SLS 404

MARS LANDING AND RECONNAISSANCE MISSION ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM STUDY

CONTRACT NAS 9-1701

MID TERM REPORT

(Fourth monthly progress report)

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1.0 Introduction

This report presents the results of the first half of the Mars Landing and Reconnaissance Mission Environmental Control and Life Support System Study being performed by Hamilton Standard under NASA Contract NAS 9-1701. This first half of the study has been concerned with analysis of the various subsystems for a complete Environmental Control and Life Support System. The data generated during this portion of the study has been presented in parametric form to permit evaluation of each subsystem, and selection of the best subsystem in each area during the second half of the study.

This report is intended to familiarize those people interested in the study with the work which has been done thus far. It presents the detailed results in summary form, and indicates the most likely choices in various areas. However, due to the interaction of various subsystems, a final selection cannot be made until integration problems are considered. Therefore, this data should be considered as design tools rather than representing a final selection. The final report will present more detailed data on each of the subsystems areas as well as integrated systems for each of the three Mars Vehicle Modules.

2.0 Summary

2.1 General

This report presents the results of the main subsystem study areas of the Mars Landing and Reconnaissance Mission Environmental Control and Life Support System Study, NASA Contract NAS 9-1701. The contract covers the investigation and analysis of methods of life support and environmental control for space vehicles. These methods will be analyzed from the present state-of-the-art and for predicted performance which might be expected in the future to be ready for a 1973 mission. This information is to be prepared in a parametric form so to be useful as future changes take place in the vehicles or the mission profile. This information will then be used to devise integrated systems for the three vehicle modules. The areas covered by this study are: Atmospheric Supply, Atmospheric Conditioning, Thermal Control, Instrumentation, Water Management, Waste Management, Personal Hygiene, and Pressure Suit Integration.

The purpose of this report is the presentation of the work done in this study up to the present time, for use by NASA and others interested in the Mars Mission. The data is presented in summary form but is complete enough to be used as design tools. Work in the areas of Personal Hygiene, Pressure Suit Integration, and Waste Management were completed too late to be included in this report.

The purpose of this section is to present a brief summary of the areas covered in the body of the report. More complete details can be found in sections 4 through 8.

2.2 Atmospheric Supply

The atmosphere for the spacecraft can be supplied from storage tanks (either as a liquid or in a gaseous form), reclaimed from the CO_2 produced by the crew, or stored as water, or some other easily storable chemical, and decomposed as required. The optimum method, or combination of methods, will be selected for the Mars mission. It was the purpose of the subsystem studies to provide the detailed parametric data which can be used for this selection. The following sections will summarize the work done in each area.

2.2.1 Oxygen and Nitrogen Storage

The study considered four methods as potential candidates for storage of the Mars Vehicle atmospheric constituents to makeup for metabolic useage, cabin leakage, and cabin repressurization. Those methods are supercritical cryogenic, subcritical cryogenic storage with thermal pressurization, subcritical storage with positive expulsion, and gaseous storage. The following describes each briefly.

2.2.1 (Continued)

1) Supercritical cryogenic storage - Storage of oxygen or nitrogen at elevated pressure where no phase distinction exists between portions of fluid in the tank and the mixture is essentially homogeneous; thus eliminating vapor-liquid separation problems in zero g.

2) Subcritical cryogenic storage with thermal pressurization - Storage in a two-phase form with heat provided to vaporize liquid at a rate sufficient to keep the vessel at the required pressure. This two-phase characteristic creates metering problems in zero g, but the method provides a weight advantage. Proper metering and heat exchange equipment design can overcome these problems and provide a gaseous supply to the cabin.

3) Subcritical cryogenic storage with positive expulsion - Storage as in 2 above except a pressurized bladder or piston is used to assure liquid delivery to the metering device. Weight is comparable to that of 2 but many development problems exist in the design of bladders.

4) Gaseous storage - Atmospheric constituents stored as a high pressure gas. This method assures pressure whenever required, but weight and volume penalties are high. It was considered here for possible use to permit rapid repressurization.

The subcritical storage method appears to be the lightest over a wide range of requirements. Detail curves are provided in Section 4.1.

2.2.2 Oxygen Reclamation From CO_2

This section treats only the reclamation of oxygen from CO_2 after it has been removed from the atmosphere and delivered to the reclamation unit. Collection from the atmosphere is treated separately in another section, and integration of these two functions will be covered in the final report.

Five major CO_2 reduction concepts have been analyzed to date--thermal or radiation decomposition, the Bosch reaction, the methoxy or Sabatier reaction, solid electrolyte, and molten carbonate electrolysis. The study has assumed that concentrated CO_2 will be available as the inlet gas to the system. A review of each reduction approach follows:

1) Decomposition by radiation using nuclear energy, or by thermal energy, breaks the CO_2 into CO and O_2 with the O_2 liberated and the CO being converted to CO_2 plus C.

2) The Bosch reaction utilizes a high temperature catalytic reaction of CO_2 and H_2 to form H_2O and carbon. The water is then electrolyzed into O_2 and H_2 with the H_2 recycled to continue the reaction.

2.2 (Continued)

3) In the methoxy or Sabatier process, the carbon dioxide is reacted, in the presence of an iron catalyst, to form methane and water. The methane is then decomposed by an arc discharge to form acetylene (C_2H_2) and hydrogen (H_2). The hydrogen is then passed through a palladium - silver filter and returned to the carbon dioxide reaction chamber. The acetylene, which will not pass through the palladium-silver filter is discharged overboard. The water which was formed in the initial reaction is dissociated in an electrolysis cell to form oxygen, which is returned to the space cabin, and hydrogen, which is returned to the carbon dioxide reaction chamber.

4) The solid electrolyte process converts CO_2 into CO plus O_2 in the solid electrolyte reactor and then catalytically reacts the CO to form CO_2 and C with the CO_2 being recycled and the carbon removed.

5) The molten carbonate system electrolytically dissociates the CO_2 into carbon and O_2 in a molten alkali carbonate. The O_2 is liberated at the anode while the carbon is deposited at the cathode.

Only decomposition by radiation can be ruled out at this time due to integration problems, and poor inherent efficiency. Of the others, no firm conclusion can be made until the effects of integration with the removal system have been fully evaluated, a summary of weight for a 6-man unit for 420 day mission is shown in Figure 2-1. More details may be found in section 4.2.

2.2.3 Water Electrolysis

The oxygen required could be stored as water and then electrolyzed. This looks particularly attractive if a method of oxygen reclamation from CO_2 which is used includes an electrolysis cell. To properly evaluate the operation of such cells, either alone or as part of a CO_2 reduction system, several approaches were investigated. The basic principle of operation is the same in all systems with the main difference existing in the solution of the zero g separation of the gas from the electrolyte. The following is a summary of approaches with more details appearing in Section 4.3.

1) In the rotating cell with conventional electrodes studied, the gas-liquid separation is accomplished by providing an artificial gravitational field.

2) A rotating cell with a hydrogen diffusion cathode was studied which separates the O_2 by the artificial gravitational field and the H_2 by the diffusion cathode.

3) A porous electrode system was studied which feeds the H_2O through a wick system and separates the gases by electrodes which do not allow liquid passage, thus reducing water carry-over to the vapor with which the gases are saturated.

4) A cell using a pair of contoured wall vortex separators mounted axially on either side of a diaphragm was studied. The electrolysis is carried out on either side of the diaphragm.

CO_2 REDUCTION SUMMARY

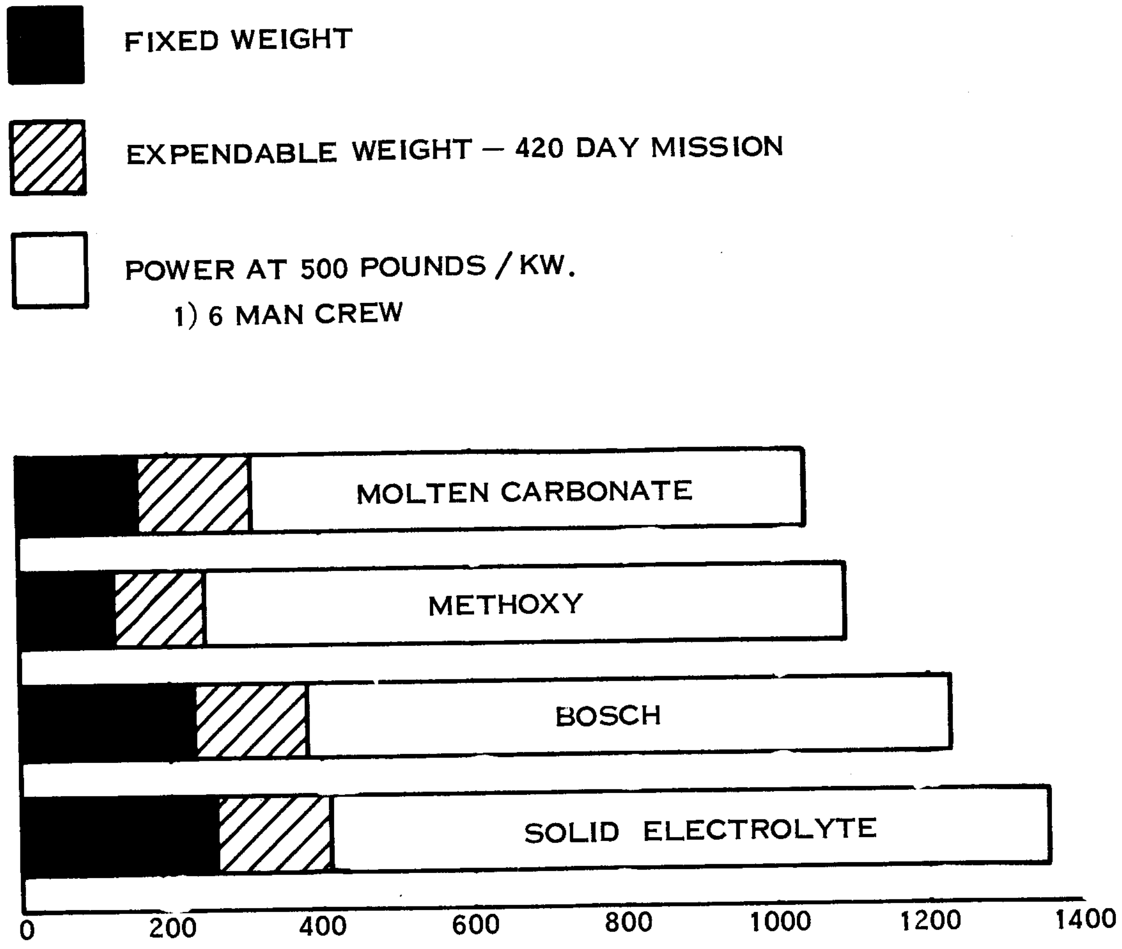


FIGURE 2 - 1

2.2.3 (Continued)

5) The last approach included in this report is an organic membrane cell with a cation permselective membrane which permits passage of the hydrogen ion but not the hydroxyl ion.

Although a specific approach has not been selected, the approaches are compared in Figure 2-2. The weights shown are for a six man size unit operating from a 500 pound per kilowatt penalty power source.

2.3 Atmospheric Conditioning

The atmospheric conditioning is broken into two main areas which will be treated separately here. They are 1) CO_2 removal, and 2) control of other contaminants.

2.3.1 CO_2 Removal

Six different methods were considered as potential candidates for the Mars Vehicle. These approaches are summarized below and treated in detail in Section 5.2.

1) Solid adsorption uses a solid chemical material which adsorbs CO_2 from the air stream and retains it in the microporous structure of the material. Regeneration is possible by exposure to vacuum or by the addition of heat.

2) Liquid absorption utilizes a chemical reaction of the CO_2 with a recirculating liquid as the removal method. Regeneration is provided by heat addition which frees the CO_2.

3) Membrane diffusion removes CO_2 by diffusion through thin walled membranes which are more permeable to CO_2 than air.

4) In mechanical freeze-out, the CO_2 is solidified by an air expansion device and retained in a collector. Warm air melts the CO_2 and allows its removal in order to regenerate the collector.

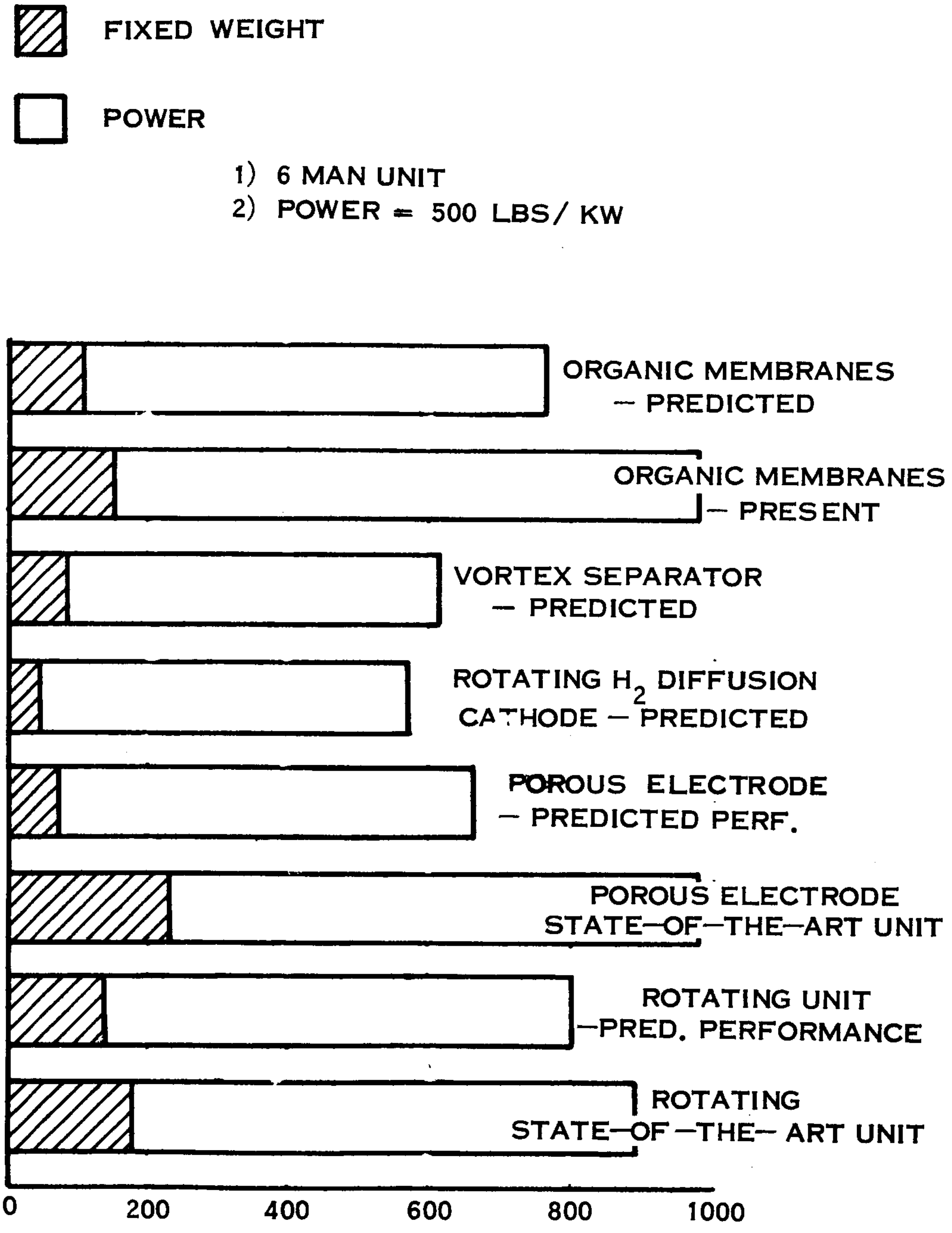
5) Cryogenic freeze-out utilizes a subcritical oxygen to freeze CO_2 from the air stream and employs sublimation to vacuum for CO_2 removal.

6) Electrodialysis utilizes electrochemical reactions to convert the CO_2 to ionic species which then migrate out of the absorption zone through membranes prior to reforming as CO_2 gas.

Figure 2-3 presents a weight summary of a 6 man unit for a 420 day mission. It can be seen that solid adsorption, liquid absorption, and cryogenic freeze-out appear

FIGURE 2–2

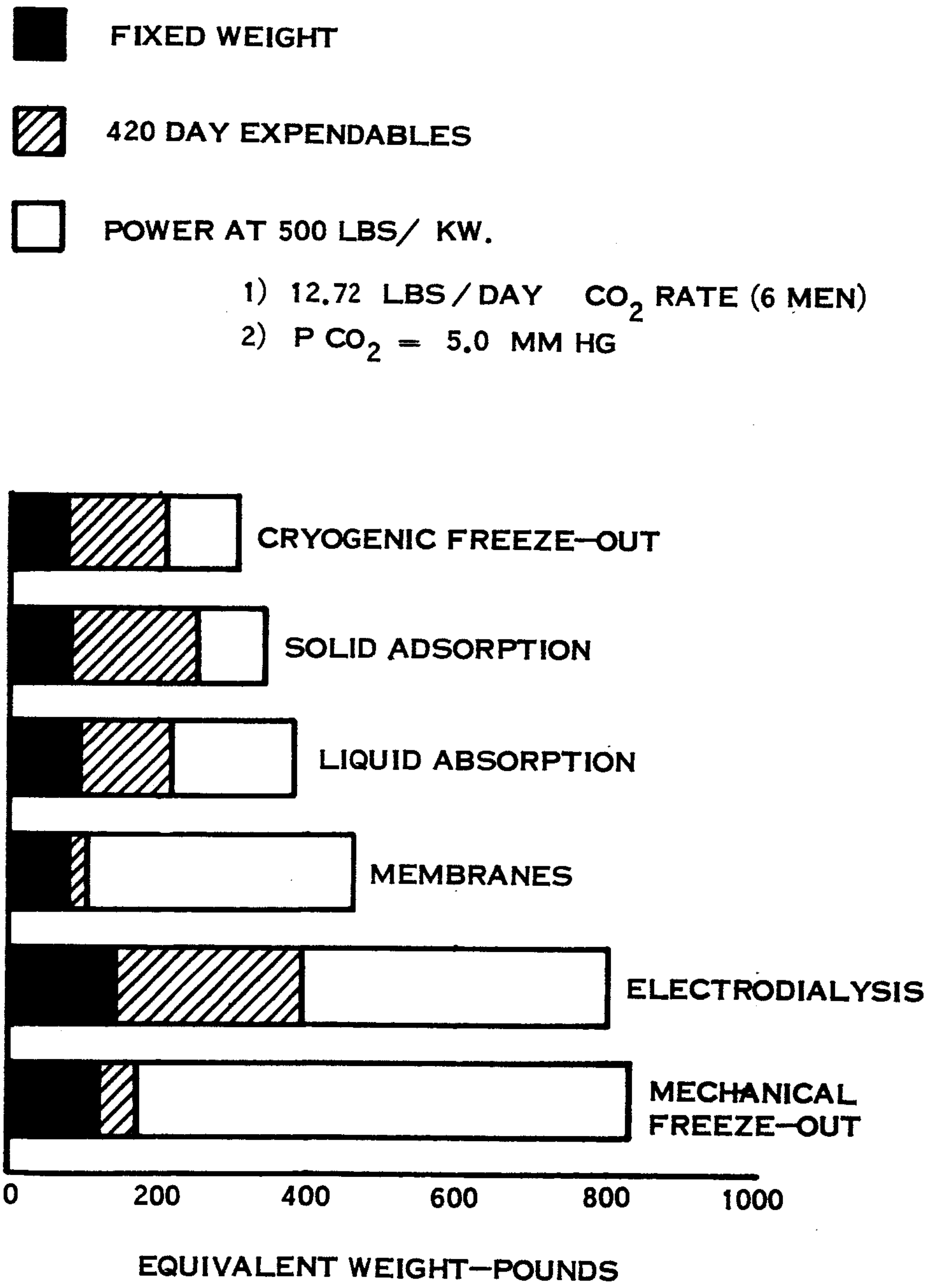
WATER ELECTROLYSIS CELL SUMMARY



1) 6 MAN UNIT
2) POWER = 500 LBS/ KW

FIGURE 2–3

CO_2 REMOVAL SUMMARY



2.3.1 (Continued)

to be the best methods. However, the final selection cannot be made until integration with the CO_2 reduction device has been considered. It is possible for the weight disadvantage of one of the other methods to be offset by ease of CO_2 transfer.

2.3.2 Contaminant Control

In addition to CO_2 removal it is necessary to control the concentration of many other trace contaminants which could build up to dangerous levels in the Mars Vehicle. The contaminants have been divided into seven groups according to chemical composition, and a system devised to remove these groups of contaminants. Three basic methods are required and the system selected consists of a charcoal bed, a chemisorbent bed, and a catalytic burner. The details of this system and weight and power figures are given in section 5.1.

2.4 Thermal Control

The thermal control portion of the subsystem study was intended to accumulate pertinent design data for use in the system definition part of the study. Investigations of coolants, radiator coatings, meteroid protection devices, vehicle orientation, evaporative cooling devices, and Mars atmospheric convectors were conducted and are reported in detail in section 6 of this report.

The coolant survey accumulated the properties of potential candidate fluids into one reference table for use in the final coolant selection. Preliminary considerations of pumping power requirements per unit amount of heat conducted indicate that FC-75 offers good properties, but a final selection was not made since other considerations such as freezing point, availability, toxicity, etc. to be included during final radiator design, were not established at this time.

The coating survey followed the same purpose as the coolant study and lists applicable coatings in one reference table. Preliminary considerations indicate that a zinc oxide - potassium silicate composition is most suitable to Mars requirements.

The meteoroid protection study took the form of a determination of relative protection weight penalties for various protection schemes. This calculation, carried out for an estimation of the final radiator configuration, indicates that the minimum penalty occurs for a scheme where the tube is set below the vehicle skin and is shielded by a solid section and the fin itself. Final determination, however, is dependent upon the eventual radiator configuration.

Estimates were made of the total thermal loads and a radiator sized for a sun-oriented

2.4 (Continued)

vehicle, and for a vehicle which is allowed to tumble in a random fashion. It became clear from this analysis that it was necessary to orient the vehicle. Further discussion was held with NASA and it was decided that the vehicle would be oriented. Therefore, future radiator design will assume sun-orientation.

2.5 Water Management

The subsystem investigation of water reclamation was conducted based on the source of the contaminanted water which determines the contaminant level. This report presents the results for both the urine and the wash water systems.

Six approaches were considered and are summarized here. They are treated in detail in section 7 of this report.

1) Electrodialysis utilizes alternate pairs of anion and cation permeable membranes to remove electrolytes from the process liquid. Non-electrolytes are removal by filtration prior to the electrodialysis stack. The process liquid is recirculated through the stack until the required degree of desalinization is achieved.

2) Air evaporation utilizes a wick evaporator to evaporate the water in the urine and a condenser and water separator to recover it. The contaminants remain in the wicks which are periodically changed.

3) The ELF system electrolyzes the urine into H_2 and O_2 then uses the H_2 and O_2 as fuel for the fuel cell which produces the water as part of the power generation process.

4) Vapor compression utilizes an evaporator to evaporate the water, a compressor to add energy to the system and provide regenerative heat transfer, and a condenser to provide the liquid water. Contaminants appear as scale on the evaporating surfaces.

5) Oil jet vapor compression flashes the urine across a nozzle into a circulating oil stream. The vapor and oil are then separated with the vapor then compressed and condensed, and the oil reheated and recycled. This modification to vapor compression utilizes the oil to wash the evaporator walls thus allowing contaminants to be removed from the oil by filtration.

6) Vacuum distillation with vapor pyrolysis utilizes a boiler to evaporate the water, a high temperature catalyst to purify it, and a condenser to recover it.

2.5 (Continued)

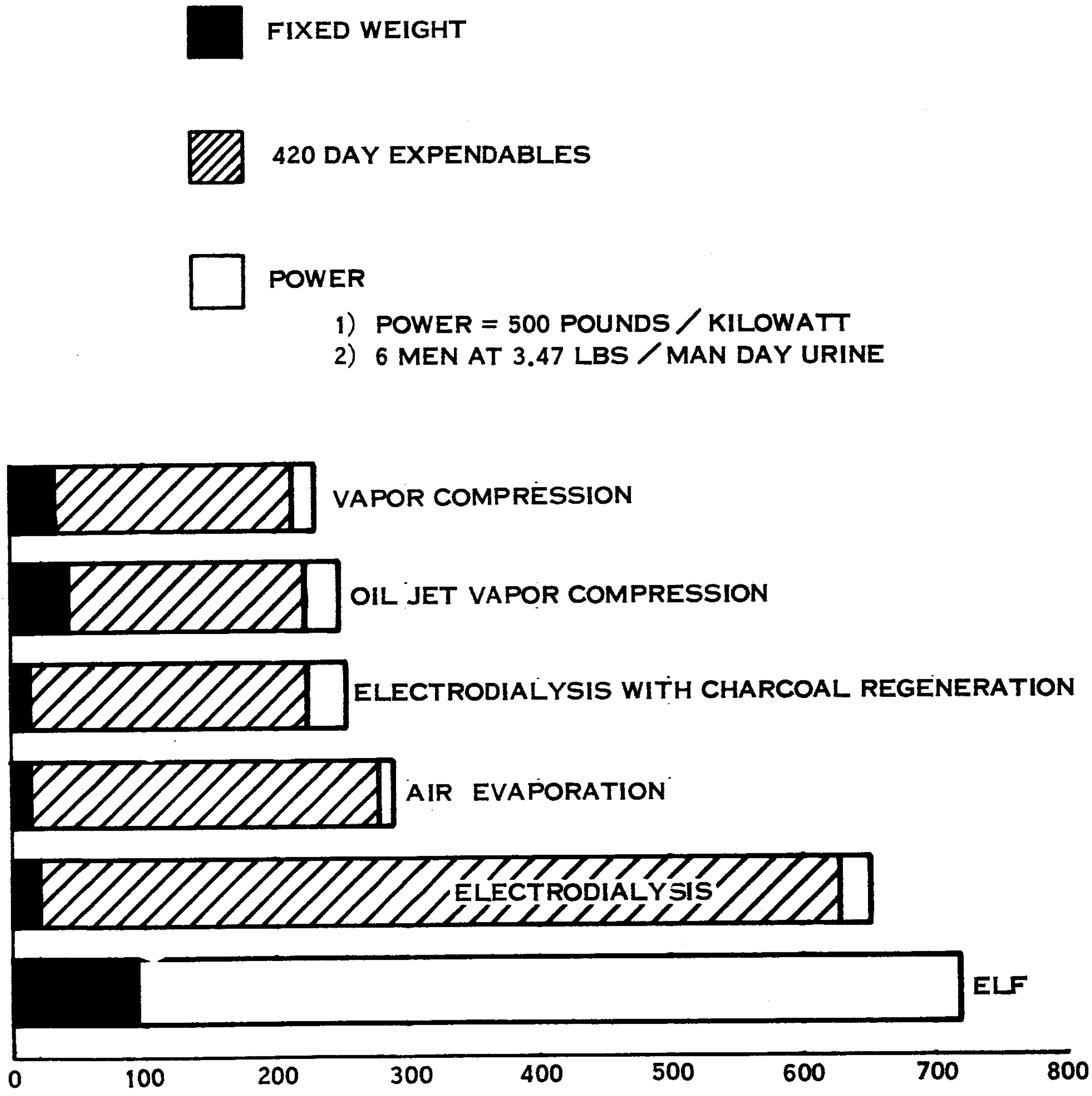
Figure 2-4 presents a weight summary for the urine reclamation system, and Figure 2-5 presents a summary for the wash water system. Both of these are for a 6 man 420 days mission system. It can be seen that vapor compression, electrodialysis (with charcoal regeneration) , and air evaporation are the most competetive systems for urine purification, and the air evaporation (either open or closed loop) and electrodialysis are the most competitive for wash water reclamation.

2.6 Instrumentation

The instrumentation study to date has been interested in the general evaluation of candidate methods of pressure and temperature sensing, atmosphere composition monitoring, stored fluid quantity determination, water potability determination, and leakage indication. Since conclusions on any of these requirements are dependent upon final subsystem selections for the integrated system, this report has been limited to a general discussion of atmospheric monitoring devices.

The discussion in Section 8 presents the operating characteristics and general merits or disadvantages of equipment in three broad classes -- absorption spectroscopy, gas chromatography, and mass spectrometry.

WATER RECLAMATION SUMMARY
URINE



1) POWER = 500 POUNDS / KILOWATT
2) 6 MEN AT 3.47 LBS / MAN DAY URINE

EQUIVALENT WEIGHT — POUNDS

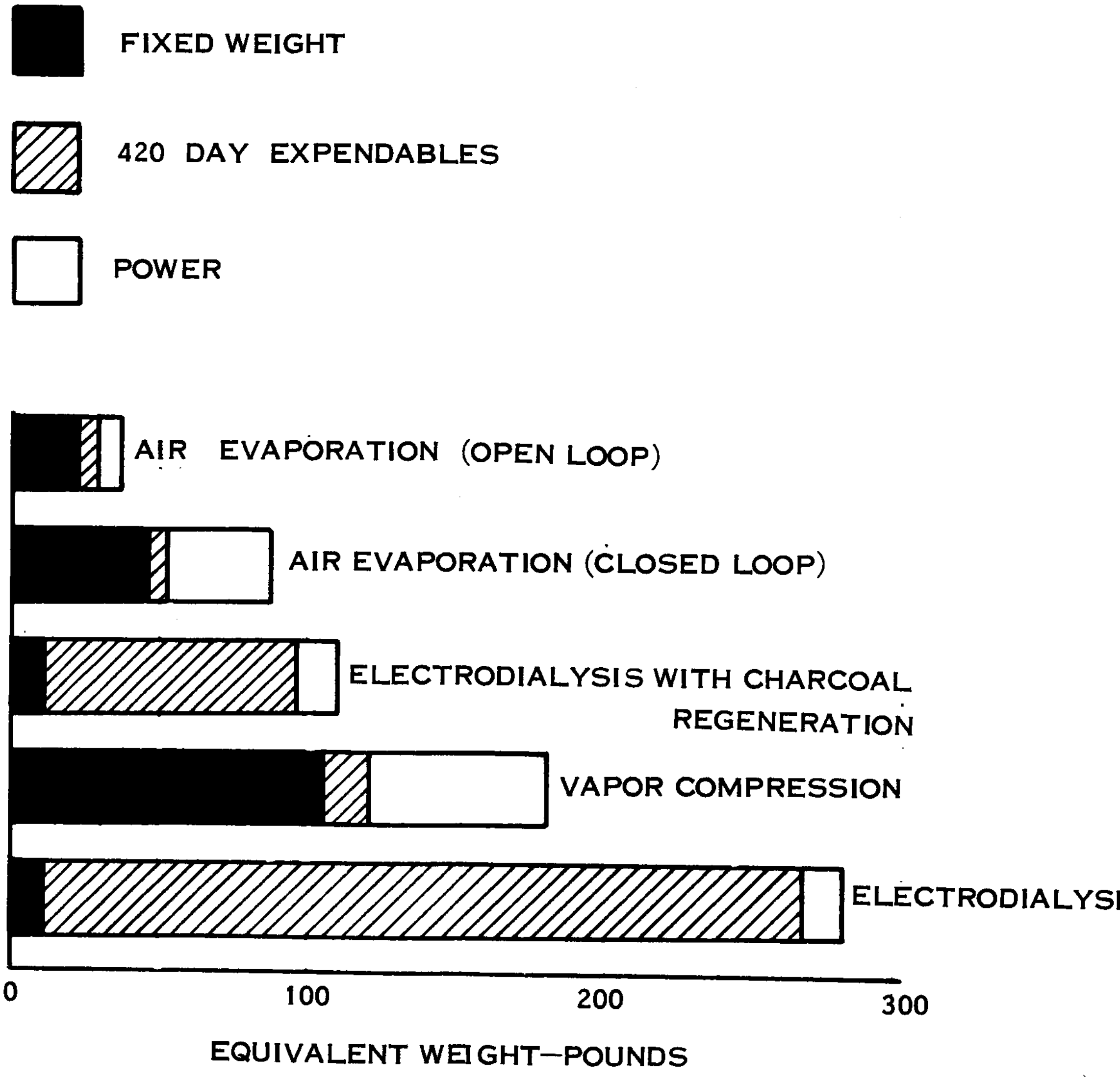
FIGURE 2–4

FIGURE 2–5

WATER RECLAMATION SUMMARY
WASH WATER

1) 6 MAN CREW AT 40 LBS / MAN DAY

2) POWER = 500 POUNDS / KILOWATT



3.0 STUDY PLAN AND SPECIFICATION REVIEW

3.1 Study Plan

This study of the Environmental Control and Life Support System for the Mars Landing and Reconnaissance Mission Vehicle was initiated on July 15, 1963. The study has been divided into two major phases: subsystem definition and system integration. Figure 3-1 presents the overall schedule for the study.

The subsystem definition phase consisted of investigation of a wide range of potential subsystem approaches, and preparation of parametric data for the most promising approaches. From this parametric data, a further selection can be made. Figure 3-2 presents the subsystem work schedule.

The system integration phase will combine the selected subsystems into an integrated system for each of the three modules of the Mars Vehicle. This phase is just beginning at the present time.

3.2 Specification Review

The subsystem analysis was intended to be general and useful throughout a wide range of life support requirements. However, it was necessary to establish requirements for the Mars mission to define the appropriate range of interest. Therefore, the specification shown on the following pages was established.

STUDY SCHEDULE

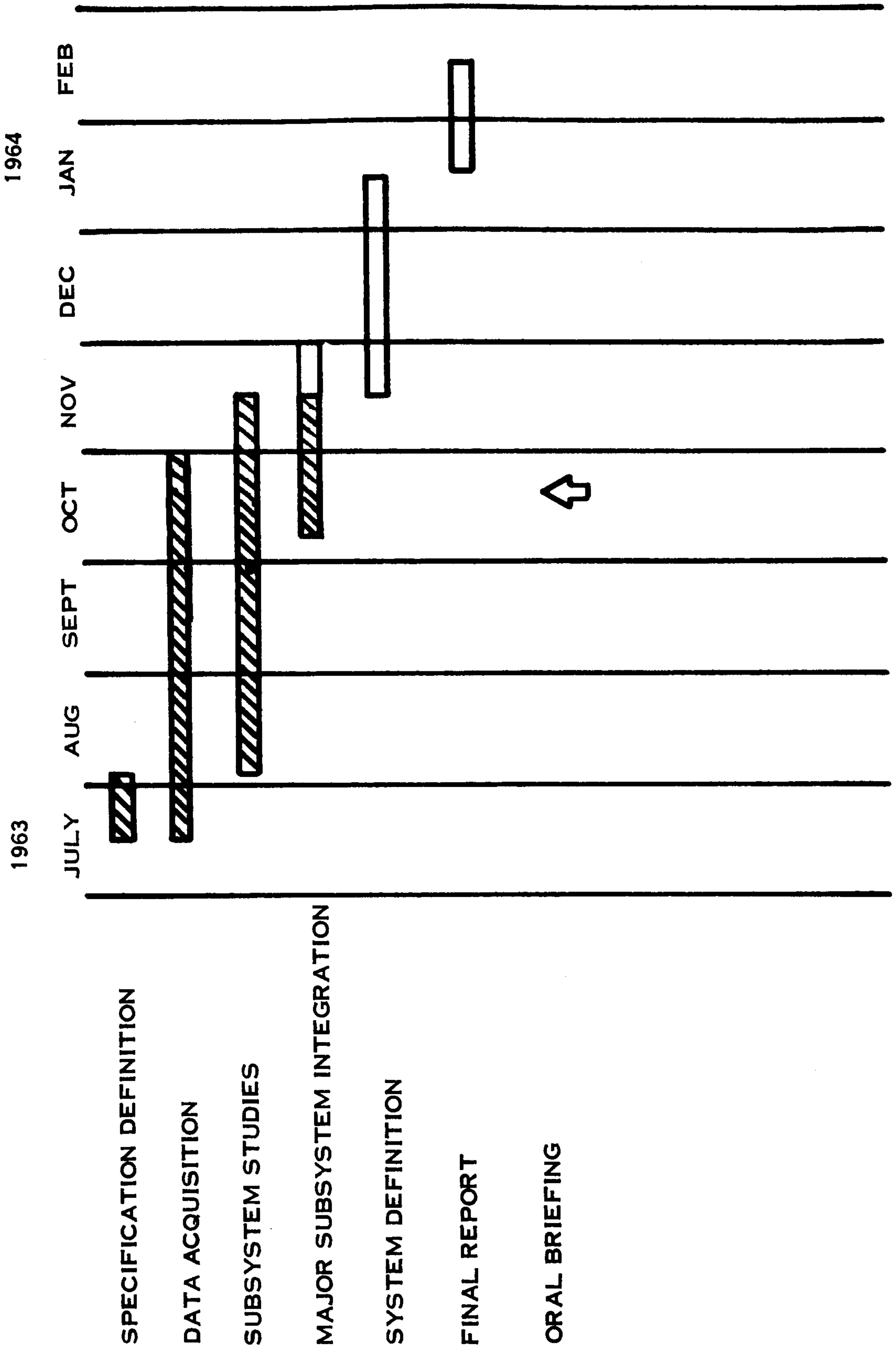


Figure 3-1

STUDY SCHEDULE

SUBSYSTEM DEFINITION PHASE

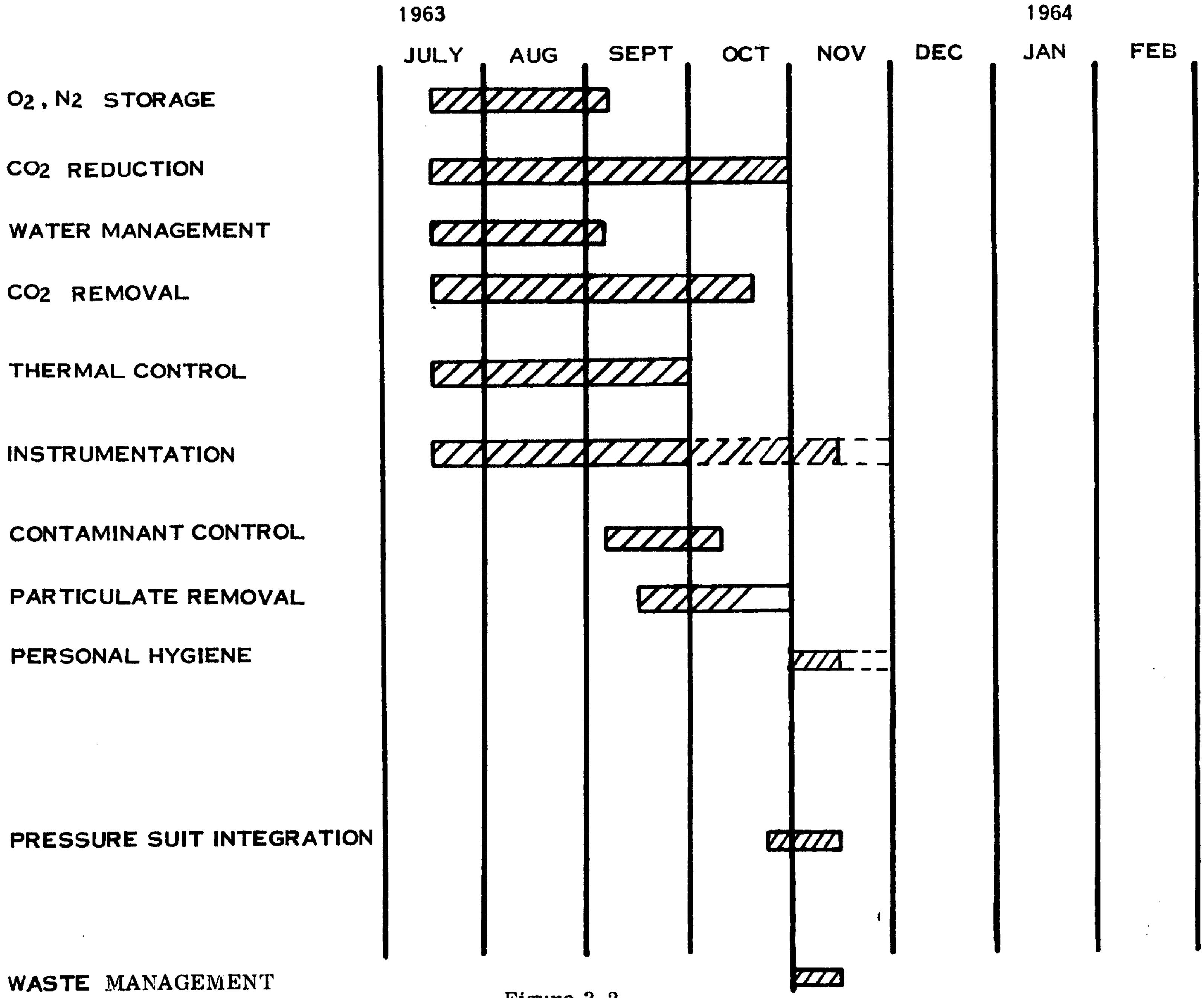


Figure 3-2

MARS STUDY SPECIFICATION

ITEM	DESCRIPTION
Vehicle Configuration	Three module vehicle - An earth re-entry module which will transfer the crew from earth to the orbiting ship and return the crew to earth at the end of the mission. A mission module which will carry the crew to Mars orbit and return them to earth orbit. A Mars excursion module which will land men on Mars for exploration and return them to the mission module which is in Mars orbit.
Flight Plan	a. Launch earth re-entry module into earth orbit to join with balance of ship in 12 hours. b. Transit to Mars in mission module about 120 days. c. MEM descent in 30 minutes. d. Mars stay time - 10 to 40 days. e. MEM return to mission module in 55 hours maximum. f. Transit from Mars to earth in mission module about 260 days. g. Return to earth in earth re-entry module about 3 hours.
Launch Date	About 1973
Crew Size	a. 6 men - earth entry module b. 6 men - mission module c. 2 men - Mars excursion module during Mars landing and stay d. 4 men - Mars excursion module during ascent and rendezvous with mission module.
Free Air Volume	a. ERM - 320 ft^3 b. MMM - 3000 ft^3 to 3500 ft^3 c. MEM - 1000 ft^3.
Vehicle Orientation	Vehicle will be sun oriented.

MARS STUDY SPECIFICATION
(Continued)

ITEM	DESCRIPTION	Mission Module	Earth Re-Entry and Mars Landing Module	Extra-Vehicular
Metabolic Data				
	1. O_2 Input (#/man-day)	1.84	2.21	3.6
	2. CO2 Output (#/man-day)	2.12	2.5	4.32
	3. Total Heat Output (BTU/man-day)	11,200	14,400	22,320
	a) Latent Heat			
	1) Lungs	2,800	4,800	5,520
	2) Sweat	0	0	12,840
	b) Sensible	8,400	9,600	3,960
	4. Water Balance			
	In			
	Food & Drink (gms/man-day)	2,800	3,600	9,120
	H_2O of oxidation (gms/man-day)	350	350	350
	Out			
	Urine (gms/man-day)	1,500	1,515	1,200
	Respiration (gms/man-day)	1,300	2,085	2,400
	Perspiration	0-300	0-300	5520-5820
	Fecal Water	50-350	50-350	50-350
	5. Wash Water 12-40 #/man-day (None in ERM)			
	Metabolic water of oxidation not available for reuse.			
	Wash contaminants to be based on Life Sciences Data Book.			
Cabin Pressure	Normal = 7 psia with pO_2 = 3.5 psia for all modules.			
Relative Humidity	35 to 70% (Controllable if possible)			

MARS STUDY SPECIFICATION
(Continued)

<table>
<tr><th>ITEM</th><th>DESCRIPTION</th></tr>
<tr><td>CO_2 Limits</td><td>Normal pCO_2 = 5.0 mm Hg; maximum pCO_2 = 7.6 mm Hg.</td></tr>
<tr><td>Temperature</td><td>65 to 75°F design point.</td></tr>
<tr><td>Thermal Loads (Watts)</td><td>
<table>
<tr><th></th><th>ERM</th><th>MMM</th><th>MEM</th></tr>
<tr><td>Communication</td><td>500</td><td>2,900</td><td>1,345</td></tr>
<tr><td>ECS</td><td>300</td><td>4,600</td><td>290</td></tr>
<tr><td>Instrumentation</td><td>240</td><td>830</td><td>565</td></tr>
<tr><td>Control and Guidance</td><td>200</td><td>500</td><td>800</td></tr>
<tr><td>Scientific</td><td>---</td><td>300</td><td>300</td></tr>
<tr><td>Subtotal</td><td>1,240</td><td>9,130</td><td>3,300</td></tr>
<tr><td>20% Contingency</td><td>248</td><td>1,826</td><td>660</td></tr>
<tr><td>Total</td><td>1,488</td><td>10,956</td><td>3,960</td></tr>
</table>
</td></tr>
<tr><td>Airlock Operations</td><td>A trade-off study is to be made comparing vacuum pumps with stored supplies. The airlock on the mission module will be operated 25 times and the airlock on the excursion module will operate 100 times.</td></tr>
<tr><td>Power Supply</td><td>a. Earth Re-entry Module - APU
b. Mission Module - Combination of nuclear and solar
c. Mars Excursion Module - Nuclear</td></tr>
<tr><td>Food Supply</td><td>To be assumed dehydrated.</td></tr>
<tr><td>Air Circulation</td><td>Sufficient flow for crew comfort shall be provided.</td></tr>
<tr><td>Areas of Study</td><td>Specifically, requirements will be established for the entire environmental control systems which include the following subsystems and functional areas:
1. Atmospheric Supply
a. Storage
b. Reclamation</td></tr>
</table>

MARS STUDY SPECIFICATION
(Continued)

ITEM	DESCRIPTION
Areas of Study (Cont.)	2. Atmospheric Conditioning a. Circulation, humidity control, particulate removal b. Carbon dioxide control c. Contaminant control 3. Thermal Control a. Radiation to space b. Evaporative cooling c. Convective cooling to Mars atmosphere 4. Controls and Instrumentation a. Cabin pressure b. Oxygen partial pressure c. Carbon dioxide partial pressure d. Temperature e. Humidity f. Atmospheric Composition analyzer 5. Water Management a. Waste water reclamation b. Water dissociation (to reclaim oxygen) c. Atmospheric water collection 6. Waste Management (solid) a. Storage b. Disposal c. Reclamation 7. Pressure Suit Integration a. Complete integration b. Partial integration c. Independent systems 8. Personal Hygiene a. Wet bath b. Impregnated cloths c. Oral hygiene d. Shaving e. Barbering

MARS STUDY SPECIFICATION
(Continued)

ITEM	DESCRIPTION
Areas of Study (Cont.)	9. Maintenance a. Spares b. Commonality of components c. Commonality of functions d. Scheduled maintenance shutdowns
Leakage	a. Earth Re-entry Module ----- .2 #/hr b. Mission Module ------------- .1 #/hr c. Mars Excursion Module ----- .2 #/hr
Thermal Control Limits	Maximum liquid cooled electronic temperatures = 160°F. Liquid cool as much equipment as possible.
Repressurizations	a. Earth Re-entry Module ------ 1 b. Mission Module ------------ 3 c. Mars Excursion Module ------ 1
Contaminant Production Rates	HSD to determine from literature and past experience. Inputs from other studies on vehicle equopment rates will be requested.
Space Cleanliness Requirements	Any gases may be dumped to space (i.e. feces desorption, charcoal regeneration). Solids should not be dumped.
PLSS Mission Schedule	a. Earth Re-entry Module -------- 6 charges b. Mission Module ------------- 12 charges c. Mars Excursion Module ------- 80 charges Each charge shall support one man for 4 hours.
Access Door Dimensions	To come from vehicle studies. Present guidelines are a maximum diameter of 36" for equipment.

MARS STUDY SPECIFICATION
(Continued)

ITEM	DESCRIPTION
Heat Leakages	To be determined by HSD from vehicle drawings or obtained from vehicle study contractors.
Radiator Area	Assume the entire vehicle skin available until vehicle studies dictate otherwise.
Gravity Environment	All components must operate with zero gravity.

4.0 ATMOSPHERIC SUPPLY

4.1 Oxygen and Nitrogen Storage

4.1.1 Objectives

The subsystem analysis of atmospheric storage methods was conducted to provide sufficient data input to the system integration phase in the area of atmospheric supply. In this phase the carbon dioxide removal and reduction subsystems will be combined with the atmospheric storage tanks to provide atmospheric supply throughout the mission. 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 useable form to eliminate the need for sizing calculations for each step in the later integration studies. Thus, the desirable points are presentations of stored fluid tankage weights as a function of the useful fluid and investigation of the effect on this parameter 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. 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.

4.1.2 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 tankage weight as a function of useful fluid weight. Thus, upon determination of the desired fluid quantity to be stored, the tankage or storage weight associated with this can be determined.

4.1.2 (Continued)

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.

4.1.3 Cryogenic Storage

4.1.3.1 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, 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, it was felt that contact with each of them was not required at this phase in the study, since variation of the generalized design data is not great between suppliers. In addition, 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 4-1 illustrates a typical operation of a supercritical storage system on a pressure-enthalpy diagram. Spherical tanks, as shown in Figure 4-2, 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 in the tank, although temperature and, therefore, density gradients will exist within the 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
AVERAGE PATH FOLLOWED BY THE FLUID

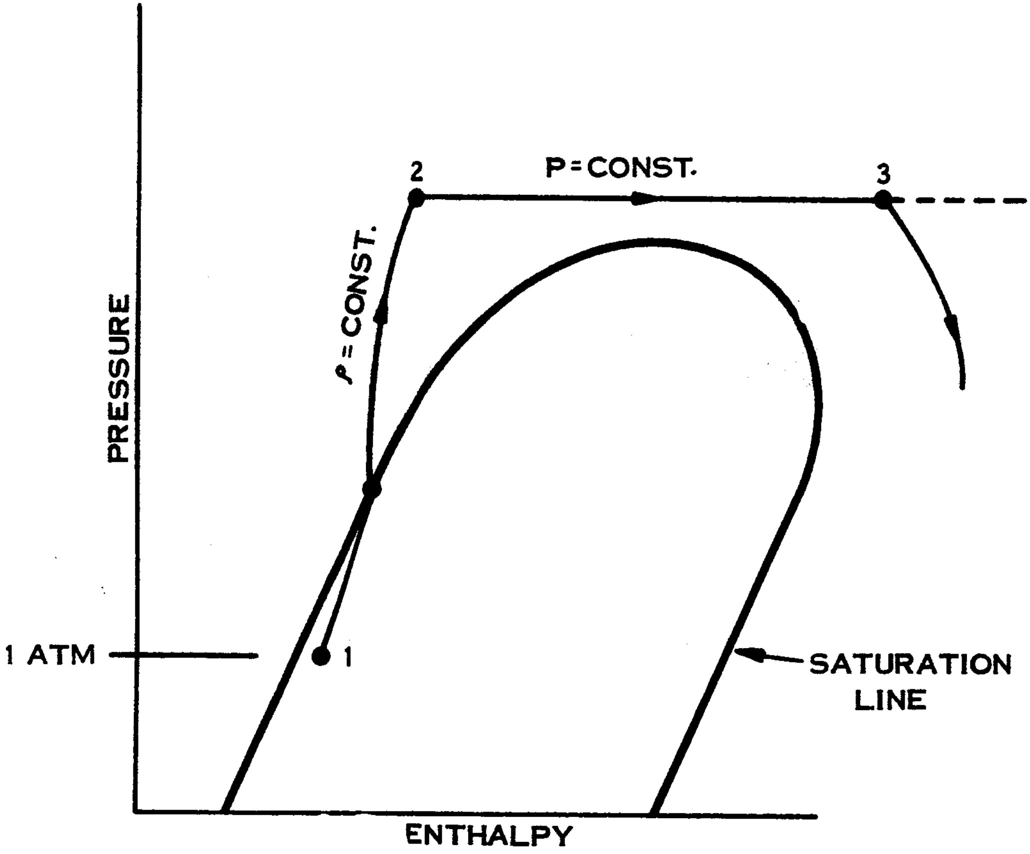


FIGURE 4-1

SUPERCRITICAL STORAGE TANK CONFIGURATION

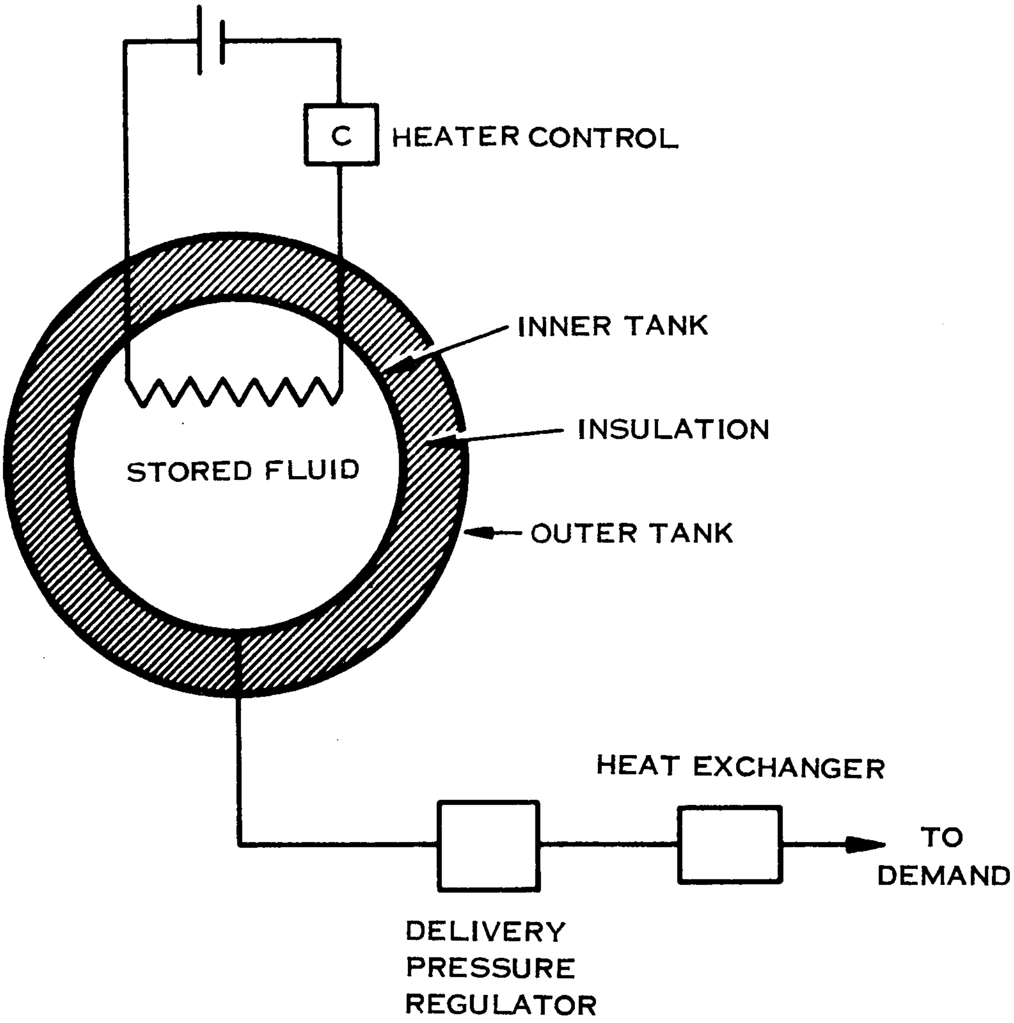


FIGURE 4-2

4.1.3.1 (Continued)

Figure 4-3 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 dependent upon the operating pressure and the fluid density. Figure 4-4 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.

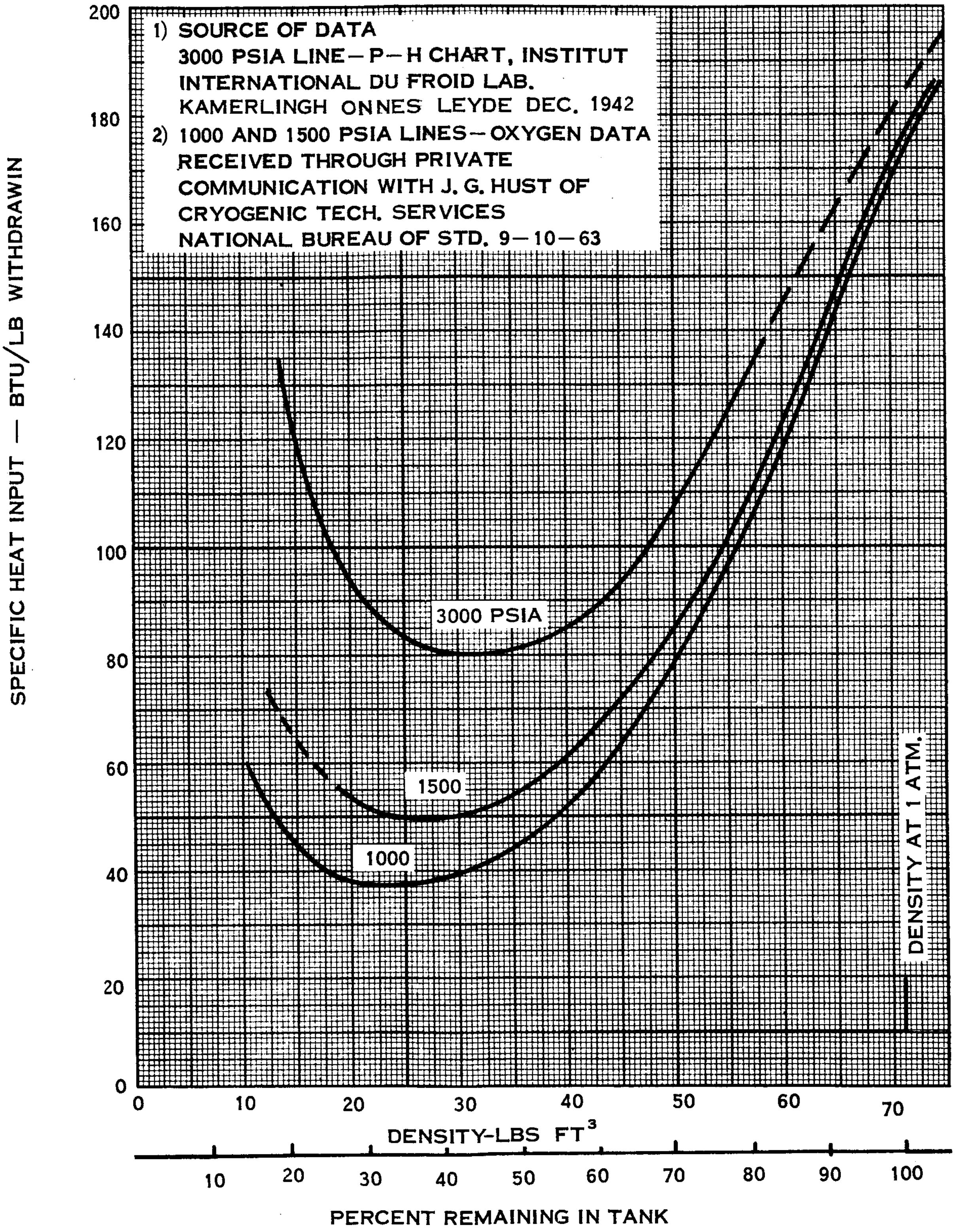
The schematic presents the storage system only to the point of the initial pressure regulating valve. In actuality, atmospheric storage is controlled by a demand system within the overall life support system pressure control equipment. Upon demand from this equipment and its associated sensors, the fluid 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 light weight containers. The system reliability may be somewhat lower than a simple gas system with an inflow valve, however, weight savings are considerable 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.

4.1.3.2 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 4-5, 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.

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



1) SOURCE OF DATA
3000 PSIA LINE – P–H CHART, INSTITUT INTERNATIONAL DU FROID LAB. KAMERLINGH ONNES LEYDE DEC. 1942

2) 1000 AND 1500 PSIA LINES – OXYGEN DATA RECEIVED THROUGH PRIVATE COMMUNICATION WITH J. G. HUST OF CRYOGENIC TECH. SERVICES NATIONAL BUREAU OF STD. 9–10–63

FIGURE 4-3

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

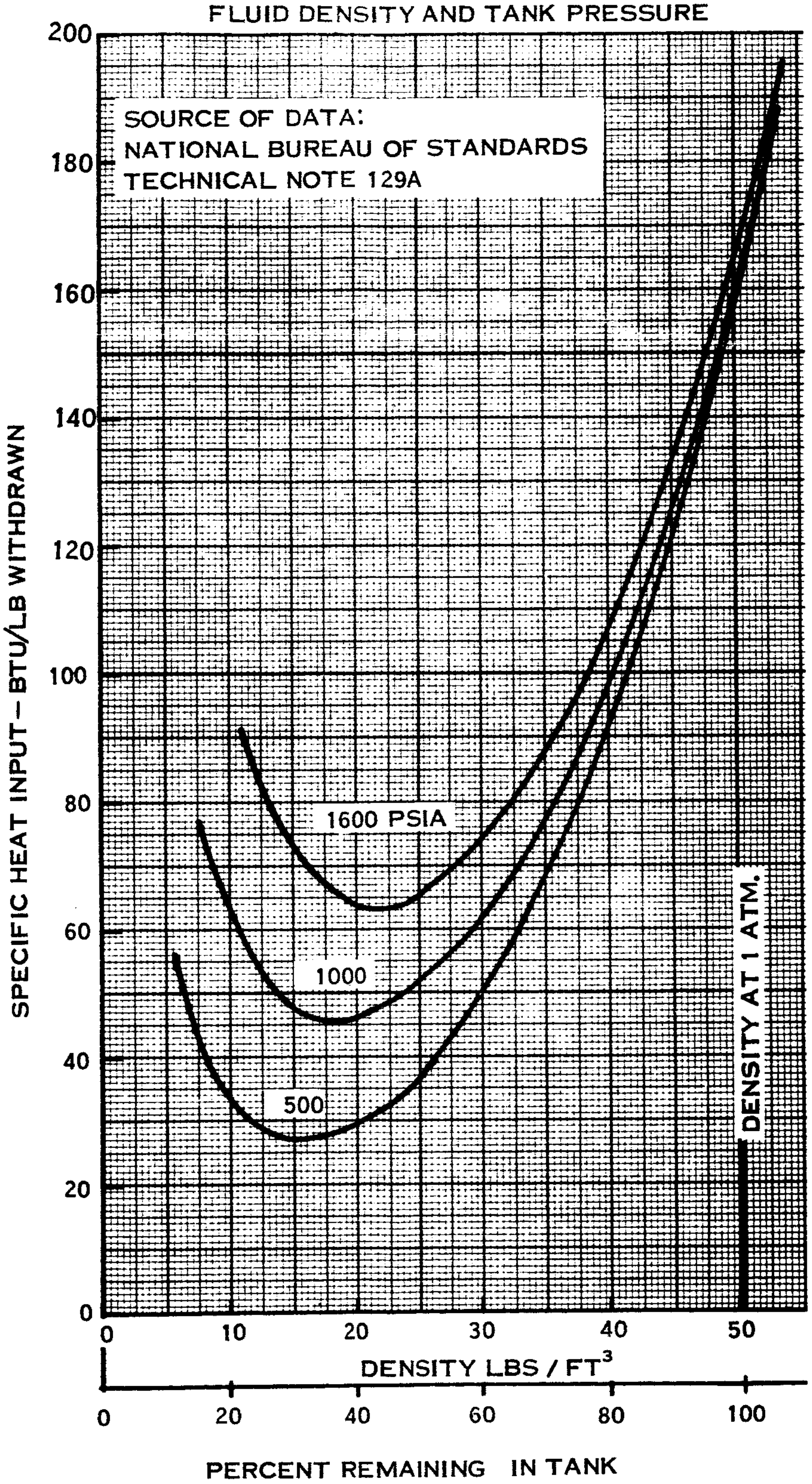


FIGURE 4-4

SUBCRITICAL STORAGE
AVERAGE PATH FOLLOWED BY THE FLUID

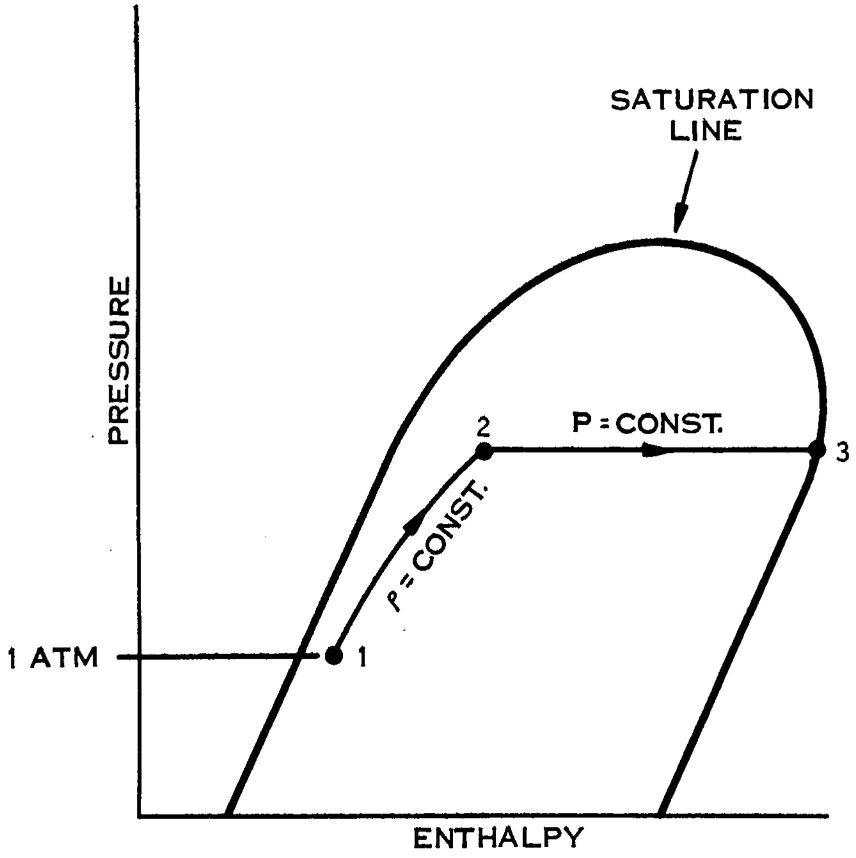


FIGURE 4-5

4.1.3.2 (Continued)

The storage tank is partially filled at a pressure of one atmosphere and sealed at point one 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 4-6 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.

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 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

SUBCRITICAL STORAGE SYSTEM SCHEMATIC

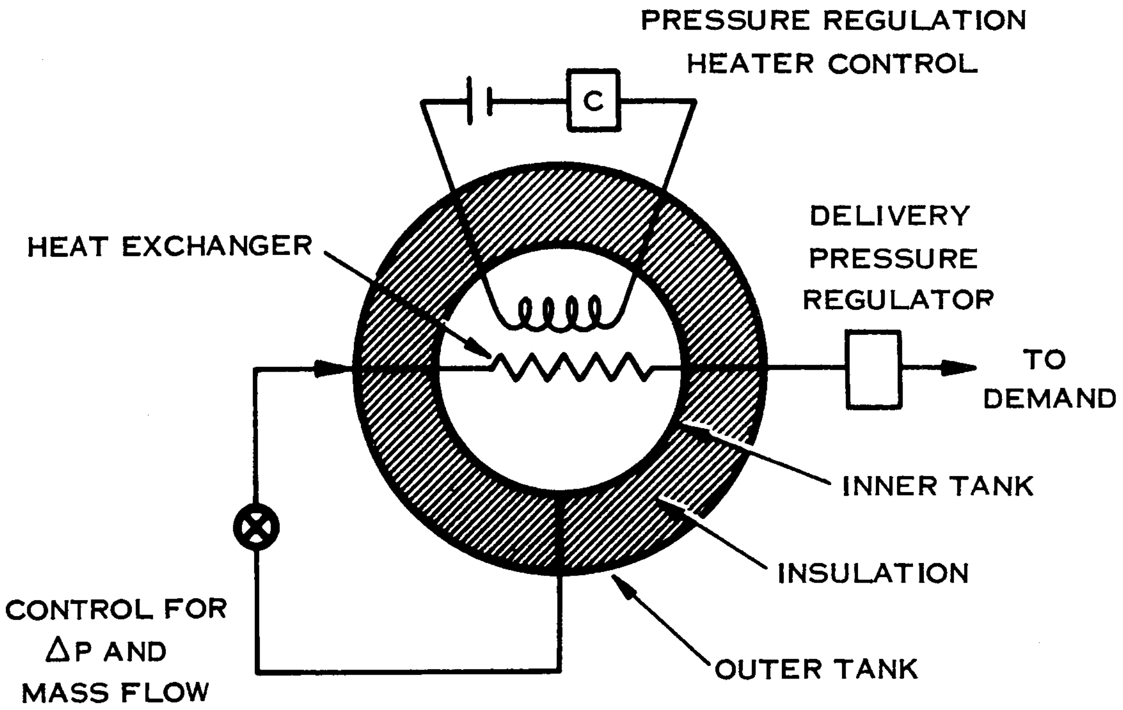


FIGURE 4-6

4.1.3.2 (Continued)

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.

4.1.3.3 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 4-7 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 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 4-8 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.

POSITIVE EXPULSION CRYOGENIC STORAGE SYSTEM SCHEMATIC

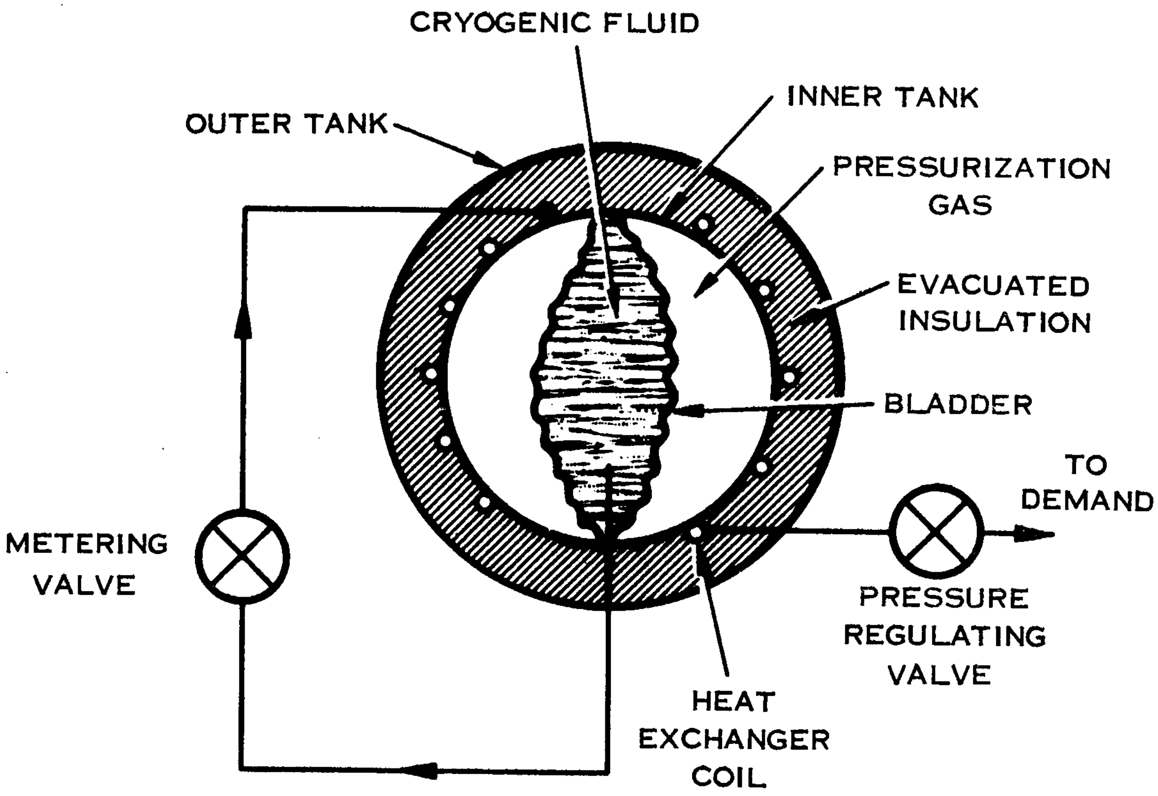


FIGURE 4-7

POSITIVE EXPULSION CRYOGENIC STORAGE
AVERAGE PATH FOLLOWED BY FLUID

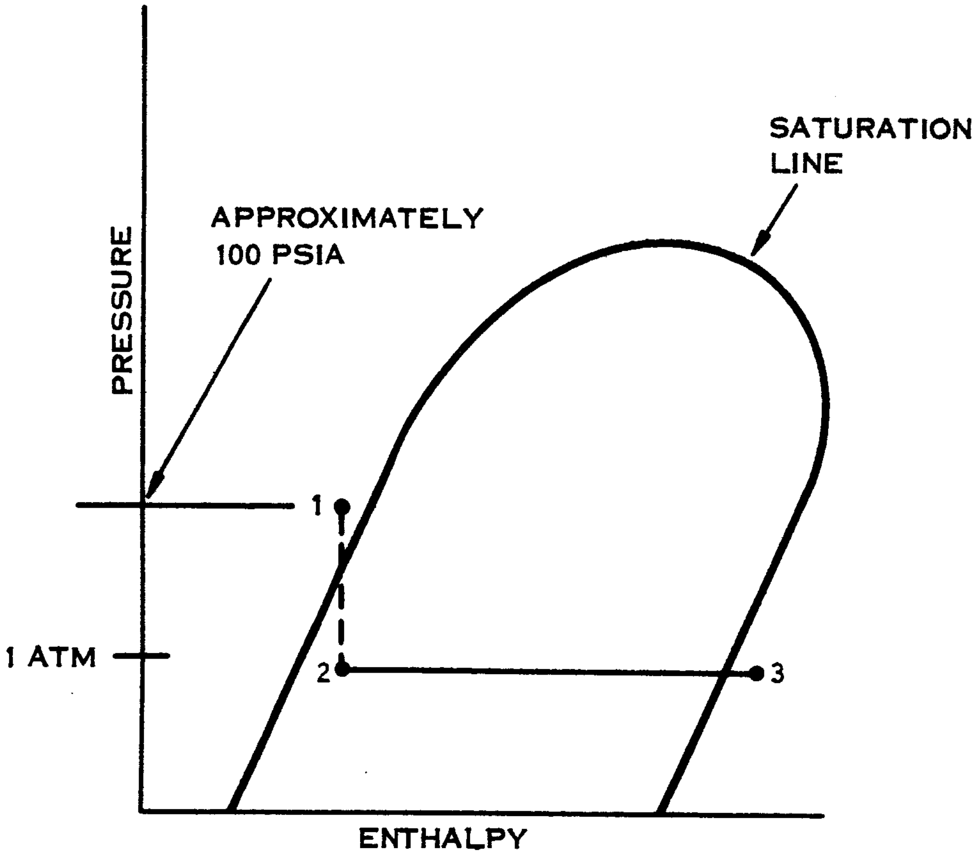


FIGURE 4-8

4.1.3.3 (Continued)

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.

4.1.3.4 Results

The data associated with the supercritical and subcritical storage systems is presented in the following pages. Certain major assumptions associated with the preparation of the data will be repeated here to be applied to most of the curves for overall understanding.

1. System tankage will be designed to eliminate venting for pressure control.
2. The 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 x 10^{-5} BTU per. ft. degree ranking.
3. The 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 common basis for comparative data, 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 4-2 and 4-6.

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 4-9 presents the results of the analysis of total system weight vs. usable fluid weight for cryogenic oxygen. The range shown was considered adequate for the range of storage requirements in this study because as the tank size becomes larger, it becomes advantageous to use several tanks.

CRYOGENIC O_2 STORAGE

TOTAL SYSTEM WEIGHT VS. FLUID RATE

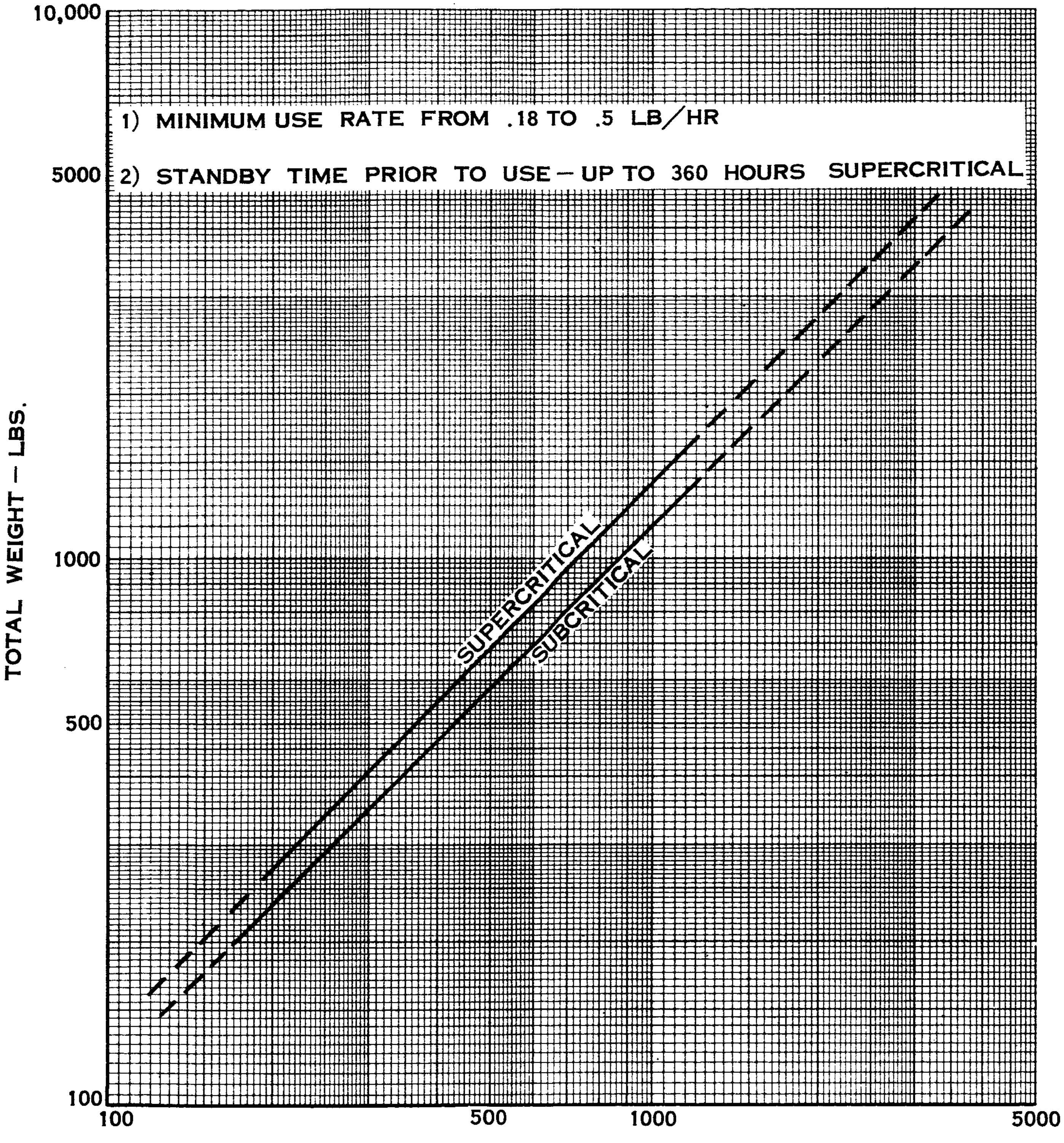


FIGURE 4–9

4.1.3.4 (Continued)

Figure 4-10 presents the same results for oxygen for the MEM where there is a 120 day hold time. This curve shows that even with the 120 day hold time the subcritical system weighs less than either the supercritical or gaseous storage.

Figure 4-11 presents the total weight of a subcritical storage system for nitrogen as a function of useable fluid weight and minimum use rate. It can be seen that as the minimum use rate decreases, the heat leakage through the supports and insulation becomes a very important factor in the weight. This same trend is shown on Figure 4-12 for a supercritical storage system. A comparison of the two methods is shown on Figure 4-13.

The heaters shown in the schematics are for pressure control within the tank. It is expected that these heaters will be heat exchangers which will utilize waste heat to evaporate the fluid. Thus, no power penalty has been added to any of these curves.

4.1.4 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 instanteous and rapid use, repressurization requirements may well be accomplished by gaseous storage. It is too premature in the study to make a firm selection, however, since gaseous storage is a potential candidate, some analysis was done at this time to simplify the problem at a later date.

Gaseous storage is also being considered for the Earth Re-entry Module and the return portion of the Excursion Module. In these cases the quantity of gas to be stored is not large and the added reliability may off set the weight of the storage technique.

Figure 4-14 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 4-15 presents the same comparison 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,

OXYGEN STORAGE FOR MEM
120 DAY HELD TIME

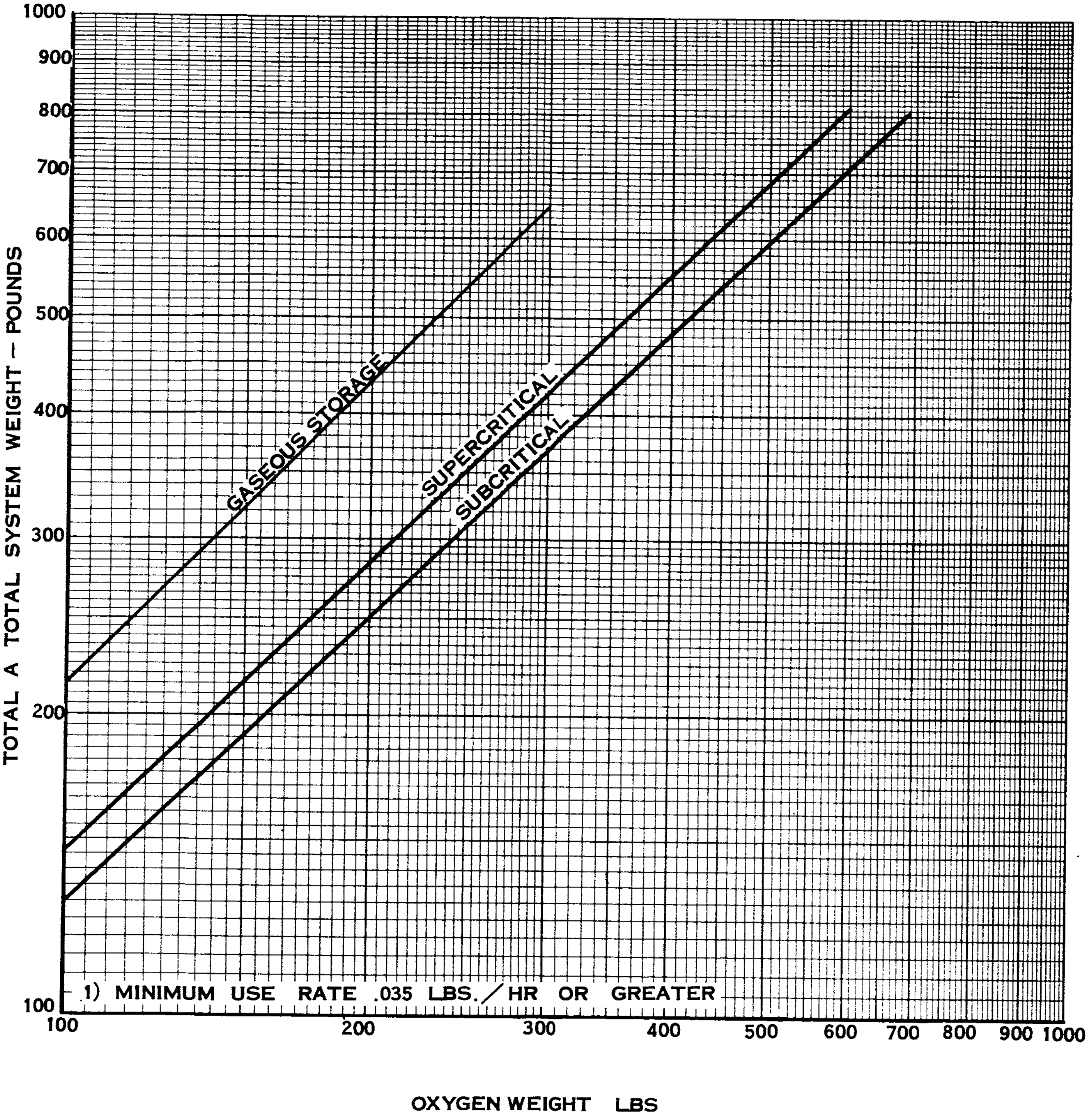


FIGURE 4 — 10

SUBCRITICAL N_2 STORAGE
TOTAL SYSTEM WEIGHT VS FLUID WEIGHT

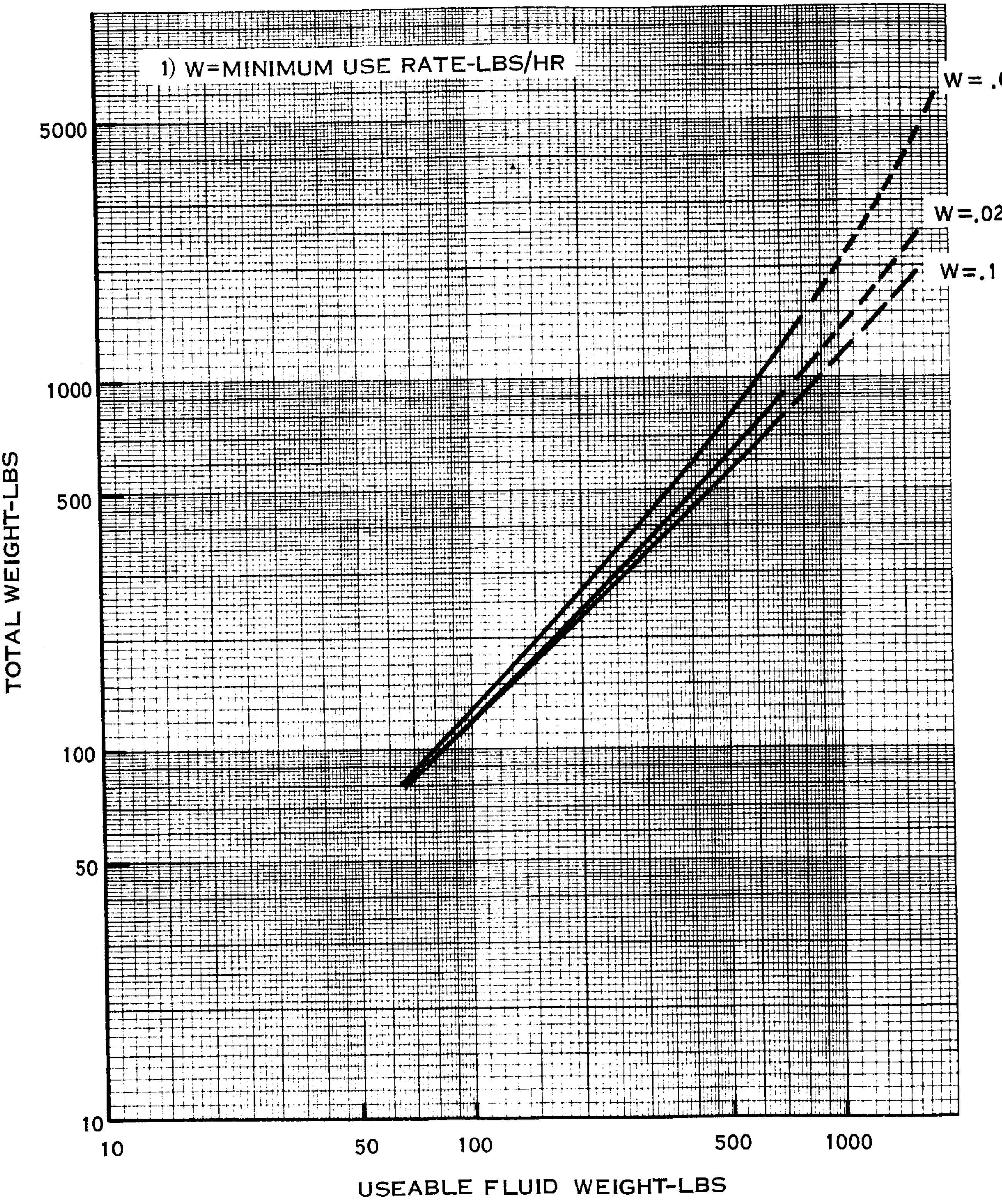


FIGURE 4-11

SUPERCRITICAL N_2 STORAGE
TOTAL SYSTEM WEIGHT VS FLUID WEIGHT

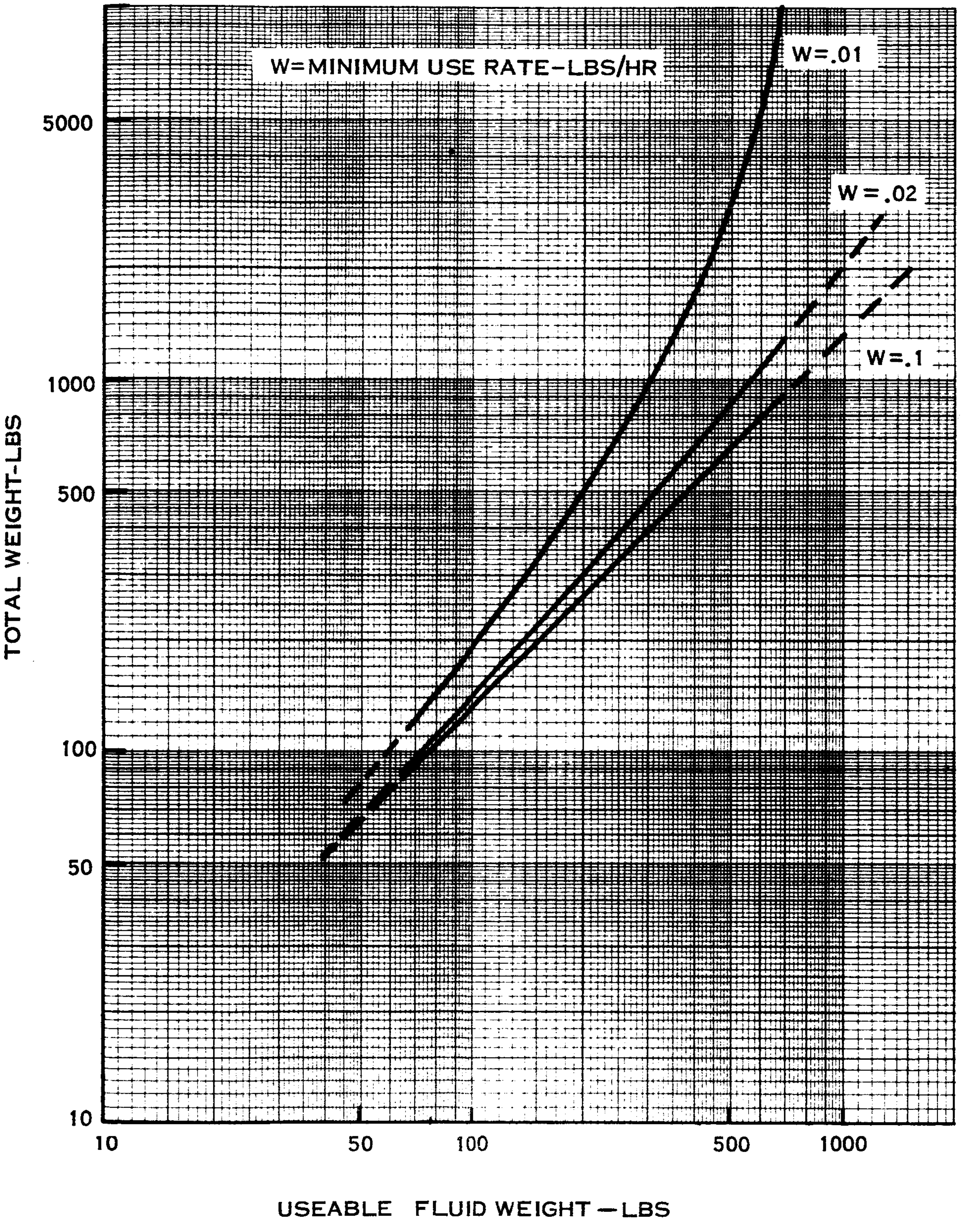
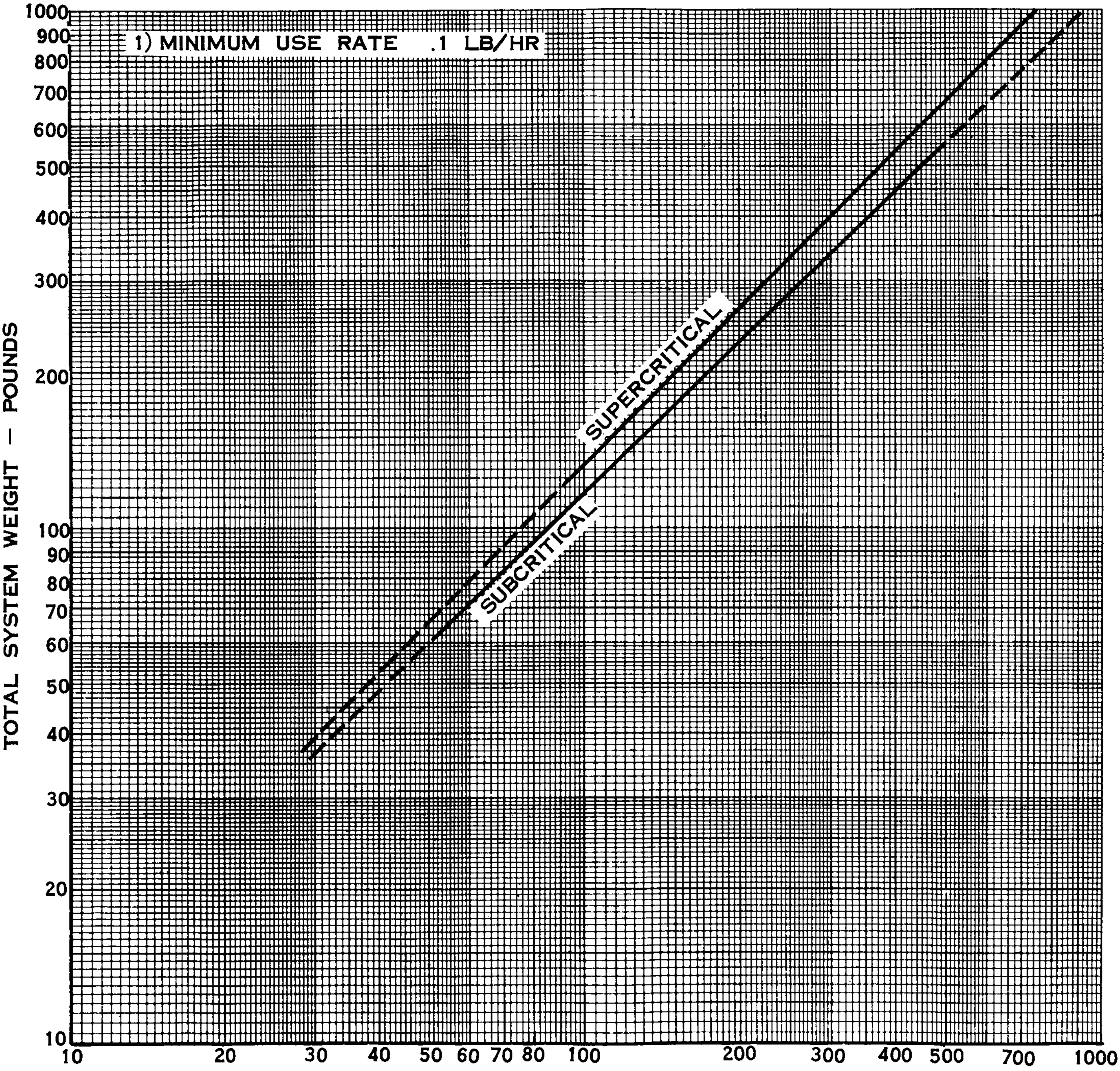


FIGURE 4-12

CRYOGENIC N_2 STORAGE

TOTAL SYSTEM WEIGHT VS. USEFUL FLUID WEIGHT



USEFUL FLUID WEIGHT — POUNDS

FIGURE 4—13

GASEOUS STORAGE
NITROGEN TANKAGE DETERMINATION

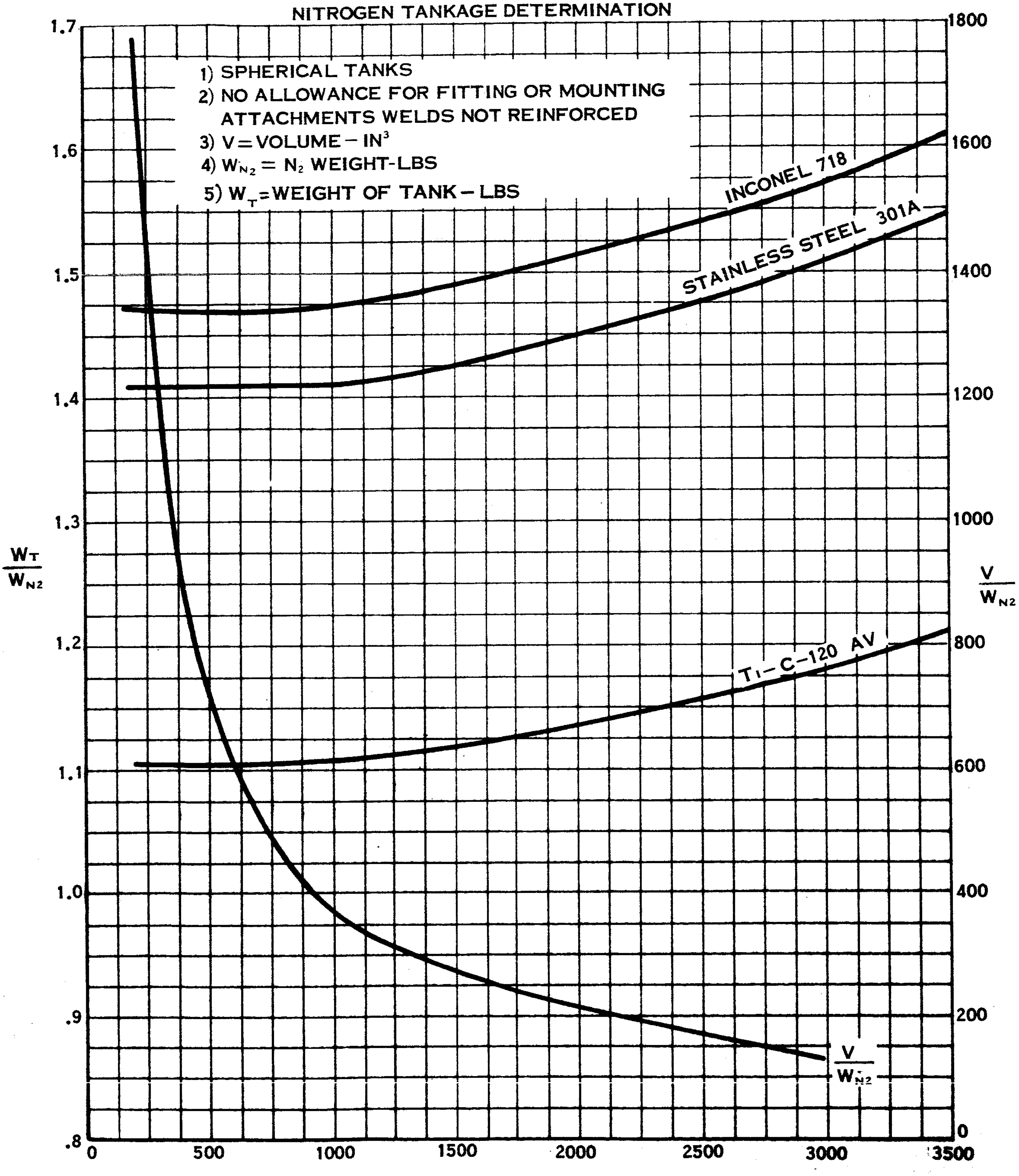


FIGURE 4-14

GASEOUS STORAGE
OXYGEN TANKAGE DETERMINATION

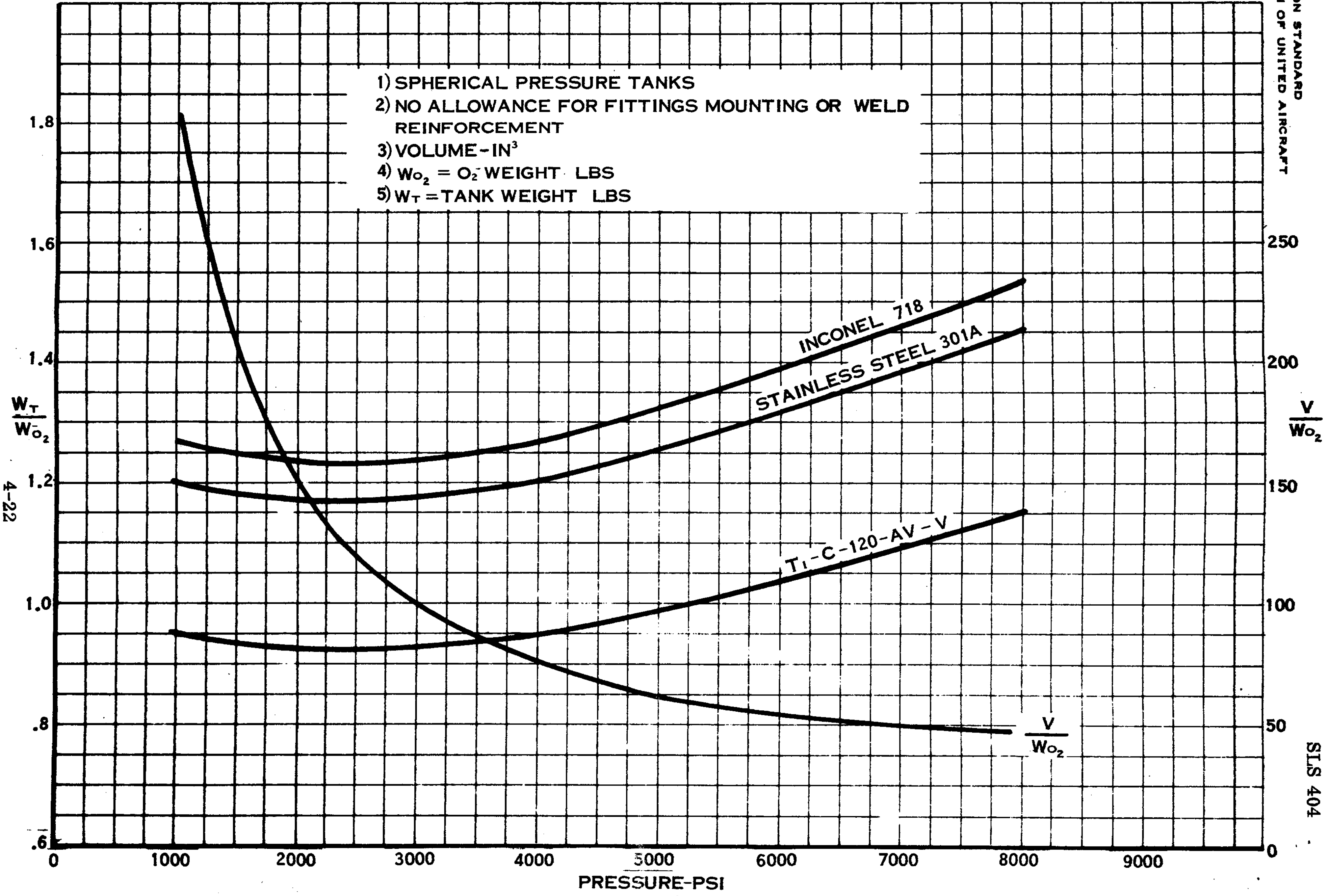


FIGURE 4-15

4.1.4 (Continued)

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 compatability of titanium and high pressure oxygen.

Figure 4-16 and 4-17 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 4-14 and 4-15.

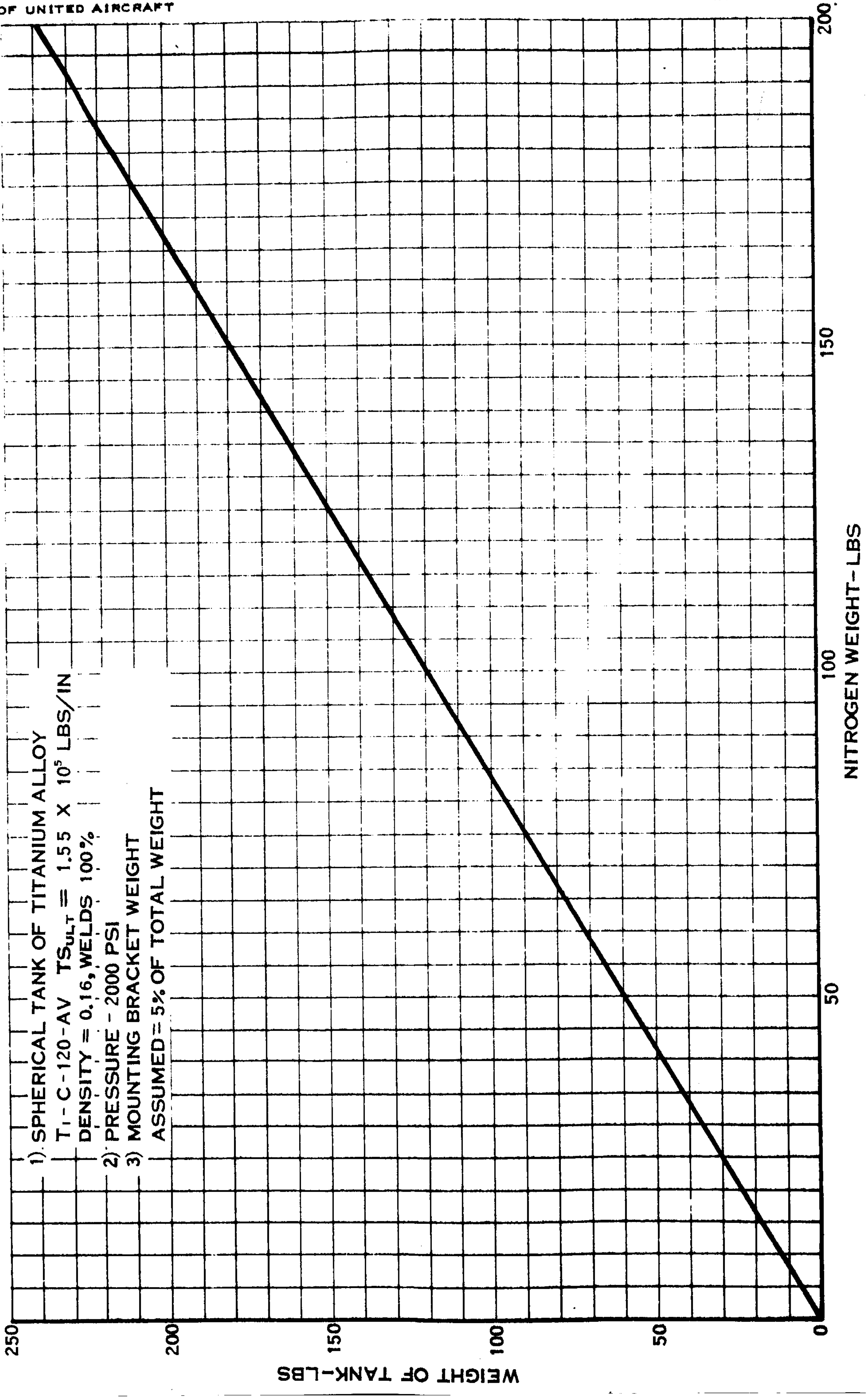
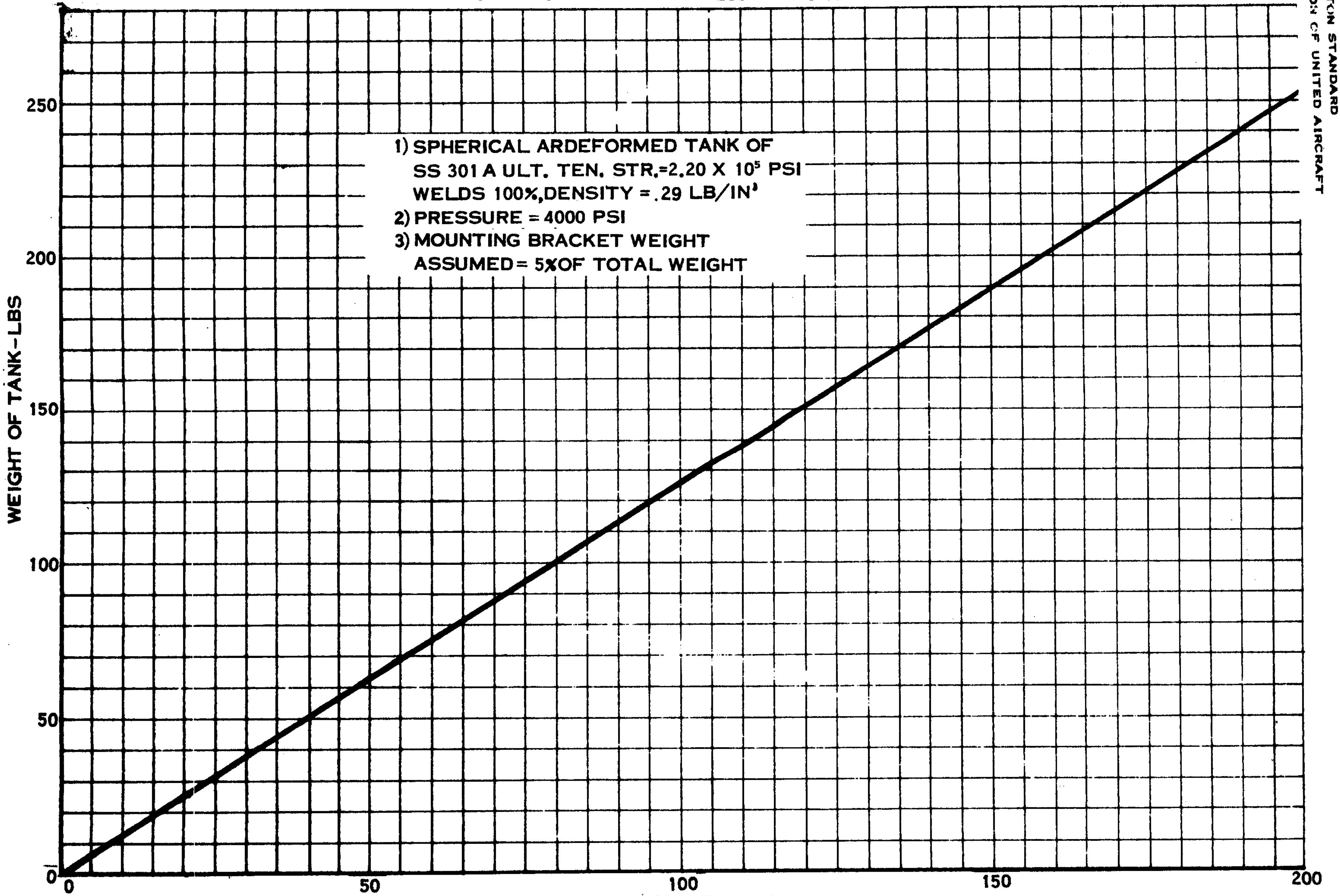

GASEOUS N₂ STORAGE
TANKAGE WEIGHT VS FLUID WEIGHT
1) SPHERICAL TANK OF TITANIUM ALLOY
TI-C-120-AV TS_ULT = 1.55 X 10^5 LBS/IN
DENSITY = 0.16, WELDS 100%
2) PRESSURE - 2000 PSI
3) MOUNTING BRACKET WEIGHT
ASSUMED = 5% OF TOTAL WEIGHT
0
50
100
150
200
250
WEIGHT OF TANK-LBS
0
50
100
150
200
NITROGEN WEIGHT-LBS

FIGURE 4-16

GASEOUS O_2 STORAGE
TANKAGE WEIGHT VS FLUID WEIGHT



1) SPHERICAL ARDEFORMED TANK OF
SS 301 A ULT. TEN. STR.=2.20 X 10^5 PSI
WELDS 100%,DENSITY = .29 LB/IN^3
2) PRESSURE = 4000 PSI
3) MOUNTING BRACKET WEIGHT
ASSUMED= 5%OF TOTAL WEIGHT

FIGURE 4-17

4.2 Oxygen Recovery

4.2.1 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 story, 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 studied 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 4.3 of this report.

This section also presents the results of the early phases of the transfer system study to illustrate the relative penalties associated with the integration of CO_2 removal and reduction. For comparative purposes, three of the candidate CO_2 removal systems were considered. At this point in the study, consideration of the potential system integration advantages for CO_2 removal equipment were also considered to provide a more realistic penalty approximation.

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. The sizing characteristics presented to-date illustrate the gross penalty of the reduction systems and, although close to the final penalties, may change somewhat when the removal and transfer systems are integrated into the overall study during major subsystem integration.

4.2.2 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. As previously mentioned, 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.

4.2.3 CO_2 Decomposition Using Radiation

A brief review of the state-of-the-art for this type of system was conducted to determine applicability to Mars requirements. There is not enough data available to allow a parametric presentation of this approach, and it does 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.

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:

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

$$2NO_2 + 2O = 2NO + 2O_2 \qquad (2)$$

$$2NO + O_2 = 2NO_2 \qquad (3)$$

The sum of the above equations then yields:

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

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. $C_x O_y$) 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 reductor.

The radiator 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.

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 result in a CO^{60} source of 73 kilocuries. In actuality, it is

4.2.3 (Continued)

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.

One possibility would be the use of an oxygen concentration cell such as the solid electrolyte being developed by Isomet. Since the theoretical voltage requirements of such a unit are proportional to the log of the pressure ratio, the higher oxygen concentration from the radiation unit would reduce the theoretical power to a small value. Further, the higher oxygen concentration would serve to minimize the problem of oxygen contamination in the CO_2 supply. There may also be regenerative chemical techniques for recovering oxygen from the reactor product stream but none are immediately obvious at this time. Any system proposed must present a barrier to contaminants such as carbon dioxide.

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 large amount of CO to the cabin in the event of some component failure.

At present, no experimental work has been done on radiation reduction systems operating under ECS conditions, however, if further development can achieve a solution to the major problems mentioned, the use of a radiation unit in conjunction with a solid electrolyte could result in a reduction in the oxygen contamination of the CO_2 feed stream problem, and significant decrease in the theoretical power requirements of the concentration cell.

4.2.4 Bosch CO_2 Reduction System

4.2.4.1 Introduction and Data Source

The Bosch 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 form water and carbon as follows:

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

4.2.4.1 (Continued)

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. Predicted catalyst usage is about 1 pound of catalyst per 10 pounds of carbon formed. 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.

4.2.4.2 System Description

Figure 4-201 illustrates the MRD approach to this system and Figure 4-202 is the TAPCO system. Comparison of the two indicates that the basic components are similar but TAPCO includes carbon removal equipment which enables them 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 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 over the iron catalyst in the reactor presents a development problem in this type of system. MRD and TAPCO have attacked the problem in slightly different

BOSCH REACTION CO_2 REDUCTION SYSTEM

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

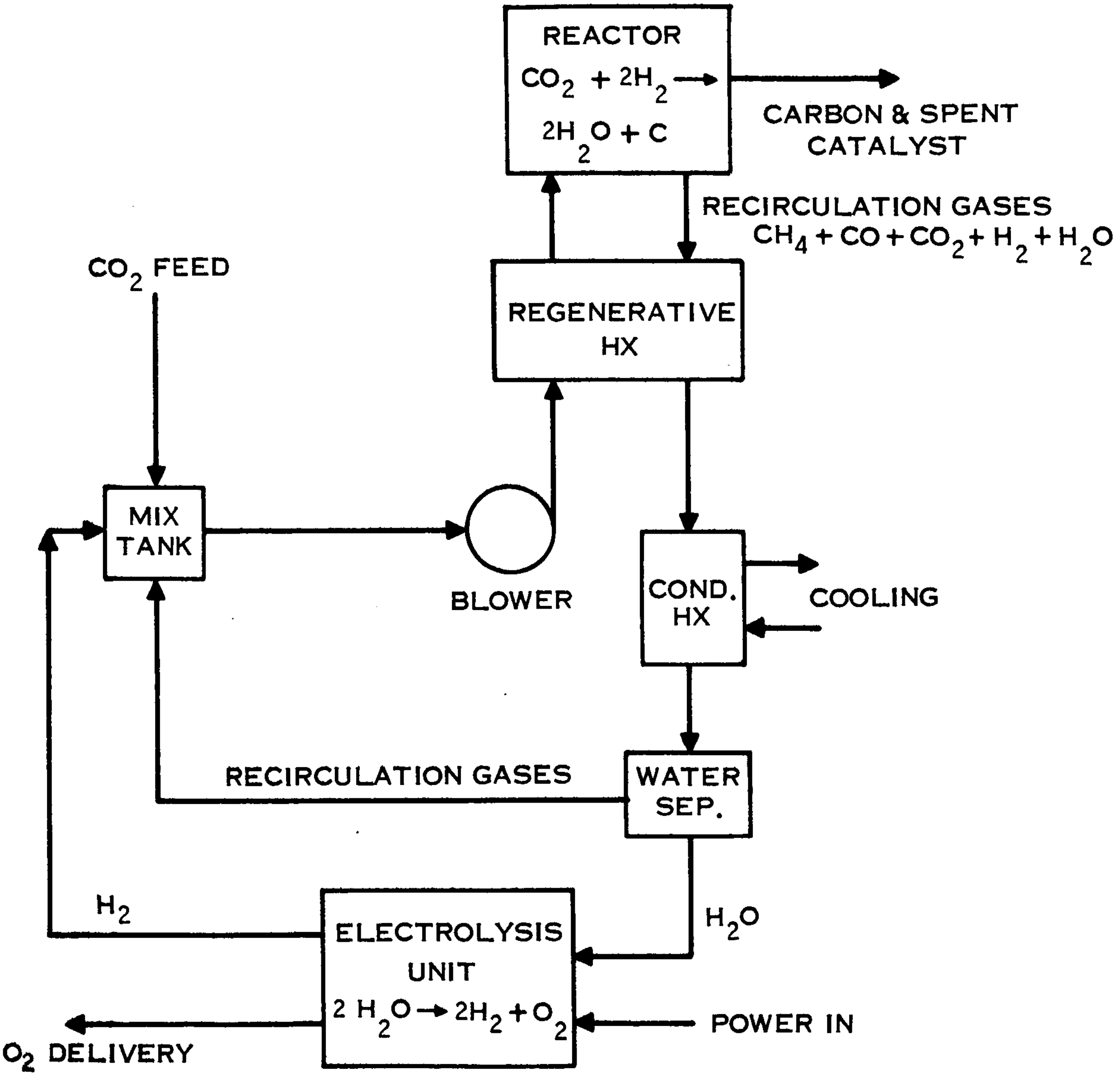


FIGURE 4-201

4.2.4.2 (Continued)

ways. 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 (use of 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 4-202) 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.

4.2.4.3 Conclusions

The Bosch reaction system is one of the heaviest (in equivalent weight) of the candidate systems, but remains of interest since the reaction producing water may be accomplished in one step. A potential savings in weight and power consumption exist because:

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.

4.2.5 Methoxy CO_2 Reduction System With Acetylene Dump

4.2.5.1 Introduction and Data Source

The Sabatier chemical reaction, also called methanization, and the Methoxy reaction

HYDROGENATION CO_2 REDUCTION SYSTEM

REFERENCE :(TAPCO DIVISION – THOMPSON RAMO WOOLRIDGE)

NOTE :

RECIRCULATION GASES ARE CH_4, CO, CO_2, & H_2

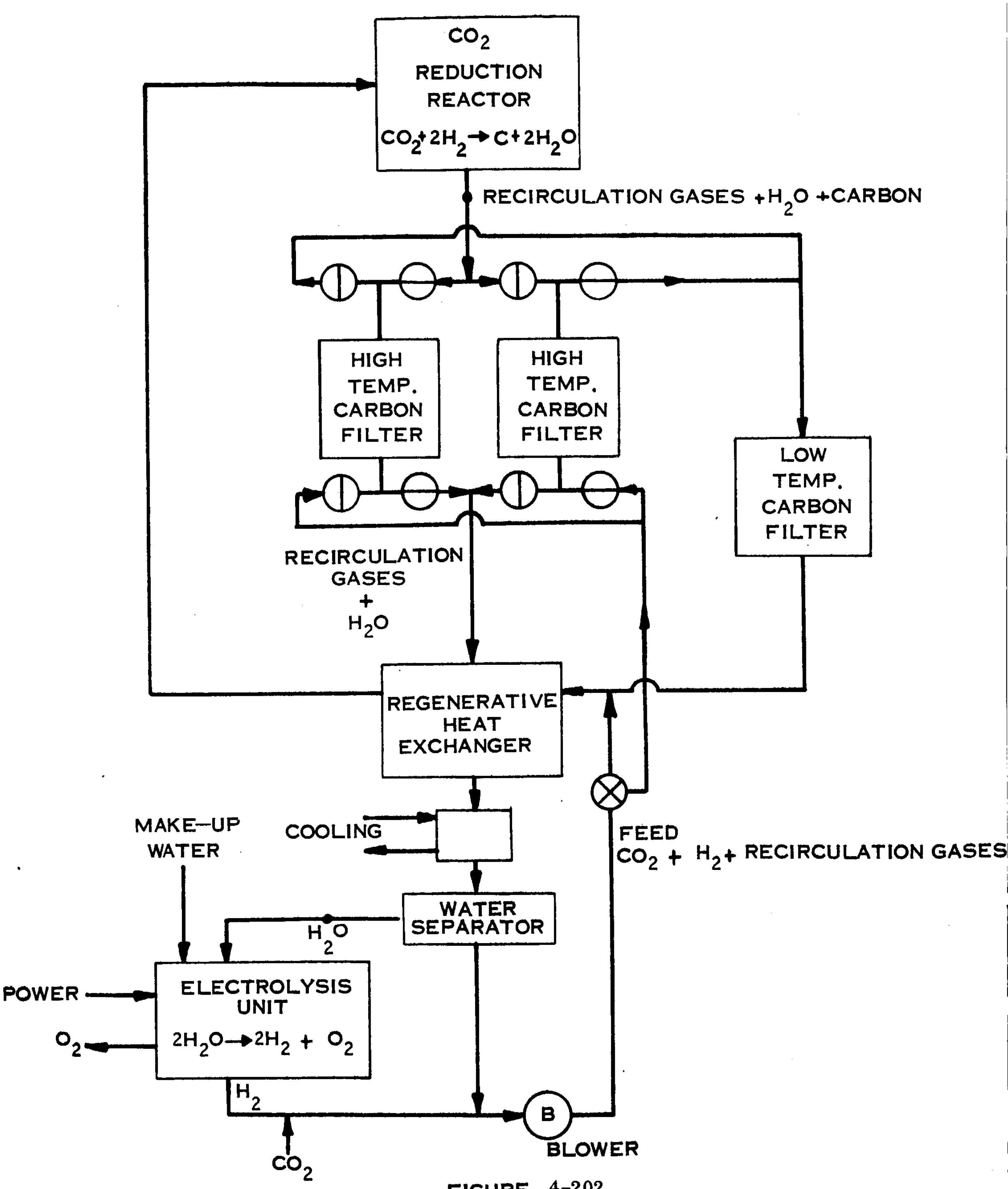


FIGURE 4-202

4.2.5.1 (Continued)

by the Isomet Corporation, can be described by the equation:

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

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 temperature about 390°F. Hydrogen is supplied partially by subsequent electrolysis of the water, partially by further reduction of the methane, and partially by a makeup feed. Increase in the recirculation rate has been found necessary to produce high CO_2 conversion efficiencies. Isomet, whose work is the major source for this analysis, claims that 99% conversion efficiencies may be obtained using a nickel catalyst.

Methane produced in the basic reaction may be:

1. Dumped to space after the water is removed for electrolysis.
2. Further reacted in a methane decomposer ($CH_4 \longrightarrow C + 2H_2$) for reclamation of all the hydrogen.
3. Further reacted with CO_2 at low temperatures ($CH_4 + CO_2 \longrightarrow 2C + 2H_2O$)
4. Converted to acetylene (C_2H_2) in an electric arc ($2CH_4 \rightarrow C_2H_2 + 3H_2$) with H_2 filtration and C_2H_2 dump.

4.2.5.2 System Description

The schematic of the system considered is shown in Figure 4-203. CO_2 and H_2 from the electrolysis unit, acetylene former, and makeup feed are directed into the methoxy reactor by the blower. The reactor is constructed such that it acts as a regenerative heat exchanger. Although high conversion occurs at temperatures such as 390°F, it is actually desirable to have a greater part of the reaction occuring at 570° to 660°F in the high temperature portion of the catalyst bed. Gas leaving the unit is cooled by inlet gas. Energy input driving the regenerative function is supplied by the reaction itself, which is slightly exothermic. Combination of the high and low temperature regions of the reactor result in a small reactor volume with high overall conversion efficiency.

Gas flow leaving the reactor enters a condensing heat exchanger in which water formed in the reaction is cooled and condensed at about a 50 to 55°F dew point. The gas and liquid condensate then enters liquid-vapor water separator and the water removed is passed into the electrolysis unit for further reduction to H_2 and O_2.

METHOXY CO_2 REDUCTION SYSTEM WITH ACETYLENE DUMP

(REFERENCE: ISOMET CORPORATION)

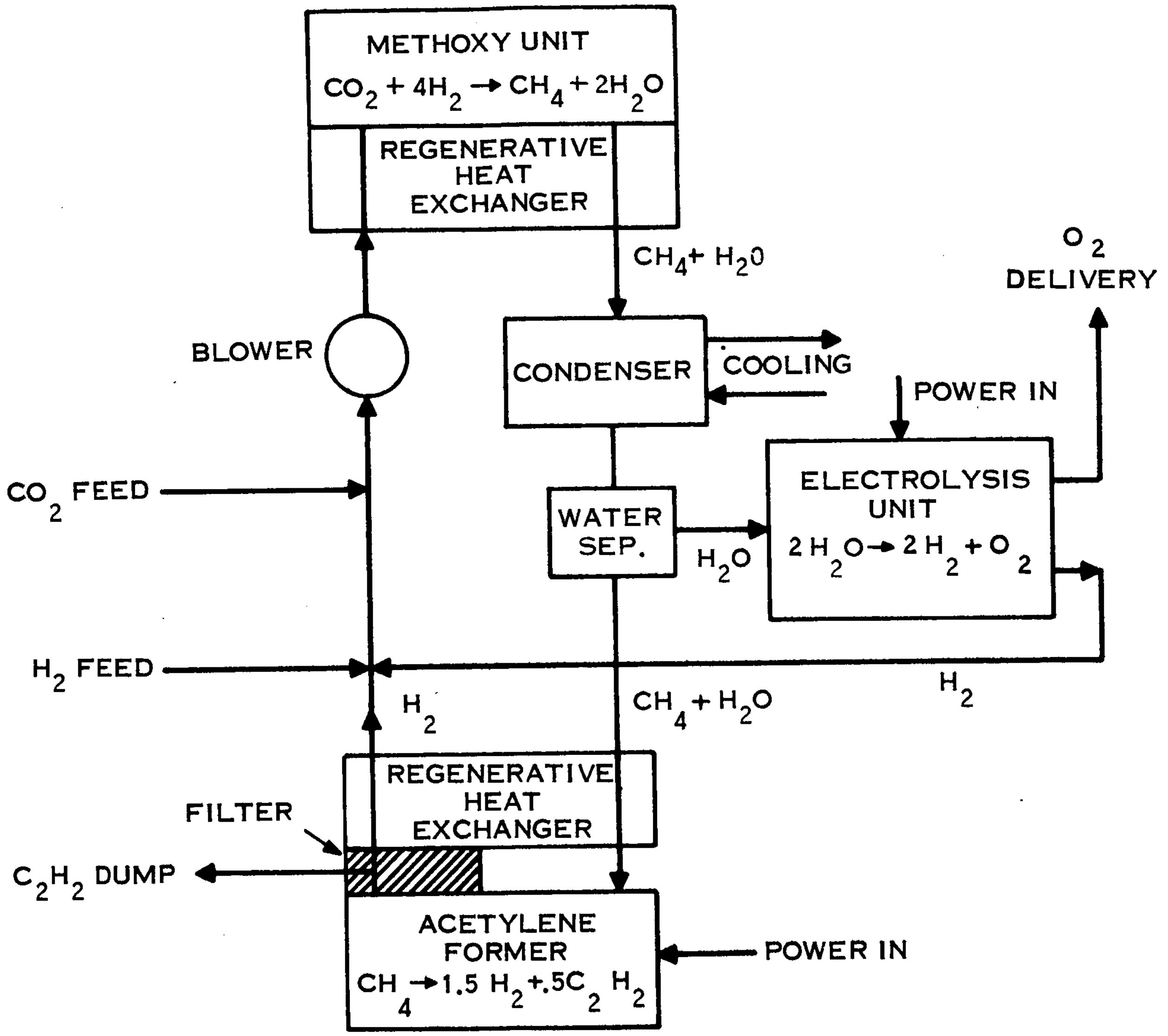


FIGURE 4-203

4.2.5.2 (Continued)

Since approximately 5% of the water is still contained in the gas flow out of the separator, it is desirable to remove this water before the gas stream enters the acetylene former and is subsequently dumped to space. Quantities of water vapor contained in the recirculating stream may be removed by a solid adsorbent, such as a granular zeolite bed, and returned to the methoxy unit through cyclic desorption of a pair of beds.

The acetylene former uses an electric arc to react the methane. In the reactor, hydrogen is also formed which must be reclaimed. This is effected by use of a palladium-silver membrane through which H_2 passes but C_2H_2 will not. The filtration must occur at high temperatures to be effective, and the path through the filter must be long and torturous so all the H_2 will have been removed from the stream prior to overboard discharge of the methane.

Mixing of the filtered H_2, H_2 from the electrolysis cell, makeup H_2, and CO_2 feed occurs at a low temperature, thus relieving the blower design problems.

4.2.5.3 Conclusions

The methoxy CO_2 reduction system appears attractive in that a low temperature reaction forming water is employed, and most of the hydrogen of the methane is recovered without the use of a carbon forming reaction. Its total equivalent weight is lower than the solid electrolyte and Bosch reaction systems. Since water is formed in the CO_2 reduction reaction, the system becomes flexible enough for integration with several types of CO_2 collection and transfer systems. 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.

The expendable in this system becomes the hydrogen makeup. Actually, the quantity of H_2 required for makeup is dependent upon the amount of metabolic water electrolyzed and also depending on the method of replenishment of vehicle gas leakage. If water is used as the oxygen source, the amount of H_2 required as makeup may be minimized. No penalties for packaging of the H_2 have been included in the penalty studies.

4.2.6 Solid Electrolyte CO_2 Reduction

4.2.6.1 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 inter-

4.2.6.1 (Continued)

mediate 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.

4.2.6.2 System Description

Figure 4-204 presents the basic schematic for the solid electrolyte system. The primary component is the solid electrolyte reactor which consists of ceramic tubes 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 generated inside the tube.

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 cells is split about equally between energy to decompose the CO_2 and I^2R heating of the elctrolyte. The circulation gas stream provides cooling in the cell to prevent overheating. The large quantity of I^2R heating in the solid electrolyte cell requires a high recycle rate to keep gas stream temperature changes in the cell at tolerable levels. The auxiliary heaters, one in each tube, can be designed to bring the system to temperature (1832°F) in 4 hours with the normal operating power if the system is operated with no cooling. No expendable weight is required for the operation of the electrolytic 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. This should happen when the carbon to catalyst ratio is between 10 to 1 and 20 to 1. The reaction occuring 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.

SOLID ELECTROLYTE CO_2 REDUCTION SYSTEM
(REFERENCE: ISOMET CORPORATION)

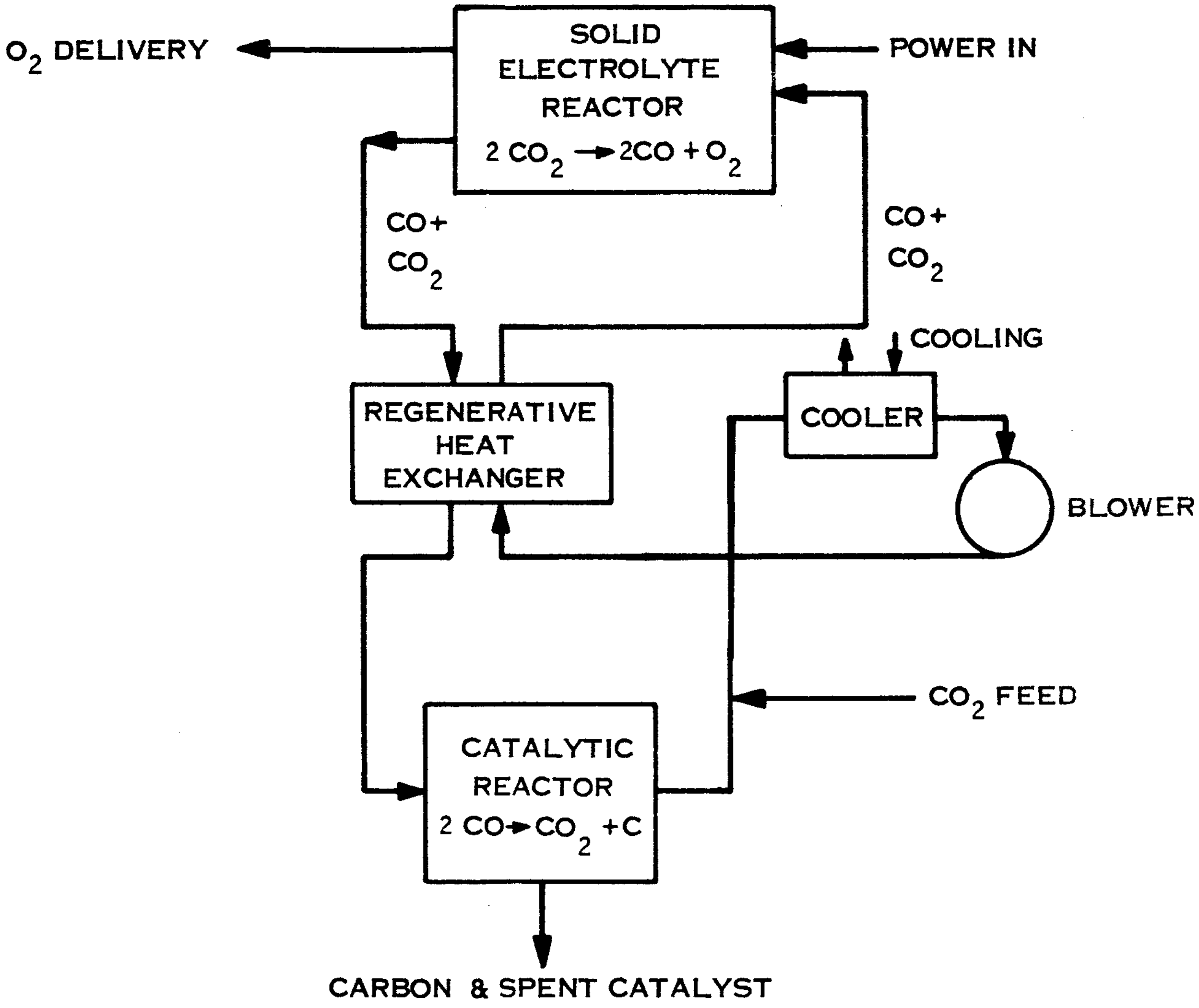


FIGURE 4-204

4.2.6.3 Conclusion

Solid electrolyte system feasibility has already been proven and the major chemical and physical problem 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; improvement of the solid electrolyte 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.

Tests performed on the solid electrolyte cell and the catalytic reactor have established system operation and have provided the design data used for this study. The summary curves at the end of this section were developed from this data and basically represent current state-of-the-art. A strong possibility exists, however, that significant improvements can be made in the unit weight and power requirements with further development.

4.2.7 Molten Carbonate CO_2 Reduction

4.2.7.1 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. Additional data on the molten carbonate approach is expected from Mine Safety Appliance Research Co. in the near future as an extension to preliminary data already on hand.

4.2.7.2 System Description

Figure 4-205 presents a simplified schematic of a molten carbonate system. In general, the concept is that a molten alkali carbonate may be electrolyzed so as to produce oxygen at the anode, carbon at the cathode, and an alkali oxide at the cathode. The alkali oxide reacts with input CO_2, thereby replenishing the carbonate. 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, reabsorption of CO_2 at the anode is an important requirement. Experimentally, it has been shown that reabsorption 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

MOLTEN CARBONATE CO_2 REDUCTION SYSTEM

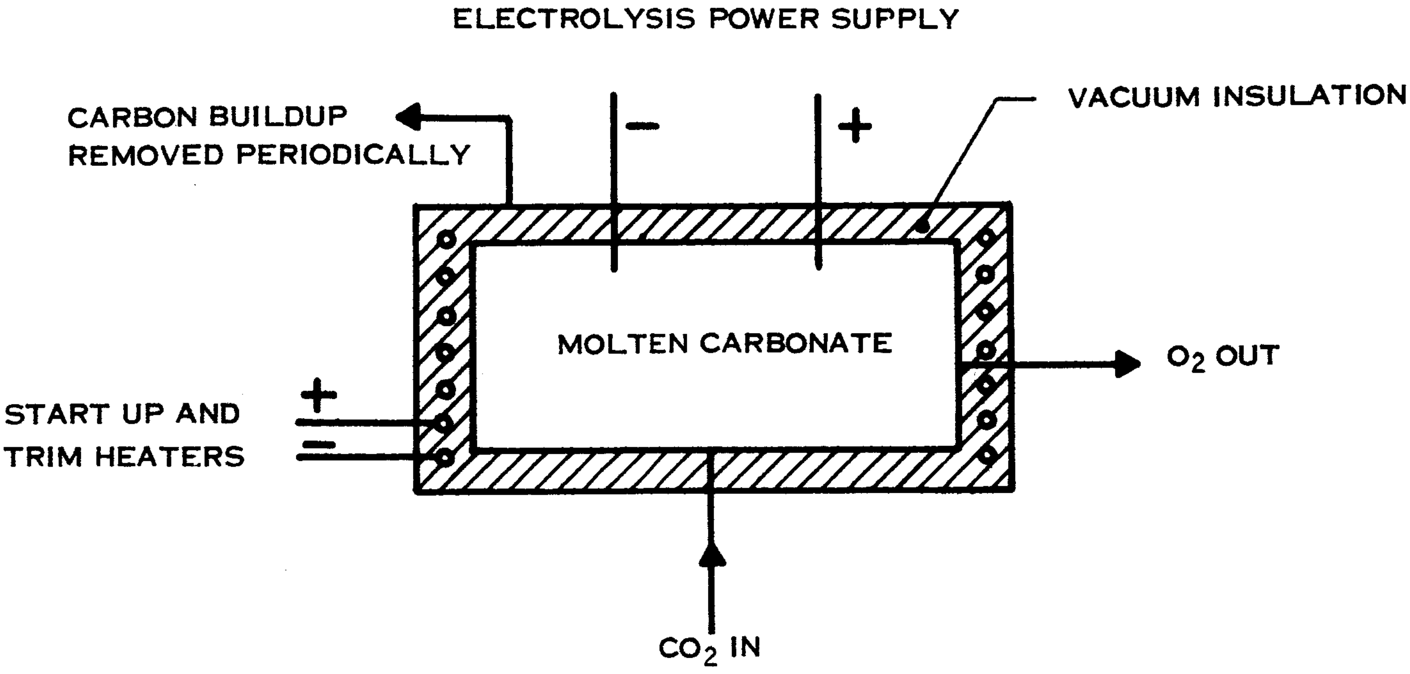


FIGURE 4-205

4.2.7.2 (Continued)

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 buildup 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 machines of this type. As might be expected, machine size and weight will vary as the anode area. If a series of machines are designed to several levels of operating voltages (i.e. efficiency), the more efficient machines will be larger. When machine 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 on 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.

4.2.7.3 Conclusions

The molten carbonate process is attractive in that it reduces the CO_2 to O_2 in one step and eliminates need for additional equipment such as that required for reduction systems having water as an intermediate. 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 simulation problem has not been fully considered. The basic approach is attractive enough to warrant

4.2.7.3 (Continued)

further consideration in the system integration phase.

4.2.8 Comparison of CO_2 Reduction Methods

Figures 4-206 through 4-209 illustrates the comparison of the various CO_2 reduction systems from a fixed plus expendable weight, power, and total equivalent weight standpoint. These curves are useful only for selecting weights for system integration portion of the study and cannot be used separately to evaluate any system. It is possible to select the best method only after consideration of integration with the CO_2 removal, transfer, and reduction systems. This work is presently being done, and the details of this effort will be covered in the final report of this study.

CO_2 REDUCTION

FIXED WEIGHT AND EXPENDABLES VS CO_2 PROCESS RATE

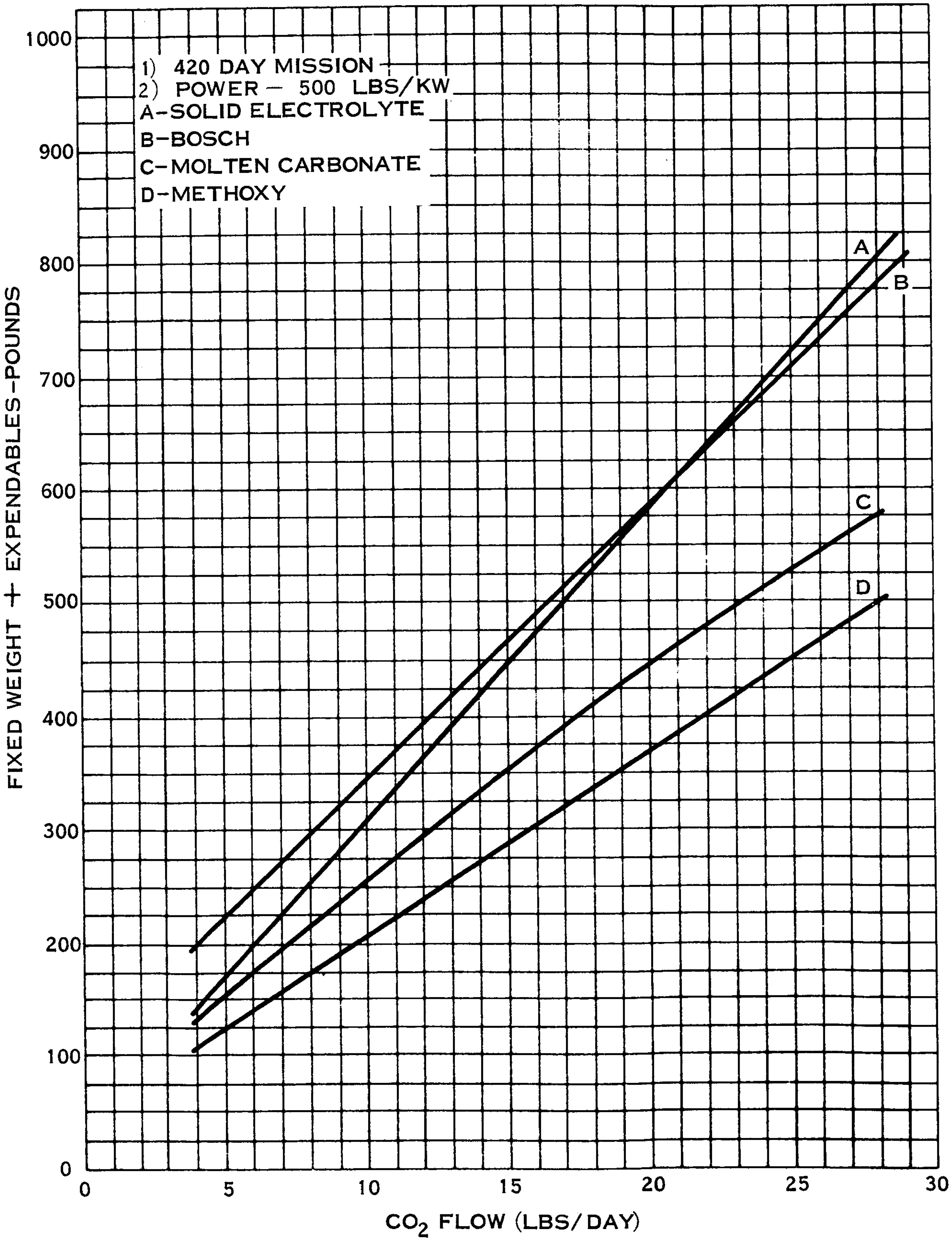
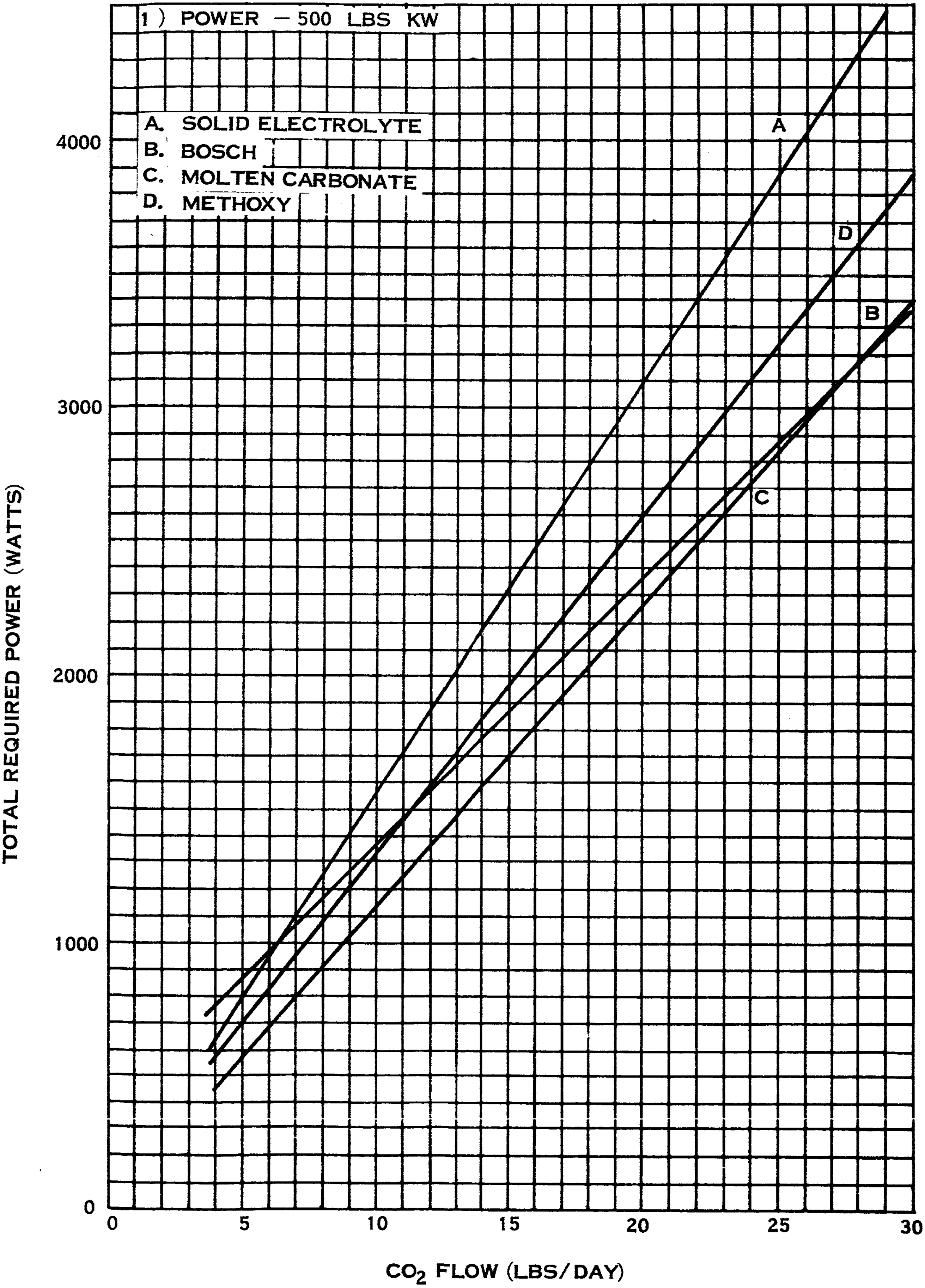


FIG. 4-206

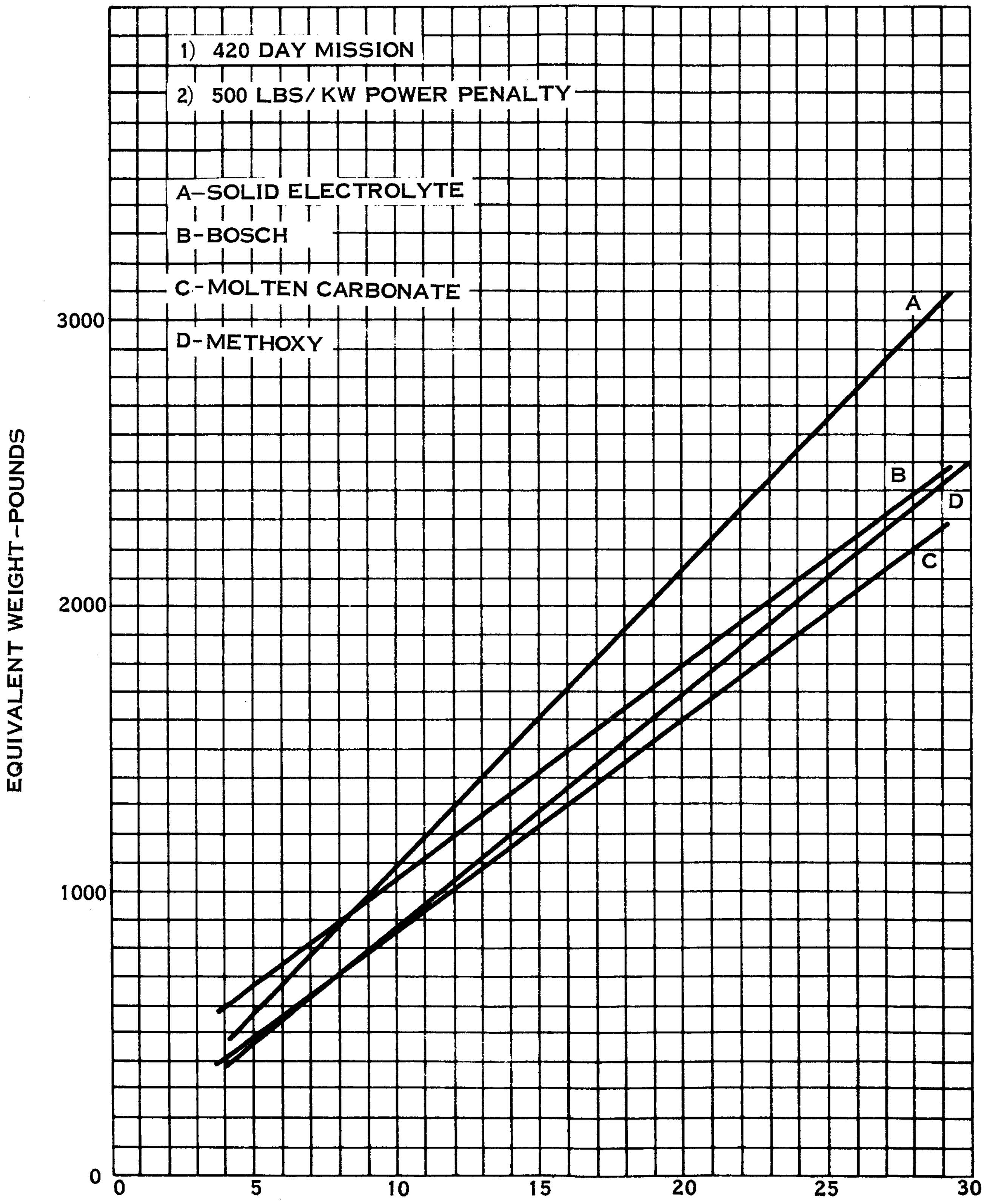
FIG. 4-207

CO_2 REDUCTION

TOTAL POWER REQUIRED VS CO_2 PROCESS RATE



CO_2 REDUCTION
TOTAL EQUIVALENT WEIGHT
VS
CO_2 PROCESS RATE



CO_2 FLOW (LBS/ DAY)

FIG. 4-208

4.3 Water Electrolysis

4.3.1 Objectives

There are many variations to the basic electrolysis process being considered throughout industry. The objective of this part of the study is to determine the best approach so it can be applied to the other subsystems.

Electrolysis systems are of interest for this study for two applications. The first application is as a potential oxygen generation device replacing the more conventional stored oxygen. If electrolysis systems are utilized for oxygen generation, the storage problems for systems without CO_2 reduction are simplified, in that water is stored rather than cryogenic or gaseous oxygen at elevated pressures. The second area of interest for water electrolysis systems is that of a portion of the CO_2 reduction systems. CO_2 reduction equipment using hydrogenation processes has, as an intermediate product, water. Thus, to attain the end product, oxygen, it becomes necessary to dissociate the water to provide this oxygen and also to regenerate the hydrogen for recycling within the system. Some methods of water reclamation also use an electrolysis cell as part of the reclamation process.

It was felt that, for purposes of this study, a review of the various electrolysis approaches being taken throughout industry would be necessary to determine the potential weight, power and equivalent weight characteristics of electrolysis systems to be used in further system integration work. Since the integration considerations for all electrolysis systems are somewhat similar, it was not necessary to make a firm selection of approach at this point. Instead, a system configuration which could be considered typical of all systems was identified for further integration work. Thus, the analysis takes the form of an optimization of each of the approaches to determine minimum weight points and then selection of a representative approach for amplication into working data for the rest of the system integration study. By pursuing the study in this fashion, the output of the subsystem phase is sufficient design data for integration in open system oxygen supply equipment or closed system CO_2 reclamation equipment.

As system integration becomes better defined and desired operating characteristics for water electrolysis systems become established, it will be necessary to establish the one best approach for final system integration and definition. However, at this stage of the study, each of the approaches is considered a potential candidate with data presentation to be amplified for what appears to be the best approach at this time.

CO_2 REDUCTION

TOTAL EQUIVALENT WEIGHT VS MISSION TIME

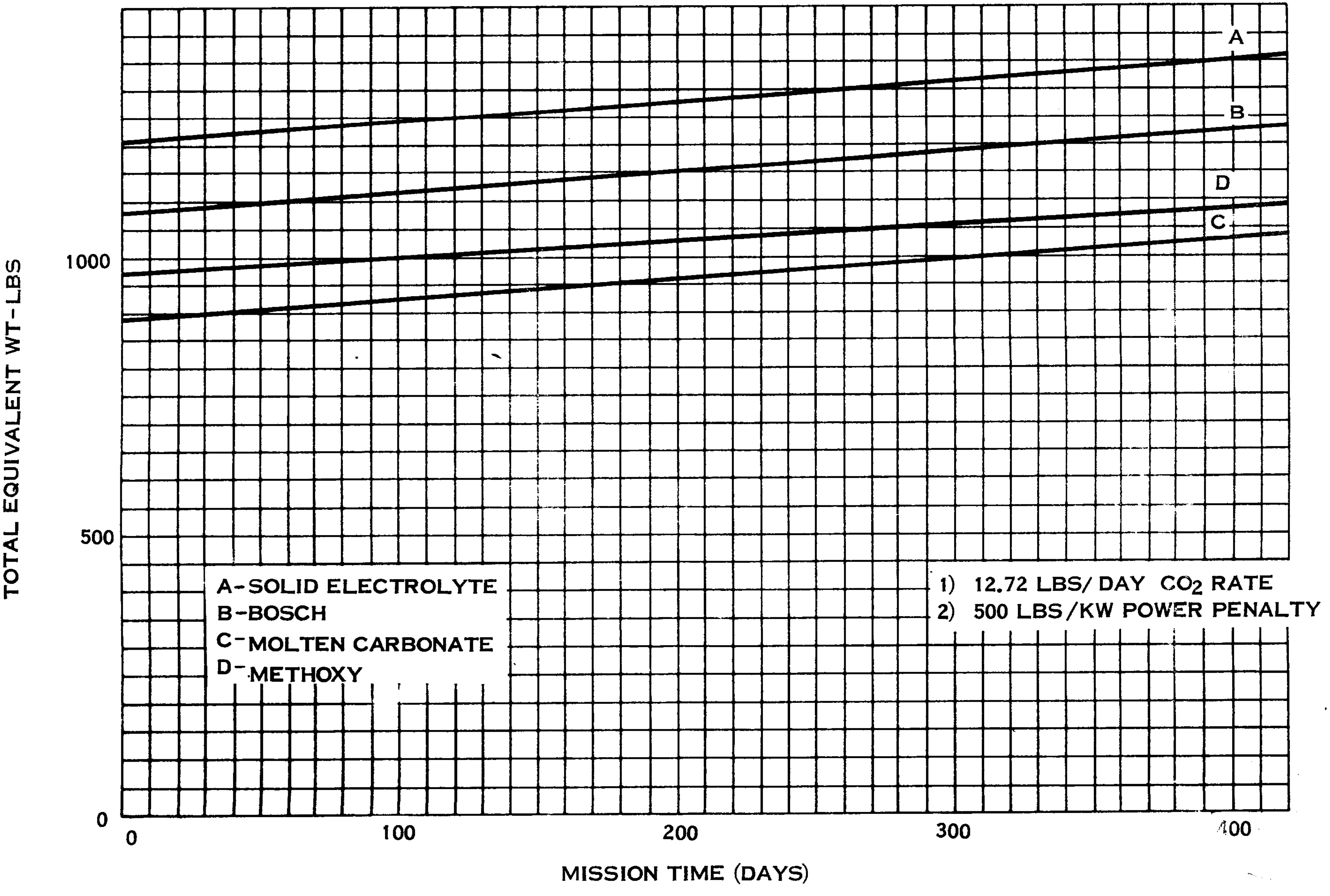


FIG. 4-209

4.3.2 Discussion of Data Presentation

The organization of this section is somewhat different from preceding 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 of the processes in basic principles.

An optimization is presented for each variation to be considered, to allow determination of the minimum system equivalent weight for current state-of-the-art equipment, and, in many cases, for predicted performance of improved equipment in the near future. A simplified system schematic and a brief description are presented for each variation of system design to allow understanding of the differences in operation.

The basic intent of the subsystem studies is to provide data to be used later in the program for integration with other subsystems. Therefore, the data is presented in two forms. The first form is an illustration of the weight and power requirements as a function of the oxygen used. Second, 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 analysis is more general and allows more flexibility for use in integration with CO_2 reduction systems.

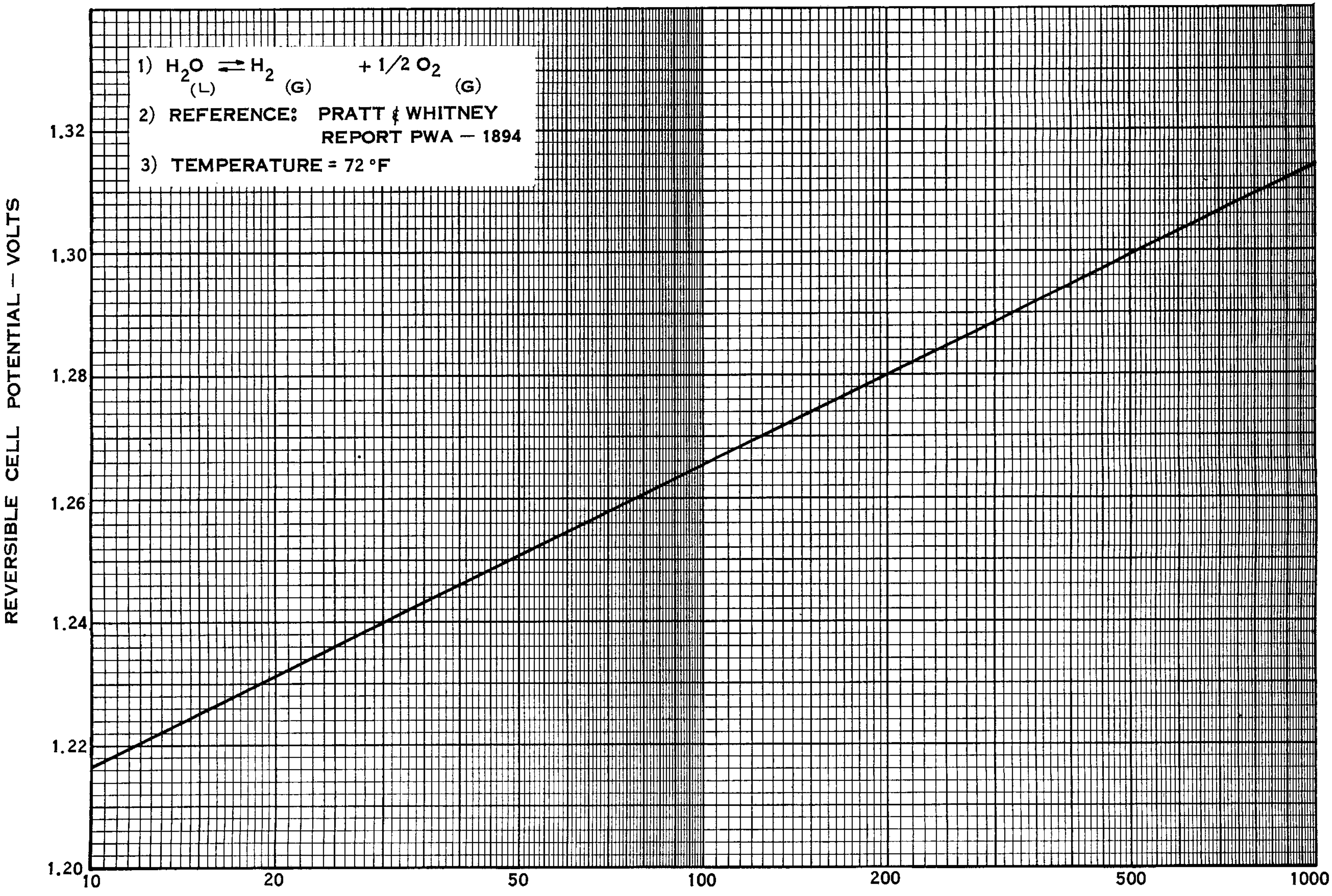
4.3.3 General Discussion of Process

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 $H_2O \rightarrow .111\ H_2 + .889\ O_2$.

To allow the electrolysis 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 4-301 and 4-302. 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.

H_2O ELECTROLYSIS SYSTEM
REVERSIBLE CELL POTENTIAL CHARGE VS. PRESSURE

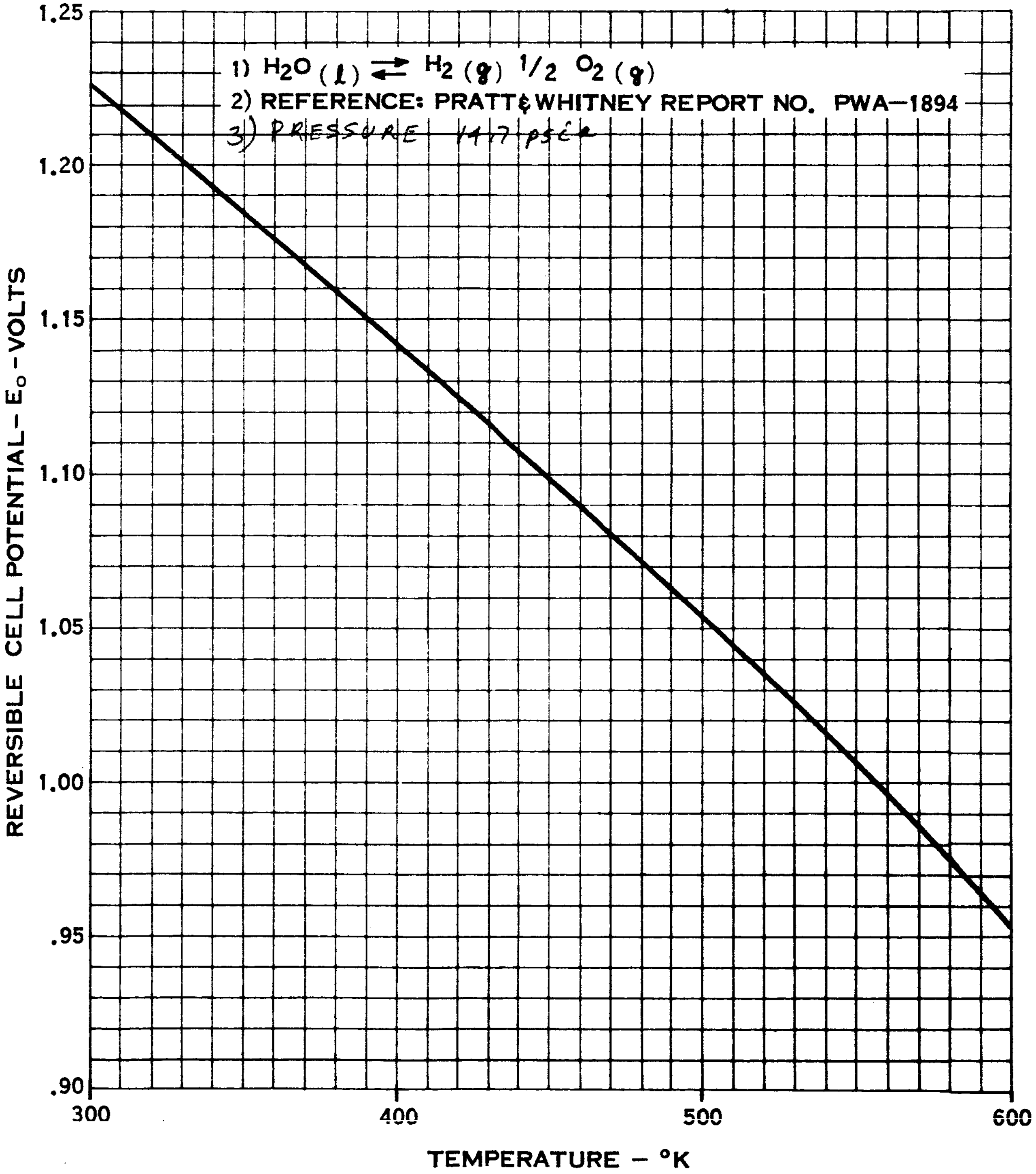


PRESSURE — PSIA

FIGURE 4—301

H_2O ELECTROLYSIS SYSTEM

REVERSIBLE CELL POTENTIAL VS. TEMPERATURE



1) $H_2O\,(l) \rightleftharpoons H_2\,(g)\ 1/2\ O_2\,(g)$
2) REFERENCE: PRATT & WHITNEY REPORT NO. PWA–1894
3) PRESSURE 14.7 psia

FIGURE 4-302

4.3.3 (Continued)

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 artificial gravity field to the use of selective ion transfer membranes. Operation of these systems in a one g environment indicates ready 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. 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 faradayic or current 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.

4.3.4 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 4-301 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% solution of potassium hydroxide in water by weight. 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.

ROTATING H_2O ELECTROLYSIS CELL

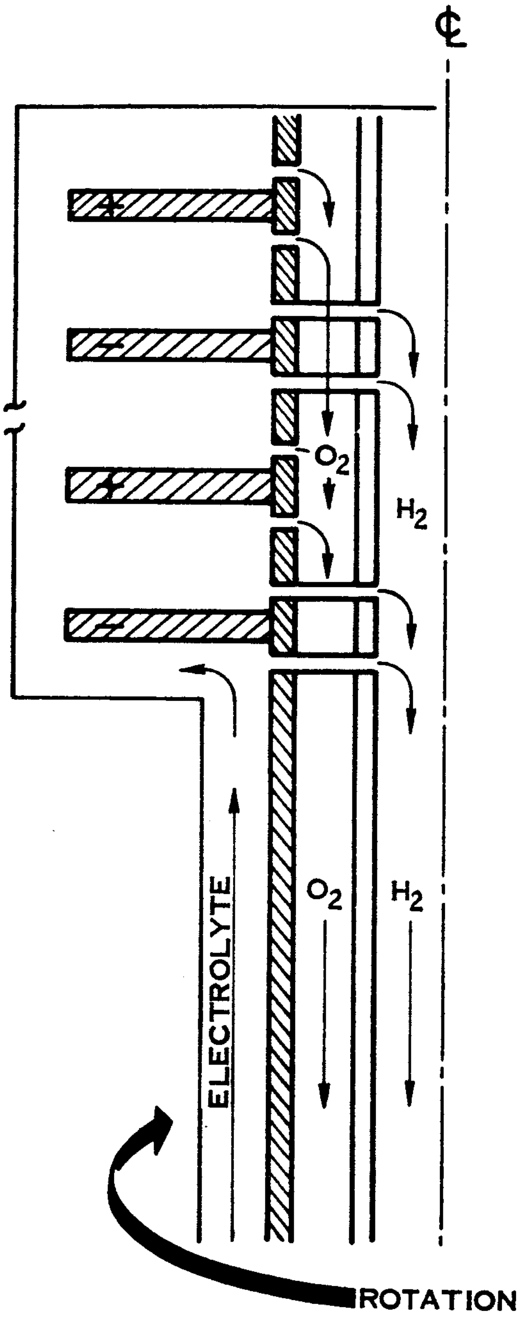


FIGURE 4-303

4.3.4 (Continued)

Figure 4-304 illustrates the optimization of this system approach to determine the lowest equivalent weight operating parameter. As seen in the figure, the optimum equivalent weight occurs at a density of 215 amp/ft^2 at the power penalty under consideration (500 lbs/kw). However, no indication of polarization at 159 amps/ft^2 was noted; thus, the system may be capable of successful operation at higher current density. If cell cooling causes a problem, this could potentially be overcome by the addition of a cell cooling system. Figure 4-305 presents an estimate of the potential performance of the system with added development effort and modification. As illustrated by comparison of Figures 4-304 and 4-305, the optimum equivalent weight at a power penalty of 500 lbs/kw could be reduced from 900 to 800 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.

4.3.5 Porous Electrode Electrolysis System

This system under development by the TAPCO Division of Thompson Ramo Wooldridge, Inc., has been analyzed utilizing TAPCO Report No. ER-5482 "MOSS and MARS Environmental System Studies."

The system under development by TAPCO appears to provide operation independent of gravity. The basic cell construction as illustrated in Figure 4-306 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. The generated gases flow 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.

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 amp/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 established, the only problem to be anticipated is a change in the electrolyte film characteristics on the screen side of the electrodes. This may affect water carry-over. However, it is believed that this problem may be solved by proper water feed regulation. Figures 4-307 and 4-308 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 indicates an expected reduction in equivalent weight from 980 to 670 lbs, which is a considerable change if the anticipated development improvements can be accomplished.

H$_2$O ELECTROLYSIS SYSTEM

ROTATING STATE–OF–THE–ART UNIT

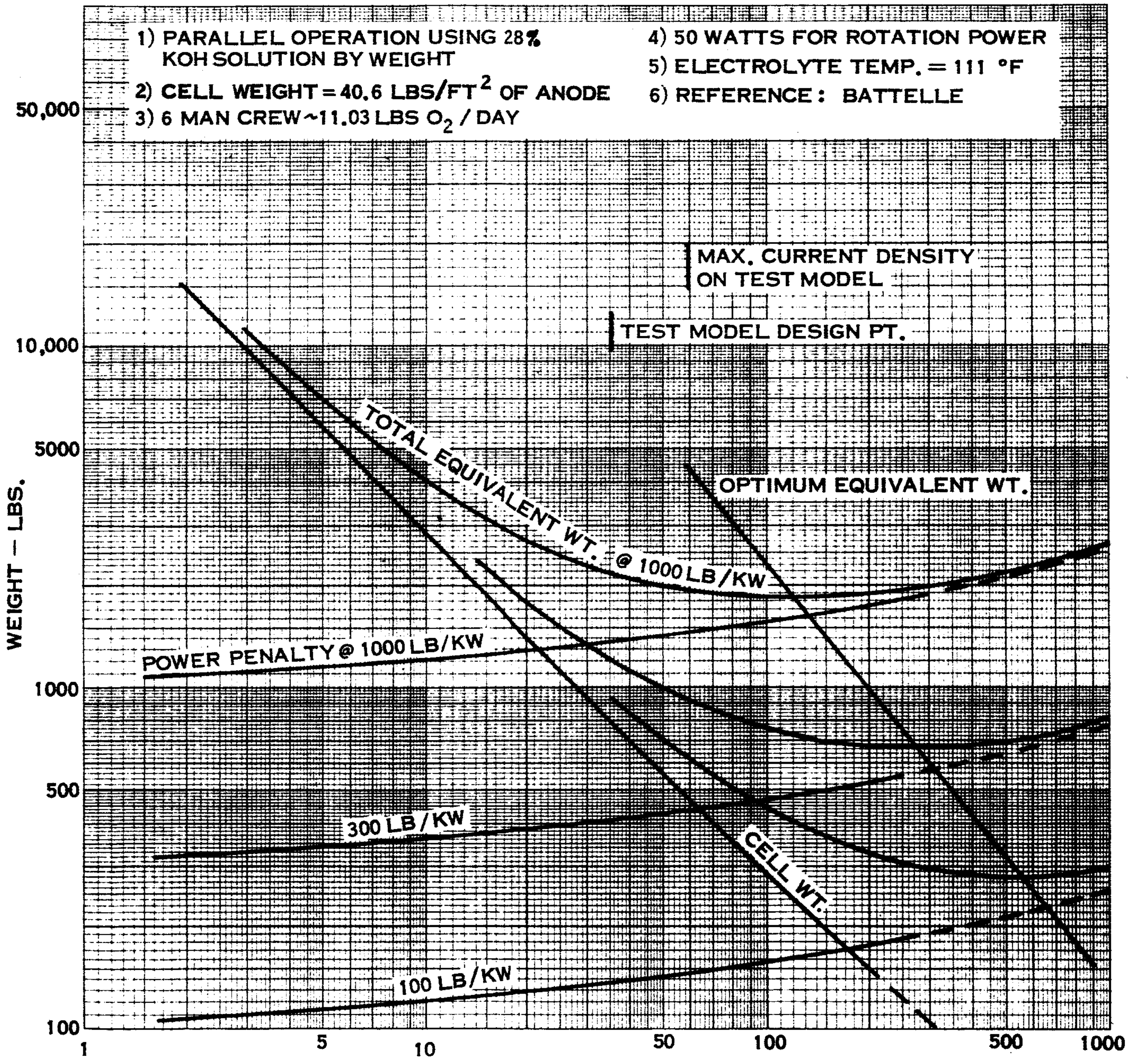
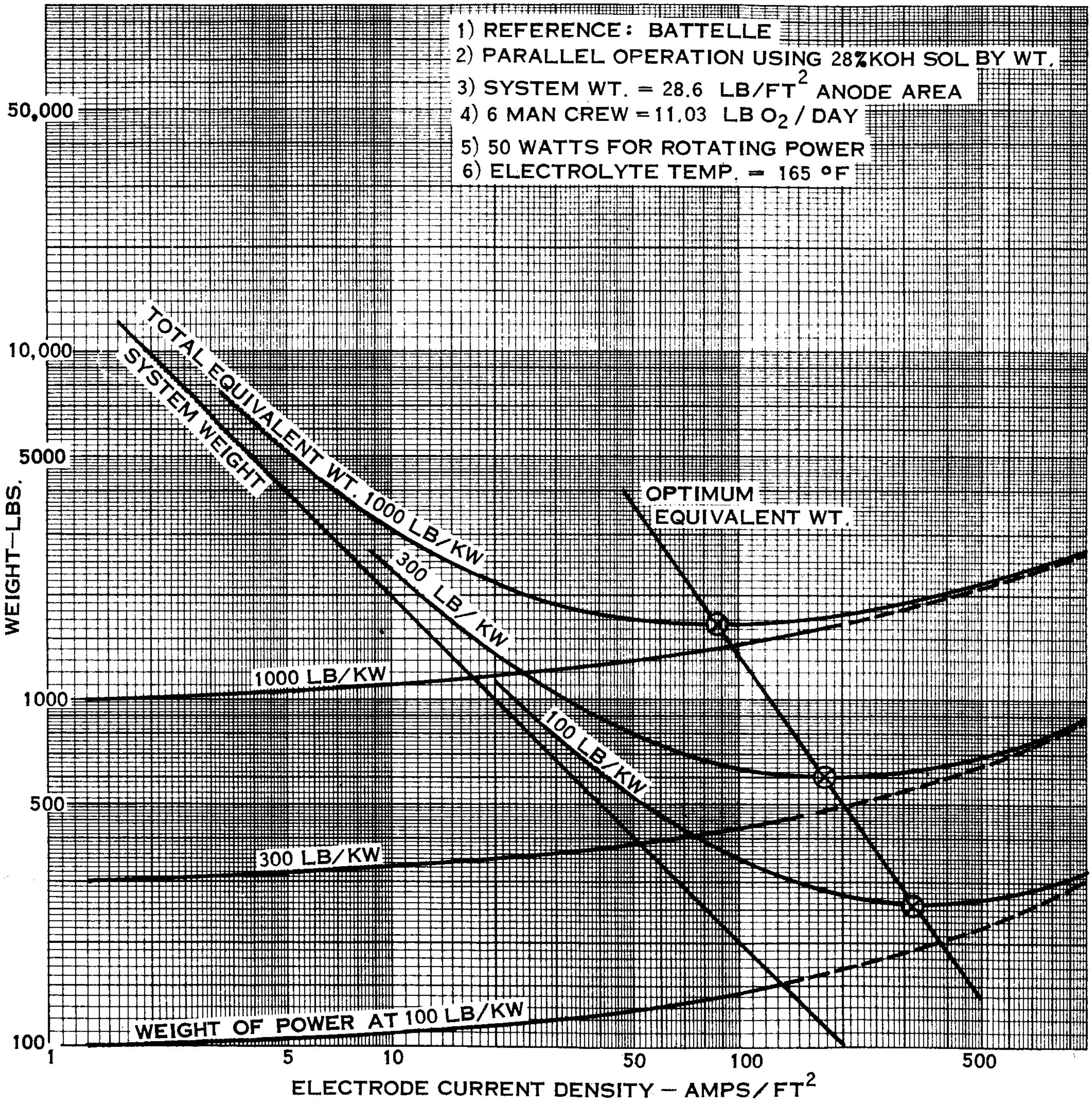


FIGURE 4-304

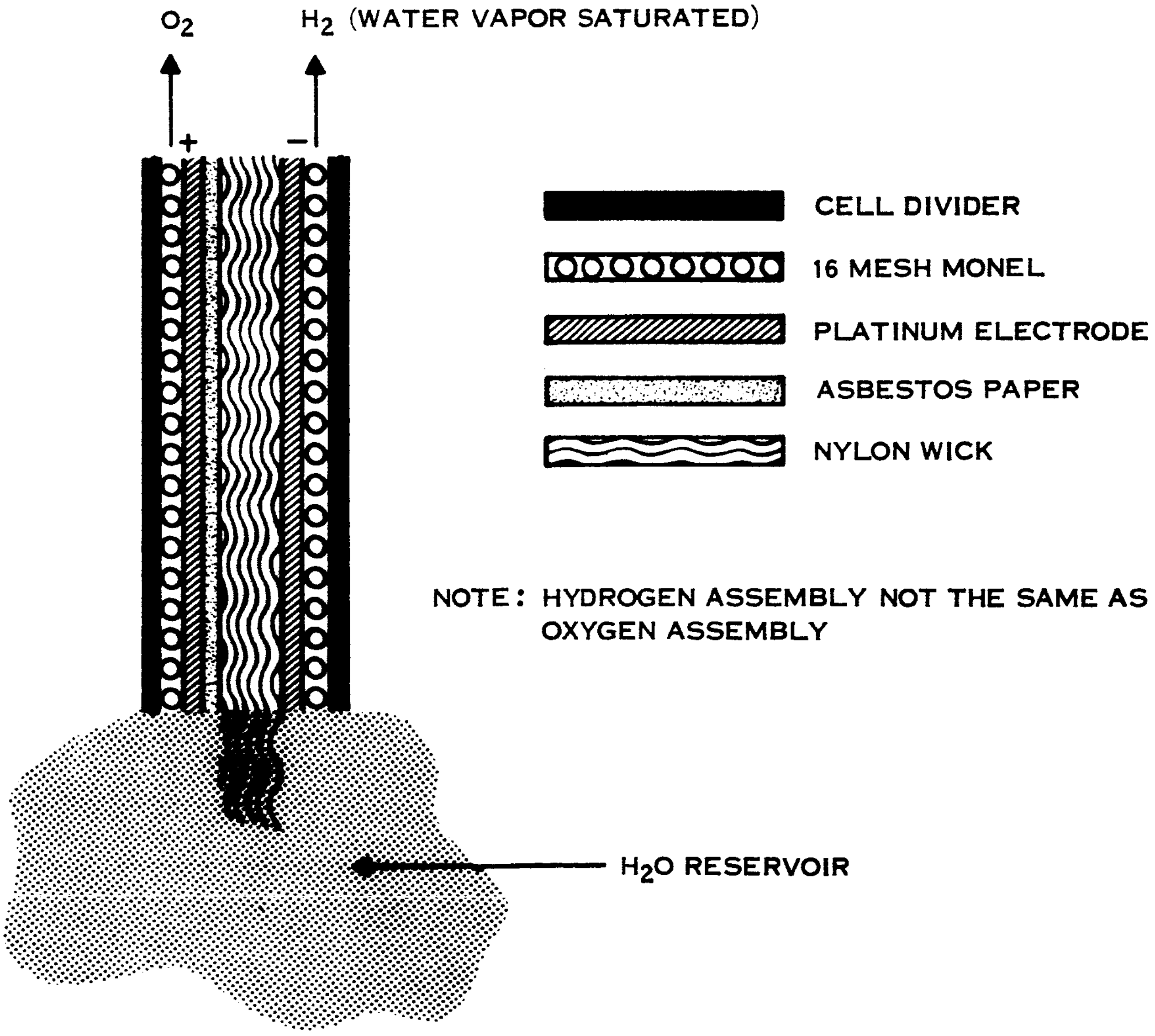
H_2O ELECTROLYSIS SYSTEM
PREDICTED PERFORMANCE–ROTATING UNIT



1) REFERENCE: BATTELLE
2) PARALLEL OPERATION USING 28%KOH SOL BY WT.
3) SYSTEM WT. = 28.6 LB/FT^2 ANODE AREA
4) 6 MAN CREW = 11.03 LB O_2 / DAY
5) 50 WATTS FOR ROTATING POWER
6) ELECTROLYTE TEMP. = 165 °F

FIGURE 4 - 305

H_2O ELECTROLYSIS SYSTEM
POROUS ELECTRODE CELL



NOTE: HYDROGEN ASSEMBLY NOT THE SAME AS OXYGEN ASSEMBLY

FIGURE 4-306

H_2O ELECTROLYSIS SYSTEM

STATE–OF–THE–ART POROUS ELECTRODE UNIT

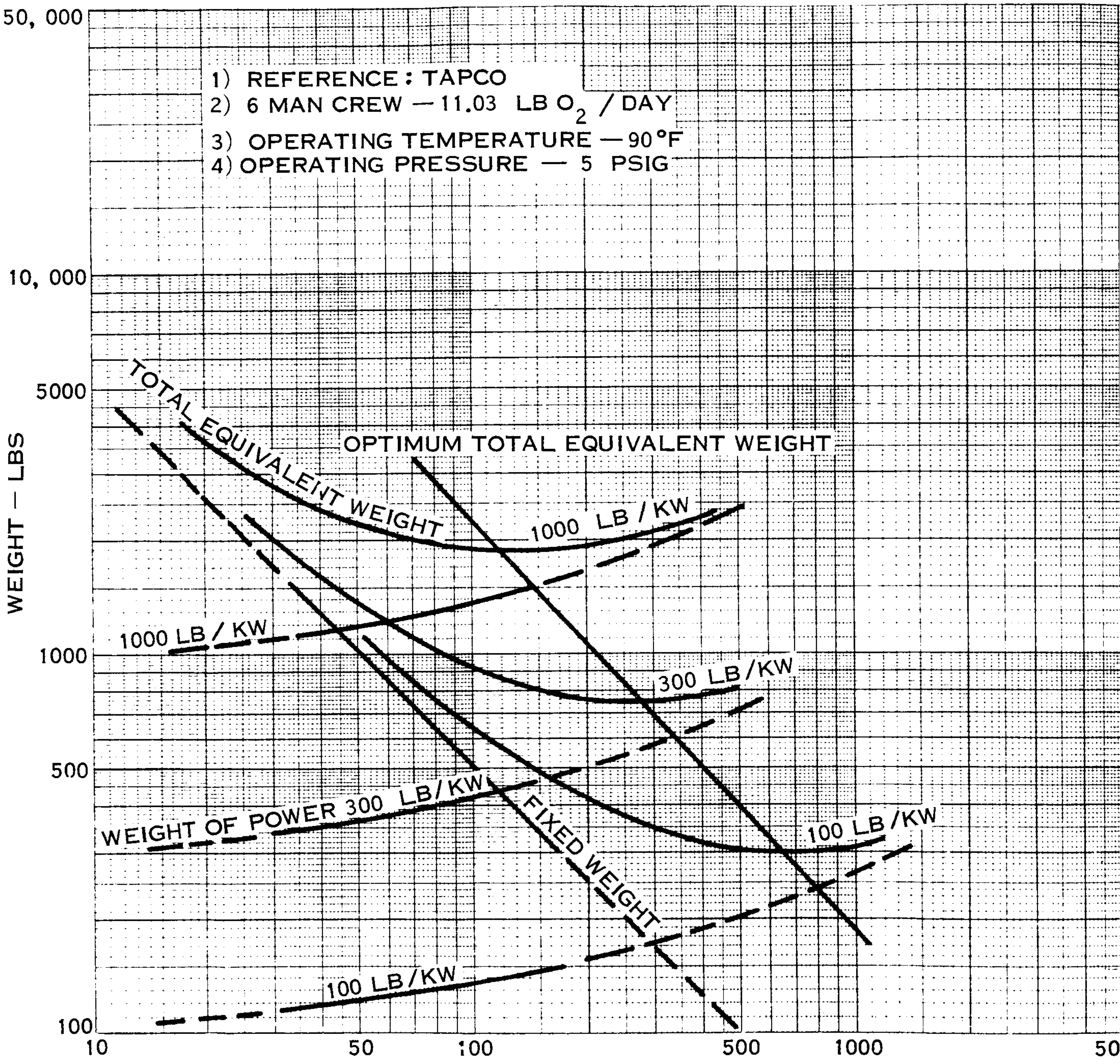


FIGURE 4-307

4.3.6 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 developed 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 in a gaseous phase on the side of the cathode opposite the side on which hydrogen is deposited by electrolysis of water. The cathode operation is diffusion, thus, independent of gravity. Figure 4-309 illustrates a possible method of constructing this particular electrolysis cell.

Battelle data indicate 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 570 lbs may be achieved after further development. This is illustrated in Figure 4-310. 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 115 amps/ft^2. All of these data must be considered very optimistic at this time due to the very early stages of development for this particular approach.

4.3.7 Combined Electrolysis Vortex Separator Cell

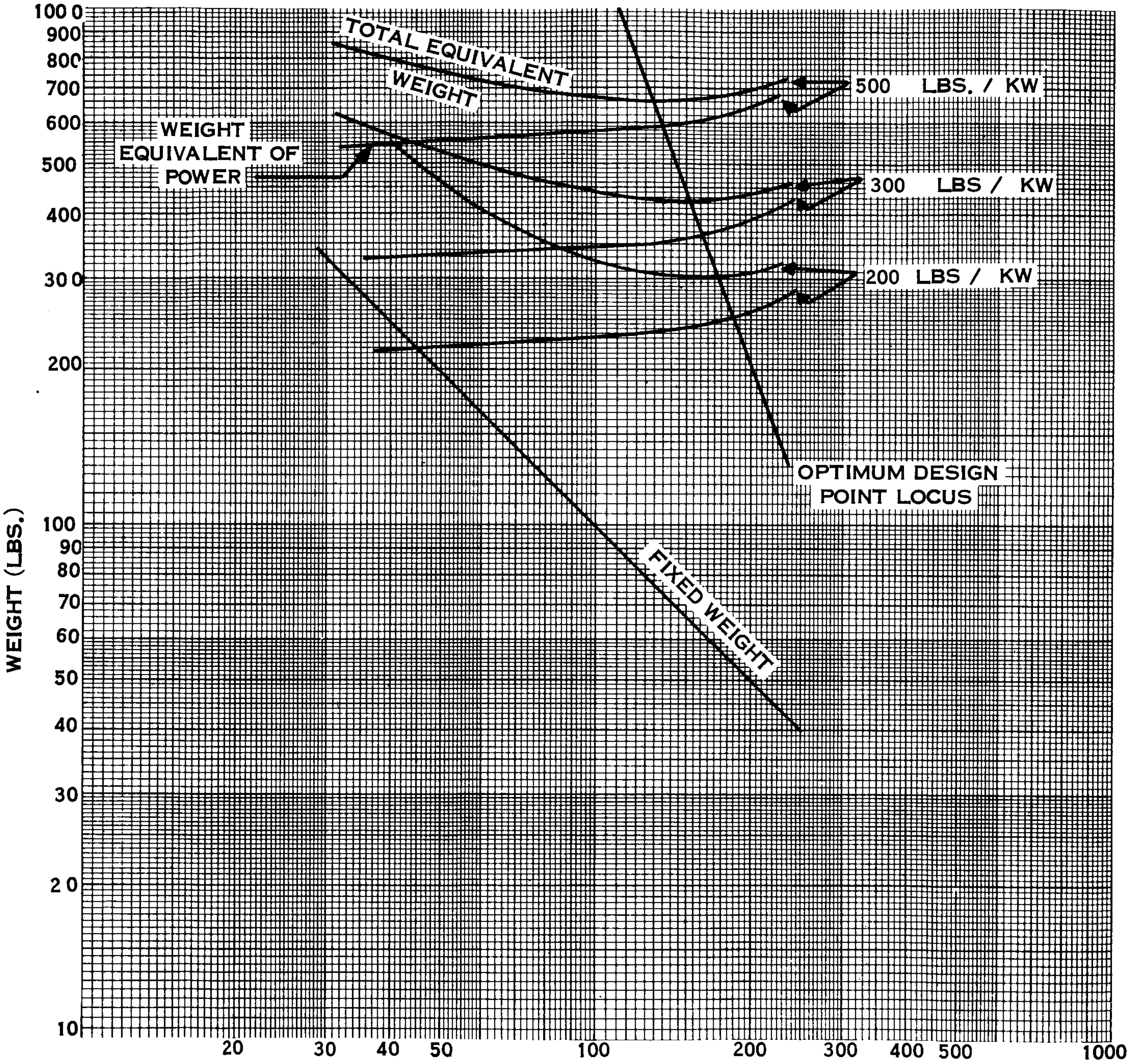
The Pratt & Whitney Aircraft Division of United Aircraft Corporation has performed preliminary testing toward the development of a 500 watt solar regenerative hydrogen-oxygen fuel cell power supply system designed to operate in an equatorial orbit. This work was done under contract No. DA 36-039-SC 85259 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 4-311.

In this unit the electrolyte is pumped into 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 densities 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 4-312 illustrates the optimum weight consideration for this particular approach.

FIGURE 4-308

H_2O ELECTROLYSIS SYSTEM

PREDICTED PERFORMANCE — POROUS ELECTRODE UNIT



ROTATING CELL WITH HYDROGEN — DIFFUSION CATHODE

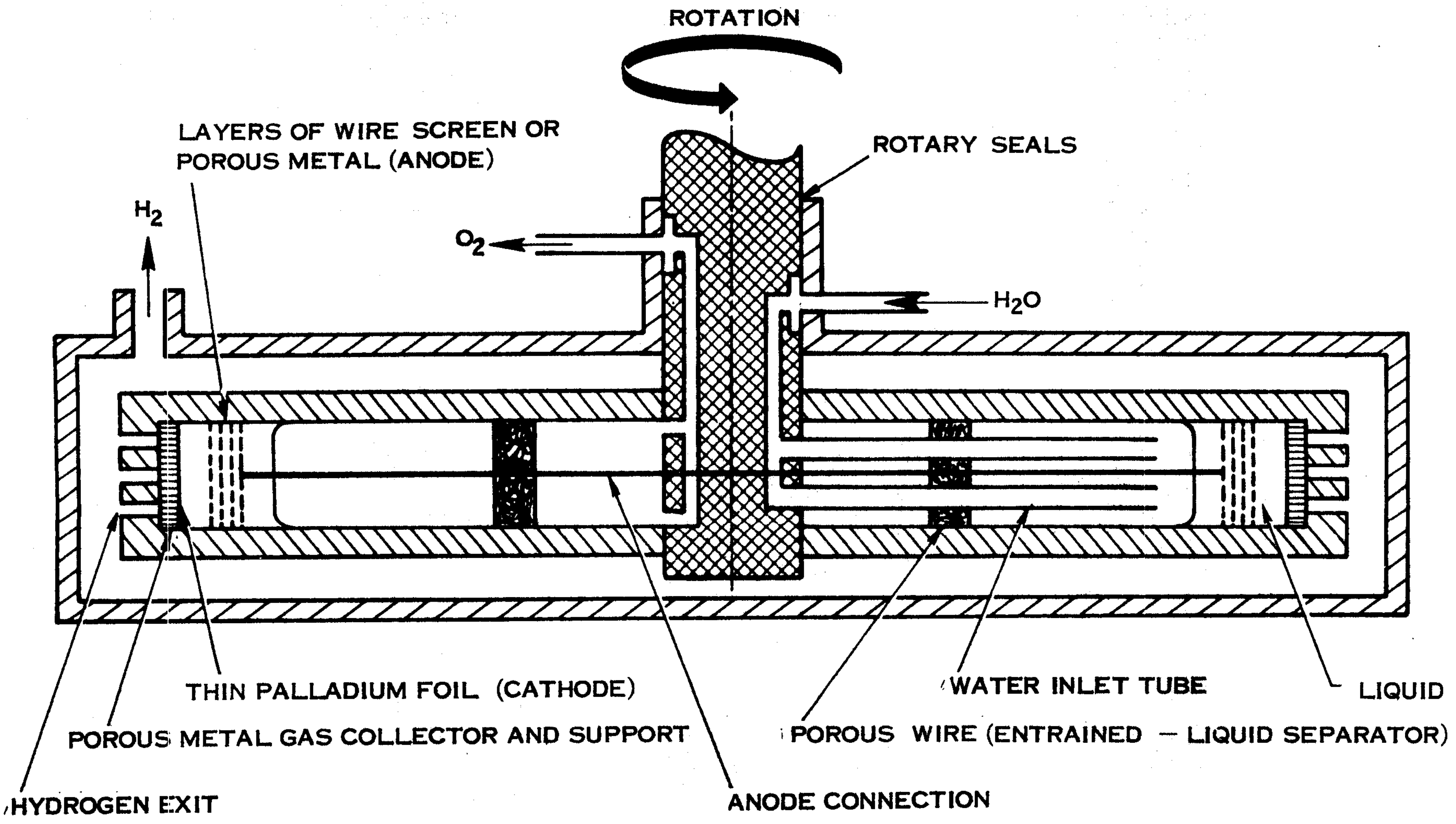


FIGURE 4-309

H_2O ELECTROLYSIS SYSTEM
ROTATING CELL – HYDROGEN DIFFUSION CATHODE
PREDICTED PERFORMANCE

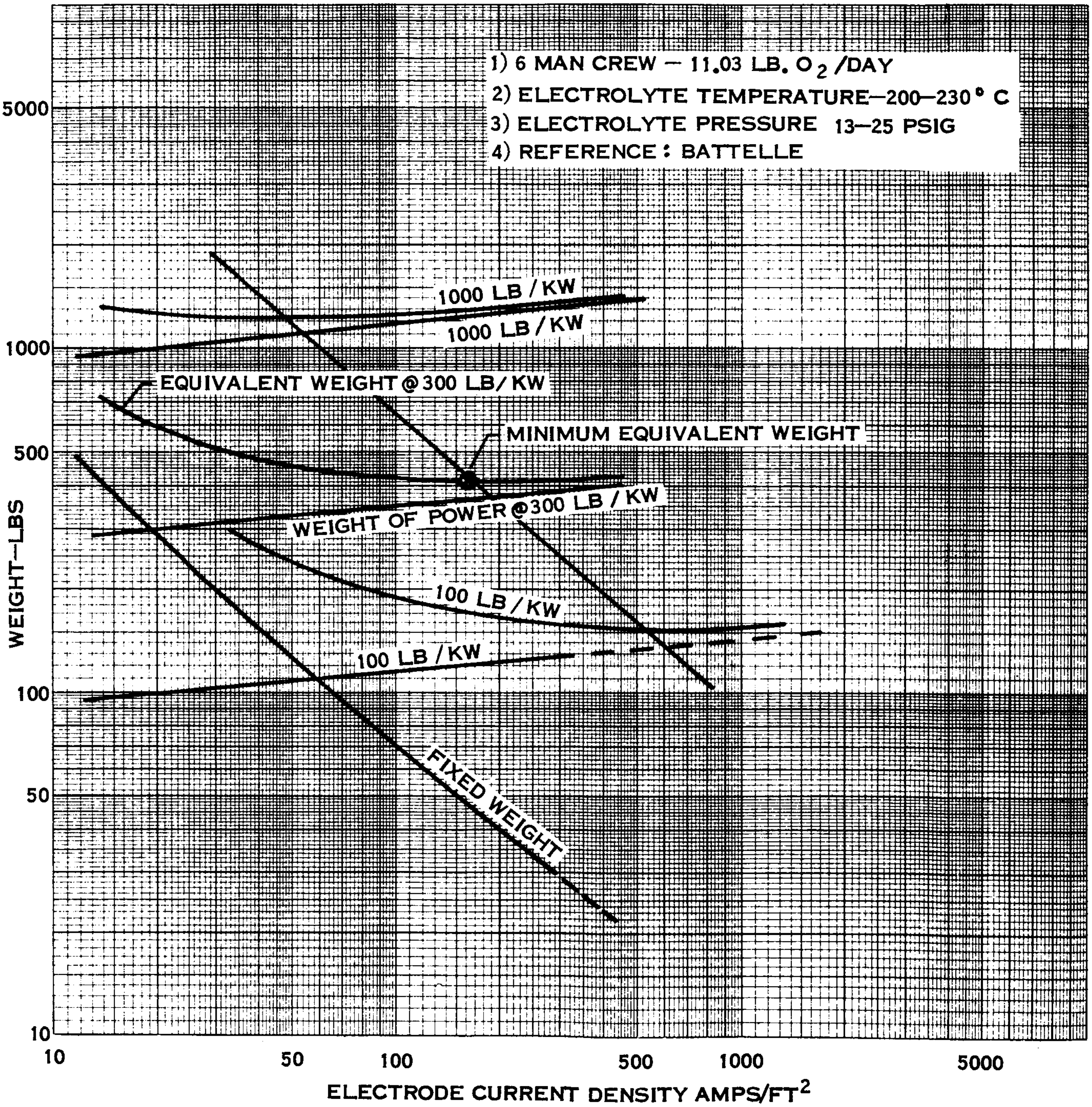
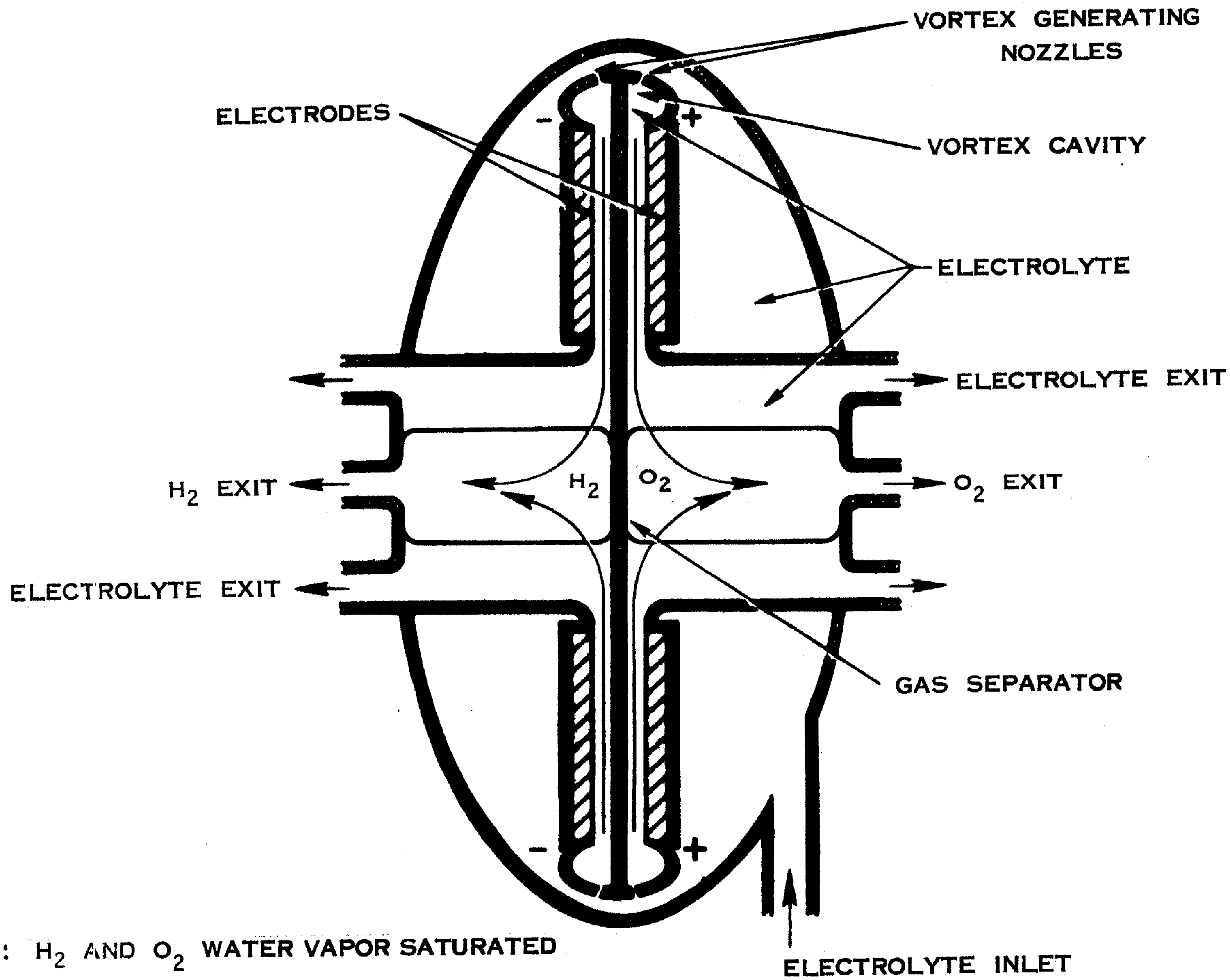


FIGURE 4-310

H_2O ELECTROLYSIS SYSTEM

COMBINED ELECTROLYSIS — VORTEX GAS LIQUID SEPARATOR UNIT



NOTE: H_2 AND O_2 WATER VAPOR SATURATED

FIGURE 4—311

H_2O ELECTROLYSIS SYSTEM

COMBINED ELECTROLYSIS – GAS SEPARATOR

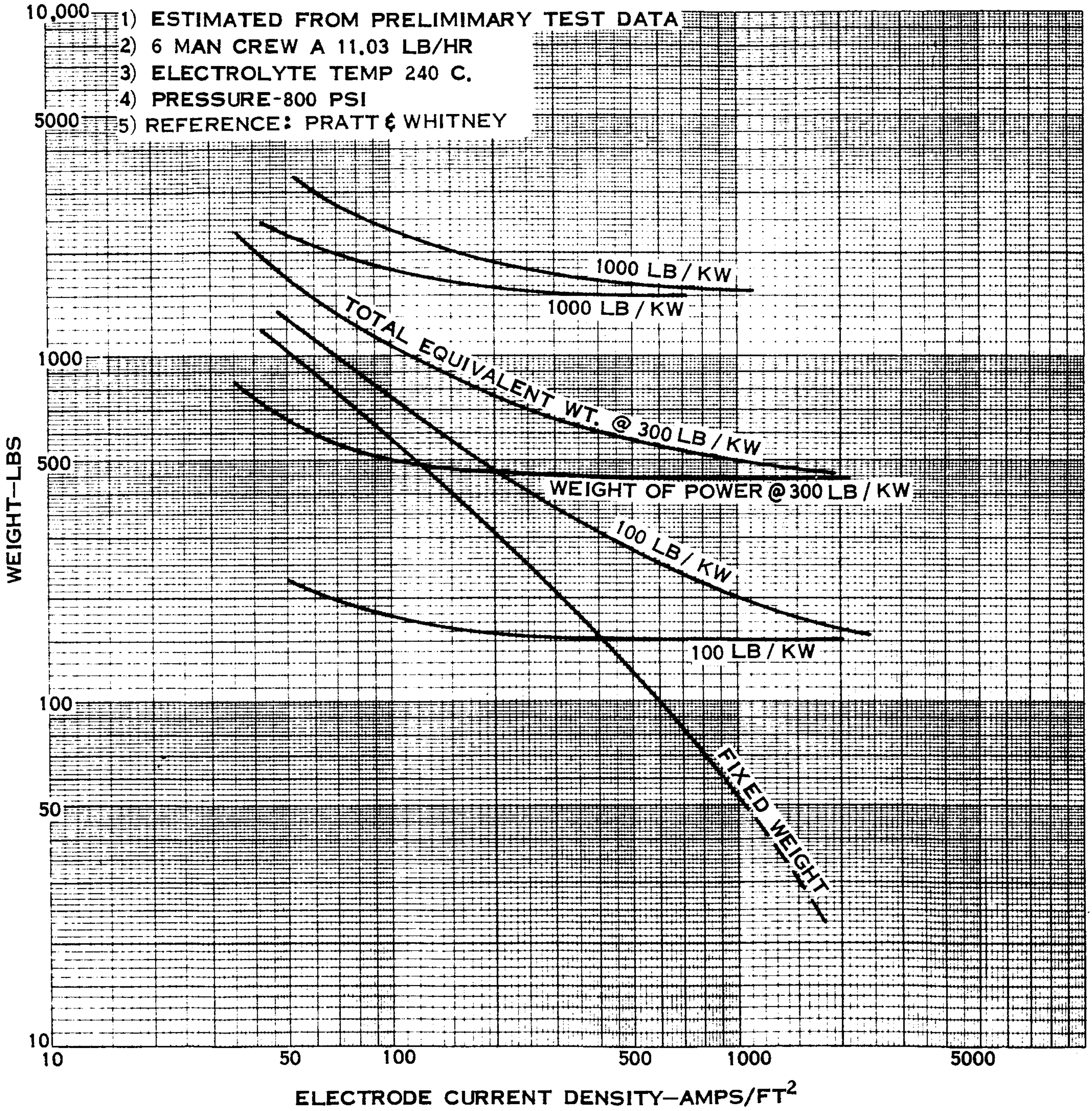


FIGURE 4-312

4.3.8 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-selective membrane, which permits the passage of the hydrogen ion but not the hydroxyl ion as illustrated in Figure 4-313. 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 4-314.

Figure 4-315 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 6.8 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 4-315, the equivalent weight at the 500 lbs/kw penalty is about 940 lbs. Predicted performance estimates by Ionics indicate a reduction of equivalent weight to the order of 750 lbs by 1973. This is illustrated in Figure 4-316. This particular system approach looks very promising for further spacecraft utilization.

4.3.9 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 4-317 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.

Preliminary data for this approach was obtained from Air Force Report No. ASD-TR-61-162 (Analytical Methods for Space Vehicle Atmospheric Control Processes) prepared by the AiResearch Manufacturing Co. Further discussions of this system approach are planned for the near future in this study to obtain a better estimation of its potential applicability for this system application. The

H_2O ELECTROLYSIS SYSTEM

ORGANIC MEMBRANE CELL OPERATION

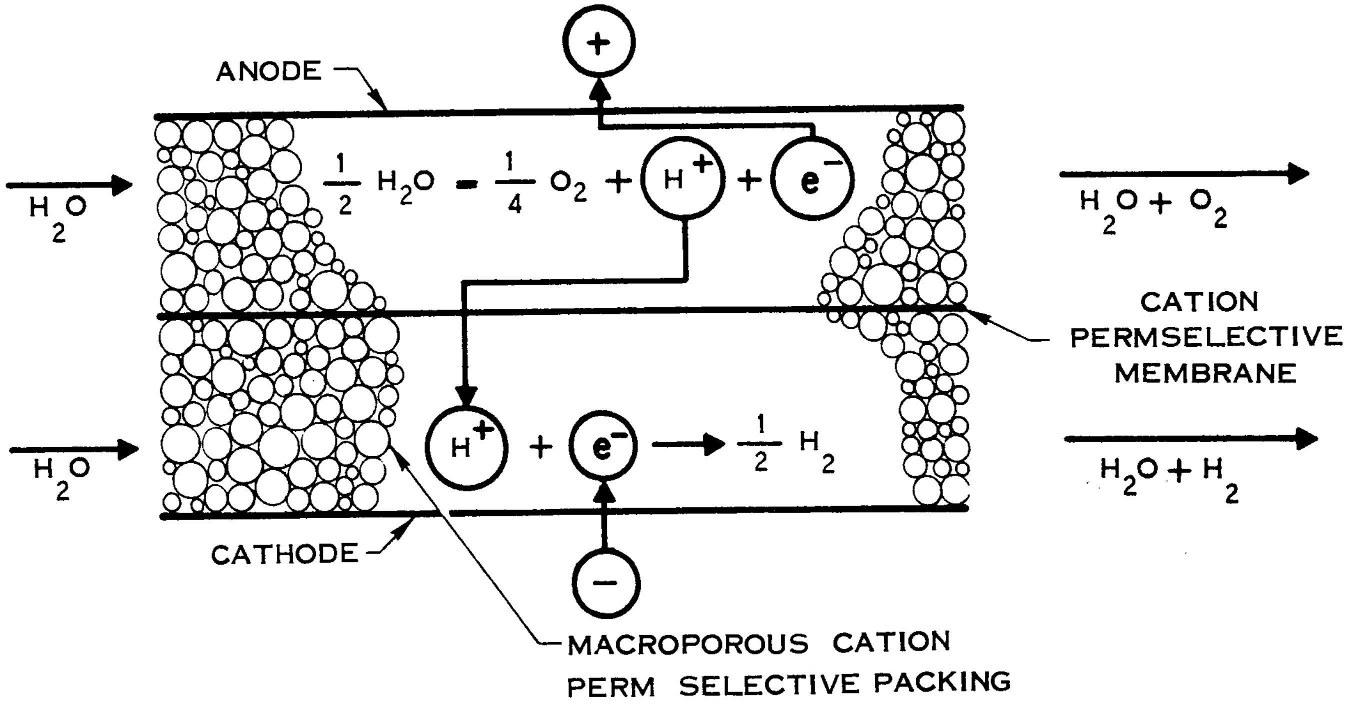


FIGURE 4-313

H_2O ELECTROLYSIS SYSTEM
ORGANIC MEMBRANE FLOW DIAGRAM

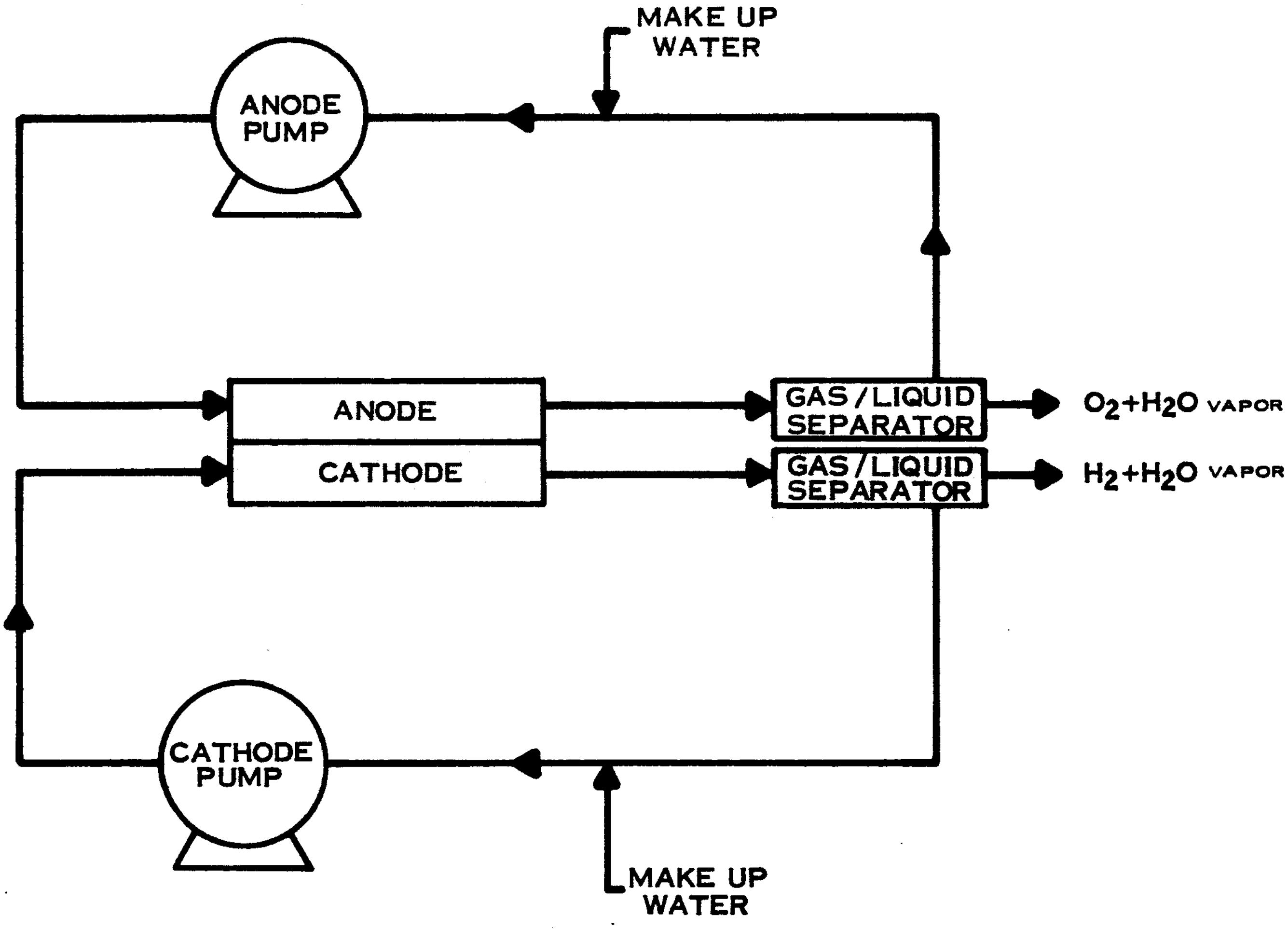


FIGURE 4-314

H_2O ELECTROLYSIS SYSTEM
STATE–OF–THE–ART–ORGANIC MEMBRANES

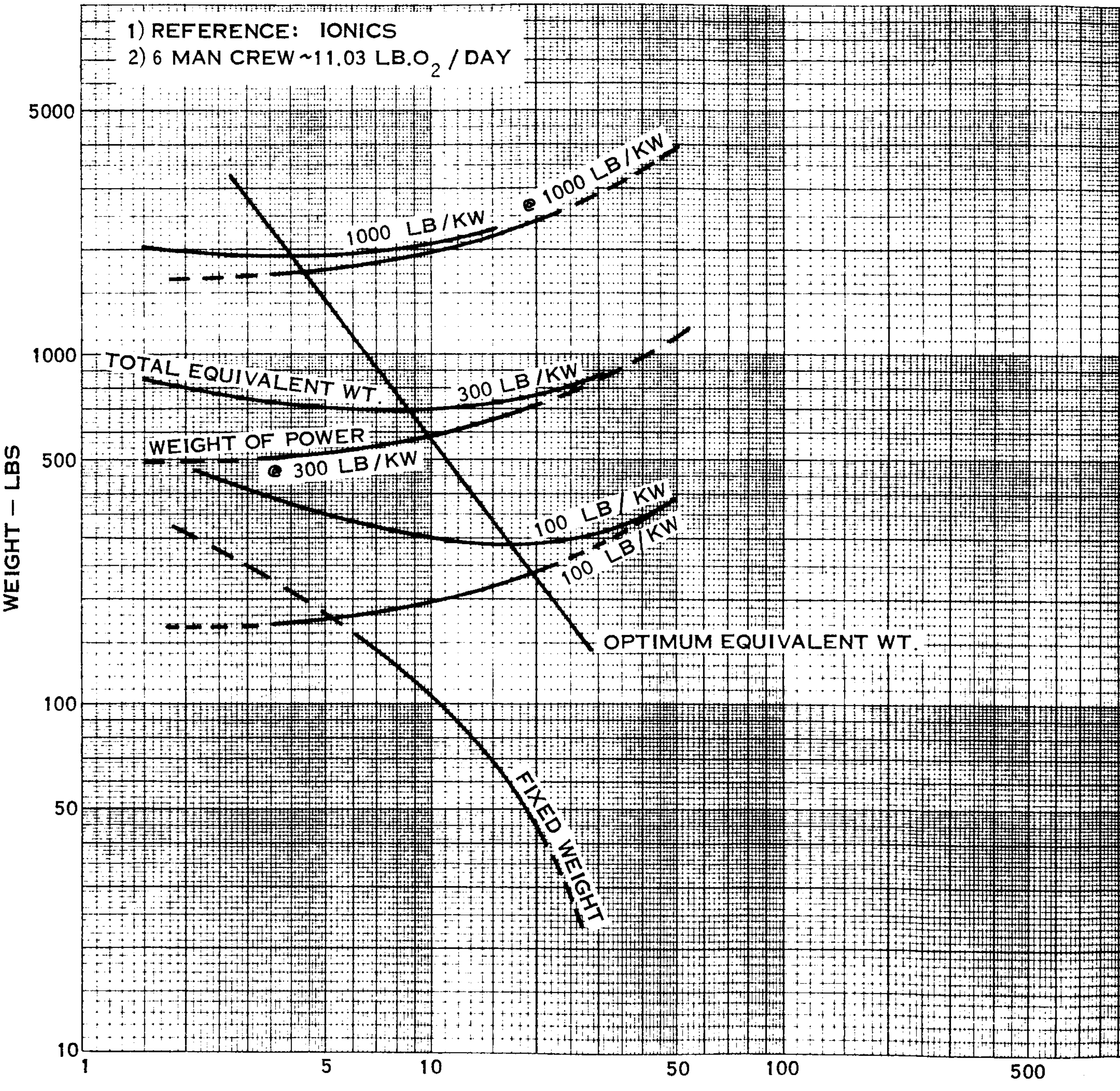


FIGURE 4-315

H_2O ELECTROLYSIS SYSTEM
PREDICTED PERFORMANCE — ORGANIC MEMBRANES

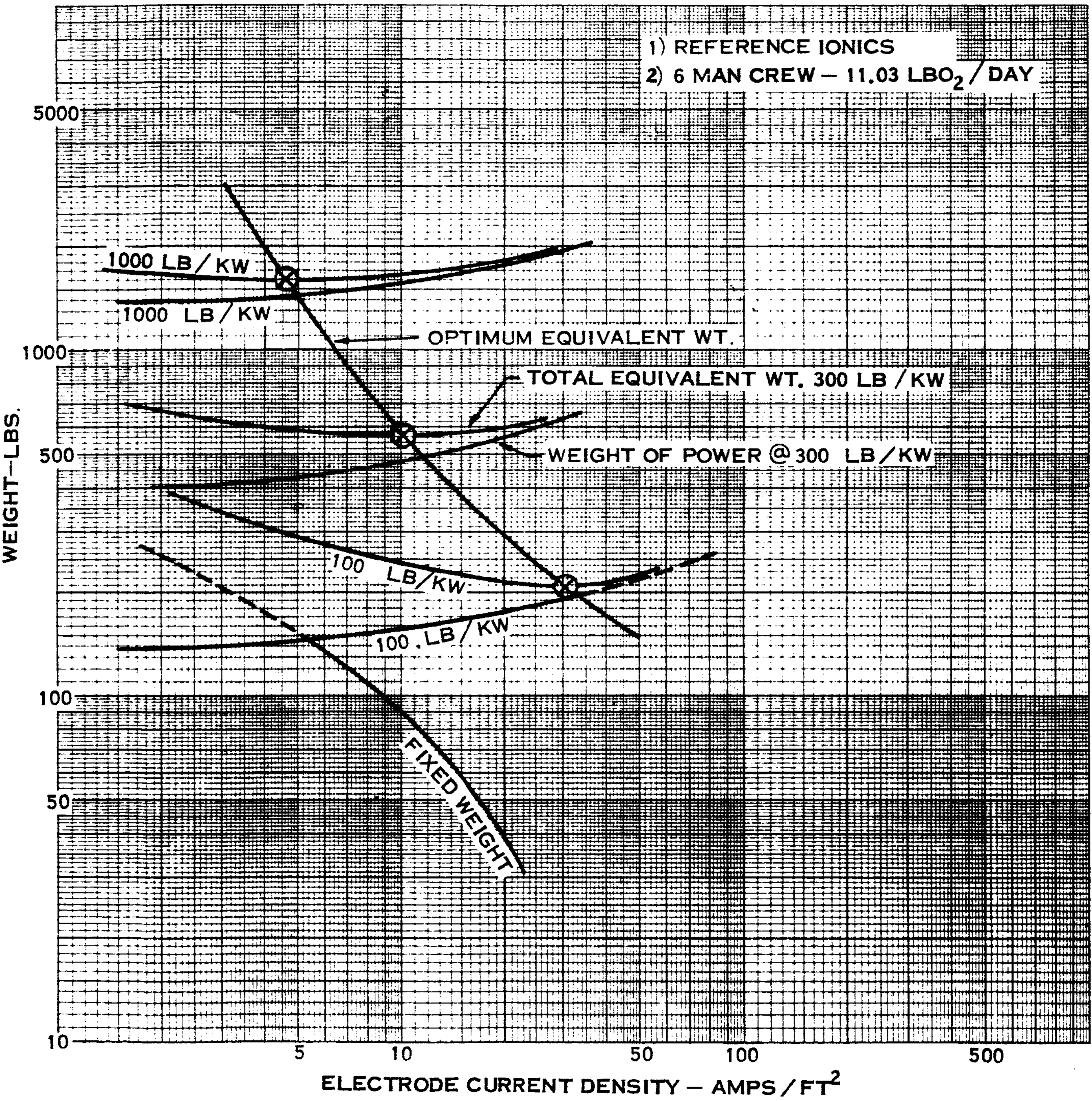


FIGURE 4-316

H_2O ELECTROLYSIS SYSTEM
ION EXCHANGE MEMBRANE ELECTROLYSIS CELL

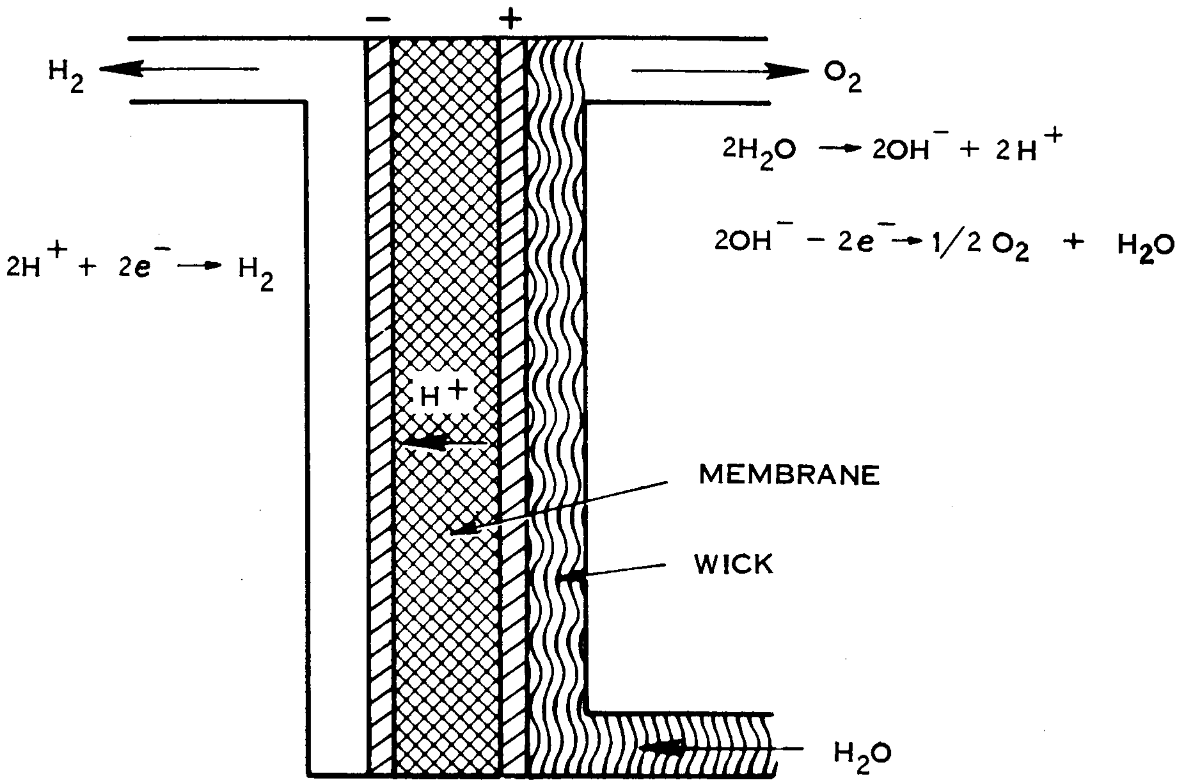


FIGURE 4-317

4.3.9 (Continued)

Illinois Institute of Technology Research Center has indicated an interest in the overall study and potential discussions with their personnel are hoped to indicate more fully the comparative merits of this system approach. It is mentioned in this report only as a candidate system due to the insufficient data available on it at this time.

4.3.10 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 investigated to date. However, to provide a representative set of data for further analysis, one system was selected as a representative candidate.

Of the systems investigated, the porous electrode unit being developed by TAPCO was selected for integration with other subsystems. It should not be concluded from these remarks that this system is the most promising and may ultimately be the optimum. However, the system does appear to be promising from an equivalent weight point of view. For system integration purposes, it is usually possible to consider the electrolysis system as a "black box" which takes in water 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.

It was decided to utilize the predicted performance data for the TAPCO cell as system inputs to the rest of the study because the Mars mission is far enough in the future that the performance should be attainable by that time.

To allow rapid utilization of this data in the system integration phase, several optimization curves are presented here. Figure 4-318 presents optimum fixed weight of the system on a function of water process rate and power penalty. Figure 4-319 presents the power used by the system selected from Figure 4-318 and the fixed weight and power are combined in Figure 4-320 to show the optimum equivalent weight.

In using these curves, it should be kept in mind that these curves represent optimizations and therefore apply to operation at that point only. If off-design performance is desired, it will be necessary to go back to the detail design curves to predict performance. This is particularly important in the case of increased water process rate, where the power may increase at a much more rapid rate with process rate than indicated by the optimization curves.

FIGURE 4–318

H_2O ELECTROLYSIS SYSTEM
OPTIMIM FIXED WEIGHT
VS.
WATER PROCESS RATE

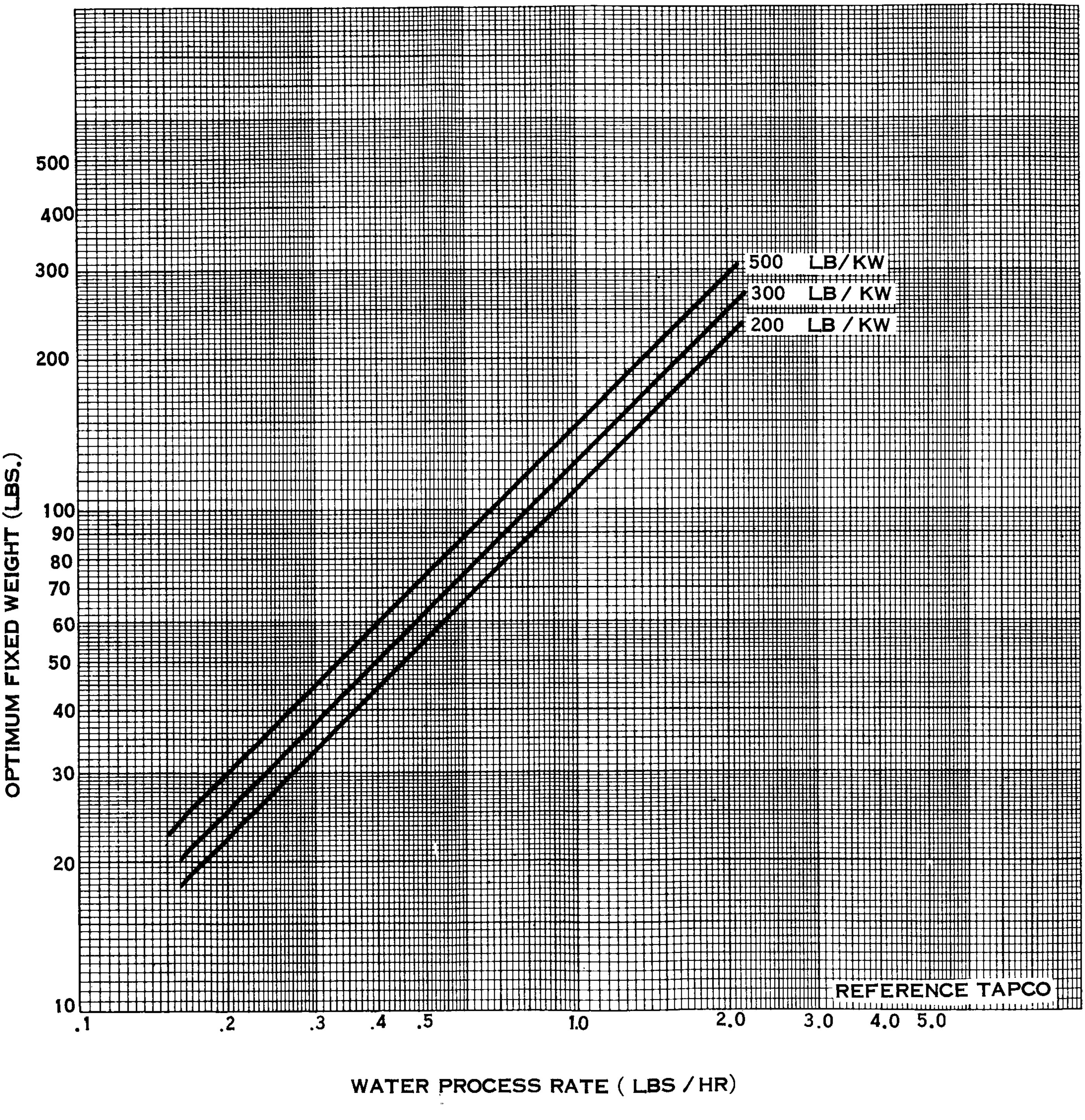


FIGURE 4–319

H_2O ELECTROLYSIS SYSTEM
OPTIMUM POWER
VS.
WATER PROCESS RATE

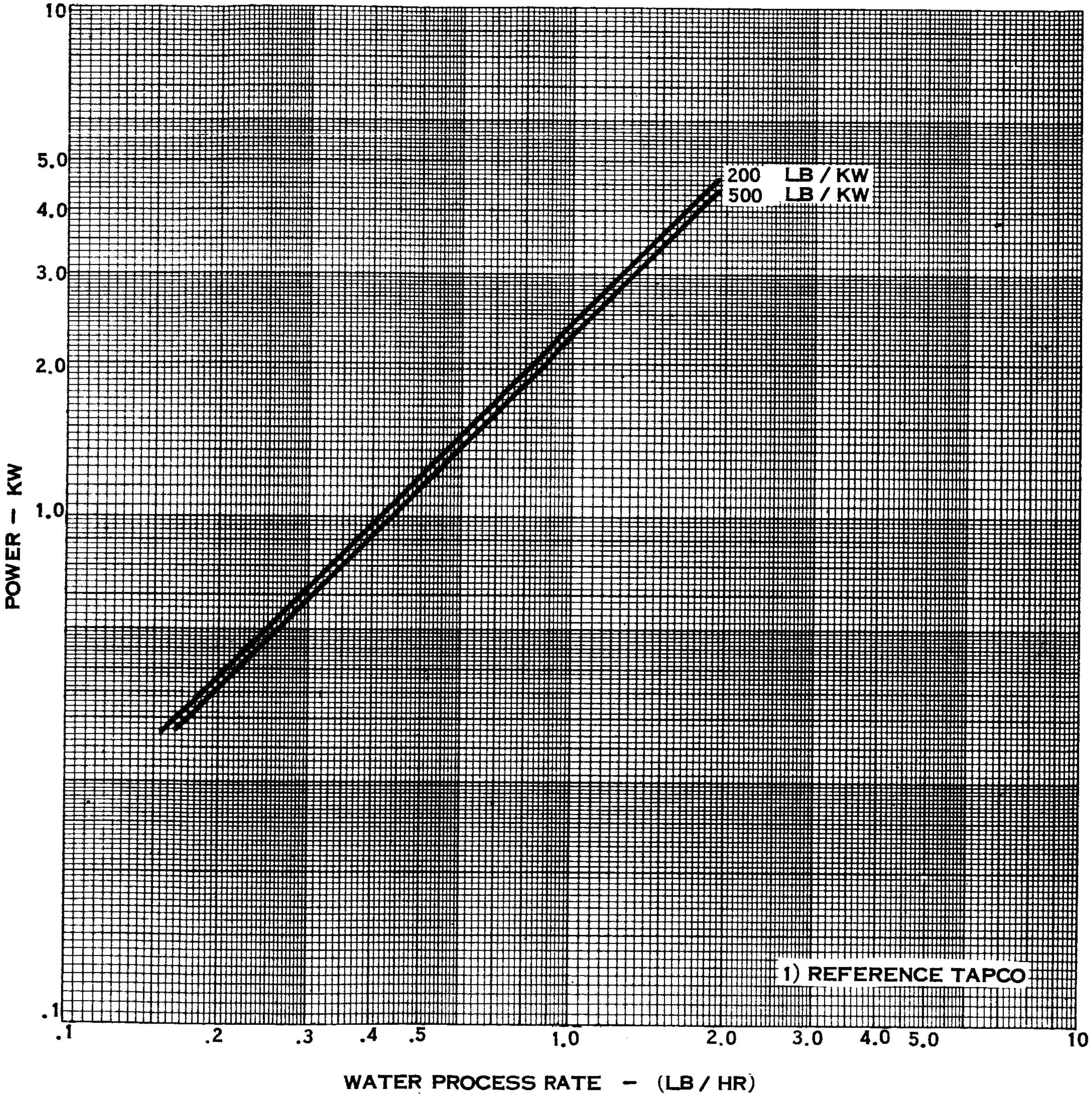
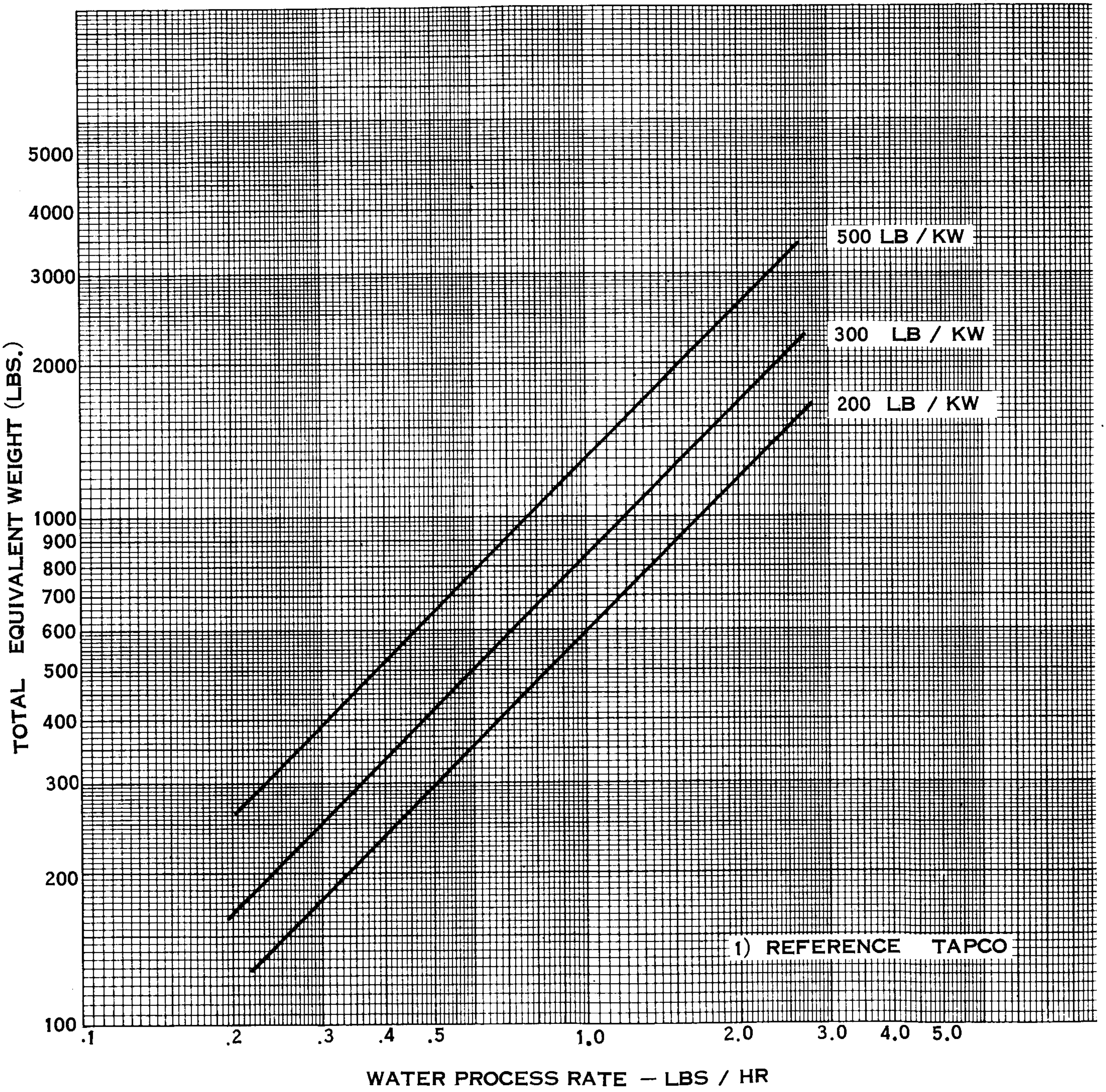


FIGURE 4–320

H_2O ELECTROLYSIS SYSTEM

OPTIMUM EQUIVALENT WEIGHT WATER
VS. WATER PROCESS RATE



5.0 ATMOSPHERIC CONDITIONING

5.1 Contaminant Control

5.1.1 Objectives

The purpose of the contaminant control subsystem is to insure a purified, breathable atmosphere by removing contaminant gases which could result in a toxic or explosive hazard. This system will have to cope with a wide variety of compounds produced both metabolically and from the vehicle systems.

The significant aspect of contaminant control is the fact that a space cabin is a small closed environment and for long term missions this will pose problems that do not exist in a normal earth environment. There are a great many compounds produced by man and his environmental equipment that are normally of no concern because the concentration always remains low and exposure is intermittent. However, in a small closed system these contaminants will progressively build up to toxic levels if they are not removed before concentration becomes critical. For example it has been reported that carbon monoxide is metabolically produced at a rate of about ten cubic centimeters per man day and is exhaled in the breath.

The only experience to date of man in closed environment is that from atomic submarines and project Mercury flights. Before a Mars Mission is undertaken this data 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 it is expected that this will be increased with later experimentation. However, all the substances found to-date can be classified into seven groups that can be removed or purified by three methods plus filtration. These three methods are:

(a) Adsorbtion on activated charcoal.

(b) Reduction in a catalytic burner

(c) Absorption in a chemisorbent cartridge.

It is believed that any future possible contaminants will also be controllable by the means outlined here. It should be mentioned at this point that water vapor and carbon dioxide are produced in such quantities that separate subsystems have been provided for their removal and control. The discussion of contaminant control will consist of three sections:

(a) A discussion of the anticipated contaminants.

(b) Discussion of methods of detection of major contaminants.

(c) Methods for removal of contaminants

5.1.2 Discussion of Contaminants

Since the prediction of future spacecraft contaminants is based on observations of the atmosphere on Project Mercury flights and on atomic submarines it would be logical to start by listing the contaminants that have been found to date. Table 5-1 taken from Reference 5, lists the contaminants found to be present in the atmosphere of a Mercury capsule. Table 5-2 lists contaminants identified in the atmosphere of nuclear submarines (Reference 2)

These contaminants are produced either metabolically or by any of the subsystem equipment. Although many potential sources of contamination exist within a space cabin the rate of generation is unknown since the sources are so unpredictable. Some of the major sources are:

1. Electrical equipment
2. Lubricants
3. Paints and other coatings
4. Leakage of stored gases
5. Chemical changes of materials caused by radiation

Extensive ground testing of the proposed space vehicle will reveal if the contaminant generation rate from the vehicle subsystem is high enough to warrant special removal treatment.

TABLE 5-1

A Compilation of All Contaminants Identified in the Atmospheres of Mercury Spacecraft

	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

TABLE 5-1 (Continued)

Contaminant	Formula	Concentration (ppm)**
26. Formaldehyde	CH_2O	-
27. Hexamethylcylotrisiloxane	$(CH_3)_6(SiO)_3$	-
28. Freon-22	CHF_2Cl	-
29. Freon-23	CHF_3	-
30. Freon-12	CF_2CCl_2	-
31. Freon-125	CF_3CF_2H	-
32. Hexene-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 minimum concentrations which would have ensued had all of the recovered contaminant been dispersed in the free volume of the cabin at one time. A dash indicates that quantitative values were not determined.

Reference: "Contamination Pattern in the Enclosed Atmospheres of Mercury Spacecraft," ASD-TDR-63-260, R. A. Saunders, U. S. Naval Research Laboratory, Washington, D. C.

TABLE 5-2

Contaminants that have been found in the atmospheres of nuclear submarines. The following have been identified quantitatively

Acetylene

Ammonia

Carbon Dioxide

Carbon Monoxide

Chlorine

Freon 12

Hydrocarbons

Hydrogen

Methane

Methyl Alcohol

Monethanolamen

Nitrogen

Nitrous Oxide

Oxygen

Stibine

Water Vapor

Cigarette Smoke

The following have been present in trace amounts.

Arsine

Benzene

Dimethylethybenzen

Ethylen

Paraethyl-Toluene

Freon 114

Gasoline Vapors

Hydrochloric Acid

Mesitylene

Propane

Pseudocumene

Sulphur Dioxide

Toluene

Zylene

TABLE 5-3

Sources & Production Rates of Valative Metabolically Generated Contaminants

Source	Contaminant	Daily Production Rate/Man		References
		Avg. or Range	Maximum	
Flatus		2,100 ml	2,650 ml	1, 2, 3
	Methane	108 ml	153 ml	1, 3
	Hydrogen	345 ml	446 ml	1, 3
	Hydrogen Sulfide	.0042 ml	.0064 ml	1, 3
*Feces		115 gs		
	Ammonia	25-84 mg	84 mg	4
	Phenols	0-210 mg	210 mg	4
	Total Volatile acids	2.66 ml .1 N	4.45 ml .1N	4
	Indole	90 mg	---	2
	Skatole	trace	---	2
	Hydrogen Sulfide	trace	---	2
	Methane	trace	---	2
	Methyl mercaptan	trace	---	2
*Urine		.6-2L		2, 6 (ref. 62)
	Acetone bodies	20 mg	---	4
	Ammonia	700mg	1380 mg	4
	Phenols	200 mg	330 mg	4
	Citric, formic, lactic acids	3.0 - 4.1 gs	4.1gs	4
Respired Air	Carbon Monoxide	10 ml	---	2, 5, 8
Perspiration		720 ml		
	Ammonia	60 mg	252 mg	4, 6
	Phenol	36 mg	57.6 mg	4,6
	Total volatile acids	2.4 - 5.6 ml .1N	5.6 ml .1N	4
	Lactic acid	1.6 gs	3.2 gs	4
*Saliva		864 ml		6
	Ammonia	38 mg		6 (ref 33)

TABLE 5-3 (Continued)

Other Constituents of Human Odor (Non quantitative)	Butyric acid, propyl mercaptan, ethereal sulfates Caprylic acid, valeric acid Ethyl Alcohol, Ethyl mercaptan (Ref. 7)

*Only a very minor portion of these should reach the breathable environment.

1. Taylor, E. R. "Physical and Physiological Data for Bioastronautics" School of Aviation Medicine, Randolph Air Force Base, Texas, 1958

2. Clemedson, C. J. "Toxicological Aspects of the Sealed Cabin Atmosphere of Space Vehicles" Astronautik 1 (1959):4 (Swedish)

3. Kirk, Gastroenterology 12:782-794, 1949

4. Wallman, H. and Barnett, S. "Water Receovery Systems (Multivariable)" Wadd TR 60-243, Mar. 1960.

5. Bogatkov, P. I., Et Al, "Presence of Carbon Monoxide in Confined Chambers" Voyenno - Meditsinskiy Zhurnal, No. 2, Feb. 1961, 37-39 (Russian), English Translation in: Military Medical Journal, 1961 (2): 55-58

6. Blood and Other Body Fluids, ASD TR 61-199, 1961

7. Air Conservation Engineering Connor Engineering Corp., Danbury, Connecticut, 1953.

8. Hamilton Standard Test Experience

TABLE 5-4

Recommended Maximum Allowable Concentrations

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 Tetrachlorine	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	
Pethyl 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	---	5.3%- 14% * (explosive)
Methyl Alcohol	200	
Methyl Cellosolve	25	
Methyl Ethyl Ketone	200	

TABLE 5-4 (Continued)

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

References:

1. American Conference of Governmental Industrial Hygienists, "Threshold Limit Values for 1961"
2. * Sax, N.I., "Dangerous Properties of Industrial Materials, Reinhold Publishing Corporation, New York, 1957.

TABLE 5-5

EFFECTS OF CONTAMINANTS ON MAN

1. Asphyxiants

Simple

- Carbon Dioxide
- Helium
- Hydrogen
- Methane
- Nitrogen

Chemical

- Carbon Monoxide
- Cyanogen
- Hydrogen Cyanide
- Nitro Benzene

2. Dusts

Nuisance

- Slate
- Taic

Fibrosis Producing

- Asbestos
- Silica

3. Irritants

Upper Respiratory Tract

- Ammonia
- Sulfur Dioxide

Upper Respiratory Tract and Lungs

- Bromine
- Chlorine
- Fluorine
- Iodine
- Ozone

4. Narcotics

- Acetone
- Ether
- Ethyl Alcohol
- Propane
- Propyl Alcohol

5. Poisons

- Antimony
- Arsenic
- Benzene
- Carbon Disulfide
- Lead
- Mercury
- Methyl Alcohol
- Phenols
- Phosphorous
- Sulfur
- Toluene

Reference: Breeze, R. K.; "Space Vehicle Environmental Control Requirements Based on Equipment and Physiological Criteria"; ASD TR 61-161, Part I, Dec., 1961.

5.1.2 (Continued)

The metabolically produced contaminants are much more predictable and their rates of generation have been documented. In this study it has been assumed that the crew would be composed of non-smokers, thus eliminating one source of contaminants. Table 5-3 is a list of the anticipated metabolic contaminants.

Table 5-4 specifies the level of each contaminant which can be tolerated before becoming toxic or hazardous. It should be remembered that these valves 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 dissipate before another exposure, and to reduce to very low levels over week-ends. However, since the exposure in the spacecraft will be continuous, lower levels of concentration may have to be maintained. Table 5-5 illustrates the classification of contaminants according to physiological considerations.

5.1.3 Methods of Detection

A complete contaminant control system 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 preceeding 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 environments will be required to positively establish which contaminants need 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.

5.1.4 Methods of Contaminant Removal

The tables in the previous sections have listed a large number of contaminants that have been observed in space capsules and nuclear submarines. Due to the large number of compounds listed it is necessary to classify them into groups according to their chemical characteristics in order to discuss methods of removal. Table 5-6 has divided the various types of contaminants into seven main groups.

From analysis of the various groups of contaminants, it has been determined that these contaminants can be removed by a system which includes filtration, adsorption by activated charcoal, oxidation in a catalytic burner, and absorption in a chemisorbent bed. Table 5-7 illustrates which contaminants can be removed by each method. These four methods will be combined into an integrated subsystem as shown by the schematic on Figure 5-1.

5.1.4.1 Functioning of Components

5.1.4.1.1 Debris Trap

The 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.

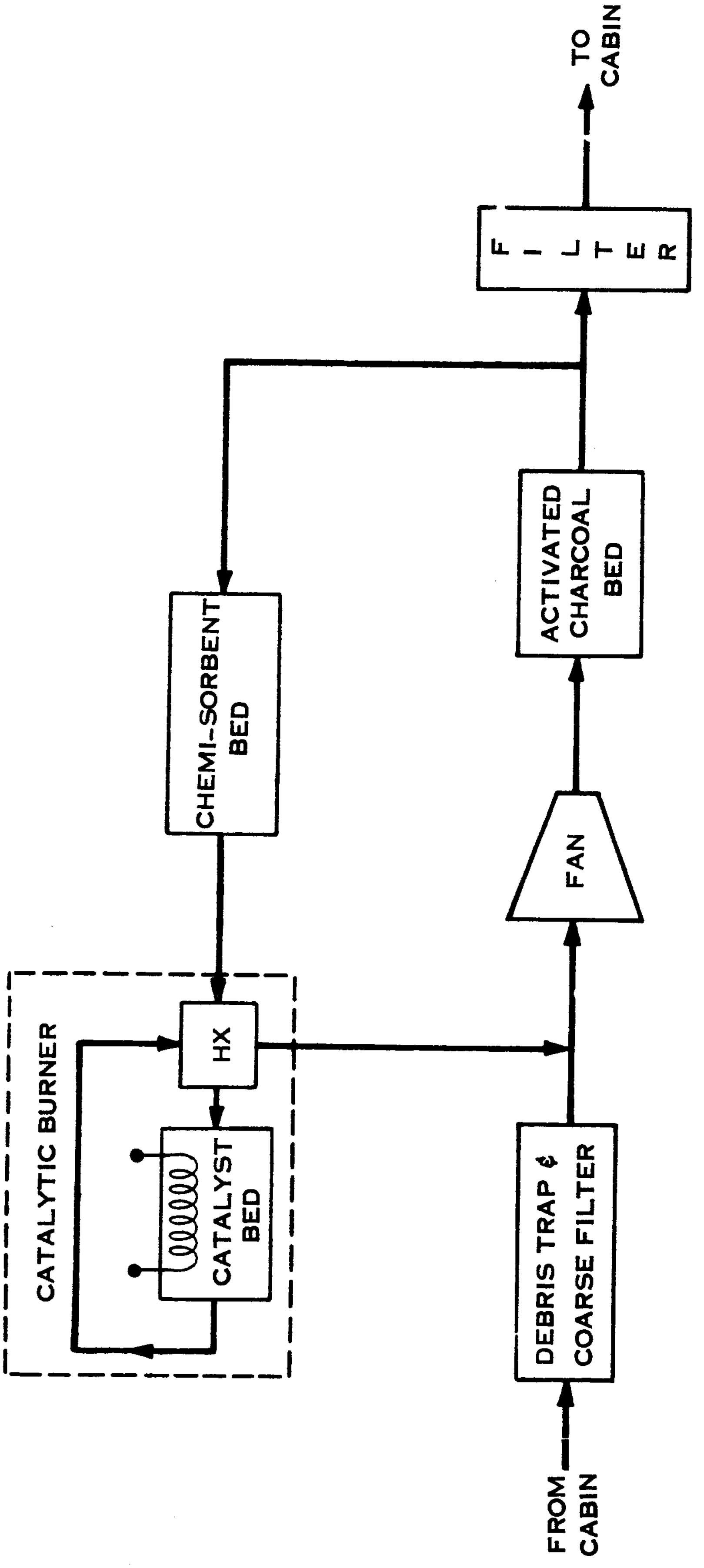
5.1.4.1.2 Fan

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.

5.1.4.1.3 Activated Charcoal Bed

Referring to Tables 5-6 and 5-7, the high molecular weight constituents of Groups I through V can be physically adsorbed in such materials as activated charcoal. An adsorbent such as charcoal removes contaminants by trapping molecules in a submicroscopic 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 Wall's forces.

Activated carbon is prepared by burning away 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 on internal surface area of approximately five million square feet, therefore providing the tremendous capacity of this material.



PRELIMINARY SYSTEM SCHEMATIC

FIGURE 5-1

TABLE 5-6

Identification and Classification of Contaminants

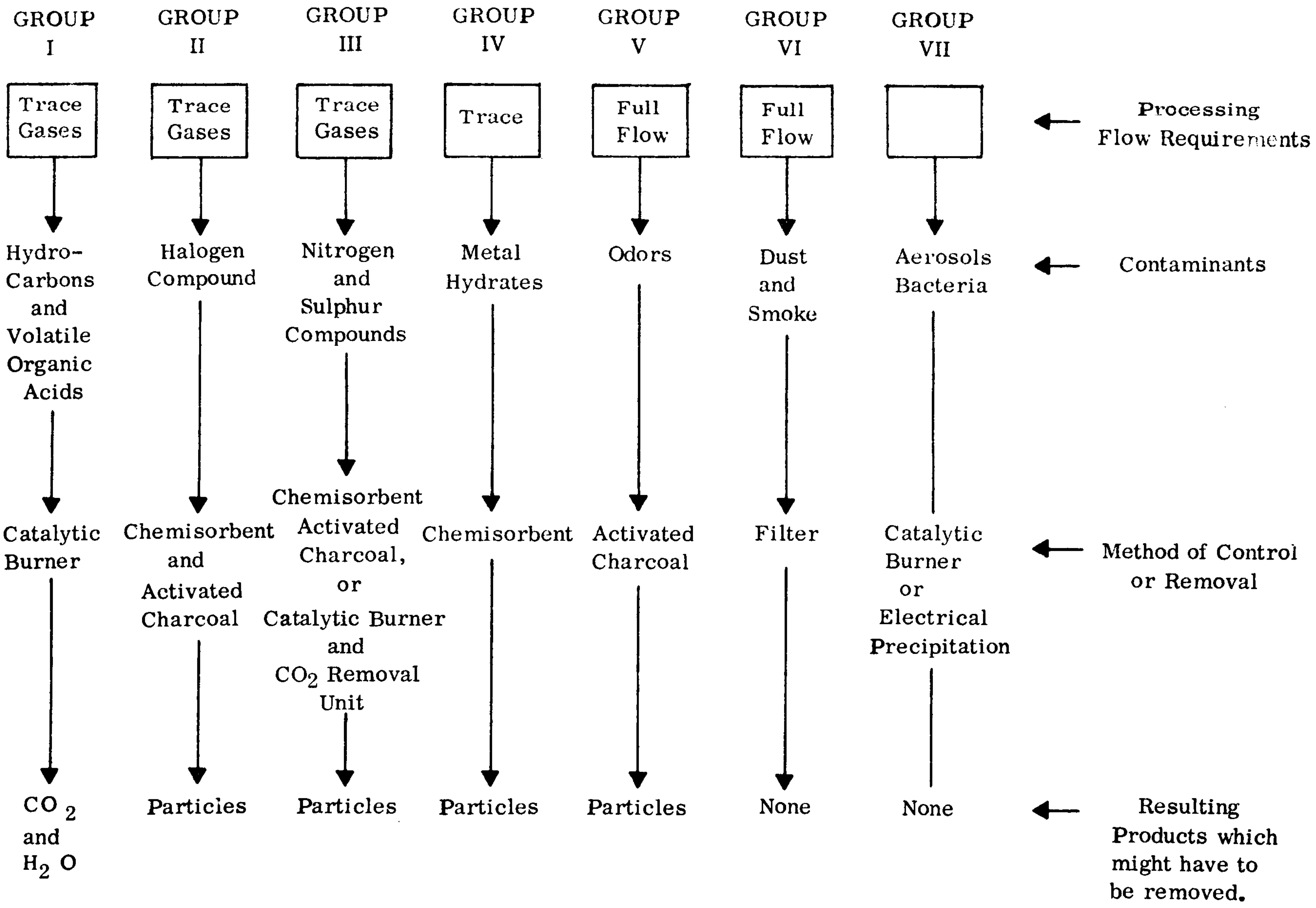
	Group I Oxidizable to CO_2&H_2O	Group II Halogen Compounds	Group III Nitrogen & Sulfur compounds	Group IV Metal Hydrides	Group V Odors	Group VI Dusts & Smoke	Group VII Other
Quantitatively identified in submarines	Acetylene Carbon Monoxide Hydrocarbons (General) Hydrogen Methane Methyl Alcohol	Chlorine Freon 12 Hydrogen Fluoride	Ammonia Nitrogen dioxide Nitrous oxide	Stibine			Aerosols Bacteria Colon-inhabitin bacilli Diplococci Spore-forming bacilli Staphylococci Streptococci Ions
Qualitatively identified in submarines	Benzene Dimethyl-5 ethyl benzene Ethylene P-ethyl toluene Gasoline vapors Mesitylene Propane Pseudocumene Toluene O-xylene M-xylene P-xylene	Freon 114 Hydrogen Chloride	Sulfur Dioxide	Arsine			

TABLE 5-6 (Continued)

	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
Probable Others	Formaldehyde Phenols Volative organic acids (formic, butyric etc.)	Halogenated solvents	Volative amines & amino acids Hydrogen cyanide Skatole Hydrogen sulfide Indole Mercaptans		Body odors Equipment odors Food odors	Ash particles Inorganic dusts Metallic dusts Organic dusts	

Reference:

"Chemical Constituents of Submarine Atmospheres"
NRL Report 5465, U.S. Naval Research Laboratory
Washington D. C., 1960



	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	Halogen Compound	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

ANALYSIS OF THE PRELIMINARY SYSTEM DESIGN REQUIREMENTS

TABLE 5-7

.1.4.1.3 (Continued)

The factors that increase the tendency for a substance to be adsorbed on charcoal are:

(a) high molecular weight
(b) low vapor pressure
(c) Presence of a large number of carbon atoms in the molecule
(d) 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.

Upon leaving the charcoal bed, a small portion of the flow (approximately 1%) is split off from the main stream and circulated through the chemi-sorbent bed and catalytic burner then back to the main stream to remove the remaining contaminants.

.1.4.1.4 Chemi-sorbent Bed

The chemi-sorbent 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 hydrates 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 chemi-sorbent 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:

(a) Removal of ionic contaminants - Ammonia is the principal anionic contaminant and is the only one to be removed by the chemi-sorbent 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.

5.1.4.1.4 (Continued)

(b) Neutralization of acidic and basic gases - Acidic gases can be absorbed on Li OH and basic gases on "Acid washed" silica gel.

(c) 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.

(d) 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.

It is anticipated that nitrogen oxides will be removed by the CO_2 removal system.

5.1.4.1.5 Catalytic Burner

The catalytic burner was selected as the most practical method of controlling the contaminants listed in Group 1 of table 6, particularly carbon monoxide, hydrogen and methane since these could be present in relatively large quantities. The portion of the atmospheric-flow that passes through the chemi-sorbent bed and catalytic burner would be heated to 550°F in the presence of a catalyst and the contaminants would be oxidized to carbon dioxide and water. At Hamilton Standard extensive testing has been carried out on a prototype catalytic burner.

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 fiber-glass and aluminum foil sealed in an evacuated cylinder. This insulation and the heat exchanger maintain the power requirements at a minimum level.

5.1.4.1.6 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.

4.2 (Continued)

System Sizing

Analysis of the contaminants, their generation rate and the maximum acceptable concentration 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. It has been observed that a concentration of CO as low as 10ppm can result in carelessness and inattention over an extended period of time. Therefore the MAC has been set at a partial pressure corresponding to 5 ppm in a normal earth environment (STP) in order to size this system flow.

Figure 5-2 shows the time required to reach the MAC for a given production rate and process rate. The process rate is the sum of the flow through the catalytic burner plus the cabin leakage. Time in days divided by cabin volume in cubic feet is plotted as a useful parameter. The following table shows the time parameter for the various modules.

Module	MMM	MEM	ERM
Men	6	2 or 4	6
Time	420 days	40 days or 55 hr.	12 hr
Volume	3000 ft^3	1000	320
t/vc	0.14	.04 or .00229	.00156

These values of t/Vc can be used to illustrate the use of the Figure 5-2. It can be seen that for the MMM and the 40 day mission in the MEM the process rate is on the vertical asymptotic portion of the curve. For the MMM the process rate required is too great to be achieved with cabin leakage and a catalytic burner is required. In contrast with this the short missions in the MEM and ERM have a t/Vc below the curve so no leakage or catalytic burner is required, provided that the atmosphere is pure at the commencement of the mission.

Figure 5-3 can be used to size the catalytic burner and chemi-sorbent bed. For example, for the MMM, assuming zero leakage the required process flow would be 0.72 lb/hr. As a margin of safety assume a 1.0 lb/hr. flow and the required weight and power would be 7.8 lb and 13.5 watts.

FIGURE 5–2
ACCUMULATION TIME VS. PROCESS RATE
FOR CO AS CRITICAL CONTAMINANT

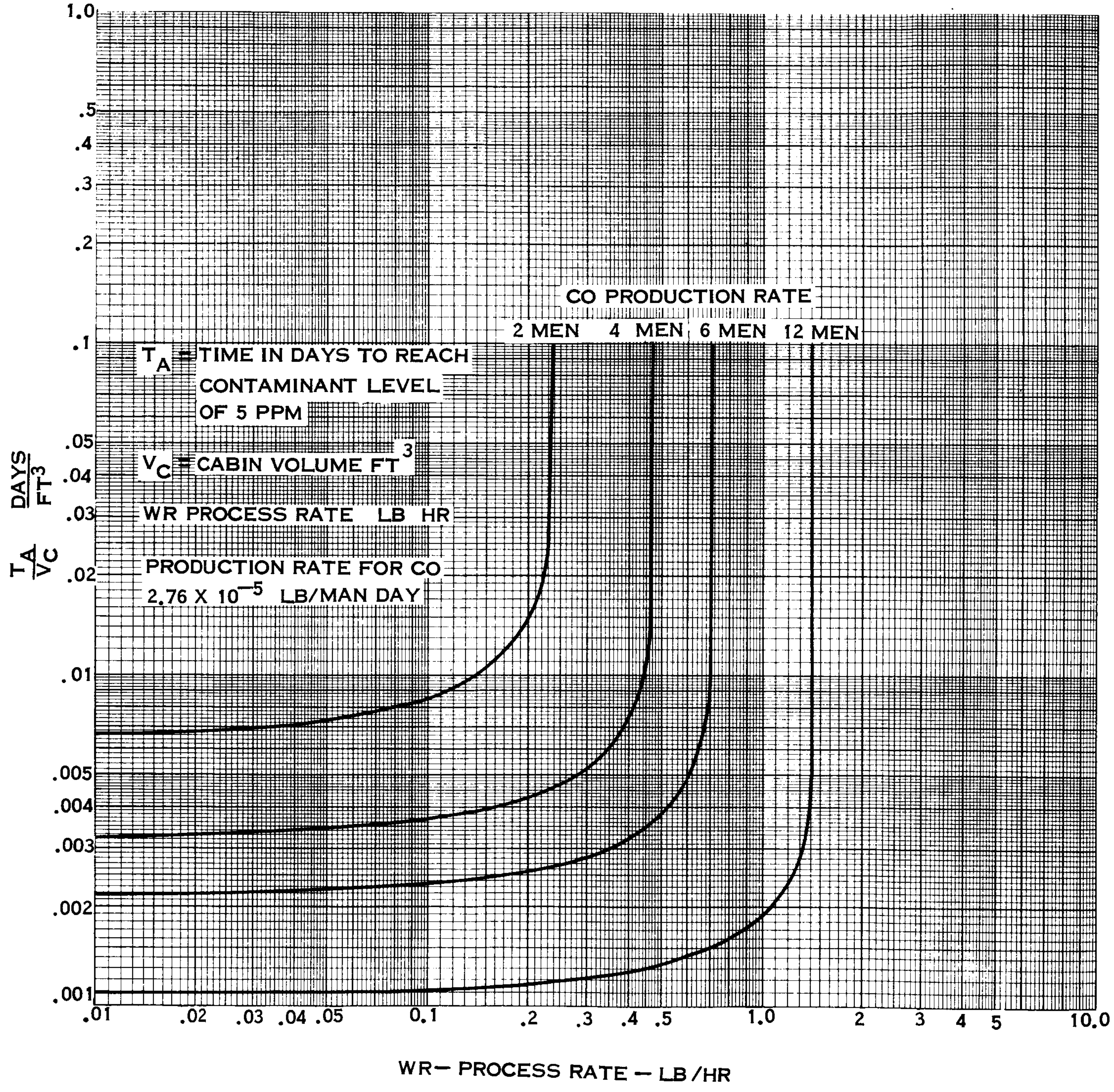
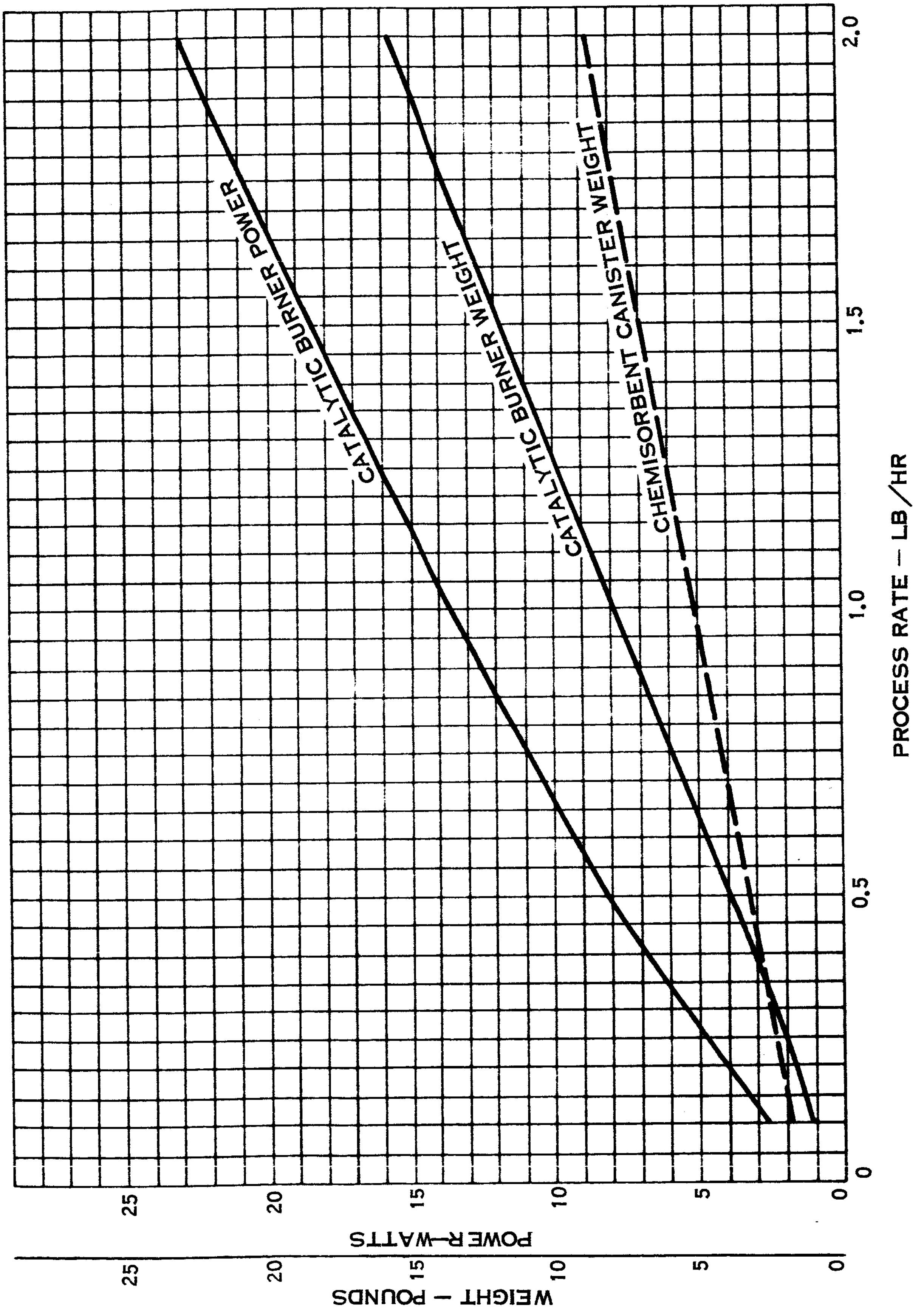


FIGURE 5–3

POWER AND WEIGHT VS. PROCESS RATE FOR CATALYTIC BURNER AND CHEMISORBENT CANISTER



5.1.5 References

1) Hamilton Standard - EPC3806 - 1
February / 63 Prototype Air Purification System for Moss

2) USN Medical Research Laboratory
Department 367 Dec/61
Atmosphere Control in Closed Space
Environment (Submarine) LCDR, MC Arnest

3) TP-63 - 03
Trace Analysis of Fixed Gases by Gas Chromatography May/63
Sid Russel AIHA Conference

4) MRL - TDR - 62 - 68
Sanitation & Personal Hygiene
During Aerospace Missions, June/62
Contract No. AF33 (616) - 7754 by Spacelabs Inc.

5) Report NRL Progress P13 181409
January/63
Atmosphere Contamination in the Space 'Cabin
R. A. Saunders

6) NASA Tech Note D-1825
GAS Chromatographic Measurement of Trace Contaminants in a
Simulated Space Cabin by H. C. McKee
Southwest Research Institute

7) ASD Technical Report 61-161
Part 1
Space Vehicle Environmental Control Requirements
December/61
R. K. Breeze N.A.A.

5.2 CO_2 REMOVAL

5.2.1 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 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 and expendable weights on an equal basis for the so-called open life support system approach.

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. These will be considered during the system integration portion of the study. Therefore, the data presented in this section and the analysis and discussion assumes that no requirement exists for CO_2 collection.

The comparative curves presented 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 from the data presented. The detailed analysis of these systems was performed for power penalties from 200#/KW to 500 #/Kw. However, based on instructions from NASA, the 500 #/KW value was used for comparison studies. 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 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 is in process, this point will be re-evaluated for the candidate systems in an attempt to lower the overall equipment weight. In this analysis, however, the maximum temperature specified for the thermal control coolant loop (140°F) was considered as the maximum available. 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 create needless extra effort. Upon elimination of non-candidate systems, these other factors will be considered more fully as selection criteria.

5.2.2 Discussion of Data Presentation

The schematic presented for each system is an individual system schematic without

5.2.2 (Continued)

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 the information presented on each individual system, the important parametric curves are presented in a summary form so that all systems can be compared conveniently.

5.2.3 CO_2 Removal By Membrane Diffusion

5.2.3.1 Introduction & Data Source

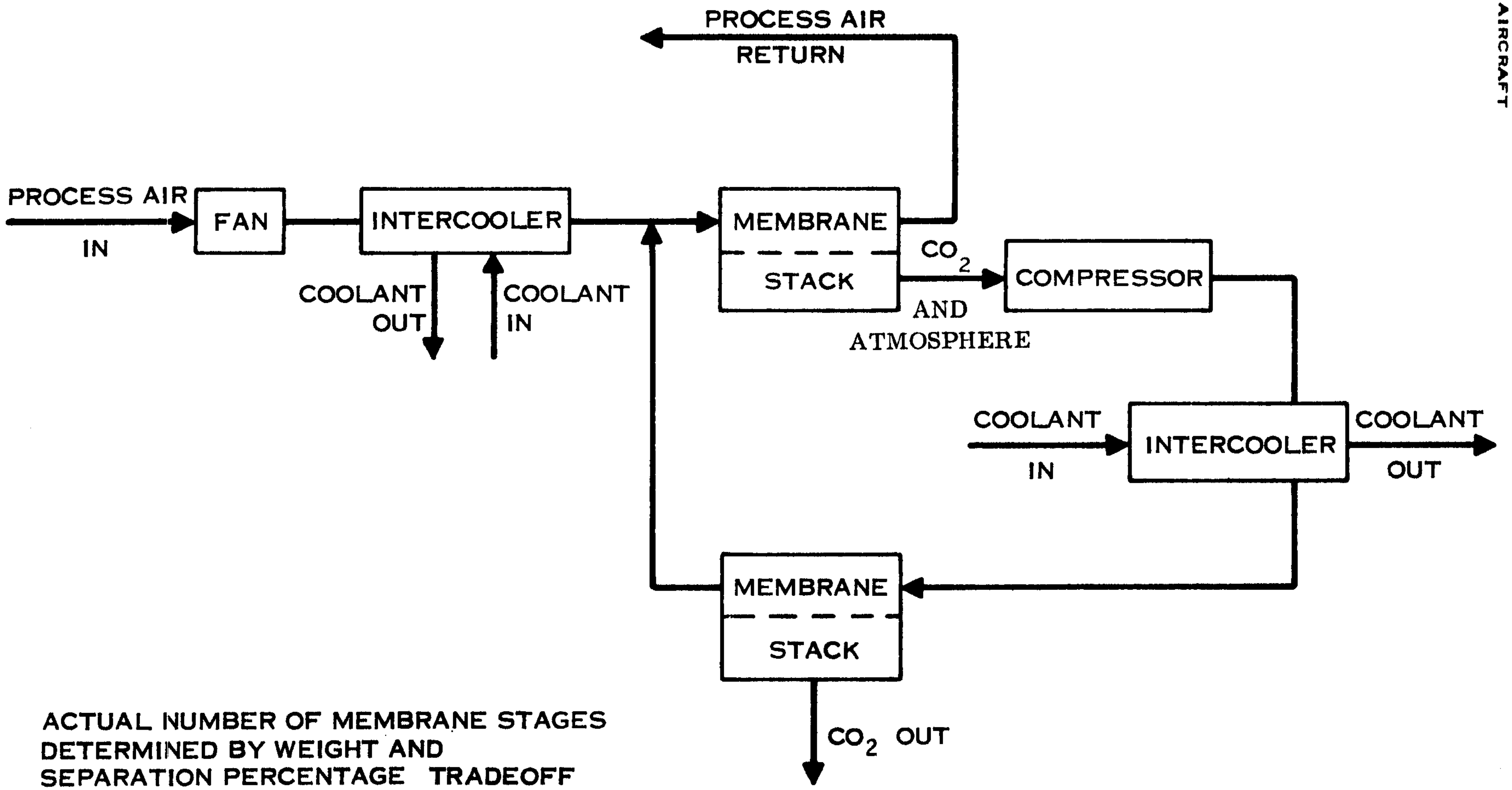
The analysis of a CO_2 removal system using selective permeability membranes as the concentration media was based on previous Hamilton Standard design data and limited information available in current progress reports from the State University of Iowa to the NASA on a current contract (Reports Number 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.

5.2.3.2 System Description

Figure 5-201 presents the schematic approach to the system considered in this analysis. 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 heat of compression of the fan is rejected to a circulating coolant from the main thermal control system. 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 sta is returned to the cabin or main environmental control system.

MEMBRANE DIFFUSION CO_2 REMOVAL



ACTUAL NUMBER OF MEMBRANE STAGES DETERMINED BY WEIGHT AND SEPARATION PERCENTAGE TRADEOFF

FIGURE 5-201

5.2.3.2 (Continued)

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 re-cooled 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 second 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. From the second stage membrane stack and any further stack, the process air which has passed through the membrane stack is returned to the inlet of the previous stage where the cycle is repeated. The gas permeated through the last 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. Eight stages are necessary representing 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 stack could lead to serious design and manufacturing problems.

5.2.3.3 Conclusions

The membrane diffusion process is attractive in that it exhausts the CO_2 at some pressure as opposed to space vacuum desorption, thus offering simplified integration with CO_2 reduction equipment. Weight, developmental status, and complexity weigh heavily against it at this time. Compressor reliability as well as required compressor power are very unattractive for this type of system, 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 structual members may prove to be a considerable design problem when faced with actual flight hardware design.

5.2.4 CO_2 Removal by Mechanical Freeze-out Processes

5.2.4.1 Introduction and Data Source

Mechanical freeze-out is one of the two freeze-out processes considered in this study. It is somewhat attractive method of CO_2 removal in that the CO_2 may be returned for further application 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 previous in-house Hamilton Standard subsystem selection work in CO_2 removal.

5.2.4.2 System Description

The system considered in this analysis is presented schematically in Figure 5-202. 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. This was deemed necessary because freezing out water vapor as well as the CO_2 is impractical due to the high heat of condensation of water which makes regenerative heat exchange difficult without providing a higher temperature differential across the air motor. Eliminating water freeze-out reduces system operating pressure and compressor weight and power since lower compressor temperatures can be utilized. Thus, the more optimum method is utilization of a desiccant to pre-dry the air prior to processing.

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 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 vaporize the CO_2 in the off line collector and to dry out the off line 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.

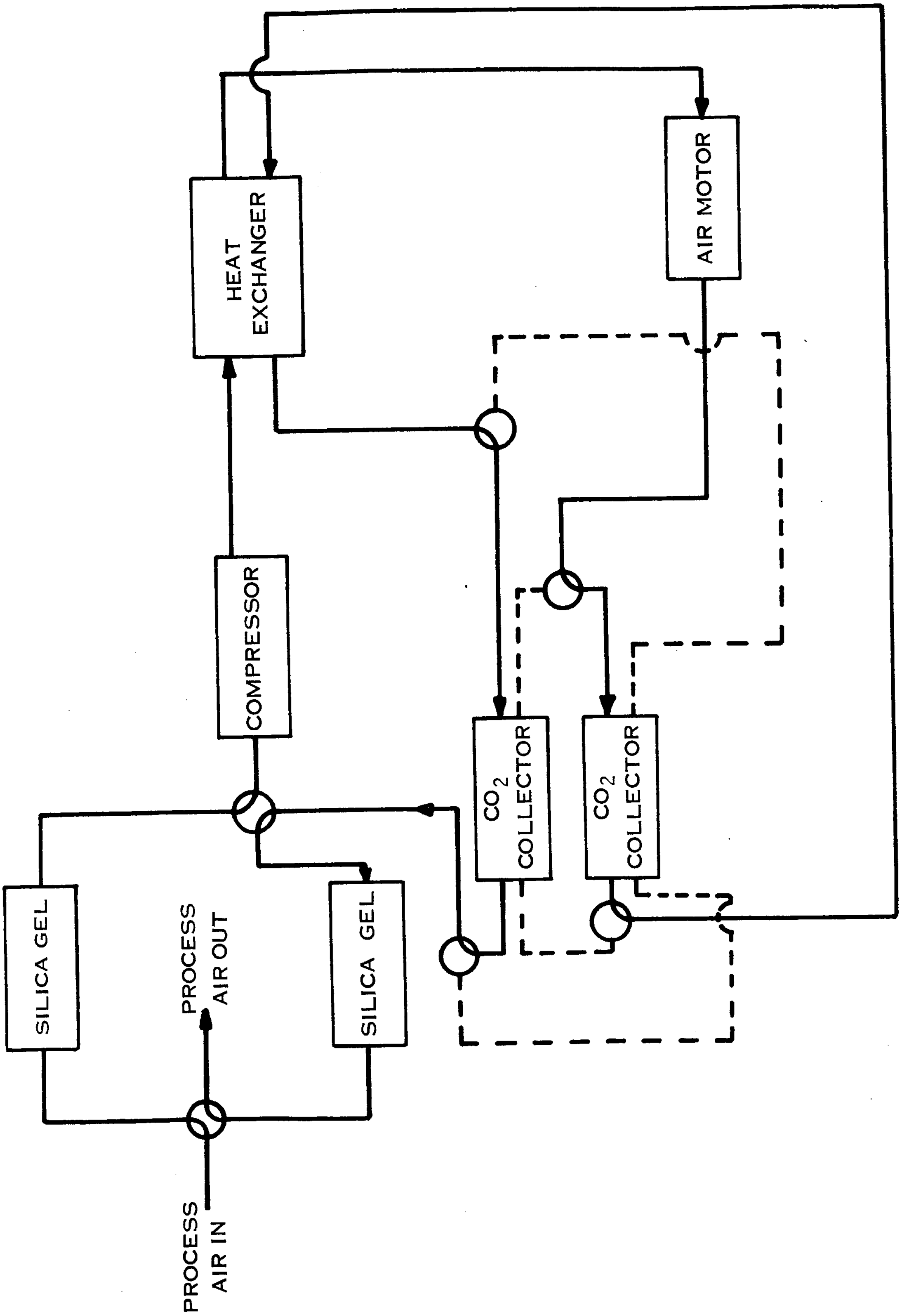


FIGURE 5-202
MECHANICAL FREEZE-OUT CO_2 REMOVAL

5.2.4.2 (Continued)

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.

5.2.4.3 Conclusions

Mechanical freeze-out as a CO_2 removal method for the Mars Mission 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.

5.2.5. CO_2 Removal With Cryogenic Freeze-out

5.2.5.1 Introduction and Data Source

Cryogenic freeze-out is the other method of CO_2 freeze-out of both the CO_2 and the moisture with subsequent sublimation to space. This proves unattractive for Mars Mission use, however, due to the water loss with the CO_2. 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 adsorbtion with a heated purge return to the cabin and cryogenic freeze-out for CO_2 removal only.

Figure 5-203 presents the system schematic analyzed in the study. Process air from the main thermal control system enters the system at a temperature of 50°F and proceeds to a moisture adsorbtion 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 it is used to freeze the CO_2. 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

CRYOGENIC FREEZE–OUT CO_2 REMOVAL

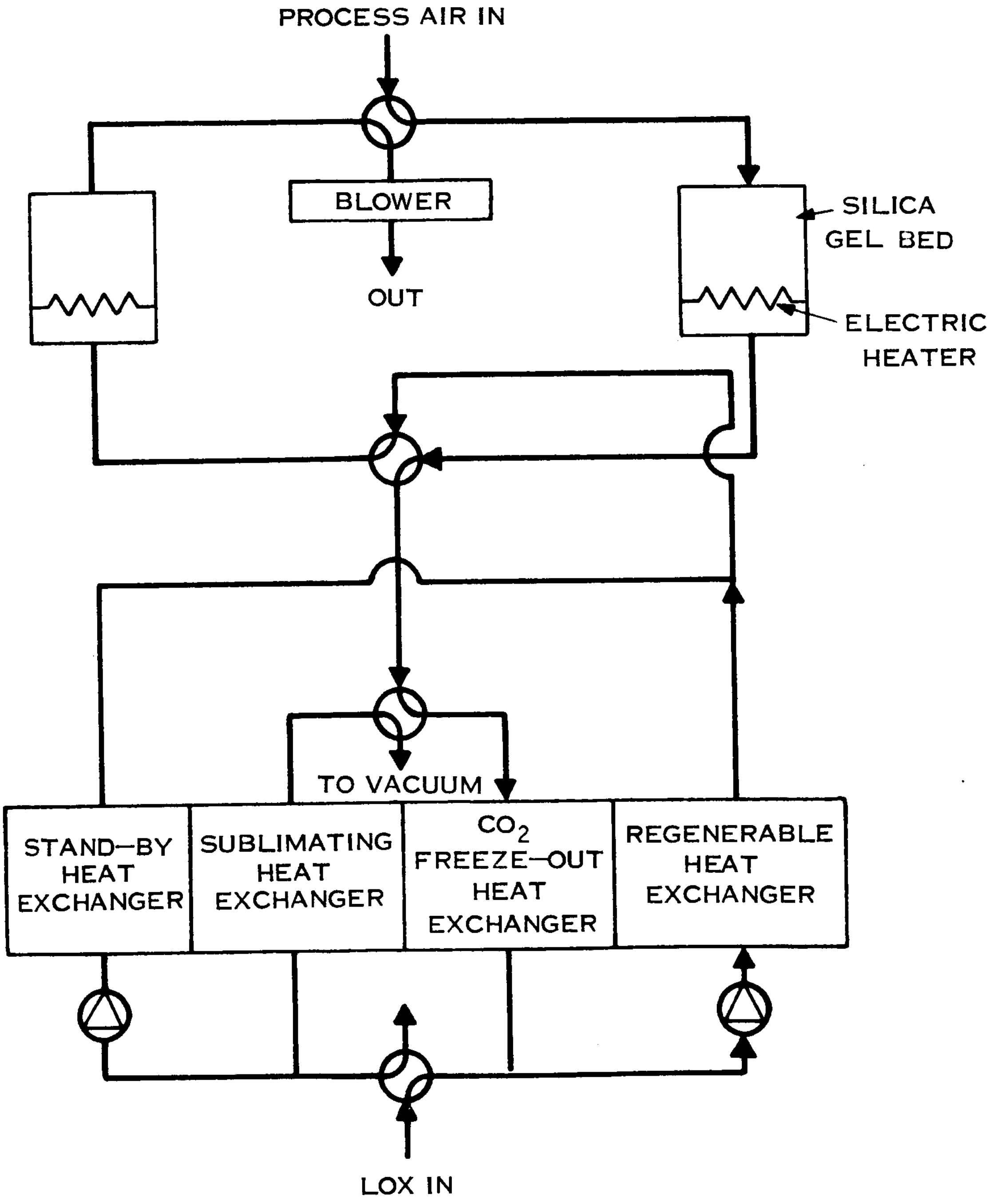


FIGURE 5-203

5.2.5.1 (Continued)

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 exchangers maintains continuous system operation.

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.

5.2.5.2 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, it can only be used with subcritical cryogenic storage and, as such, the storage should be from a source with the flow rate equivalent to the crew metabolic inputs. Thus, it is somewhat limited to an overall system not utilizing oxygen reclamation from CO_2. 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.

5.2.6 CO_2 Removal With Regenerable Solid Adsorbents

5.2.6.1 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 on this approach for CO_2 removal. 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.

5.2.6.2 System Description

The system is presented schematically in Figure 5-204. 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 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 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. Where the CO_2 is to be collected for later use in a CO_2 reduction system, an analysis will be performed to determine an optimum transfer method (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 and CO_2 adsorption canister and the included chemicals. This amounts to more than 50% of the total system weight with the rest of the weight distributed between the other components.

SOLID—ADSORPTION CO_2 REMOVAL

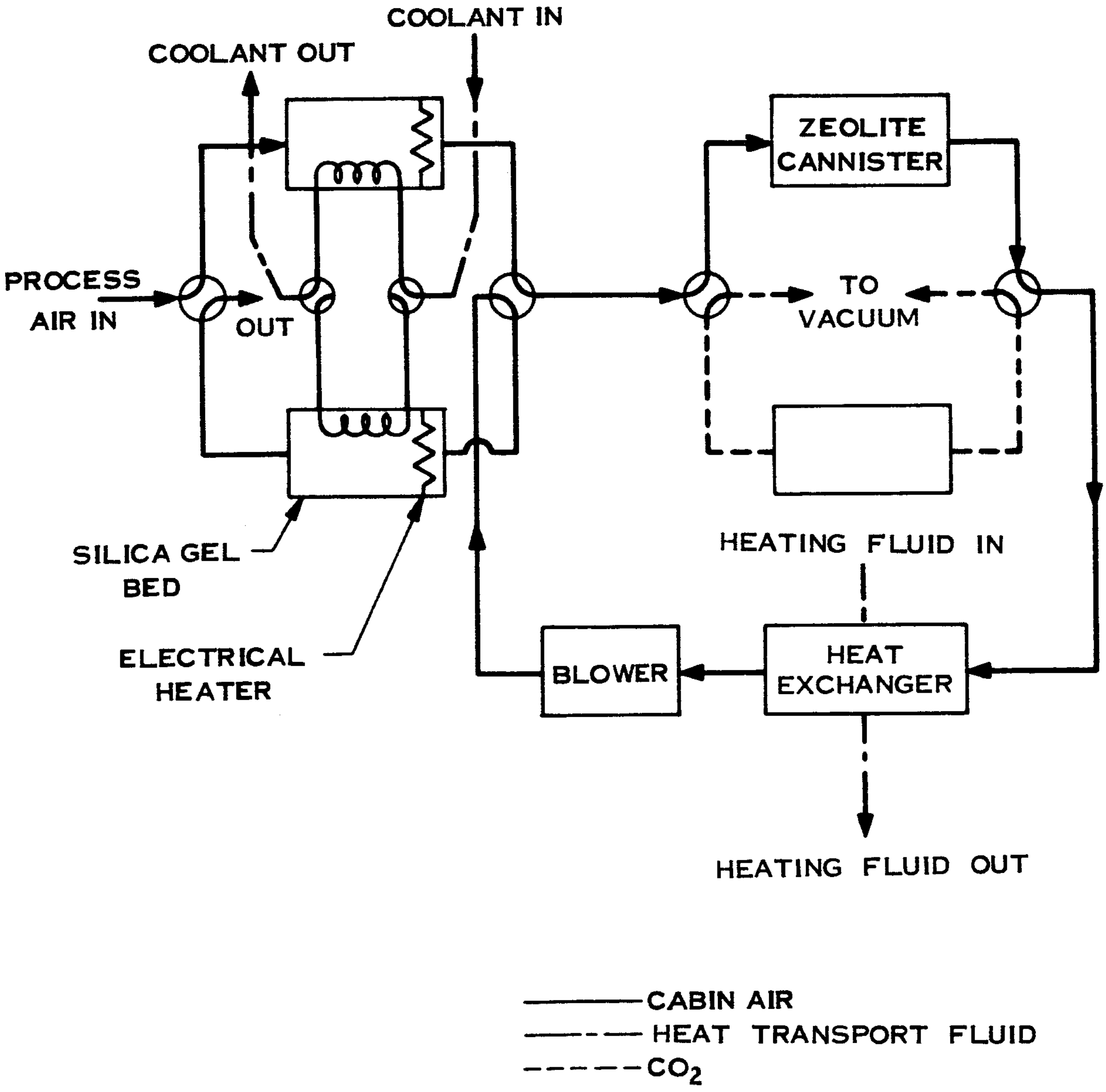


FIGURE 5-204

5.2.6.3 Conclusions

The trade-off presented here is a consideration of this system standing alone, as previously mentioned, 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 dew 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.

5.2.7 Liquid Absorption

5.2.7.1 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 media contained within the system and is driven off to collection or disposal by regeneration of the media. 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 early state-of-the art work at Hamilton Standard has provided an adequate foundation for system sizing.

5.2.7.2 System Description

Figure 5-205 presents the schematic utilized for the liquid absorption studies. The circulating liquid chosen for this study is a potassium carbonate (K_2CO_3) solution. This was chosen as the best liquid media 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 contactor utilizes a spray nozzle arrangement to force the liquid into the contactor through the nozzles, thus mixing with the gas upon entrance. 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

LIQUID ABSORPTION CO_2 REMOVAL

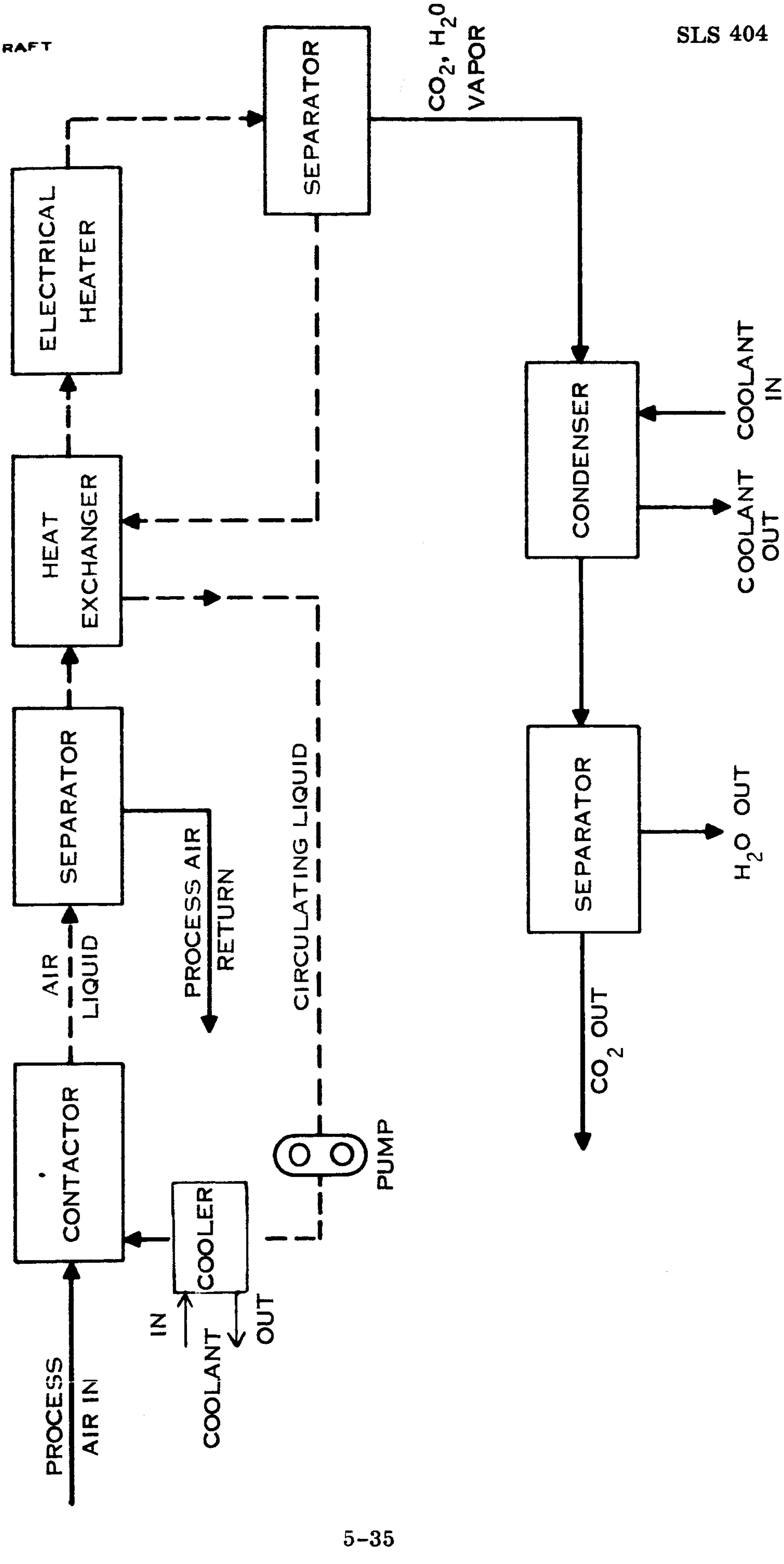


FIGURE 5-205

5.2.7.2 (Continued)

to the liquid droplets 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.

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, CO_2 and potassium carbonate. 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 pass through a heat exchanger to cool the mixture and condense the water droplets. A third separator then removes the water from the CO_2. Thus, CO_2 removal is completed for the case of CO_2 removal alone. If 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 parameters.

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 liquid flow rate required for this operation was taken as 575 lbs per hour independent of the CO_2 removal rate for this range of interest. This rate provides the greatest possible surface area of liquid droplets created per second, and thus the most rapid rate of mass transfer with the smallest contactor size. The maximum liquid temperature reached in the system is 159°F downstream of the electrical hea System weight is made up of three major items in addition to the associated secondary items. However, the liquid inventory, the regenerable heat exchanger, and the contactor make up about 65% of the total system weight.

5.2.7.3 Conclusions

The liquid absorption CO_2 removal approach has combinations of good and bad points which make it intriguing in some instances and non-competitve 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 adsorption then becomes

5.2.7.3 (Continued)

quite attractive due to its ease of delivery of the $CO2$ 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. In summary, the system is probably non-competitive for applications without CO_2 reduction; however, with CO_2 reduction it bears further investigation and estimation of development status prior to a final conclusion on this approach.

5.2.8 CO_2 Removal by Electrodialysis

5.2.8.1 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, Mass. 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" was the major source of the data in this analysis.

5.2.8.2 System Description

Carbon dioxide removal with this approach is accomplished by means of electrochemical reactions which convert the $CO2$ to ionic species (e.g., carbonate or bi-carbonate ions) and by electrodialysis which causes the ionic species to migrate out of the absorption zones. The CO_2 is recovered in a separate stream of high purity. Under normal operating conditions, the equipment utilized for $CO2$ 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 4.3 of this report.

Figure 5-206 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 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

ELECTRODIALYSIS CO_2 REMOVAL

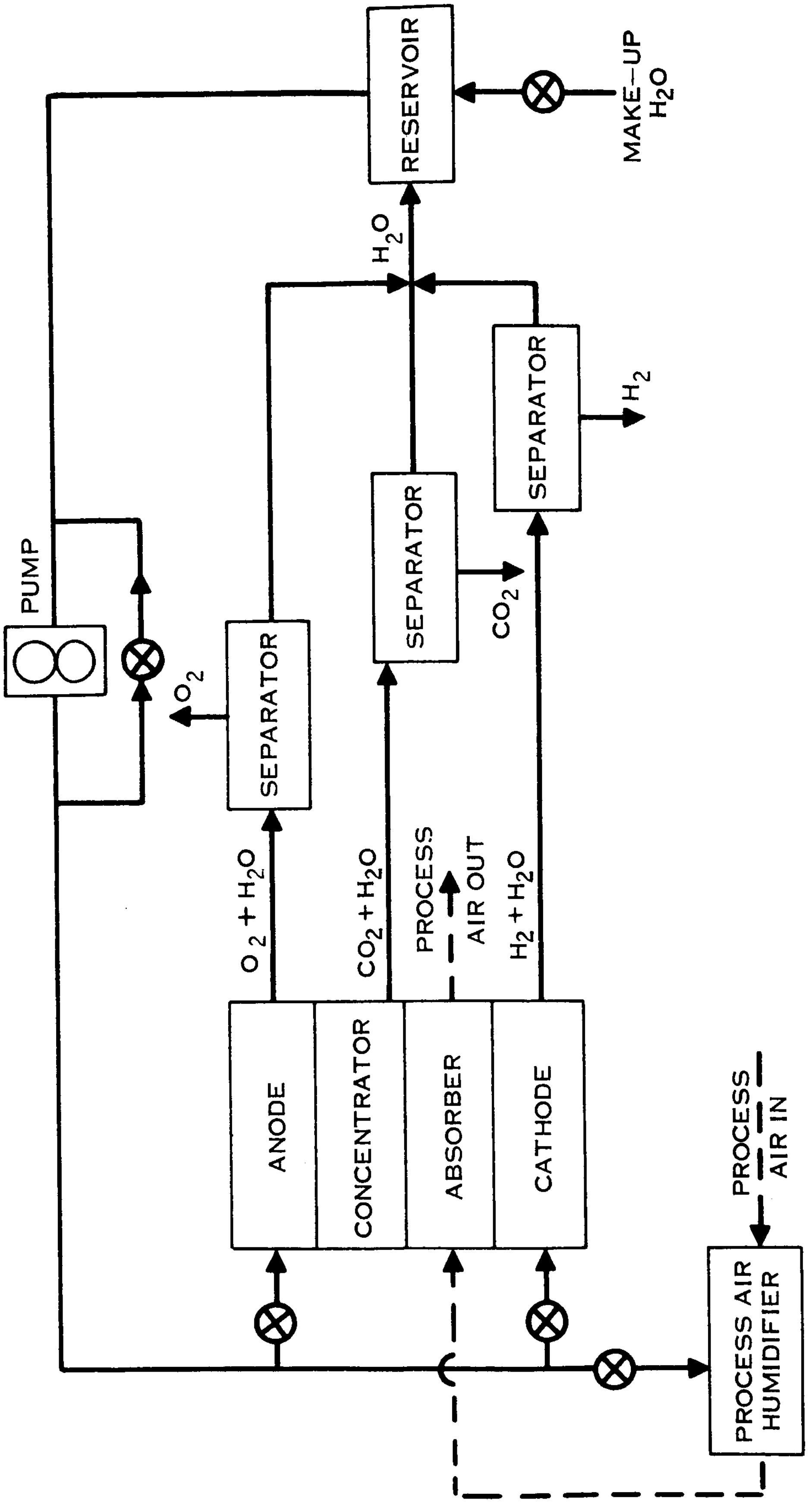


FIGURE 5-206

5.2.8.2 (Continued)

further to reform CO_2 gas. At the electrodes, water is electrolized to form oxygen and hydrogen.

The processed air minus the CO_2 returns from the absorber to the cabin system. The CO_2 exiting from 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 are transferred through highly selective ion transfer membranes under the influence of direct current. 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 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. In actuality, 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 hydrogen gas.

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.

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.

5.2.8.3 Conclusion

However, to complete the investigation of CO_2 removal approaches, it was included in this aspect of the study. Further work in conjunction with systems utilizing CO_2 reduction will illustrate more fully the complete potential of the system. Ionics seems to have achieved considerable success in system design and is currently in process of conforming a research and development contract for the National Aeronautics and Space Administration which should improve the development status of this approach. The membrane stack may present some problems for long duration mission since systems of this type have not been subject to extended duration testing. However, this is a developed item for zero g and, aside from the sheer number of separators, should not present any major design problems during system qualification. The high power requirements for this approach make its best utilization at instances where the cost of power in pounds is low.

The system should operate well in zero gravity application. Another advantage is the adaptability to intermittent operation, thus, allowing utilization of direct solar cell power if possible. The exhaust of CO_2 at elevated pressures improves integration potential with many CO_2 reduction systems making the system worthy of further investigation during the system definition phase of the study.

5.2.9 CO_2 Removal by Silver Oxide

Silver oxide (Ag_2O) has often been mentioned 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:

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

5.2.9 (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). Unless such a difference in rates, which is not likely, is proved to exist, the use of silver oxide as a CO_2 removal agent is unfeasible.

Because this system approach does not appear feasible and there is very little information available, no parametric curves were prepared for it.

5.2.10 Non-Regenerable CO_2 Removal Systems

5.2.10.1 Introduction And Data Source

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.

5.2.10.2 System Description

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:

$$2\ LiOH + CO_2 \longrightarrow Li_2CO_3 + H_2O$$

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

5.2.10.2 (Continued)

Tests were run at Hamilton Standard resulting in curves relating removal efficiency to contact time. Using this data it was then possible to calculate the system weight as a function of time and of CO_2 production rate. The results of this calculation are shown in Figure 5-213. It can be seen that the use of Li OH is feasible only for short missions where the CO_2 will not be recovered.

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 Li OH. 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) $Li_2O + H_2O \longrightarrow 2\ Li\ OH$
2) $2\ Li\ OH + CO_2 \longrightarrow Li_2\ CO_3 + H_2O$

Therefore the amount of water needed must be taken into account in the weight calculation, and the equilibrium ratio becomes the same as for Li OH. This water requirement may be ignored for the case of a relatively short mission, since a surplus of water is being generated during this time period.

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 Li OH 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 bettern than the equilibrium figure for Li OH. 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:

$$CaO + CO_2 \longrightarrow Ca\ CO_3$$

The equilibrium ratio is 1.27 lbs CaO/lb. CO_2. This is worse than that for Li OH,

5.2.10.2 (Continued)

and the reaction rate is very slow except at elevated temperatures. This absorbent should not be considered further.

5.2.10.3 Conclusions

The non-regenerable CO_2 absorbents were considered primarily for the short duration portions of the mission such as earth blast-off and rendezvous with the mission module, short time extravehicular excursions in deep space, Mars blast-off and rendezvous with the Mission Module, and earth re-entry. Of the absorbent considered, only Li OH or Li_2 O show much promise. Li OH enjoys a much better development status than Li_2 O and therefore figure 5-213 is shown here as representing a non-regenerable absorbent. It is possible that future work on Li_2O may indicate a slight advantage over Li OH.

5.2.11 Comparative Discussion

To permit proper evaluation of the various methods of CO_2 removal, comparison plots have been made. Figure 5-207 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. Figure 5-209 presents the fixed weight plus expendables for a 420 day mission. This represents the entire weight required at earth launch, but does not include any penalty for power required or packaging weight of the expendables. The power required by each of these systems is shown in Figure 5-208. This curve is provided so that changes in power penalty can be evaluated to determine a revised equivalent weight.

Figure 210 illustrates the total equivalent weight as a function of CO_2 production rate for a 420 day mission in a vehicle with a power supply whose penalty is 500#/KW. It can be seen from this plot that the solid adsorption, cryogenic freeze-out, and liquid absorption are the most competetive systems. However, as mentioned previously, each of these has special circumstances under which it can or cannot be used, and the final system selection can only be made in conjunction with the CO_2 reduction system.

Figure 5-211 presents the same comparison as 5-210 for a six man crew as a function of mission duration. It can be seen from these curves that the same three methods are competetive from very short duration missions up through and even exceeding the 420 day mission.

CO_2 REMOVAL SUMMARY

FIXED WEIGHT VS. CO_2 PRODUCTION RATE

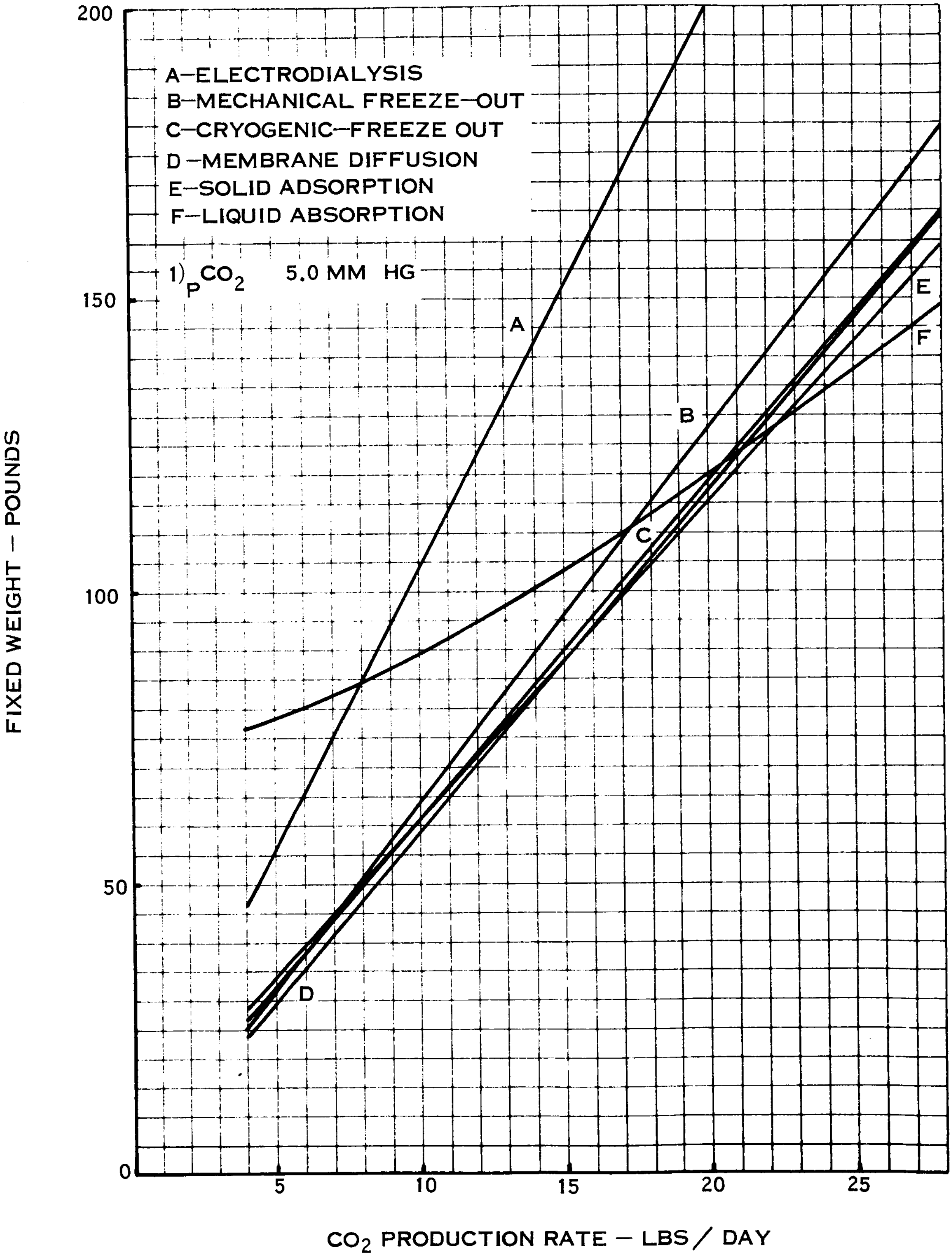


FIGURE 5–207

CO_2 REMOVAL SUMMARY

POWER VS. CO_2 PRODUCTION RATE

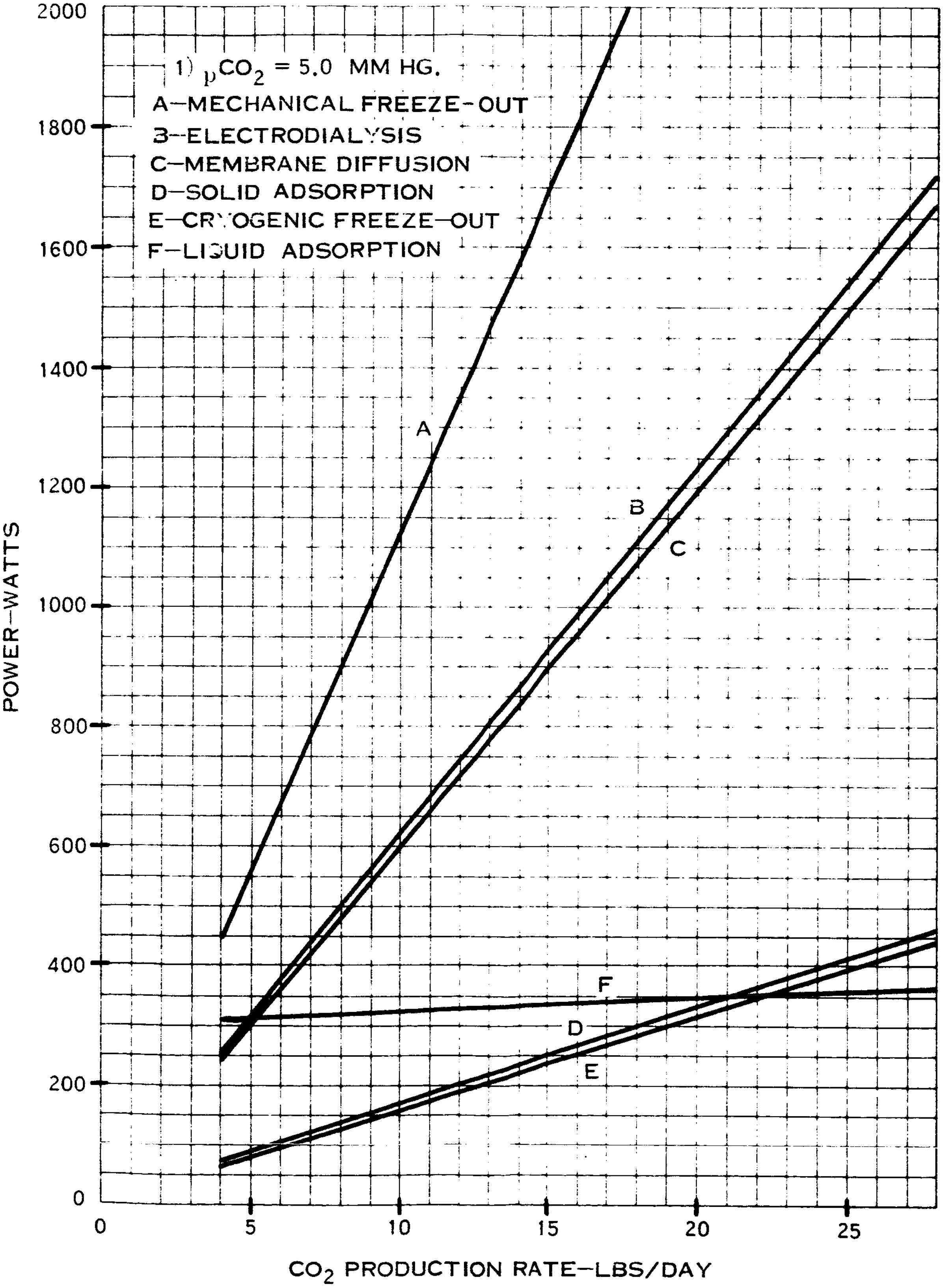
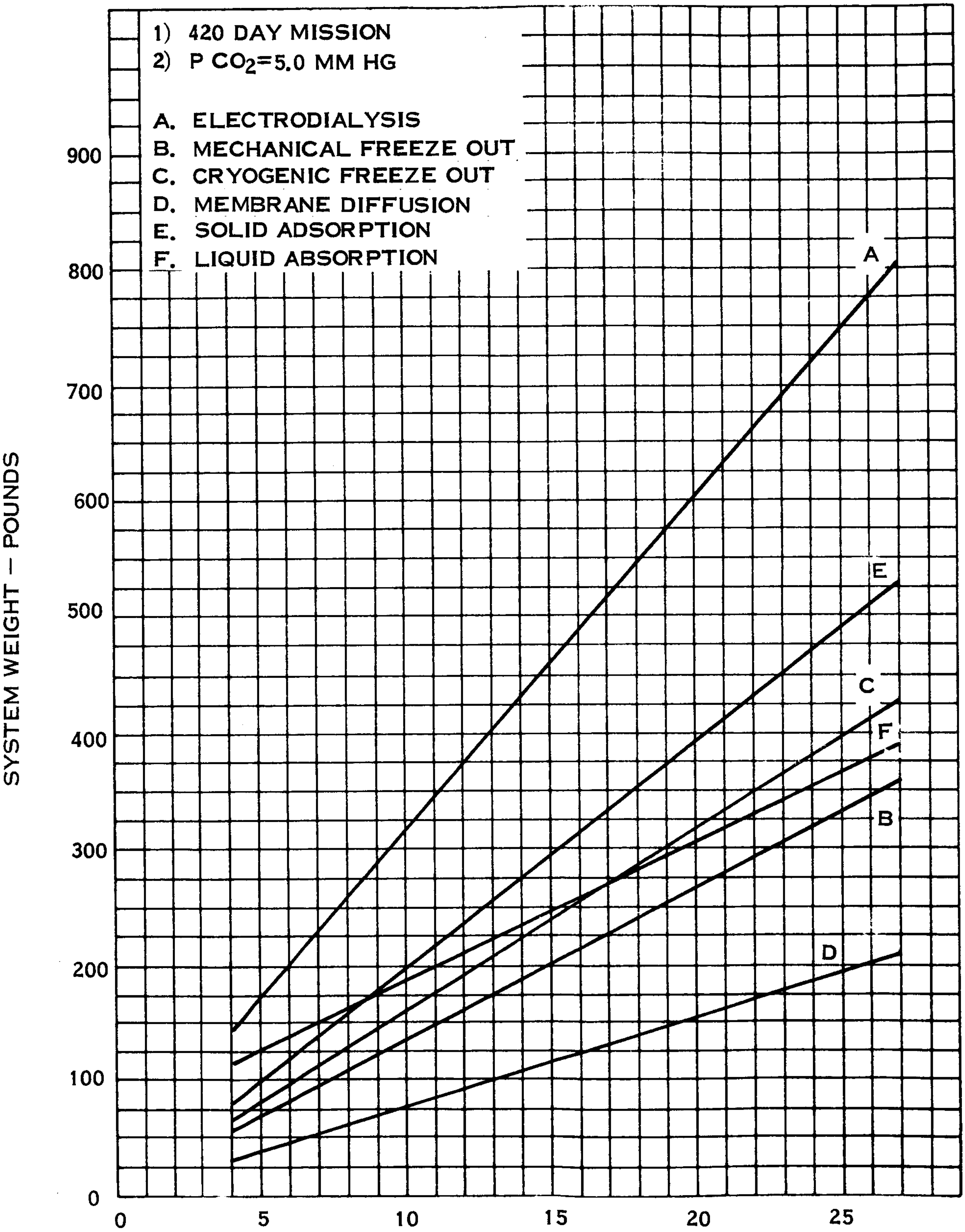


FIGURE 5-208

FIG 5-209

CO_2 REMOVAL SUMMARY

FIXED WEIGHT PLUS EXPENDABLES VS CO_2 PRODUCTION RATE

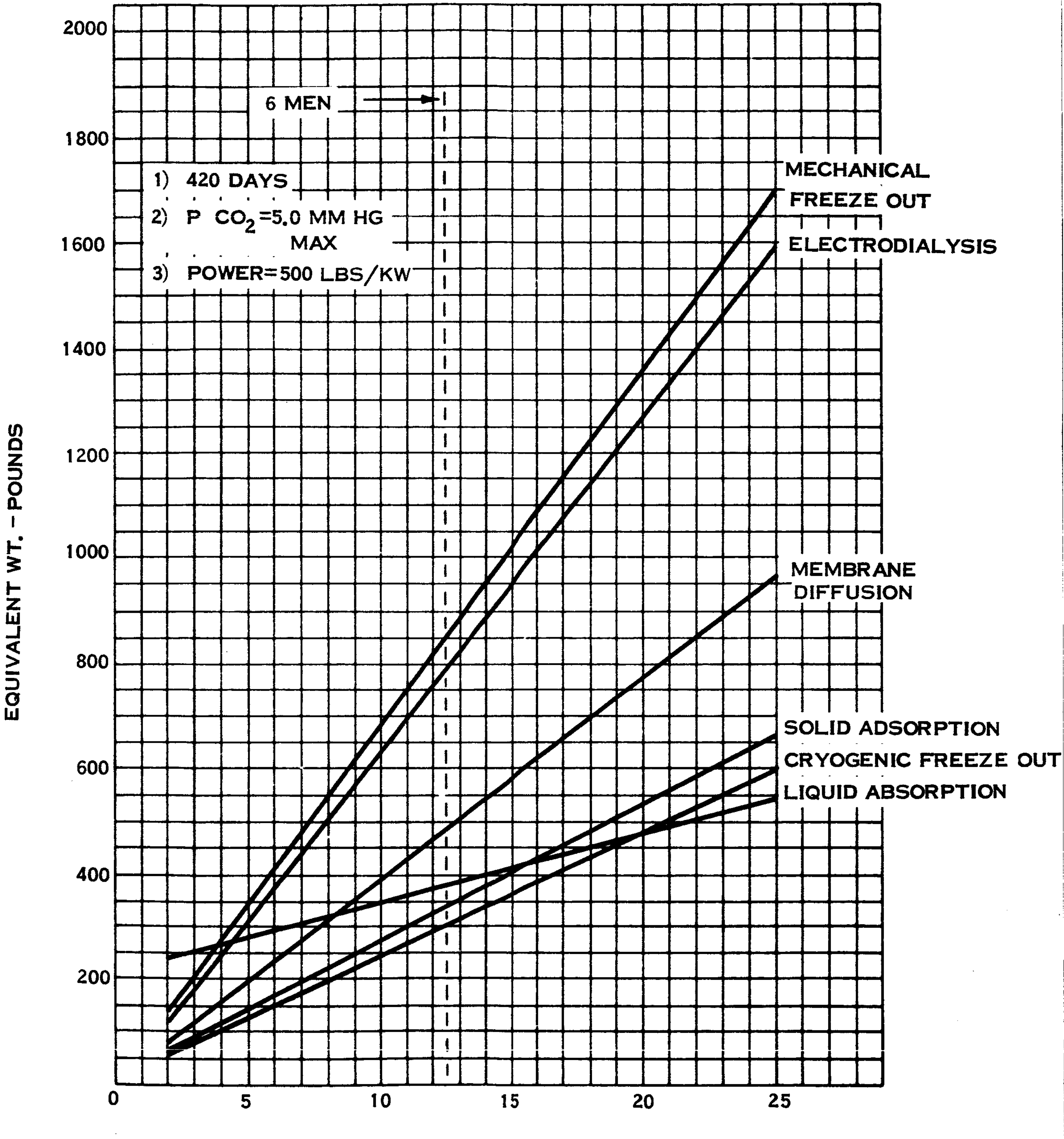


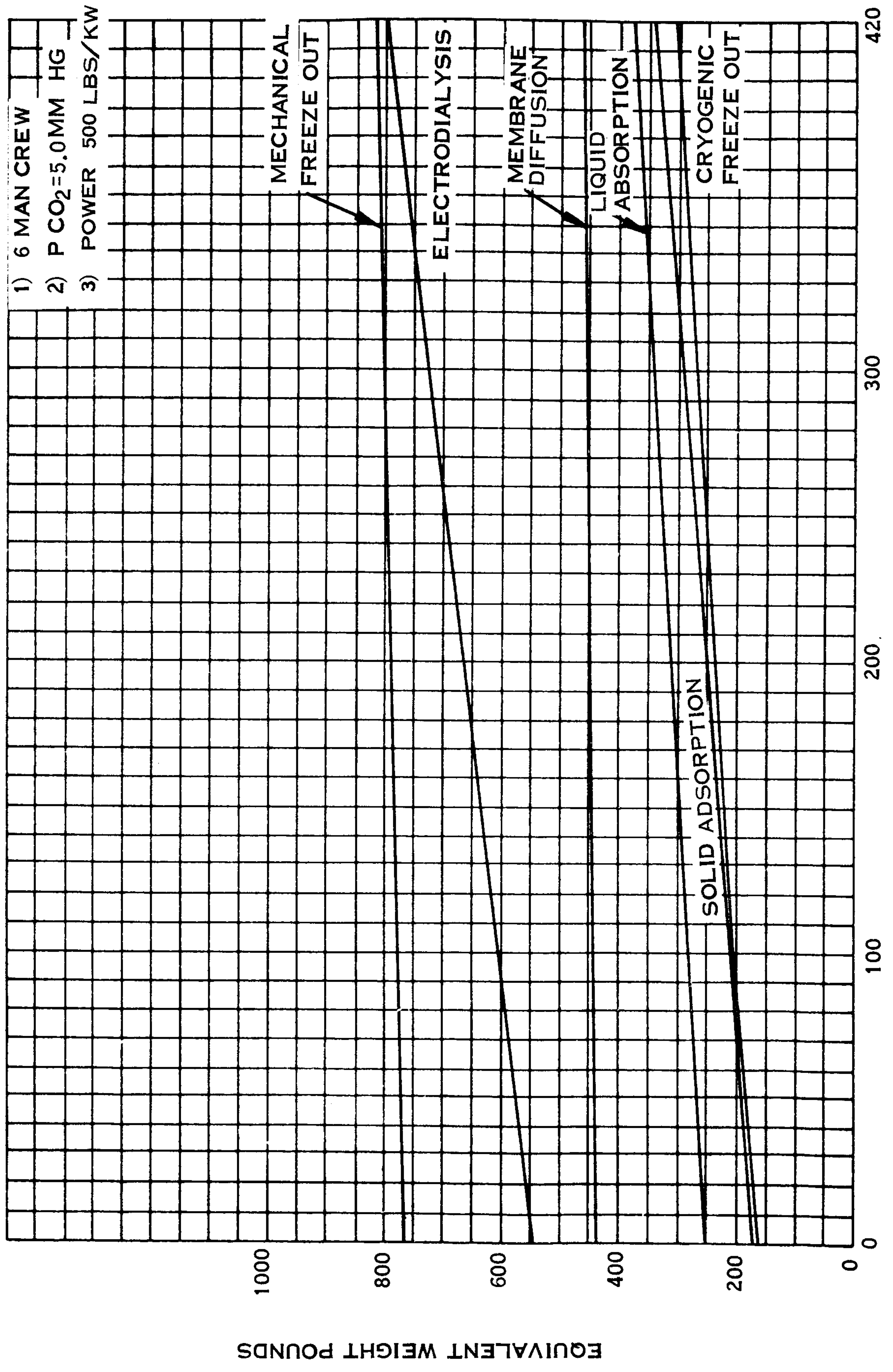
CO_2 PRODUCTION RATE LBS DAY

FIG. 5-210

CO_2 REMOVAL SUMMARY

EQUIVALENT WT VS CO_2 PROD. RATE





CO$_2$ REMOVAL SUMMARY
EQUIVALENT WEIGHT VS MISSION TIME

MISSION DURATION DAYS

5.2.11 (Continued)

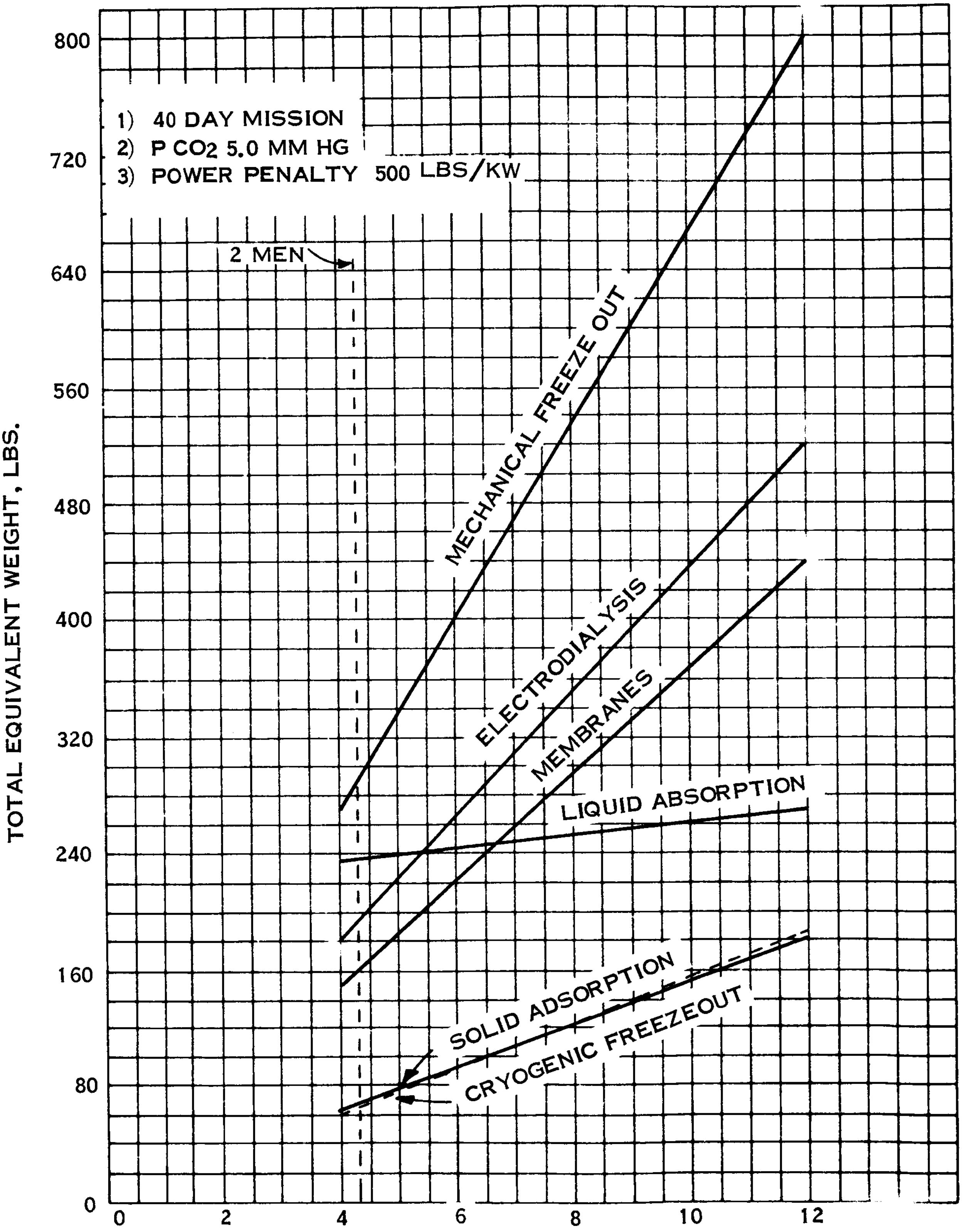
Figure 5-212 presents total equivalent weight vs. CO_2 production rate for a 40 day mission. This is useful in selecting a system for the Mars Excursion Module. It can be seen from this figure that solid adsorption and cryogenic freeze-out are the lightest systems. However, the limitation on cryogenic freeze-out mentioned previously must be kept in mind in evaluating this system.

Figure 5-213 is included to illustrate the use of Li OH as a possible CO_2 removal method for the earth re-entry modle, and possibly for use on the Mars surface to Mission Module rendezvous portion of the Excursion Module.

FIG. 5-212

CO2 PRODUCTION RATE, LBS DAY

TOTAL EQUIVALENT WEIGHT VS CO2 PRODUCTION DATA



CO2 REMOVAL SUMMARY

LITHIUM HYDROXIDE SYSTEM WEIGHT VS. MISSION DURATION

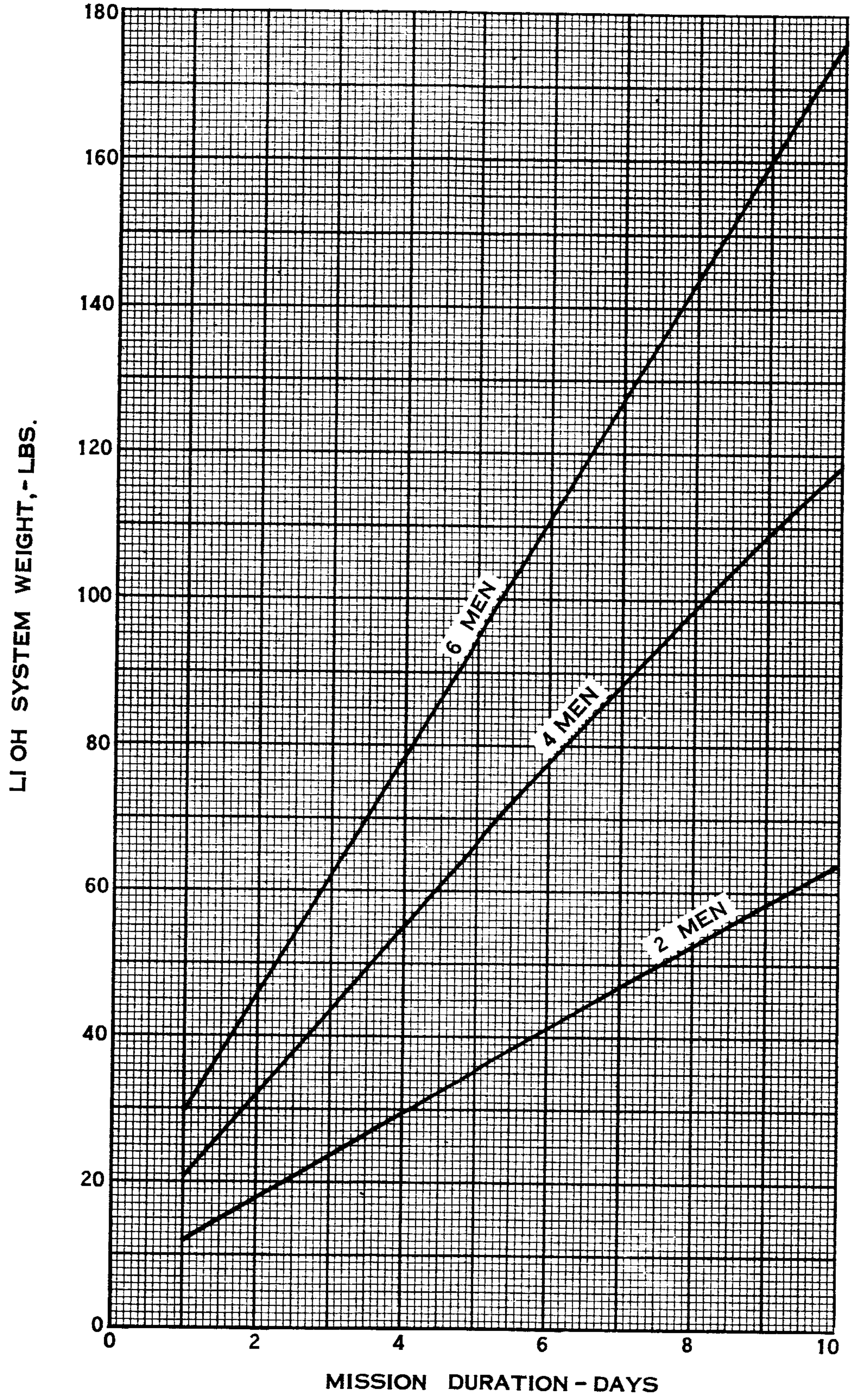


FIG. 5 – 213

6.0 THERMAL CONTROL

6.1 Space Radiator Study

6.1.1 Objectives

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, the circulating coolant, 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 and coolant studies consisted of a review of available materials and fluids and their properties to provide an indication of the most desirable coating and coolant for the end 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 three 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.

The results presented in this section will document the preliminary work done on the radiator and allow understanding of the reasons behind the selection of the final radiator.

6.1.2 Use of Data

The results of the general studies on radiator design have been included in this report to provide a topic of general discussion. Care must be exercised in the interpretation of this data to avoid being overspecific on any particular point. Since each final radiator design is a specific case in itself, a general series of curves applicable to all designs is not possible. 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.

The tabulated results of the coolant and coating surveys are factual and may be taken as such, but the comparative figure for coolants indicates the general trend only and should not be considered a firm conclusion for any application.

The intent of the meteoroid protection survey was a gross comparison of methods to simplify later usage and should not be considered firm for all applications due to the

6.1.2 (Continued)

many variables which were assumed fixed for the analysis. The intent of the discussion is a general indication of the effect on meteoroid shielding requirements of the flux distribution data and the protection scheme.

A final radiator design will be provided during the system integration phase for both the Mission Module and for the Excursion Module. The data presented in this section serves to reduce the variable design choices for these radiators and, as such, has served its basic intent.

6.1.3 Coolant Survey

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 6-1 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 which is proportional to the ratio of pumping power to heat transfer conductance was derived.

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

$$\Delta P = \frac{2fLpW^2}{Dpg\,\rho Ap^2} \qquad (1)$$

$$f = \frac{16}{Re_p} = \frac{16\,A_p\,\mu}{W\,Dp} \qquad (2)$$

6.1.3 (Continued)

$$Nu = 0.023 \cdot Re_h^{0.8} \cdot Pr^{0.33} \qquad (3)$$

where: $Nu = \frac{h\,Dn}{k}$

$Re_h = \frac{W\,D_n}{A_n \mu}$

$Pr = \frac{\mu\,Cp}{k}$

$$Q = W\,Cp\,(Tf_1 - Tf_2) \qquad (4)$$

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, Ap, Dp, Dn, An, Q and $(T_{f1} - T_{f2})$ are essentially the same for all fluids.

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

$$\text{Pumping Power} = \frac{W\,\Delta P}{\rho} = \frac{32\ Lp\ \mu\,W^2}{Dp^2\ g\ Ap\,\rho^2}$$

The assumptions reduce this equation to the following proportionality:

$$\text{Pumping Power} \propto \frac{\mu\,W^2}{\rho^2}$$

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

$$\text{Pumping Power} \propto \frac{\mu}{\rho^2\,C_p^2}$$

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

$$h \propto \frac{k^{0.67}}{(Cp\,\mu)^{.47}}$$

TABLE 6 - 1 - COMPARISON

Property	Units	Ethylene Glycol Solution (60-40)	Coolanol 35 (Monsanto)	Coolanol 45 (Monsanto)	OS-45-I (Monsar
Boiling Temp. @ 1 ATM.	°F		> 600	> 500	> 700
Pour Point	°F		< -120	< -85	< -85
Flash Point	°F		370	370	370
Toxicity		NIL	NIL	NIL	
Operating Temp. Range	°F	-65/300	-65/300	-65/400	
Density @ -65°F	lb_m/ft^3	71.5	58.9	59.3	
Density @ 100°F	lbm/ft^3	67.0	54.1	54.5	55.6 @7
Viscosity @ -65°F	lb_m/ft-hr	3050	$2.10x10^3$	$5.52x10^3$	
Viscosity @ 100°F	lb_m/ft-hr	6.8	1.37x10	2.75x10	$^{(2}$ 2.8x10@
Specific Heat @ -65°F	Btu/lb_m-°F	.588	.378	.377	
Specific Heat @ 100°F	Btu/lb_m-°F	.767	.467	.462	.45@77
Thermal Conductivity @ -65°F	Btu/hr-ft-°F	.230	$.0505^{(1)}$	$.0622^{(1)}$	
Thermal Conductivity @ 100°F	Btu/hr-ft-°F	0.221	.0706	.0753	.08@77
Relative Pumping Power @ -65°F	Pump HP Pump HP For Glycol @ 100°F	6.74×10^2	$1.65x10^3$	$4.28x10^3$	
Relative Pumping Power @ 100°F	Pump HP Pump Hp For Glycol @ 100°F	1.0	8.4	17.0	17.3 @

Notes:

(*1) obtained by linear interpolation between two points.
(*2) obtained by linear extrapolation beyond two points.
(*3) assuming density data point is at 32°F
(*4) assuming OS-139 curve of viscosity fitted to MC-1928 (2) test points.
(*5) extrapolated from Monsanto curve.

TABLE 6 - 1 - COMPARISON

OS-139 (Monsanto)	MC-198 (Monsanto)	FC-75 (3M)	Oronite 8200	QF-1-0077 (Dow Corning)
	460	210-224	> 500	> 600
< -100	< -120	-148	-100	-80
340	170	None	450	405
	Somewhat @ 300°F	NIL	NIL	
-100/300	-	-80/210	-65/500	
59.9	59.9	122.3	61.2	
55.2	55.5	107.5	56.4	54(1)
$5.45x10^2$	62.0	2.52x10	$5.43x10^3$	$2.74x10^3$(2)
9.09	3.65	2.78	7.16x10	2.50x10(1)
.38(2)	.40	0.215	.29	
.46(1)	.45	0.252	.39	.446
		0.088		
.0734(1)	.058(1)	0.0775	.080	.076
$4.1x10^2$		14.1	$6.7x10^3$	
5.5	4.96	1.47	57.6	16.8

TRANSPORT FLUID COMPARISON

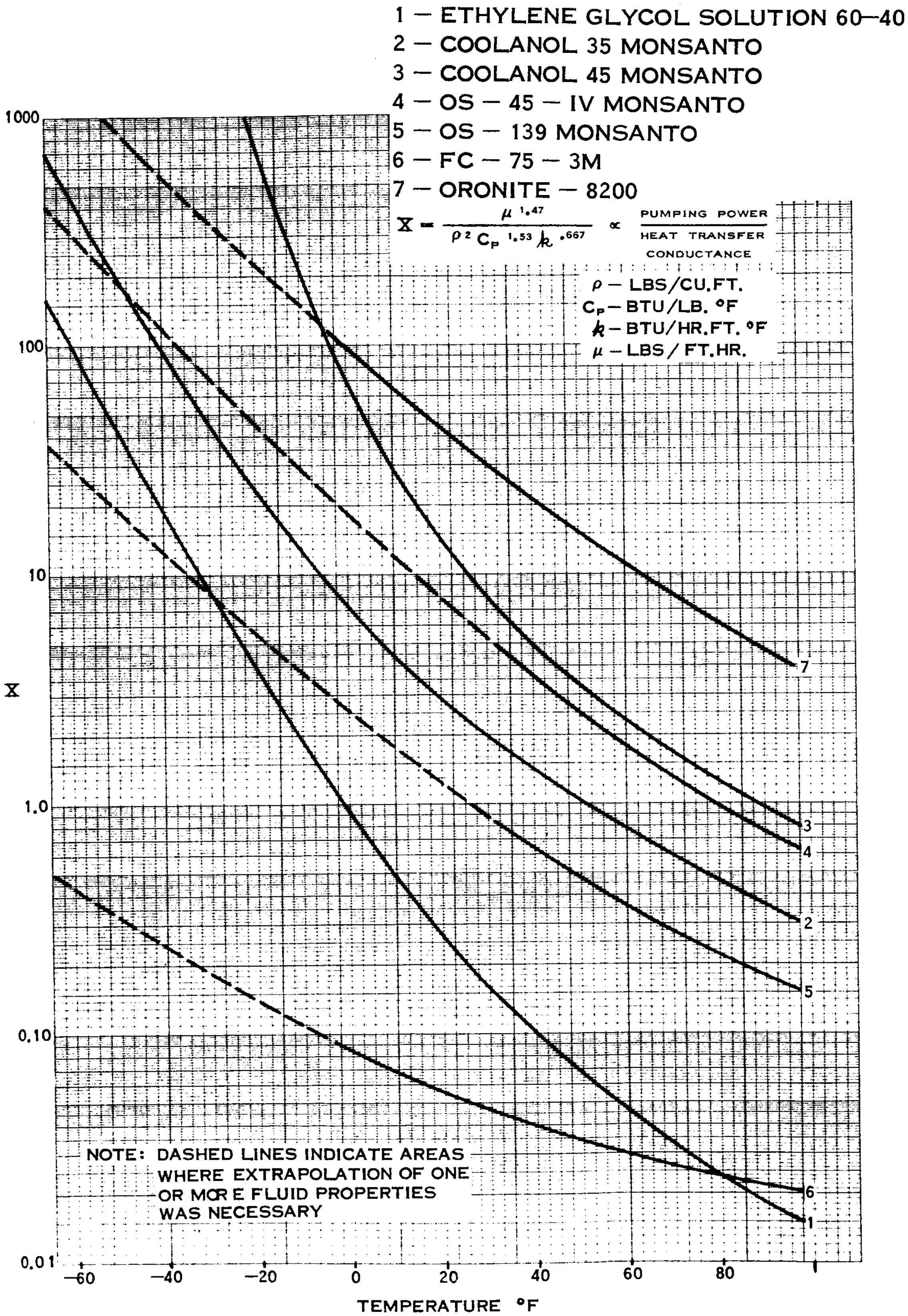


Figure 6-1

TRANSPORT FLUID COMPARISON

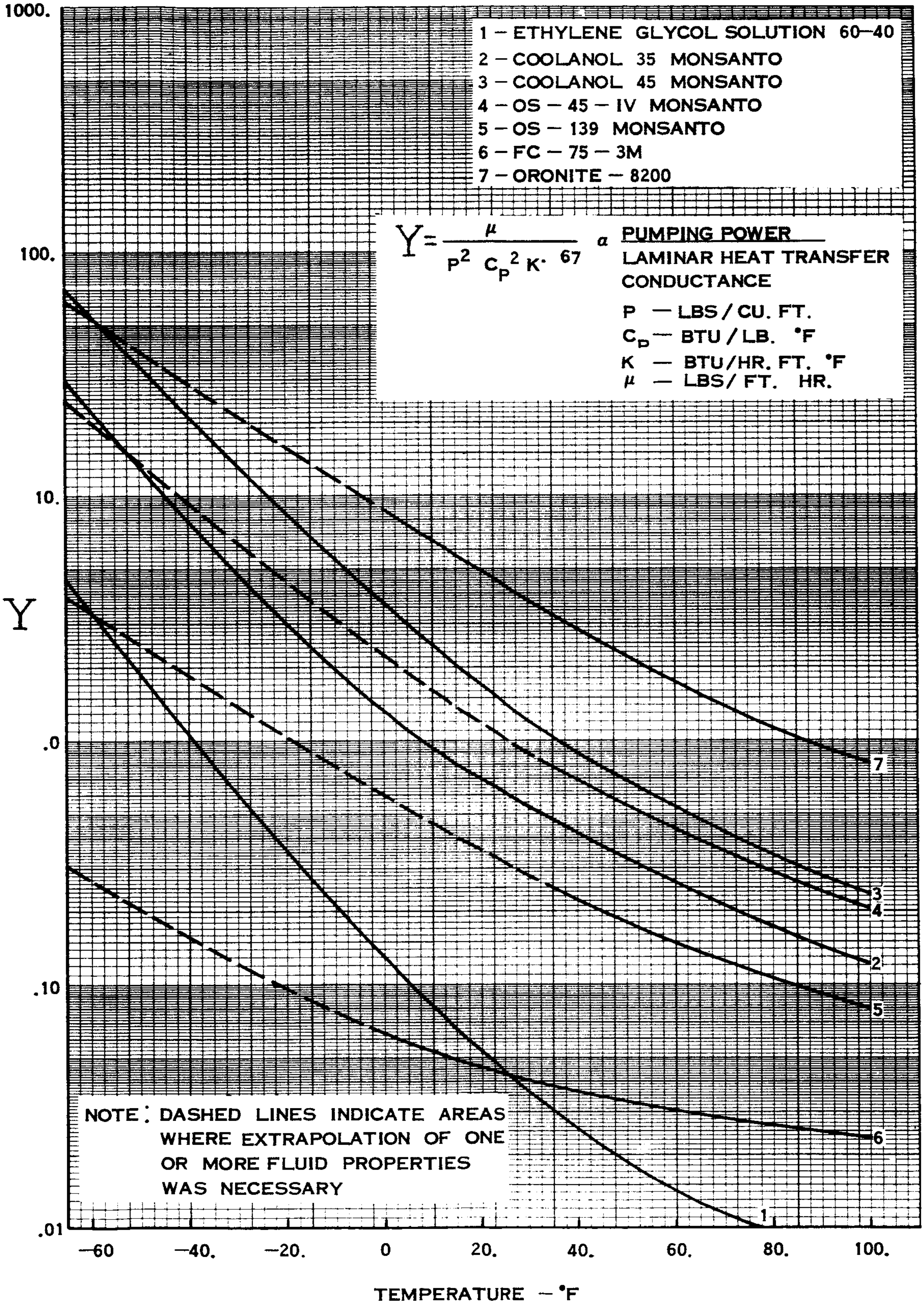


FIGURE. 6 – 1 – 1

6.1.3 (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:

$$\frac{\text{Pumping Power}}{\text{Heat Transfer Conductance}} \quad \alpha \quad \frac{\mu^{1.47}}{\rho^{2}\, C_p^{1.53}\, k^{0.67}}$$

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

$$Nu = 1.86\, Re^{1/3}\, Pr^{1/3} \left(\frac{Dn}{L}\right)^{1/3} \left(\frac{\mu_a}{\mu_s}\right)^{.14}$$

where: $Nu = \frac{h\, D_n}{K}$

$Re = \frac{W\, Dn}{An\, \mu}$

$Pr = \frac{\mu\, C_p}{K}$

From this:

$$\frac{hD}{K} = \text{Constant} \left(\frac{W\, D_n}{A_n\, \mu}\right)^{.33} \left(\frac{\mu\, C_p}{K}\right)^{.33}$$

$$h = \text{Constant} \left(\frac{1}{C_p\, \mu}\right)^{.33} \left(\frac{\mu\, C_p}{K}\right)^{.33} K$$

$$h \propto k^{.67}$$

And pumping power varies as follows:

$$\text{Power} \propto \frac{\mu}{p^2\; Cp^2}$$

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

$$\frac{\text{Pumping Power}}{\text{Heat Transfer Conductance}} = Y \propto \frac{\mu}{p^2\, C_p^2\, k^{.67}}$$

6.1.3 (Continued)

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 exchanger and space radiator if it is acceptable on other bases such as toxicity, freezing point, stability, etc.

Figure 6-1 presents the comparison of fluids for this parameter for laminar flow in the interconnecting piping and turbulent flow over the heat transfer surfaces, while Figure 6-1.1 presents this comparison for laminar flow throughout the entire system. All fluids considered except MC 198 by Monsanto are illustrated. Recent data acquired on this fluid was received too late to permit its inclusion for this report. However, it will be considered during final system integration work. As noted on the figure, FC - 75 offers the lowest pumping penalty per BTU rejected over the range illustrated and may be considered a prime candidate for future analysis.

6.1.4 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 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 vaccum, and any other environmental conditions.

Table 6-2 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

6.1.4 (Continued)

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 emmissivity. 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 the table indicates that all but two of the coatings (#6 and #8) are of the "single 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 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 sub-surfac 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 the above table was 0.003 to 0.006 of an inch.

The percentage composition of pigment and vehicle making up the coating also has considerable effect on the radiant characteristics. Table 6-3 for zinc oxide and potassium silicate illustrates this. (Reference 4)

TABLE 6-2 - 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	"
3	2	1	0.100	0.165	0.871	0.876	0.188	Potassium Silicate	Zirconium Silicate	"
4	3	1	0.09	0.186	0.907	0.905	0.206	Potassium Silicate	Zircon	"
5	4	1	0.158	0.184	0.888	0.878	0.210	Silicon Resin	Zinc Oxide	"
6	5	1	0.197	0.211	0.947	0.935	0.226	Phosphate Bonded Cr-Ni Spinel-silcate Sn O_2		"
7	2	1	0.129	0.181	0.862	0.873	0.207	Silicone	Titanium Dioxide	"
8	6	2	0.16	0.18	0.67	0.69	0.26	Anodized with Brytal Process		Polished aluminum alloy
9	6	3	0.19	**	0.76	**	**	Anodized with Alzak Process		"

List of Suppliers:
1. **Armour Research Foundation** 2. **Lockheed Missle and Space Division** 3. **Space Technology Laboratory** 4. **Jet Propulsion Lab.**
5. **North American Aviation, Los Angeles Div.** 6. **Aluminum Co. of America**

*After simulated solar-vacuum exposure for 300 hours for coatings 1-7 and 96 hours for coatings 8 & 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.

6.1.4 (Continued)

Table 6-3

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

Composition Ratio Pigment Weight/Vehicle Weight	α_s		ϵ	
	Before	After	Before	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 zince oxide-potassium silicate composition has been made based on the data currently available. This composition has the lowest α_S/E ratio and is clearly the stablest which makes it very attractive for Mars Vehicle use.

6.1.5 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 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 be the highest solar influx part of the mission.

Figure 6-4 illustrates the solar influx to a blackbody facing toward the sun while travelling the path of the Mars Mission Module. It can be seen that the design point will be conditions on about the 350 th day of the mission. If this solar influx is assumed, along with the assumption that the radiator is flashing through the direct rays of the sun and α =.15 and ϵ =.92, figure 6-7 illustrates the resulting radiator area and weight as a function of the heat load to be dissipated.

FIGURE 6–4

MARS MISSION MODULE SOLAR INFLUX VARIATION

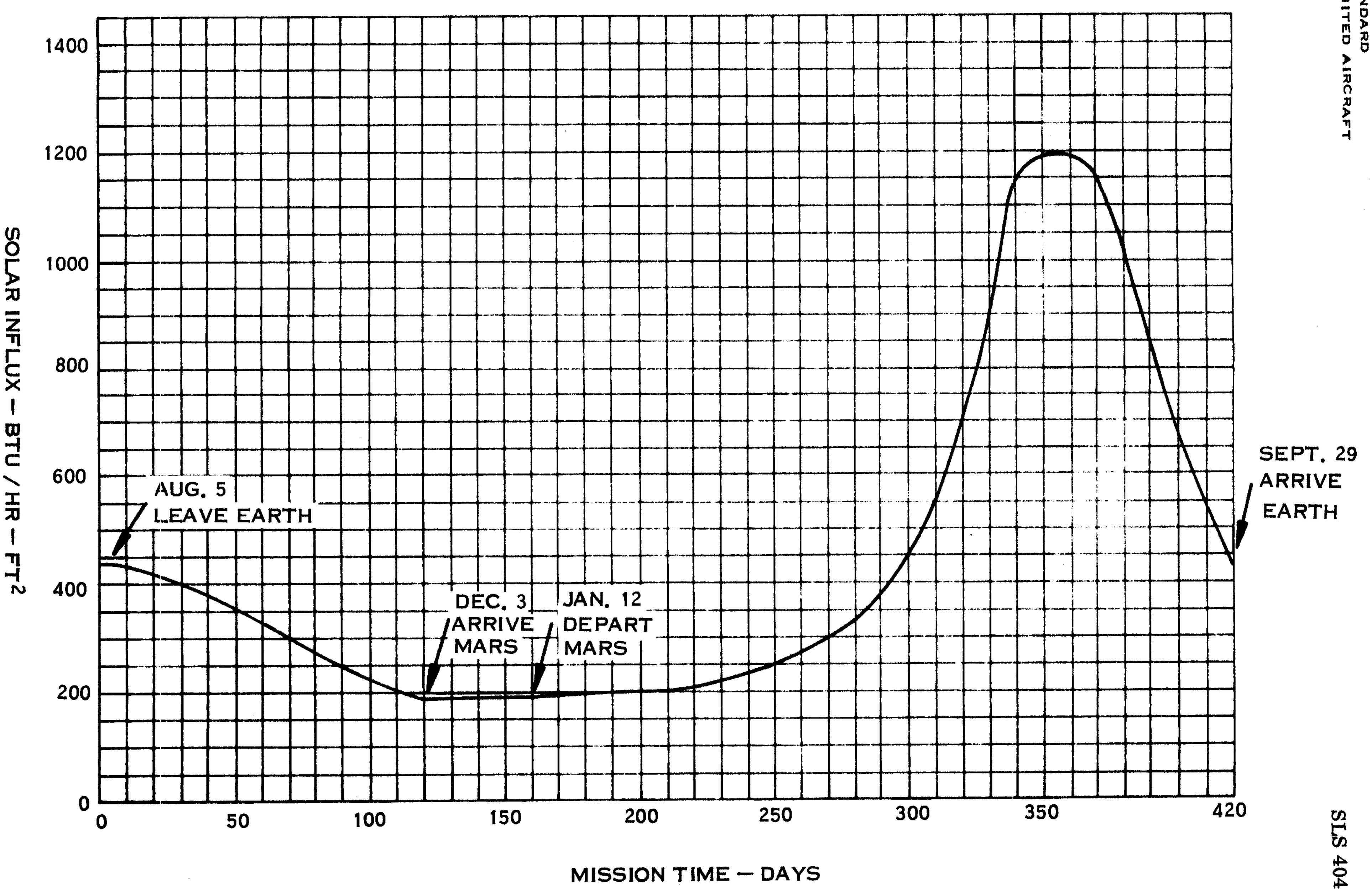
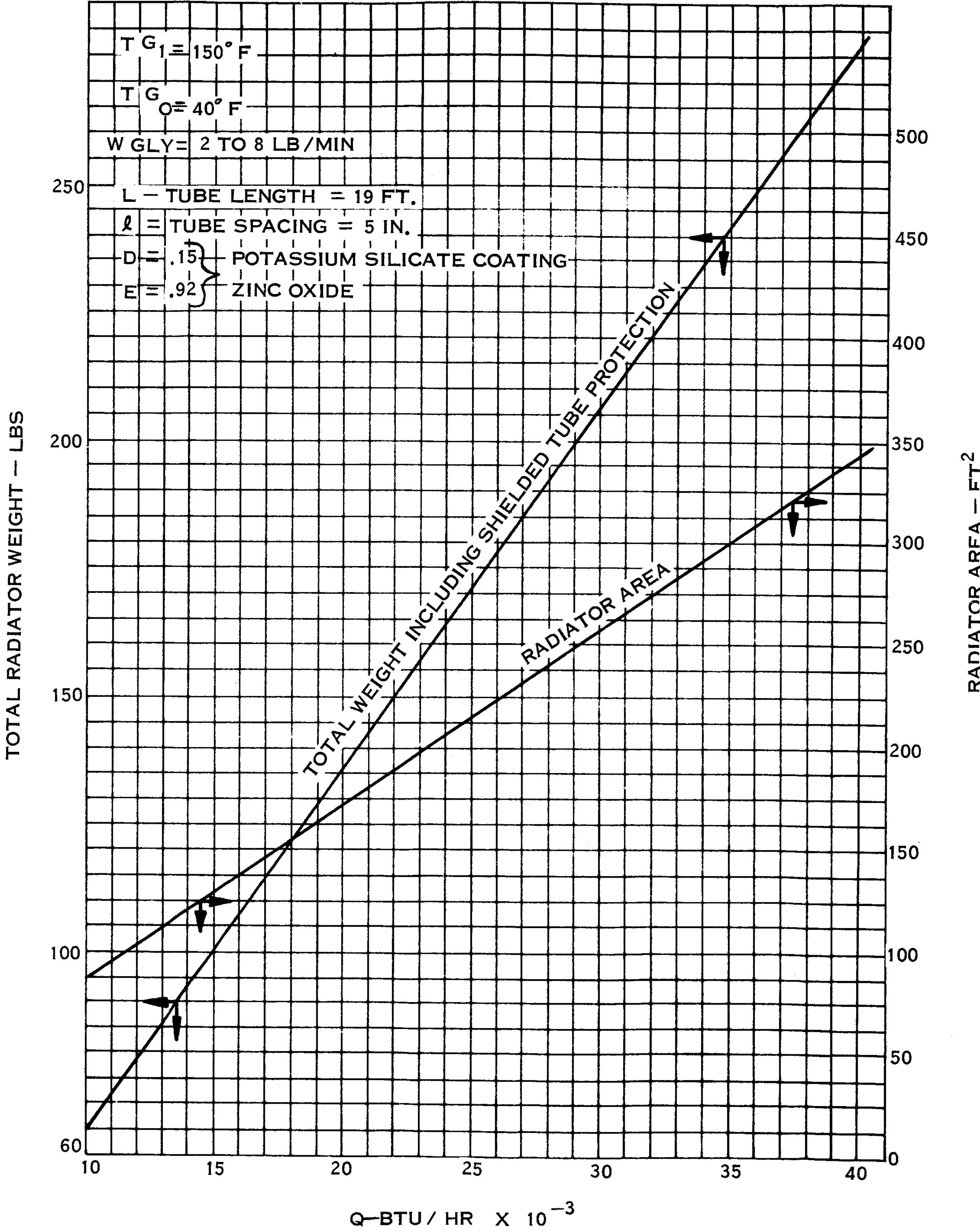


FIGURE 6 — 6

MARS MISSION MODULE

ZERO INFLUX RADIATOR SIZES AND WEIGHTS
(RADIATOR ORIENTED 90° FROM SUN)



6.1.5 (Continued)

If this radiator is compared with the zero influx radiator shown by figure 6-6, it can be seen that there is a large weight penalty for not orienting the vehicle. In fact, the estimated radiator heat load of about 40,000 BTU/hour required more area than the entire external surface of one side of the proposed Mission Module if it is not oriented. Therefore, it is necessary that the vehicle be specifically oriented with its spin axis radial to the sun.

6.1.6 Meteoroid Protection Requirements

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

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 thicknesses required to prevent penetration.

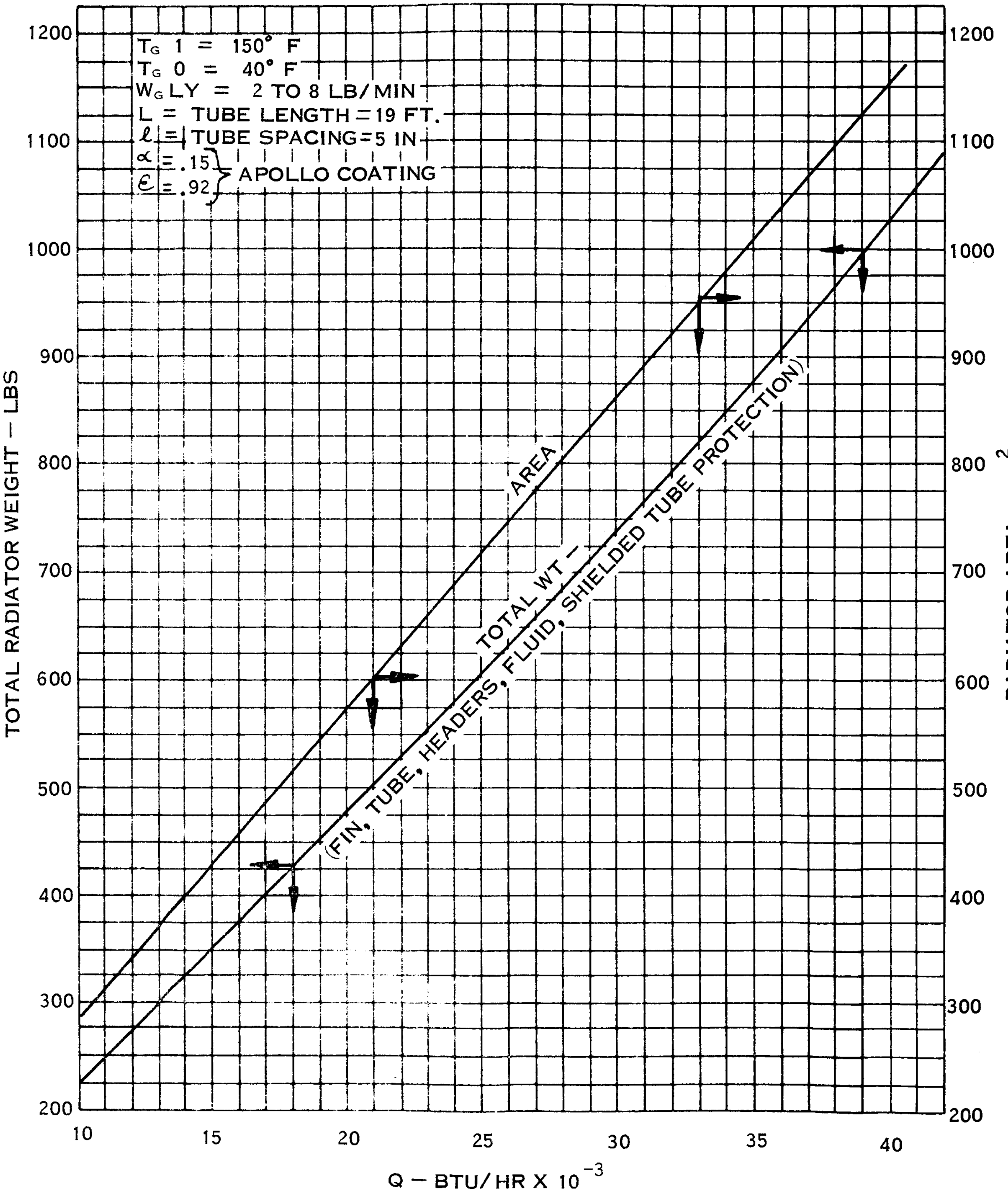
A complete discussion of these areas is far beyond the scope of this report, but Reference 6 contains an excellent review of these areas. However, a brief review will be presented of work in these three areas pertinent to the discussion.

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. Characteristic of this, is the work of Whipple (5,6, 11) in relating flux and mass as a log-linear distribution of the form (5,6)

$$\text{Log}\,(\psi) = \text{Log}\,\alpha + \beta\,\text{Log}\,(m) \qquad (1)$$

The meteoroid density is governed by certain physical relationships dictating minimum size for particles going through space. Yet, estimates of this size vary due to observational differences and various theories as to the origin of meteoroids. As more data is obtained, these relationships have varied, as shown by Figure 6-2 a plot of ψ versus meteoroid mass. Particle velocity also varies inversely as the mass, with the physical limits set as 36,000 ft./sec. to 240,000 ft./sec.; and average velocity has been computed as 98,400 ft./sec. (30 km./sec.), (5,9)

FIGURE 6–7
MARS MISSION MODULE
K=85 AVERAGE TOTAL INFLUX RADIATOR SIZES AND WEIGHTS
(RADIATOR ORIENTED AT RANDOM WITH RESPECT TO THE SUN)



METEOROID FLUX DISTRIBUTION

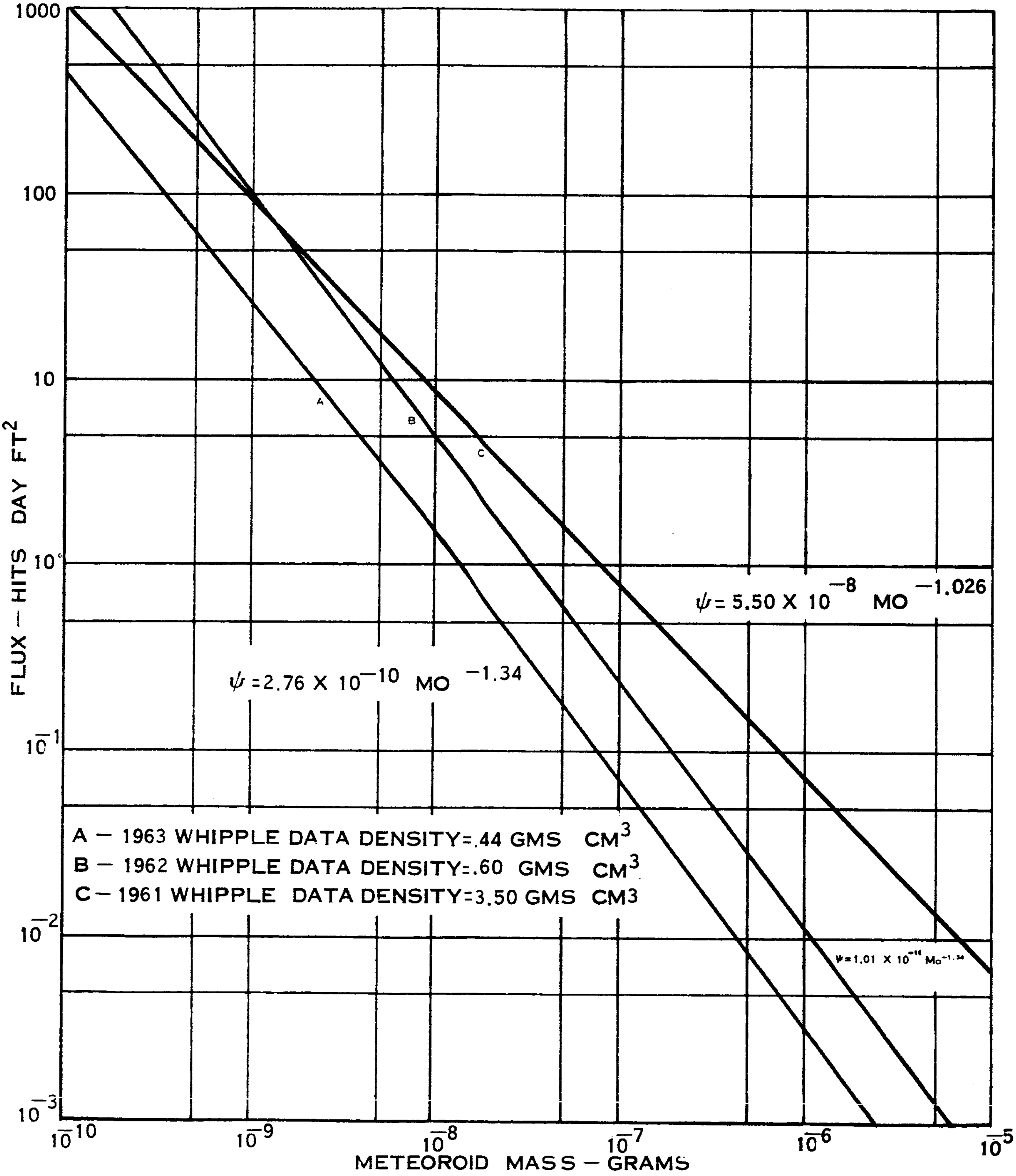


Figure 6-2

6.1.6 (Continued)

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 yet, 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.

By postulating that projectile kinetic energy is proportional to penetration depth, Charter's and Summer's (5) derived a relationship between non-dimensional penetration depth, and the physical properties of a spherical meteoroid as,

$$(p/d) = K \left(\frac{\rho p}{\rho t} \right)^{1/3} \left(\frac{V}{C} \right)^{2/3} \tag{2}$$

Experimental work showed that penetration did not exactly follow this relationship due to the various velocity regime dependent physical mechanisms in the target (stress build-up, **elastic** deformation, etc.). For the analysis here, Charter's and Summer's expression,

$$(p/d) = 2.28 \left(\frac{\rho p}{\rho t} \right)^{2/3} \left(\frac{V}{C} \right)^{2/3} \tag{3}$$

will be assumed for the penetration criteria. Many other alternative relationships dependent on various theoretical assumptions and experimental data are given in Reference 6.

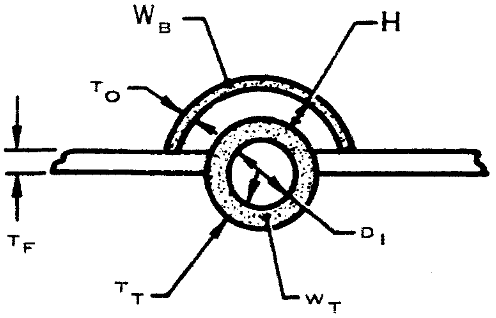
The penetration of a meteoric particle on a space radiator tube can cause damage of both a structural and performance nature. These include the loss of coolant due to leakage, as well as explosive damage due to high energy shock waves being created in the fluid and tubes. To prevent or lower the probability of this type of damage occuring, certain analytical and experimental work has been carried out with various protection schemes.

There are basically two schemes for protecting against penetration. The first is a single shield of sufficient thickness and the second consists of a multiple shield arrangement. The theory behind the equations representing the protection of each of these arrangements is as follows:

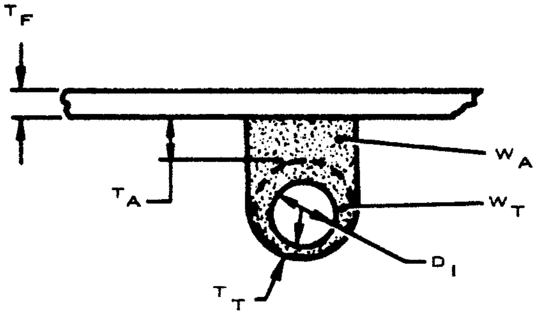
> In the first case, penetration depth was assumed to be represented analytically by Equation 3. Experimental work has shown that a projectile that will make a crater of depth P in a semi-infinite target, will just penetrate a single sheet of thickness 1.5P (5,6). A criteria for penetration protection for a single shield will be based on this. Two schemes for this single shield protection are shown in Figure 6-**3**, configurations (b) and (c).

RADIATOR METEOROID PROTECTION SCHEMES

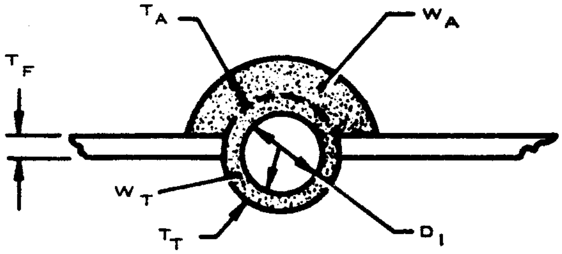
Ⓐ BUMPER



Ⓑ SHIELD



Ⓒ HEAVY TUBE



NOTE: SHADED SECTIONS REPRESENT WEIGHTS COMPUTED IN THE STUDY

FIGURE 6-3

6.1.6 (Continued)

The multiple shield arrangement (configuration (a)) is based on the fact that the initial shield will absorb a portion of the energy of the projectile, causing it to be fragmented into smaller pieces of reduced energy, which will then disperse over a larger area upon striking the second shield. Experimental investigation (7, 8, 10) has shown that with the total thickness to resist penetration still given as 1.5 P, the equivalent double shield penetration depth is given as P = 2d. The optimum initial plate thickness is $t_b = .50d$, thus the final plate (the radiator tube as defined in Figure 6-3, configuration (a)) is $t_T = 2.5d$. In order to obtain a sufficient reduction in energy of the particles striking the tube, the bumper should be a stand-off distance of 8d from the tube.

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,

$$P(n) = \frac{(\psi A \tau)^n}{n!} \, e^{-\psi A \tau} \qquad (5)$$

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

Since for a radiator zero penetrations can be tolerated,

$$P(o) = e^{-\psi A \tau} \qquad (6)$$

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

$$\psi = \alpha \, m^{\beta} \qquad (7)$$

where for the assumption of spherical meteoroids,

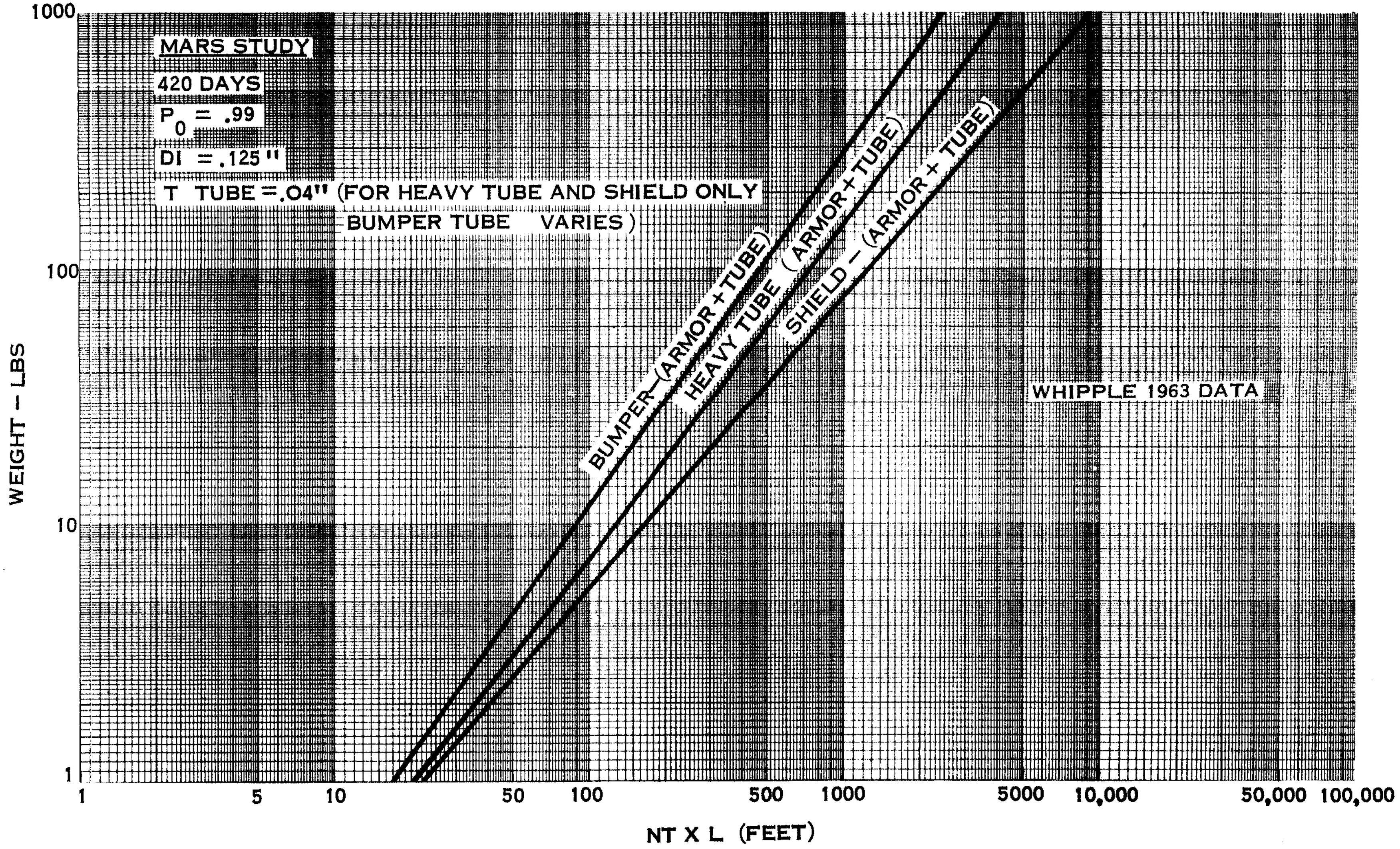
$$m = \left[\frac{\pi}{6} \, \rho_p \, d^3 \right] \qquad (8)$$

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) (di). This presents a good basis on which a parametric curve of meteoroid protection can be based, for inclusion in a radiator optimization study.

As a part of the preliminary investigation of the heat rejection system, plots of meteoroid protection weight and shield thicknesses were prepared. Figure 6-3 illustrates the results of this study based on 1963 Whipple data of flux vs. meteoroid mass and

FIGURE 6—5

RADIATOR METEOROID PROTECTION WEIGHT



6.1.6 (Continued)

an average meteoroid velocity of 30 km/sec. (98,400 ft./sec.). The initial accumulation of data was based on the Whipple data since it appeared most representati of the expected flux distribution. Revised meteroid data has recently been received from NASA and will be factored into the protection requirements for the final radiator.

As a comparison of the three approaches, Figure 6-5 presents the total weight requirements as a function of the total equivalent length for the NASA data. This figure indicates a weight savings is available by using the shielded tube approach so this method has been selected for further study.

The variables which have been fixed for this analysis (tube diameter, fin thickness, etc.) are considered representative for the eventual end application, but should not be considered as firm design points at this time. The actual determination of overa protection penalties cannot be established until these variables are established by other considerations, thus, the word of caution against a strict interpretation of the data to-date.

6.1.7 Nomenclature:

6.1.7.1 Coolant Survey

Ap	Pipe flow area
An	Heat exchanger or radiator fluid flow area
Cp	Fluid specific heat
Dp	Pipe diameter
Dn	Diameter of heat exchanger or radiator fluid passages
f	Friction factor
g	Acceleration of gravity
h	Heat transfer convection coefficient
k	Fluid thermal conductivity
Lp	Fluid loop pipe length
Nu	Nusselt number
Pr	Prandtl number
ΔP	Pressure drop of the fluid loop
Q	Heat exchanger or radiator heat load
Rep	Pipe Reynolds number
Re_n	Heat exchanger or radiator Reynolds number
Tf1	Heat exchanger or radiator inlet temperature
Tf_2	Heat exchanger or radiator outlet temperature
W	Fluid Flowrate
μ	Fluid Viscosity
ρ	Fluid Density

6.1.7.2 Meteoroid Protection Study

ψ	Meteoroid flux
m	Meteoroid mass
α	Flux distribution intercept
β	Flux distribution slope
V	Meteoroid velocity
c	Sonic velocity of target = c= $\sqrt{\frac{Eg}{\rho T}}$
E	Young's modulus
g	Gravity
ρ	Meteoroid density
ρ_t	Target, shield, tube density
P	Meteoroid penetration depth
d	Meteroid diameter
t	Thickness
T	Tube
B	Bumper
A	Armor
P (o)	Probability of no puncture
W	Weight
NT x L	Number of tubes times radiator length
d_i	Tube inner diameter

6.1.8 References

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6.2 Mars Surface Convectors

The Mars atmosphere has been considered as a potential heat sink during the Mars exploration. Atmospheric temperature varies from -94°F to 86°F at the equator throughout the Mars day. Since the 86°F is too high to use exclusively for the heat sink, a combination of convectors and radiators was investigated. For the heat loads estimated, the lightest combination of radiators and convectors would have an equivalent weight of about 530 pounds at a power penalty of 500 pounds per kilowatt, while a radiator sufficient to do all the cooling would weigh only 320 pounds. Most of this high equivalent weight is the power required. Therefore, if the power penalty could be decreased to about 150 pounds per kilowatt this system might be feasible. However, at 500 pounds per kilowatt it should not be considered further.

6.3 Evaporative Cooling

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 will be studied as part of the system integration phase when the heat loads are known and it can be determined whether this is the optimum method of cooling for those portions of the mission previously mentioned.

7.0 WATER RECLAMATION

7.1 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 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. Methods of wash and humidity water reclamation will be considered in the system investigation phase. Chemical treatment is not presented in this discussion since it is not deemed suitable for urine reclamation, although it may prove feasible for the other reclamation requirements.

The primary objective of the 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, allowance was made for this in the penalty trade-offs.

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 could 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.

7.2 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. These are presented such that a comparative evaluation of all systems can be made.

7.2 (Continued)

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

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 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. All of these factors must be taken into consideration in the final integration phase, but it was felt unnecessary at this time to attempt a premature system sizing.

7.3 Urine Reclamation by Electrodialysis

7.3.1 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.

7.3.2 System Description

Figure 7-1 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 premeable 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. The initial removal of contaminants from the water is accomplished by a series of charcoal beds and filters upstream of the membrane stack to remove the non-electrolytes. The inlet urine is treated by a complexing agent which precipitates the urea and allows it to be filtered out by the charcoal and millipore filters. The treated urine is then passed to the inlet of the electrodialysis stack.

The ions are evenly distributed at the inlet to the stack. However, upon coming in contact with the potential difference across the membranes, separation does initiate. The positively charged ions pass through the cation premeable membrane 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 until the required degree of desalinization is achieved. The concentrate stream contains a certain quality of endosmotic water that has dissolved in it all the salts and represents a fraction of the original water that cannot be recovered by this process. After completion of desalinization in the electrodialysis cell, the processed water is final treated by charcoal filtration and irradiation with ultra violet 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 productions 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.

A membrane permeation unit is proposed in the Ionics approach to achieve greater recovery efficiency of the inlet urine. This membrane permeation unit will increase reclamation efficiency from 95% to approximately 96.8% but does so at a decrease in system reliability. The basic unit, through a process quite similar to vacuum distillation, removes moisture from the stack concentrate and delivers it to storage through the charcoal filter and ultra violet lamp.

ELECTRODIALYSIS H_2O RECLAMATION

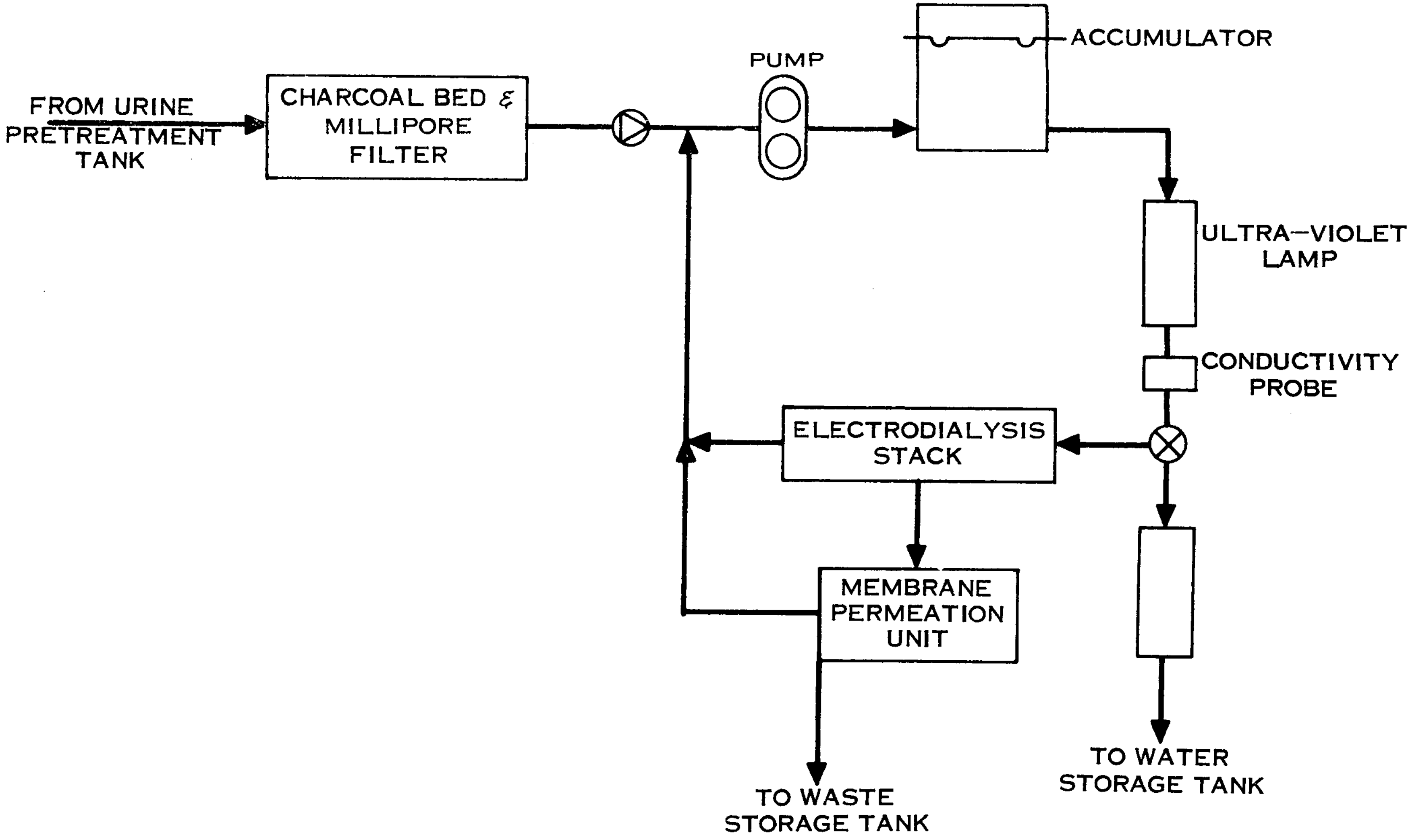


FIGURE 7-1

7.3 Conclusions

The electrodialysis process has many problem areas which must be resolved prior to its suitability for Mars Mission applications. The 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 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 membranes may exhibit problems in passing large ions which could lead to eventual carry-over to storage of unsatisfactory element during system operation. This area should also be evaluated experimentally prior to system selection.

If achievement of the areas previously mentioned is possbile, electrodialysis is a very promising system approach in 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.

7.4 Air Evaporation Urine Reclamation

7.4.1 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.

7.4.2 System Description

Figure 7-2 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 evaluation of this means can be substantiated.

AIR EVAPORATION H_2O RECLAMATION

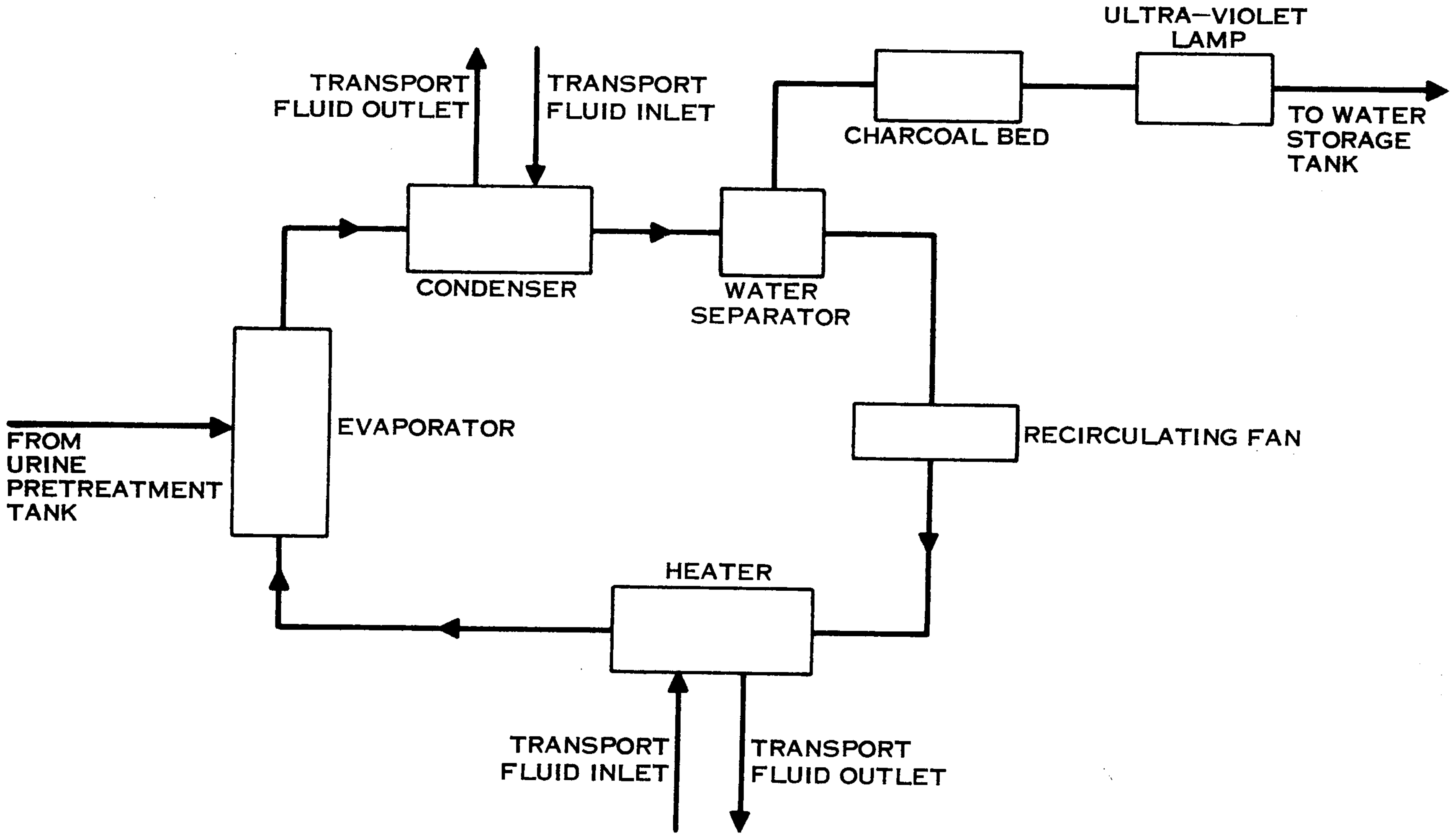


FIGURE 7-2

7.4.2 (Continued)

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 coolant 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 then pumped out of the system to storage or post-treatment as required depending upon its eventual use.

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. 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 thus should not require any severe development problems since the primary requirement is adequate sizing of equipment rather than extending its performance requirements or capabilities.

4.3 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. 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 weight is probable since condenser

7.4.3 (Continued)

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

The system requires expendables for pre-treatment and post-treatment, as well as periodic changing of the wicks in the evaporator. However, the rate of utilization of these expendables is not an excessive amount (in the order of 3% by weight of the urine processed).

7.5 ELF Water Reclamation

7.5.1 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 solid electrolyte ion exchange membrane fuel cells for the water reclamation application. The system description and data presented in this report is 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.

7.5.2 System Description

Figure 7-3 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 dissociated 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 doubts 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 the membrane replacement unit will be a low weight penalty to the overall vehicle.

ELF H_2O RECLAMATION

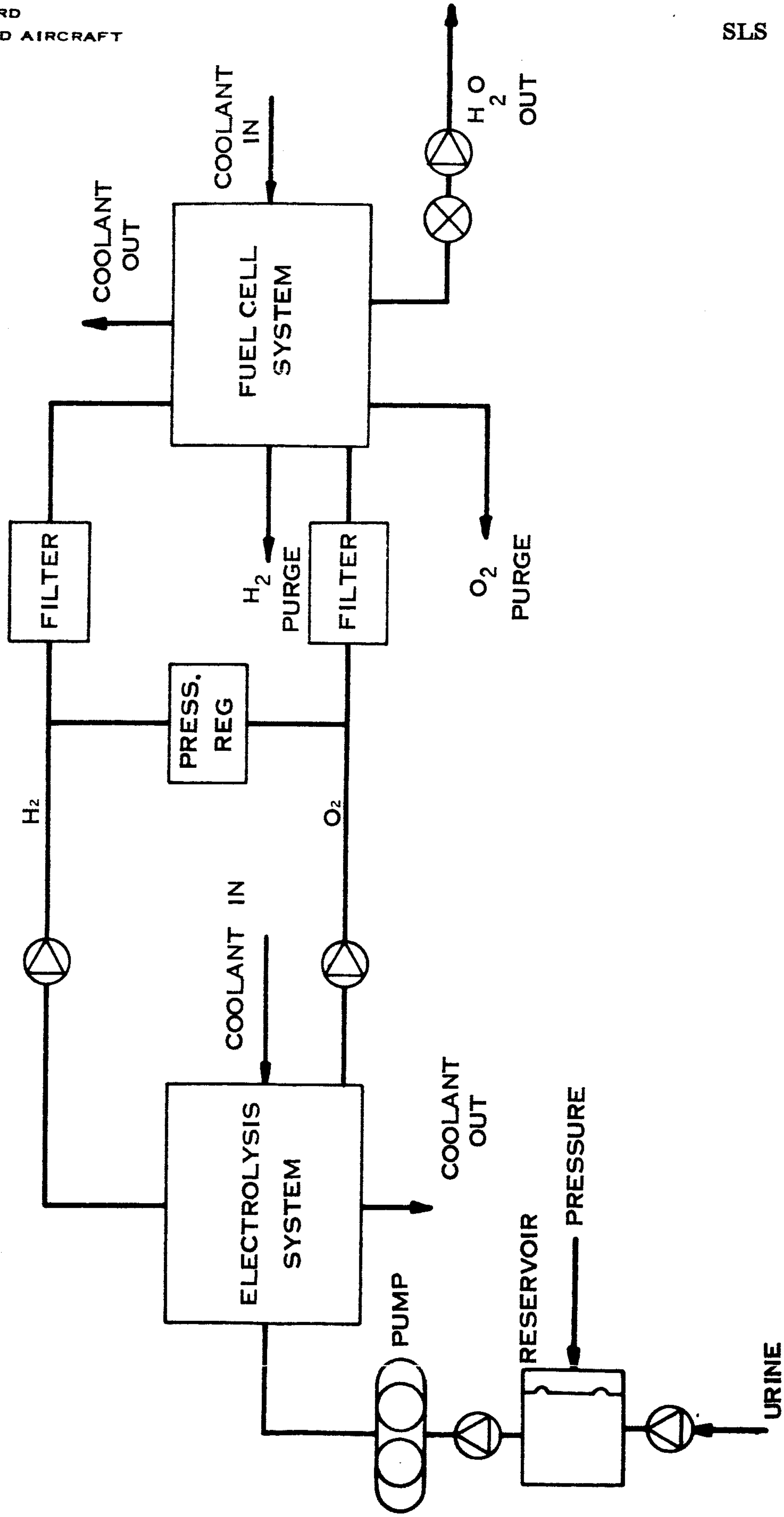


FIGURE 7-3

7.5.2 (Continued)

Another problem area in the ELF system may be the electrolysis cell itself. Since raw urine is introduced directly into the cell, urea and other contaminants may build up within the cell. This may require additional expendables to protect the membranes or more frequent replacement of these membranes.

7.5.3 Conclusions

The ELF urine reclamation system has as its main potential advantage the lack of expendable requirements and a simplified stop-start procedure in comparison with many water reclamations systems. However, the very high power requirements for this process may make the system non-competetive for missions with a high power penalty, and the membrane life question may rule it out for longer duration missions. Qualitatively, the sy reliability should be considerably less than that of some of its counterparts due to the rathe 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.

7.6 Oil Jet Evaporation Water Reclamation

7.6.1 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.

7.6.2 System Description

Figure 7-4 illustrates the oil jet evaporator system considered in this study. As 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.

7.6.3 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 vapor compression system and make this approach worthy of consideration upon initial evaluation.

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%.

OIL JET H_2O RECLAMATION SYSTEM

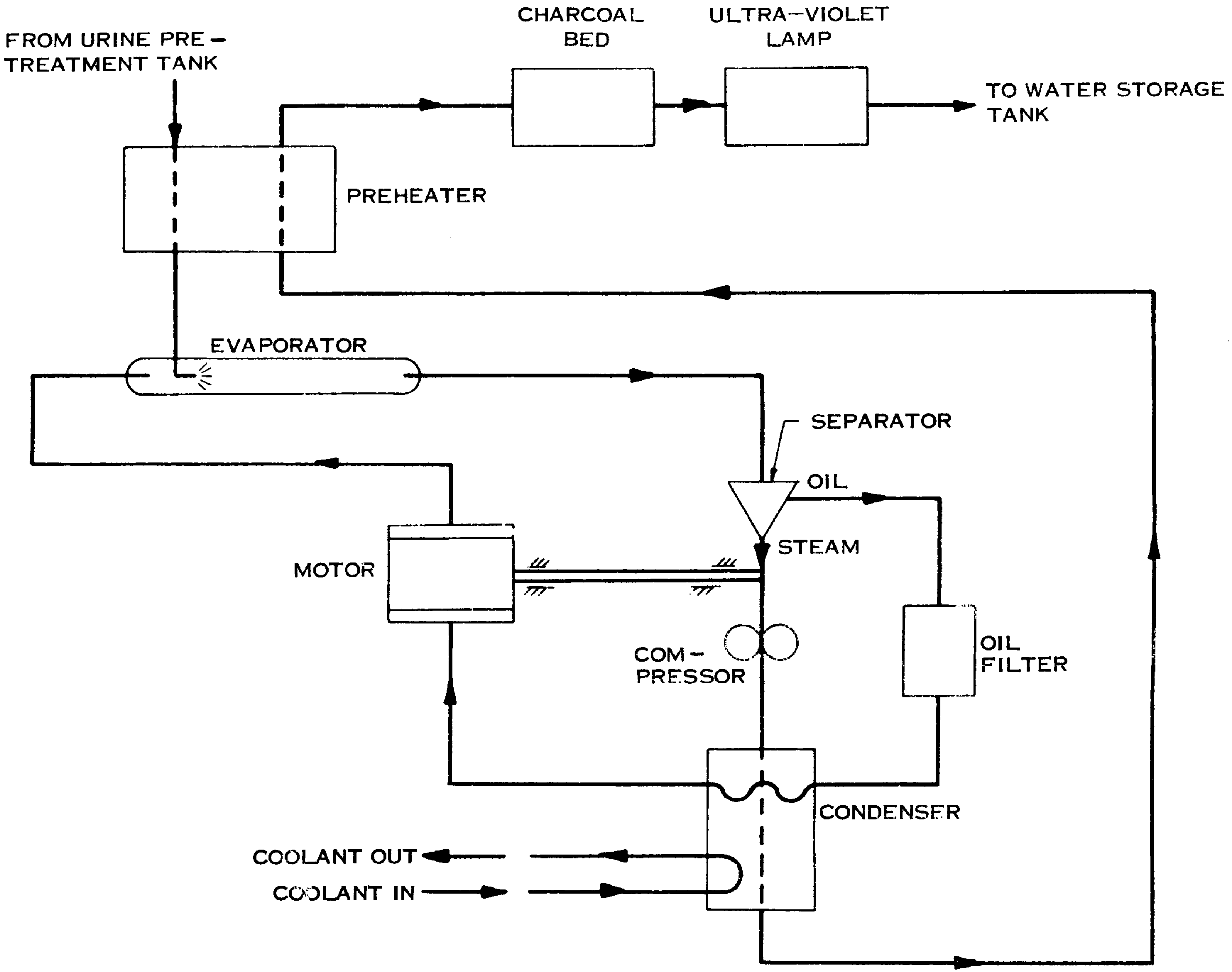


FIGURE 7-4

7.6.3 (Continued)

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 and as such, tends to make the system unattractive for a system in which scheduled down time would be used for maintanence.

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.

7.7 Vapor Compression Water Reclamation

7.7.1 Introduction and Data Source

A more direct vapor compression approach 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 Division of General American Transporation 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 this approach is the most attractive of the candidate systems.

This study analysis has been based upon information in Mechanics Research Division reports on the system numbered MR1186-30 and MR7614-10. 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.

7.7.2 System Description

Figure 7-5 presents a simplified schematic approach of the vapor compression system considered in this study. The system consists essentially of a urine evaporator,

VAPOR COMPRESSION H_2O RECLAMATION

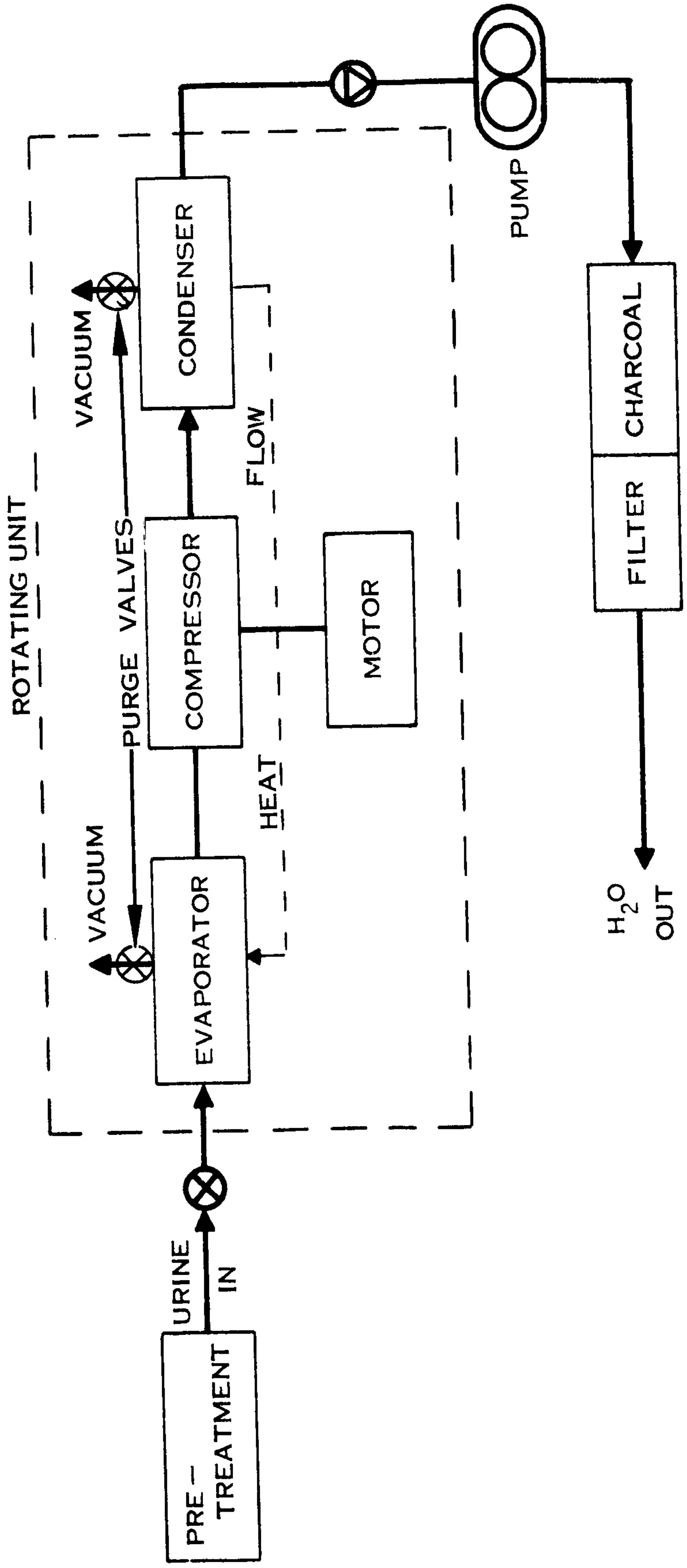


FIGURE 7-5

7.7.2 (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 in the evaporator at a saturation temperature of about 84°F. The evaporated water is then compressed to raise its saturation temperature to about 106°F. The steam is then condensed in the condenser with the heat being used to boil the urine in the evaporator. The condensate is then drawn off the condenser, post-treated, and then passed to the water storage tanks.

This system has the primary problem that the oil jet concept was trying to avoid; 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.

7.7.3 Conclusions

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 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.

7.7.3 (Continued)

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 is that of controlling the two phase mixture in both the evaporator and the condenser. This is necessary to insure that the liquid is in contact with the heat transfer surfaces of the evaporator, and to insure that the heat transfer surfaces of the condenser can be cleared of the condensed liquid so high effectiveness is maintained. It is also important to eliminate any carry over of liquid from the evaporator to the condenser which would contaminate the distillate. The present method of rotating the evaporator and condenser to create an artificial gravity field seems to be the most direct solution to this problem. The third area of concern is that of the presence of non-condensables in the condenser. The present design utilizes a purge to vacuum to rid the condenser of these non-condensables. This appears to be a satisfactory approach but results in a penalty for the air lost to vacuum during the purge. The primary disadvantages of the system are:

(1) Reliability problems associated with the mechanism for rotating the evaporator and condenser.

(2) Leakage problems associated with operation at reduced pressure in the system.

(3) Difficult start-up and shut-down procedures resulting in poor adaptability to intermittent operation.

All of these require additional analysis and development work.

7.8 Vacuum Distillation with Pyrolysis

7.8.1 Introduction and Data Source

The investigation of vacuum distillation as a potential means of water reclamation for the manned orbiting space station utilized an approach developed by the General Electric Co. known as a vapor pyrolysis. This approach, utilizes the addition of a catalyst to a more conventional vacuum distillation system.

The primary sources of data for this analysis are U.S. Air Fource 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.

7.8.2 System Description

Figure 7-6 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 1800° Fahrenheit. The catalyst oxidizes the trace gas contaminants present in the vapor and 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. The quantity of cabin atmosphere lost is about 6.3 pounds for a six man system for 420 days.

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.

7.8.3 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 particularily 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.

VACUUM DISTILLATION H_2O RECLAMATION SIMPLIFIED SCHEMATIC

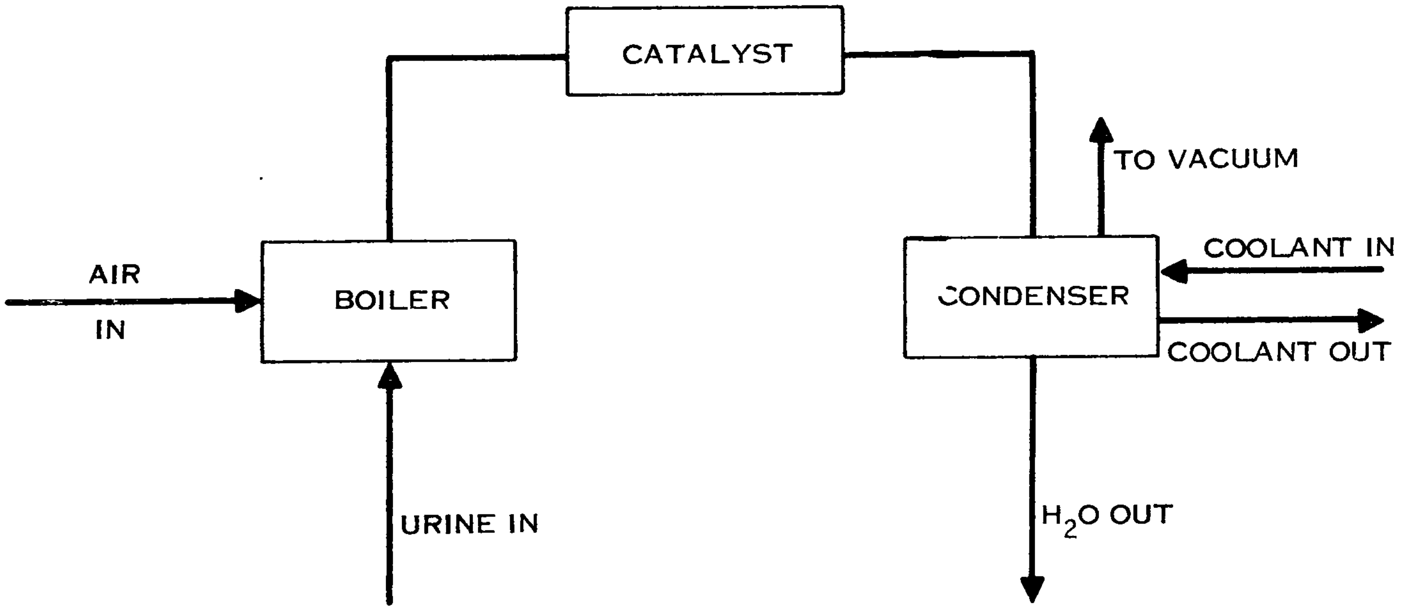


FIGURE 7-6

7.8.3 (Continued)

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 also is 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 would probably have to be accomplished by a method such as artificial gravity, membranes, or some other applicable process which would tend to reduce the inherent reliability of this system which is apparent for operation in the case where gravity is present. Finally, the vapor flow to the catalyst and the catalyst operating temperature might prove to be a control problem not 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.

7.9 Comparative Discussion

To summarize the evaluation of the various water reclamation methods a series of curves has been prepared. These curves compare the fixed weight, the expendables, the required power, and the equivalent weight of the various systems.

It can be seen from Figure 7-7 that the air evaporation system of water recovery from urine has the lightest weight of installed equipment of all the systems presented regardless of the urine process rate. However, all the systems are reasonably competetive with the exception of the ELF system.

Figure 7-8 illustrates the expendables which must be carried along for a 420 day mission as a function of the urine process rate. This must be added to the fixed weight to obtain the total weight of the system for a 420 day mission. Since the weight of expendables is a function of the total weight of urine processed, these curves can be used to determine the expendables for any mission from a total urine production of 2500 pounds up to 17,000 pounds. It can be seen from this figure that all systems fall in a competetive range except the electrodialysis without charcoal regeneration.

Figure 7-9 illustrates the power required to operate each of these systems. This

FIGURE 7-7

URINE RECLAMATION SUMMARY

FIXED WEIGHT VS. URINE PROCESSED

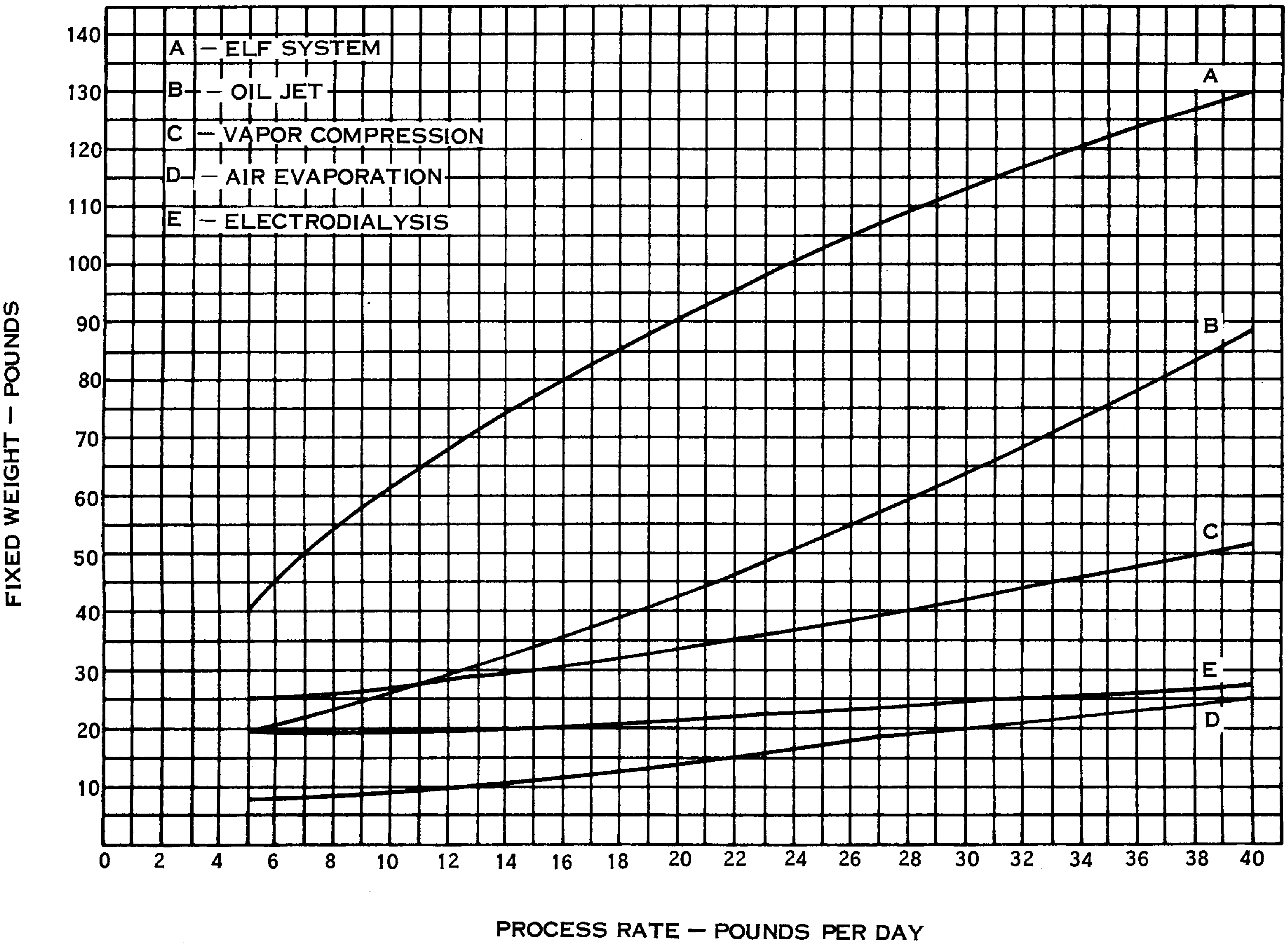


FIGURE 7–8

URINE RECLAMATION SUMMARY
EXPENDABLES VS. PROCESS RATE
420 DAY MISSION

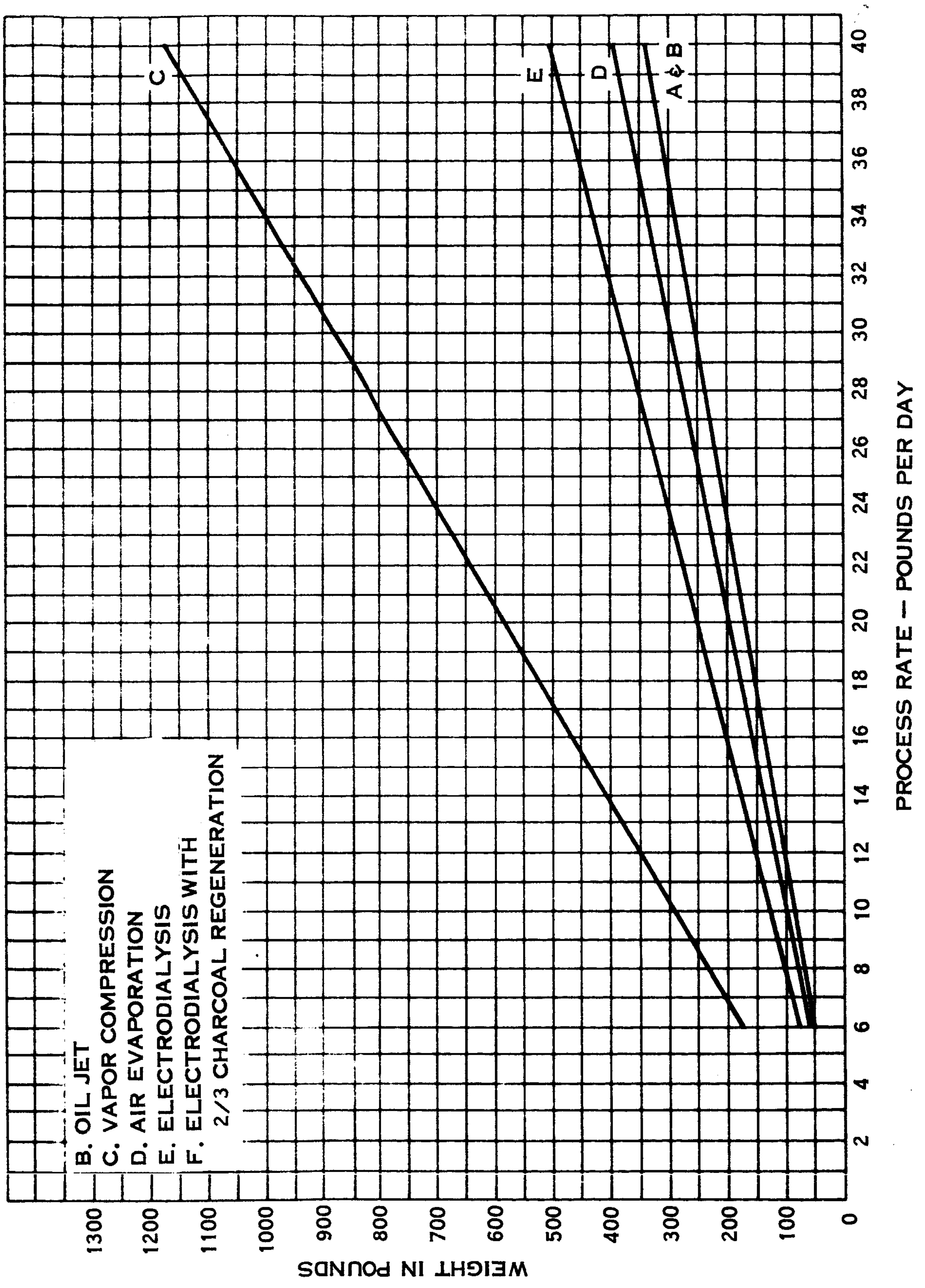
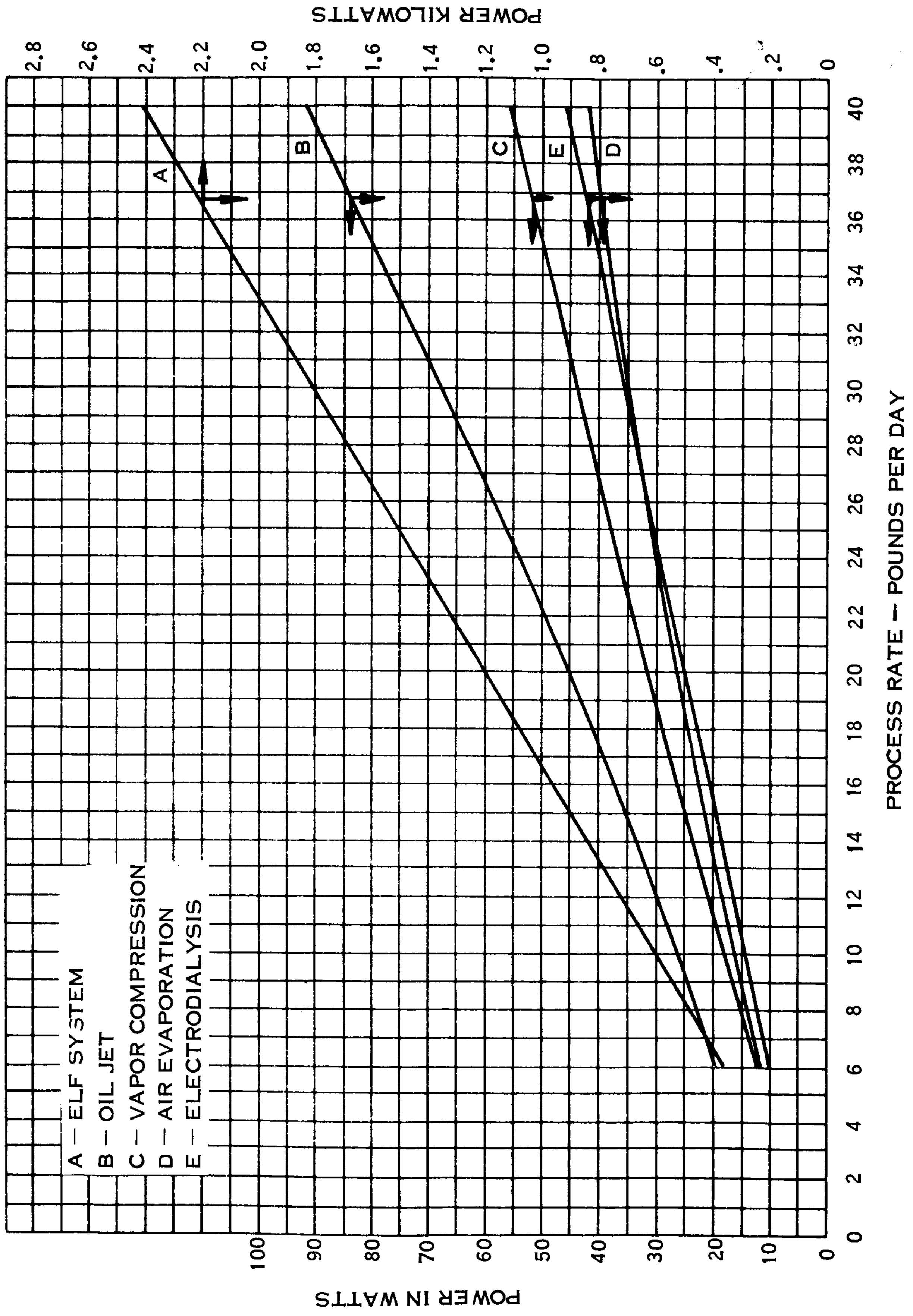


FIGURE 7 — 9

URINE RECLAMATION SUMMARY
POWER VS. PROCESS RATE



7.9 (Continued)

power can be converted to an equivalent weight when the appropriate power penalty has been determined and a total equivalent weight can be determined for each system. Figure 7-10 shows such a comparison for a 420 day mission at a power penalty of 500 pounds per kilowatt.

From Figure 7-10 it can be seen that electrodialysis and the ELF methods are so heavy as to disqualify them from consideration. However, electrodialysis with charcoal regeneration, air evaporation, oil jet evaporation, and vapor compression all appear competitive. Of these four, only oil jet evaporation and air evaporation recover 100% of the water processed. In a mission such as the Mars Mission where a ground rule states that the metabolic water cannot be considered reclaimable, any water not recoverable must be made up by stored water. Therefore, during the system integration phase the vapor compression and electrodialysis systems will be penalized for this inefficiency.

Of these four candidate systems, the air evaporation appears to have the highest degree of development and the best reliability. It has low fixed weight and low power requirements. Most of the weight consists of the pretreatment chemicals, the post-treatment filter and the expendable wicks. It appears feasible to decrease the weight of the pre-treatment and regenerate the charcoal from the final filter. It may also be possible to regenerate the wicks, thus decreasing the weight even more.

Another variation of this process uses cabin air to evaporate the water thus utilizing the cabin fan, condenser, and water separator in dual roles and saving weight. However, more development work must be done on the potential odor problem of this system before it can be considered a competitive system.

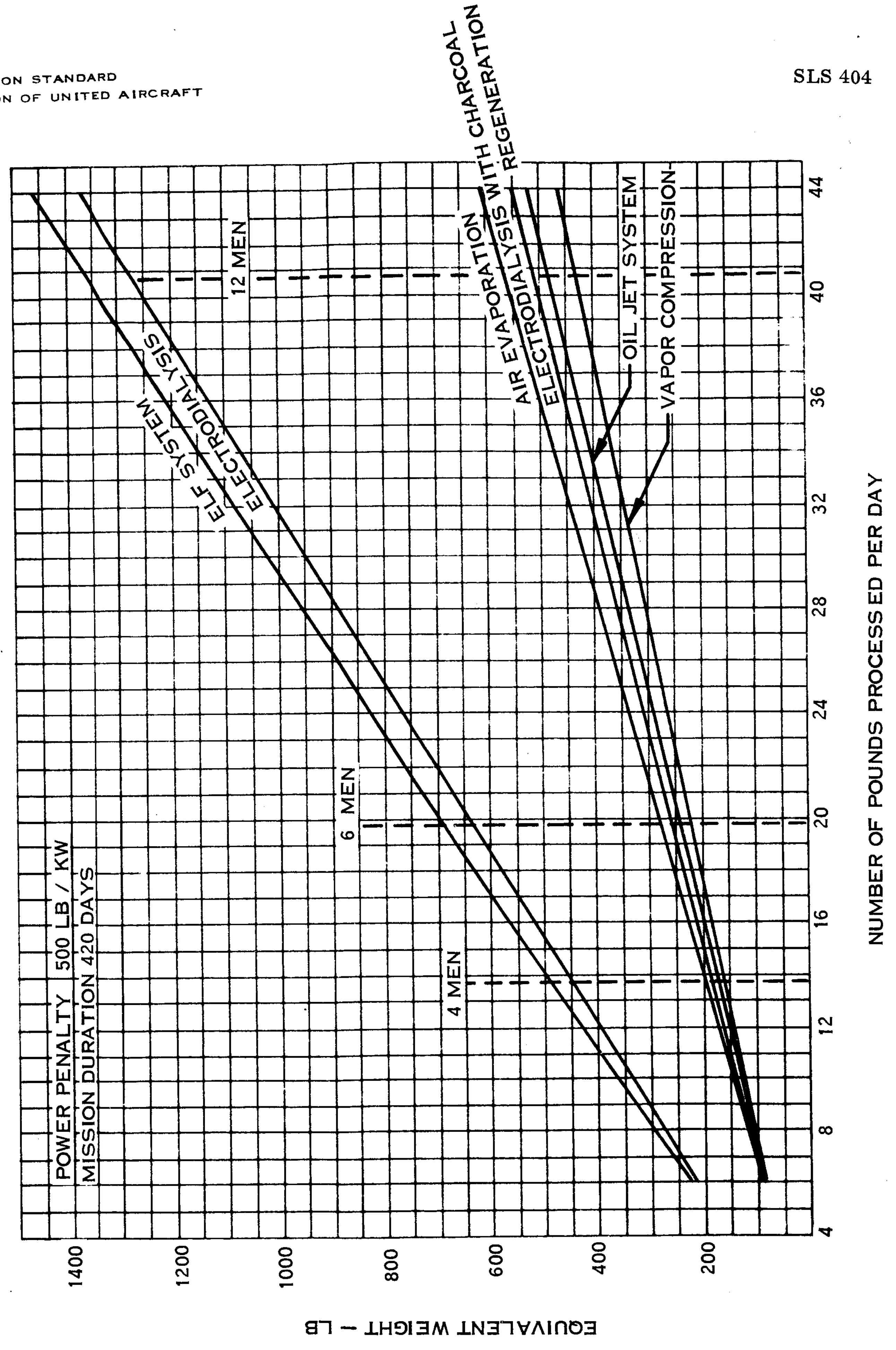
Electrodialysis with charcoal regeneration looks attractive if a method can be found to adequately regenerate the charcoal. The curves in this section for electrodialysis with charcoal regeneration assume 66% regeneration. Thus far, not much work has been done on this. However, it may be particularly difficult to regnenerate the charcoal from this process because it is used to filter precipitated urea. Another problem is that the reliability of the membranes has not been proven and there is a possibility that the membranes may deteriorate and pass unsatisfactory water. More experimental work should be done on this phase of the process.

The oil jet system is attractive in that it recovers 100% of the water and does not have an evaporator scaling problem. However, it does require a highly effective zero g condenser. This system has had very little development work and therefore can not be considered competitive at this time, but it does warrant consideration for the future.

FIGURE 7–10

URINE RECLAMATION SUMMARY

EQUIVALENT WEIGHT VS. PRODUCTION RATE



7.9 (Continued)

Vapor Compression appears to be the lowest weight system considered. However, the fact that it does not recovery 100% of the water adds another penalty to its weight. This system has been receiving considerable development attention in recent months, but it still has several problem areas. It too requires a highly effective zero g condenser and a solution to the scaling problems in the evaporator.

Figure 7-11 shows the previously discussed comparative information in a different form to permit evaluation of the effects of mission time on the equivalent weight of the various systems for a six man crew and 500 pounds per kilowatt power penalty.

Figure 7-12 illustrates the equivalent weight of the urine reclamation system for the Mars Excursion Module for missions up to 40 days. It can be seen that air evaporation, vapor compression, and electrodialysis are all competetive but air evaporation is the lightest.

Figures 7-13 and 7-14 illustrate the approach to wash water reclamation for the Mission Module and the Excursion Module respectively.

An analysis was performed of the contaminant level of the used wash water, and it was found that if 14 pounds per man day or less was used the contamination was such that the entire amount of water had to be processed to maintain the proper purity level. However, if more than 14 pounds per man day was used, the entire amount could be filtered to remove solids, put through an ionic resin to remove the soap, subjected to UV radiation or have a germicide added to kill bacteria, and then 14 pounds per man day processed to remove salts etc, rather than processing the entire amount. This method appears satisfactory to maintain the wash water at a potable level. Therefore, the figures 7-13 and 7-14 have been drawn for the maximum wash water considered, 40 pounds per man day, with only 14 pounds per man day going through the entire treatment. This conclusion is based on analytical results and discussions with people in the filter, soap, and resin industries. Up to this time very little experimental work has been done in this area, and much additional development work will be necessary before these filters and resins can be considered satisfactory. It can be clearly seen that Open Loop Air Evaporation and Electrodialysis with charcoal regeneration are the most likely methods of wash water purification. Both of these methods are considered feasible due to the low odor level and the small amount of urea present in the wash water.

FIGURE 7–11

URINE RECLAMATION SUMMARY EQUIVALENT WEIGHT VS. MISSION DURATION

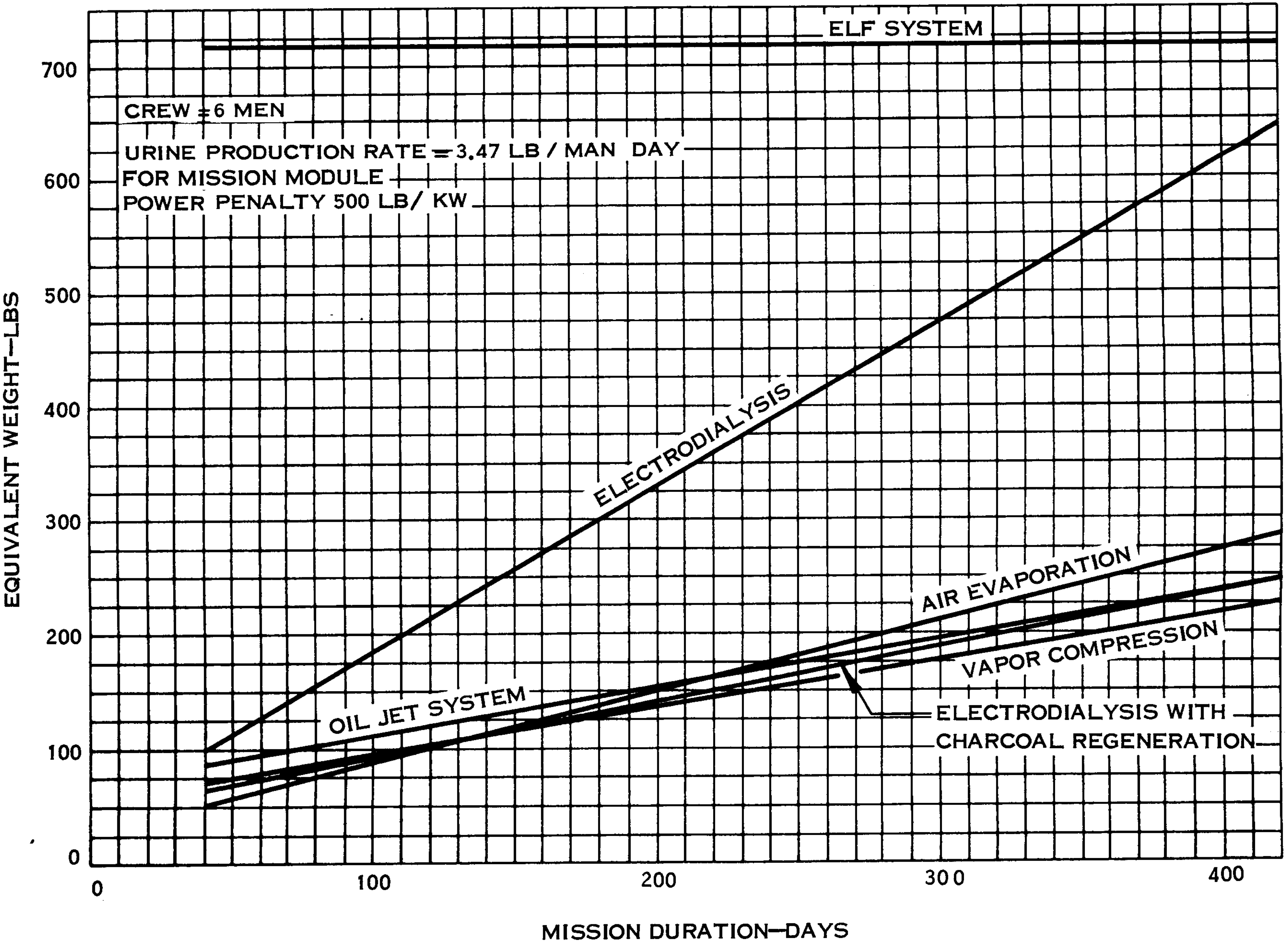


FIGURE 7–12

URINE RECLAMATION SUMMARY
EQUIVALENT WEIGHT VS. MISSION DURATION

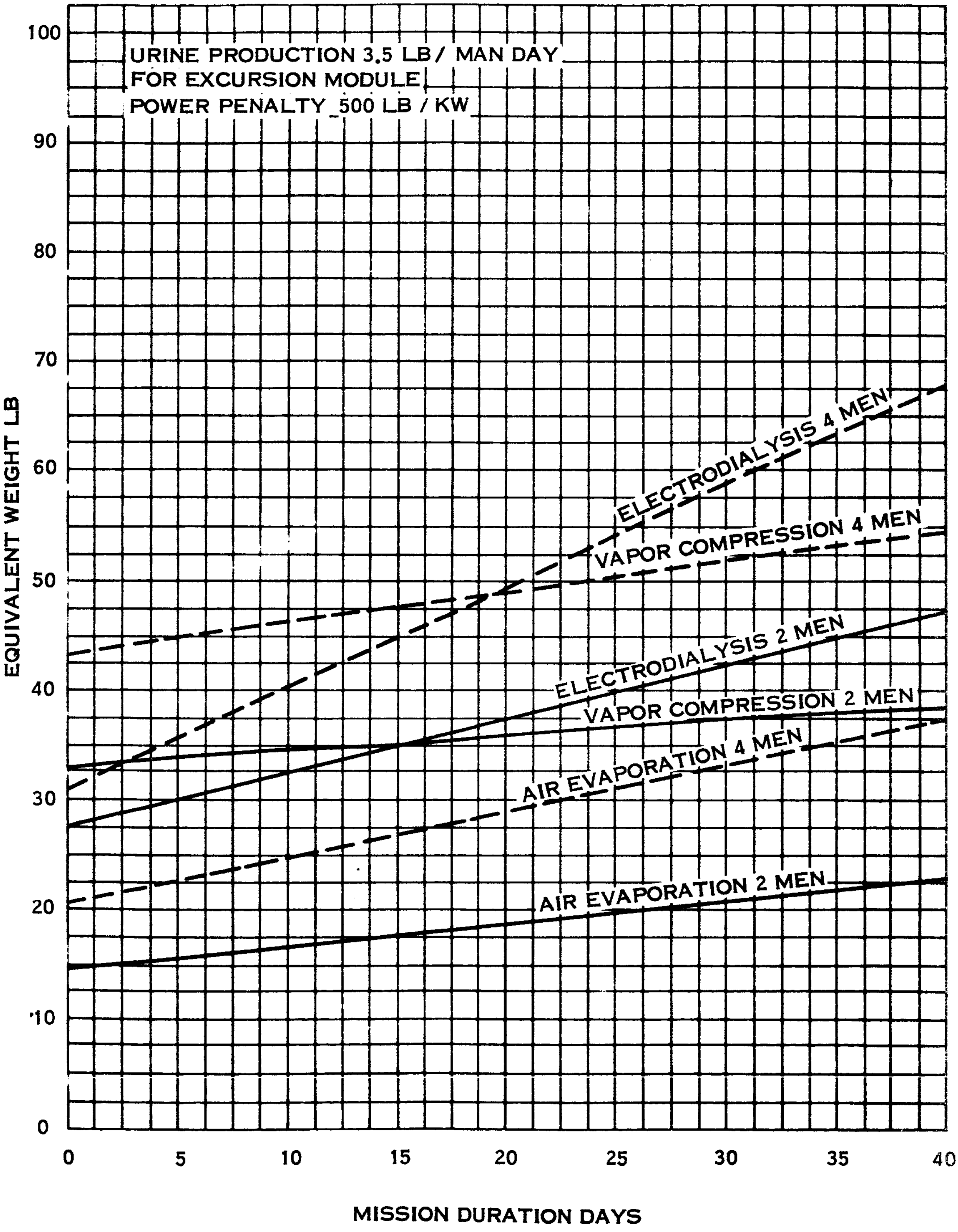


FIGURE 7–13

WASH WATER RECLAMATION SUMMARY

EQUIVALENT WEIGHT VS. MISSION DURATION

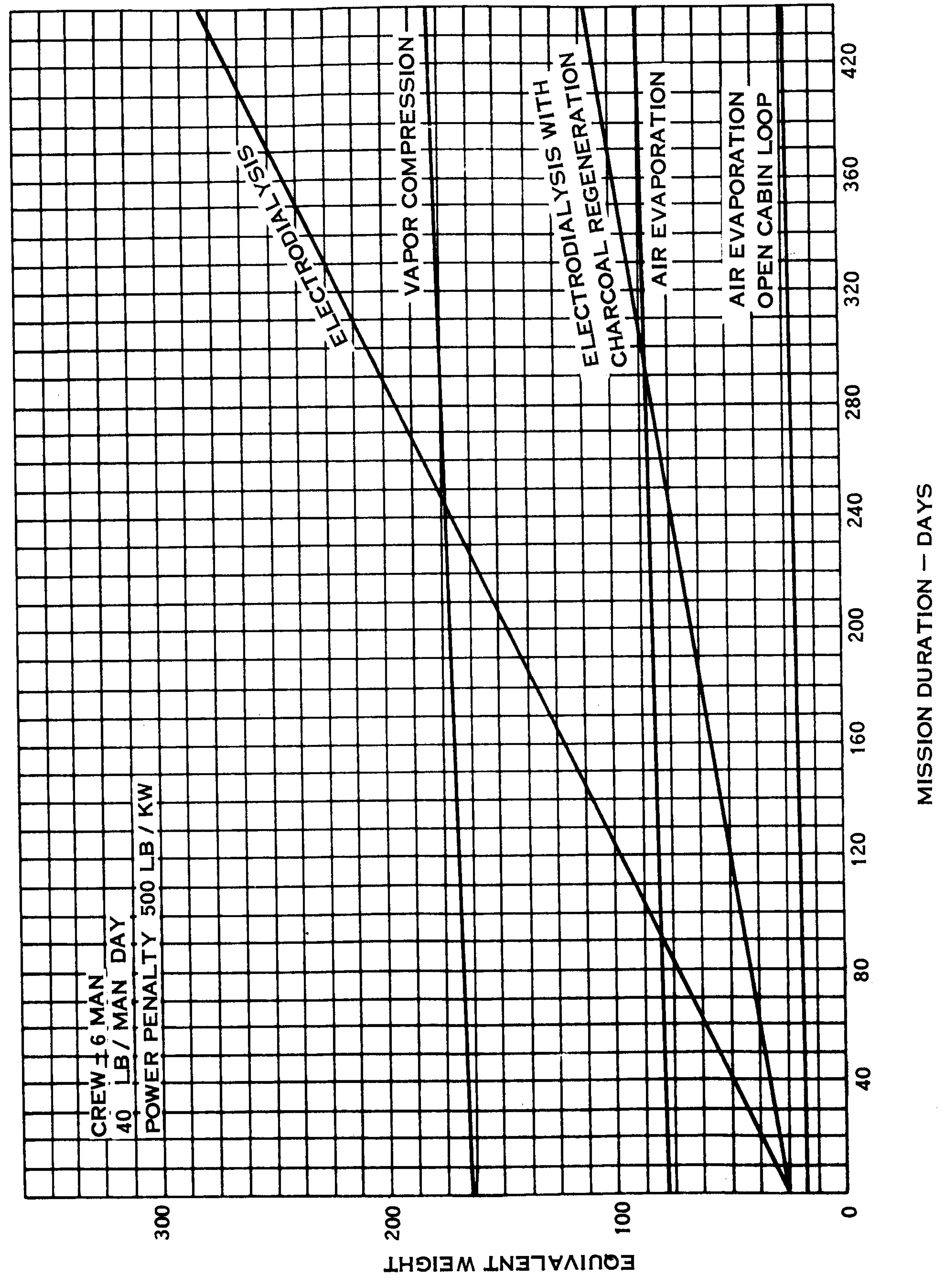
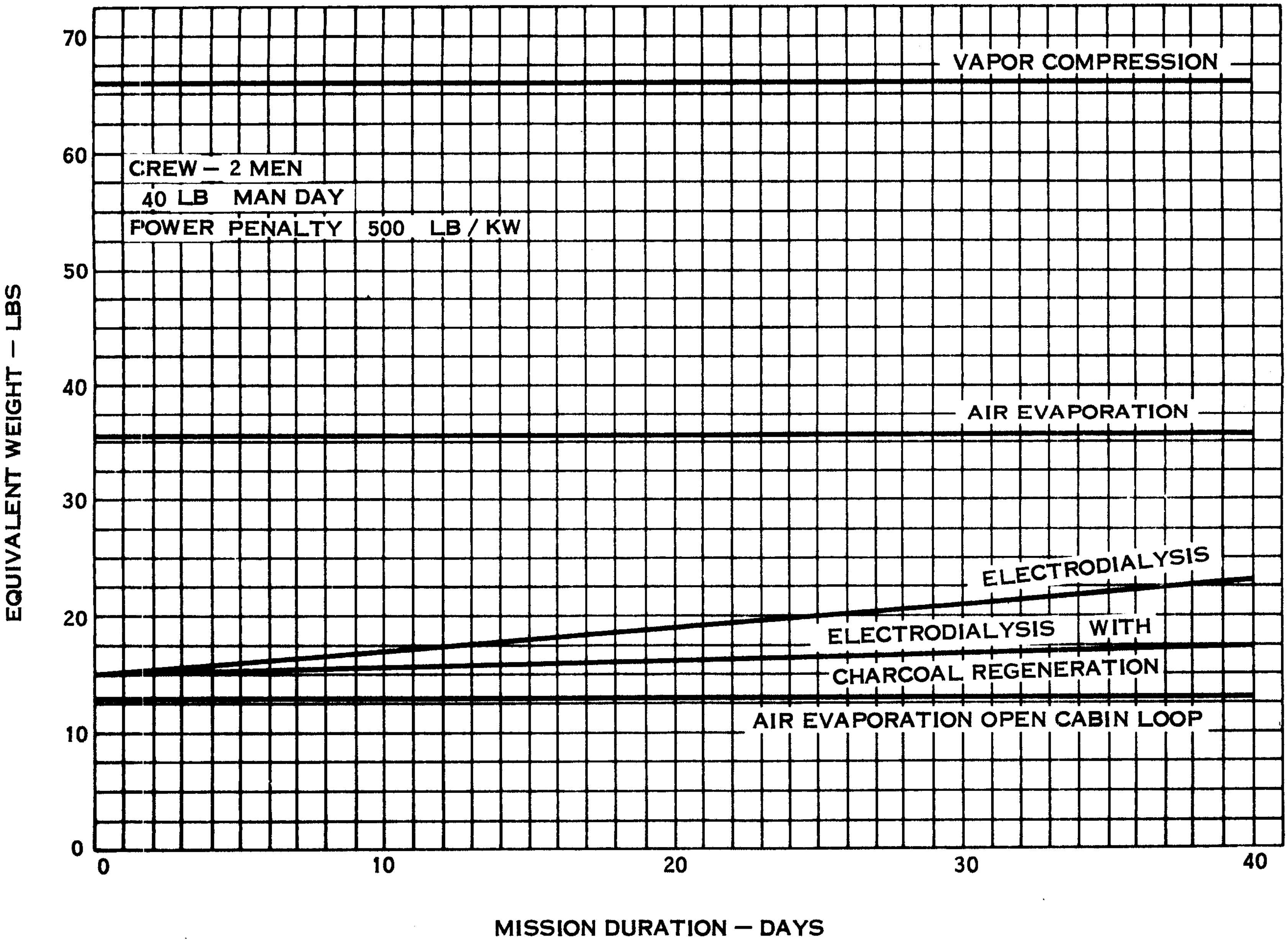


FIGURE 7–14

WASH WATER RECLAMATION SUMMARY

EQUIVALENT WEIGHT VS. MISSION DURATION



8.0 INSTRUMENTATION

8.1 Objectives

The study of system instrumentation requirements at the subsystem level is necessarily limited to a general analysis and evaluation of approaches. This is true due to the integration requirements with the rest of the life support system. Since the primary functions of instrumentation in a life support system are monitoring and control, an instrument cannot easily be selected and the system designed to meet its requirements (sensitivity, response time, temperature levels, etc.) Instead, a survey of potential approaches is made and the final selection becomes a topic of the system integration phase.

At the subsystem level, the study is interested in determination of potential methods of monitoring cabin atmospheric content, pressure, temperature, stored fluid quantities, water potability, and leakage detection. The first is the most nearly independent item since all of the others depend upon final selection of the system for their specification requirements. For this reason, the primary emphasis to date has been on a general survey of the potential methods of monitoring the constituents of the cabin atmosphere. Upon completion of all subsystem studies, more detailed attention will be paid to the other requirements.

For this mid-term report, the instrumentation discussion will be limited to the potential methods of gas analysis which have been reviewed. Based upon a preliminary specification of gas analyzer requirements, general discussions with potential suppliers led to the comments presented in the following pages.

Gas analyzers occupy an important position in any extended duration life support system due to the potential atmospheric contaminants which, if allowed to build up, could be dangerous to the safety of the crew. There is a recognized need for a continued surveillance of cabin atmosphere 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. Numerous compounds have been identified in closed systems but very little data is 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. 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.

8.1 (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.

8.2 Gas Analyzers

8.2.1 Absorption Spectroscopy

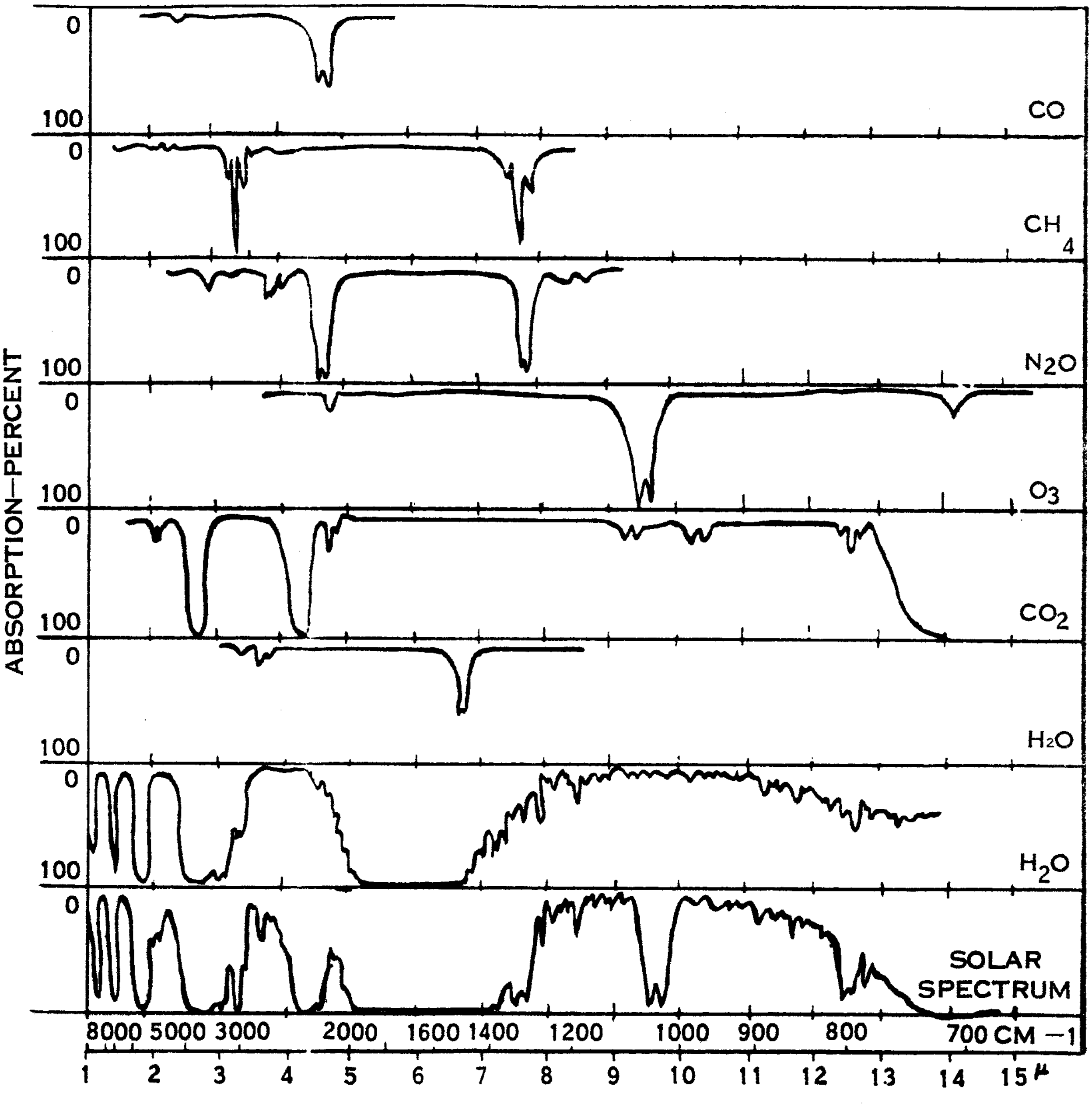
Regardless of the wave length, the type of radiation source or the means of detection utilized, these systems are characterized by the use of the selective absorption bands exhibited by the various gases.

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 determing 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.

8.2.1.1 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 consist 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 8-1 which was submitted by Minneapolis-Honeywell.

The detection of CO is masked by the presence of N_2O which displays an absorption band at essentially the same wave length. To circumvent this problem, a non-dispersive



NEON INFRARED ABSORPTION SPECTRUM FOR VARIOUS GASES

FIGURE 8-1

8.2.1.1 (Continued)

technique can be used where the detector is a cell containing the particular component of interest, as in the case of CO. The energy absorption bands are then perfectly matched and detection is a function of the energy absorbed in the cell. This particular type of unit is not well suited to the requirements of space hardware and, as in the case of the filter photometer, does not qualify as a gas analyzer except that it is capable of detecting more than one constitudent.

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 length.

8.2.1.2 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 is based upon the fact that the absorption bands are actually not continuous but made up of resonant peaks on the order of .5 angstroms in width. Because these peaks are specific for each gas, 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.

8.2.1.3 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 conversi 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 an a particular radiation frequency alternately interferes and reinforces itself at a frequenc that is directly proportional to mirror velocity and inversely proportional to the radiatio 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.

8.2.1.4 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:

8.2.1.4 (Continued)

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 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 = s 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 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_3,F, C_2H_2O, CH_2O, CH_3Cl, SO_2, CH_3OH, C_2H_5OH, CH_3COOH, $(CH3)_2$, HNO_3, CH_2, CHCHO, etc.

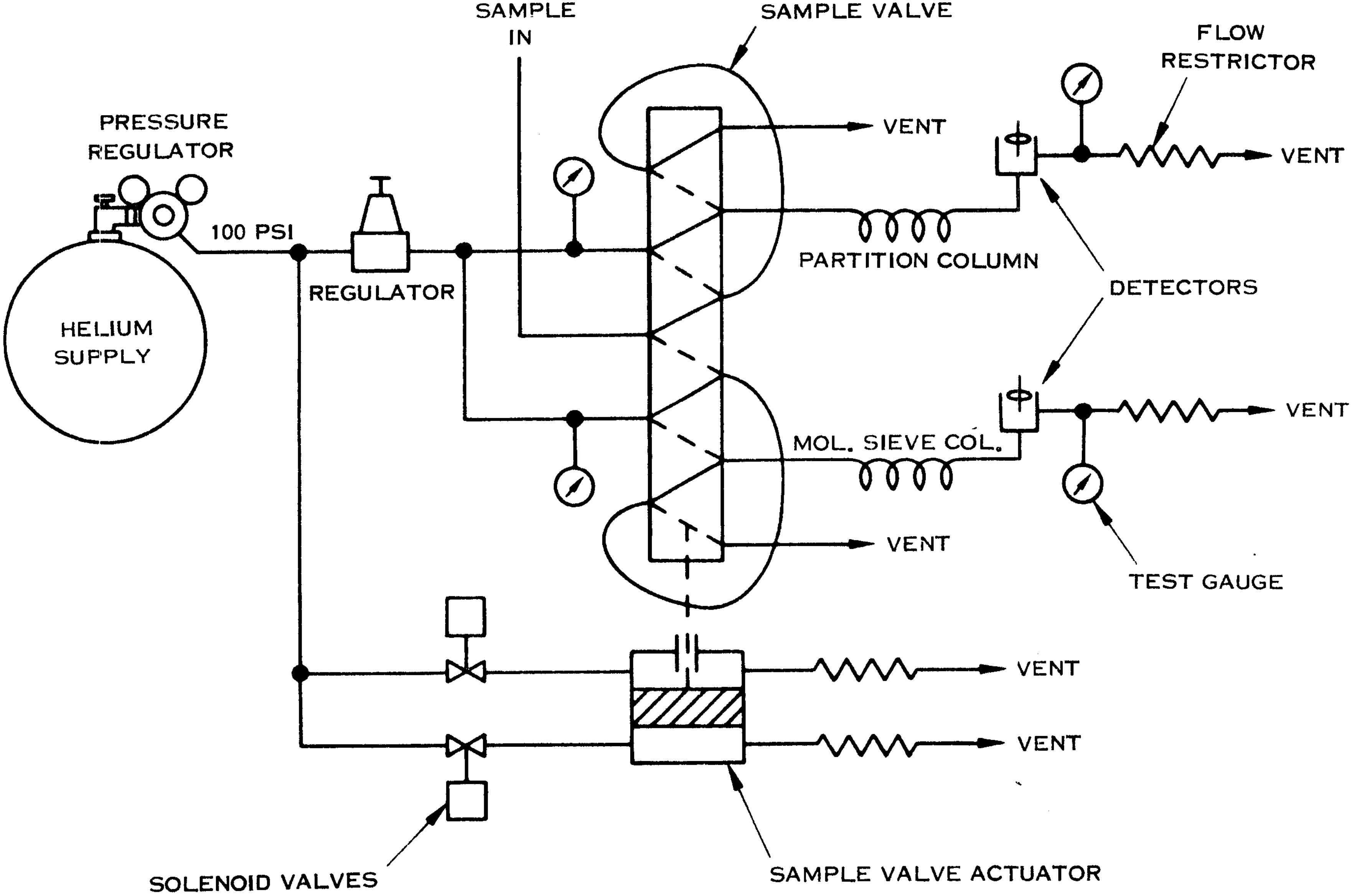
8.2.2 Gas Chromatography

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 chromatograph 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 8-2). 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. 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 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.



FUNCTIONAL SCHEMATIC FOR THE GAS CHROMATOGRAPH

FIGURE 8-2

8.2.2 (Continued)

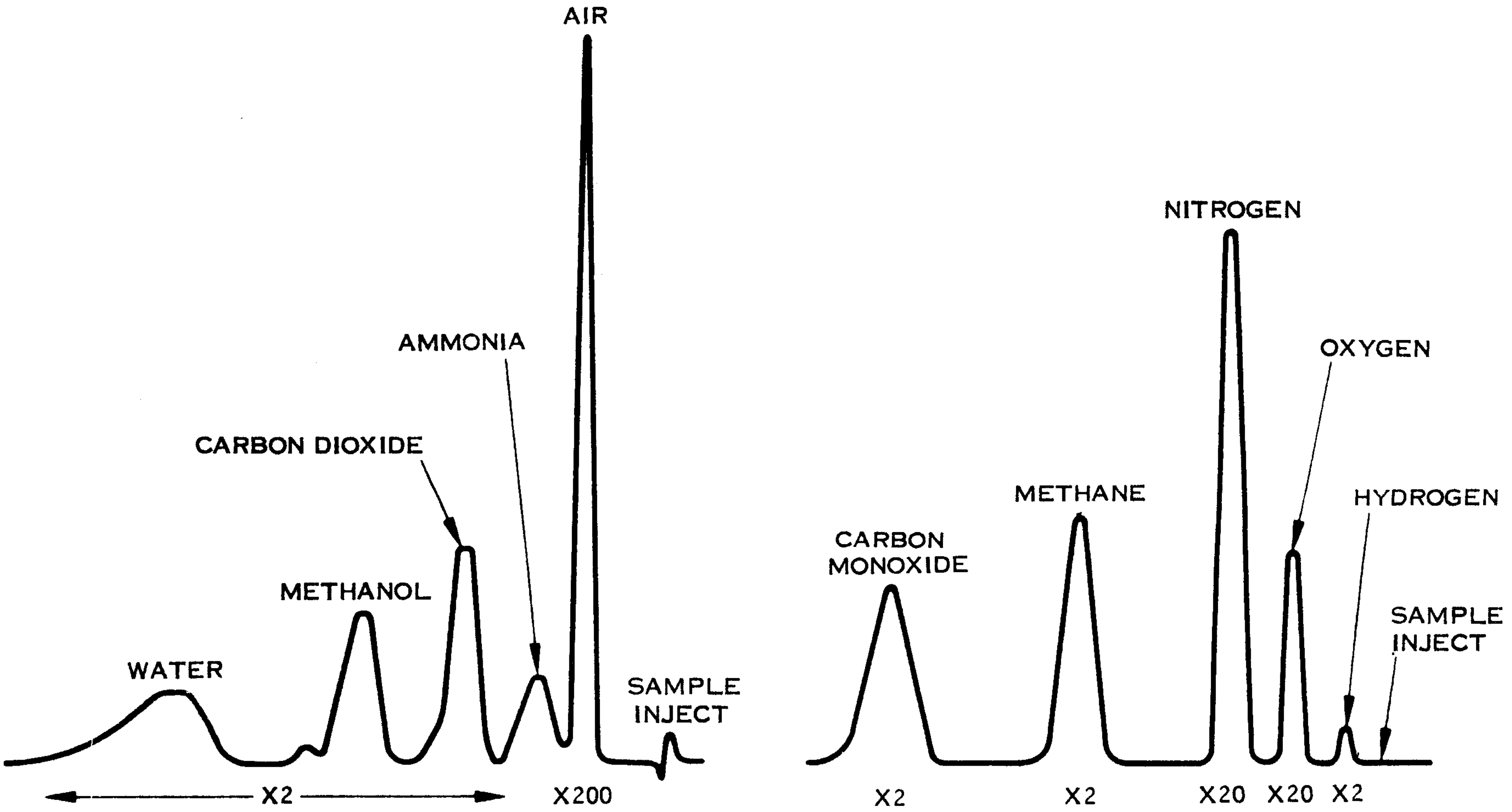
The output signal from the detector is a series of peaks, each peak representing a separate constituent. This signal is normally amplified and displayed on a strip chart recorder, or can be telemetered to Earth. By properly gating the output signal, particular constituents such as oxygen, nitrogen and carbon dioxide can be read out on individual indicators, thereby providing a continuous reading for these key constitue 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 metabo will build up to dangerous concentrations in less than 30 minutes, particularly within th volume of the Mars vehicle modules. On the other hand, from a safety standpoint, the partial pressure of oxygen and carbon dioxide should be continuously monitored so that 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 8-3. 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 concerne 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 o months.

The chromatograph is ideally suited to intermittent monitoring of specific components. Its use in the identification of unexpected gases is based on the interpretation of the output data by the crew or through telemetry to earth. The column design will determine the number and type of compounds that will be separated. Therefore, all possible gases will have to be considered during the design.

The use of helium carrier gas adds a minimum of 3 lbs./month to the expendable weig of the chromatograph. However, by using individual sensors to measure the major gases, the sampling interval can be lengthened and helium use reduced.



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

GC SPECTRA OF ADSORPTION AND PARTITION COLUMNS

FIGURE 8-3

8.2.2 (Continued)

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. 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.

8.2.3 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 through 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 correspondi 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 which is being developed by the AiResearch Division of the Garrett Corporation. 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

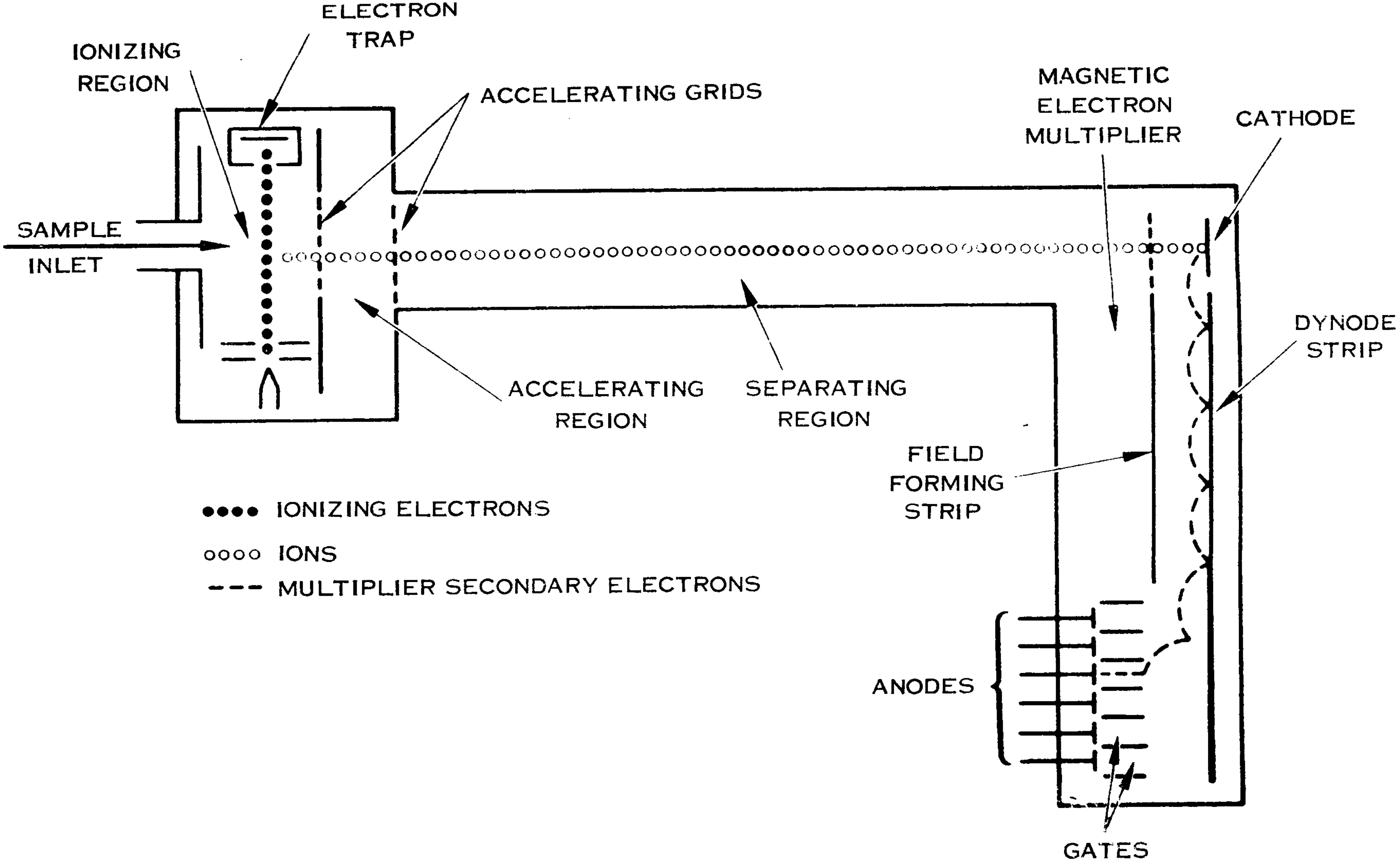
8.2.3 (Continued)

a low ionization rate to insure that only one ion is in flight at a time. The 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.

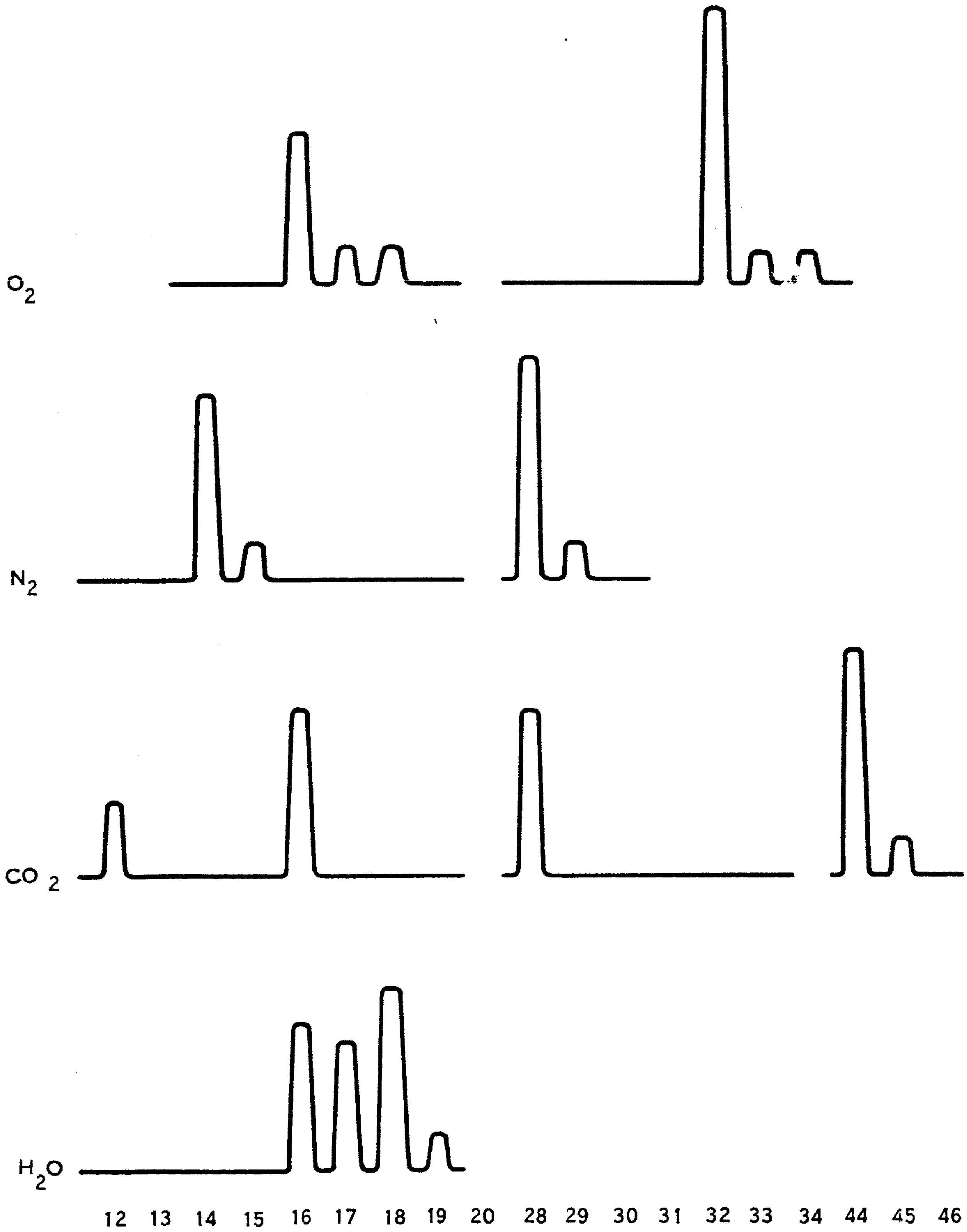
The essential elements of the Bendix time of flight spectrometer are shown in figure 8-4. The accelerating grid and electron beam within the ionization chamber is pulsed which causes pulsations of positive ions to be ejected from the ionization chamber, (their velocity being a function of mass). As each pulse passes through 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 8-5. 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.



ESSENTIAL FEATURES OF THE TIME—OF—FLIGHT MASS SPECTROMETER



FRACTIONATING PATTERN FOR MAJOR ATMOSPHERE CONSTITUENTS

FIGURE 8-5

8.2.3 (Continued)

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.

8.3 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 mission. 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 intelligence necessary for this decision.