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DEFINITION OF A RESISTOJET CONTROL SYSTEM FOR THE MANNED ORBITAL RESEARCH LABORATORY FINAL REPORT

VOLUME III
BIOWASTE UTILIZATION

MAY 1968

Prepared under Contract No. NAS 1-6702
by Douglas Aircraft Company
Missile and Space Systems Division
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PREFACE

This report is submitted to the National Aeronautics and Space Administration's Langley Research Center (NASA-LRC), Langley AFB, Virginia. It has been prepared under Contract No. NAS1-6702 and describes the results of a detailed assessment of the use of a resistojet control system for the MORL.

The study results are documented in five volumes:

DAC-58130	I	Summary
DAC-58131	II	Resistojet Control System Analysis
DAC-58132	III	Biowaste Utilization
DAC-58133	IV	Ground and Flight Test Plan
DAC-58134	V	Resistojet Design and Development

Volume I is a summary report in which the significant results are presented. Volume II contains a detailed definition of the selected resistojet control system, the recommended orbit injection system, the supporting system analyses and integration, and comparative evaluation data. Volume III presents the biowaste utilization analysis. Volume IV details the ground and flight test program for a resistojet control system. Volume V presents the results of the resistojet design and development program. Life test data will be provided in a separately bound addendum to Volume V at the conclusion of the life test.

Requests for further information concerning this report will be welcomed by the following Douglas representative:

- Mr. T. J. Gordon, Director, Advance Space
  and Launch Systems
  Huntington Beach, California
  Telephone: 714-897-0311, Extension 2994

FOREWORD

Units, abbreviations, and prefixes used in this report correspond to the International System of Units (SI) as prescribed by the Eleventh General Conference on Weights and Measures and presented in NASA Report SP-7012. The basic units for length, mass, and time are meter, kilogram, and second, respectively. Throughout the report, the English equivalent (foot, pound, and second) are presented for convenience.

The SI units, abbreviations, and prefixes most frequently used in this report are summarized below:

Basic Units

Length	meter	m
Mass	kilogram	kg
Time	sec	s
Electric current	ampere	A
Temperature	degree Kelvin	^oK

Supplementary Units

Plane angle	radian	rad

Derived Units

Area	square meter	m^2	
Volume	cubic meter	m^3	
Frequency	hertz	Hz	(s^{-1})
Density	kilogram per cubic meter	kg/m^3	
Velocity	meter per second	m/s	
Angular velocity	radian per second	rad	
Acceleration	meter per second squared	m/s^2	
Angular acceleration	radian per second squared	rad/s^2	
Force	newton	N	$(kg\text{-}m/s^2)$
Pressure	newton per sq meter	N/m^2	
Kinematic viscosity	sq meter per second	m^2/s	
Dynamic viscosity	newton-second per sq meter	$N\text{-}s/m^2$	

Work, energy, quantity of heat	joule	J	(N-m)
Power	watt	W	(J/s)
Electric charge	coulomb	C	(A-s)
Voltage, potential difference, electromotive force	volt	V	(W/A)
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	(V/A)
Electric capacitance	farad	F	(A-s/V)
Magnetic flux	weber	Wb	(V-s)
Inductance	henry	H	(V-s/A)
Magnetic flux density	tesla	T	(Wb/m^2)
Magnetic field strength	ampere per meter	A/m	
Magnetomotive force	ampere	A	

Prefixes

Factor by which unit is multiplied	Prefix	Symbol
10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ

CONTENTS

FIGURES

TABLES

DEFINITION OF A RESISTOJET CONTROL SYSTEM FOR THE MANNED ORBITAL RESEARCH LABORATORY

FINAL REPORT

VOLUME III – BIOWASTE UTILIZATION

By A. Pisciotta, Jr., R. V. Greco, and R. M. Byke

INTRODUCTION

The biowaste utilization analysis is one phase of a study to define a resistojet control system for the Manned Orbital Research Laboratory (MORL). This analysis was conducted in parallel with the evaluation of ammonia (NH_3) and hydrogen (H_2) resistojet systems. Requirements such as thrust level, duty cycle, location, and arrangement are the same as those defined for the H_2 system and the recommended NH_3 system reported in Volume II. Where feasible, the study was conducted to provide parametric data that would be generally applicable to a range of mission and vehicle parameters. To permit the biowaste thrustor systems to be compared in a useful manner with other candidate systems, the design points and selection criteria are based on a specific mission and a baseline vehicle: the MORL mission as defined in ref. 1 and the baseline vehicle as defined in ref. 2.

Although the biowaste resistojet is an attractive candidate, its present use in the baseline MORL is severely penalized by the oxidizing nature of the biowaste propellants. Basic research is therefore necessary to develop oxidation-resistant thrustor materials that can withstand long periods of operation at temperatures of $1600^{o}K$ ($3000^{o}R$) or higher. A detailed study of the vehicle and mission objectives should be performed for each application and specific criteria established for assessment of biowaste resistojet applicability.

In the following pages, the type, quantity, and composition of the useful biowastes are defined, and collection penalties are determined. Candidate thrustor systems are defined and evaluated in regard to performance and power requirements. The optimum biowaste thrustor system is then compared with the H_2 and NH_3 systems for the MORL mission.

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ENVIRONMENTAL CONTROL AND LIFE SUPPORT (EC/LS) SYSTEM DESCRIPTION

The baseline EC/LS system is designed to support a six- to nine-man crew. The system operates basically on an open-oxygen (O_2) cycle, but may be converted in service to a closed-O_2 cycle. A simplified schematic of the open-loop system is shown in fig. 1.

The laboratory atmosphere is 50% O_2 and 50% N_2 at a total pressure of 48.2 kN/m^2 (7 psia). A circulation loop with adsorb/desorb molecular-sieve beds controls the level of carbon dioxide (CO_2). The beds are desorbed and, thus, regenerated by the application of waste heat to the bed material and simultaneous exposure directly to space. O_2 makeup is provided by electrolysing resupplied water and excess metabolic water into O_2 and H_2. The H_2 is discharged from the electrolysis cells at a pressure of 272 kN/m^2 (39.5 psia) and vented overboard. In the open-loop system, the gaseous CO_2 and H_2 outputs may be readily collected and stored for use as propellants. In addition, a sufficient amount of water is in the fecal matter to warrant its consideration as a propellant candidate. In the baseline system, water sublimes from the fecal waste and is vented directly overboard. In order to utilize the fecal water, the waste-collection system must be changed so that the water is separated, vaporized, subjected to catalytic combustion, condensed, and stored.

Closed O_2-cycle operation may be accomplished by the addition of a Bosch hydrogenation reactor, as shown in fig. 2. In the closed-loop system, the CO_2 and H_2 are recombined to produce carbon (in the form of fine powder) and water. No potential propellant candidates are available, except for the fecal water. Although water resupply is eliminated (for the six-man system), propellants must be resupplied. The baseline system does not provide a complete closed O_2-regeneration loop for a nine-man crew because the hydrogenation reactor is sized for only six men; thus, make-up water must be resupplied for larger crews.

The detailed input-output mass balance for the open-loop system is shown in table 1. Examination of the outputs shows that only the CO_2, H_2, and fecal water exist in sufficient quantity and are controlled enough to be considered practical resistojet propellants. Chemical analyses of the applicable biowastes (H_2, CO_2, and fecal water) are shown in table 2. The analyses for H_2 and CO_2 are based on limited test data supplied by the processing equipment manufacturers (electrolysis cells--General Electric Company; molecular sieve--Hamilton Standard Division of United Aircraft Corporation). The CO_2 is 98% pure and acceptable for resistojet use as an oxidizing propellant. The fecal water is 99+% pure, but does contain solids which can deposit on heat-exchanger components and create difficulties. The H_2 is

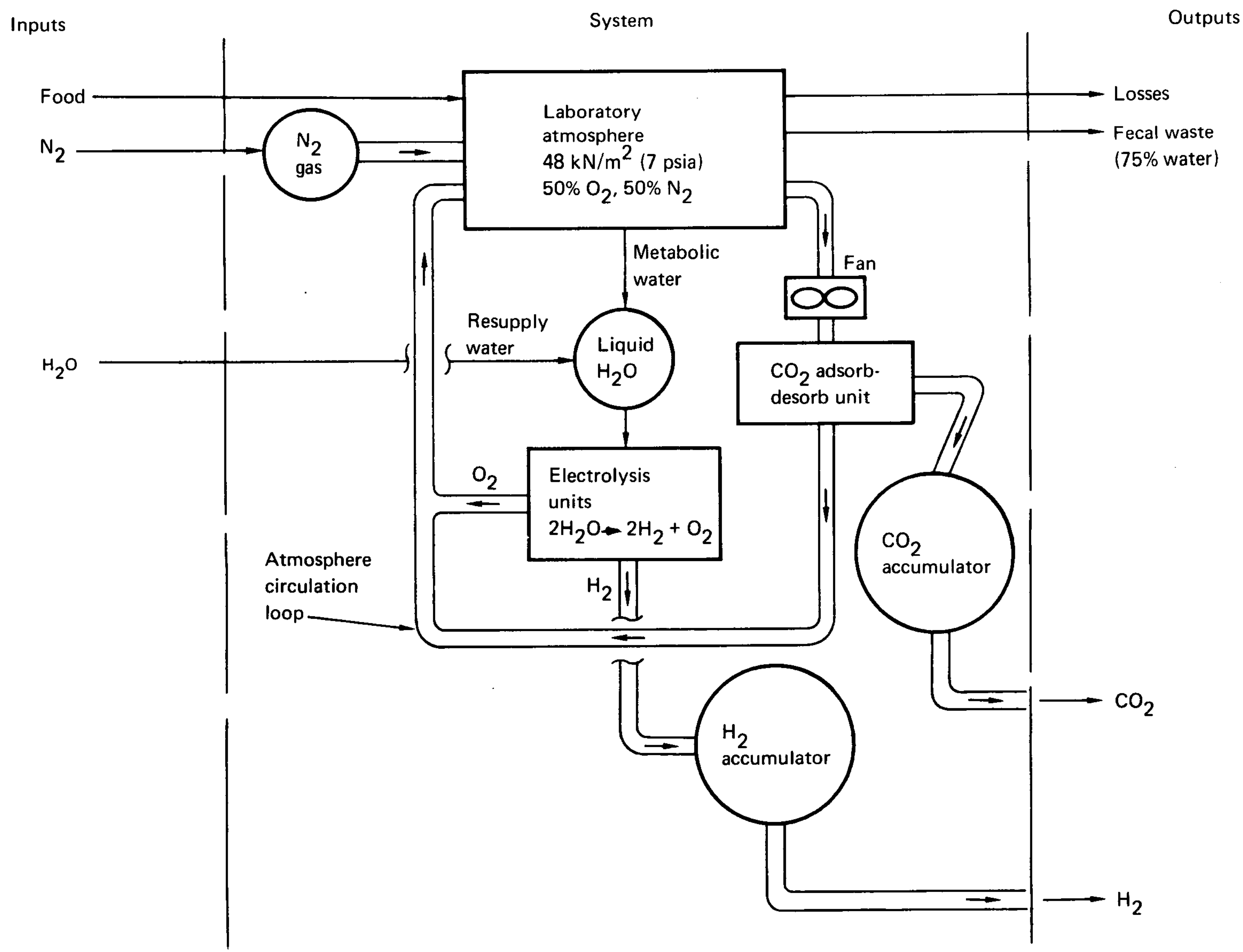

Figure 1. EC/LS System – H_2O Electrolysis

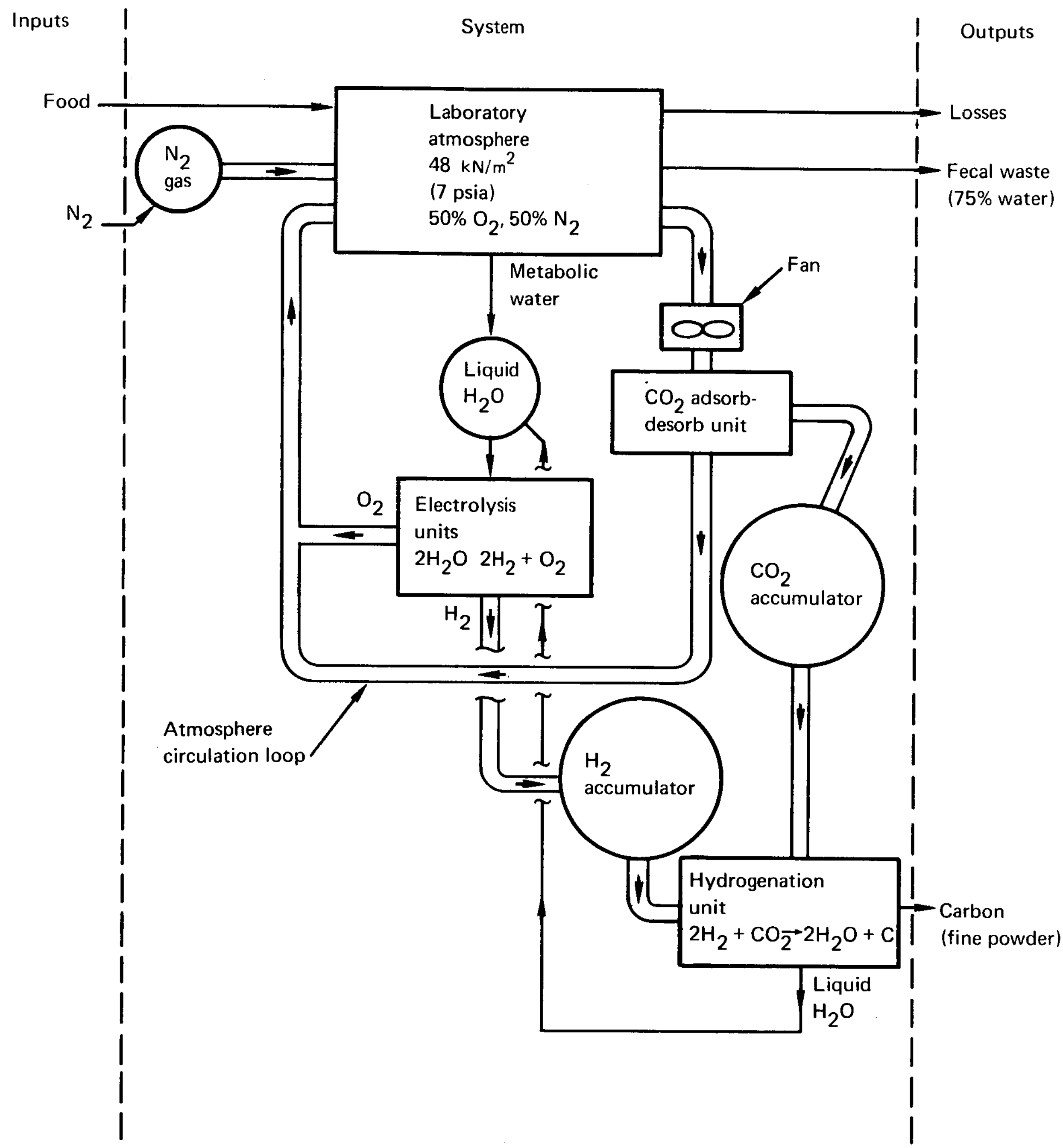

Figure 2. EC/LS System – O_2 Regeneration

Table 1

MORL METABOLIC MASS BALANCE

(Open-loop system; six-man crew)

Item	Mass balance	
	kg/day	lbm/day
Supplies		
Dry food	4.35	9.6
N_2	0.59	1.291
H_2O	5.18	11.402
	10.12	22.293
Biowastes		
CO_2	6.46	14.22
H_2	0.73	1.613
Available H_2O	0.0	0.0
Fecal H_2O	0.74	1.62
Fecal solids	0.26	0.57
Urine solids	0.43	0.954
H_2O and N_2 vapor	0.04	0.096
N_2 and O_2 leakage and miscellaneous losses	1.46	3.22
	10.12	22.293

only 94% pure and contains a sufficient amount of oxidizing contaminants to warrant its classification as an oxidizing propellant, as opposed to propellant-grade cryogenic H_2, which is nonoxidizing.

Table 2

CHEMICAL ANALYSES OF APPLICABLE BIOWASTES

CO_2		H_2		Fecal H_2O[a]	
Component	Amount	Component	Amount	Component	Amount[b]
CO_2	98%	H_2	94%	H_2O	+99%
O_2	0.9%	H_2O	3.9%	CO_2	20 ppm
N_2	0.9%	N_2	1.7%	NH_3 as N	0.04-35 ppm
Trace element	0.2%	CO_2	0.22%	Chloride as Cl	0.5-3.5 ppm
		O_2	0.19%	Total phosphate	1.3 ppm
		Argon	0.02%	Ortho phosphate	1.3 ppm
		Acetone	26 ppm (by volume)	Nitrate as NO_3	0.0-0.1 ppm
		Unknown hydrocarbon	20 ppm (by volume)	Nitrate as NO_2	0.0-0.22 ppm
		CH_4	0.4 ppm (by volume)	Sulfate as SO_4	0.0-0.4 ppm
		C_2H_6	0.05 ppm (by volume)	Free mineral acid	2.0 ppm
				Total solids	2-100 ppm
				Methyl orange	
				Alk. as $CaCO_3$	2-6 ppm
				pH	2.8-11.8

[a] H_2O recovery by evaporation plus vapor pyrolysis.
[b] Maximum and minimum values where more than one analysis was available.

BIOWASTE COLLECTION AND STORAGE

Various methods were evaluated for collecting the biowaste outputs. The evaluation was performed parametrically with pressure up to 1034 kN/m^2 (150 psia). The collection systems were selected primarily on the basis of (1) minimum collection-power penalties and (2) and evaluation of resistojet performance characteristics. In general, the criteria were to minimize power, volume, and weight (in the order stated) and to avoid undue system complexity.

Carbon Dioxide

By compression pumping, CO_2 can be collected instead of being vented to space. Parametric analyses show that pumping power requirements increase with pressure. This effect, however, is offset by resistojet power requirements, which decrease with increasing pressure. Accumulator weight and volume also decrease with increasing pressure (for constant available propellant capacity). Evaluation of these interdependent effects resulted in the selection of 1034 kN/m^2 (150 psia) for the CO_2 accumulator pressure. This design point was used to establish the CO_2 biowaste collection system.

For purposes of this design, the CO_2 accumulator was assumed to be part of the propulsion system, because its capacity is based upon propulsion system requirements. Also, the accumulator pressure was assumed to be constant at 1034 kN/m^2. Actually, the accumulator pressure will vary between 1034 kN/m^2 and the minimum thrustor operating pressure because the CO_2 use can exceed the accumulator fill rate. This assumption leads to a slightly conservative estimate of the CO_2 pumping power requirements and was made to simplify the design interface.

Two identical atmospheric purification loops are used on the MORL, one for the main laboratory and the other for the hangar/test area, as shown in fig. 3. The loops are interconnected so that either can purify the atmosphere for each compartment. This redundancy always makes a compartment available to the crew should one become uninhabitable for any reason. Therefore, two compression units are required for the CO_2 collection system.

The selected CO_2 collection system (shown in fig. 4) consists of three pumping stages and four heat-exchanger passes. Each pumping stage is identical and is designed for a 4.25:1 compression ratio. The molecular-sieve canister pressure and the pumping mass flows are constantly changing during these phases, resulting in varying power requirements,

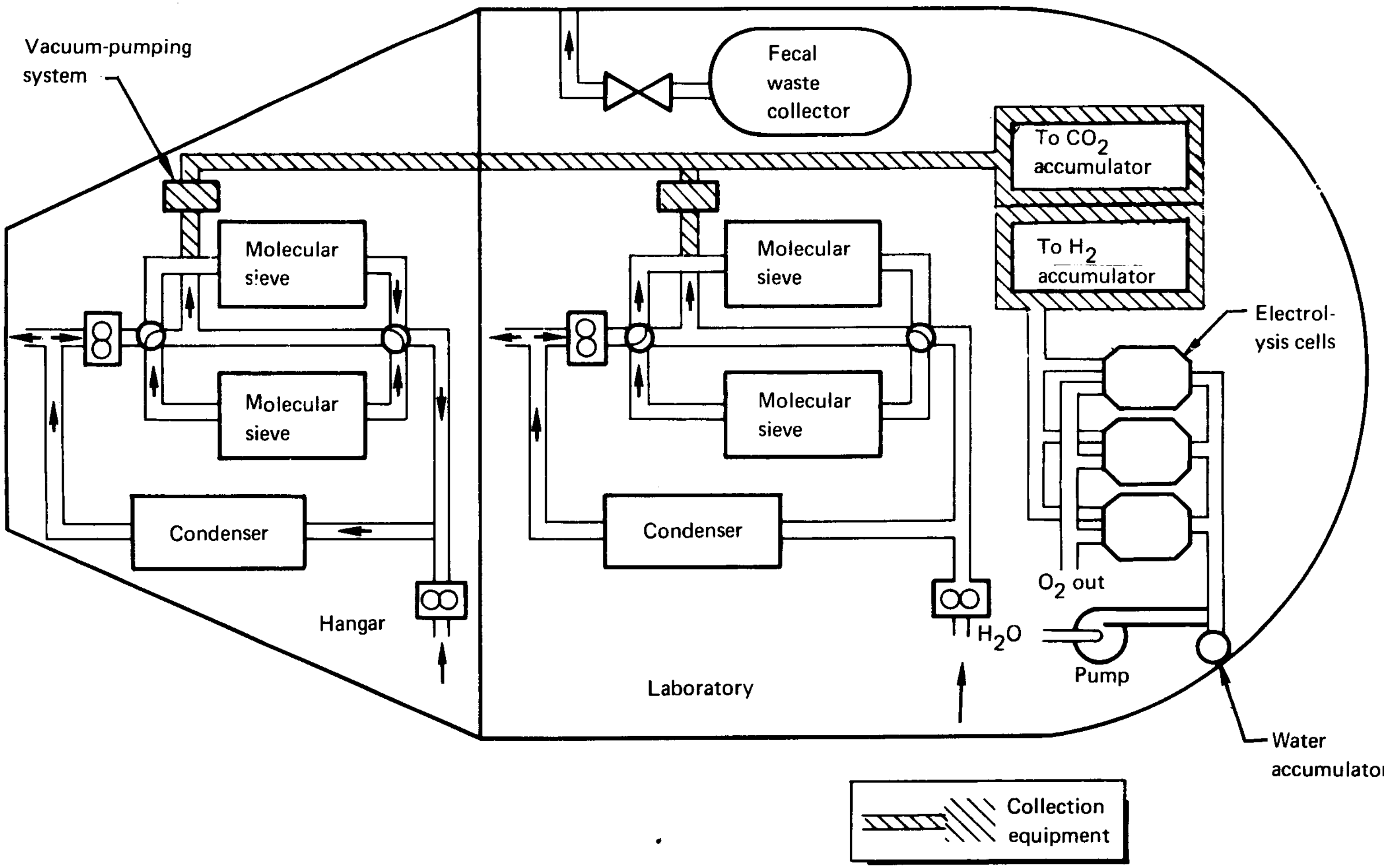

Figure 3. EC/LS System – Simplified Schematic

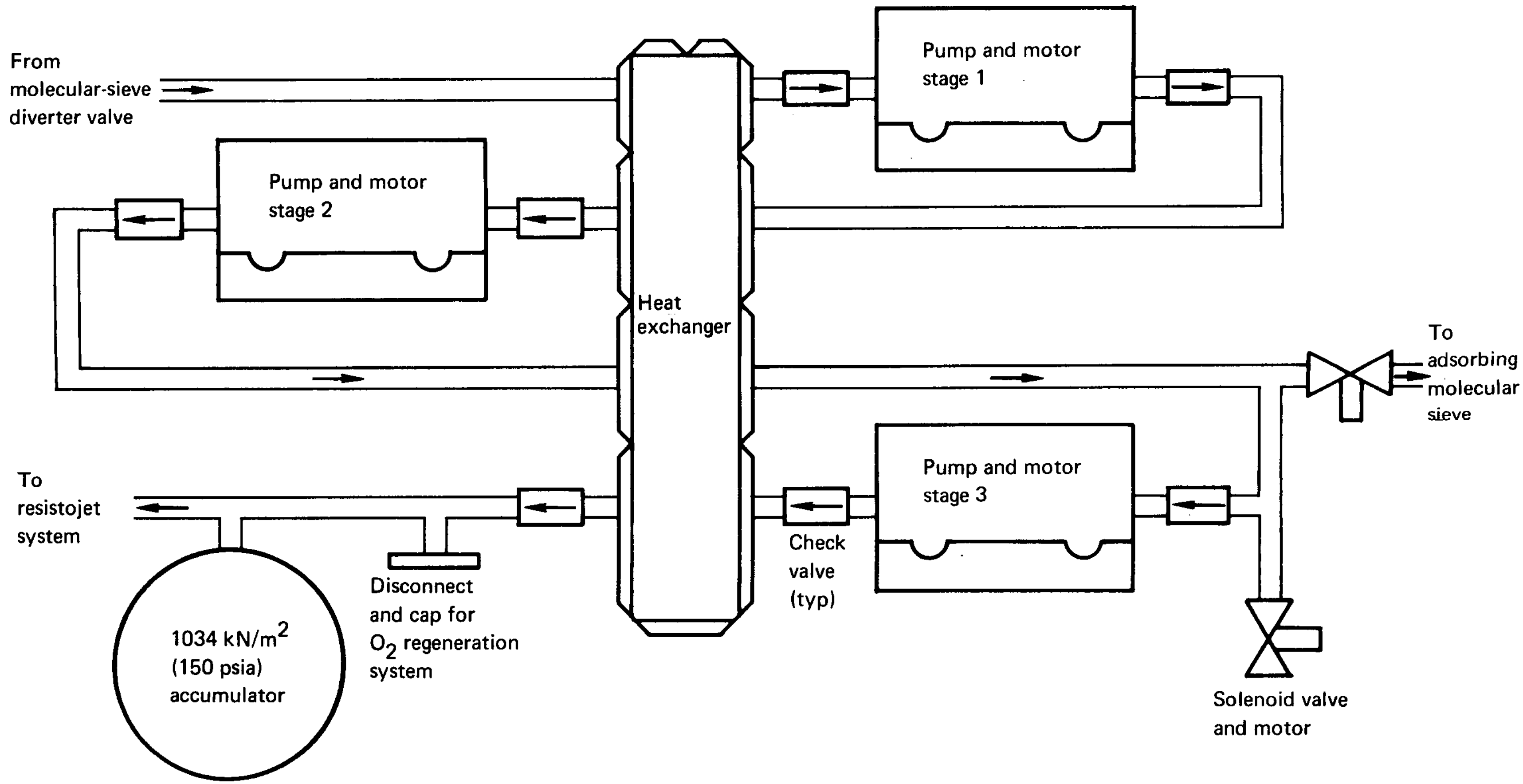

Figure 4. CO_2 Collection Subsystem

as shown in table 3. The first column in the table represents the average power required during the particular pumping phase. The overall desorption cycle is 40 min, and there are 36 cycles per day. This results in an overall average power penalty of 150 watts, chargeable to the biowaste propulsion system, as is shown in the last column. Even though two CO_2 collection systems are required for MORL, one for the laboratory and one for the hangar/test area, the total power penalty remains 150 watts. The reason for this is as follows: If all six crewmen are located in either the laboratory or the hangar, only one CO_2-removal system will be operating and 36 desorption cycles of 40-min duration will occur each day. If the crew is split between the laboratory and the hangar, both sets of molecular sieves will be adsorbing CO_2 below the design rate. The adsorption cycle will automatically increase because the control system is based upon the partial pressure of CO_2 in the atmosphere, and the desorption cycle does not begin until the bed is fully loaded. A 40-min desorption cycle then follows, regardless of the length of the preceding adsorption cycle. Since the hangar and laboratory CO_2 removal systems are independent of each other, it follows that it is possible that desorption cycles will occur simultaneously; however, the total number of desorption cycles over a long period of time will average out to the same 36/day, regardless of how the crew occupies the two MORL compartments. Therefore, the power penalty for only one CO_2 pumping system is assessed. The three pumpout phases, identified in Table 3, contribute to the pumping power requirement in the following manner.

(1) Ullage pumpout, in which the first two stages are used to pump the ullage atmosphere from the desorbing molecular-sieve canister to the adsorbing molecular-sieve canister. This will require an average of 20 watts for 10 min.

(2) Heated desorption, in which all three stages pump to the accumulator, with the desorbing molecular-sieve bed being heated. This will require an average of 230 watts for 20 min.

(3) Cooled desorption, in which all three stages pump to the accumulator, with the desorbing molecular sieve being cooled. This will require an average of 120 watts for 10 min.

Table 3

PUMPING POWER REQUIREMENTS--CO_2 COLLECTION

Pumping phase	Average power required (W)	Time (min)	Time (% of cycle)	Average power penalty (W)
Ullage pumpout	20	10	25	5
Heated desorption	230	20	50	115
Cooled desorption	120	10	25	30
Overall	N/A	40	100	150

The addition of the CO_2 collection system increases the net weight of the hardware by 9.1 kg (20 lbm). The system has the capability to collect all the CO_2 produced by the crew, a total of 6.5 kg/day (14.22 lbm/day). If it should be desirable to collect less than the maximum available, the fixed hardware weight will not change. However, the pumping power penalty would decrease. The power penalty is linear from 5 watts at zero CO_2 collected to 150 watts at 6.5 kg/day collected, as shown in fig. 5. The 5-watt penalty for no collection occurs because the ullage-pumpout portion of the cycle would still be necessary, even if the CO_2 is dumped overboard. The capability to dump CO_2 overboard is retained in the collection system in case all of the available CO_2 is not required to meet the daily impulse requirements. The collection system also retains the capability of the baseline system to be converted to a closed-locp system. This feature provides a means-of-flight qualification of O_2 regeneration hardware for advanced missions.

Hydrogen

Two methods of H_2 collection were evaluated: (1) compression of the H_2 after it leaves the electrolysis cells and (2) operation of the cells at a pressure sufficient to provide the desired storage pressure. Cell operation at high pressure is achieved by means of pumping the feed water and referencing the entire electrolysis cell operation to this pressure.

Because of the nature of the cell design, the H_2 is automatically provided at a pressure 7 kN/m^2 (1.0 psia) above the water pressure. Water pumping requirements are of short duration and demand considerably less power than gas compression. Also, significant volume advantages resulted at a minimal weight increase with the high-pressure electrolysis cell technique. These advantages were notable throughout the pressure range evaluated and were most significant at the higher pressures.

The selected H_2 collection method consists of operating the entire water electrolysis subsystem at a 1034-kN/m^2 (150-psia) pressure rather than at the baseline 275.8-kN/m^2 (40-psia) pressure. Two changes are required to accomplish this: (1) Water at 1034 kN/m^2 must be available to the electrolysis cells and (2) a pressure shell enclosing the five electrolysis cell modules must be provided to accommodate the increased internal pressure. Fig. 6 shows the subsystem for the electrolysis of water and the collection of the vented H_2 in an accumulator. Water for the electrolysis cells is pumped at a rate of 6.7 kg/day (14.9 lbm/day). The pressure is raised from 48.3 to 1034 kN/m^2 (7.0 to 150 psia) in the 11.4-kg (25-lbm) capacity water accumulator tank. This requires 85 watts for 6 min each day and is the only power penalty involved with collecting H_2 at 1034 kN/m^2 instead of 275.8 kN/m^2. On a daily basis, this amounts to an increase of only 0.35 watts, which is considered negligible. This power penalty is invariant with the quantity of H_2 collected.

A single, encapsulating pressure housing is provided for the required five stacks of electrolysis cells. The O_2 is allowed to vent directly into the free volume of the housing. This design is better than having five separate

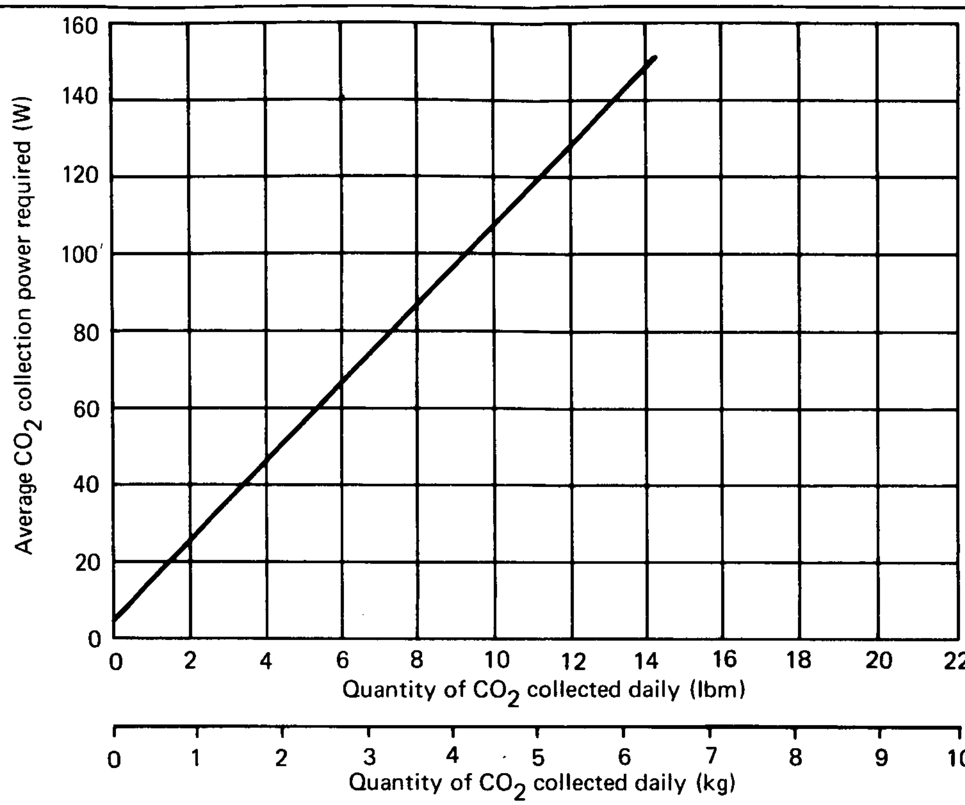

Figure 5. Average Power Requirements – CO_2 Collection Subsystem

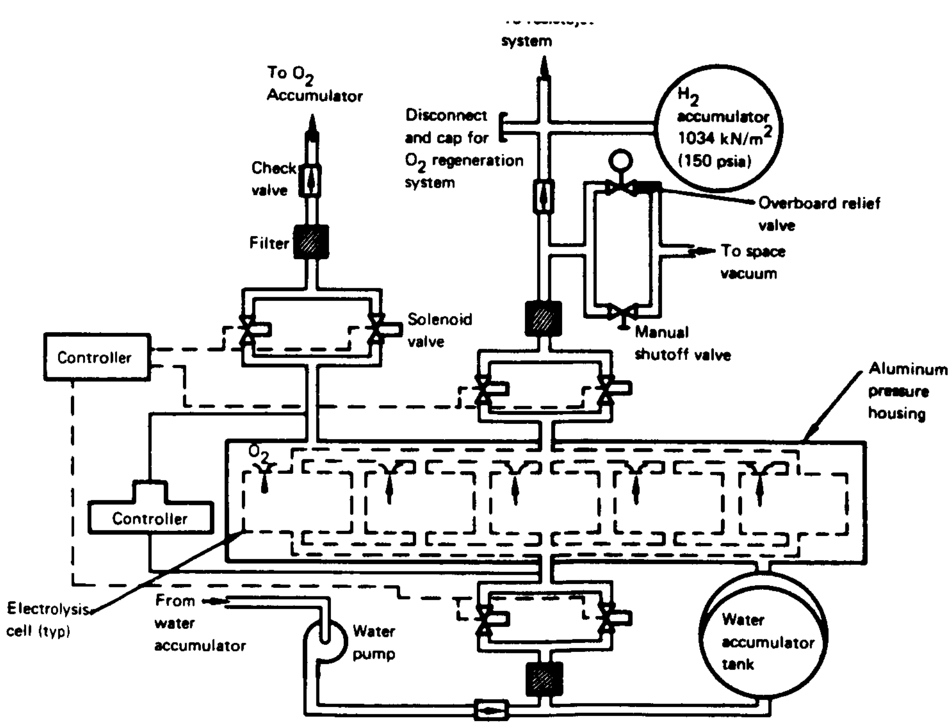

Figure 6. H_2 Collection Subsystem

pressure housings, because it reduces the number of O_2, H_2, and H_2O control valves required and it minimizes housing weight. It also places all the electrolysis cells at the same internal pressures for H_2, O_2, and H_2O. Fail-safe redundant solenoid valves and controllers regulate the H_2O, O_2, and H_2 flows. An overboard relief valve and manual dump valve are in the H_2 line. The pressure housing is designed so that the electrolysis cell modules can be replaced in the event of failure. Capability for operation in an O_2-regeneration mode is retained by means of a connector in the H_2 line.

The net effect of these changes on the weight of the baseline electrolysis system is an increase of 5.3 kg (11.7 lbm). Also, as a result of the reduction in size of the O_2 accumulator, there is a volume saving of 0.226 m^3 (8 ft^3). It is intended that the EC/LS system be modified to operate the electrolysis cells at 1034 kN/m^2 whether or not the H_2 is used as a resistojet propellant. The large reduction in volume at minimal weight increase shows sufficient system advantage to justify this change.

Fecal Water

The baseline fecal-waste management system stores and freezes the wet waste; consequently, modifications are necessary to separate the water from the waste. Water reclamation concepts considered included the following:

(1) Addition of heat and/or application of a vacuum sufficient to reach the vapor point of water in the wastes.

(2) Air evaporation.

(3) Freeze sublimination.

(4) Freeze crystalization.

(5) Nonelectrical membrane process.

(6) Ion-exchange membrane process.

(7) Capillary or thermal diffusion.

(8) Physio-chemical treatments.

(9) Gas hydrate formation.

(10) Solvent extraction.

(11) Catalytic combustion.

(12) Electrolysis.

(13) Miscellaneous mechanical systems.

The selected concept operates by waste-heat evaporation to separate the water from the feces, with pyrolysis of the vapors (fig. 7). The process of fecal-waste collection is the same as that used in the baseline MORL.

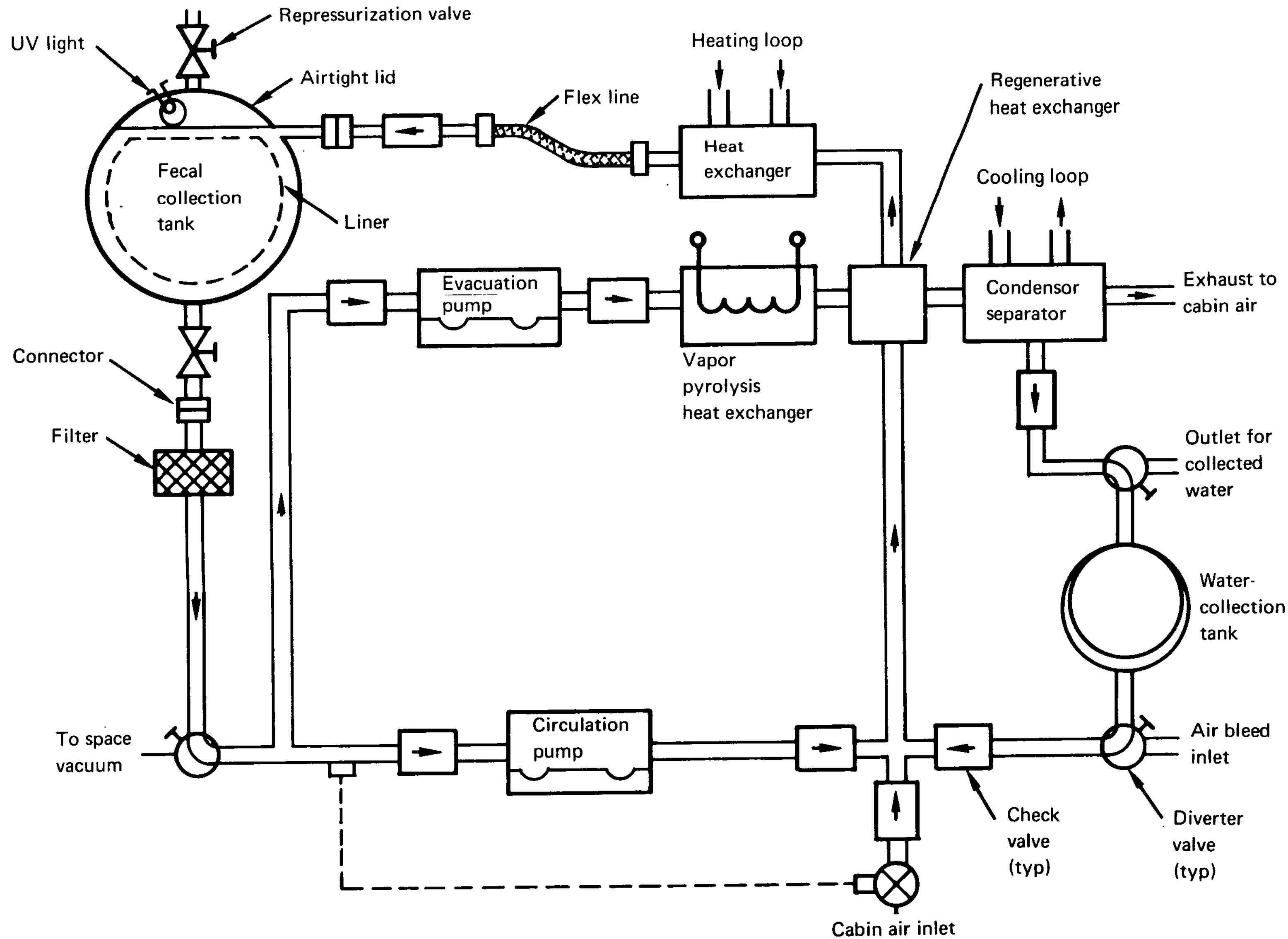

Figure 7. Fecal-Collection Subsystem with Water Reclamation

Wastes are collected in a spherical tank until the tank is filled, at which time it is replaced by an empty one. Instead of venting the collection tank to space between uses, a heating cycle/pumpdown process evaporates water from the feces, and a vapor pyrolysis/condensation process collects sterilized water. The tank for water storage contains a bladder to expel the contents for use by the resistojet control system. This system requires an additional 25 watts of power and approximately 18.2 kg (40 lbm) of fixed weight. Theoretically, 100% water recovery is possible; however, a value of 75% is assumed until higher efficiency is demonstrated. This system combines proven concepts, but has not been tested or developed as an integrated unit.

Collection Penalty Summary

The resulting weight and power penalties for the selected collection systems are shown in table 4. The weight values in the table represent the net increase to the EC/LS system. For example, the weight of CO_2 collection hardware is partially offset by the deletion of items not required if the gas is to be collected. The power requirement shown in the third column is the power needed for collecting the total output.

For comparative purposes, the last column in the table shows the average power required to collect a unit mass of propellant.

Table 4

BIOWASTE COLLECTION PENALTIES

Item	Collection system weight[b]		Power[a]	
	kg	lbm	watts	watts/kg[c]
CO_2	9.1	20	150	23.2
H_2	5.3	11.7	0.35	0.48
Fecal water	18.2	40	25	45.0

[a]For collection of total output, as previously described.

[b]Total weight, less deletion of overboard vent hardware.

[c]Average power in watts required to collect the daily output, divided by the daily output in kg.

PERFORMANCE AND POWER REQUIREMENTS

The maximum operating temperature for the biowaste resistojets, consistent with the system's design-life goal, is limited to 1667°K (3000°R). This is the result of the oxidizing nature of CO_2 and fecal water. A chemical analysis of the biowaste H_2 output (table 2) reveals that it contains approximately 6% impurities, most of which are oxidizing compounds; therefore, it too is constrained to 1667°K. The performance of the biowaste propellants (including combinations) was determined for chamber pressures from 0.1×10^5 to 10×10^5 N/m^2 (0.10 to 10.0 atm) and chamber temperatures of 1589° to 2700°K (2860° to 4860°R). The performance (specific impulse) and minimum required resistojet power for a 1667°K operating temperature as a function of operating pressure for each of the propellants and propellant combinations are presented in figs. 8 and 9. Examination of these figures shows that a severe performance degradation and a large power penalty result for operating pressures below 138 kN/m^2 (20 psia). These losses occur primarily because of the low Reynolds Number effects, which result in large viscous and expansion losses. Fabrication and geometric considerations limit the maximum operating pressure to approximately 310 to 345 kN/m^2 (45 to 50 psia). These restrictions led to the selection of 275.8-kN/m^2 (40 psia) operating pressure at which to perform an assessment of the biowaste propellants.

Table 5 presents the individual and combined propellants considered for MORL use. The delivered specific impulse and resistojet minimum required power were obtained from figs. 8 and 9 at the selected 275.8-kN/m^2 chamber pressure and 1667°K chamber temperature condition. The daily usable quantity for the propellant combinations shown represents the sum of the individual quantities.

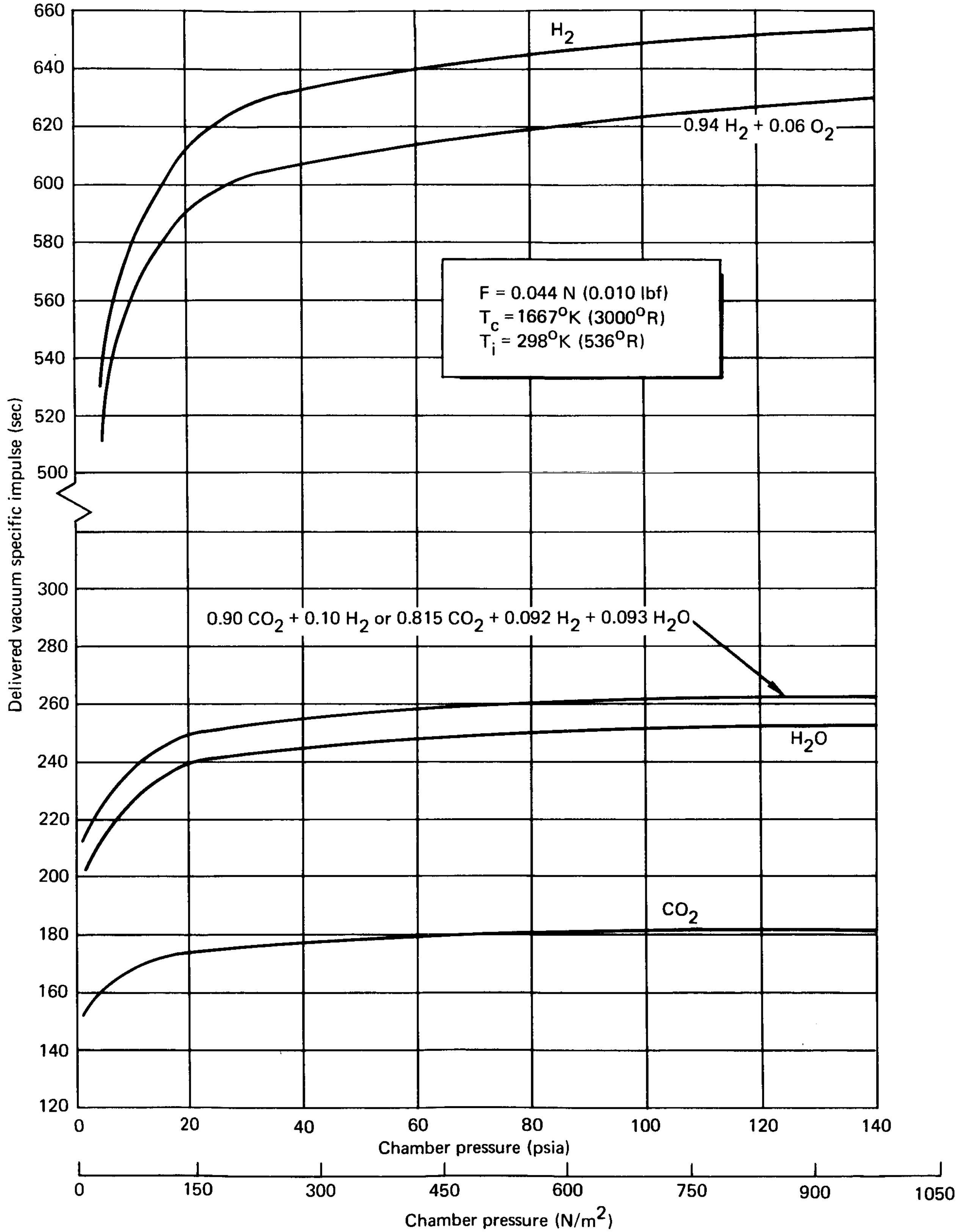

Figure 8. Chamber Pressure Effects on Biowaste Resistojet Performance

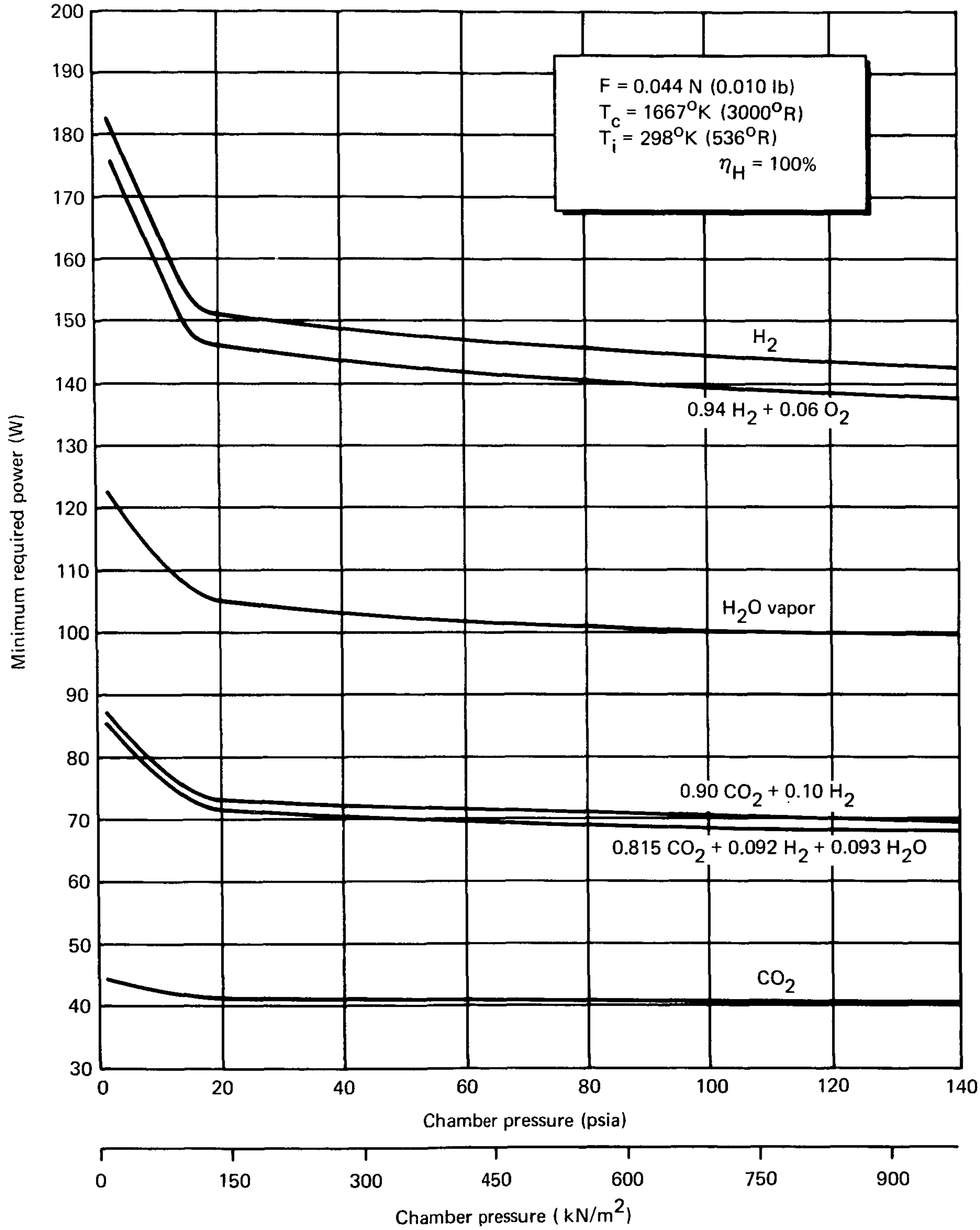

Figure 9. Chamber Pressure Effects on Biowaste Resistojet Power Requirement

Table 5

BIOWASTE RESISTOJET PERFORMANCE AND POWER REQUIREMENTS[a]

Propellant	I_{sp} del (sec)	Thrustor[b] minimum required power (watts)	Usable output		Available total impulse[c]		Thrustor power to I_{sp} ratio (watts/sec)
			$\dot{(kg/day)}$	(lbm/day)	(N-sec/day)	(lb-sec/day)	
H_2 (biowaste)	602	143	0.73	1.613	4 320	970	0.238
CO_2	178	41.5	6.46	14.22	11 280	2 535	0.233
H_2O (fecal)	246	103	0.55	1.21	1 325	298	0.418
90% CO_2 + 10% H_2							
Used in combination	255	72	7.19	15.83	18 100	4 050	0.282
Independent use average	221	69.6	7.19	15.83	15 600	3 505	0.315
83.5% CO_2 + 9.5% +7% H_2O							
Used in combination	255	70	7.74	17.04	19 350	4 350	0.275
Independent use average	223	72.2	7.74	17.04	16 900	3 803	0.324

[a] All values for F = 0.044 N (10 mlbf), P_c = 276 kN/m^2 (40 psia), T_c = 1667°K (3000°R), T_i = 298°K, P_d = 0.0.

[b] Heater efficiency of 100% assumed.

[c] MORL daily total impulse requirement is 8321 N-sec/day (1870 lb-sec/day).

BIOWASTE SYSTEMS EVALUATION AND SELECTION

Table 5 shows that the combined use of biowaste outputs (that is, those fired in the specified combination through a single thrustor) has a significantly higher performance capability than that achieved through independent use (same total propellant quantities fired in separate thrustors for each propellant). This synergistic effect is attributable to the chemical kinetics of the reaction. This fact, combined with increased control and hardware associated independent thrustors for each propellant, eliminated such use from further consideration.

The MORL baseline vehicle, in a 1972 atmosphere, requires a daily total impulse of 8321 N-sec (1870 lbf-sec) for the orbit operation functions of the resistojet/CMG control system. Table 5 shows that CO_2 alone can provide the required daily total impulse with about a 35% excess for growth potential. The biowaste H_2 can provide 4317 N-sec (970 lbf-sec) if used independently. The MORL daily total impulse requirement can be fulfilled with combined use of H_2 and CO_2. Fecal water can provide a daily total impulse of only 1326 N-sec (298 lbf-sec) and has the highest ratio of resistojet power to specific impulse. This fact, combined with the highest collection power penalty (45.0 watts/kg average) and the difficult storage and usage requirements, makes fecal water the least attractive biowaste. As a result of this evaluation, it was decided to eliminate the systems using fecal water.

Fig. 10 shows the delivered specific impulse and resistojet power requirement (including heater efficiency) variation with propellant combination. Fig. 11 shows the variation in the daily biowaste quantities of CO_2 and H_2 required for an 8321 N-sec/day (1870 lbf-sec/day) total impulse as a function of the propellant combination. It should be noted that the maximum CO_2 quantity required is 4.77 kg/day (10.5 lbm/day), which is significantly below the 6.5 kg/day (14.22 lbm/day) available. The daily quantity of biowaste H_2 available--0.73 kg (1.61 lbm)--establishes the other limiting propellant combination of 0.678 CO_2 + 0.322 H_2 (all biowaste H_2 supplemented with 1.55 kg/day [3.41 lbm/day] of CO_2).

A method of determining the total power requirement for operation of a biowaste resistojet has been established. As previously presented (table 5) resistojet power is defined for the thrustor operation conditions (chamber pressure, temperature, and thrust level). The collection power is given as average power over a day and, in the case of CO_2, varies with the quantity of propellant collected (fig. 5). It is possible to relate the collection power and the resistojet power by the following method: the total collection power over a daily period (average collection power x time) is determined

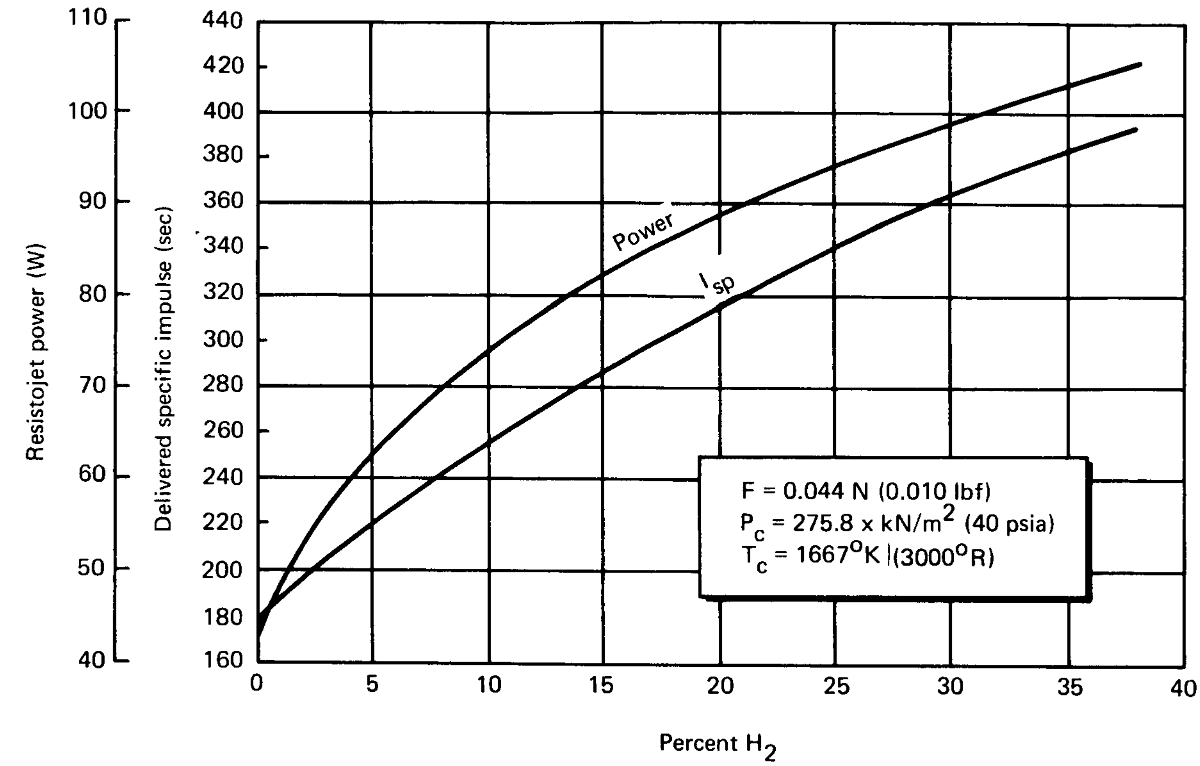

Figure 10. CO_2 and H_2 Mixture Ratio Effects on Resistojet Performance and Power

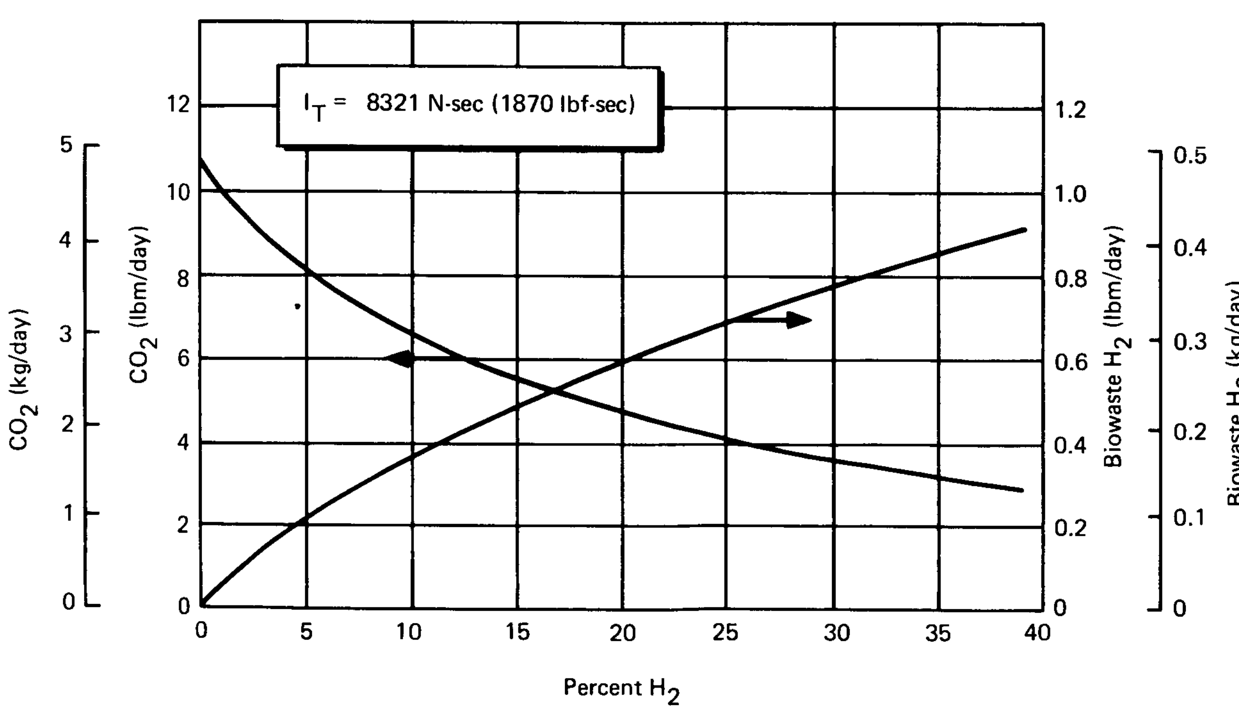

Figure 11. CO_2 and H_2 Mixture Ratio Effects on Daily Propellant Requirement

and divided by the total thrustor-operating time (daily total impulse divided by resistojet thrust level). The collection power defined in this manner can be directly added to the resistojet power to obtain a valid "true" total power. Fig. 12 shows the collection power variation with propellant combination. The values shown represent the CO_2 penalty which varies with the quantity collected. (The H_2 collection penalty, about 0.35 watts, is invariant with the quantity collected.) The curve in fig. 12 is not linear with propellant combination because of the nonlinearity of specific impulse, which determines the quantity of propellant combination required.

The combined collection power and resistojet power is shown as a function of propellant combination in fig. 13 for the 8321-N-sec/day (1870 lbf-sec/day) system. It can be seen that the lowest power requirement is obtained with CO_2 alone and increases with the increasing ratio of biowaste H_2. The ratio of delivered specific impulse to total power is also shown to increase with the increasing ratio of biowaste H_2. By using fig. 13 and the values for delivered specific impulse shown in fig. 10, one can see that there are two biowaste resistojet propellant combinations worthy of further examination: one uses all CO_2 and provides low performance at a lower power requirement with the highest biowaste propellant density, and the other uses all the biowaste H_2 available and sufficient CO_2 to provide the daily impulse requirement: 0.678 CO_2 + 0.322 H_2. This combination provides high performance at the highest ratio of delivered specific impulse to total power, with a propellant combination of low-bulk density.

Figs. 14 and 15 are simple schematics of the CO_2 and the 0.678 CO_2 + 0.322 H_2 systems, respectively.

The all-CO_2 system has a 1034-kN/m^2 (150-psia) accumulator or storage tank supplied by both CO_2 collection subsystems. Check valves prevent backflow of propellant during the desorption cycling of the molecular-sieve beds. The accumulator has a burst disk and a relief valve to protect against overpressurization. The propellant flows from the accumulator through a normally open solenoid valve which permits shutdown and isolation of the accumulator should the feed system require maintenance. The propellant then flows through a filter which removes any particulate matter. A three-way, solenoid-actuated valve provides flow through either of the redundant pressure regulators. These regulators maintain the downstream pressure at 275.8 kN/m^2 (40 psia) and require a minimum pressure drop of 138 kN/m^2 (20 psia) or 4.4 kN/m^2 (60 psia) minimum upstream pressure.

Regulator check valves prevent backflow of propellant should a regulator fail. It was determined that an accumulator feed line should be provided to maintain supply pressure during resistojet cold startup which requires flow in excess of the design requirement. A hand valve (normally open) is provided to isolate the thrustor module during replacement or repair.

The 0.678 CO_2 + 0.322 H_2 system (fig. 15) has separate CO_2 and H_2 accumulators at 1034.3-kN/m^2 (150-psia) pressure. The CO_2 is supplied from the two separate CO_2 collection subsystems; biowaste H_2 is supplied from the electrolysis cell outputs. Each of the accumulators is protected from overpressurization by relief valves and burst disks. The independent

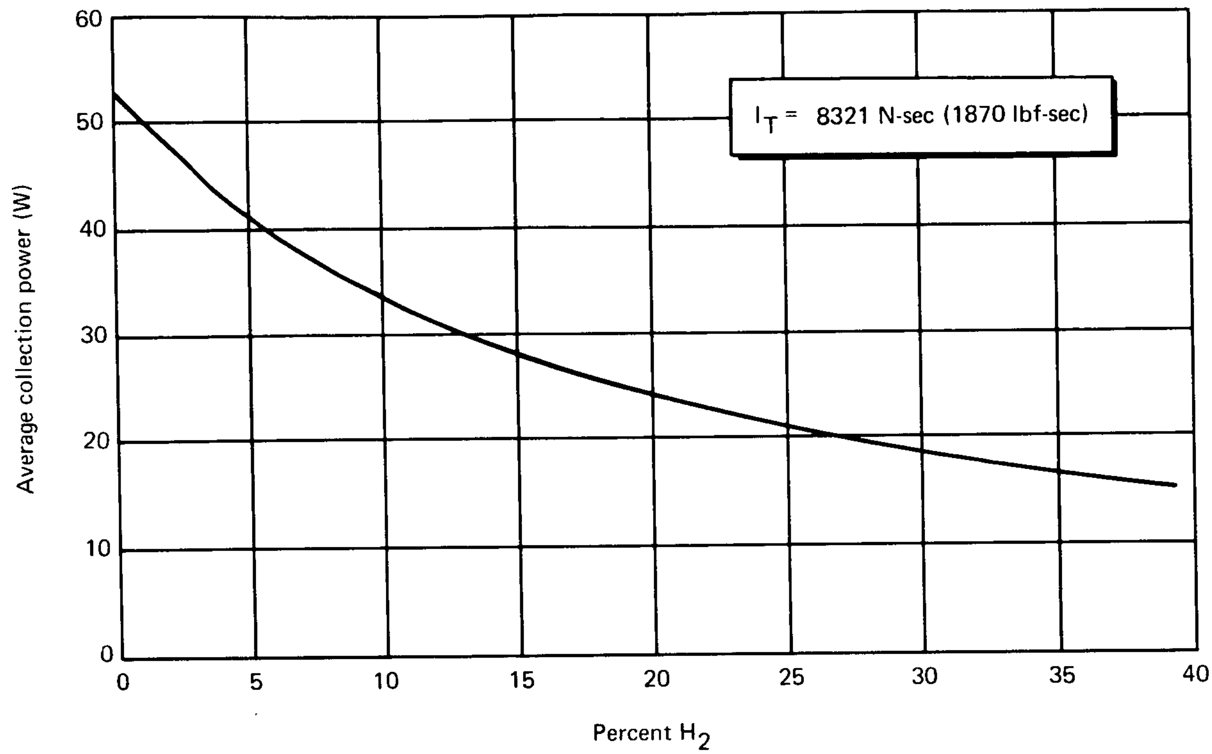

Figure 12. CO_2 and H_2 Mixture Ratio Effects on Average Collection Power

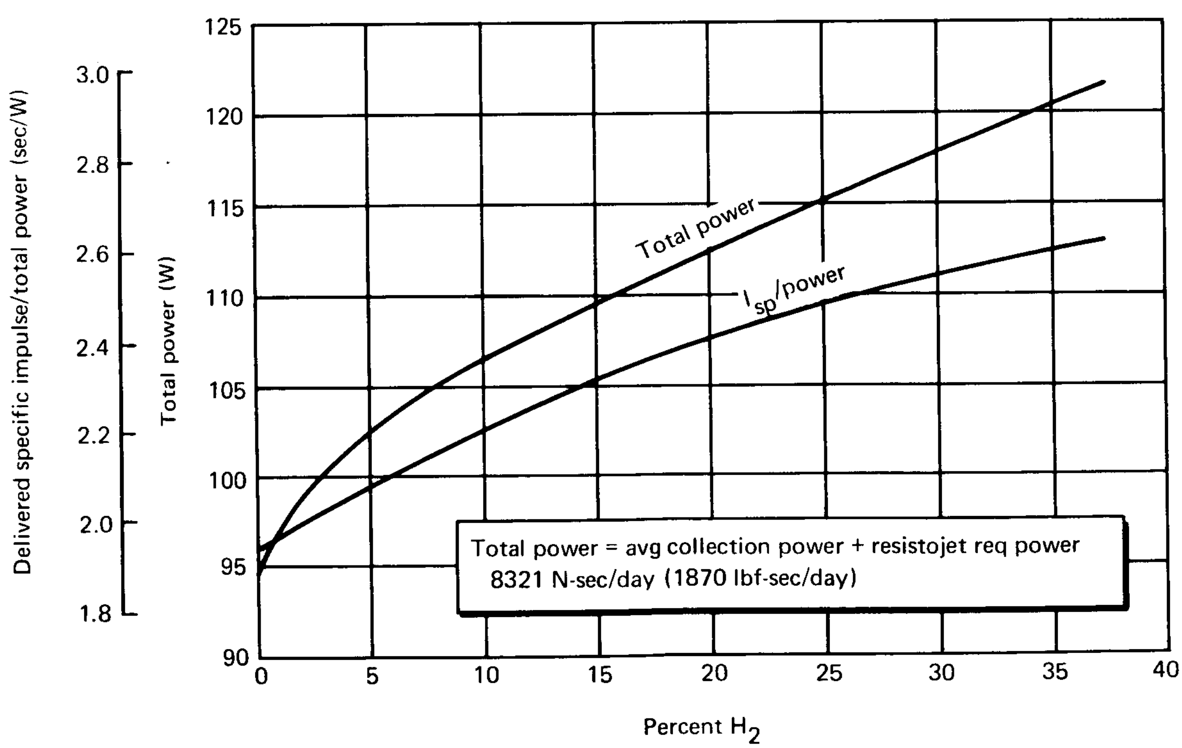

Figure 13. CO_2 and H_2 Mixture Ratio Effects on Power and Performance

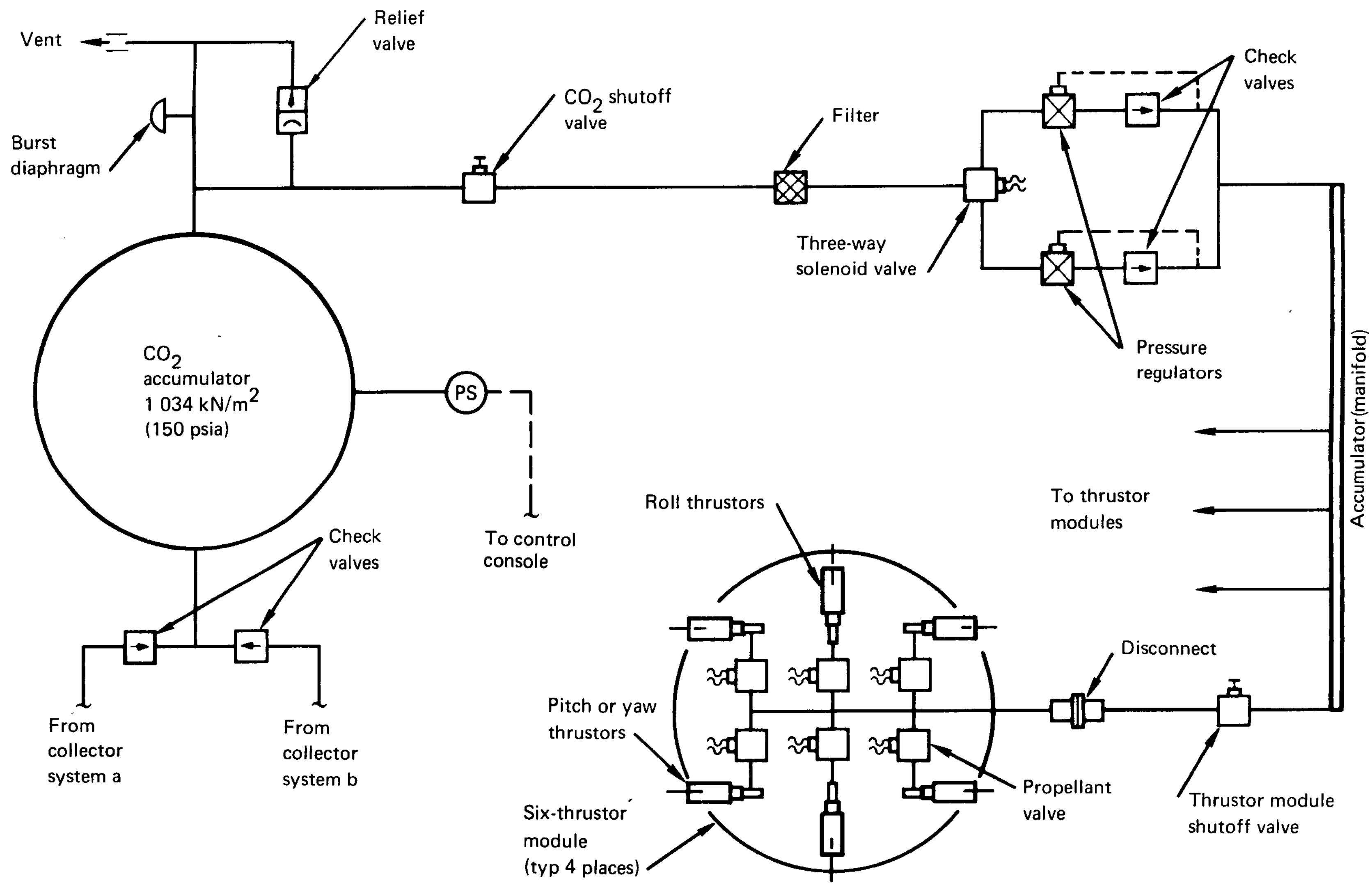

Figure 14. CO_2 Resistojet System

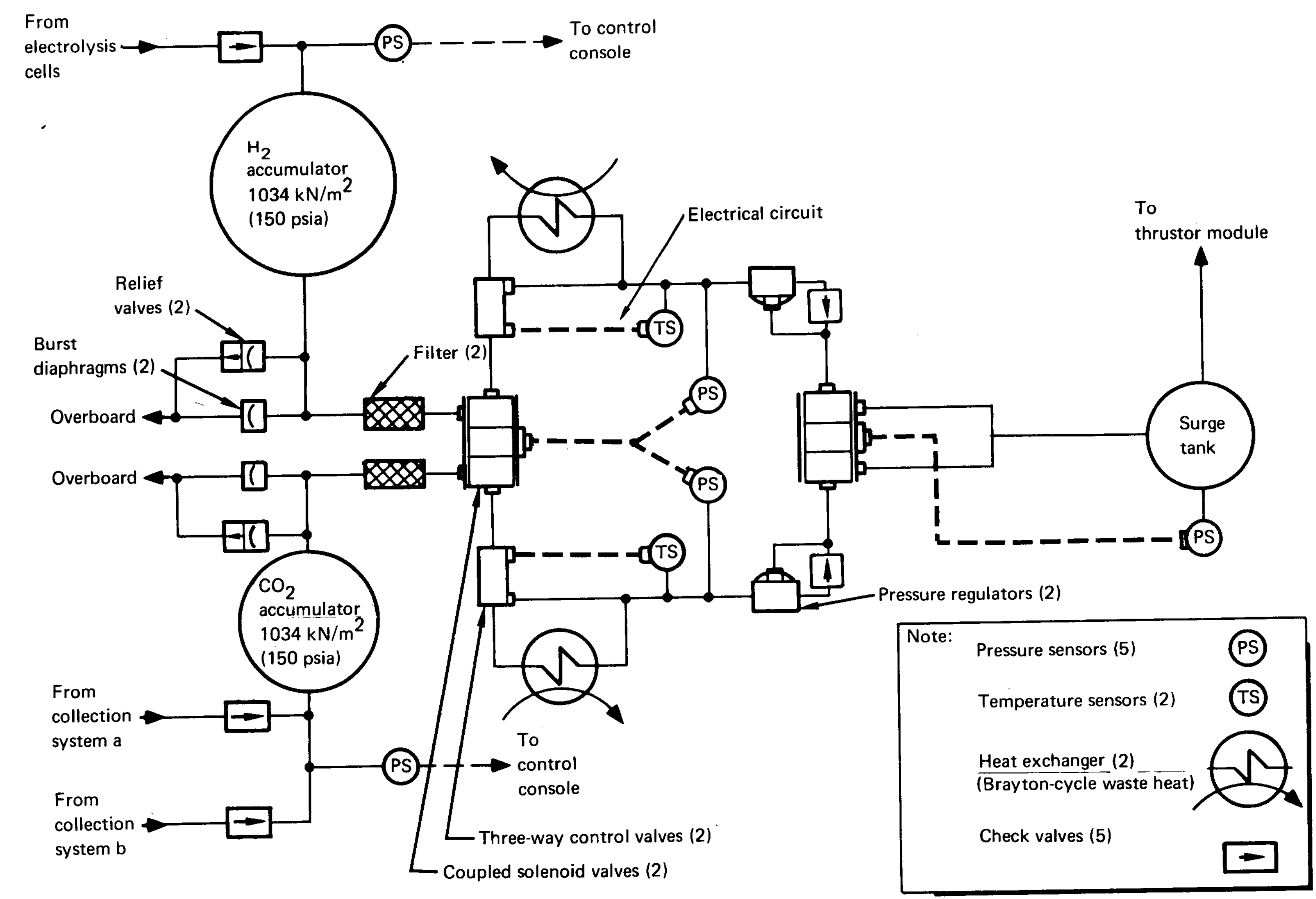

Figure 15. Combined CO_2 and H_2 Storage and Feed System

propellants flow through filters to eliminate contaminants and past coupled solenoid valves and independent temperature sensors. Should either or both propellants require temperature conditioning, the electric heaters are switched on. Thermal control is required to ensure accurate metering of the independent propellants.

Three-way, solenoid-actuated valves are used in each of the propellant-flow systems to provide flow through either of the redundant pressure regulators. These regulators maintain a downstream pressure of 275.8 kN/m^2 (40 psia) and require a minimum pressure drop of 138-kN/m^2 (20-psia) or 414-kN/m^2 (60-psia) minimum upstream pressure. Check valves prevent backflow of propellants should any of the regulators fail. The independent propellants are then mixed. As in the all-CO_2 system, an accumulator feed line is required to maintain supply pressure during startup of the cold thrustor, and the hand valve (normally open) is provided to isolate the thrustor module for repair or replacement.

The preliminary system design requires determination of accumulator requirements and surge-tank requirements. It was decided that the total accumulator capacity for each system be capable of delivering 0.178 N (40 mlbf) of thrust for 8 continuous hours without EC/LS output. This requirement approximates the inertial-orientation and maneuvering requirements for a similar time period. With the previously specified performance data, this criterion permits the deliverable propellant quantities to be determined.

The propellants are to be stored at a nominal pressure of 1034.3 kN/m^2 (150 psia) and nominal temperature of 325^{o}K (585^{o}R). The all-CO_2 system and the 0.678 CO_2 + 0.322 H_2 system both require a minimum accumulator pressure of 414 kN/m^2 (60 psia). Propellant in the accumulator below minimum supply pressure is not usable. Therefore, the accumulator storage capacity must provide for the required usable and the residual propellant at minimum supply pressure. The nominal storage pressures and the minimum supply pressures were used to establish the accumulator storage capacities.

The results of the design of the accumulators are presented in table 6 for both the all-CO_2 system and 0.678 CO_2 + 0.322 H_2 system. This table shows that significant volume and weight differences exist for the accumulators, with those of the all-CO_2 system being the lesser. The accumulators reflect the predominant system weight and volume differences. The thrustor modules and system plumbing would be essentially identical for both systems. The flow control of the combined propellant system would be more complex because of the flow system coupling and the precise propellant metering required. Table 7 summarizes the power requirements and performance for the two systems.

On the basis of data presented in this section, it was concluded that the most favorable biowaste system for MORL was the all-CO_2 system. The lower power requirements, relative simplicity, and lower weight and volume of this system justify its selection. The system has growth capability to provide up to 35% increase in MORL impulse requirements.

Table 6

ACCUMULATOR DESIGNS

Propellant	CO_2	$0.678\ CO_2 + 0.322\ H_2$		
		H_2	CO_2	Combined
Usable propellant quantity	2.85 kg (6.28 lbm)	0.46 kg (1.01 lbm)	0.97 kg (2.14 lbm)	1.34 kg (3.15 lbm)
Stored propellant quantity	4.76 kg (10.48 lbm)	0.77 kg (1.69 lbm)	1.62 kg (3.56 lbm)	2.39 kg (5.25 lbm)
Accumulator volume	0.25 m^3 (8.8 ft^3)	0.91 m^3 (32.2 ft^3)	0.055 m^3 (1.91 ft^3)	0.97 m^3 (34.11 ft^3)
Accumulator diameter	0.78 m (30.8 in.)	1.21 m (47.5 in.)	0.047 m (18.5 in.)	--- ---
Accumulator weight	5.0 kg (11.0 lbm)	15.9 kg (35.0 lbm)	1.59 kg (3.5 lbm)	17.5 kg (38.5 lbm)

Table 7

MORL BIOWASTE-PROPELLANT CANDIDATES

Propellant	CO_2	0.678 CO_2 + 0.322 H_2
[a]Delivered specific impulse	178 sec	373 sec
Required resistojet power	43.0 W	100.5 W
[b]Collection power	52.0 W	18.0 W
Total power	95.0 W	118.5 W
Daily CO_2 quantity	4.77 kg (10.5 lbm)	1.54 kg (3.41 lbm)
Daily H_2 quantity	0	0.73 kg (1.61 lbm)
Daily total propellant quantity	4.77 kg (10.5 lbm)	2.28 kg (5.02 lbm)
Specific impule to power ratio	1.87 sec/W	3.14 sec/W

[a]0.044 N (10 mlbf), 275.8 kN/m^2 (40 psia), 1666.6°K (3000°R).

[b]8321 N-sec/day (1870 lbm-sec/day).

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MORL RESISTOJET SYSTEM COMPARISONS

The preceding sections have delineated the considerations which resulted in selection of an all-CO_2 system as the most advantageous biowaste system for MORL. To assess the system, it was necessary to compare it to resistojet systems using NH_3 and H_2. The effect of a closed-loop EC/LS system on biowaste utilization was also assessed. The result was that the all-CO_2 system (with open-loop EC/LS) remained competitive with H_2 and NH_3 resistojet systems (with closed-loop EC/LS).

The criteria used in the assessments included performance, power requirement, launch weight, growth potential, development risk, maintainability, reliability, and resupply weight. System selection for specific applications will of course depend on the importance assigned to the various criteria.

The comparison of resistojet systems for the MORL with a 90-day resupply schedule is shown in table 8. This table summarizes the pertinent system parameters for the H_2, NH_3, and CO_2 systems. The comparisons were performed for an 8321-N-sec/day (1870-lbf-sec/day) impulse requirement and a 0.044-N (10-mlbf) thrust-level resistojet.

There is an appreciable difference in the performance of the candidate propellants. H_2 has the highest specific impulse and the highest power requirement. NH_3 and CO_2 have significantly reduced impulse and power requirements. The specific impulse is pertinent only in the H_2 and NH_3 comparisons since it establishes the quantity of propellant to be resupplied. However, since the biowaste system does not require propellant resupply, specific impulse is not a critical parameter as long as sufficient CO_2 output is available to meet the daily impulse requirement.

The chargeable launch weight of the H_2 system is higher than the NH_3 system, in spite of the H_2 system's higher specific impulse and lower propellant-weight requirement. This results from the large propellant-tank volume and weight (low propellant density), combined with a higher weight assessment for electric power. The volume of the H_2 tank is about five times that of the NH_3 tank. Since the propellant tanks contain only a 20-day propellant supply at launch, the difference in propellant weight between the H_2 and NH_3 systems represents only a small percentage of the launch weight penalty.

Table 8

RESISTOJET SYSTEMS SUMMARY[a]

(Open-Loop EC/LS System)

Item	H_2	NH_3	Biowaste CO_2
Chamber temperature	2420°K	2420°K	1665°K
Delivered specific impulse	735 sec	364 sec	177 sec
Propellant tank volume	3.34 m^3 (118 ft^3)	0.68 m^3 (24 ft^3)	0.25 m^3 (8.8 ft^3)
Total required power per thrustor	249 W	159 W	102 W
Weight assessment for electric power	107 kg (236 lbm)	69 kg (151 lbm)	44 kg (97 lbm)
[b]Total chargeable launch weight	246 kg (543 lbm)	196 kg (431 lbm)	98 kg (216 lbm)
Total chargeable 90-day resupply weight	238 kg (525 lbm)	297 kg (653 lbm)	

[a]Thrust--0.044 N (10 mlbf) P_c = 241 kN/m^2 (35 psia).

[b]Includes weight assessment for power consumption.

The biowaste system has the lightest launch-weight penalty because only 23.1 kg (10.5 lbm) of propellant is stored on-board. Furthermore, the propellant tank (accumulator) is small because it stores only about a 1-day supply of CO_2 as opposed to the H_2 and NH_3 tanks, which must be sized to store a 147-day propellant supply. The all-CO_2 system also requires the least power and, therefore, the lowest power-weight assessment.

Evaluation of resupply shows a significant advantage to the all-CO_2 biowaste system. This system has no chargeable resupply weight since no propellants or pressurants are required. The impact of the high specific impulse of H_2, when compared to NH_3, is evident in the loaded resupply propellant weight. This advantage is offset somewhat by the heavier tankage for H_2 and the larger resupply volumetric requirement.

All systems are limited in growth potential by the maximum power available. On the basis of this criterion, the all-CO_2 biowaste system has the greatest growth capability, followed by NH_3, with H_2 having a minimum growth potential (assessment is based on the thrust-to-power ratio). Each of the systems has an additional growth limitation. The NH_3 and H_2 systems are limited by the maximum volume in the MORL aft interstage. The NH_3 system, because of the higher propellant density, has the greater growth potential of the two and will also maintain a launch-weight advantage. The all-CO_2 biowaste system is limited by the biowaste quantity available. For the operating conditions listed, the all-CO_2 system has a 35% total impulse growth capability, which could be utilized with only a slight increase in accumulator size. Should the total impulse requirements exceed the all-CO_2 system capability, it is possible to go to the CO_2 + H_2 system, which can provide more than double the MORL baseline daily impulse requirement. This system, although more complex and requiring additional accumulator volume, could still compare favorably with the H_2 and NH_3 systems.

The NH_3 system requires the minimum development effort since the resistojet is in development testing and has demonstrated performance approaching the design goals. Although the H_2 resistojet has the same development status, the design of cryogenic tankage and the definition of cryogenic propellant resupply are considered system development areas requiring concentrated effort. The biowaste CO_2 resistojet is presently in the design evaluation phase and has not yet been development tested. Performance and operating life must be demonstrated.

The preceding comparisons for MORL clearly show that the all-CO_2 biowaste resistojet system can provide appreciable system gains over both the NH_3 and H2 resistojet systems. The reduced launch weight, the elimination of propellant resupply (and the associated crew time and system complexity), the lower power requirement, and the lower propellant-tank volume requirement are primary advantages. The biowaste system becomes even more advantageous if the vehicle impulse requirement increases. For such a case, the average thrust level (and, therefore, the average required power) would increase proportionally for all systems, with a corresponding increase in weight assessment for power. The propellant-tank volumes (and, therefore, tank weight) would increase proportionally for all systems. The H_2 and NH_3 systems, however, will also incur an increase in the requirement for loaded propellant weight. The sum of these effects would show the total chargeable launch weights to increase appreciably more for the NH_3 and H_2 systems than for the all-CO_2 biowaste system. An increase in impulse requirements would also raise the NH_3 and H_2 resupply weights without affecting the biowaste system. This evaluation would hold even if impulse requirements necessitated the use of the combined CO_2 + H_2 biowaste system.

CLOSED-LOOP COMPARISON

To further evaluate the potential of the biowaste resistojet system, a comparison was made between the CO_2 resistojet system with open-loop EC/LS and the NH_3 or H_2 resistojet systems with closed-loop EC/LS.

In the closed-loop or O_2-regeneration mode, the CO_2 and H_2 are not available for propulsion but are recombined in a hydrogenation unit to form water and carbon (see fig. 2). The water is then recycled through the electrolysis units. The use of the closed-loop system results in the addition of 116 kg (255 lbm) of O_2-regeneration hardware, which is offset by a saving of 114 kg (250 lbm) of water and tankage weight. However, an assessment penalty must be imposed for an increase in power requirement of 388 watts, and for system reliability, maintainability, and operability considerations. Spare parts will be required for the added hardware, and crew time will increase for monitoring, operating, and maintaing the more complex closed-loop system. In return for these penalties, the make-up water normally resupplied is not required, resulting in a net reduction in combined reaction control system and EC/LS logistics weight.

A launch weight, power, and logistics evaluation was performed for MORL and is summarized in table 9. Examination of the table shows that the all-CO_2 biowaste resistojet system with an open-loop EC/LS system has a significantly lower system launch weight and electric-power requirement than the H_2 and NH_3 resistojets with the closed-loop EC/LS system. The logistics resupply weight is, however, higher for the biowaste system. The significance of this assessment shows that O_2-regeneration capability of the EC/LS system will not diminish or eliminate the applicability of an all-CO_2 biowaste resistojet system operating with an open-loop EC/LS system. A detailed study of the MORL vehicle and its mission objectives will have to be performed, and the results will depend in part on the criteria established for assessment. It can be concluded, however, that the biowaste resistojet system will be competitive in the evaluation. The biowaste system will appear even more advantageous for a vehicle with a basic open-loop EC/LS system, because it must be remembered that normally it is not as simple to convert an open-O_2 EC/LS system to a closed-O_2 EC/LS system as indicated by fig. 2. It is only possible as shown because O_2 regeneration is an alternate operating mode for MORL, and many other changes to accommodate O_2-regeneration are already included in the baseline system. These include water electrolysis, CO_2-collection capability, increased waste-heat provisions, and increased waste-heat rejection capability. If a total tradeoff is accomplished, an even more pronounced launch-weight and operating-power advantage will occur for an all-CO_2 biowaste resistojet system. Furthermore, as shown in the previous system comparison, the biowaste system

Table 9

INTEGRATED EC/LS RESISTOJET SYSTEM COMPARISON

EC/LS system	Closed loop		Open loop
Resistojet system	H_2	NH_3	CO_2
Thrustor system average power	574 W	366 W	236 W
O_2-regeneration power	388 W	388 W	---
Total power	962 W	754 W	236 W
Weight assessment for power at 136 kg/kW (300 lbm/kW)	169 kg (372 lbm)	130 kg (287 lbm)	44 kg (97 lbm)
Resistojet system launch weight	140 kg (307 lbm)	127 kg (280 lbm)	54 kg (119 lbm)
O_2-regeneration hardware weight	116 kg (255 lbm)	116 kg (255 lbm)	--- ---
Open-loop water and tankage weight	--- ---	--- ---	114 kg (250 lbm)
Total chargeable launch weight	425 kg (934 lbm)	373 kg (822 lbm)	212 kg (466 lbm)
Total chargeable 90-day resupply weight	238 kg (525 lbm)	296 kg (653 lbm)	467 kg (1030 lbm)

advantage is enhanced with increasing vehicle-impulse requirements. In this event, the resistojet power requirements and launch weights of the resistojet system would show the previously described biowaste-system gains. The most noticeable effect, however, would be in logistics resupply, which would increase for both the H_2 and NH_3 systems and reduce the resupply advantages of these systems.

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CONCLUSIONS

As a result of the MORL resistojet system evaluations, it was shown that the all-CO_2 biowaste resistojet system has significant advantages over the H_2 and NH_3 resistojet systems, and that system competitiveness was maintained when compared with an O_2-regeneration EC/LS system using H_2 or NH_3 resistojet-control systems. In addition to the MORL system results, the following generalized conclusions were reached:

(1) Biowaste utilization by a resistojet system will be most competitive where vehicle impulse requirements necessitate almost complete usage of the vehicle outputs.

(2) The low power-to-thrust ratio and minimal propellant storage requirements of the biowaste resistojet system will be significant for power- and/or volume-limited vehicles.

(3) Propellant resupply is eliminated with the biowaste system reducing logistics requirements, propellant transfer difficulty, and complexity.

(4) Resistojet utilization of biowaste outputs will be competitive even if a closed-loop EC/LS system can be provided, and it should be compared for each specific vehicle and mission.

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2. Subsystem Performance Specifications (Report on the Optimization of the MORL System Concept). Douglas Report SM-48150, Contract NAS 1-3612.