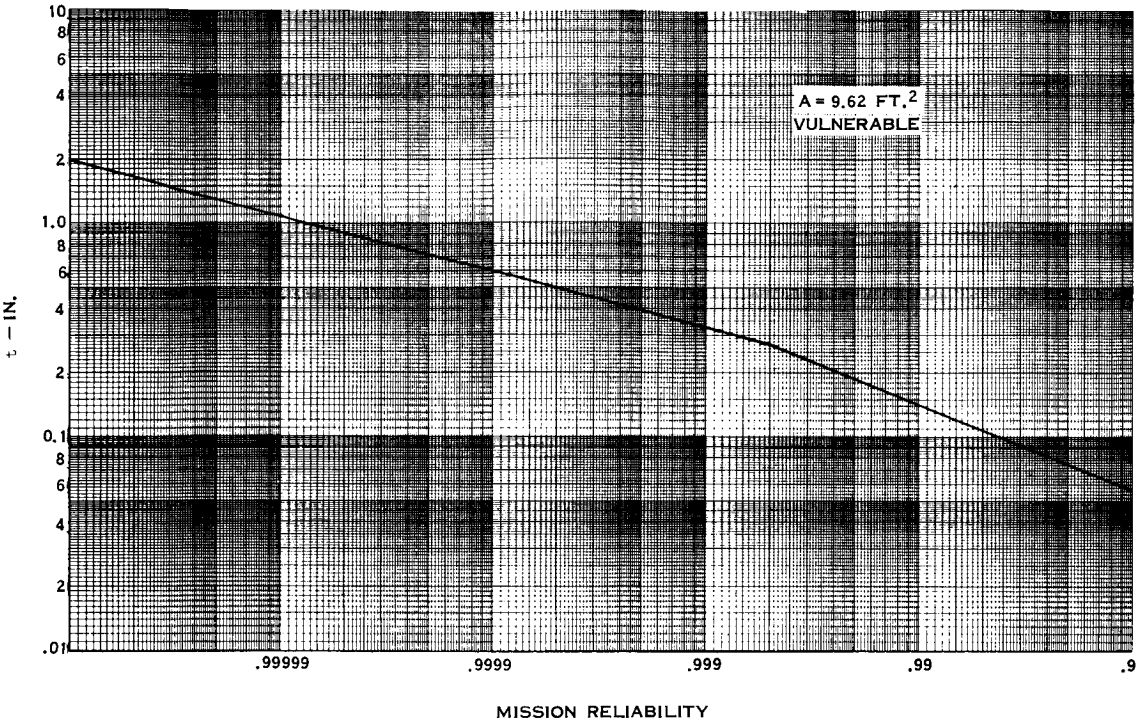


FIGURE 10–22

SINGLE SHEET METEOROID PROTECTION FOR MMM
BJORK PENETRATION CRITERIA

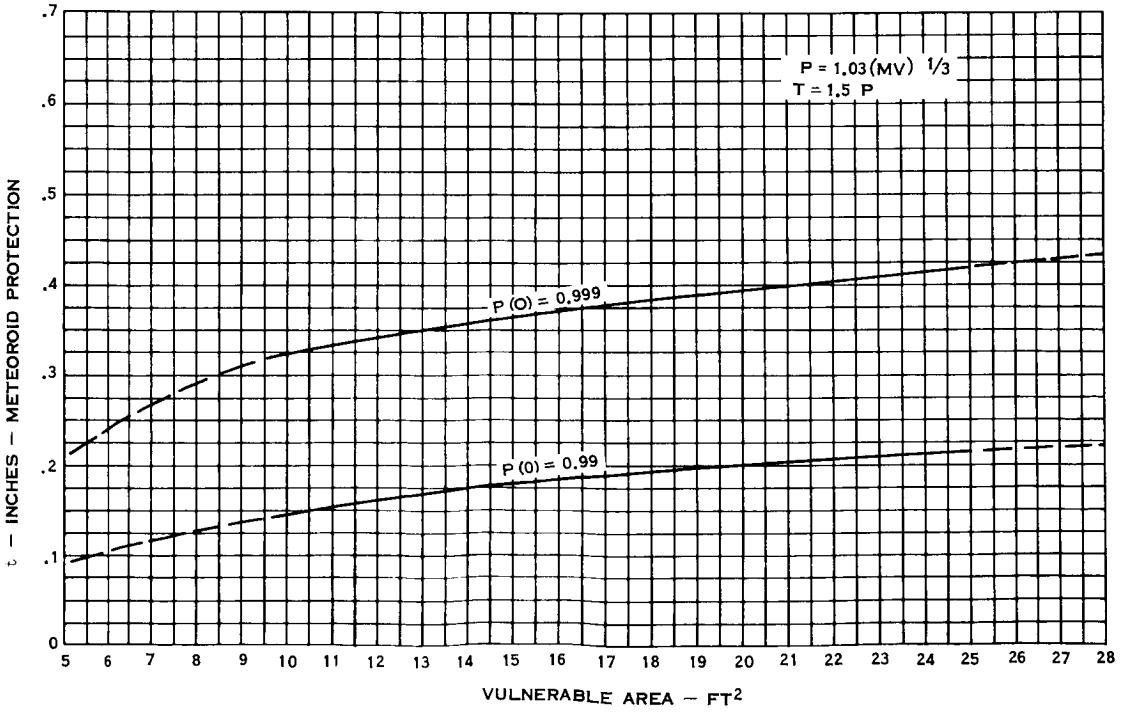


FIGURE 10–23

MULTI-SHEET METEOROID PROTECTION FOR MMM
CHARTER'S AND SUMMER'S PENETRATION CRITERIA

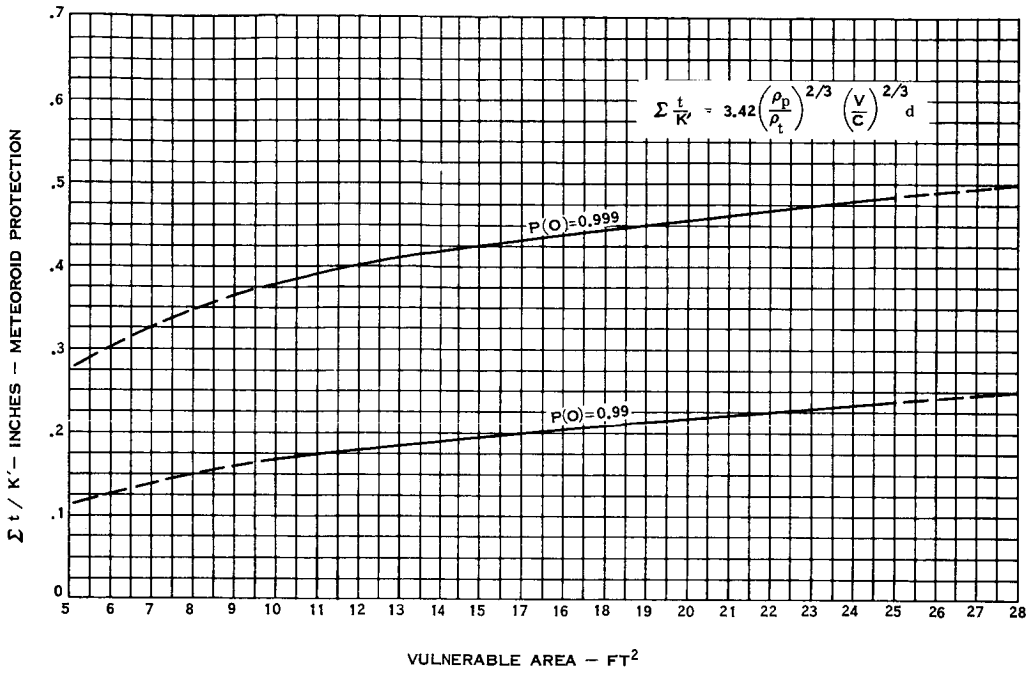


FIGURE 10-24

MEM RADIATORS – METEOROID PROTECTION
SINGLE SHIELD
BJORK CRITERIA

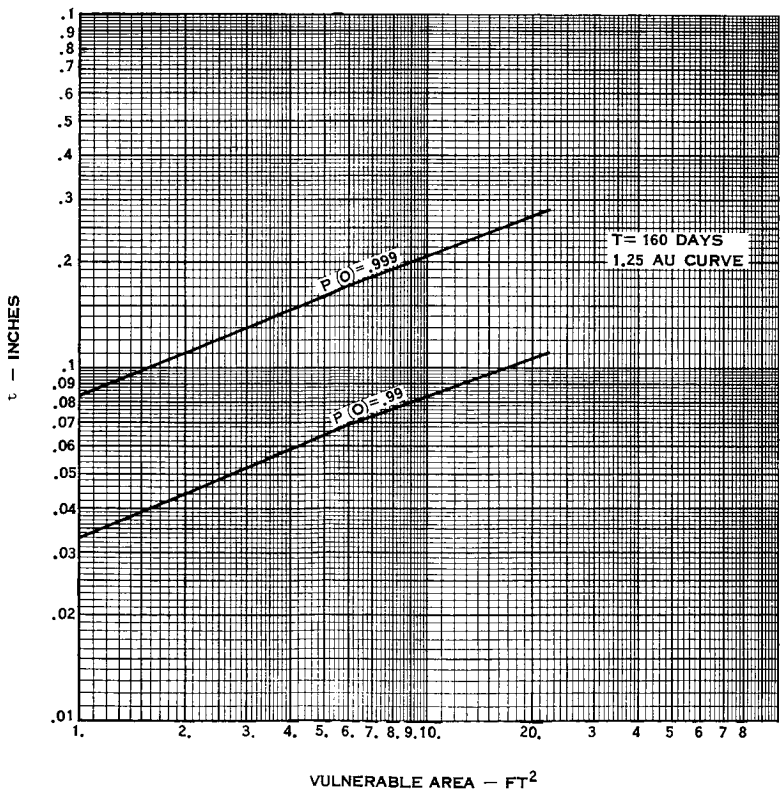


FIGURE 10-25

MARS EXCURSION MODULE
MULTI-SHIELD
METEOROID PROTECTION
CHARTER'S – SUMMER'S
PENETRATION CRITERIA

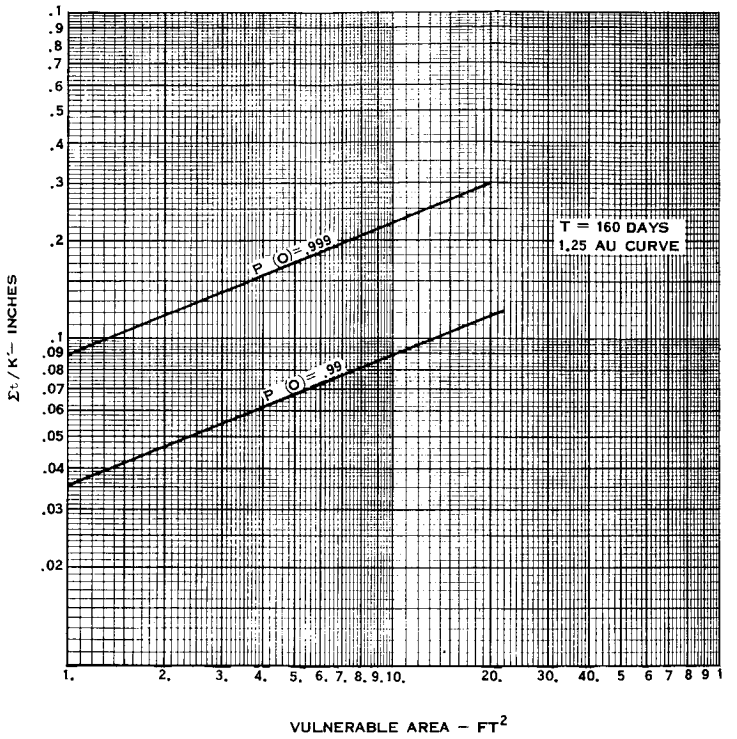


FIGURE 10-26

MARS MISSION MODULE
CABIN FLOW AND HUMIDITY VS SENSIBLE LOAD

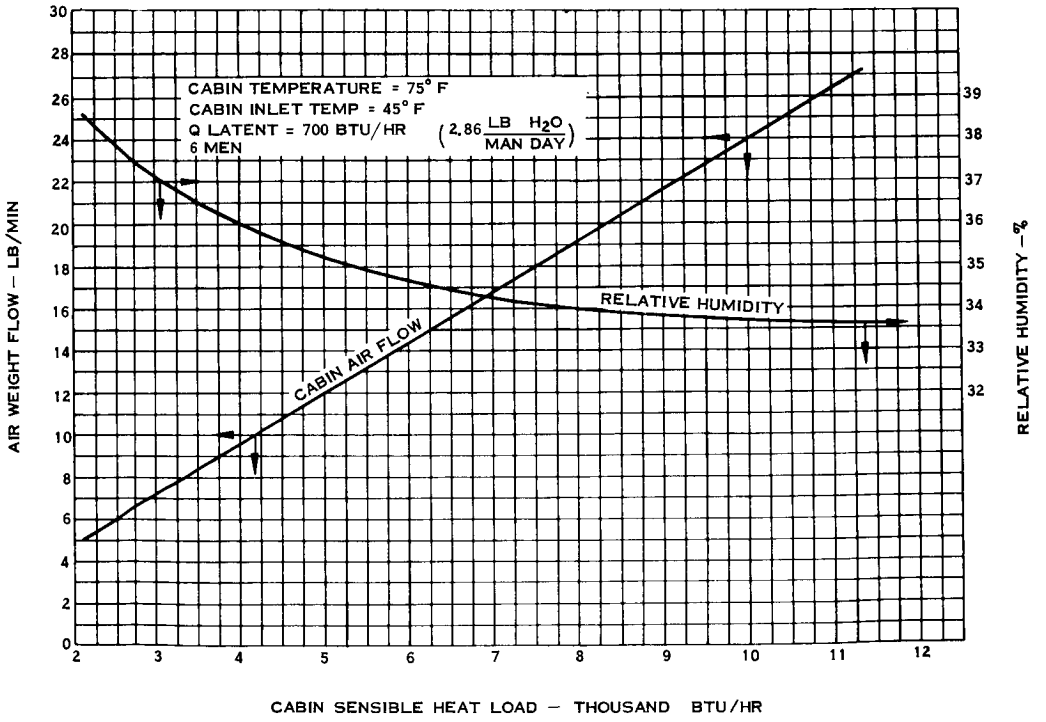


FIGURE 10-27

10.3.6.4 Meteoroid Protection Nomenclature

ψ	Meteoroid flux
M	Meteoroid mass
α	Flux distribution intercept
β	Flux distribution slope
V	Meteoroid velocity
C	Sonic velocity of target - $c = \left[\frac{Eg}{t}\right]^{1/2}$
P(0)	Probability of no puncture
K'	Multi-sheet penetration factor
NT x L	Number of tubes times radiator length
d_i	Tube inner diameter
AU	Astronomical Unit
E	Young's modulus
g	Gravity
ρ_p	Meteoroid density
ρ_t	Target, shield, tube density
P	Meteoroid penetration depth in semi-infinite target
d	Meteoroid diameter
t	Thickness
T	Time

10.4 Circulation and Humidity Control

The initial work on circulation and humidity control was done with single air loops, and curves were drawn for the three modules showing the effect of cabin heat exchanger outlet temperature on humidity and cabin air flow requirements. The sensible cabin loads used in this phase of the study were based on the crew sensible load plus 25 to 50% of the electrical load excluding the estimated load for the ECS. To minimize air weight flow and therefore fan power, the highest allowable cabin temperature of 75°F was selected for the modules. Since the heat loads originally taken were subject to change, curves were also prepared to show air flow and humidity variation as the sensible cabin heat load increased.

Figures 10-27 and 10-28 show the required air flow and resultant humidity as the cabin sensible heat load varies for all the modules. It can be seen that as the air weight flow and cabin sensible heat load increase, the relative humidity lines become asymptotic with limiting values below the 35% RH minimum requirement set in the Mars Study specification.

Figures 10-29, 10-30, 10-31 and 10-32 are also for a single air loop and show for a 75°F cabin temperature the effect of varying the humidity control heat exchanger outlet temperature on the required air flow and the resultant relative humidity for the ERM with a latent load based on 6 men, the MEM with 2 men, the MEM with 4

MARS EXCURSION MODULE – EARTH RE-ENTRY MODULE
CABIN FLOW AND HUMIDITY VS SENSIBLE LOAD

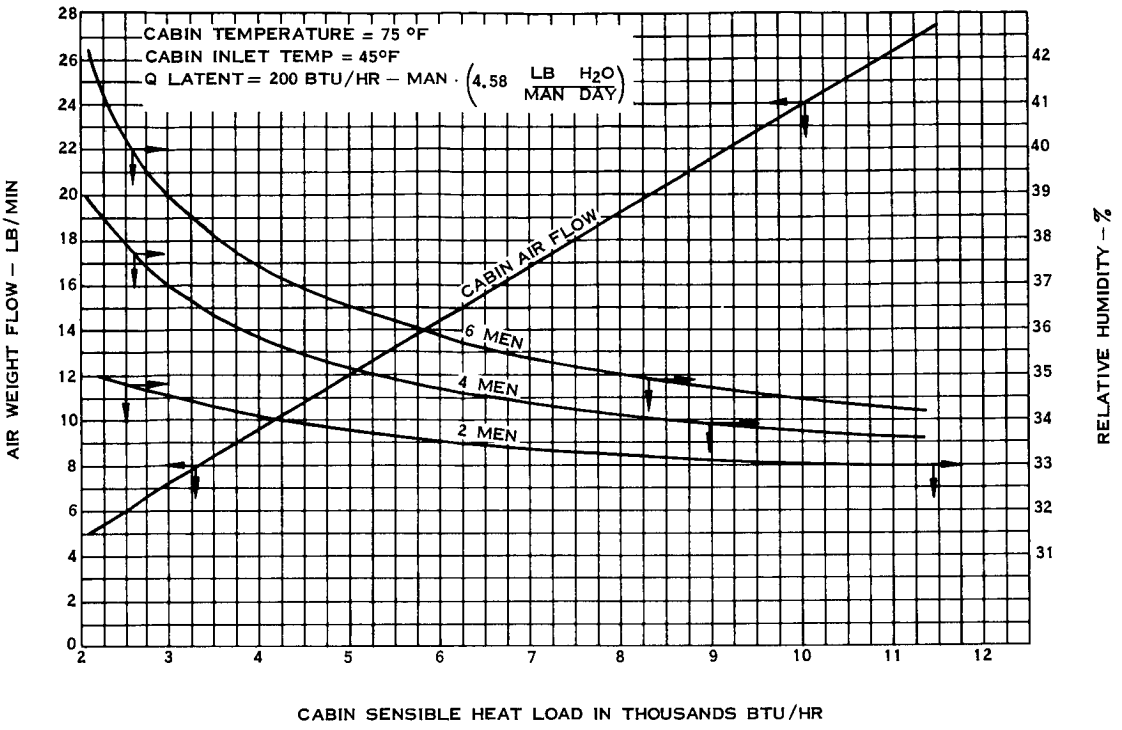


FIGURE 10-28

EARTH RE-ENTRY MODULE
CABIN AIR FLOW AND HUMIDITY VS RELATIVE HUMIDITY

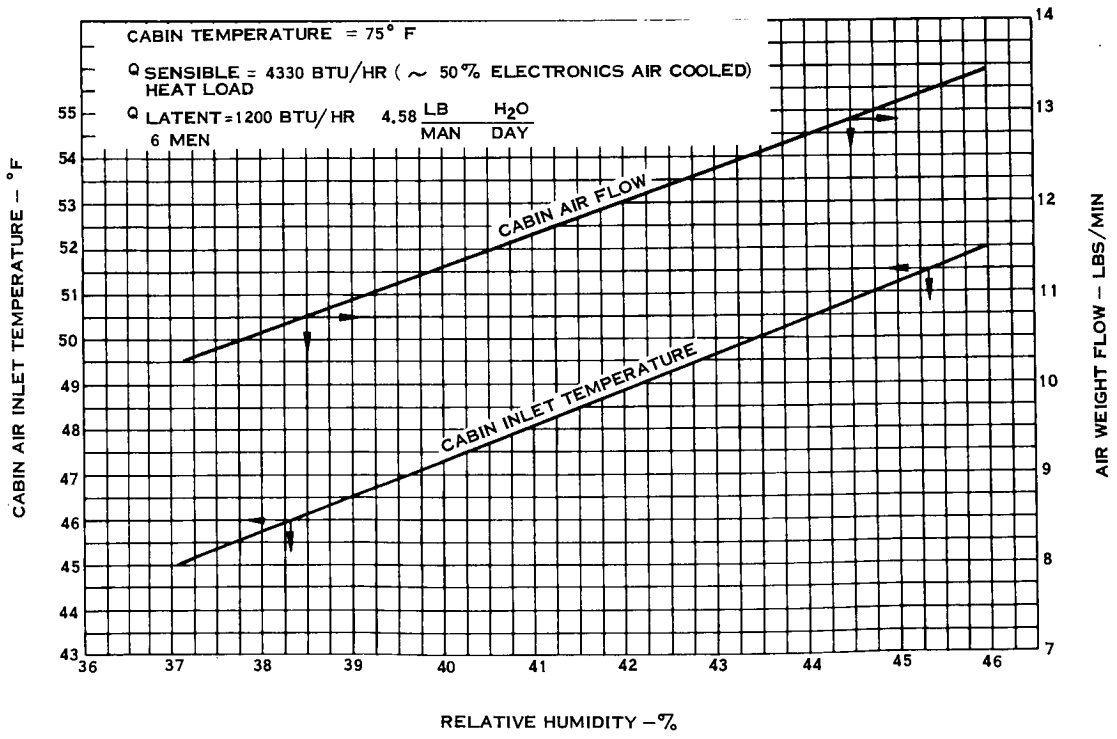


FIGURE 10-29

MARS EXCURSION MODULE
CABIN AIR FLOW AND TEMPERATURE VS RELATIVE HUMIDITY

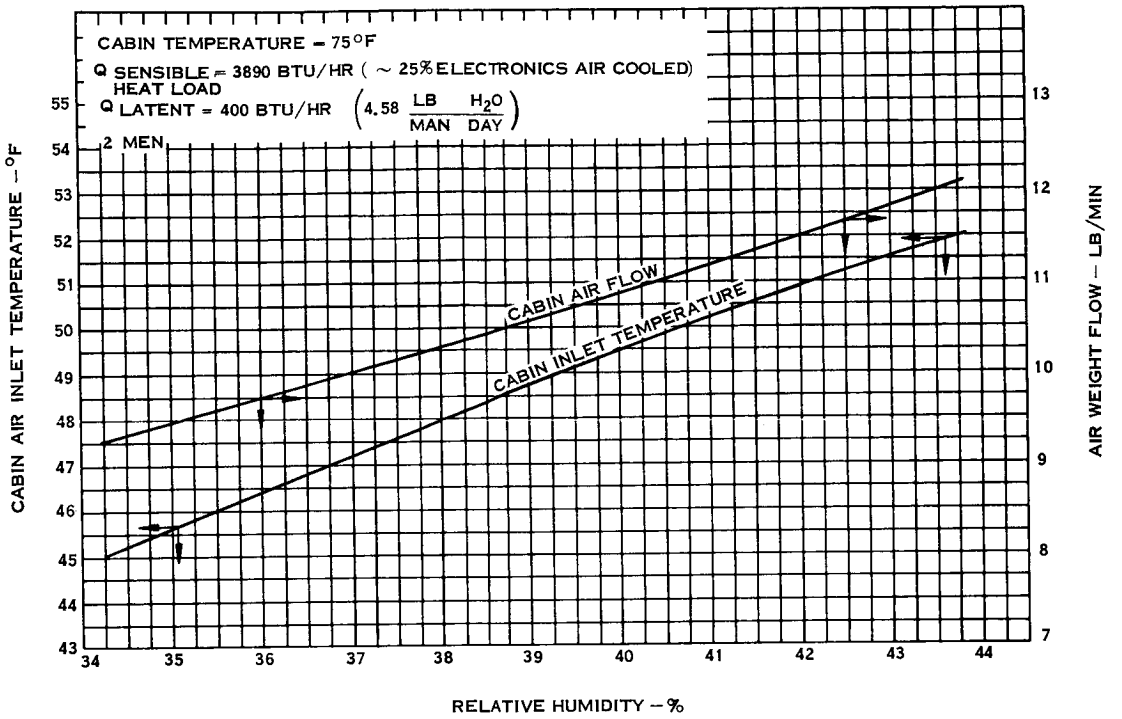


FIGURE 10-30

MARS EXCURSION MODULE
CABIN AIR FLOW AND TEMPERATURE VS RELATIVE HUMIDITY

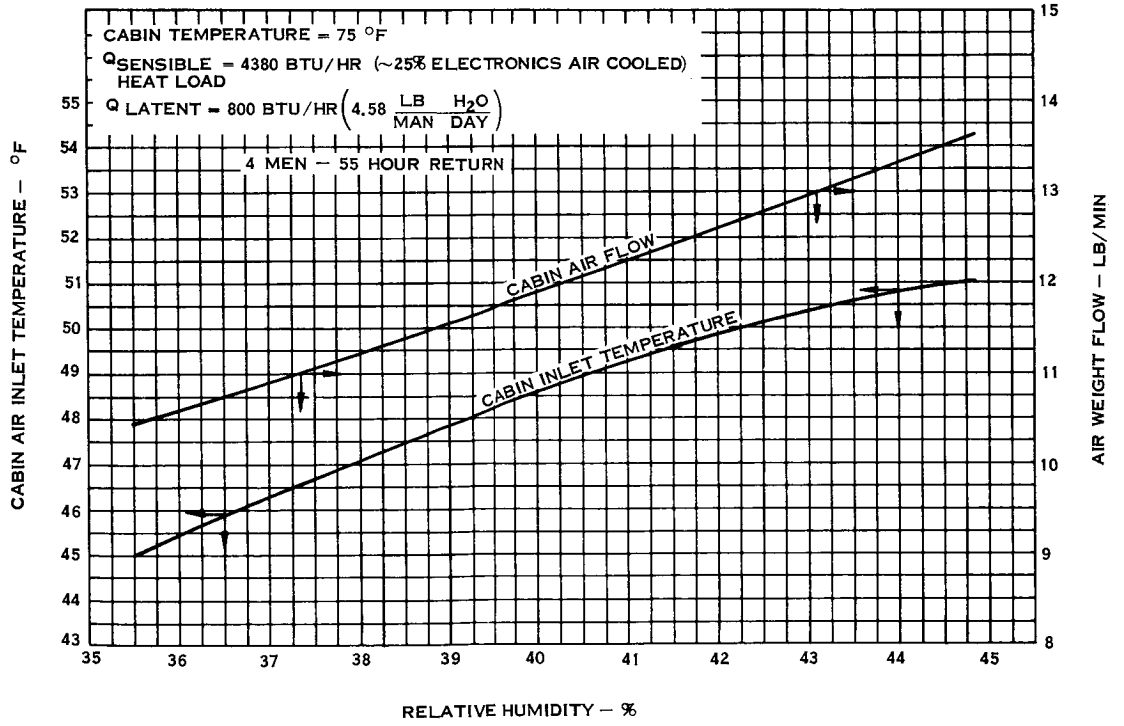


FIGURE 10-31

MARS MISSION MODULE
CABIN AIR FLOW AND TEMPERATURE VS RELATIVE HUMIDITY

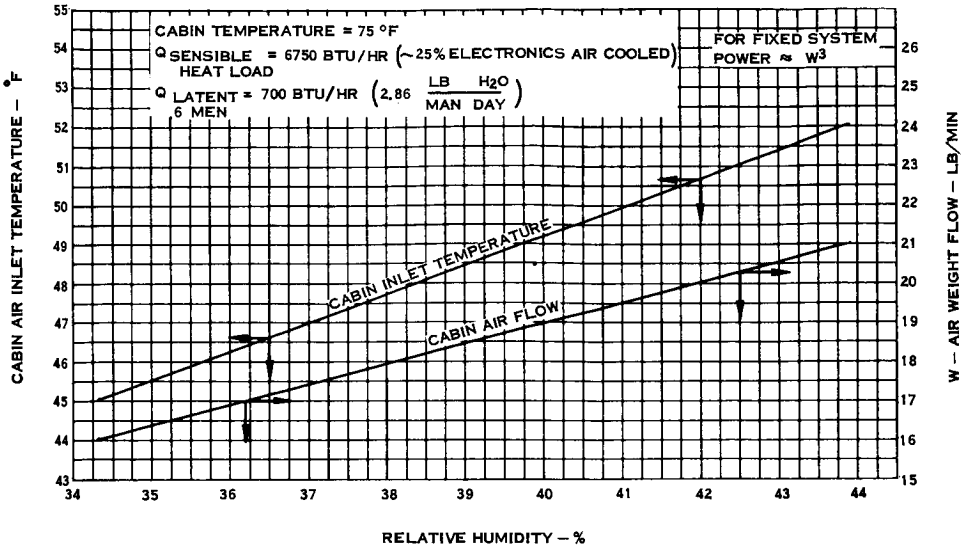


FIGURE 10–32

OPTIMIZATION STUDY FOR MARS SURFACE FAN
0.1 PSI PRESSURE RISE

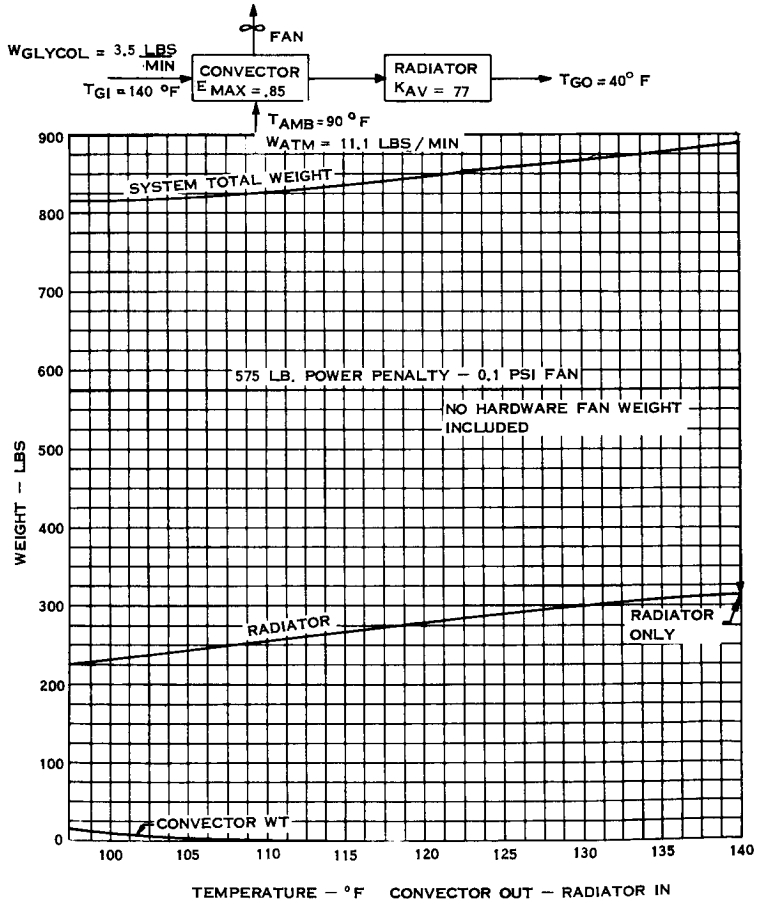


FIGURE 10–33

10.4 (Continued)

men, and the MMM with 6 men. Again, the cabin heat loads used in these figures were preliminary, and are not to be taken as final values, but to show trends.

The curves reveal that for single air loops, the cabin relative humidity is set by the humidity control heat exchanger leaving temperature, and that the cabin sensible load removed by this circuit should be kept low to reduce the required air flow. As much of the electronic load as possible should be liquid cooled for this reason; it also requires less power to cool with a transport fluid than with air.

Later in the study, it became apparent that double air loops can provide a further reduction in fan power. The primary loop, with a low air flow, goes through the major pressure drop components and a latent load or humidity control heat exchanger to control the humidity. The secondary loop handles the higher air flow, but at a lower pressure drop, and at a temperature level to cool the major portion of the sensible load, but still not cause condensation to occur in the secondary heat exchanger. Since double air loops require less fan power, and can more readily set cabin relative humidity above the 35% minimum set in the Mars Study specification, they were used in the system integration portion of the study.

10.5 Mars Surface Convectors

This part of the study was performed using a glycol-water solution as the coolant. Investigation of fluids at a later date indicated that FC-75 would be a better fluid. However, the effect of changing fluids on system weights is negligible, and the conclusions are still valid for FC-75.

The Mars atmosphere has been considered as a potential heat sink for convectors during the Mars exploration. Since the atmospheric temperature varies from -94°F to 90°F at the equator throughout the Mars day, the maximum temperature was used as the inlet temperature of the atmospheric flow through the convective heat exchanger as drawn by the fan. To yield a 40°F level of transport fluid (60-40 glycol) in the system, a radiator was added in series to the convector. The mass flow ratio of the convector was made 1, which required 11.1 lbs./min. of fan flow. A glycol flow of 3.5 lbs./min. was needed to reject the Q = 15,943 BTU/hr. estimated load with a convector entering temperature of 140°F and a radiator leaving temperature of 40°F. The vertical flat plate radiator had an absorbed influx of 77 BTU/hr.-Ft^2 based on the sum of the solar, albedo and direct surface emission to a vertical plate as shown in Figure 10-9.

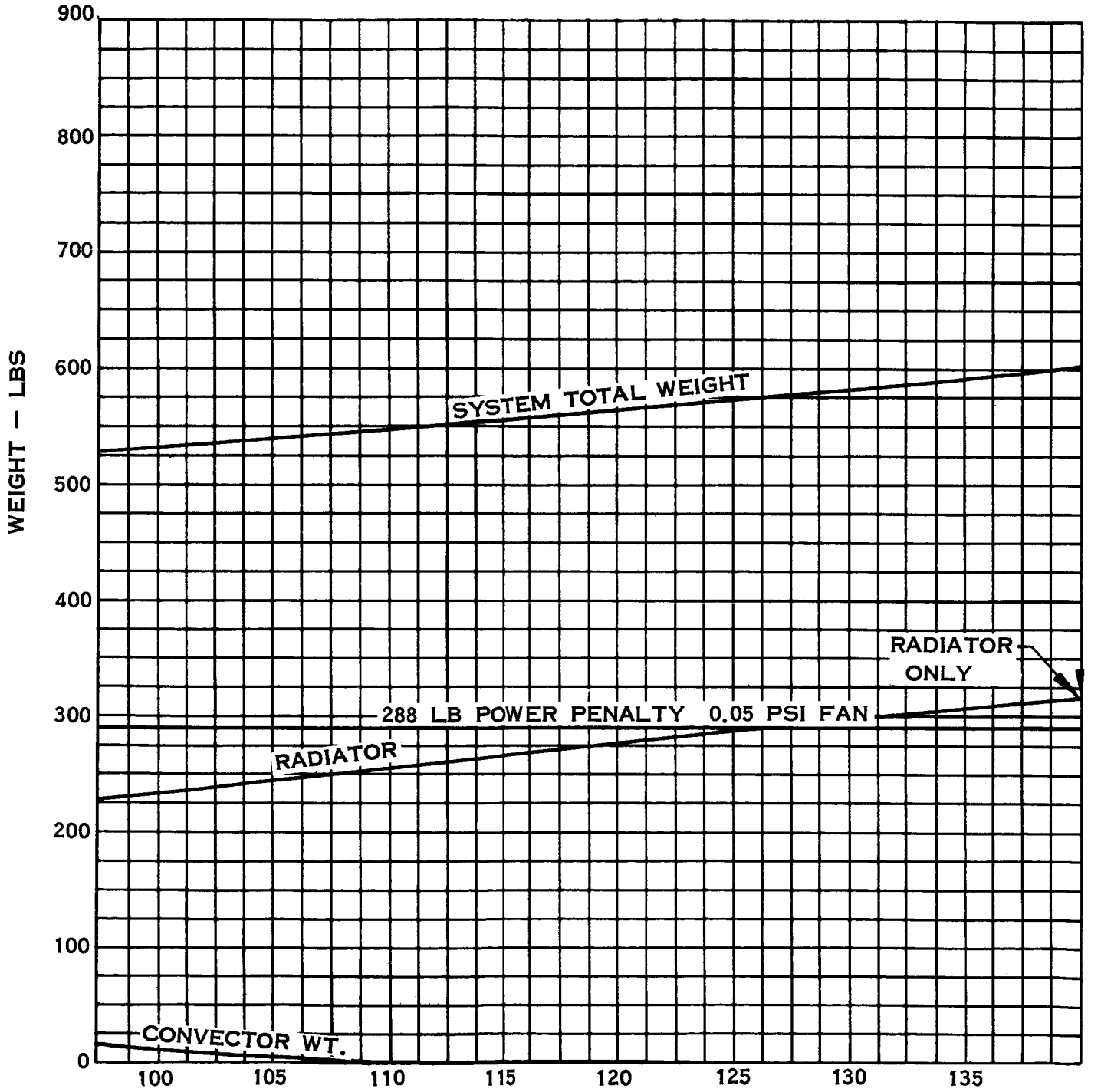
10.5 (Continued)

The Mars atmosphere was considered transparent to radiation into space (no gas radiation from CO_2 or water vapor), and no free convection was considered to be occuring on the radiator surface. (It has been calculated using Lorenz's equation for free convection that for the model Mars atmosphere and gravity, the heat transfer coefficient is only 0.22 BTU/hr.-ft^2 °F for a 1 ft. vertical surface and a temperature difference of 80°F. If the temperature difference is reduced to 19°F. the free convection heat transfer coefficient is reduced to 0.15. Actually, free convection would act with the 90°F ambient to transfer heat into the radiator. but most of the time with the ambient temperature lower than the radiator temperature, convection helps the radiator.) The convector atmospheric pressure drops (fan pressure rises) were taken as 0.05 and 0.1 psi to find the effect of pressure drop on convector size and fan power with an assumed overall fan-motor efficiency of 40%. Convectors and radiators were sized for different load splits and their weights added to the power penalty for the two pressure drop systems. The maximum effectiveness of the convector was taken as 85%. which gave weights including power penalty of 817 lbs. and 531 lbs. for convector. radiator and fan penalty for the 0.1 psi and .05 psi systems respectively. The weight of either system with only a radiator to handle the total load was only 320 lbs. (no fan or convector). This result was due to the power penalty of 500 lbs./KW, which imposed penalties of 575 lbs. and 288 lbs. for the 0.1 psi and 0.05 psi fans. The maximum convector had a wet weight of only 17 lbs. so convector weights are insignificant. Due to the low atmospheric density, the volume flow of the fans was 1415 cfm, which when combined with an assumed speed of 20,000 rpm indicated from the calculated specific speed that axial fans would be required for the Mars Surface. However, the study indicates that the radiator alone gives the lowest system weight. Landing sites other than the equator would reduce the radiator size and weight to even lower values. The results of this investigation are presented in Figure 10-33 and 10-34.

The power penalty of 500 lbs./KW is for a nuclear power source. If a fuel cell is used, the power penalty becomes 1590 lbs./KW which would increase the fan penalties to 1830 lbs. and 915 lbs. for the two fans.

The maximum radiator weight of 320 lbs. includes fin weight plus the shield tube mode of meteoroid protection. Actually, the influx on this radiator could be reduced by a more favorable orientation such as 35° to the horizontal with a resultant decrease in size and weight, and the fins could then be integral with the vehicle. The example is given to point out the high penalty paid for the Mars atmosphere circulating equipment.

OPTIMIZATION STUDY FOR MARS SURFACE FAN
0.05 PSI FAN



TEMPERATURE – F CONVECTOR OUT – RAD. IN

FIGURE 10-34

10.6 Evaporative Cooling

The Mars surface atmospheric pressure used in the study was 1.26 psia, which gives a water boiling temperature of approximately 110°F. Since the cabin air supply temperature requirements may be as low as 45°F, a water boiler alone will not suffice, but can only be used to handle the high temperature portion of the load. A cooling tower was also considered for the Mars surface, but would require more water than is available as waste from a fuel cell or urine. The heat would have to be removed from the transport fluid inside the tubes by water evaporating from wicks on the surface of the tubes with the Mars atmosphere being drawn across the wicks by a fan. Even if all the water available went into cooling the transport fluid only 22% of the heat load could be handled. Actually, some of this water would be evaporated by the high temperature of the entering Mars atmosphere and not by the transport fluid with a further reduction in useful cooling. It has already been shown in Section 10.5 on Mars Surface Convectors the high penalty paid for using fans. All these factors indicate that a cooling tower for the Mars surface is not practical.

Evaporative cooling is obviously not feasible for extended periods of time on a long term mission such as the Mars mission. However, there are short duration periods during the mission when evaporative cooling may be the most optimum cooling method. These are:

1. Immediately after Earth blast-off.
2. Re-entry into the Earth atmosphere.
3. Aerodynamic braking into Mars Atmosphere.
4. Aerodynamic braking during Mars Landing.
5. Mars blast-off and rendezvous with Mission Module.

The most common fluid for this type of cooling is water because it has a very high latent heat of vaporization and is relatively easy to store and control. Therefore, it will be considered for this study.

The state-of-the-art of water evaporators is well advanced because this type of device has been used in Mercury and will be used in Gemini, the Apollo Space Suit Portable Life Support System, and the Lunar Excursion Module Life Support System. Therefore, since sizing information is readily available, a subsystem study was not performed on evaporative coolers. The coolers were studied as part of the system integration phase and are discussed in the system integration portion of this report.

10.7 Miscellaneous Heat Rejection Methods

The major emphasis on methods of heat rejection for the Excursion Module on the Mars surface has been placed on space radiators. This was done because there are many indications that radiators will perform well on the Mars surface.

The atmospheric pressure specified for the model atmosphere is 1.26 psia. This reduced pressure, combined with the reduced gravity, results in a natural convection coefficient considerably less than that on Earth, indicating that convection is detrimental only during the hottest part of the day when atmospheric temperatures are above 40°F.

The Mars atmosphere should be transparent to radiation because it contains no water vapor and only 2% CO_2. Therefore, the radiator should "see" deep space temperatures. This conclusion is further strengthened by the wide variation in surface temperature indicating rapid radiational cooling.

The distance of Mars from the sun also increases the radiator performance in that the solar influx to a blackbody is only 186 BTU/Hr.-ft^2 compared to 440 for Earth.

It can be seen that the radiator performance predictions are dependent on the properties of the Martian Atmosphere. Recently published articles have indicated that the atmosphere may be very different than the model used for this study. Atmospheric pressure may be as low as .3 psia and the atmosphere may contain clouds of dust, ice crystals, solid CO_2, or nitrogen tetroxide. There is also the possibility of high velocity surface winds. For these reasons, the radiator may not prove to be optimum when more is known about the Mars surface and atmosphere. Therefore, the following alternate methods of heat rejection should be considered in more detail if future information indicates that radiators are not feasible.

If convection during the hot portion of the day presents problems, it may be feasible to freeze the waste water during the cold portion and melt it during the hot portion of the day. Also, a complete transient analysis may indicate sufficient thermal lag to the system without using ice as a thermal storage device.

Since the fuel cell will be used for electrical power, any system which uses electrical power becomes very unattractive. This is true of convectors due to the large volumes of air which must be circulated over them, and any mechanical refrigeration devices used to provide a greater temperature difference between the convector and the atmosphere. However, an absorption refrigeration system using an isotope heat source may be feasible.

10.7 (Continued)

Another alternative would be to restrict the landing site to an area of Mars which is cold enough to provide adequate cooling of the MEM.

10.8 Heat Exchangers

Since optimum heat exchanger design is limited to specific input parameters for each requirement, a generalized discussion to cover all possible combinations is beyond the scope and intent of this study. To illustrate the procedure and the variance in size possible by relative emphasis on weight and power criteria. an example of the sizing procedure is included in this section.

Representative performance requirements for the main heat exchanger were established to allow initial sizing. The heat exchanger is air to FC-75 with the coolant choice influencing the final size but not the overall trends. Fin selection is as follows:

Air Side: 0.156-18-.002 Ruffled (Stainless)
FC-75 Side: 0.075-18-.002 Herringbone (Stainless)

Stainless steel fins were selected for extended mission reliability since lighter aluminum fins may not provide the required life. Fin spacing and heights are typical values for illustration purposes and are not fully optimized. The core selected for this application is sketched in Figure 10-35.

Figure 10-36 presents core weight and volume as a function of the core pressure drop for this application. Also included is the equivalent weight of the pumping power increase as a function of the pressure drop. This pumping power considers the air side only since coolant pumping power is negligible in comparison.

Summing the power and fixed weight curves yields the total equivalent weight of the heat exchanger as a function of the pressure drop. From an equivalent weight basis. the optimum core has an air side ΔP of approximately 0.20 inches of water for the input parameters of this example. The header weight and coolant weight must be added for the final design which shifts the optimum point to 0.31 inches of water.

To indicate a general weight variation for this purpose, Figure 10-37 has been prepared. The weight is optimum only at the design point, but an indication of the weight variation due to a flow or temperature change can be obtained.

SAMPLE CORE CONFIGURATION

MULTI–PATH CROSS COUNTERFLOW PLATE AND FIN TYPE HX

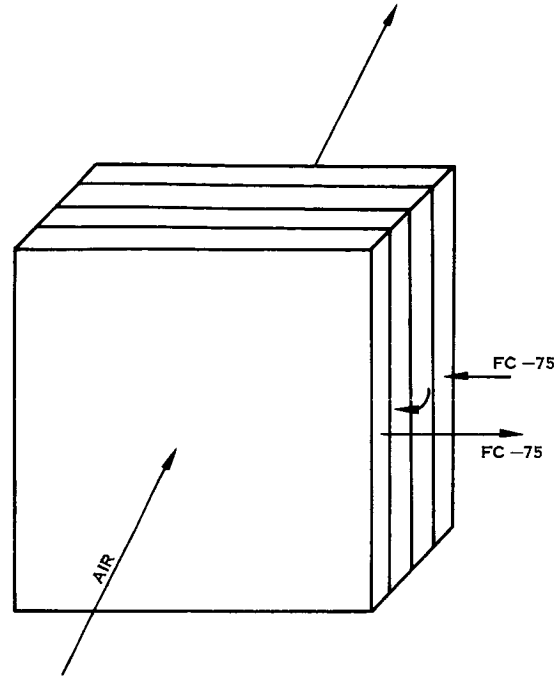


FIGURE 10 – 35

CABIN HEAT EXCHANGER
SIZING EXAMPLE

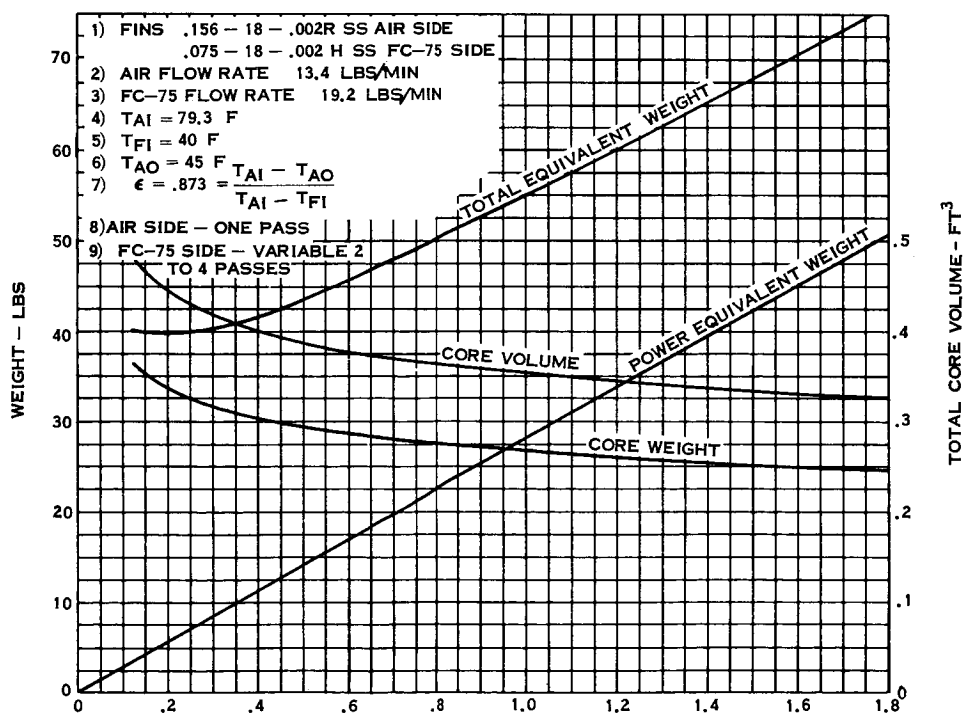


FIGURE 10 – 36

CORE WEIGHT PER UNIT MASS FLOW VS MASS FLOW RATIO AND EFFECTIVENESS

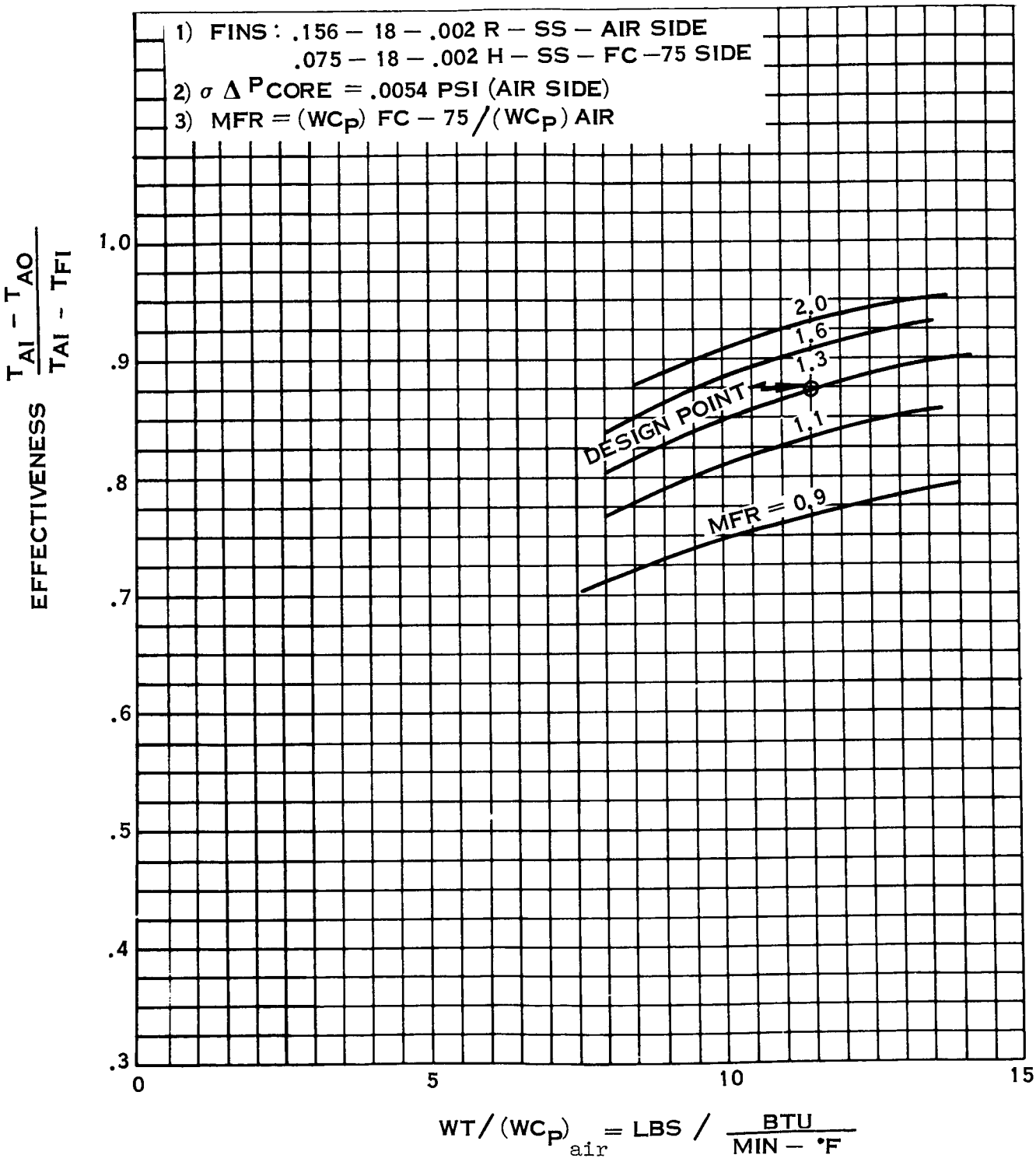


FIGURE 10 – 37

10.8 (Continued)

Final header weight is a function of the eventual core geometry. For the same volume core, the header weight may vary considerably as the dimensions are varied. Since this is a function of the end envelope, no general treatment is possible. As a rough ball park estimate for this example, header weights may be assumed as approximately 30% of the core weight.

10.9 Air Recirculation Fans

The information describing the cabin recirculation fan is being presented in parametric form for design point operation. The range of the affecting variables has been selected to cover the main area of interest for this application and the data may be used over that range. Since fan speed cannot be simply presented as a variable, a fixed operating speed of 11,400 rpm was considered. Nominal inlet temperature was taken as 70°F based on early system performance data. Changes of fan inlet temperature in the order of 5 or 10°F will have a negligible effect on fan performance. A speed of 11,400 rpm was selected since it is consistent with good reliability and long life, and yet fast enough to permit reasonable size machinery.

Motor and fan efficiencies were estimated with consideration given to size and speed of the machinery and varied accordingly. Efficiencies were estimated for all operating points investigated. The basis for these estimates were analytical and test results obtained by various investigators.

Figure 10-38 indicates rotor tip diameter as a function of design point inlet volume flow rate and reduced pressure rise. The Figure indicates that different types of machinery must be designed depending on the actual design point required. The dashed lines are not to be construed as sharp divisions in machinery types, but rather as a guide to optimum areas of operation for the various classes of machinery. A method of analysis using specific speed and specific diameter has been used to generate this figure.

Figure 10-39 gives the fan weight as a function of the rotor tip diameter, which can be obtained from Figure 10-38. The weights for a selection of fans were taken from the Joy Company catalog and a mean curve drawn through the scatter of points so Figure 10-39 gives a fair approximation of the weights for the types of fans shown. Use of this approximation is justified since fan weight is a small portion of the total equivalent weight. Figure 10-40 describes the power requirements of the units designed to operate at various pressure rises and inlet volume flows based on analysis and test experience. Figure 10-41 gives the motor weight as a function of the Figure 10-40 power. Figure 10-42 illustrates the combined

RECIRCULATING FAN TYPE SELECTION

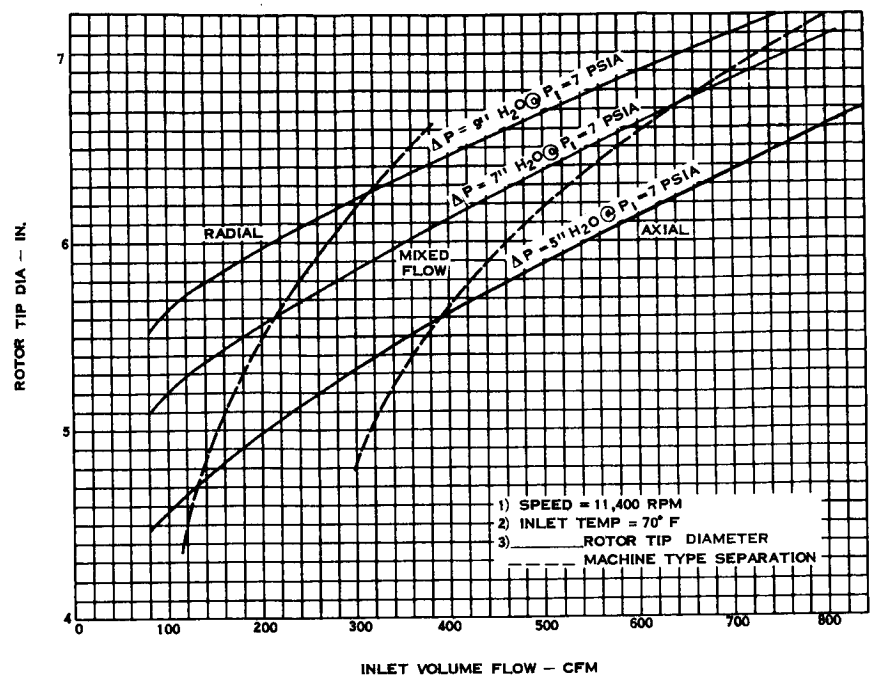


FIGURE 10 – 38

FAN WEIGHT
VS
FAN ROTOR TIP DIAMETER

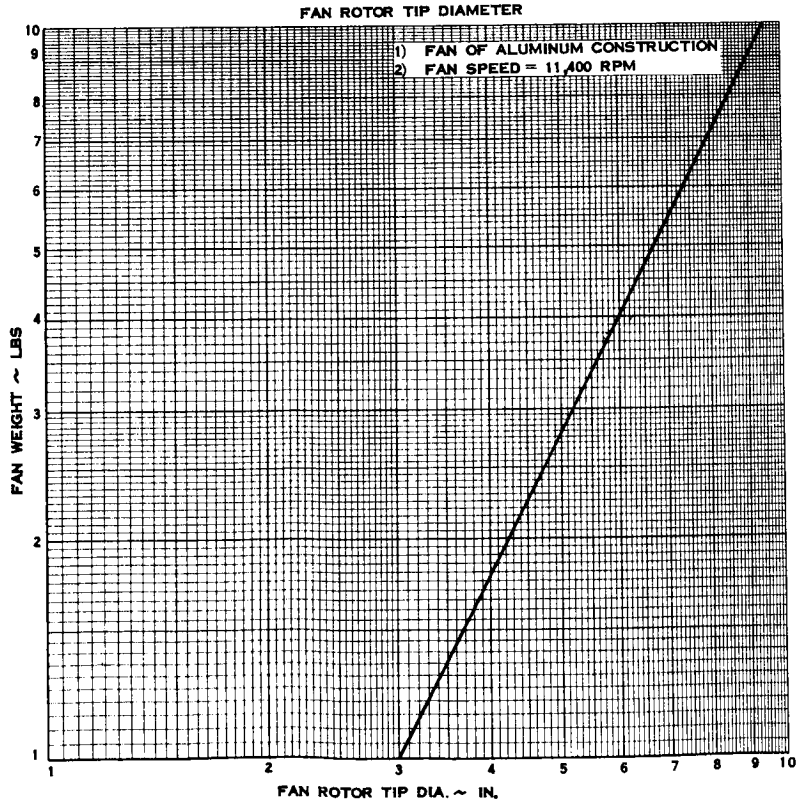


FIG. 10–39

RECIRCULATING FAN
INPUT POWER VS AIRFLOW

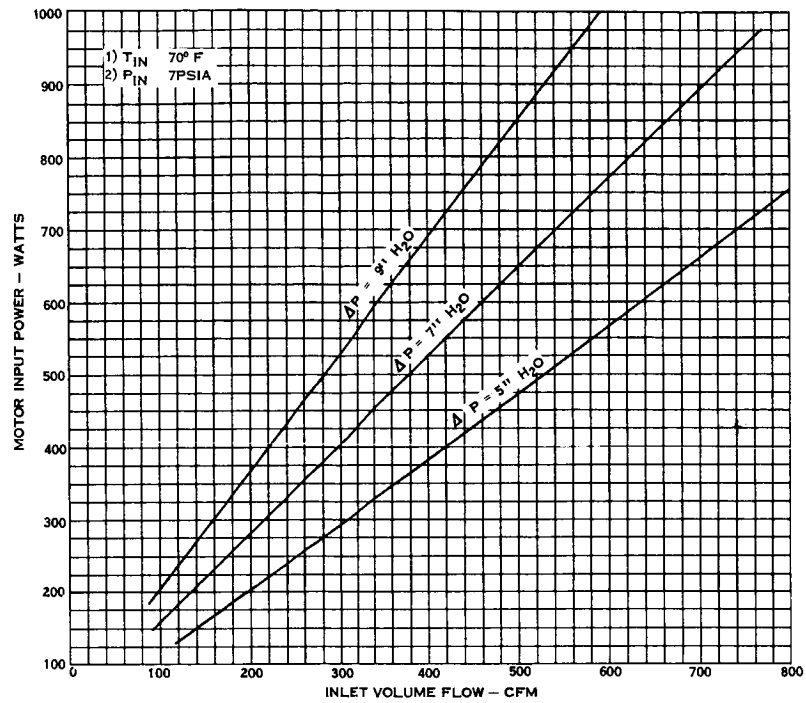


FIGURE 10 – 40

MOTOR WEIGHT
VS
MOTOR INPUT POWER

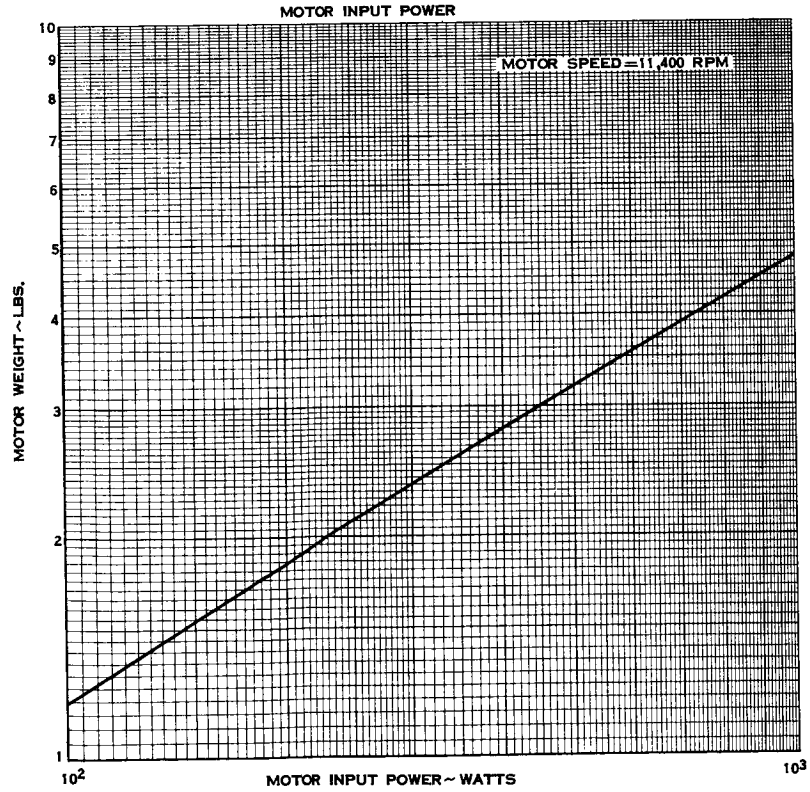


FIGURE 10–41

RECIRCULATING FAN FIXED WEIGHT VS AIRFLOW

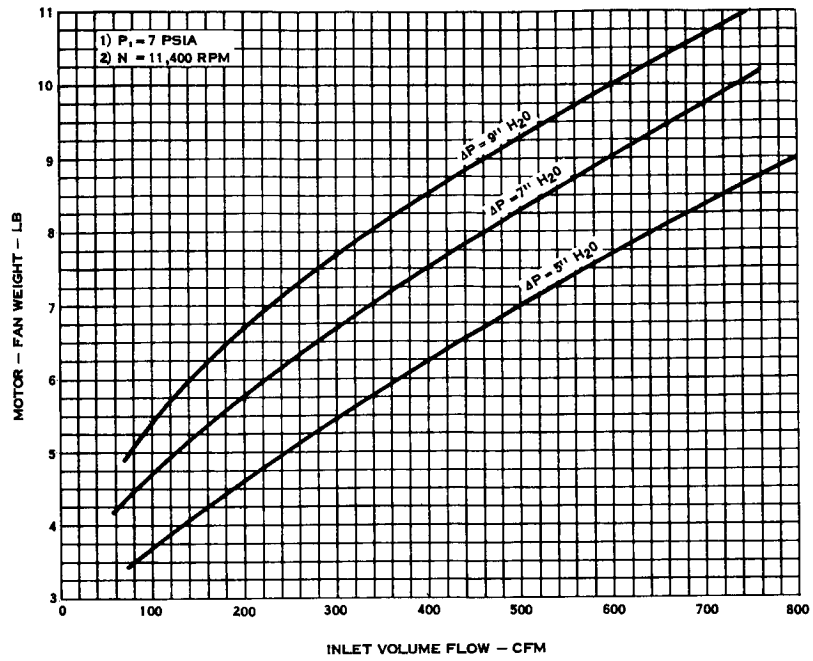


FIGURE 10 – 42

RECIRCULATING FAN
EQUIVALENT WEIGHT VS AIRFLOW

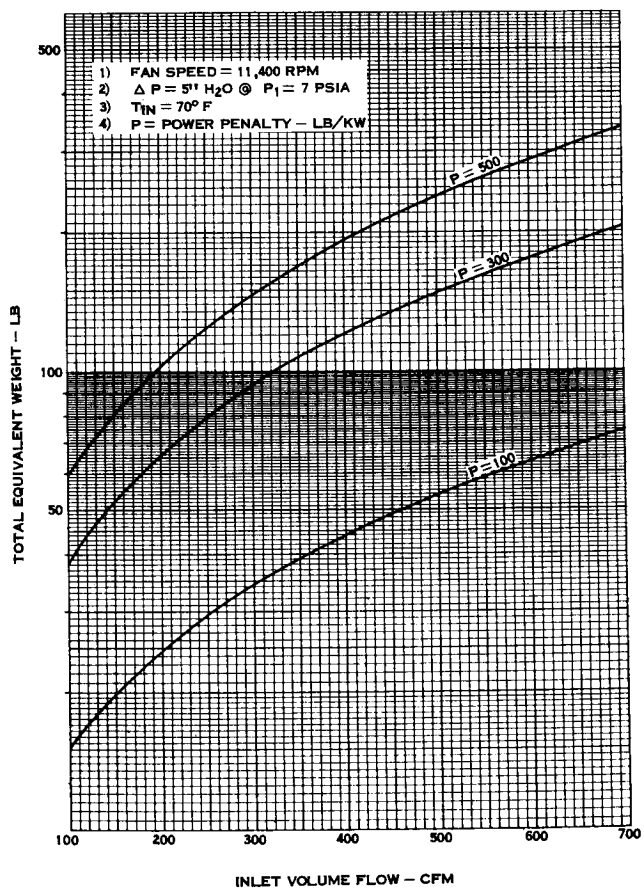
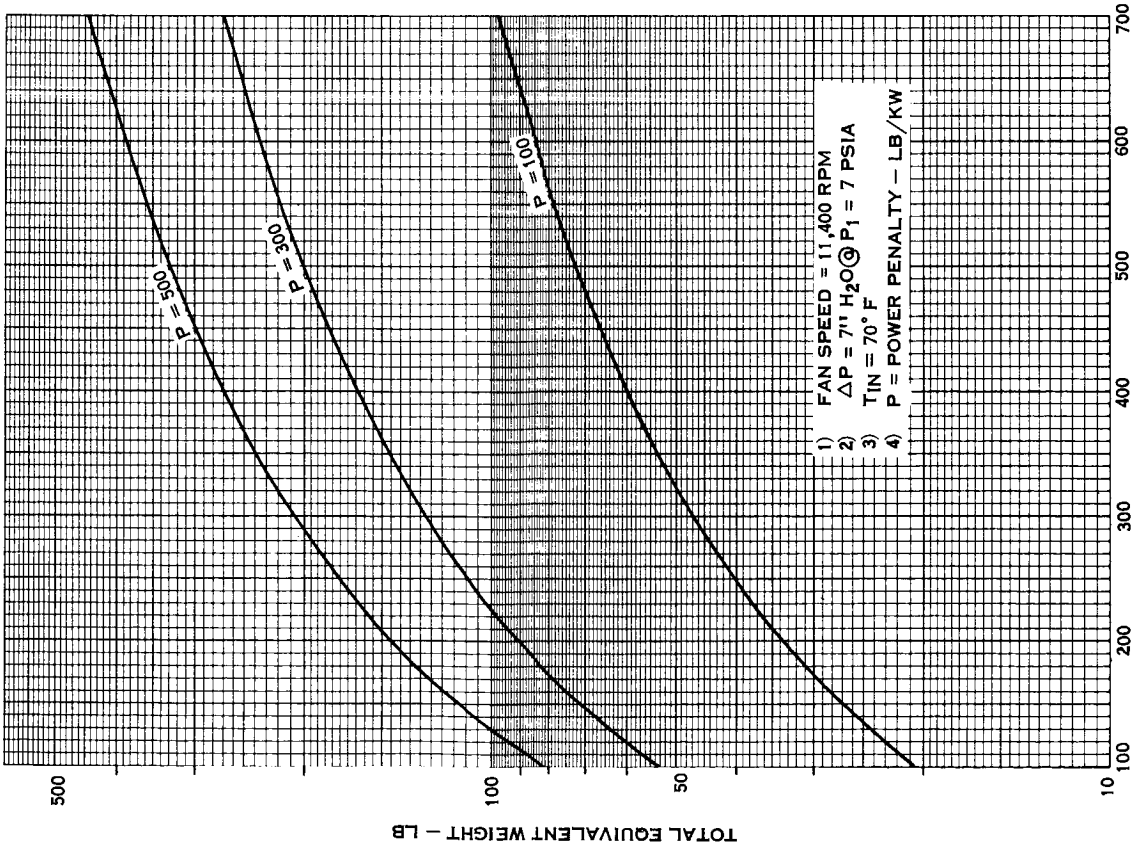


FIGURE 10 – 43

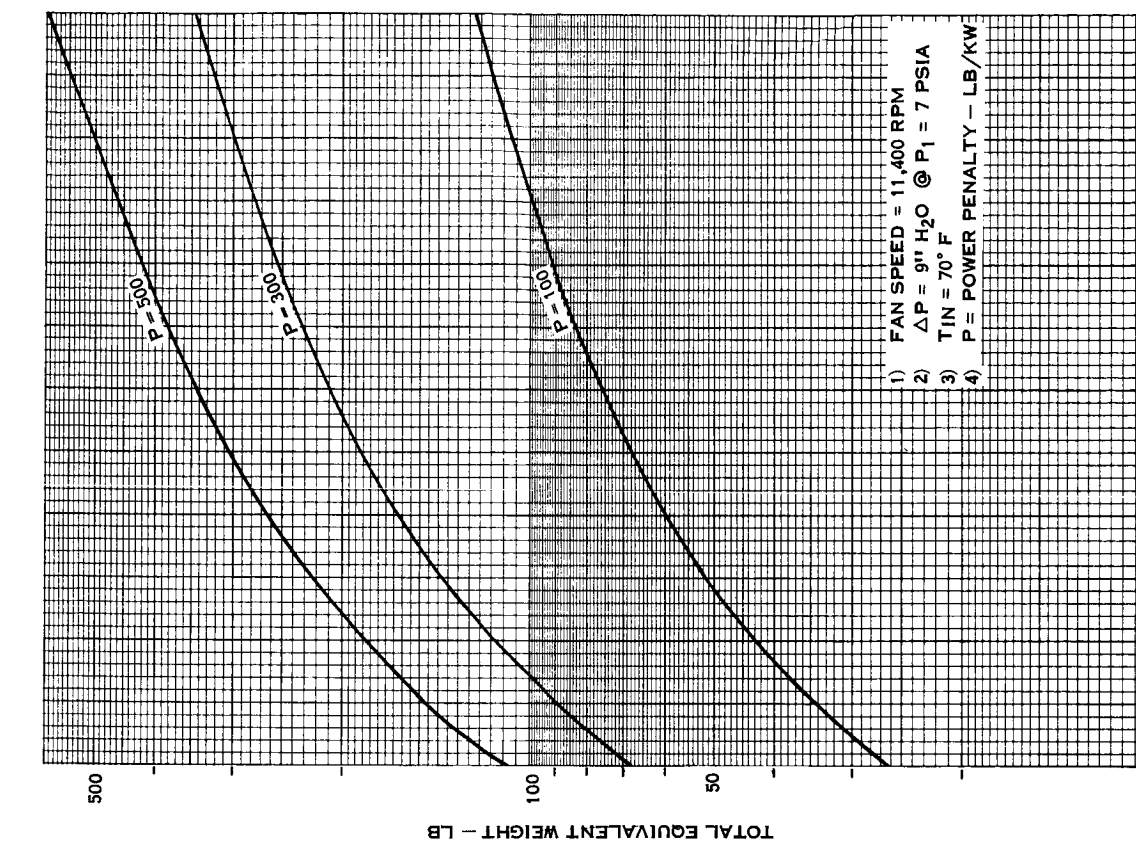
RECIRCULATING FAN
EQUIVALENT WEIGHT VS AIRFLOW



INLET VOLUME FLOW – CFM

FIGURE 10-44

RECIRCULATING FAN
EQUIVALENT WEIGHT VS AIRFLOW



INLET VOLUME FLOW – CFM

FIGURE 10-45

10.9 (Continued)

fan and motor weight in one curve against the inlet volume flow for fixed values of fan inlet pressure and speed. Motor-Fan equivalent weight is illustrated in Figures 10-43, 10-44, and 10-45 as a function of inlet volume flow rate and power penalty for three values of pressure rise at a fixed fan inlet pressure of 7 psia.

The fan power required to establish a given cabin relative humidity was briefly examined at the subsystem level. Since cabin exit temperature is essentially fixed at 70°F and, for a given design and crew size, the cabin sensible cooling load has a fixed design point, relative humidity can be changed only by changing water separator exit temperature. However, by raising separator exit temperature, the temperature drop across the cabin is diminished thereby requiring a greater air flow rate to absorb the sensible heat load. Thus, to raise cabin relative humidity, an increase in pumping power is required. The relationship between pumping power and cabin relative humidity for a 6 man crew is shown in Figure 10-46. A 5°F differential between water separator and cabin inlet was provided at the design point, so that cabin inlet temperature can be adjusted to meet off-design sensible heat loads while maintaining a constant cabin relative humidity. As would be expected, pumping power increases very rapidly as cabin inlet temperature approaches exit temperature.

RECIRCULATING FAN
INPUT POWER VS CABIN RELATIVE HUMIDITY

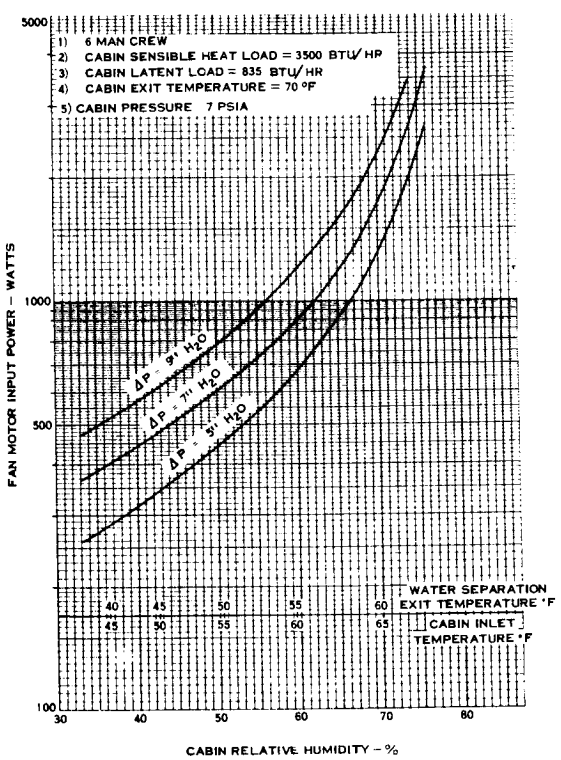


FIGURE 10-46

10.10 Water Separators

Introduction

The moisture added to the cabin atmosphere by the latent heat rejection of the crew and any other evaporative processes must be removed to maintain the cabin at a comfortable humidity level. This is accomplished by cooling the air below its dew point, thus causing a portion of the moisture to condense. Addition of a water separator to the conditioning equipment makes removal and collection of this excess moisture possible.

Many approaches have been investigated to serve this requirement in spacecraft environmental control systems. The most promising candidates will be briefly reviewed here. Due to the long term mission requirements, physical adsorption or absorption systems have not been considered since other mechanical devices show more promise for continuous operation. The major area of interest is devices utilizing capillary action or centrifugal force to separate the moisture. A review discussion of the major operating principles of the approaches considered is included at this point.

A cellular type sponge may be placed in the air ducting to collect and hold the free moisture in its cell structure. Primary disadvantages of this approach are the large pressure drop associated with the sponge size and the problems of collecting the water from the sponge and reclaiming it. Recovery of the water requires a complex squeezing mechanism with an elaborate sealing arrangement to prevent the water from going back into the air stream. Periodic replacement of the sponge is necessary since long term operation will lead to deterioration. Also, organic materials will be collected which will deteriorate within the cell structure causing an odor problem. This method was not considered competitive for this application.

Another method is collection of the free water in the form of frost on a cold heat exchanger surface. In this case as in the preceding, intermittent operation is required, since the frost must be thawed and the water drained periodically. This draining process must be independent of gravity and may be accomplished by wicking or a centrifugal field. In addition, sizing of the space radiator is quite affected due to the low temperature operational point.

Another approach utilizes the centrifugal field generated by the swirl of the vortex flow to accelerate water droplets to the walls of the collector where they impinge on the porous wall material as shown in Figure 10-47.

10.10 (Continued)

VORTEX WATER SEPARATOR

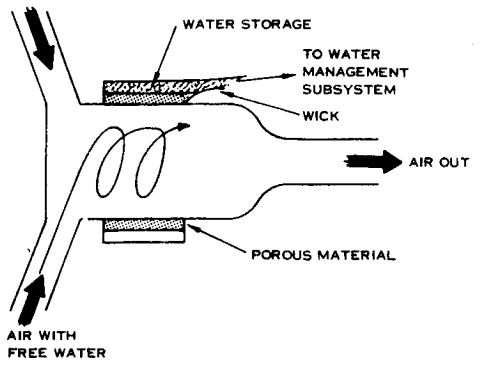


FIGURE 10—47

A somewhat reduced pressure is supplied behind the porous wall. Carryover of air with the water can be minimized by using a wick for water transport. The fraction of free water removed is a function of the length of the porous wall and the strength of the vortex. In other words, power and unit weight increase with water removal efficiency.

The elbow separator is similar to the vortex separator in that a centrifugal field is set up as the air flows around the elbow, thus causing the water droplets to impinge on the outside wall as shown in Figure 10-48.

ELBOW WATER SEPARATOR

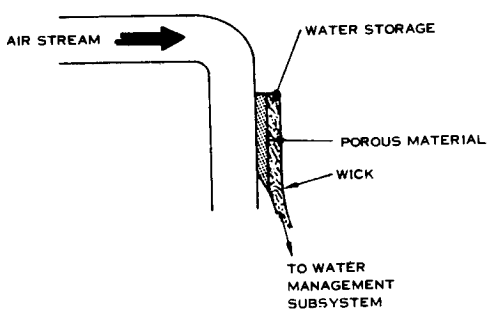


FIGURE 10—48

10.10 (Continued)

The water flows through the porous wall due to capillarity and the reduced pressure behind the wall. Here again, wicking may be provided to minimize air carryover. Similar to the vortex unit, separation efficiency goes up as the length of the porous wall is increased and as the radius of the bend is decreased.

Another approach under current development is the integrated condenser-water separator. A schematic representation of this unit is shown in Figure 10-49. In all of the above systems except for the freeze-out unit, a condenser upstream is required. In this system, moisture condenses on the fins and coolant passage surfaces.

INTEGRAL CONDENSER-WATER SEPARATOR

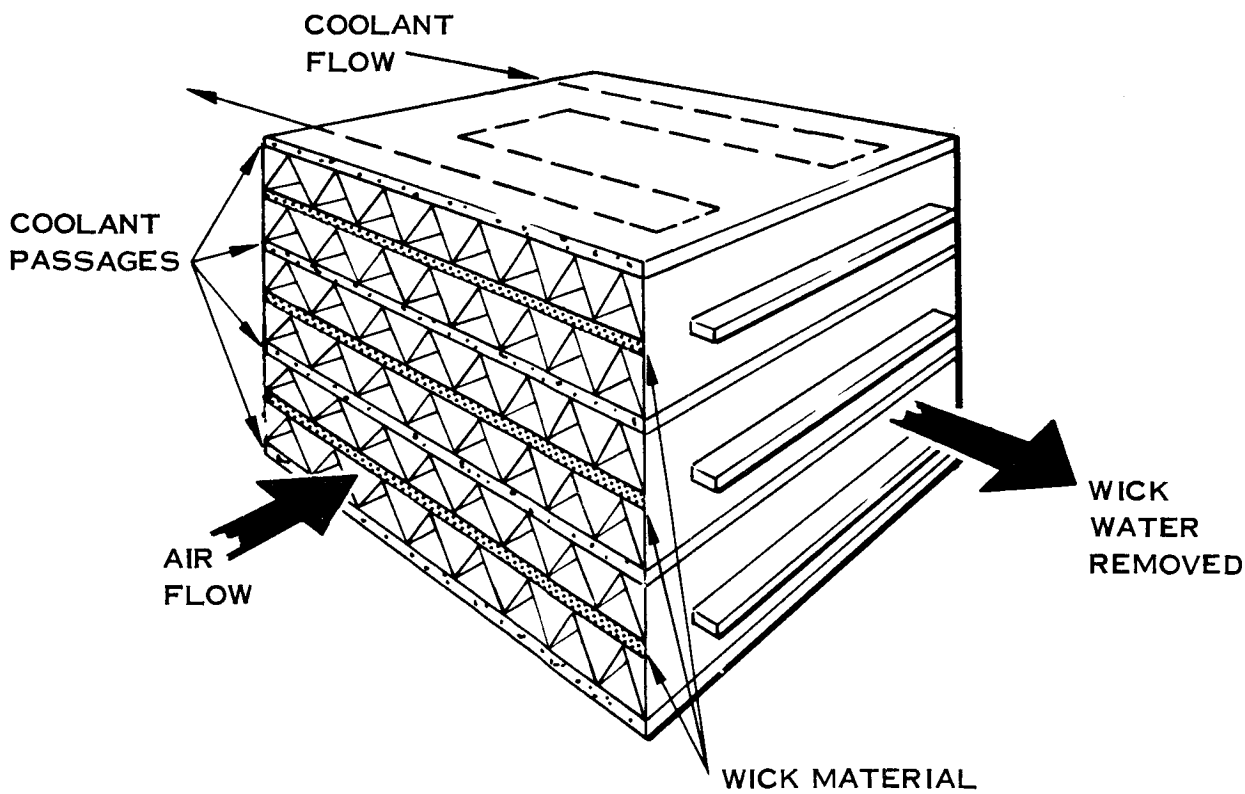


FIGURE 10—49

10.10 (Continued)

In "zero g", the condensed water is transfered to the wick material along the fins by surface tension forces. The flow of water within the wick is by surface tension which is assisted by a pressure gradient. If the pressure gradient is kept below a certain value, it is claimed that there is no air leakage through the wick. The fact that the condensed water is removed as it is formed would prevent liquid build-up and the resulting increased pressure loss. With the prevention of this pressure loss phenomenon, the condenser should provide a lower pressure drop than other condenser types. Although the unit will be larger than an ordinary condenser, it may weigh less than a system consisting of a condenser followed by a separator. This unit is in its early development stages.

In all the above systems, a wicking material has been used to transport the water to the water management subsystem. It would appear desirable to avoid such a transport media especially in a large vehicle where relatively long transport lines may be required. Also, the potential long duration contamination problem must be solved. The following separation systems would be self-pumping and would not use a wick transport media.

The schematic of a rotary water separator is shown in Figure 10-50. Air containing free moisture enters the rotating wire mesh and the centrifugal field thus formed.

ROTARY WATER SEPARATOR

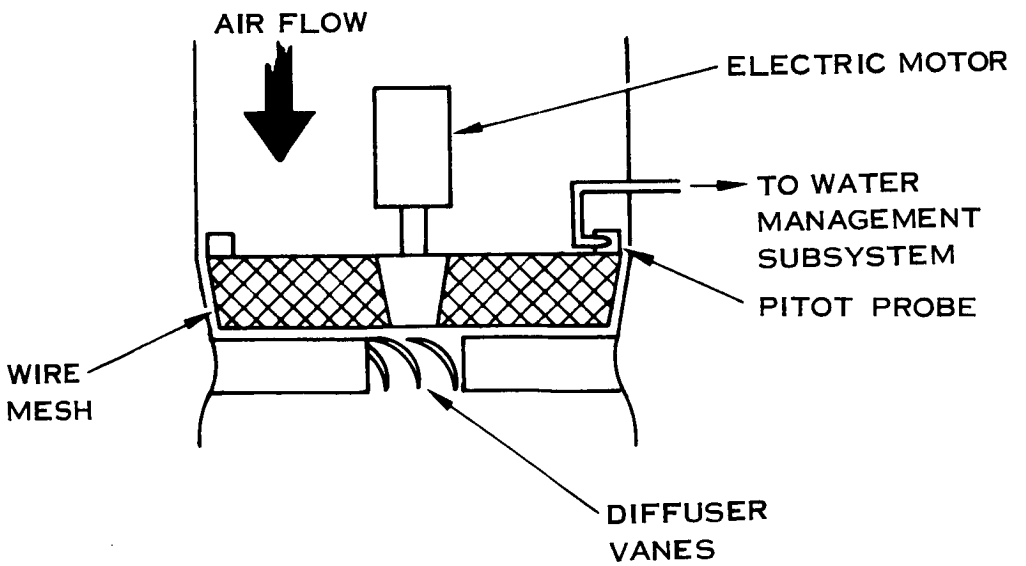


FIGURE 10—50

10.10 (Continued)

Due to the centrifugal field, the water droplets are accelerated in an outward radial direction and impinge on the wall of the conical drum. The centrifugal forces continue to cause the water to travel along the drum until it reaches the gutter and maximum drum radius. A pitot tube converts the kinetic energy of the water into a pressure head. The water is thus pumped out of the separator to the water management subsystem. Experience at Hamilton Standard indicated that the separation efficiency of such a unit is 100%. The performance of this type of separator is indicated in Figures 10-51 and 10-52. The rotating mesh is actually a crude fan. If diffuser vanes are provided at the mesh exit, some of the energy put into rotating the air stream may be recovered in raising the separator exit pressure, thus, reducing the pressure drop across the unit. Figures 10-51 and 10-52 were drawn for separators having no diffuser vanes and a pressure drop of .5 inches of water. For a volume flow of 336 cfm, if diffuser vanes were provided, the pressure drop would be reduced to .36 inches of water.

The reliability of such a unit should be very good since the rotating speed is under 1000 rpm and the bearings carry extremely light loads.

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MOTOR DRIVEN – ROTOR WATER SEPARATOR
(ESTIMATED PERFORMANCE)

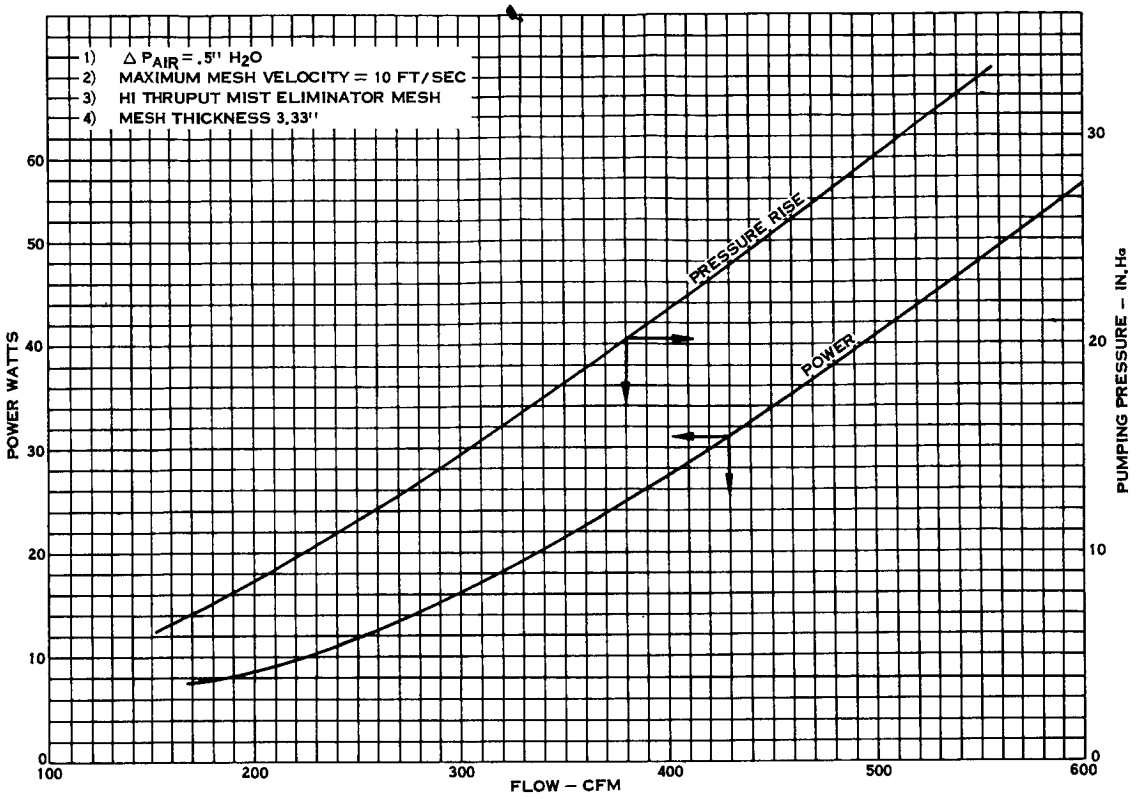

FIGURE 10–51

MOTOR DRIVEN – ROTARY WATER SEPARATOR
(ESTIMATED PERFORMANCE)

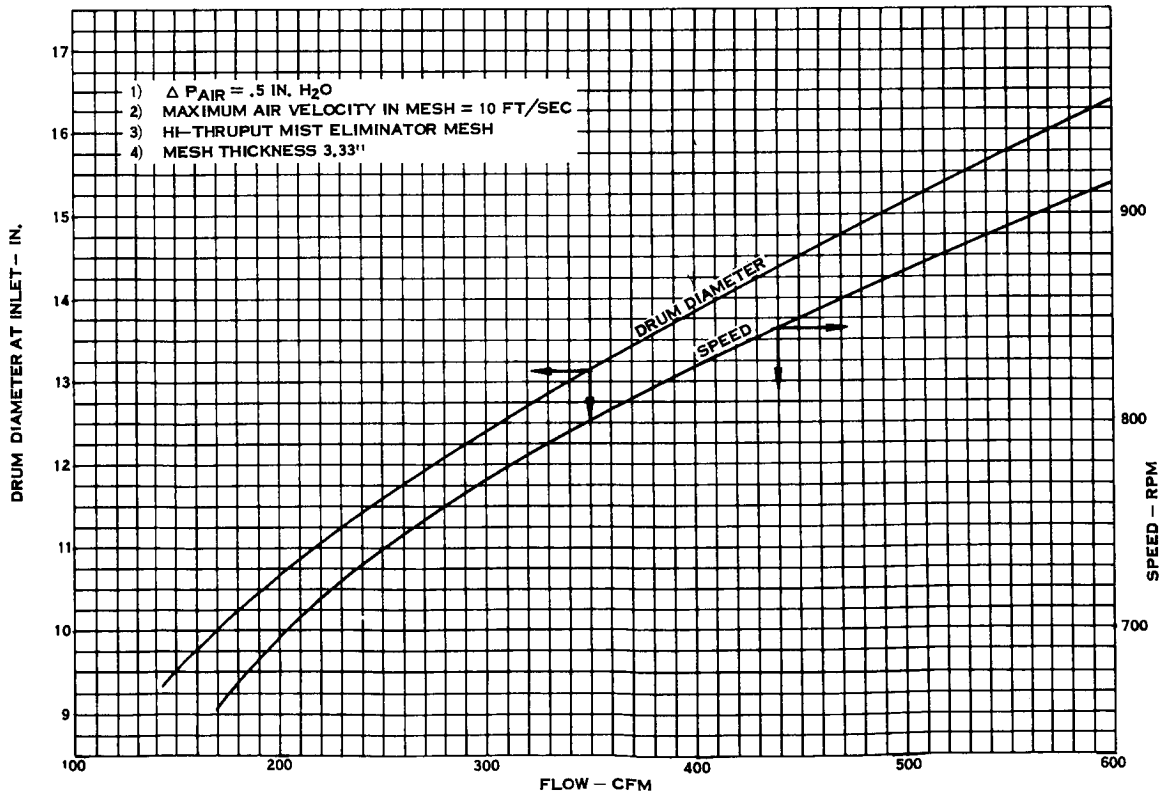

FIGURE 10 – 52

10.11 (Continued)

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SECTION 11.0

CONTAMINANT CONTROL

11.0 CONTAMINANT CONTROL

11.1 Objectives

Contaminant control is a major life support system element needed to insure a purified, breathable atmosphere by removing contaminants which could result in a toxic or explosive hazard. The system must cope with a wide variety of compounds produced both metabolically and from the vehicle systems. The fact that a space cabin is a closed environment poses problems that do not exist in a normal earth environment. There are a great many compounds produced by man and his equipment that are of no concern on Earth because the concentration normally remains low and exposure is intermittent. However, in a closed system, these contaminants can progressively build up to toxic levels if they are not continuously removed. This section deals with the monitoring and control of all of these contaminants with the exception of CO_2 which was discussed in Section 2.0.

The only experience to date of man in closed environments is from atomic submarines and Project Mercury flights which serve only as a preliminary indication of the actual problems of long duration missions. Before the Mars Mission is undertaken, this information will be greatly supplemented by closed system studies, both on Earth and in orbiting laboratories.

The information available to-date lists a very large number of observed contaminants and this should be increased by later experimentation. All the substances found to-date and a wide range of others can be classified into seven groups that generally can be removed or purified by one or a combination of the following methods:

a) Filtration
b) Physical adsorption
c) Chemical absorption
d) Conversion to non-contaminating constituents
e) Conversion to a more easily controllable contaminant

This discussion of contaminant control will consist of three areas:

a) A discussion of the anticipated contaminants
b) Methods for removal of contaminants
c) Discussion of methods of detection of major contaminants

11.2 Identification of Contaminants

Research in the identification of contaminants in closed environments is limited; however, data on a large number of the contaminants, particularly those of major concern, appear to be adequate for the formulation of basic control methods. Much of these available data were obtained from the research conducted in the closed environments of submarines. Most of these same contaminants are also expected to be present in manned spacecraft. Other contaminants, for which there is little data even though they are expected to be present in closed environment, exhibit similar chemical and physical properties to those for which considerable data has been compiled. It is, therefore, meaningful to categorize all the various contaminants in a number of fundamental groupings reflecting similarities in chemical make-up or in the general manner in which they may be controlled. Table 11-1 presents such a seven-category grouping of identical and probable other contaminants as obtained from the reference.

Sources and production rates of these contaminants are another area requiring definite consideration for the evolution of a contaminant control system with adequate capacity. Many potential contaminant-generating sources exist within the confines of a spacecraft; however, knowledge of the contaminant generation rates is very limited due to the unpredictability of the generating media. A partial list of the essentially unpredictable sources is presented below.

1. Electric equipment
2. Lubricants
3. Paints and other coatings
4. Leakage of stored gases
5. Chemical changes of materials caused by radiation

As an example of the range of contaminants to be expected, Tables 11-2 and 11-3 illustrate contaminants found in a Mercury capsule and a submarine, respectively. Further research on these and other similar sources will be required to more fully define the contaminant generation rates and effects on the contaminant control system capacity. However, the metabolically-produced contaminants and their generation rates have been generally defined,and represent by far the largest continuous source of contaminants. Therefore, the preliminary system description and discussion presented herein are based on the human outputs with a sufficient safety factor to cover outputs from other sources. Table 11-4 presents the sources and production rates of volatile metabolically generated contaminants along with the references from which the data were obtained. In this study it has been assumed that the crew would be composed of non-smokers, thus eliminating one source of contaminants.

TABLE 11-1

IDENTIFICATION AND CLASSIFICATION OF CONTAMINANTS

(Reference 1)

	Group I Oxidizable to CO_2 & H_2O	Group II Halogen Compounds	Group III Nitrogen & Sulfur Compounds	Group IV Metal Hydrides	Group V Odors	Group VI Dusts & Smoke	Group VII Other
Quantitatively Identified In Submarines	Acetylene Carbon Monoxide Hydrogen Methane	Chlorine Freon 12	Ammonia Nitrogen Dioxide	Stibine			Aerosols, Bacteria Colon inhabiting bacilli Diplococci Spore forming bacilli Staphylococci Ions
Qualitatively Identified In Submarines	Benzene Dimethylethyl benzene Ethylene p-Ethyl toluene Gasoline vapors Mesitylene Propane Pseudocumene Toluene o-Xylene m-Xylene p-Xylene	Freon 114 Hydrogen Chloride	Sulfur dioxide	Arsine			
Probable Others	Formaldehyde Phenols Volatile organic acids formic butyric etc.	Halogenated solvents	Volatile amines & amino acids Hydrogen cyanide Skatole Hydrogen sulfide Indole Mercaptans	Body odors Equipment odors Food odors	Ash particles Inorganic dusts Metallic dusts Organic dusts		

TABLE 11-2

A COMPILATION OF ALL CONTAMINANTS IDENTIFIED IN THE ATMOSPHERES OF MERCURY SPACECRAFT

(Reference 2 & 15)

	Contaminant	Formula		Concentration (ppm)**
1.	Freon - 114	$CF_2Cl - CF_2Cl$	*	60-6000
2.	Ethylene dichloride	CH_2Cl-CH_2Cl		0-40
3.	Toluene	$C_6H_5CH_3$	*	3-20
4.	n-Butyl alcohol	C_4H_9OH		0-4
5.	Freon-11	$CFCl_3$		0-3
6.	Vinyl chloride	$CH_2 = CHCl$		0-3
7.	Ethyl alcohol	C_2H_5OH	*	0-3
8.	m-Xylene	$C_6H_4(CH_3)2$		0-3
9.	Vinylidene chloride	$CH_2=CCl_2$	*	0-2
10.	Methylene chloride	CH_2Cl_2	*	0-2
11.	o-Xylene	$C_6H_4(CH_3)_2$		0-1
12.	Benzene	C_6H_6	*	0-1
13.	Methylchloroform	CH_3CCl_3		0-1
14.	Trichloroethylene	$CHCl=CCl_2$		0-1
15.	Acetone	CH_3COCH_3		0-1
16.	Methyl ethyl ketone	$CH_3COC_2H_5$		0-1
17.	Methyl isopropyl ketone	$CH_3COC_3H_7$		0-1
18.	Ethylene	$CH_2=CH_2$		0-1
19.	n-Propyl alcohol	C_3H_7OH		0-1
20.	Acetaldehyde	CH_3CHO		0-1
21.	Ethyl acetate	$CH_3COOC_2H_5$		0-1
22.	Freon-114, unsym.	$CFCl_2CF_3$		0-1
23.	Methyl alcohol	CH_3OH	*	0-1
24.	1, 4-dioxane	$(CH_2)4O_2$	*	0-1
25.	Cyclohexane	$(CH_2)_6$	*	0-1
26.	Formaldehyde	CH_2O		-
27.	Hexamethylcyclotrisiloxane	$(CH_3)6(SiO)_3$		-
28.	Freon-22	CHF_2Cl		-
29.	Freon-23	CHF_3		-
30.	Freon-12	CF_2CCl_2		-
31.	Freon-125	CF_3CF_2H		-
32.	Hexeme-1	C_6H_{12}		-
33.	Propylene	C_3H_6		-
34.	n-Butane	C_4H_{10}		-
35.	Butene-1	C_4H_8		-
36.	iso-Pentane	C_5H_{12}		-
37.	n-Pentane	C_5H_{12}		-
38.	Propane	C_3H_8		-
39.	n-Hexane	C_6H_{14}		-
40.	2, 2-Dimethylbutane	C_6H_{14}		-
41.	trans-Butene-2	C_4H_8		-
42.	Cis-Butene-2	C_4H_8		-
43.	Ethylene	C_2H_4		-
44.	Acetylene	C_2H_2		-
45.	3-Methylpentane	C_6H_{14}		-
46.	Carbon dioxide	CO_2	*	-

* These contaminants were common to the atmospheres of the first three U.S. manned orbital flights.

** The values listed represent the approximate concentrations which would have ensued had all of the desorbed contaminant been dispersed in the free volume of the cabin at one time. A dash indicates that quantitative values were not determined.

TABLE 11-3

CONTAMINANTS THAT HAVE BEEN FOUND IN THE ATMOSPHERES OF NUCLEAR SUBMARINES

(Reference 3)

The following have been identified quantitatively.

Acetylene	Methyl Alcohol
Ammonia	Monoethanolamine
Carbon Dioxide	Nitrogen
Carbon Monoxide	Nitrous Oxide
Chlorine	Oxygen
Freon 12	Stibine
Hydrocarbons	Water Vapor
Hydrogen	Cigarette Smoke
Methane	

The following have been present in trace amounts.

Arsine	Hydrochloric Acid
Benzene	Mesitylene
Dimethylethylbenzene	Propane
Ethylene	Pseudocumene
Paraethyl-Toluene	Sulphur Dioxide
Freon 114	Toluene
Gasoline Vapors	Xylene

TABLE 11-4
SOURCES & PRODUCTION RATES OF VOLATILE
METABOLICALLY GENERATED CONTAMINANTS

Source	Contaminant	Daily Production Avg. or Range	Rate/Man Maximum	References
Flatus		2,100 ml	2,650 ml	4,5,6
	Methane	108 ml	153 ml	4,6
	Hydrogen	345 ml	446 ml	4,6
	Hydrogen Sulfide	.0042 ml	.0064 ml	4,6
*Feces		115 gs		
	Ammonia	25-84 mg	84 mg	7
	Phenols	0-210 mg	210 mg	7
	Total Volatile Acids	2.66 ml .1 N	4.45 ml .1N	7
	Indole	90 mg	---	5
	Skatole	trace	---	5
	Hydrogen Sulfide	trace	---	5
	Methane	trace	---	5
	Methyl Mercaptan	trace	---	5
*Urine		.6-2L		5,9 (ref. 62)
	Acetone bodies	20 mg	---	7
	Ammonia	700 mg	1380 mg	7
	Phenols	200 mg	330 mg	7
	Citric, formic, lactic acids	3.0 - 4.1 gs	4.1 gs	7
Respired Air	Carbon Monoxide	10 ml	---	5,8,11
Perspiration		720 ml		
	Ammonia	60 mg	252 mg	7,9
	Phenol	36 mg	57.6 mg	7,9
	Total volatile acids	2.4 - 5.6 ml .1N	5.6 ml .1N	7
	Lactic acid	1.6 gs	3.2 gs	7
*Saliva		864 ml		9
	Ammonia	38 mg		9 (ref. 33)
Other Constituents of Human Odor (Non quantitative)		Butyric acid, propyl mercaptan, ethereal sulfates, caprylic acid, valeric acid, ethyl alcohol, ethyl mercaptan (ref. 10)		

* Only a very minor portion of these should reach the breathable environment

11.2 (Continued)

The recommended maximum allowable concentration for industrial applications of a partial listing of the many contaminants is presented in Table 11-5. It should be remembered that these values of M.A.C. (Maximum allowable concentration) have been largely determined from industrial experience. This means that they have been based on limited continuity of exposure, usually the eight hour working day. Except for a few compounds this allows buildup of the contaminant in the body to be dissipated before another exposure, and to be reduced to very low levels over week-ends. However, since the exposure in the spacecraft will be continuous, it is necessary and/or desirable to stay well below these concentrations, thus requiring the use of some safety factor in the design of the contaminant control system. Tests conducted at Hamilton Standard with a catalytic burner used to oxidize methane also verified that it was necessary to remain below the metabolic limits to avoid overheating the burner.

In addition to identifying contaminants, it is useful to understand in what way or manner these items can be considered contaminants in order to have some basis for defining the absolute degree of control required. A list of contaminants, and their effect on a human is presented in Table 11-6.

11.3 Identification of Control Methods

Determination of the specific control method for each probable contaminant expected in the confines of a manned space vehicle would involve a task of almost unlimited magnitude. However, due to the chemical and physical similarity of the myriad of contaminants, it is possible to define control means for chemically and physically similar groupings of these contaminants by selection of representative contaminants from each group. Table 11-1, presented earlier, presents a first and quite reasonable approach to such a grouping. Table 11-7 illustrates the potential control methods for these groupings.

The high molecular weight contaminants of Groups I through V can be physically adsorbed on such materials as activated charcoal. Some contaminants such as hydrogen, methane and carbon monoxide, which cannot be readily adsorbed, can be oxidized to carbon dioxide and water in a catalytic burner. Other constituents in these groups, which cannot be physically adsorbed or which convert to other equally harmful contaminants in the catalytic burner, can be controlled by chemical absorption in a chemi-sorbent material. These three methods would, therefore, provide control of all the contaminants in Groups I through V.

TABLE 11-5

RECOMMENDED MAXIMUM ALLOWABLE CONCENTRATIONS

(Reference 12 and 13)

Contaminant	Maximum Allowable PPM Concentration
Acetic Acid	10
Acetone	1000
Acetylene	0.5
Acrolein	15
Ammonia	100
Amylacetate	200
Amyl Alcohol	100
Arsine	.05
Benzene	35
Butyl Cellosolve	50
Carbon Disulfide	20
Carbon Monoxide	100
Carbon Tetrachloride	25
Chlorine	1
Cresol	5
Cyclohexane	400
1-3 Dimethyl-5 Ethyl Benzene	---
Dioxane	100
Ethyl Acetate	400
Ethylene	---3%-34% (explosive)
Ethylene Diamine	10
p-ethyl-toluene	---
Fluorine	.1
Formaldehyde	5
Freon 12	70
Freon 114	1000
Hydrazine	1
Hydrogen	--- 4.1%-74.2% (Explosive)
Hydrogen Chloride	5
Hydrogen Fluoride	3
Hydrogen Peroxide, 90%	1
Hydrogen Sulfide	20
Mesitylene	---
Methane	---
Methyl Alcohol	200
Cellosolve	25
Methyl Ethyl Ketone	200

Contaminant	Maximum Allowable PPM Concentration
Mono Ethanol Amine	1
Nitrogen Dioxide	.1
Nitrous Oxide	27
Ozone	.1
Perchlorethylene	100
Phenol	5
Phosgene	1
Phosphine	0.05
Propane	---2.3 - 7.5% (Explosive)
Pseudocumene	--
Stibine	1
Sulfur Dioxide	10
Toluene	200
Trichlorethylene	100
Xylene	200

Positive Ions 1000 - 5000/cc

Particulate Matter 99.7 efficiency to .3 microns

Aerosols (range from .1 to 1.0 microns, majority larger than .35; a .3 micron filter will therefore remove majority)
Limits not defined.

Bacteria - Undefined

TABLE 11-6

EFFECTS OF CONTAMINANTS ON MAN

1. Asphyxiants

Simple	Chemical
Carbon Dioxide	Carbon Monoxide
Helium	Cyanogen
Hydrogen	Hydrogen Cyanide
Methane	Nitro Benzene
Nitrogen	

2. Dusts

Nuisance	Fibrosis Producing
Slate	Asbestos
Talc	Silica

3. Irritants

Upper Respiratory Tract	Upper Respiratory Tract and Lungs
Ammonia	Bromine
Sulfur Dioxide	Chlorine
	Fluorine
	Iodine
	Ozone

4. Narcotics

Acetone	Ethyl Alcohol	Propyl Alcohol
Ether	Propane	

5. Poisons

Antimony	Methyl Alcohol
Arsenic	Phenols
Benzene	Phosphorous
Carbon Disulfide	Sulfur
Lead	Toluene
Mercury	

TABLE 11-7

ANALYSIS OF THE PRELIMINARY SYSTEM DESIGN REQUIREMENTS

	GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V	GROUP VI	GROUP VII
Processing Flow Requirements	Trace Gases	Trace Gases	Trace Gases	Trace	Full Flow	Full Flow	
Contaminants	Hydro-Carbons and Volatile Organic Acids Carbon Monoxide Hydrogen	Halogen compounds	Nitrogen and Sulphur Compounds	Metal Hydrates	Odors	Dust and Smoke	Aerosols Bacteria
Method of Control or Removal	Catalytic Burner	Chemisorbent and Activated Charcoal	Chemisorbent Activated Charcoal, or Catalytic Burner and CO_2 Removal Unit	Chemisorbent	Activated Charcoal	Filter	Catalytic Burner or Electrical Precipitation
Resulting products which might have to be removed.	CO_2 and H_2O	Particles	Particles	Particles	Particles	None	None

11.3 (Continued)

Group VI, particulate matter, can be simply and efficiently controlled by appropriate filtration.

The extent of control required for Group VII is presently undefined; however, it is felt that most of these contaminants can be effectively controlled by one or more of the processes described above. Aerosols can be removed in the filtration, oxidation and sorption processes. Bacteria can be destroyed in the catalytic burner. On the other hand, ions may require electrical grounding or neutralization if they are not sufficiently captured by the aerosols present, and the bacteria may require an additional control source, such as ultra violet light, if they cannot be sufficiently controlled by the processes available.

To illustrate the interrelationship of the various system components, Figure 11-1 has been prepared. Although it is not necessarily the optimum arrangement under total system considerations, it serves as an adequate discussion basis. Each of the components is briefly described below:

PRELIMINARY SYSTEM SCHEMATIC

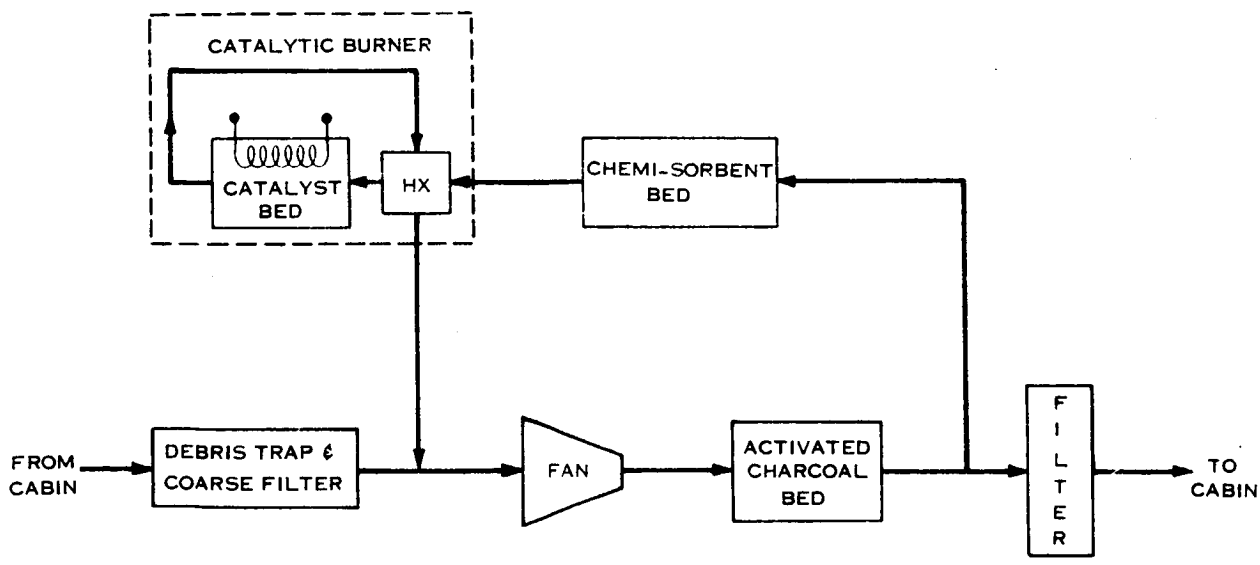


FIGURE 11 -- 1

11.3 (Continued)

a) Debris Trap

A debris trap is provided to remove both solid and liquid particles from the entering air stream to prevent possible contamination of the chemical beds. The debris trap consists of a sponge lined vortex chamber to capture liquid droplets, and a cartridge type filter element to remove solid particles. This filter has a removal efficiency of 90% for 50 micron particles.

b) Fan

The fan is shown in the schematic in order to demonstrate a complete system. In an actual installation, the flow would probably be provided by the main atmosphere circulating fans.

c) Activated Charcoal Bed

An adsorbent such as charcoal removes contaminants by trapping molecules in a sub-microscopic sponge structure which has tiny capillary passages not much larger than the molecules adsorbed. The tremendous surface area of this structure holds the molecules through van der Waal's forces. Activated carbon is prepared by removing part of the carbon with high pressure steam to provide a large amount of internal surface area. It has been estimated that the grains in one pound of activated charcoal have an internal surface area of approximately five million square feet, therefore providing the tremendous capacity of this material.

The factors that increase the tendency for a substance to be adsorbed on charcoal are:

1) high molecular weight
2) low vapor pressure
3) presence of a large number of carbon atoms in the molecule
4) a chemical structure that is unsaturated

The use of activated charcoal for contaminant control is particularly attractive since it is capable of removing most of the contaminant gases that may be expected to exist in a space vehicle cabin, including many odorous compounds that may exist only in trace amounts. The charcoal beds are very stable and do not deteriorate with time. In addition, the unit is compact, efficient and contains no moving parts.

11.3 (Continued)

Upon leaving the charcoal bed, a small portion of the flow (approximately 1%) is split off from the main stream and circulated through the chemisorbent bed and catalytic burner, then back to the main stream to remove the remaining contaminants.

d) Chemisorbent Bed

The chemisorbent bed will be used to remove those contaminants that cannot be adsorbed on the charcoal or cannot be completely oxidized to carbon dioxide and water in the catalytic burner. These will be principally the nitrogen and sulphur compounds, halogens and metal hydrides and in addition, any trace compounds that might poison the catalyst in the burner.

Since a large number of contaminants are to be removed, the chemisorbent canister will consist of several layers of materials, each for the removal of specific substances. The chemicals required for a completely satisfactory chemisorbent cartridge have not been fully defined and further development is required. Hamilton Standard is currently carrying out in-house research and development on methods of removing various contaminants. The following materials have been suggested as a result of this work. The major sections required are:

1) Removal of ionic contaminants - Ammonia is the principal contaminant and is the only one to be removed by the chemisorbent bed that is present in more than trace quantities. A cationic resin known as "Amberlyst" has been successful in removing ammonia.

A similar type of anionic resin could be used to remove cationic contaminants such as sulphates.

2) Neutralization of acidic and basic gases - Acidic gases can be absorbed on LiOH and basic gases on 'acid washed' silica gel.

3) Removal by active metals - It has been found that a thin coating of silver on a substrate of Linde 5-A molecular sieve will react with sulphur compounds to form sulphides.

4) Absorption by polar and non-polar solvents. Some contaminants such as trichlorethylene or propylene can be dissolved in liquids on a substrate. It is proposed to use mineral oil for a non-polar solvent and a high molecular weight glycol as a polar solvent on activated charcoal substrate.

11.3 (Continued)

5) It is anticipated that nitrogen oxides will be removed by the CO_2 removal system.

e) Catalytic Burner

The catalytic burner was selected as the most practical method of controlling the contaminants listed in Group I of Table 11-1 that would not be readily adsorbed on charcoal. These are, in particular, carbon monoxide, hydrogen and methane, since these could be present in relatively large quantities. Hamilton Standard test experience illustrates that the portion of the atmospheric flow that passes through the chemisorbent bed and catalytic burner should be heated to 550°F in the presence of a catalyst to oxidize the contaminants to carbon dioxide and water.

The airstream first enters a regenerative heat exchanger, where it is heated by the outgoing flow. From the heat exchanger it impinges on an electrical heating element and then passes over a packed catalyst bed. The entire unit is surrounded by super insulation composed of fiberglass and aluminum foil sealed in an evacuated cylinder. This insulation and the heat exchanger maintain the power requirements at a minimum level.

f) Particulate Filter

A high efficiency filter is required to remove aerosols, dust, smoke and other matter of very small size. Commercial filters are available that are over 99% efficient on particles of 0.3 micron size. These consist of glass asbestos sheets closely pleated and separated by aluminum foil. This filter is able to function satisfactorily at temperatures as high as 250°F and up to 100% relative humidity.

11.4 System Sizing

Two aspects of system sizing are presented in this section. The first is a steady state analysis based upon maintaining the metabolic contaminants below a predetermined level since these are the only contaminants for which ample quantitative data was available. However, it is recognized and discussed later in this section, that ultimately a space vehicle will have to cope with contaminant overloads due to equipment failures. The second aspect presents a generalized transient analysis which can be used to monitor the contaminant concentration over the total mission time for any contaminant and can be applied to complex situations involving time varying production and process rates.

11.4 (Continued)

The following symbols are used in the system sizing presentation:

Variables

C = concentration, parts per million
T = temperature, °R
t = time, days
V = volume, Ft^3
W_{CP} = contaminant gas production rate, lb/day
W_R = process air handling rate, lb/hr.
W_L = cabin mixture leakage rate, lb/hr.
W_F = flow through contaminant removal system, lb/hr.
n_R = contaminant removal system removal efficiency
(Amount of contaminant removed/amount entering removal system)

Subscripts

A = Allowable
B = Cabin Module
C = Contaminant
M = Carrier Gas Mixture
S = Steady State

Analysis of the metabolic contaminants, their generation rate and the maximum acceptable concentration (Table 11-8) has shown that carbon monoxide will be the most critical contaminant and, therefore, will determine the flow rate and size of the contaminant control system. Although the Maximum Allowable Concentration (MAC) of CO for short term exposure is 100 ppm, according to Table 11-5, extended exposure to only 10 ppm has been observed to result in carelessness and inattention. Therefore, the MAC has been set at a partial pressure corresponding to 5 ppm in a normal Earth environment (STP) in order to size the system flow.

11.4 (Continued)

TABLE 11-8

METABOLIC CONTAMINANTS

Contaminant	Production Rate (lb/man-day)	Max. Allow. Conc. (ppm by vol. at 1 atm. unless otherwise specified)	Potential Danger	Accumulation Time (day/ft^3/man)
CO_2	2.12	6.58×10^3	Poison	3.53×10^{-4}
CO	2.76×10^{-5}	5.0	Poison	1.31×10^{-2}
H_2S	4.32×10^{-7}	2.0×10^1	Poison	4.06
H_2	1.97×10^{-4}	4.1 %	Explosion	5.16×10^{-1}
CH_4	1.73×10^{-3}	5.3%	Explosion	6.05×10^{-1}

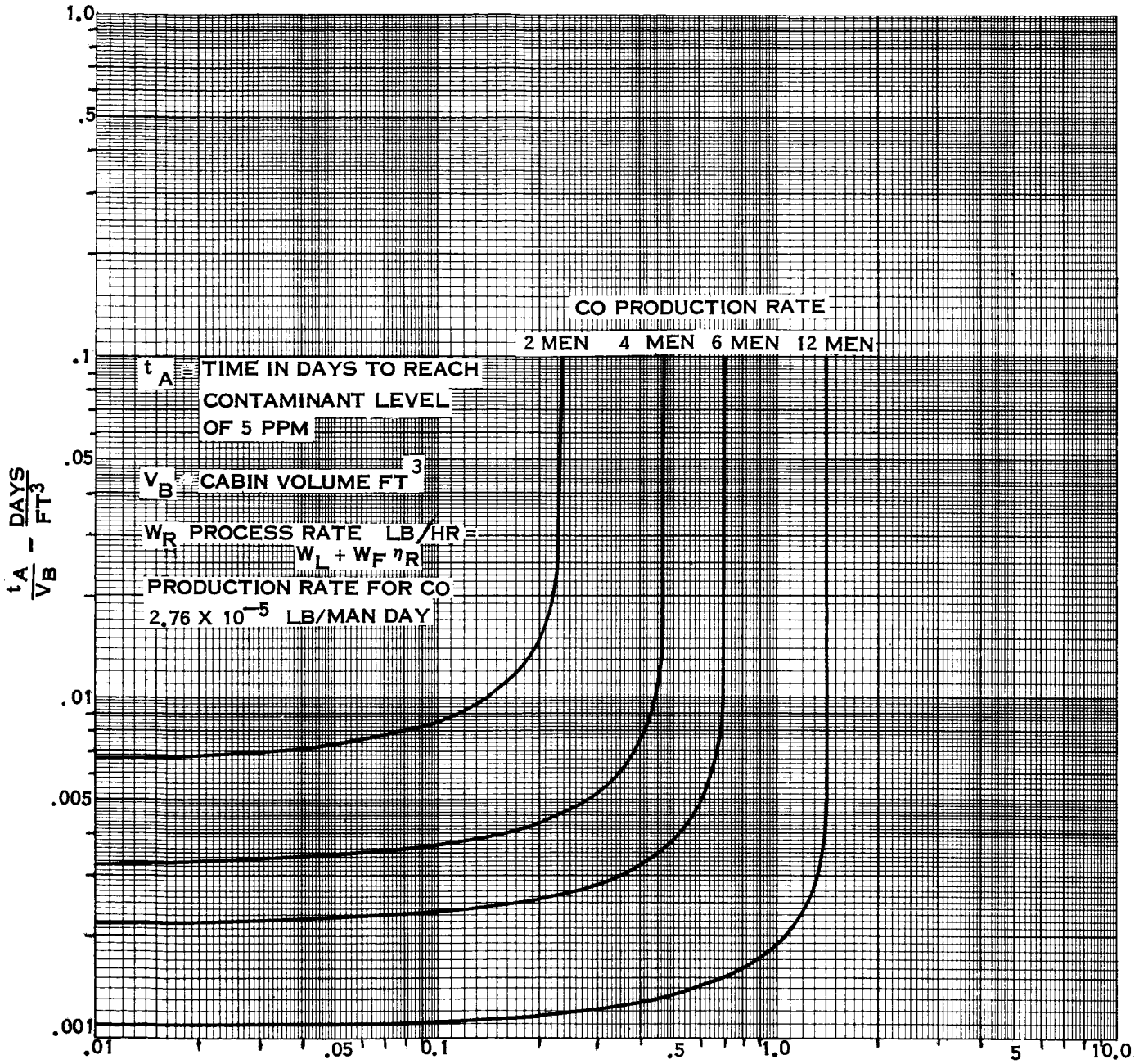
Note: H_2 and CH_4 Maximum Allowable Concentrations are given in percent instead of parts per million because the explosion hazard is a function of concentration rather than absolute partial pressure.

Of primary importance in determining the power and weight characteristics of a contaminant removal system is the required process air handling rate which is defined as the sum of cabin leakage and contaminant removal system flow rate times its corresponding removal efficiency ($W_R = W_L + W_F \; n_R$). Figure 11-2 shows the time required to reach the maximum allowable concentration as a function of process flow rate for various CO production rates assuming an initially contaminant-free module. For a given production rate, the vertical asymptote to the curve represents that flow required such that the maximum allowable concentration is never reached. The horizontal asymptote shows the time required to reach the allowable level with no leakage or provision for contaminant removal. The curve can be used to determine the required process flow and shows the proximity to the flow for limitless duration operation.

It is often desirable to monitor the contaminant concentration over the mission duration. The schedule of contaminant concentration as a function of time from the start of a mission is a function of several variables.

ACCUMULATION TIME VS. PROCESS RATE

FOR CO AS CRITICAL CONTAMINANT



W_R – PROCESS RATE – LB/ HR

FIGURE 11 – 2

11.4 (Continued)

If a source of contaminant removal exists, a steady state concentration value is approached as a limit but never actually reached in a finite time. This steady state value is a function of the contaminant production to process air removal rate ratio for fixed contaminant and carrier gas fluid properties (7 psia 70°F cabin) as shown in Figure 11-3 for various contaminant gases. The steady state concentration is divided by the maximum allowable concentration to indicate a relative measure of danger. The rate at which the steady state value is approached is a function of only the process air flow for constant contaminant and carrier gas fluid properties. This is shown in Figure 11-4 which is noted to apply for all contaminants. The abscissa is the ratio of the instantaneous concentration to the steady state while the ordinate is the corresponding ratio of instantaneous time value to module free volume. Figures 11-3 and 11-4 can, therefore, be used to determine the contaminant concentration schedule and can be applied to situations involving variable production and process air handling rates as is illustrated in the following example:

Problem: For a given contaminant, determine the concentration (C_C) as a function of time (t).

Given: The contaminant production rate (W_{CP}) and process air handling rate (W_R) are given as a function of time (t) in Figure 11-5A. In addition, the cabin free volume (V_B) and allowable concentration (C_{CA}) are given. It is noted that W_{CP} and W_R remain constant over the time period from time equals t_0 to time equals t_1. By definition, let the subscript "a" refer to this time period with $t_a = t - t_0$. Similarly, let the subscript "b" refer to the time period between time equals t_1 and t_2 with $t_b = t - t_1$ (See Figure 11-5B). The subscript "1" will be used to denote the instantaneous time of t_1 at which the production and process rate changes. Subscript "2" denotes the instantaneous final time.

Procedure:

1. Calculate W_{CP_a}/W_{R_a}
2. Determine the corresponding $(C_{CS}/C_{CA})_a$ from figure 11-5C.
3. Follow the W_{R_a} line of Figure 11-5D and note $(C_C/C_{CS})_a$ as a function of $(t=t_0 + t_a)/V_B$ until $(t_1/V_B)_a$ is reached.
4. At each point calculate $C_C = (C_C/C_{CS})_a \times (C_{CS}/C_{CA})_a \times C_{CA}$ and record on Figure 11-5B for respective t.
5. At $t-t_1$ calculate W_{CP_b}/W_{R_b}
6. Determine corresponding $(C_{CS}/C_{CA})_b$ from Figure 11-5C.
7. Calculate $(C_{C1}/C_{CS})_b = \dfrac{(C_{C1}/C_{CA})}{(C_{CS}/C_{CA})_b}$

CONTAMINANT STEADY STATE CONCENTRATION VS PRODUCTION – PROCESS RATIO

W_{CP} = CONTAMINANT PROD. RATE – LB/ DAY
W_R = PROCESS AIR FLOW RATE – LB/HR = $W_L + W_F \eta_R$
C_{CS} = STEADY STATE CONTAMINANT CONCENTRATION – PPM
C_{CA} = CONTAMINANT MAXIMUM ALLOWABLE CONCENTRATION – PPM

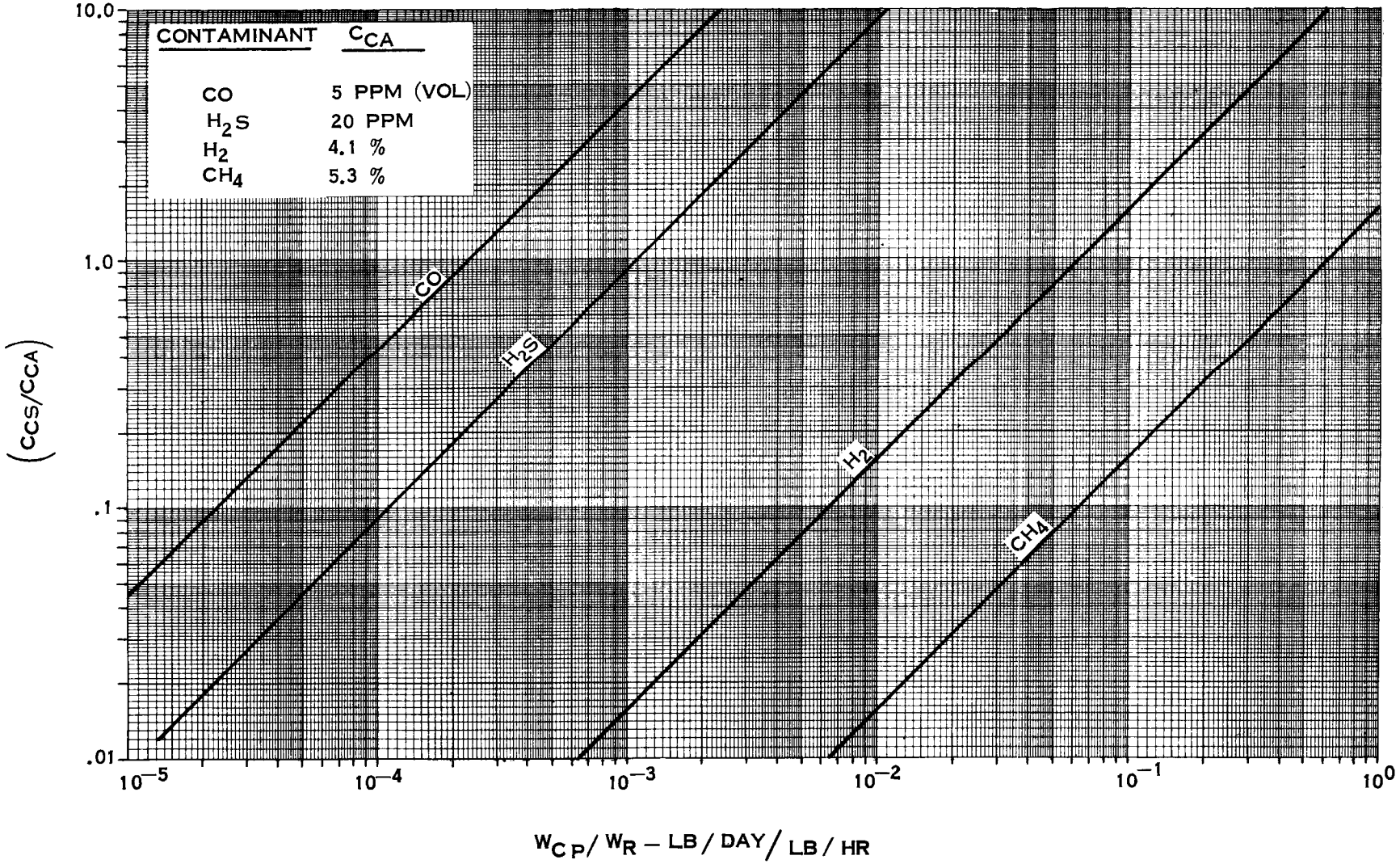


FIGURE 11–3

CONTAMINANT CONCENTRATION SCHEDULE

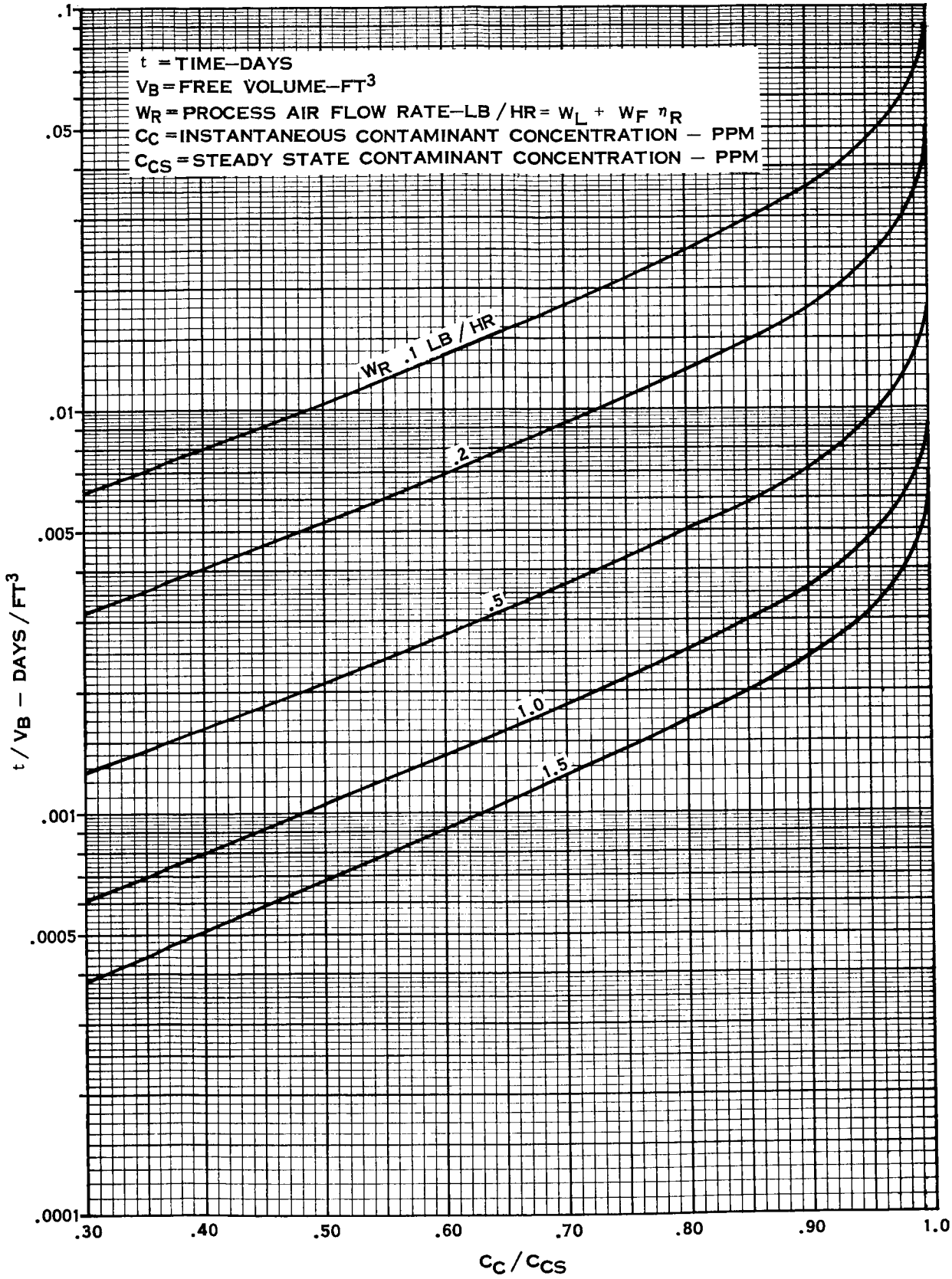


FIGURE 11 – 4

CONTAMINANT CONTROL FLOW SIZING PROCEDURE

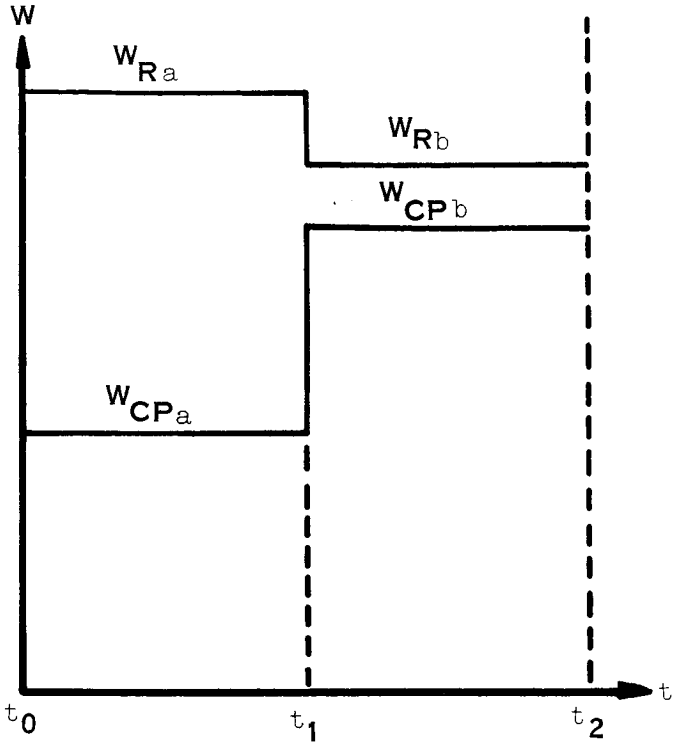


FIGURE A

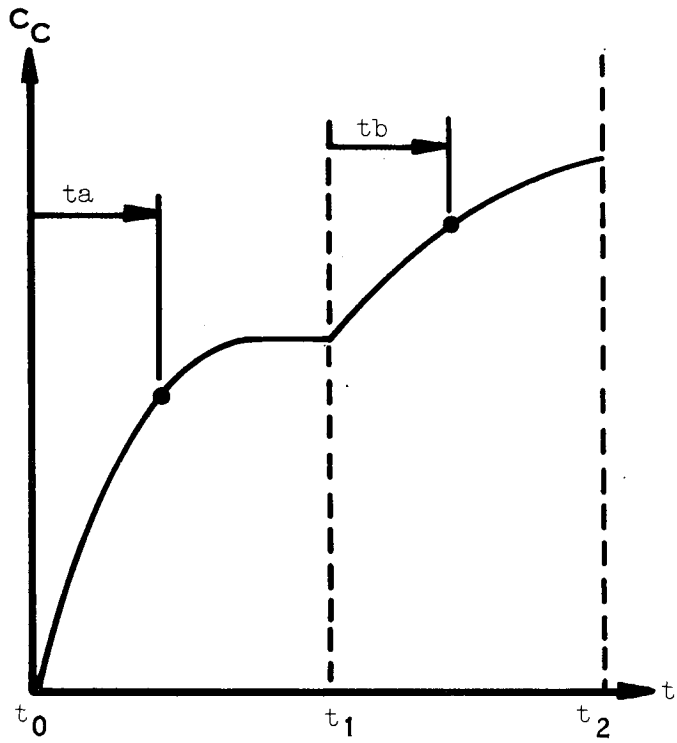


FIGURE B

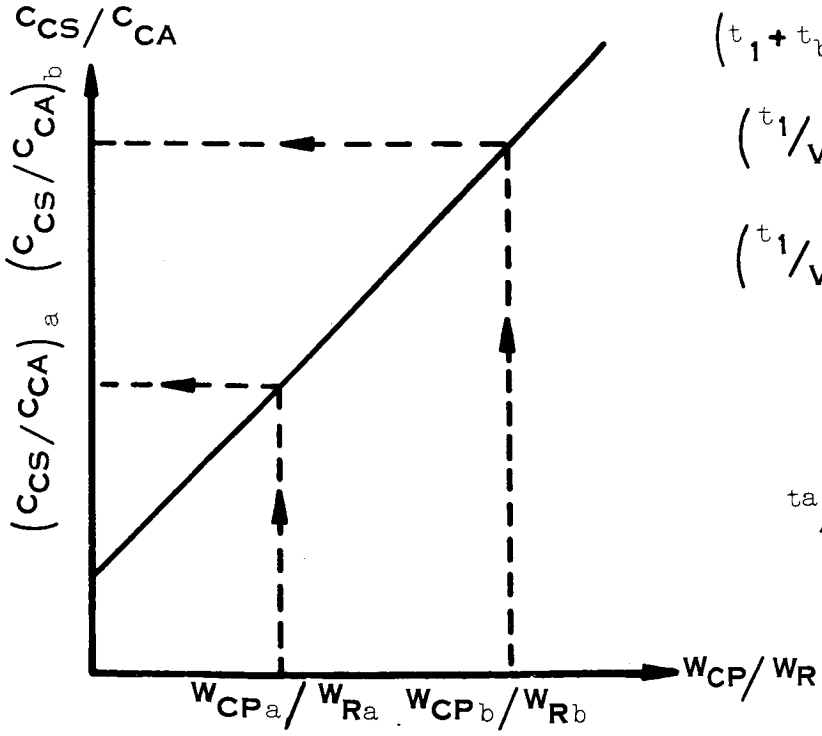


FIGURE C

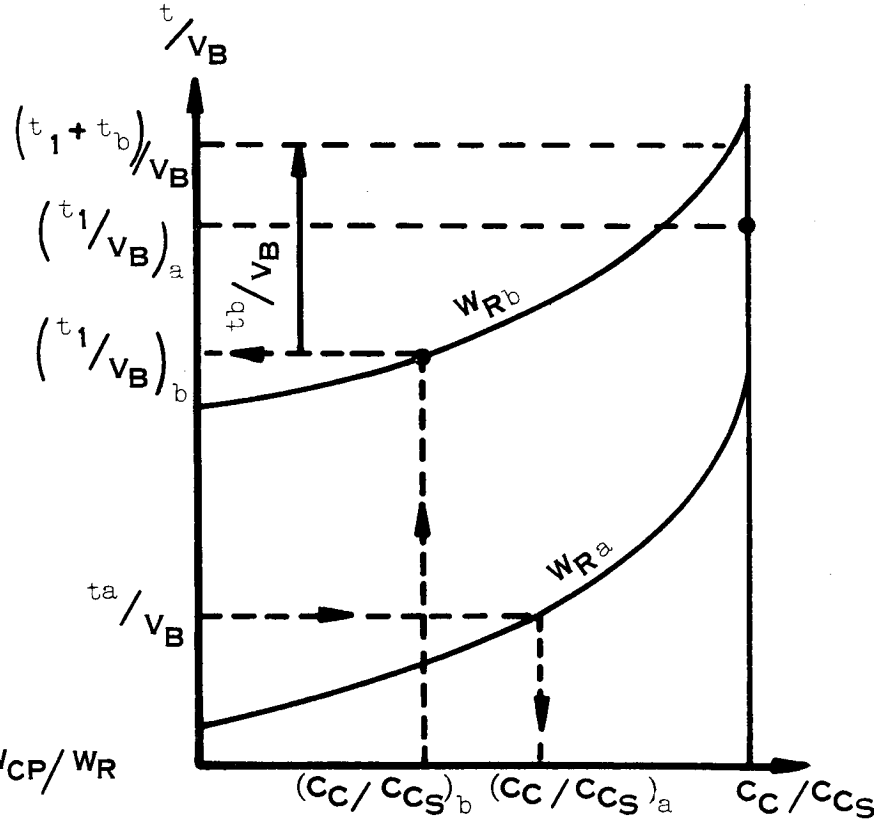


FIGURE D

FIGURE 11 — 5

11.4 (Continued)

8. Enter Figure 11-5D at this value and W_{R_b} and determine $t/V_B = (t_1/V_B)_b$. Note that $(t_1/V_B)_a \neq (t_1/V_B)_b$. That is, the right hand side of the inequality is used as a superficial initial time reference for any time t_b falling between t_1 and t_2. Therefore the t portion of the ordinate t/V_B parameter now equals $t_1 + t_b$.
9. Follow the W_{R_b} line and note $(C_C/C_{CS})_b$ as a function of $(t = t_1 + t_b)/V_B$ until t_2/V_B is reached.
10. At each point calculate and record in Figure 11-5B.

$$C_C = (C_C/C_{CS})_b \times (C_{CS}/C_{CA})_b \times C_{CA}$$

The catalytic burner is used as the removal device for the CO contaminant. Upon choosing the design removal system flow rate (W_F), Figure 11-6 can be used to determine the associated weight and power requirements. The data presented are based on the results of extensive testing on a prototype catalytic burner at Hamilton Standard.

As mentioned earlier the need may arise to cope with transient overloads in the contaminant system. The most probable cause of such contaminant would be a fire or overheating of electrical equipment. There is a need for information on the materials that would be used in a space capsule and the products of combustion that would result from a case of fire or overheating. If, for example, teflon is used for electrical insulation, contaminants can be produced from severe overheating. It has been observed that people exposed to fumes from overheated teflon can develop "Polymer fume fever" but chemical analysis has not identified the specific contaminant responsible nor have experimental animals been affected by the fumes.

Although it is difficult to accurately establish the contaminants which would develop in an emergency, some general observations can be made as to which ones might be expected and how they may be controlled. If care is taken in selecting materials for the spacecraft the contaminants may be confined to carbon dioxide, carbon monoxide, heavy organics, and acid gases. If this proves to be the case, an emergency system which would process the cabin air while the crew members retreat to suit operation could be designed. Such a system would consist of a recirculating fan, possibly the same as the humidity control loop fan, and an emergency contaminant removal canister. This canister would be sealed during storage and inserted into this emergency system only when needed. A throw away type canister would be used with the number of spares being carried a function of the expected failures.

11.4 (Continued)

The emergency canister would contain a debris trap and coarse filter at the inlet primarily for control of free moisture which may be in the cabin and large particles. The filter could serve as a retainer for Lithium Hydroxide which is the first layer of the canister. The hydroxide is required to remove any acid gases and carbon dioxide formed in the emergency. Next in the canister would come a desiccant which would maintain the low moisture level required for proper performance of the rest of the bed. This material could be a non-regenerable type for simplicity as the amount required to remove all of the cabin moisture will not be large. Further, the requirements on this material are not severe, as a 0°F degree dew point is adequate. The next material in the canister would be activated charcoal for removal of the heavy organic materials formed. This would be followed by a catalyst for conversion of any CO formed to CO_2. This material was recommended as being very effective by the Mine Safety Appliances Company, provided that it is kept dry. It consists of a mixture of oxides of manganese and copper and has been found effective above 20°F. The last portion of the emergency canister would be a fine filter to remove any fine particles of the chemicals used in the bed.

CATALYTIC BURNER AND CHEMISORBENT CANISTER
POWER AND WEIGHT VS. FLOW RATE

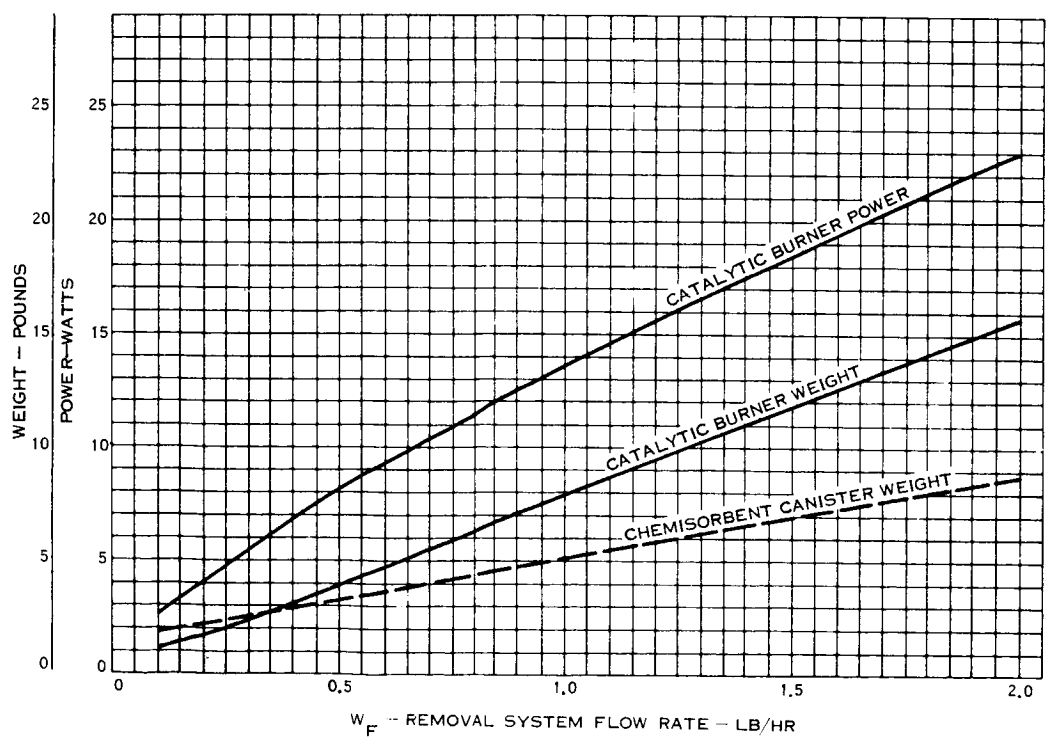


FIGURE 11 – 6

11.5 Methods of Detection

A complete contaminant control subsystem must include methods for detection of the major contaminants expected in the cabin. Specific detectors will be used for O_2 and CO_2 since complete subsystems will be provided for the individual control of these two gases. For the remaining major contaminants a gas analyzer will be provided. It is not possible, within the confines of a space cabin, to provide positive detection of every solitary contaminant listed in the tables on the preceding pages It is, however, possible to detect and measure a reasonable number of those compounds expected to exist in the greatest concentrations. Extensive ground testing in a closed spacecraft environment will be required to positively establish which contaminants need to be considered for detection.

At present it is planned to use the analyzer to detect H_2, CO, NH_3, H_2S and CH_4 as well as the primary gases. In addition to being the most common of the contaminants this group includes compounds that are removed by both the chemisorbent and the catalytic burner. Therefore, measurement of the concentration of these gases will provide a measure of the performance of these units. No suitable measurement has been determined to provide a similar check of charcoal performance because of the random nature of the compounds that will be removed by this bed. Two indications of charcoal performance remain available. These are the sense of smell of the crew and telemetry of gas analyzer data to an earth situated computer to identify heavier trace contaminants. The use of the sense of smell must be determined by test since this may be dulled by gradual exposure.

Continued surveillance of cabin atmosphere is required not only to monitor the primary constituents, but the numerous trace gases that may be produced by the occupants, eluted from equipment or generated by an equipment failure. As mentioned earlier, numerous compounds have been identified in closed systems but very little data are available on the significance of the majority of these for long duration missions. Further, the compounds that have been identified do not constitute the entire spectra that may be encountered in actual extended missions. Because of the difficulty involved in closed atmosphere testing and in the separation and identification of the compounds, the potential trace gases have not been completely catalogued at this time. Before a long journey, such as the Mars mission,is undertaken, further information will be required and it is hoped that this will be provided by the operation of an orbiting space station or extensive ground testing. Therefore, in addition to specific gas detection it is desirable that the analyzer be capable of providing information to enable identification of trace gases.

For this study, the requirements for the gas analyzer have been broken into two parts. The first is sensing of the gases commonly observed in the atmosphere, and the second is the growth capability of the instrument to enable detection of additional compounds that may be specified at a later date, as well as to provide information to identify unexpected contaminants.

11.5 (Continued)

The analyzers that have been considered fall into three distinct categories:

1) Absorption spectroscopy
2) Chromatography
3) Mass spectrometry

A detailed description of specific hardware was omitted for this report, since final equipment definition has not yet been pursued. Instead, the discussion is intended to outline the basic operation and characteristics of the three types of analyzers mentioned.

11.5.1 Absorption Spectroscopy

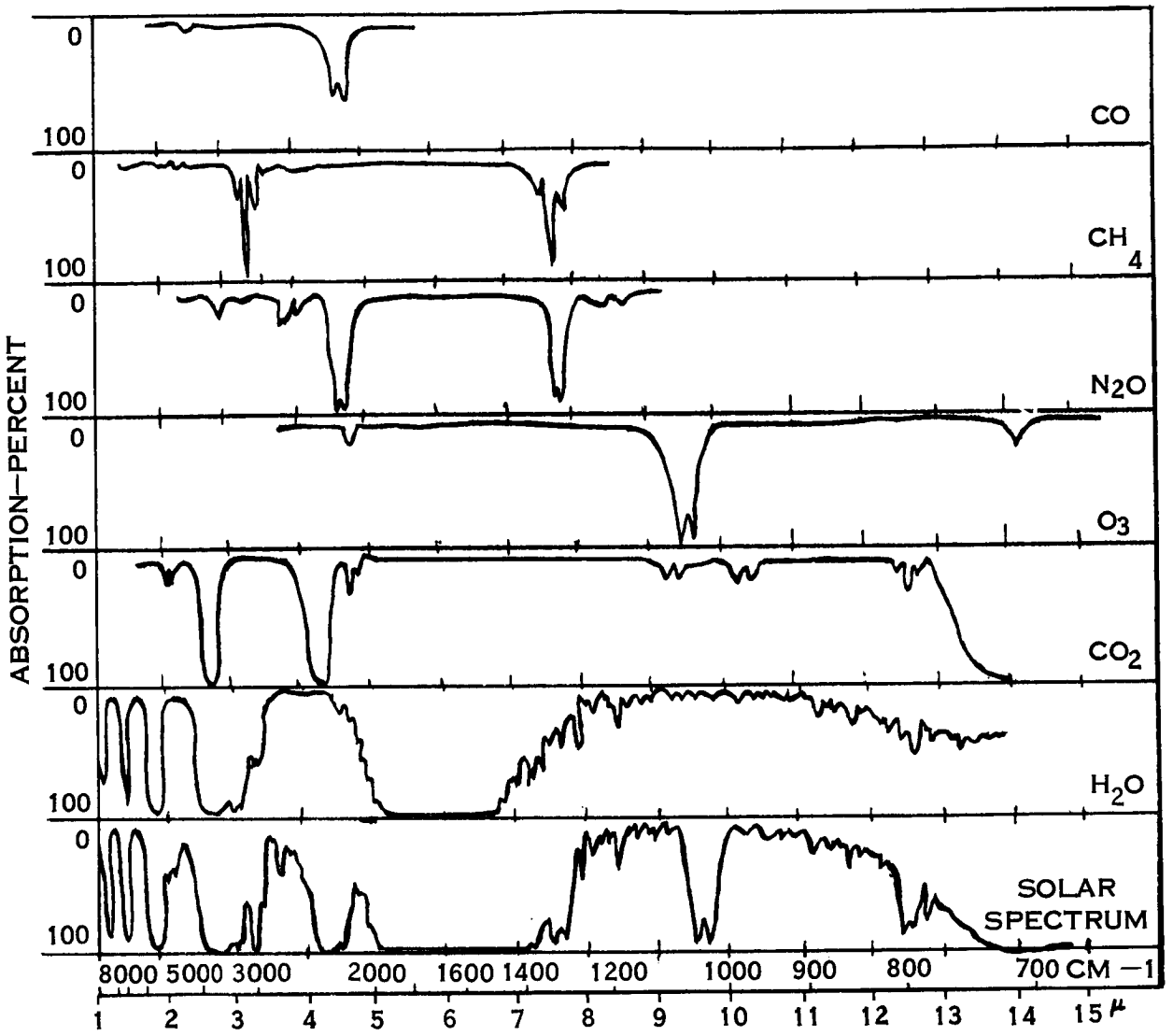
Regardless of the wave length, the type of radiation source or the means of detection utilized, these systems are characterized by the use of the selective absorption bands exhibited by the various gases.

As a result, these instruments perform best when sampling for previously specified gases. Unexpected components can be detected by scanning the spectrum for absorption peaks and utilizing the resultant data as a means of determining these components. In general, however, trace amounts are difficult to detect since they result in only small changes in energy at their absorption wave lengths. The measurement, therefore, requires determining the difference between two large signals.

11.5.1.1 Infra-red Systems

This particular part of the spectrum has found wide use for the detection of specific components that have distinctive absorption bands. The Perkin-Elmer CO_2 detector utilizes the absorption of CO_2 at 4.3 microns to detect concentration. The device consists of a two wave length filter photometer which continuously monitors the atmospheric attenuation at 4.3 microns and compares it to the transmission at 4.1 microns where there is no absorption. By using a resonant reed to move the wave length switching filter, a compact and rugged instrument can be built that is well suited to spacecraft use. Several other gases can be detected by this means; however, masking of absorption peaks presents a serious problem as can be seen in Figure 11-7 from Minneapolis-Honeywell.

For example, it appears that it would not be possible to detect CO by this method since it would be masked by the presence of N_2O which displays an absorption band at essentially the same wavelength.



NEON INFRARED ABSORPTION SPECTRUM FOR VARIOUS GASES

FIGURE 11 — 7

11.5.1.1 (Continued)

However, these bands are actually not continuous but are made up of resonant peaks of the order of 0.5 angstroms in width. Because these peaks are specific for each gas, it is possible to detect them separately by using a different approach that will avoid the masking problems discussed above.

One such method, suggested by Beckman Instruments, employs a 'non-dispersive" technique where the detector is a cell containing the particular component of interest, in this case CO.

The gas to be analyzed is passed through a sample cell inserted between the detector cell and an infra-red source. Any CO present in the sample cell absorbs radiation and thereby diminishes the amount that can be absorbed by the CO in the detector cell. Therefore, the intensity of radiation absorbed in the detector cell is a measure of the partial pressure of the specific contaminant present in the sample stream.

It is felt that this particular type of unit is not well suited to the requirements of space hardware due to the delicacy of the detector required. On the other hand, the filter photometer described in the preceding paragraph appears to be a fairly rugged instrument.

Neither of these instruments qualify as general purpose gas analyzers in that a separate filter or detector is required for each gas to be detected.

A further point concerning the use of infra-red detectors is that the primary gases show no absorption bands in that region. To provide detection of these gases, use of the ultra-violet range is required. The primary difficulty here is the compatibility of the optical systems for the different wave lengths.

11.5.1.2 Molecular Resonance Technique

Simmonds Precision Products, Inc. is developing a proprietary technique that may circumvent some of the problems associated with infra-red detection. The approach, like the one described above, is based upon the fact that the absorption bands are not continuous but are made up of resonant peaks. Because of this, Simmonds feels that the masking noted in the conventional I.R. approach will be avoided. The technique requires prior specification of the gases to be detected. It warrants further consideration as a possible means of gas detection in the closed system.

11.5.1.3 Interferometer Techniques

The use of an interferometer spectrometer for measurement of the infra-red spectra has been investigated by Block Associates, Inc. The interferometer effectively changes the frequency of the radiation and enables detection of the infra-red spectra and conversion to electrical signal. The Michelson optics utilize the motion of a mirror to vary the length of one of two light paths. The output of the optics is the sum of these two paths and a particular radiation frequency alternately interferes and reinforces itself at a frequency that is directly proportional to mirror velocity and inversely proportional to the radiation wave length. Because all wave lengths are scanned simultaneously and converted to analogous electrical frequencies, regions of known interest can be simultaneously and continuously monitored by the use of filters at the output of the detector. This system is subject to the previously mentioned limitations of infra-red analyzers.

11.5.1.4 Microwave Spectrometry

The Tracerlab Division of the Laboratory for Electronics, Inc. has proposed to use the microwave spectra to monitor and identify trace gases. The following is their brief description of the proposed system:

The system will consist of a relatively small, lightweight, low power microwave spectrometer installed in the space vehicle. This instrument will be equipped to operate between 50-300 KMc/sec and will analyze most of the common atmospheric contaminants. In addition, the instrument will have the capability of monitoring the total oxygen content of the craft to insure the continuous existence of a breathable atmosphere for crew members. An atmosphere to be analyzed will be continuously drawn into a sample cell wherein individual molecular species produce identifiable absorption peaks at characteristic frequencies. Careful consideration has been given to such practical problems as power requirements, instrument design, operation range, and gas characteristics to insure that the microwave spectrometer has the versatility and sensitivity to respond to the wide range of gas concentrations expected, and the specificity for identifying not only the various anticipated gases, but also the unforeseen components of the gas mixture.

The microwave spectrometer consists of three basic assemblies: (1) the source, (2) the sample cell, and (3) the detector. In principle,microwave energy from the source is absorbed at a characteristic frequency by the gas in the sample cell, and the resulting changes in microwave power are recorded by the detector. In the microwave region, the absorption of the source energy by a gas is usually attributed to excitation of the rotational state of the molecule. However, changes in structure (inversion spectra), moments of inertia, excited ground states, induced dipoles, and various electronic and magnetic phenomena may also cause molecules to exhibit

11.5.1.4 (Continued)

spectra in the microwave region. The absorption at a particular frequency, therefore, is an unambiguous qualitative analysis of the gas present because the highly resolved absorption peaks from the gases in a mixture (1/2 width = 3 mc/sec) have negligible probability of overlapping. The fraction abundance of gas present (concentration) is determined by measuring the height of the absorption peak. The height of an absorption peak is independent of pressure provided the relative concentrations of the gases remain constant. If the normally accepted operation pressure of 1 mm Hg should vary, only the peak width will vary and no error will occur in the quantitative and qualitative aspects of the monitoring system.

The total number of gases which are analyzable by this technique depends only on the allowable time per complete analysis. For a ten minute analysis time 14 gases appear reasonable. Cited below are some of the gases which are analyzable by microwave techniques. This by no means represents the total capability of the instrument, and is only intended as a representative list from which 14 gases may be selected:

H_2O, NH_3, NO_2, H_2S, O_3, O_2, CO, NO, N_2O, SbH_3, AsH_3
CH_3F, C_2H_2O, CH_2O, CH_3Cl, SO_2, CH_3OH, C_2H_5OH,
CH_3COOH, $(CH_3)_2$, HNO_3, CH_2, CHCHO, etc.

11.5.2 Gas Chromatography

Chromatography has found widespread use in process industries where it is regarded as a reliable means of analysis. Development programs for space application of the gas chromatography have been undertaken by Beckman Instruments, Inc. for both a spacecraft chromatograph and a lunar chromatograph. Their data provide the basic material in this section.

Basically, a gas chromatograph consists of three elements: a sample device, a chromatograph column assembly which physically separates the sample constituents, and a detector-amplifier which produces an electrical signal whose magnitude is proportional to the concentration of each component in the sample (Figure 11-8).

The sampling device consists of a sampling valve containing a measured volume which automatically injects a uniform sample into the column assembly on a repetitive basis. The sample sizes normally utilized range from 0.1 cc to 1.0 cc and a sample is injected as often as one minute or as infrequently as every 30 minutes.

11.5.2 (Continued)

FUNCTIONAL SCHEMATIC FOR THE GAS CHROMATOGRAPH

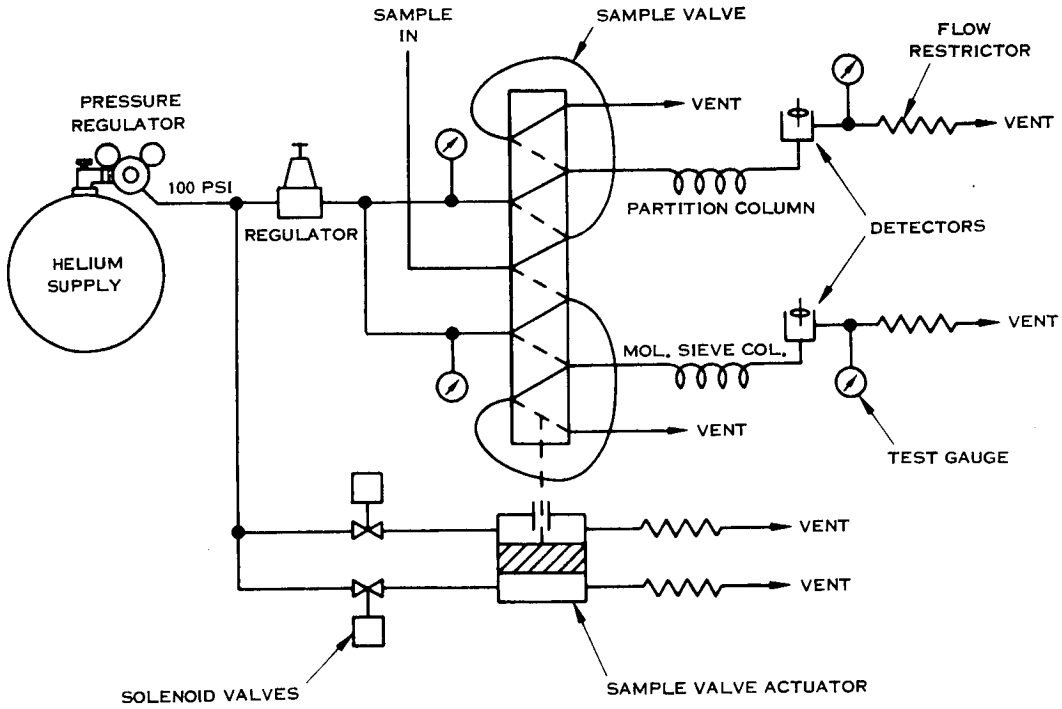


FIGURE 11 – 8

Utilizing a constant volume sample results in a partial pressure reading for each component independent of total pressure. This is important in that metabolism is affected by partial pressure variations only. If the oxygen concentration, for example, were maintained at 20% and the total pressure reduced from 760 mm to 400 mm, the oxygen partial pressure would be only 100 mm, resulting in possible hypoxia. Therefore, a percent measurement should never be utilized where accurate control of total pressure cannot be maintained.

The chromatograph column normally consists of a length of coiled tubing filled with a solid support medium which preferentially adsorbs the individual components of the sample, causing them to pass through the column at different rates of speed by a continuous flow of carrier gas. Some columns consist of adsorption materials such as Silica Gel, Alumina, or Molecular Sieve, and other types of columns consist of a solid support, usually crushed firebrick or Teflon, upon which has been placed a thin layer of a high boiling point liquid. These partition liquid columns provide good

11.5.2 (Continued)

separation for organics and hydrocarbons, whereas the adsorption types are normally used for separation of the fixed gases. The separation ability of the column is a function of its length, the operating temperature, the flow rate of the carrier gas and the type of material which it contains. The fact that the chromatograph column physically separates each constituent prior to detection eliminates the requirement for a computer or the use of simultaneous equations to determine the relative concentration of each constituent.

As the individual components emerge from the column they pass through a detector cell which generates an electrical signal proportional to the concentration of the component. The detector should be nonspecific and only be sensitive to the presence of the components in the carrier gas. Ionization detectors are now available which can provide sensitivity to virtually all eluted components in the ppm range or less.

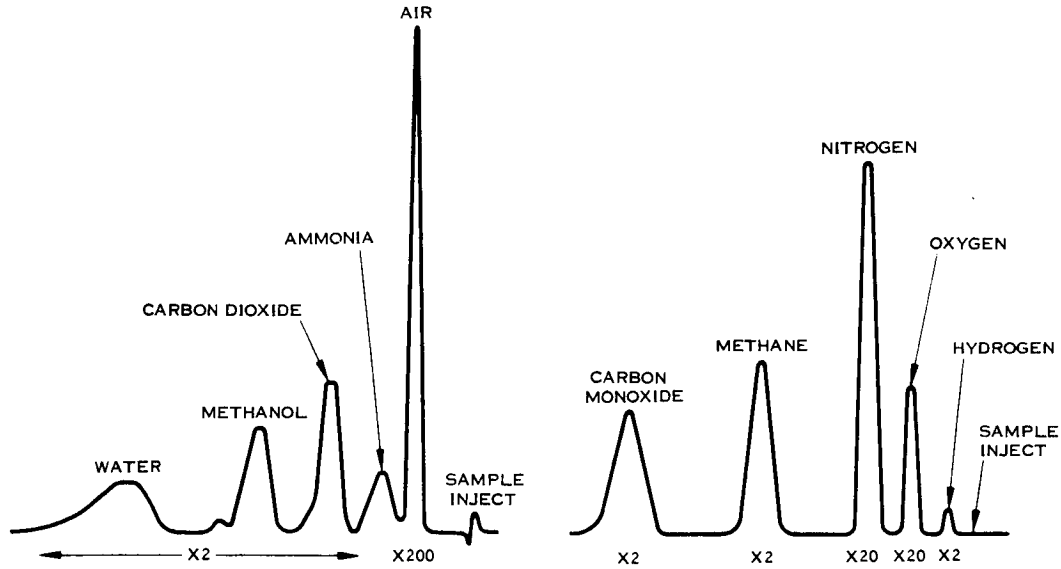
The output signal from the detector is a series of peaks, each peak representing a separate constituent. This signal is normally amplified and displayed on a strip chart recorder, or can be telemetered to Earth. By properly gating the output signal, particular constituents such as oxygen, nitrogen and carbon dioxide can be read out on individual indicators, thereby providing a continuous reading for these key constituents within the capsule.

The time required to elute specific constituents is a function of the type of column and its operating characteristics. It is possible, for example, to provide a quantitative analysis for oxygen, nitrogen, and carbon dioxide in less than ten seconds. However, the usefulness of the gas chromatograph is greatly extended by permitting longer analysis times per cycle so that a large number of constituents can be analyzed. It is improbable that any toxic constituent evolved from equipment or as a product of metabolism will build up to dangerous concentrations in less than 30 minutes, particularly within the volume of the Mission Module. On the other hand, from a safety standpoint, the partial pressure of oxygen and carbon dioxide should be continuously monitored so that any failure of the control system will not result in danger to the personnel. The gas chromatograph, therefore, would ideally be backed up with continuously monitoring sensors for oxygen and carbon dioxide, the output signals from these sensors being used to control the partial pressure of these gases. An example of the separation achieved by an adsorption and liquid partition column is shown in Figure 11-9. Much of the difficulty involved in adaptation of the chromatograph to space operation is caused by the column characteristics.

An extremely accurate temperature regulator is used to maintain proper component elution times. Because the columns have a finite life, long missions must be

11.5.2 (Continued)

GC SPECTRA OF ADSORPTION AND PARTITION COLUMNS



COLUMN – 1/4 " BY 5'
PACKED WITH 3%ARMEEN S.D. AND 9%CARBO WAX 4A ON TEFLON T 5
CARRIER GAS – HELIUM 60 CC / MIN.
TEMPERATURE – 80°C

PARTITION COLUMN CHROMATOGRAM

COLUMN – 1/4" BY 5' WITH MOLECULAR SIEVE 5 A 20–40 MESH
CARRIER GAS – HELIUM 60 CC/MIN.
TEMPERATURE – 40°C

ADSORPTION COLUMN CHROMATOGRAM

FIGURE 11 – 9

concerned with either replacement or reconditioning of the columns. The adsorbent column is susceptible to degradation since it will hold water and CO_2 indefinitely. Provision will have to be made to either bake out these columns or replace them after a period of months.

The use of helium carrier gas adds a minimum of 3 lbs/month to the expendable weight of the chromatograph. However, by using individual sensors to measure the major gases, the sampling interval can be lengthened and helium use reduced.

In summary, the chromatograph will accurately measure all specified components and will do so in the presence of many constituents. It is basically simple and rugged and can be adapted to different analyses. Detectors are available that will provide high sensitivity to all types of compounds. The disadvantages include the possibility of encountering unexpected gases that are not separated by the columns.

11.5.2 (Continued)

The discontinuous readout is not serious if individual sensors are used for the common gases. Column replacement and carrier gas requirements produce a weight penalty for long duration missions.

11.5.3 Mass Spectrometry

The principle of mass spectrometry involves the ionization of a sample into charged particles which are then separated into their characteristic mass to charge ratios and finally detected. The means of separation forms the basis for distinction between the types of mass spectrometer.

In the magnetic field type of spectrometer, the particles are accelerated by an electric field. Each mass to charge ratio is accelerated to a characteristic velocity dependent upon the accelerating voltage. They then pass thru a magnetic field where the degree of deflection is a function of the mass to charge ratio of the particles. The field separates the ions into beams, each of a different mass to charge ratio. By varying the accelerating voltage the resultant beams are successively directed through a resolving slit and onto a collector. The resultant current is amplified and provides a measure of the number of ions at each mass to charge ratio. The radio frequency spectrometer uses an RF accelerator to separate the different masses. Following ionization, the charged particles pass into an RF accelerator which consists of a series of plates charged with a radio frequency voltage. Only ions of a given mass to charge ratio will "resonate" at the impressed frequency and geometry and emerge from the accelerator with high energy. These ions are separated by virtue of their high energy, and a single mass to charge ratio reaches the collector. The resultant current is amplified and provides a measure of the ion current corresponding to the frequency of the accelerator.

The "time of flight" spectrometer is of particular interest since development of two instruments of this basic type is being pursued. The first is the Bendix Time-of-Flight Mass Spectrometer and the second the Johnston Laboratories Coincidence Mass Spectrometer. Both measure time of flight of the various mass to charge ratio particles, all of which are accelerated by a fixed field.

The primary difference lies in the means of determining the time at which the ion was formed and accelerated. The Johnston Laboratories Coincidence Spectrometer uses a low ionization rate to insure that only one ion is in flight at a time. The

11.5.3 (Continued)

electron produced by the ionization is accelerated in the direction opposite that of the ion toward an electron detector. The sensing of the electron provides a zero time reference for the ion time of flight measurement. The coincidence principle requires that a pair of related events occur before an ionization can be recorded. Each ion collected must be accompanied by a corresponding electron collected at the opposite detector. This feature makes the instrument insensitive to incident radiation.

The essential elements of the Bendix time of flight spectrometer are shown in Figure 11-10. The accelerating grid and electron beam within the ionization chamber is pulsed which causes pulsations of positive ions to be ejected from the ionization chamber (their velocity being a function of mass). As each pulse passes

ESSENTIAL FEATURES OF THE TIME-OF-FLIGHT MASS SPECTROMETER

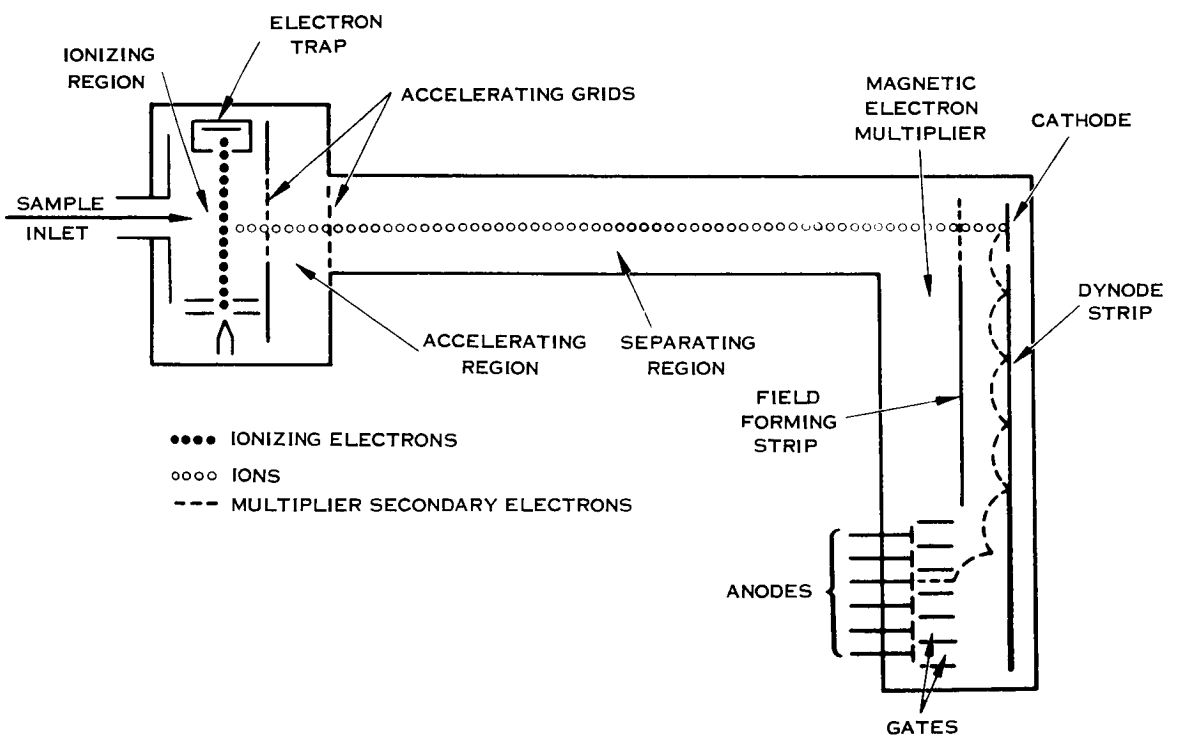


FIGURE 11 — 10

11.5.3 (Continued)

thru the separating region, the ions separate into bunches dependent upon their mass to charge ratio. This separation increases as they proceed toward the collector. As the individual mass groups arrive at the end of the tube they collide with the cathode of a magnetic electron multiplier. An electron current is produced whose value is a quantitative measure of the number of arriving positive ions. The electron multiplier is capable of producing current gains on the order of 10^7 by the time the resulting electron bunch reaches the gating section. By pulsing a particular gate, the electron packet arriving at that instant will be deflected to the corresponding anode. By successive application of these gate pulses, the electron packets corresponding to individual mass to charge ratios can be measured. The number of gates determines the number of masses measured at each pulse of the ionization chamber. Since the longest flight time is on the order of 15 microseconds, the time between ionization pulses is less than 100 microseconds and the entire mass spectrum can be scanned rapidly.

These mass spectrometers are capable of sensitivities less than one part per million. However, a major problem that is associated with the ionization and subsequent identification process is the fact that the molecules are fragmented by the ionizing beam. This causes numerous peaks to be produced for each component in the sample. The fractionating pattern for the major atmospheric constituents is shown in Figure 11-11. Because of the numerous large peaks resulting from these constituents, it is impossible to detect trace amounts of gases whose fractionating patterns are coincident with these peaks. Carbon monoxide, for example, is masked at mass numbers 12, 16 and 28 by the presence of nitrogen, oxygen and carbon dioxide.

A second problem associated with the spectrometer is the effect of oxygen poisoning of the filament resulting in a change in ionizing current and requiring recalibration. Because of the relatively low filament temperature required by the Coincidence Spectrometer, its sensitivity to this poisoning should be reduced.

The mass spectrometer satisfies the requirement that the analyzer be capable of detection and identification of unexpected trace gases provided that these are not masked by the primary atmospheric constituents. It is also capable of providing repetitive monitoring of specified atmospheric components. The estimated weight and power requirements for the mass spectrometer and gas chromatograph are roughly equal.

11.5.3 (Continued)

FRACTIONATING PATTERN FOR MAJOR ATMOSPHERE CONSTITUENTS

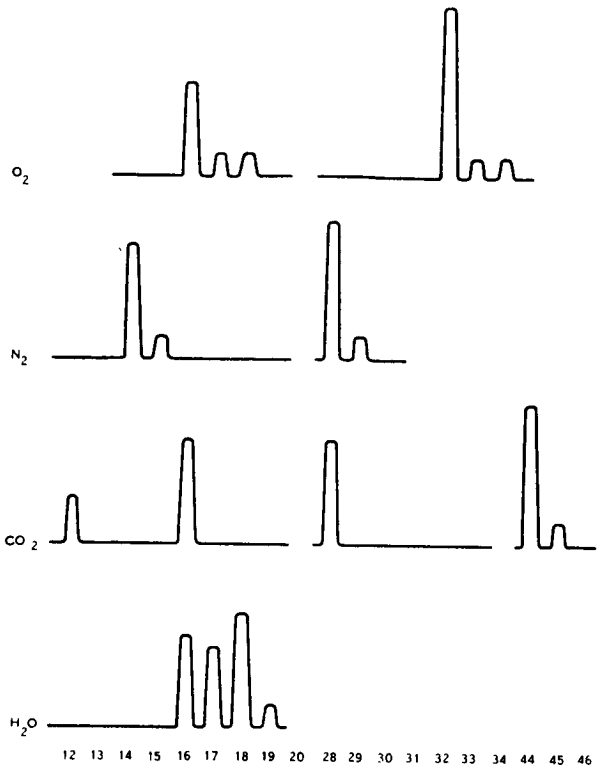


FIGURE 11 11

11.5.4 Summary Discussion - Gas Chromatography and Mass Spectrometry

Because of the inherent characteristics of both analyzers it may not be possible to make a clear cut decision as to which is best suited for the Mars vehicles. The development programs that have been initiated for both instruments, coupled with increased knowledge in the area of closed system contamination and its control, could provide the information necessary for this decision.

However, it is reasonable that both these instruments may be required to provide the necessary separation in the case of the chromatograph and identification by mass spectrometry. Such a combination has been proposed by Beckman Instruments, Inc. as a research tool and for flights of long duration such as the Mars Mission.

11.5.4 (Continued)

With such a system, the sample is first separated into its individual constituents prior to introduction into the ionization chamber. Therefore, the resulting fractionating pattern is that of a single compound making the identification straightforward. This is, in effect, an extension of the principle of pre-processing the sample to enable detection of those compounds that are masked by the primary atmospheric gases.

11.5.5 References

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SECTION 12.0

HYGIENE

12.0 HYGIENE

12.1 General

This section considers the functions of bathing, shaving, barbering, teeth cleaning and waste collection. All of these functions require consideration for the long mission to Mars. Some aspects of hygiene on a spacecraft are different from those on earth due to the absence of extraneous dirt and the necessity for operating in zero "g".

12.2 Bathing

The first function to be considered is bathing or body cleaning. During a space flight of long duration, there will be a need for complete body cleaning at specified intervals and for both long and short missions, there will be a need for frequent hand washing before meals and after doing maintenance work.

There are basically two methods of skin cleaning to be considered. The first of these is conventional washing with soap and water, and the second is wiping with impregnated pads. These two approaches will be examined in more detail and then compared.

Washing with soap and water is the conventional method of body cleaning, but for space use, this poses two major problems. The first is that in a closed system the used wash water must be reclaimed and recycled, and the second is the problems associated with controlling the flow of water in zero "g". The processing of wash water has already been considered in the section on water management.

For washing, it is proposed to use a shower type device with directed airflow to control and remove the water. In use, the astronaut will wet his body with a spray nozzle on a flexible hose. Then he will soap himself with a sponge, and finally follow this with a shower rinse. The airflow that removes the water spray will be heated to provide drying. The actual shower cabinet could be a rigid shell or the walls might be constructed of flexible plastic or waterproof fabric in order to attain minimum weight and storage volume. While such a device has not been tested under zero "g" conditions, it could probably be developed to a satisfactory condition with a reasonable amount of effort.

For hand washing, a similar but smaller device would be used. The hands would be inserted through flexible closures and the water spray turned on by a foot or knee switch.

12.2 (Continued)

For the actual cleansing agent, both conventional soaps and synthetic detergents are available. A plain, simple soap such as Castile would be well suited, since it is known that continued use will not result in skin allergy problems. An alternate cleansing agent would be a synthetic such as Phisohex. This consists of the active detergent Entsufon and in addition, it has lanolin cholesterols, petrolatum and hexachlorophene. This has had extensive use in hospitals and has been recommended for use during an extended space flight. The combination of cleansing agent, skin emolient and bactericidal agent has proven to be sound. It is felt that the presence of a bactericidal agent would be desirable to reduce the chance of infection since within the protective environment of a space capsule, the skin may become excessively tender.

An entirely different method of skin cleansing is wiping with impregnated pads. These will contain the following major constituents:

a) A cleansing agent
b) An oil or wax base substance to prevent skin dryness
c) A disinfectant
d) Alcohol to enhance drying of the applied materials.

Several cleaning agents are available such as sodium alkyl sulphates, sodium alkyl ether sulphates and tallow alcohol ethoxylates. Lotion type cleansers consisting of water in oil emulsions are also suitable. None of these agents require rinsing, although dry wiping can be accomplished with unimpregnated pads if desired.

These pads are pre-packaged, opened and used once and then reinserted in the original package for disposal.

These two methods of bathing can be compared in a number of different ways. The first evaluation is on the basis of weight. It has been estimated that suitable cleaning pads with their sealing envelopes will weigh 0.04 lb each and four should be required per man day.

For an overall weight evaluation, the pads must be compared to the weight of a shower plus water reclamation system plus soap. It has been estimated that a lightweight shower suitable for a space vehicle could be constructed to weigh 45 lb. The comparison can be summarized in the following table.

12.2 (Continued)

	Weight of Water Shower System	Weight of Impregnated Pads
6 men, 420 days	221 lb	403 lb
3 men, 40 days	71 lb	19 lb

It can be seen that the shower is lighter for the long journey in the Mission Module and the pads are lighter for the short mission of the Excursion Module. In order to be general, this comparison includes the weight of a water reclamation system which may not be necessary on the Excursion Module.

However, other factors besides system weight require consideration as follows:

a) Reliability - The simple pad system is of course more reliable than the shower system. It requires no moving parts or power supply and will not be complicated by zero "g" operation.

b) Atmospheric contamination - There should be no atmospheric contamination from the shower except small quantities of water vapor that can escape through leaks and these can be easily handled by the normal water removal system. On the other hand, the impregnated pads in use today contain alcohol or some other very volatile agent which keeps them moist during storage and enhances drying of the applied materials. These volatile substances will enter the cabin atmosphere and may put a large load on the contaminant control subsystem.

c) Efficiency of cleaning - The shower system will probably provide more satisfactory cleaning because it is the method most familiar to the astronaut on earth. In addition, there may be some uncertainty concerning the exclusive use of impregnated pads on the skin for extended periods of time such as the 420 day journey in the Mission Module.

d) Psychological Considerations - The psychological importance of providing the astronaut with a warm shower at regular intervals is a very debatable question. Some authorities minimize the importance or need for bathing in water by pointing out that in wartime many people had no bathing facilities whatsoever. However, it is doubtful that people living in a constantly "dirty" state were able to function at the maximum efficiency that will be required of an astronaut.

12.2 (Continued)

It must be borne in mind that the astronaut will unavoidably be under severe stress at many times and some relief or "luxury" must be provided if he is to remain relaxed throughout an extended space mission. It is felt that the availability of a regular hot shower could be of considerable benefit in maintaining morale and providing relaxation.

In view of the above comparisons it is recommended that impregnated pads be used on the Excursion Module and a water shower on the Mission Module.

12.3 Shaving and Barbering

These two functions can be provided by an electric razor with an alternate head for clipping the scalp hair to a short length. In addition to the normal shaving head, the unit will contain a small fan to draw hair particles into a receptacle. Barbering can be performed inside the space shower and be followed by a shower and shampoo in order to wash away any residual hair particles.

Nails

Nails can be cut with a conventional clipper. There are clippers presently available on the commercial market which collect the clippings and retain them in a receptacle.

Teeth

The cleaning of teeth will be carried out in a more or less conventional manner. Toothpaste, of an edible type, will be squeezed onto a brush and the teeth cleaned in a normal manner. The only precaution to be observed is the lips must remain closed around the handle of the toothbrush to prevent the escape of saliva and paste. Upon completion, the toothpaste will be swallowed and this can be followed by a drink of water or warm beverage.

12.4 Waste Collection

This section is concerned primarily with the collection of human wastes and the emphasis will be on reliability and simplicity of operation.

The most outstanding problems in urine collection are due to the requirement for zero"g" operation. Careful consideration will be required in order to insure that collection is absolutely complete. There is a choice here between units that make personal contact in order to provide sealing and those that do not make direct contact.

12.4 (Continued)

One of the most promising devices of the type that does not require personal contact is a centrifugal urinal developed by the Whirlpool Corporation. This consists of a rotating cup or vaneless impeller that forces the urine through a check valve under the influence of a centrifugal force. After use the unit is sprayed with a disinfectant. This has been tested under zero "g" by the Air Force. The primary objection to this is the uncertainty of complete collection at the end of the urination period. Another device that does not require personal contact is the use of a funnel with an air stream section to control and direct the liquid in zero "g". The main disadvantage of this is that the urine must then be separated from the air stream and, in addition, both fan and water separator will be subjected to the corrosive effects of urine vapor. However, both these devices have the attractive feature that they allow urination without physical contact between the man and the collector thus improving its acceptability for long duration missions by approaching earth-type operation.

Another of the alternate type device that does make a positive seal is a urine collection tube proposed by Electric Boat Division of General Dynamics (No. U411-61-168 under contract AF 33(616) - 7428). This device consists of a sealing head, a receptacle in the form of a flat rubber tube and a roller clamp to remove the urine from the tube. Since positive contact is made, each crew member will have his individual collector. This device will be rolled up to be very compact and can be stored in a pocket if desired. The sealing head makes a positive contact that eliminates any possibility of leakage and the rollers can squeeze the tube that is of normally flat cross section to transfer the urine to the water management system. Of the three collection devices discussed above, it appears that the General Dynamics collection tube is the simplest device with the most foolproof method of preventing leakage.

The problems encountered in feces collection are even more severe than for urine. There is the difficult problem of collecting the feces in zero "g" and transporting it to the waste control system and the requirement to minimize the leakage of flatus within the relatively small closed space capsule.

There are three different types of feces collection methods that were considered. The first of those is a simple hand held bag as has been proposed for the Gemini mission. Such a device has been designed and manufactured by the Whirlpool Corporation. The objection to this method is the tiring and awkward position that must be maintained during defecation. For an extended mission this method may be excessively tedious to be considered satisfactory. These bags weigh 0.13 pounds each. For the short three man mission in the MEM this is 23.4 lbs. which could be considered acceptable. However, for the long mission to and from Mars the weight would be excessive at 491 lbs.

The alternate methods of collection involve a more conventional toilet seat that would be much more acceptable for use on extended missions. With this type

12.4 (Continued)

of device some method is required to remove the feces in zero "g". One of the most promising is a directed air blast.

A variation of this is to use a water wash and flush. This has been proposed by General Electric in Project Hydro-John, contract NAS 9-1301. The objections to this system is that a very close seat-anus seal is required to prevent the escape of water and there are problems associated with the processing of the flush water.

It is felt that no entirely suitable system of feces collection has been described in the literature. This is one subsystem that requires extensive work to produce even prototype hardware.

Of course, the major problem in feces collection is the requirement for zero "g" operation. If the space vehicle is to be rotated to provide an artificial gravity field, then a properly oriented toilet could function as it does on Earth.

Even if the space vehicle operates without gravity, a special centrifuge chair may be required for the astronauts. Each astronaut will be spun in the centrifuge for a few minutes each day to maintain the body blood pressure system in order to prevent deterioration due to the absence of gravity. If a toilet could be combined with such a centrifuge chair, the problems of feces collection would be greatly alleviated.

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