# APPLICATION OF GAS EXPANSION TO FLUID CIRCULATION DEVICES IN MANNED SPACE ASSEMBLIES

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FOREWORD


This investigation was conducted by D. A. Keating, Respiratory Equipment Branch, Biotechnology Division, Biomedical Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.  The work reported herein was performed in support of Project 6373, "Equipment for Life Support in Aerospace," Task No. 637302, "Respiratory Support Equipment."  This study began in June 1964 and was completed in August 1964.

This technical report has been reviewed and is approved.

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ABSTRACT

The power required to circulate fluids for various pressure drops and flow
rates, and the power obtained from isentropic expansion of habitable gases
for manned space assembly application have been investigated.  The results
demonstrate the feasibility of using habitable gases, stored under pressure,
as potential energy sources to power fluid circulation devices.  These
findings indicate that significant weight savings can be obtained using the
gas expansion technique to furnish the required power of fluid circulation
as compared to using other power sources, such as batteries.

# SECTION I

## INTRODUCTION

The aerospace engineer has recognized the necessity to minimize power, weight, and volume requirements of life supporting systems whenever possible since man's earliest conquests of space travel.

One particular problem area has been to reduce the associated weight of all components involved with circulating fluids in manned space assemblies. Although the amount of power required to circulate fluids is relatively low, the weight of associated power sources to furnish the power is quite high.

The purpose of this study is to determine the power required to circulate fluids for various pressure drops and flow rates and to determine the feasibility of employing gas expansion techniques to furnish the required power. The gases that are used to furnish habitable atmospheres within manned space assemblies can be considered to be potential power sources since in many instances these gases are stored at relatively high pressures. Gases, such as air and its components of oxygen and nitrogen, have been analyzed to determine the available power obtained in their expansion from storage pressure to the atmosphere pressure of the spacecraft.

## SECTION II

## POWER REQUIREMENTS FOR FLUID CIRCULATION

The power required to circulate fluids within manned space assemblies can be determined from Bernoulli's equation for incompressible fluid flow as given by the following expression:

$$\frac{P_1}{\rho} + \frac{V_1^2}{2g_c} + \frac{g}{g_c} Z_1 + W = \frac{P_2}{\rho} + \frac{V_2^2}{2g_c} + \frac{g}{g_c} Z_2 + \frac{L}{\rho} \tag{1}$$

where:

| | | |
|---|---|---|
| $\rho$ | = density | $-\text{lbm/ft}^3$ |
| $P_1$ | = pressure upstream | $- \text{lbf/ft}^2$ |
| $P_2$ | = pressure downstream | $- \text{lbf/ft}^2$ |
| $V_1$ | = velocity upstream | $- \text{ft/sec}$ |
| $V_2$ | = velocity downstream | $- \text{ft/sec}$ |
| $Z_1$ | = position reference upstream | $- \text{ft}$ |

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| | | |
|---|---|---|
| $Z_2$ | = position reference downstream | – ft |
| g | = local gravitational acceleration | – ft/sec$^2$ |
| $g_c$ | = constant proportionability | – 32.179 $\dfrac{lbm - ft}{lbf - sec^2}$ |
| W | = work per pound mass | – lbf-ft/lbm |
| L | = friction losses | – lbf/ft$^2$ |

Bernoulli's equation takes into account the amount of work required to change the potential energy, kinetic energy, and flow work of the fluid while overcoming friction losses. Equation 1 can be rewritten to determine the total pressure head which must be overcome by the circulation device to obtain the desired fluid flow characteristics.

$$W\rho = (P_2 - P_1) + (V_2 - V_1)\frac{\rho}{2g_c} + (Z_2 - Z_1)\frac{g\rho}{g_c} + L \tag{2}$$

where

$$W\rho = \text{Total Pressure Head} = H - lbf/ft^2$$

The mass flow rate for fluid flow may be expressed by:

$$G = \rho VA - lbm/sec \tag{3}$$

where

| | | |
|---|---|---|
| $\rho$ | = density | – lbm/ft$^3$ |
| V | = velocity | – ft/sec |
| A | = cross sectional area | – ft$^2$ |

The volumetric flow rate for fluid flow can be expressed by:

$$Q = VA \qquad - ft^3/sec \tag{4}$$

The mass flow rate and the volumetric flow rate can be expressed by combining equations 3 and 4 to obtain:

$$G = Q\rho - lbm/sec \tag{5}$$

The power required to circulate fluids may be expressed by the following equation:

$$P = \frac{WG}{C} - hp \tag{6}$$

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where

$$C = 550 - \frac{\text{lbf-ft}}{\text{sec-hp}}$$

The power equation can also be expressed in terms of volumetric flow and total pressure head by combining equations 5 and 6 to yield the following:

$$P = \frac{W\rho Q}{C} - hp \tag{7}$$

or

$$P = \frac{HQ}{C} - hp \tag{8}$$

The power equation can be rewritten, if H is expressed in inches of water (in. $H_2O$) and Q is expressed in cubic feet per minute (cfm), to yield the following:

$$P = 0.001575 \, (H)(Q) - hp \tag{9}$$

Equation 9 is expressed by figure 1 for various total pressure heads and flow rates. The power required to circulate fluids is a linear function of volumetric flow rate and the total pressure head created by the circulation device.


SECTION III

ISENTROPIC EXPANSION


The expansion of gas from a higher pressure to a lower pressure is the process which takes place when gases, such as oxygen, are released from their high storage supply to maintain habitable atmospheres within space assemblies. This process is assumed to occur so rapidly that no heat is transferred thereby classifying it as an adiabatic process. Also, it is assumed to be an ideal adiabatic process without friction losses to classify it as an isentropic process.

Bernoulli's equation for compressible fluid flow undergoing an isentropic process is given by the following expression:

$$\Delta h_{1,2} = \frac{KRT_1}{k-1} \left[ \left( \frac{P_2}{P_1} \right)^{\frac{K-1}{K}} - 1 \right] \tag{10}$$

where:

$\Delta h_{1,2}$ = the enthalpy change from condition 1 to 2 where upstream is 1 and downstream is 2    -Btu/lbm

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$K$ = the ratio of the specific heat of the gas at constant pressure to the specific heat at constant volume, or $Cp/Cv$

$$K_{air} = K_{O_2} = K_{N_2} = 1.4$$

$R$ = gas constant for the particular gas

$$R_{air} = 53.35 - \frac{ft - lbf}{lbm - {}^\circ R}$$

$$R_{O_2} = 48.29 - \frac{ft - lbf}{lbm - {}^\circ R}$$

$$R_{N_2} = 55.16 - \frac{ft - lbf}{lbm - {}^\circ R}$$

$T_1$ = temperature upstream – °R

$P_1$ = pressure upstream – $lbf/ft^2$

$P_2$ = pressure downstream – $lbf/ft^2$

This equation may be used to determine the enthalpy change encountered during compressible fluid flow from upstream conditions to downstream conditions. Graphs of this equation, using enthalpy change vs pressure ratio, are shown in figures 2, 3, and 4 for air, oxygen, and nitrogen, respectively. These graphs are obtained for the temperature range of 50° F to 100° F. The enthalpy change becomes asymptotic as the pressure ratio approaches rather large values.

SECTION IV

AVAILABLE POWER FROM GAS EXPANSION

The available power obtained from an isentropic gas expansion can be determined from the enthalpy change which occurs and the mass flow rate. The available power can be expressed by the following equation:

$$P = (\Delta h_{1,2})(G)(C) \tag{11}$$

where

$P$ = available power obtained from isentropic expansion — hp

$\Delta h_{1,2}$ = the enthalpy change from condition 1 to 2 where upstream is 1 and downstream is 2 — $\frac{Btu}{lbm}$

$G$ = mass flow rate — $\frac{lbm}{hr}$

$C$ = conversion constant — $\frac{1}{2540} \frac{hp - hr}{Btu}$

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Graphs of equation 11 using available power vs pressure ratio for various mass flow rates at 80°F are shown in figures 5, 6, and 7. The temperature of 80°F was chosen because manned space assemblies are maintained at or near 80°F. This temperature choice will give a good approximation of available power vs pressure ratio between the temperature range from 50° to 100°F, since temperature does not greatly affect the enthalpy function between 50° and 100°F as shown in figures 2, 3, and 4. To derive the available power for a given pressure ratio at a temperature different from 80°F, yet between 50° and 100°F, use the available power data given in figures 5, 6, and 7 and multiply by $\frac{T}{540}$. The temperature (T) must be expressed in degrees Rankine.

## SECTION V

## CONCLUSIONS

The major conclusion to be derived from this study is that available energy obtained from isentropic expansion of habitable gases can be used to furnish power for fluid circulation devices within manned space assemblies.

The engineer will have to take the friction losses and inefficiencies exhibited by real devices into account when he uses figure 1 and figures 5, 6, and 7 together to determine integrated systems. For instance, suppose two astronauts are maintained within a completely sealed spacecraft and they only require a total metabolic rate of 0.2 lbm/hr of oxygen. Figure 6 indicates that $60 \times 10^{-4}$ hp can be obtained for this flow rate at a pressure ratio of $40/_1$ or where $P_1$ is 200 psia and $P_2$ is 5 psia. If circulating devices integrated with impulse turbines are used, a total efficiency of 50% can be considered as a design factor. Thus, the real available power for the aforementioned pressure drop and mass flow rate would be approximately $30 \times 10^{-4}$ hp. This device could be used to circulate fluids within the manned space assembly for typical conditions of 10 cfm at a total head pressure of 2 in. $H_2O$ or other similar condition, such as 2 cfm at a total head pressure of 10 in. $H_2O$ as indicated by figure 1.

The savings to be realized when the weight of associated fluid circulation components and valving using the isentropic expansion technique as compared to the weight of associated fluid circulation components using other power sources, such as batteries, is considerably significant. The application of the gas expansion technique to fluid circulation devices in manned space assemblies should definitely be considered when the habitable gases are stored within vessels at pressures higher than the internal atmosphere pressure of the space assembly. This technique provides a method of using the energy which was transferred to the habitable gases, while being changed to high pressures on the earth, to be recovered and used during actual manned space travel.
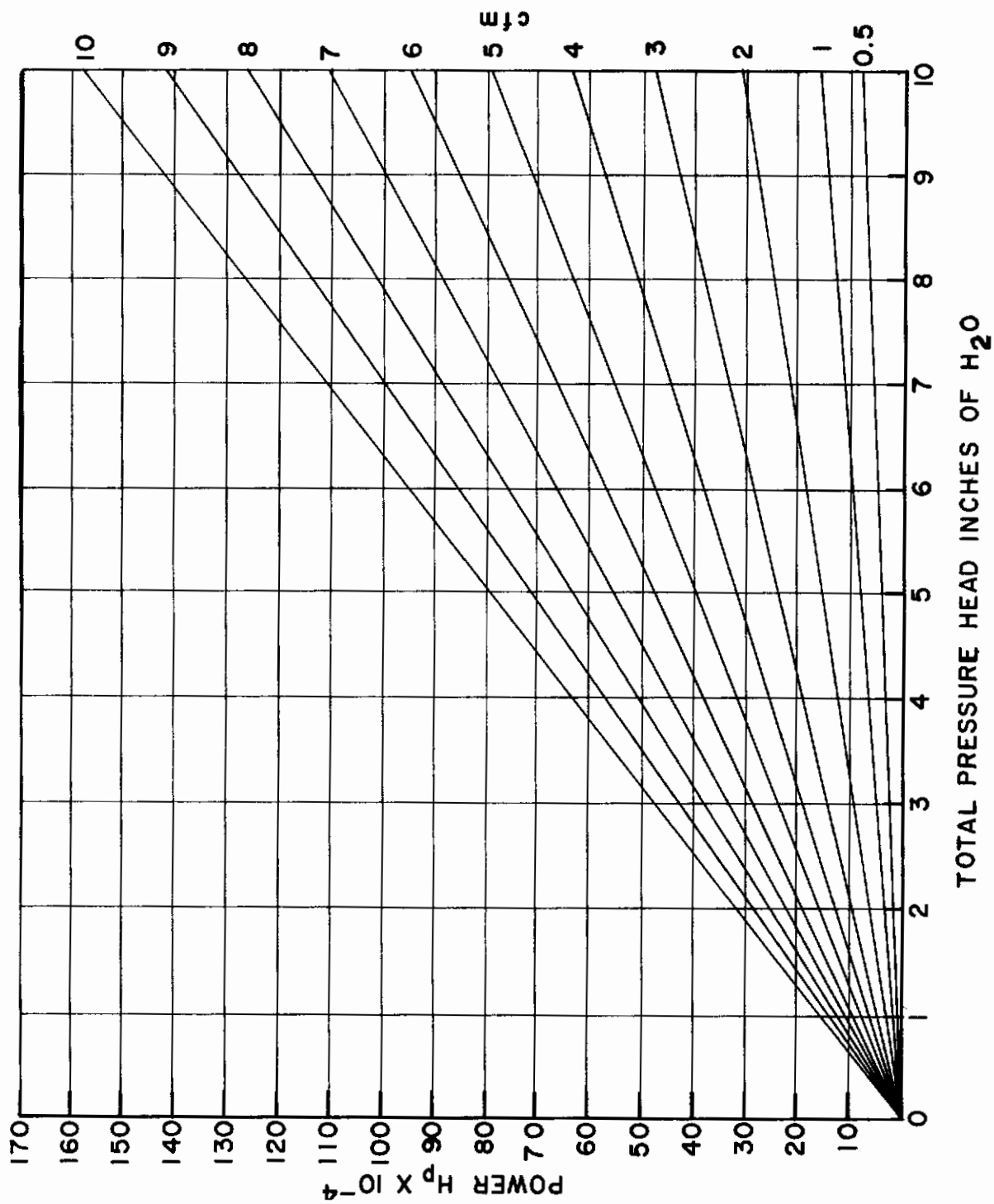
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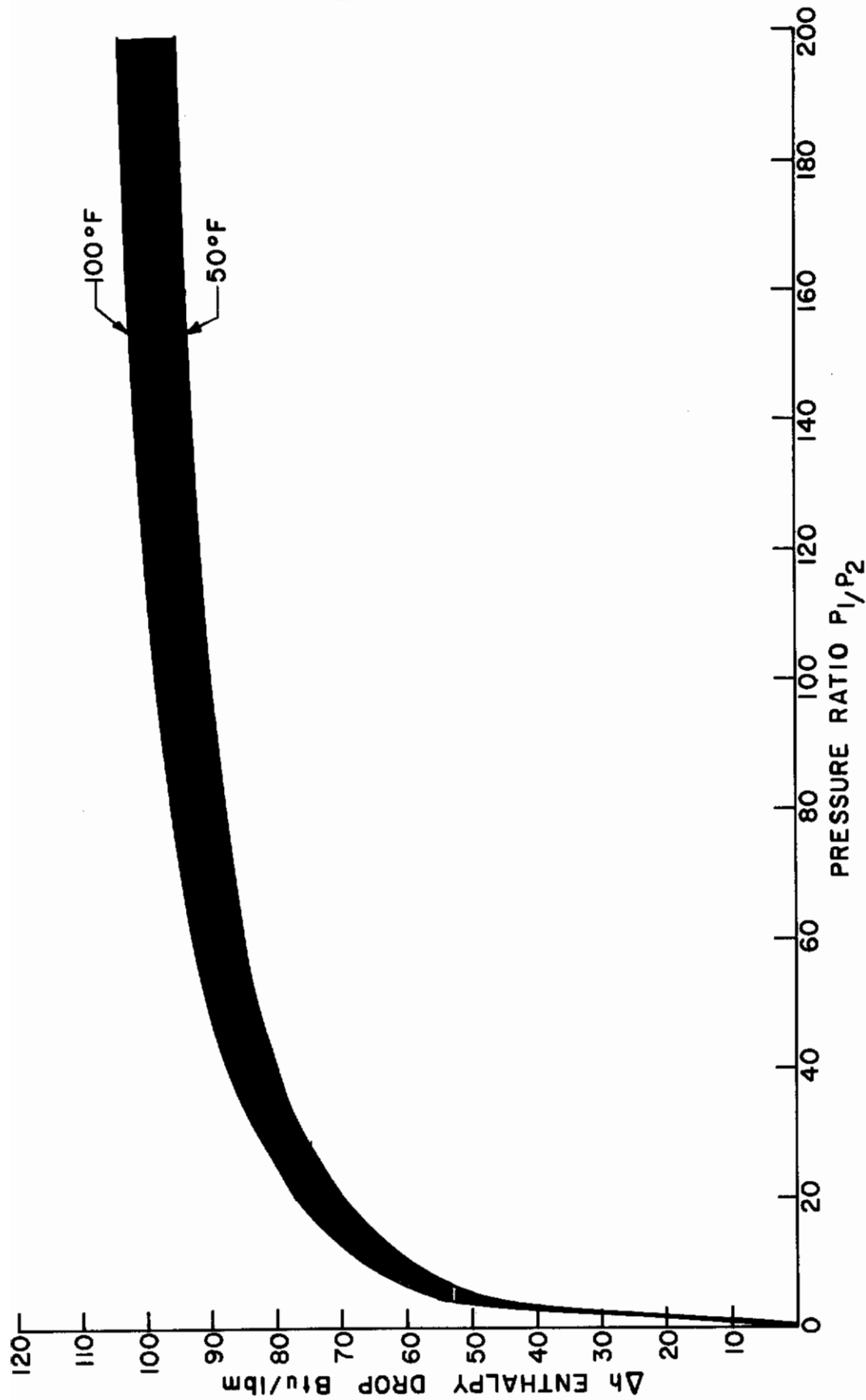Figure 1.  Required Power vs Total Head for Fluid Flow

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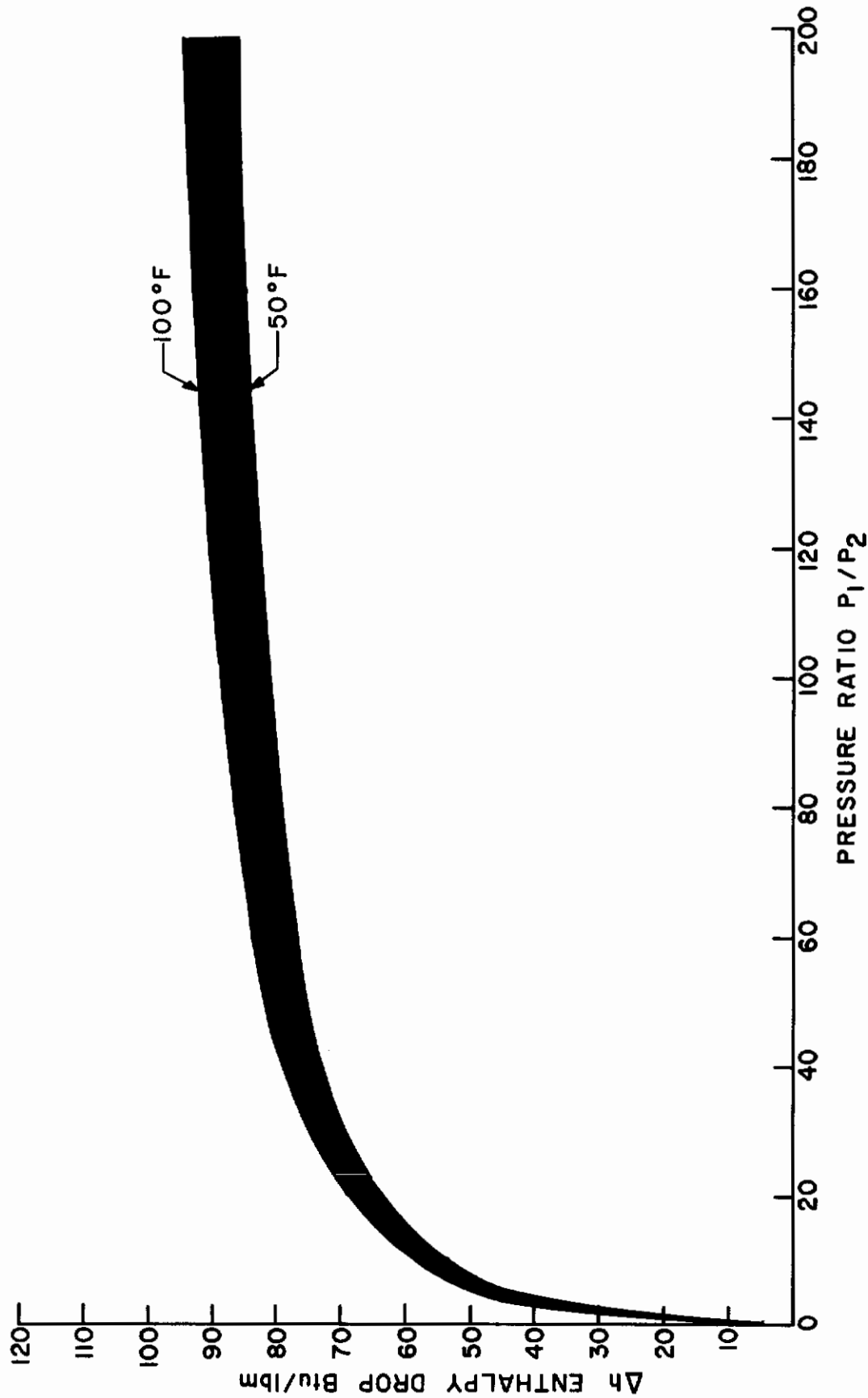Figure 2. Enthalpy Change vs Pressure Ratio for Air

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-Figure 3. Enthalpy Change vs Pressure Ratio for Oxygen

The chart shows ΔH ENTHALPY DROP Btu/lbm (vertical axis, 0 to 120) plotted against PRESSURE RATIO $P_1/P_2$ (horizontal axis, 0 to 200), with curves labeled 100°F and 50°F.
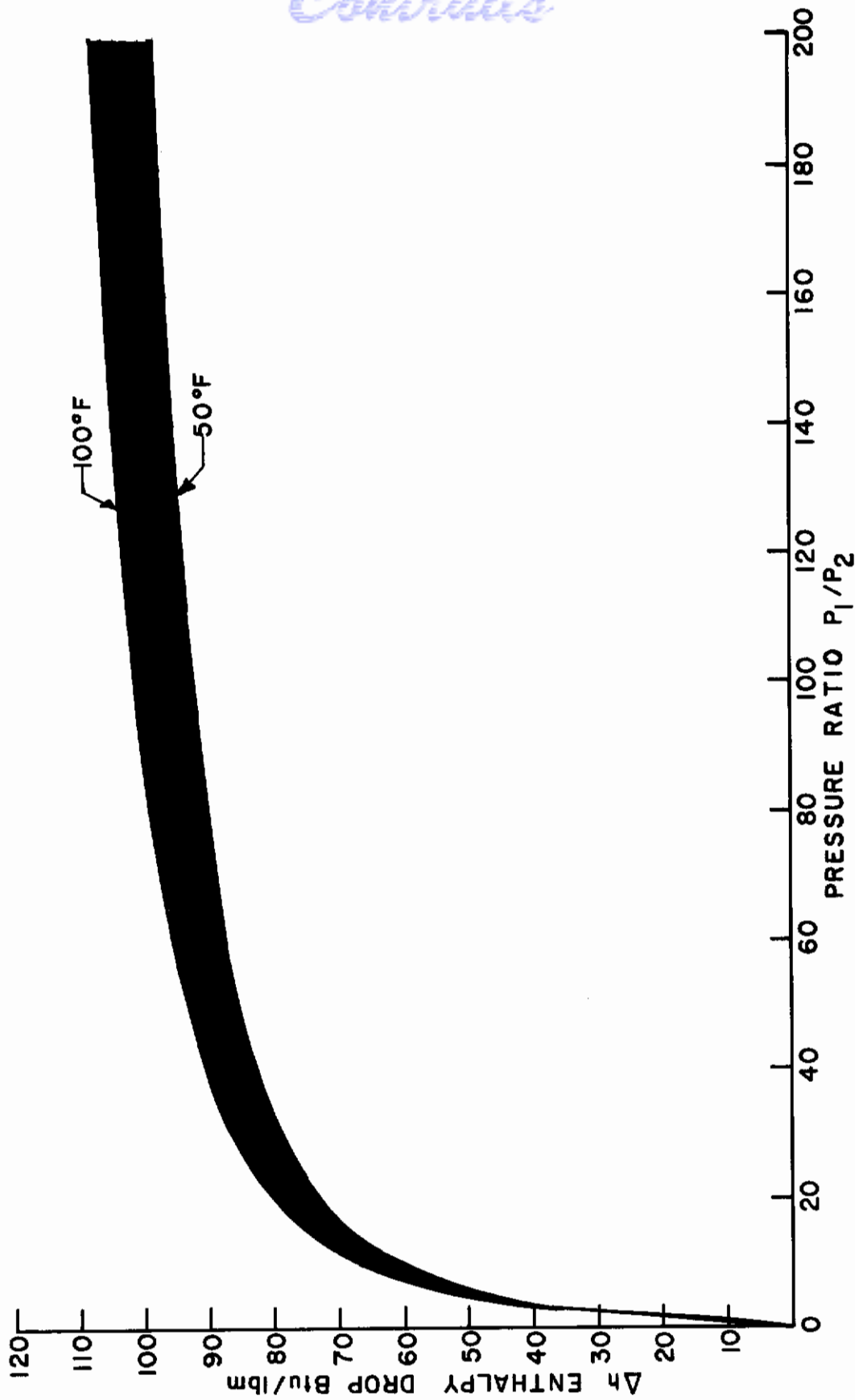
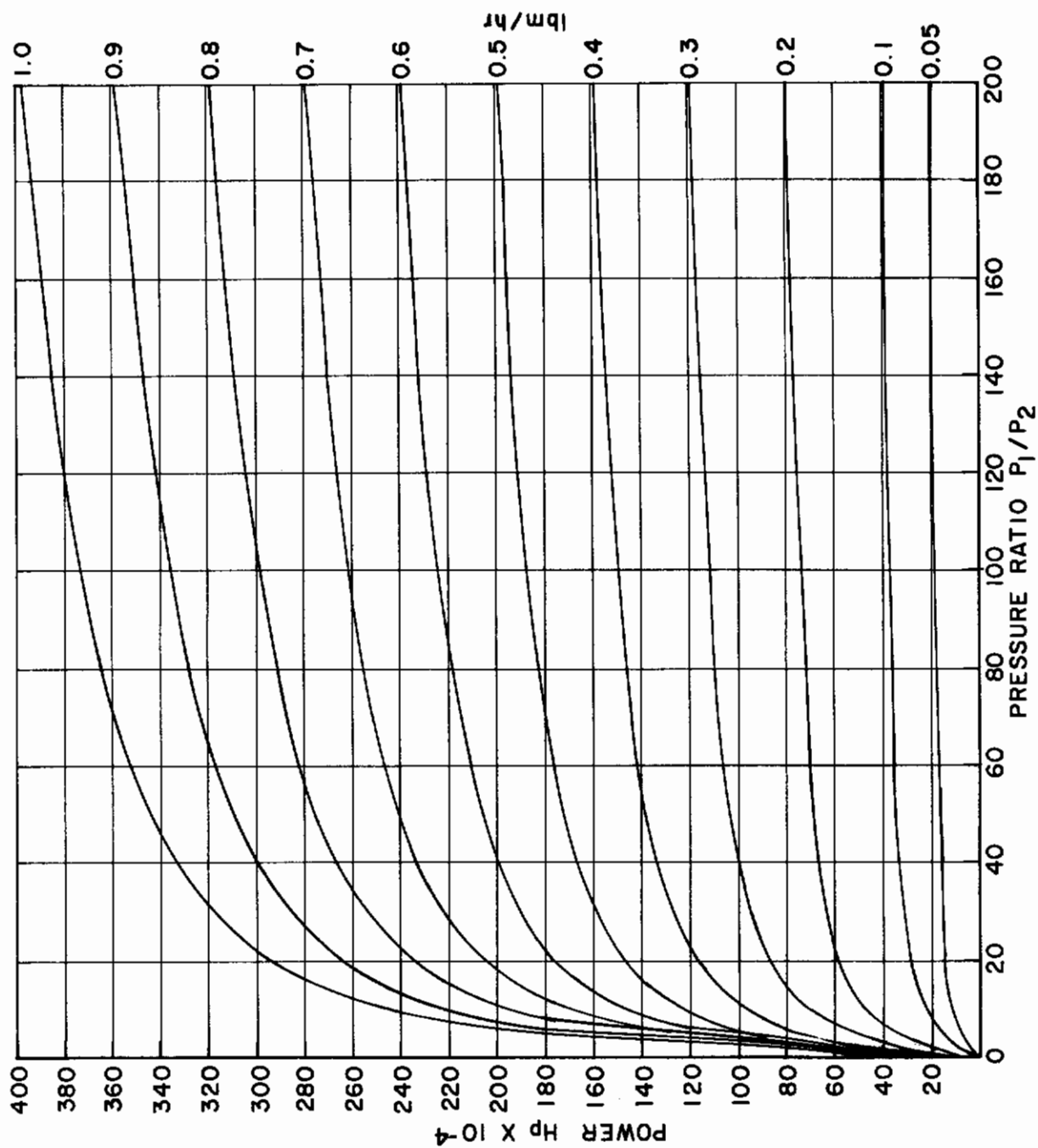Figure 4.  Enthalpy Change vs Pressure Ratio for Nitrogen

Figure 5. Available Power vs Pressure Ratio for Expansion Rates of Air at 80°F ($T_1$)
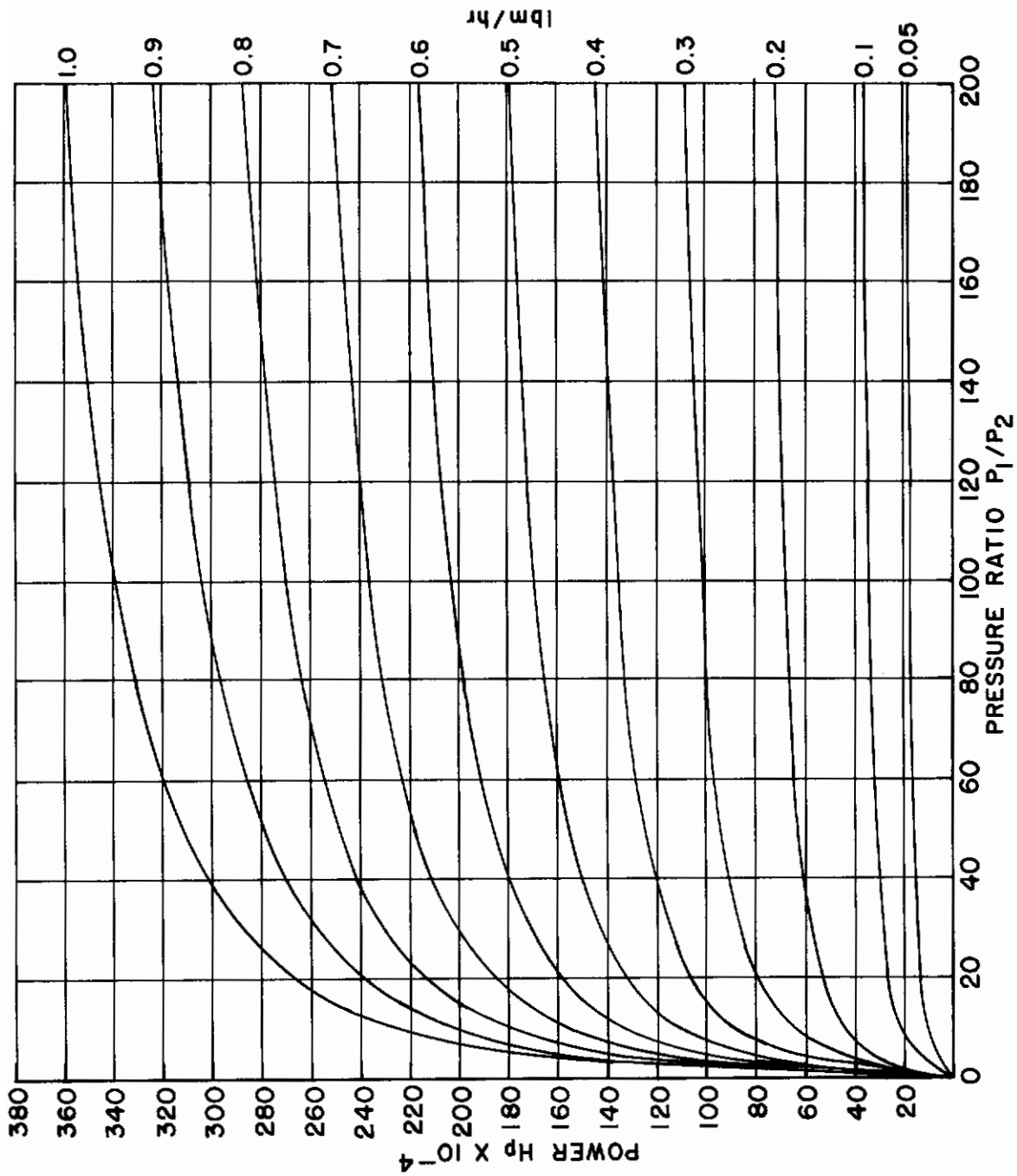
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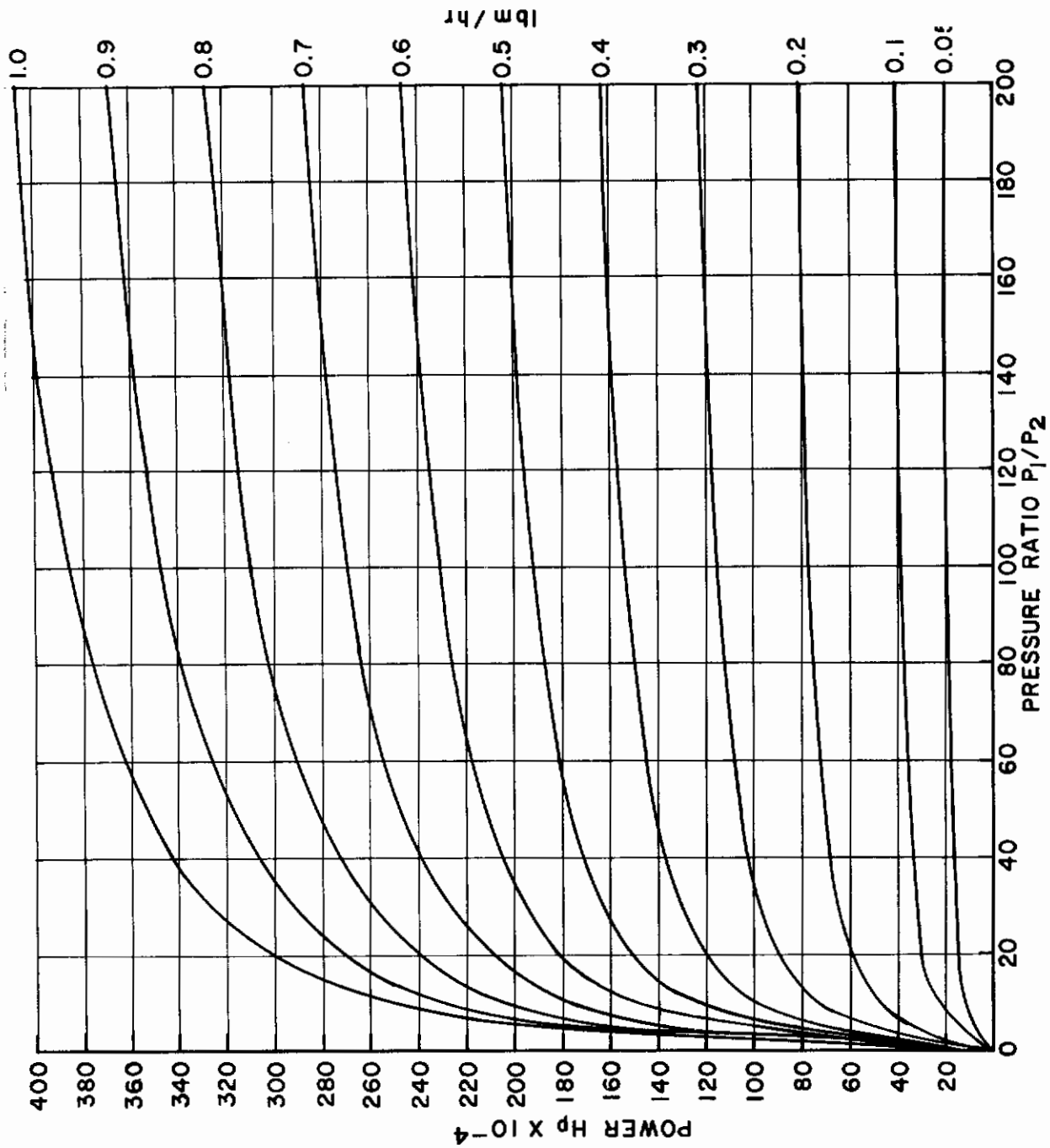Figure 6. Available Power vs Pressure Ratio for Expansion Rates of Oxygen at 80°F $(T_1)$

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Figure 7. Available Power vs Pressure Ratio for Expansion Rates of Nitrogen at 80°F ($T_1$)

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|---|---|
| Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio | UNCLASSIFIED |
| | 2b. GROUP N/A |

**3. REPORT TITLE**

APPLICATION OF GAS EXPANSION TO FLUID CIRCULATION DEVICES IN MANNED SPACE ASSEMBLIES

**4. DESCRIPTIVE NOTES** *(Type of report and inclusive dates)*

Final report, June 1964 – August 1964

**5. AUTHOR(S)** *(Last name, first name, initial)*

Keating, D. A.

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| April 1965 | 12 | None |

| 8a. CONTRACT OR GRANT NO. | 9a. ORIGINATOR'S REPORT NUMBER(S) |
|---|---|
| b. PROJECT NO 6373 | |
| c. Task No. 637302 | AMRL-TR-65-26 |
| | 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* |
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