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GAS SUPPLY SYSTEM FOR THE ST-124 INERTIAL PLATFORM

by
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ABSTRACT

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The gas supply system based on bulk storage is compared with a pump supply system. Excitation for the pump was considered for two separate power sources--battery and fuel cell. These studies were based on a 90-hour mission time, which provides sufficient life with safety for a lunar mission. Results of these comparisons for various operating pressures are presented in Tables 1, 2, 3, and 4. The operating pressure for the ST-124 components currently used is 1 bar differential (15 psid). Experimental investigation to reduce this pressure is being considered.

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ASTRIONICS LABORATORY

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The gas supply system based on bulk storage is compared with a pump supply system. Excitation for the pump was considered for two separate power sources--battery and fuel cell. These studies were based on a 90-hour mission time, which provides sufficient life with safety for a lunar mission. Results of these comparisons for various operating pressures are presented in Tables 1, 2, 3, and 4. The operating pressure for the ST-124 components currently used is 1 bar differential (15 psid). Experimental investigation to reduce this pressure is being considered.

SECTION I. INTRODUCTION

The gas supply reservoir systems for gas bearing gyros and accelerometers have made great evolutionary progress in the past several years. Contamination levels are now compatible with the gas bearings; the pressure regulation is good to ±0.014 bar; and temperature is controlled to ±1°C. Gaseous nitrogen, which is generated from liquid nitrogen, is used. This liquid nitrogen is purchased from vendors; a newly written MSFC specification holds contamination to very low levels.

Three years ago it was realized that severe weight penalties would be imposed for gas supply reservoir systems to support long space missions. At that time, a program was instituted to improve this critical area. This program took two approaches; one was to reduce gas consumption of the gas bearings, and the other was to develop a closed-loop recirculating gas supply system.

The total gas consumption of a stabilized platform has been reduced by one order of magnitude in the past three years, and progress is still being made in this area. As a comparison, under standard atmospheric conditions, the ST-80 stabilized platform required 0.23 m^3/min. STP of gas, and the ST-124M stabilized platform is expected to use only 0.0135 m^3/min. STP. Figures 1 and 2 present the gas consumption of individual ST-120 type gyros and accelerometers and the comparable ST-124 units. There are still some unknowns about a system operating in 10^{-7} torr ambient pressures, but leak rates should not increase this figure higher than 0.028 m^3/min. STP.

The recirculating gas supply system will have some advantages over bulk-stored gas for a mission. The greatest advantage appears to be weight. The heart of this system is a pump that must take the gas exhausted from the gas bearings, compress it to a suitable pressure, and recirculate it through the components. The weight penalties of a recirculating system lie principally in the power supply or the pounds of power supply (batteries) consumed per hour. For long missions, this approach appears to be the only acceptable one since any gas supply system is pound-for-pound payload.

Efforts to develop a pump have not been entirely successful. Two contractors have been used in this program, and neither has developed a satisfactory pump. In the past year, an in-house attempt has been made to develop a pump with a new approach to the mechanics of the problem; this pump uses gas lubricated bearings. This project has not been completely successful either; however, evaluation of all the results indicates that the system can now be successfully developed.

The results of a test, using one of the pumps developed with an ST-124 stabilized platform, are discussed later to show what is currently possible.

Two methods are used to supply gas to the stabilized platforms; (1) a single-ended gas supply system and (2) a recirculating gas supply system.

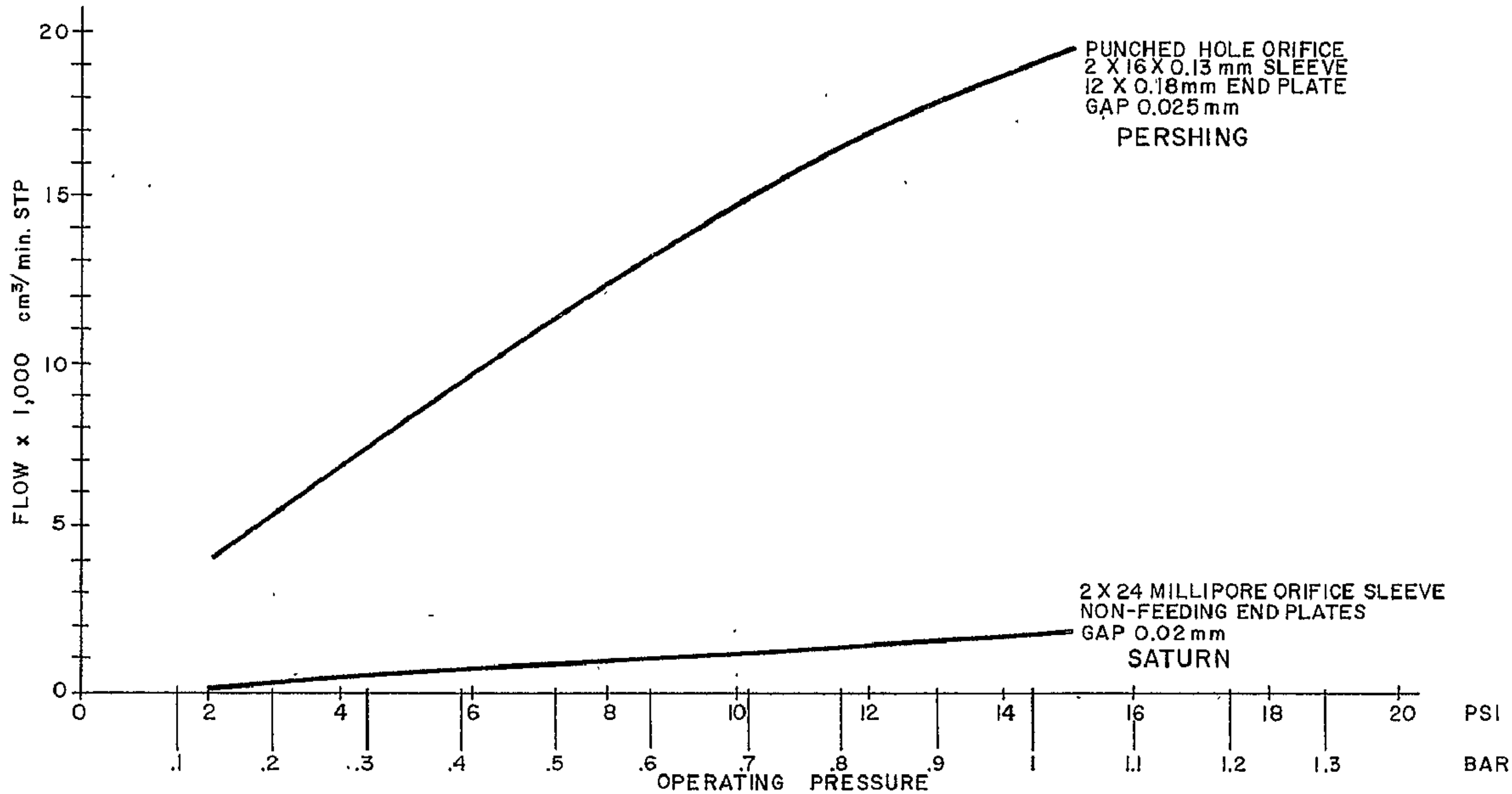


FIGURE 1. AB-5 STABILIZING GYRO GAS REQUIREMENTS

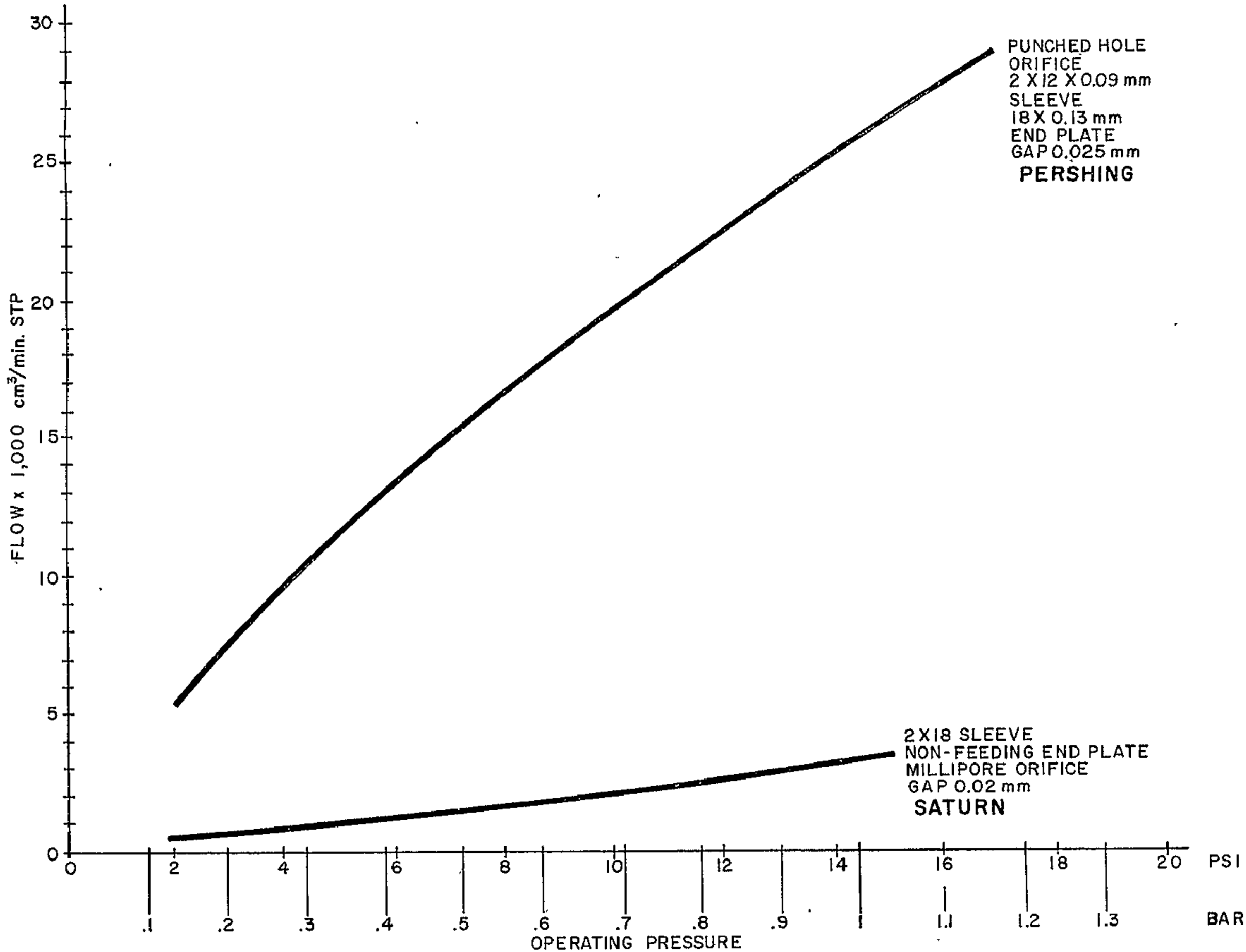


FIGURE 2. AMAB-3 INTEGRATING ACCELEROMETER GAS REQUIREMENTS

In a single-ended gas supply system, all the gas necessary for a single mission must be stored aboard the vehicle in high pressure reservoirs. The gas is dumped overboard as it passes through the gas bearings. The following discussion of a single-ended gas supply system will be confined to what can be accomplished with presently available hardware. Components of the Saturn V and Saturn IB gas supply systems are considered in the calculations that follow.

SECTION II. SINGLE-ENDED GAS SUPPLY SYSTEM

Spherical reservoirs made of titanium are presently used in the gas bearing supply systems. The weight of these reservoirs is 350 kg/m^3 (22 $lbs./ft^3$) and varies linearly with displacement. The operating pressure has been set at 200 bars (3000 psi). Regulators will exhaust the reservoirs to approximately 20 bars (300 psi) while maintaining the required pressure regulation.

The time to exhaust a reservoir will be calculated on a per cubic meter displacement basis. The values determined can then be used for any size reservoir.

The following symbols will be used to develop the general formulas:

T_r	Time to exhaust the reservoir at F_r	(min)
P_r	Reservoir operating pressure	(bar)
P_s	Standard atmospheric pressure	(bar)
D_r	Reservoir displacement	(m^3)
F_r	Flow rate of gas from reservoir	(m^3/min.) STP
V_r	Volume of gas in reservoir at P_r	(m^3) STP
V_u	Volume of usable gas in reservoir at P_r	(m^3) STP
M_r	Weight of reservoir	(kg)
M_p	Weight of plumbing and auxiliary devices	(kg)

M_n	Weight of nitrogen gas in reservoir	(kg)
M_m	Weight of a minimum system	(kg)
M_s	Weight of any system larger than M_m	(kg)
C_n	Density of nitrogen gas STP	$\left(\frac{kg}{m^3}\right)$

Basic formulas needed to compute gas supply system requirements are:

$$V_u' = \left(\frac{P_r}{P_s} - 20\right) D_r \ (m^3) \text{ STP} \qquad (1)$$

$$V_r = \left(\frac{P_r}{P_s}\right) D_r \ (m^3) \text{ STP} \qquad (2)$$

$$T_r = \frac{V_u}{F_r} \ (\text{min}) \qquad (3)$$

$$M_n = C_n V_r' \ (\text{kg}) \qquad (4)$$

$$M_m = M_r + M_p + M_n \qquad (5)$$

Equation 5 defines the mass of a minimum system. The mass increase for added time capability is a function of the added increments of reservoir and the gas to fill the added reservoir.

$$M_s = M_m + M_r + M_n \qquad (6)$$

An investigation has shown that no weight savings can be realized by using larger single reservoirs; therefore an optimum size reservoir should be chosen. Factors to be considered are (1) available space in the instrument unit and (2) an available man-rated reservoir from vendors.

The 0.086 m^3 (3 ft^3) titanium sphere which is 0.56 m (22 in.) in diameter meets all the required conditions. This spherical reservoir has the following characteristics:

Volume	0.085 m^3 (3 ft^3)
Diameter	0.56 m (22 in.)
Wall thickness	0.348 cm (0.137 in.)
Weight	29.6 kg (65.2 lbs.)
Operating pressure	200 bar (3000 psig)
Proof pressure	333 bar (5000 psig)
Burst pressure	447 bar (6700 psig)

This sphere is the reservoir for the ST-124M gas supply system for Saturn V and IB missions and can be considered a minimum system. Equations 1, 2, 3, 4, and 5 can now be applied to this minimum system to determine its operating characteristics.

The ST-124M gas supply system parameters have the following assigned values:

P_r = 200 bar (3000 psi)

P_s = 1 bar (15 psi)

D_r = 0.085 m^3 (3 ft^3)

$F_r = 2.37 \times 10^{-2}$ m^3/min. STP

M_r = 29.6 kg (65 lbs.)

M_p = 7 kg (15 lbs.)

C_n = 1.236 kg/m^3 (0.078 lbs./ft^3) STP

$$V_u = \left(\frac{200 \text{ bar}}{1 \text{ bar}} - 20\right) 0.085 \text{ m}^3 = 1.5 \text{ m}^3 \text{ STP}$$

$$T_r = \frac{1.5 \text{ m}^3 \text{ STP}}{2.37 \times 10^{-2} \text{ m}^3/\text{min. STP}} = 637 \text{ minutes} = 10 \text{ hours } 37 \text{ minutes}$$

$$V_r = \left(\frac{200 \text{ bar}}{1 \text{ bar}}\right) \times 0.085 \text{ m}^3 = 17 \text{ m}^3 \text{ (600 ft}^3\text{) STP}$$

$$M_n = (1.236)(17) \text{ kg} = 21.4 \text{ kg (47 lbs.)}$$

$$M_m = (29.6 + 7 + 21.4) \text{ kg} = 58 \text{ kg (127 lbs.)}$$

This is the calculated value of the ST-124M Saturn V basic gas supply system. The 7 kg (15 lbs.) allowed for auxiliaries is an estimate.

The minimum system can be extended to any mission time requirement by adding increments of reservoir. If the 0.085 m^3 (3 ft^3) sphere is used as increments, the mission time increment would be 637 minutes, as previously calculated. The mass increase would be:

$$M_r + M_n = (29.6 + 21.4) \text{ kg} = 51 \text{ kg (112 lbs.)}$$

or

$$\frac{51 \text{ kg}}{637 \text{ min.}} = 0.08 \text{ kg/min.}$$

$$= 4.8 \text{ kg/h (10.5 lbs./h)}$$

System weight could be further optimized by using the 0.0283 m^3 (1 ft^3) sphere, which would add time capability in increments of 212 minutes and mass in increments of (10 + 7) kg = 17 kg or 4.8 kg/h.

The curves of Figure 3 are plots of reservoir growth showing time capability versus weight for 2.37×10^{-2} m^3/min. STP flow requirement.

The diagram in Figure 4 is the ST-124M gas supply system for the Saturn V class vehicle and is the minimum system previously computed.

A tabulation of weight penalty for various operating pressures for a 90-hour mission is given in Table 1.

SECTION III. RECIRCULATING GAS SUPPLY SYSTEM

As stated earlier, the heart of the recirculating system is the pump which must be able to produce the required flow and pressure, be low in power consumption, be light in weight, and be qualified for space environments.

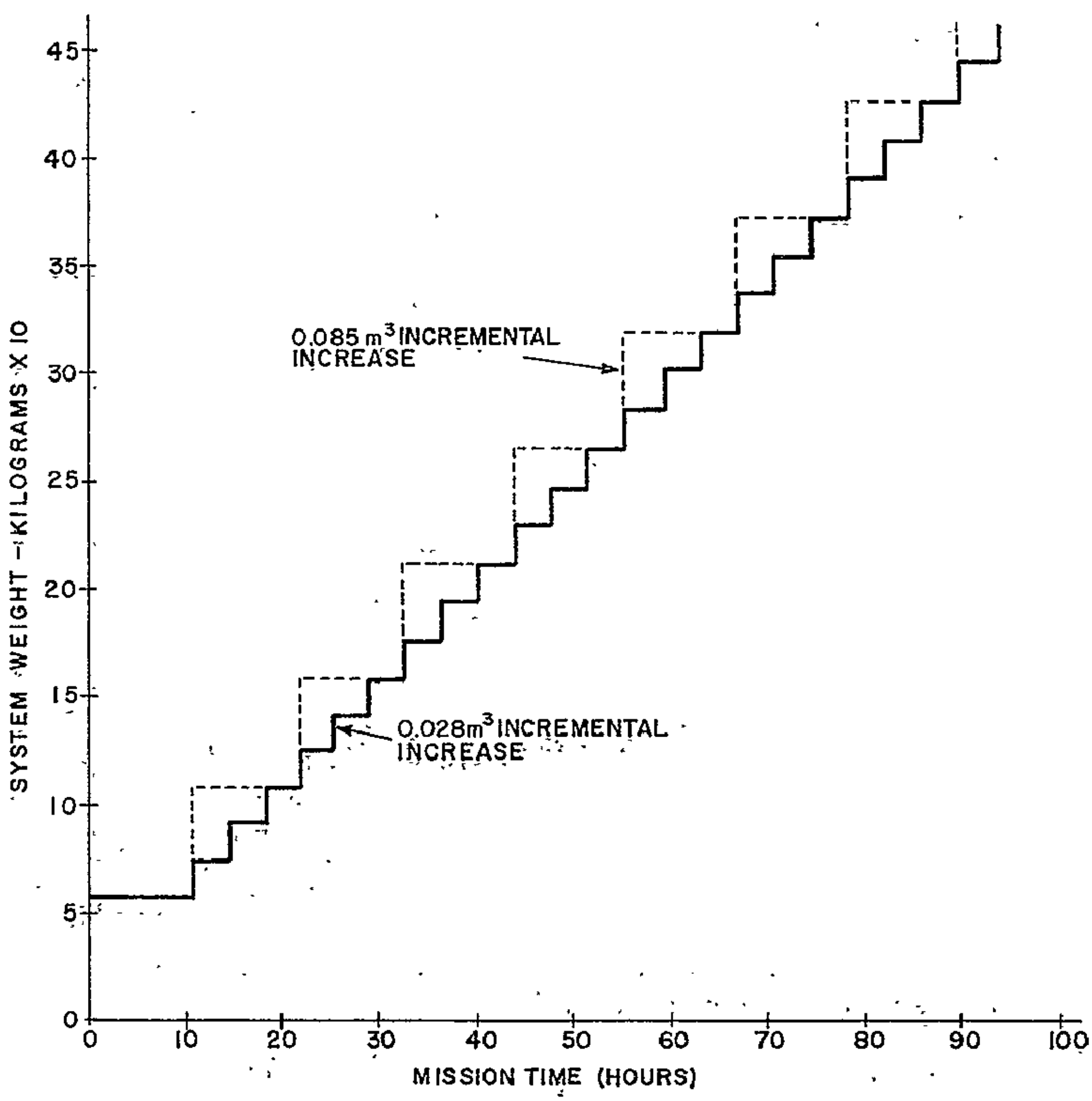


FIGURE 3. INCREMENTAL INCREASE IN SINGLE-ENDED SYSTEM

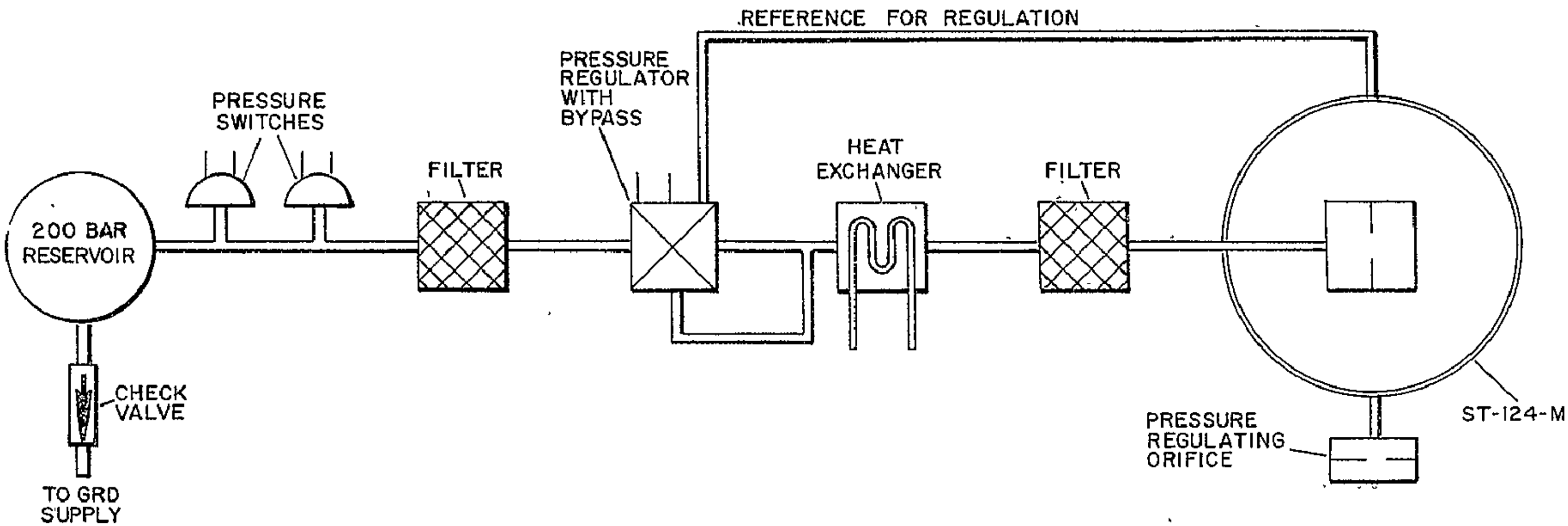


FIGURE 4. OPEN LOOP GAS SUPPLY SYSTEM

TABLE 1

ST-124M		BASIC SYSTEM RESERVOIR		
Operating Pressure Bar diff.	Flow Rate m^3/min. STP x 10^{-2}	Usable Volume V_u - m^3 STP	Minimum Weight M_m - kg	Time to Exhaust T_r - hours
1.03	2.37	15.3	58	18.9
0.86	1.07	15.3	58	23.7
0.69	0.815	15.3	58	31.3
0.55	0.628	15.3	58	40.7
0.42	0.459	15.3	58	55.2

SYSTEM GROWTH				
0.085 m^3 Increments (3 ft^3)		0.028 m^3 Increments (1 ft^3)		90-Hour Mission
Increase Time hours	Increase Weight kg	Increase Time hours	Increase Weight kg	Total Weight kg
18.9	51	6.3	17	262
23.7	51	7.9	17	211
31.3	51	10.4	17	160
40.7	51	13.6	17	126
55.2	51	18.4	17	109

The block diagram of Figure 5 shows what is required in the recirculating system. Note that some bulk-stored gas is still required in this system. The bulk-stored gas serves two purposes: (1) to inject makeup gas into the closed system as required because of leak rates and (2) to supplement the pump during high g thrust periods.

The following symbols will be used in discussing the recirculating gas supply system:

P_1	Input pressure to pump	bar
P_2	Output pressure of pump	bar
V_1	Gas flow through the pump	m^3/min. STP
W_{p1}	Work of compression	watts
W_{pm}	Work input to prime mover	watts
E_{pm}	Energy consumed by prime mover	W-h
T	Mission time	min.
M_b	Battery weight per watt-hour	kg/W-h
M_r	Gas reservoir weight	kg
M_n	Nitrogen gas weight	kg
M_p	Compressor and auxiliaries weight	kg
M_m	Weight of a minimum system	kg
M_t	Battery weight per hour	kg/h

The efficiency of a pumping system will probably be low; but as a guide, the results of the test that was run with one of the existing pumps will be used here.

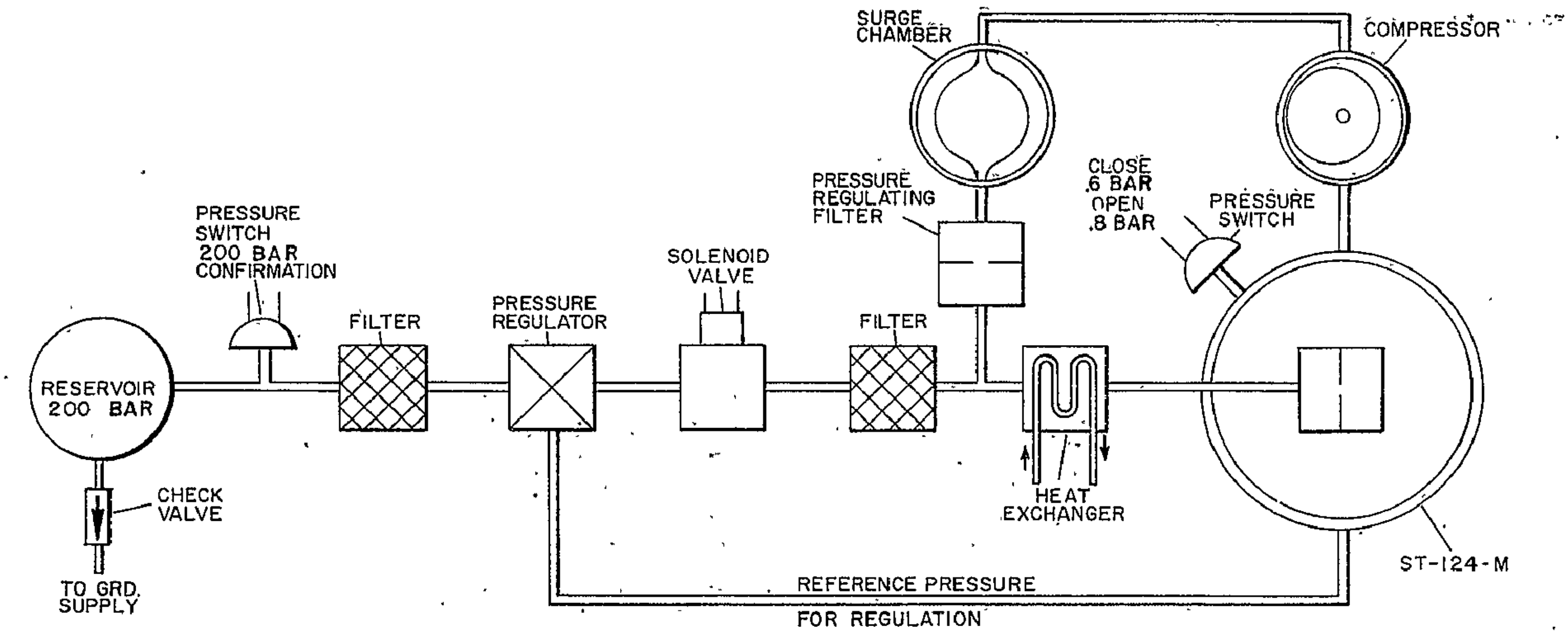


FIGURE 5. RECIRCULATING GAS SUPPLY SYSTEM

Using the equation for work required of adiabatic compression,

$$\dot{W}_{p1} = 3.463 \, P_1 \, \dot{V}_1 \left[\left(\frac{P_2}{P_1} \right)^{0.29} - 1 \right] \text{ watts.}$$

The pump test results give the following values

$P_1 = 1.03$ bar

$P_2 = 1.31$ bar

$V_1 = 3.63 \times 10^{-4}\ m^3/s$

Inserting these into equation 7 gives the following results:

$$W_{p1} = (3.463)\,(1.03 \times 10^5)\,(3.63 \times 10^{-4}) \left[\left(\frac{19}{15} \right)^{0.29} - 1 \right] \text{ watts}$$

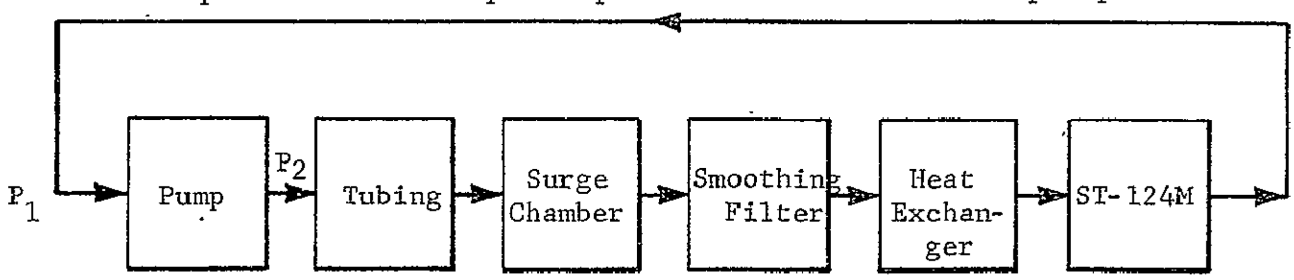
$W_{p1} = 9.1$ watts.

The actual measured power during this test was 40 watts to the pump motor.

$$\text{Efficiency} = \frac{9.1}{40.0} \times 100 = 22.3 \text{ per cent}$$

If the 22 per cent is considered an acceptable efficiency for a recirculating gas supply system, an investigation can be made for various flow rates and pressures.

Figure 6 shows the component parts of a recirculating system that would contribute to pressure drops around the loop. The sum of these drops will be the required pressure rise across the pump.



$$\Delta P_p = \Delta P_t + \Delta P_s + \Delta P_f + \Delta P_h + \Delta P_{st}$$

FIGURE 6. PUMPING SYSTEM BLOCK DIAGRAM

The first investigation will be made for a system that will supply a pressure of 1 bar to the gas bearing components of the ST-124M. Engineering estimates will be made for ΔP_t, ΔP_s, ΔP_f, and ΔP_h. The ΔP_{st}, which is the drop across the platform, will be determined from known test results; flow through the platform will be determined from Figures 1 and 2.

The following pressure drops will be allowed for components of the system when delivering 1 bar at the ST-124M gas bearings:

$\Delta P_t = 0.138$ bar differential

$\Delta P_s = 0.345$ bar differential

$\Delta P_f = 0.069$ bar differential

$\Delta P_h = 0.0345$ bar differential

$\Delta P_{st} = 1.242$ bar differential

P_1 = ST-124M internal ambient pressure

$= 0.69$ bar

$P_2 = \Delta P_t + \Delta P_s + \Delta P_f + \Delta P_h + \Delta P_{st} = 1.518$ bar differential

$P_2 = (1.518 + 0.69)$ bar $= 2.21$ bar absolute

From Figures 1 and 2, the flow rates at 1 bar are:

AMAB-3 accelerometer flow = 2400 cm^3/min. STP

AB-5 gyro flow = 1900 cm^3/min. STP

Pendulum flow = 100 cm^3/min. STP

Leakage rate = 10 per cent

Total flow = [(3) (2400) + (3) (1900) + (3) (100)] cm^3/min. STP

+ 0.1[(3) (2400) + (3) (1900) + (3) (100)] cm^3/min. STP

= 13,420 cm^3/min. STP

$V_1 = 2.24 \times 10^{-4} \quad m^3/s \text{ STP}$

To compute the theoretical power to compress the gas from pressure P_1 to P_2 at flow V_1,

$$W_p = 3.43\ P_1\ V_1 \left[\left(\frac{P_2}{P_1} \right)^{0.29} - 1 \right] \text{ watts}$$

$P_1 = 0.69$ bar

$P_2 = 2.21$ bar

$V_1 = 2.24 \times 10^{-4} \quad m^3/s \text{ STP}$

$$W_{p1} = (3.463)\ (6.9 \times 10^4)\ (2.24 \times 10^{-4}) \left[\left(\frac{2.21}{.69} \right)^{0.29} - 1 \right] \text{watts}$$

$W_{p1} = 24.5$ watts

Assuming the efficiency at 22 per cent, the power required by the pump prime mover is

$$W_{pm} = \frac{24.5}{0.22} = 111 \text{ watts.}$$

Weight penalty of the power supply (batteries) to operate the compressor will be based on 110 W-h/kg (50 W-h/lb) of battery consumed.

A general formula for computing weight penalties for various prime mover power inputs is

$$M_t = W_{pm}\ M_b$$

$$= (111 \text{ watts})\ (0.009 \text{ kg/W-h}) = 1.0 \text{ kg/h.}$$

Table 2 summarizes the results of the calculations for power consumption and weight penalties for the recirculating compressor system under varying operating pressure levels.

A reservoir of high pressure gas will be required for the recirculating system for makeup of losses caused by leaks in the low pressure ambient of space. The leakage rate of a system in an ambient pressure of 10^{-6} to 10^{-9} torr is not known at this time; therefore the leakage rate chosen here is probably pessimistic.

The Lunar Logistics vehicle mission time, generally quoted as 72 hours, will be used to define a recirculating gas supply system. To allow margin for error and to insure success of 72 hours of operating time, the system will be scaled to 90 hours of total operating capability.

In addition to the previous figures calculated, a leakage rate of one standard cubic meter per hour will be assumed.

The gas leakage rate makeup system would have the following characteristics.

Titanium sphere displacement $D_r = 0.014 \text{ m}^3$ (0.5 ft^3)

Titanium sphere weight $M_r = 5$ kg (11 lbs.)

Pump and auxiliary devices $M_p = 11.4$ kg (25 lbs.)

Operating storage pressure $P_r = 200$ bar (3000 psia)

$$V_r = \left(\frac{200 \text{ bar}}{1 \text{ bar}}\right) (0.014 \text{ m}^3) = 2.8 \text{ m}^3 \text{ STP of available gas}$$

$$V_u = \left(\frac{200 \text{ bar}}{1 \text{ bar}} - 20\right) (0.014 \text{ m}^3) = 2.52 \text{ m}^3 \text{ STP of usable gas}$$

$$T_r = \frac{V_u}{F_r} = \frac{2.52 \text{ m}^3 \text{ STP}}{0.028 \text{ m}^3/\text{h STP}} = 90 \text{ hours}$$

$$M_n = C_n V_r = (1.236 \text{ kg/m}^3)(2.8 \text{ m}^3) = 3.46 \text{ kg}$$

$$M_s = M_r + M_p + M_n$$

$$= (5 + 11.4 + 3.6) \text{ kg} = 20 \text{ kg}$$

The total weight penalties for a recirculating gas supply system with a 90-hour capability and 72-hour mission time for various operating pressures are presented in Table 3.

The weight penalty for the recirculating gas system could be greatly decreased by use of a fuel cell instead of batteries as the power source. Figure 7 defines the weight penalty for a 4 kW fuel cell system. The slope of the curve is fuel cell consumption per 4 kW or 0.42 kg/kW-h. For a comparison use 4.5×10^{-4} kg/W-h.

The basic weight of the fuel tankage is quoted as 100 kg for the 4 kW system or 2.5×10^{-2} kg/W. Using this figure, the basic fuel cell tankage weight penalty can be prorated to the gas compressor. Table 4 presents the total weight penalty for various operating pressures using a recirculating system with a fuel cell as a power source.

SECTION IV. CONCLUSION

A comparison of the two system concepts shows a weight saving for the recirculating system (Fig. 8). For the 90-hour mission capability and a 1 bar continuous stabilizer supply pressure, a net saving of 161 kg (355 lbs.) could be realized; if the fuel cell is the prime source of power, an additional 73 kg (161 lbs.) could be eliminated. The disadvantage of the recirculating system, which must be considered, is the added complexity with possible reduction in reliability. The pump has the greatest growth potential because of more efficient power supplies; therefore more efficient generating systems can be expected in the future.

The single-ended supply system has been developed and will be used on future Saturn vehicles with short mission times. Increased efforts are to be expended on the recirculating system with the expectation that, when the mission dictates the use of such a system, its development will be completed.

TABLE 2

ST-124M		GAS COMPRESSOR				
Operating Pressure Bar diff.	Flow Rate m^3/min. STP $\times 10^{-2}$	Platform Ambient Pressure Bar	Pump Input Pressure Bar diff.	Pump Output Pressure Bar	Prime Mover Power Watts	Battery Consumption kg/h
1.03	2.37	0.69	0.69	2.20	111	1.01
0.86	1.07	0.69	0.69	1.93	77.5	0.705
0.69	0.815	0.69	0.69	1.72	62.5	0.568
0.55	0.628	0.69	0.69	1.52	33	0.30
0.42	0.459	0.69	0.69	1.31	19.7	0.179

TABLE 3

ST-124		GAS COMPRESSOR		WEIGHT PENALTY FOR 90 HOURS		
Gas Bearing Pressure Bar diff.	Flow Rate m^3/min. STP $\times 10^{-2}$	Prime Mover Power Watts	Battery Consumption kg/h	Battery Weight kg	Makeup Gas System Weight kg	Total Weight Penalty kg
1.03	2.37	111	1.01	91	20	101
0.86	1.07	77.5	0.705	64	20	84
0.69	0.815	62.5	0.568	51	20	71
0.55	0.628	33	0.30	27	20	47
0.42	0.459	19.7	0.179	16	20	36

TABLE 4

ST-124M	GAS CONSUMPTION			WEIGHT PENALTY FOR 90 HOURS			
Operating Pressure Bar diff.	Flow Rate m^3/min. STP $x\ 10^{-2}$	Prime Mover Power Watts	Fuel Cell Consumption kg/h	Basic Fuel Cell Weight kg	Fuel Cell Fuel Consumption kg	Makeup Gas System Weight kg	Total Weight Penalty kg
15	2.37	111	0.05	2.8	4.50	20	27.3
12.5	1.07	77.5	0.035	2.0	3.15	20	25.2
10	0.815	62.5	0.028	1.6	2.52	20	24.2
8	0.628	33	0.015	0.85	1.35	20	22.2
6	0.459	19.7	0.009	0.5	0.81	20	21.4

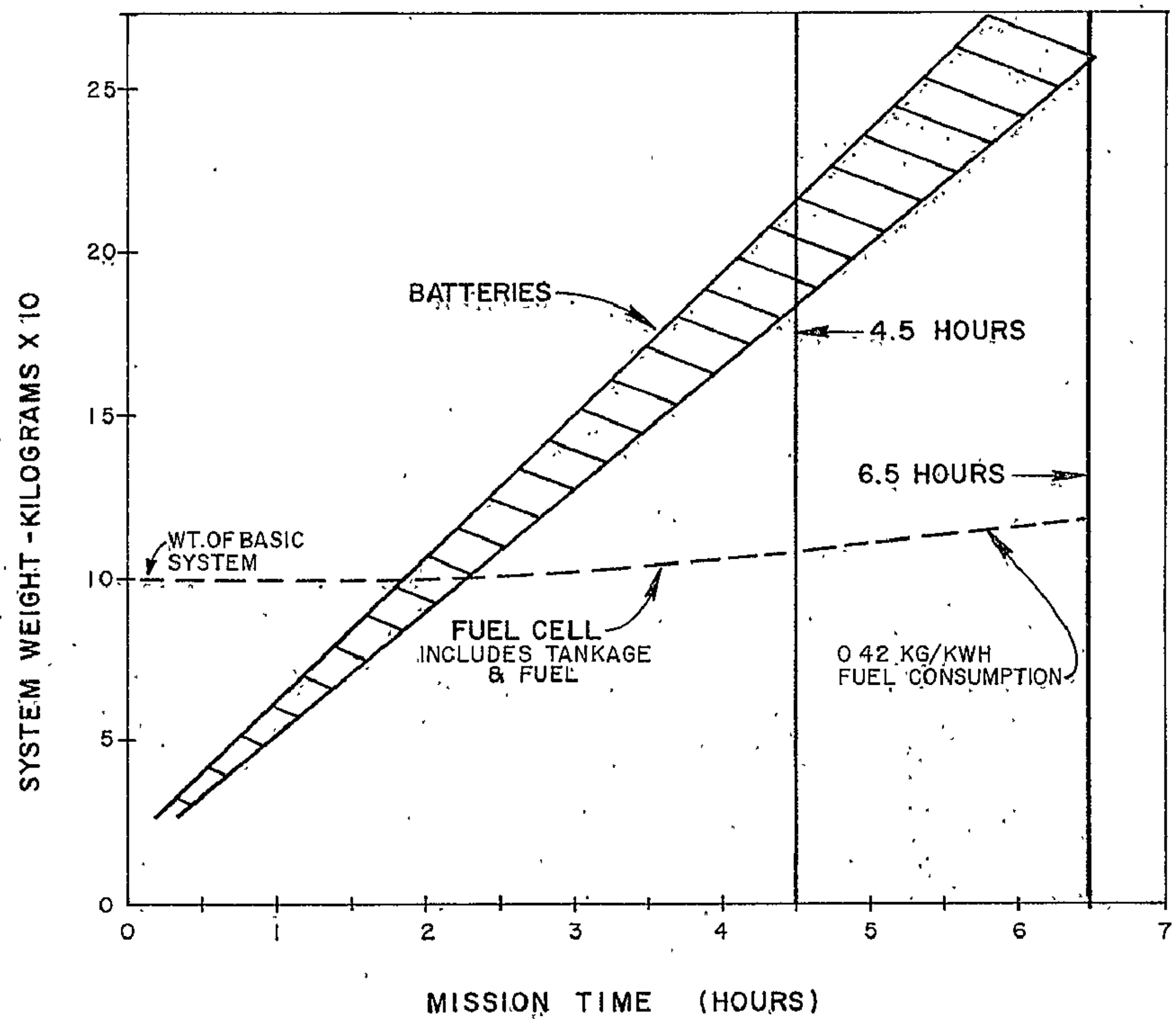


FIGURE 7. 4 kW POWER SUPPLY SOURCE

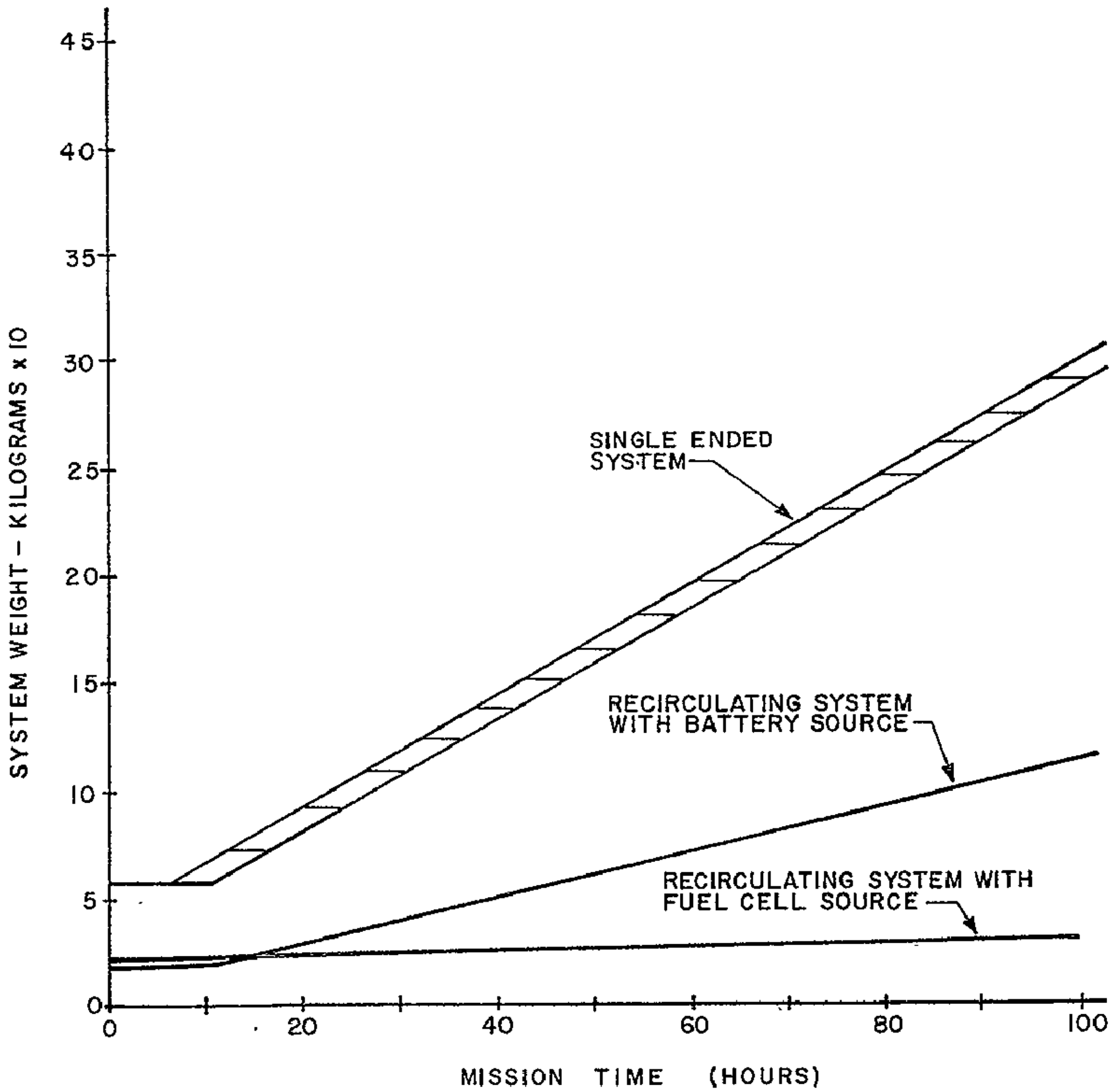


FIGURE 8. COMPARISON OF SYSTEMS' WEIGHT VERSUS MISSION TIME FOR 1.03 BAR OPERATING PRESSURE