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MASTER OF SCIENCE

REPORT

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DESIGN OF A STAGNATION HEATER FOR THE RAREFIED GAS WIND TUNNEL

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submitted in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE

(Mechanical Engineering)

at

The University of California at Berkeley

December 1990

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ABSTRACT: This report covers the fluid mechanic, heat transfer, and structural design of a stagnation heater for the Berkeley rarefied gas wind tunnel. The heater is to provide a low mass flow rate of gas for electron beam or laser diagnostic applications. The heater is compatible with oxidizing gases at mass flow rates of 0.1 to 0.3 g/s, with an output temperature of up to 2000 K. The heater consists of an inner zirconia tube for the source gas to pass through, which is surrounded by a pressure vessel . The source gas and the pressure vessel are designed to be at up to 2000 psi (136 atm). The heater will operate at pressure ratios of up to one million, producing gas flows of at least Mach ten.

Fluid mechanic analysis shows that the source gas is in laminar flow through the heater, and has a transit time of 2-3 seconds. An extensive parametric study is presented of heater outlet diameter versus source gas type, temperature, pressure, and mass flow rate.

The heat transfer analysis assumes uniform axial temperature in the core of the heater (i.e. a constant temperature boundary condition), then finds 1-D radial heat transfer by accounting for simultaneous radiation and conduction. Heat losses at the ends are estimated iteratively by sequential 1-D conduction (through the end of the heater) and radiation (to the wind tunnel).

The structural design of the heater focuses on how the pressure vessel is sealed, including determining the size and number of bolts to keep the vessel safely intact.

The vessel measures approximately 16" in length, and is 9.5" in diameter. Steel and zirconia (ZrO_2) are the primary structural materials. Tantalum wire in an argon atmosphere is used for heating. Total power requirements for the heater are estimated at 2700 Watts.

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ACKNOWLEDGEMENTS

The author gratefully acknowledges the contributions of many people for their help with this project, including:

Mr. Lawrence Gochberg, for considerable help with heat transfer analysis and mechanical design,
Prof. Al Pisano, for help with mechanical design,
Hughes Aircraft Company (Missile Systems Group, Advanced Design Division), for indirect support of this project through the author's Fellowship.

Thanks also to Prof. Franklin Hurlbut, the faculty advisor for this project, for guidance, inspiration, and motivation.

SYMBOLS USED IN THIS REPORT

A = Area
A_i = Area represented by the i^{th} node = $\pi * D_i * L$
c_p = Heat capacity at constant pressure
c_v = Heat capacity at constant volume
$c_{v_{vib}}$ = Heat capacity at constant volume due to vibrational modes
D = Diameter
D_i = Diameter for the i^{th} node
E = Modulus of elasticity
eqn = Equation
$F_{i\,j}$ = Form factor between nodes i and j
g = Acceleration due to gravity
Gr = Graetz number
k = Thermal conductivity
k_o = Thermal conductivity function for air given by equation (3.b.4)
L = Length of heated section of heater
m = Mass flow rate of source gas
M = Molecular weight of source gas (kg/kgmol)
Nu = Nusselt number
Pe = Peclet number = Re*Pr
Pr = Prandtl number
P_o = Stagnation pressure (in the heater)
P_1 = Ambient pressure (in the wind tunnel)
q = Heat flow (W)
q'' = Heat flux (W/m^2)
Q = Power requirement to overcome heat loss through heater endplates
R = Specific gas constant
R_{c_i} = Conduction resistance of i^{th} node
R_I = Equivalent conduction resistance for radiation heat transfer analysis of inner problem
R_O = Equivalent conduction resistance for radiation heat transfer analysis of outer problem
R_{r_i} = Radiation resistance of i^{th} node
R_u = Universal gas constant
Re = Reynolds number

SYMBOLS (CONT.)

T = Temperature
T_i = Temperature of the i^{th} node
T_{in} = Temperature of source gas at heater inlet
T_f = Film temperature (mean of surface and ambient temperatures)
T_m = Mean temperature of the source gas
T_o = Stagnation temperature of source gas at heater outlet (exit)
T_{out} = Temperature of source gas at heater outlet (exit)
T_w = Wall temperature
V = Mean gas velocity
x = Axial coordinate
x^+ = Non-dimensional distance for establishment of fully-developed flow (eqn. 5.a.1)
x_m = Location downstream of the nozzle of the Mach disk

α = Thermal diffusivity
β = coefficient of thermal expansion (= 1/T for ideal gas)
γ = ratio of specific heats
θ_v = Characteristic temperature for vibrational mode excitement of a specific gas
ρ = Density
ν = Kinematic viscosity
π = Ratio of circle's circumference to its diameter
σ = Boltzmann's constant = 5.669×10^{-8} W/m^{2}K^4 or Stress
Ω = Resistance (electrical)
τ = Shear stress
μ = Viscosity
μ_o = Viscosity function for air given by equation (3.b.3)

DIMENSIONS

A	= Amp
°C	= Degrees Celsius
cal	= Calorie
cc	= Cubic centimeter
°F	= Degrees Fahrenheit
g	= Gram
in	= Inch
J	= Joule
K	= Degrees Kelvin
kg	= kilogram
kgmol	= kilogram-mole
ksi	= 10^3 pounds per square inch
m	= Meter
psi	= Pounds per square inch
s	= Second
V	= Volt
W	= Watt
Ω	= Ohm

1. INTRODUCTION

This report studies the fluid mechanic, thermodynamic, and structural aspects of a high temperature and pressure heater, designed to provide a small mass flow rate of gas useful for diagnostic procedures in a rarefied gas wind tunnel. A high temperature is desired to excite the vibrational modes of the gas, which are typically not active at room temperature. High pressure provides a large pressure ratio (up to one million) between the heater and the rarefied tunnel, thereby making hypersonic flow velocities achievable.

The diagnostic procedures will involve methods of electron beam technology. These diagnostic methods rely largely on optical detectors, including the Fabry-Perot interferometer and a high resolution scanning monochrometer. An electron beam across the flow field excites molecules to a luminescent condition, generating radiation characteristic of the species and rotational/vibrational states. These states may be identified in several regions of the flow, and then used to find collision transition probabilities. These probabilities are inputs for DSMC (Direct Simulation - Monte Carlo) of rarefied gas flows.

The utility of the stagnation heater is not limited to electron beam diagnostic applications, since the flows will also lend themselves to laser diagnostic techniques.

This report will first develop the overall heater design considerations and requirements (Section 2), to clarify the conditions the heater must achieve, and what its environment will be. Thermal and fiscal considerations will be used to define tentatively the materials to be used in the heater. The basic form of the heater is a short cylinder containing heated argon, surrounding a thin ceramic tube through which the source gas will flow.

After pausing to review the relevant properties of the materials to be used (Section 3), which include two ceramics (zirconia and alumina) and two metals (steel and tantalum), the fluid mechanic conditions in the heater are found (Section 4), including the source gas velocity and Reynolds number. Because of the low mass flow rate requirements, laminar flow will be shown to exist inside the heater.

Given these conditions, and an estimate of the heater design, the axial and radial thermal profiles can be calculated (Section 5). The axial profile will be shown to be constant (in the core of the heater), and the radial profile is estimated by simultaneously accounting for 1-D radiative and conductive heat transfer. The thermal profiles are checked to insure nothing in the heater will melt or yield under worst-case conditions. Heat transfer losses due to end effects will also be included to arrive at the total power requirements of the heater, 2700 Watts.

Knowing the thermal state of the heater, the structural and mechanical design are analyzed (Section 6). The primary problem is to insure integrity of the pressure vessel, which is a special challenge due to the ceramic-to-metal joints, and the combination of high temperature and high pressure. Then the electrical aspects of the heater are discussed (Section 7) and tested experimentally (Section 8). The heat source will be a tantalum wire with DC current flowing through it. Finally, all of this information is combined to generate a preliminary design for the heater (Section 9), and describe the design details that need to be done to complete the heater.

Finally, Section 10 contains the references which made all of the other Sections possible.

It is important to realize that the design process was an iterative one, and that only the final results are presented here. Mention will be made throughout the report of several false starts and incorrect guesses that preceded the design in Section 9. Briefly, the iteration process consisted of:

Step 1. Propose a design.

Step 2. Conduct heat transfer and structural analyses. See if thermal constraints of the materials are met, and if the materials are strong enough to handle the stresses generated.

Step 3. If either 'if' fails, revise design and return to Step 1.

Step 4. If the heat transfer and structural designs are accceptable, go on to other design aspects, such as electrical design, seals, and so on. If these cause major changes to the design, return to Step 1. If not, the preliminary design is done.

This process, used with the analysis methods presented in Section 4 through 7, the data in Section 3, and the insight from the experiment in Section 8, led to the preliminary design presented in Section 9.

2. DESIGN CONSIDERATIONS

In order to form the basic design of the heater, the problem's characteristics need to be defined.

Design Output Temperature: The heater should have a high enough outlet temperature to excite some of the vibrational levels of atmospheric gases (Nitrogen, Air, Nitric Oxide, etc.). A temperature of about 2000 K can have a pronounced effect on the vibrational levels of these gases, enough to be more than adequate for initial measurements. (This effect is quantified in Section 3.b. by the change of heat capacity of the gases due to excitation of their vibrational modes.)

Source Gases to Consider: Source gases of interest are:

1. Air and its primary constituents (N_2, O_2, *argon*).
2. Nitric oxide (NO), because its vibrational states are excited at lower temperatures than pure nitrogen, and it is safer to experiment with than pure oxygen.
3. Mixtures of Helium and Oxygen. Helium is a very low molecular weight, noble gas, and helps to accelerate the oxygen to high velocities without creating a safety hazard.

These source gases will provide a wide variety of conditions in the wind tunnel for scientific analysis of the vibrational modes of gases, and will serve in hypersonic flows to meet other experimental requirements.

Ambient Pressure Environment: Because the wind tunnel is typically at very low pressure (e.g. 200 μm of Hg), only a very low mass flow rate of source gas is allowable. In the Berkeley rarefied gas wind tunnel, the tunnel pressure and mass flow rate are inversely proportional to each other, such that at one Torr pressure, the mass flow rate is one gram per second.

Output Mass Flow Rate: At a test section pressure of 200 microns of mercury, the mass flow rate for the tunnel is 0.2 g/s. This is at the high end of useful pressures in the tunnel for these experiments, since the electron beam can only penetrate through gases at pressures of a few hundred microns of mercury. In light of probable experimental models to be used in the tunnel, operating flow rates will be 0.1 to 0.3 g/s.

Overall Size of the Heater and Interfaces with the Tunnel: The physical size of the interior of the wind tunnel requires that the heater be no more than 23 inches long, and 10 inches in diameter. Because existing instrumentation is fixed in place, the heater must be movable inside the tunnel to allow measurement of various parts of the flow. The heater will be suspended in the tunnel, with hoses to supply the source gas and other necessary fluids (e.g. cooling water, argon).

Pressure in the Heater: Higher pressure inside the heater increases the maximum possible temperature rise. Hence the higher pressure, the better the heater will perform. The maximum pressure gas source readily available is at 2000 psi (136 atm), so this pressure is taken to be the maximum design operating pressure.

Heating Element: It was suggested that a wire be heated by electric current, since this is a well-established means to generate heat. In light of the high temperatures desired, the most convenient wire material is tantalum. Tungsten can also take high temperatures, but due to its brittleness must be heated to its transition temperature of 600 ^{o}F in order to be manipulated without breaking. Tantalum also resists oxidation better than tungsten.

Basic Heater Layout: The general schematic for the heater is shown in Figure 2-1 (Figures appear after Section 10, page 45). The source gas will pass through a central zirconia tube, which will be surrounded by heat shields in an inert environment (e.g. argon). The outlet of the zirconia tube will be a nozzle to achieve sonic conditions at its throat. A steel pressure vessel will enclose the zirconia tube and heat shields.

Cost: There is only modest funding available for the fabrication of this heater, so its cost is an important factor. The materials for it are expected to be around $1500, plus another $1000 for machining and assembly. It is recognized that the cost constraint will require some sacrifice of efficiency.

Materials Selection: In order to allow oxygen compounds to be the source gas, the central tube of the heater must be made of material that will not oxidize. Existing resistive heaters are made of materials such as graphite, so they can not be exposed to oxygen or oxygen compounds. Since no affordable metals can survive the harshest thermal environment, the core of the heater should be a ceramic. Of relatively common ceramics, only zirconia can be used at over 2000 K. As the temperature decreases in the heater, cheaper ceramics such as alumina can be used.

The outer shell of the heater must also serve as a pressure vessel, so some type of steel is a resonable choice. Since much machining of the pressure vessel is expected, is seems wise to avoid stainless steels, and lean toward a carbon steel.

Problem Areas: Design challenges included:

1. Sealing the pressure vessel between the steel cylinder and the endplates.
2. Achieving a sound joint between the zirconia tube and the steel pressure vessel.
3. The joint between the zirconia tube and the source gas.
4. Making the nozzle in the end of the zirconia tube.

Other areas of the design were of less concern, such as heater wire sizing, and heat transfer analysis.

3. MATERIAL PROPERTIES

3.a. Equation of State for Gases

Concern existed that the high temperatures and pressures in the heater would require the use of a complex equation of state for the source gas. The use of high pressures in the heater keeps this from being the case.

The primary source of deviation from the ideal gas equation of state is disassociation of the source gas componants. According to Ryabinin (1961), at one atmosphere the temperature required for 1% disassociation is 2600 K for O_2 and 3600 K for N_2. These temperatures increase for higher pressures. Hence at high pressure and up to 2000 K, there will not be a significant degree of disassociation of the source gas.

Ryabinin's statements confirm those by the NACA (1958), which show that O_2 and N_2 are not affected by disassociation at 2000 K and 100 atm pressure. Accordingly, the ideal gas equation of state can be used for all gases in the heater.

3.b. Other Gas Properties

From NASA (1970), the viscosity of Argon is not a function of pressure below 6000 K. The same is true of its thermal conductivity (k).

From Vincenti & Kruger (1975) the vibrational state of a gas being excited increases its heat capacity by:

$$c_{v_{vib}} = R[(\theta_v/2T)/(\sinh(\theta_v/2T)]^2$$

where: θ_v = Characteristic Temperature = 2270 K for O_2

3390 K for N_2

2740 K for NO

and the total heat capacity is given by the kinetic theory of gases as:

$$c_v = 3/2*(R) + R + c_{v_{vib}}$$

As T goes to infinity, $c_{v_{vib}}$ goes to R. At $T = \theta_v$, $c_{v_{vib}} = 0.92*R$. At T = 2000 K, $c_{v_{vib}}$ for N_2 is 0.79*R, for NO is 0.86*R, and for O_2 is 0.90*R. This is a substantial change in heat capacity, and is the basis for the claim in Section 2 under Design Output Temperature that 2000 K had a pronounced effect on the vibrational level of these gases.

From Anderson (1989) for air we have:

$$\mu_o = 1.462x10^{-5}\ T^{1/2}/(1 + 112/T) \quad g/cm\ s$$

$$k_o = 1.364\ \mu_o \quad W/cm\ K$$

From Anderson's Figure 16.3, $\mu/\mu_o = 1$ for T < 3000 K, and from Figure 16.4, $k/k_o = 1$ for P > 10 atm and T < 3400 K. The Prandtl number of air is nearly linear to 2000 K for P > 100 atm.

Some properties for air, which is taken to be a typical source gas for this analysis, are shown in Table 3-1.

3.c. Properties of Solids

The thermal and mechanical properties of zirconia, alumina, tantalum, and mild steel are summarized in Table 3-2. Notice that the thermal conductivity of zirconia is nearly 14 times lower than alumina's, making zirconia a very good insulator. One ceramics supplier claims that zirconia insulation causes a 450 ^oF temperature drop for the first inch of thickness, then 300 ^oF for each successive inch.

Some ceramics companies claim useful temperatures for very pure (99.5%) alumina over 1900 ^oC. The information presented is from Ceramic Source (1987) for the ceramics, and from CRC (1988) for the metals.

At one atmosphere pressure (14.7 psi):

Temperature (K)	ρ (kg/m3)	c_p (J/kgK)	μ (kg/m*s)	k (W/mK)
300	1.774	1006	1.8462×10^{-5}	0.02624
1150	0.3076	1170	4.57×10^{-5}	0.0757
2000	0.1762	1338	6.50×10^{-5}	0.124

At 136 atm (2000 psi):

Temperature (K)	ρ (kg/m3)	Other properties the same as at one atm.
300	160.2	
1150	41.85	
2000	23.97	

Table 3-1. Properties of Air (from Holman (1981)).

	Zirconia	Alumina	Tantalum	Mild Steel
Density (g/cc)	5.4	3.98	16.54	7.9
Thermal Expansion Coeff. (10^{-6} K^{-1})	10.9	8.1	6.5	11.5
Thermal Conductivity (W/mK)	2.1	29.	54.	53
Heat Capacity (J/kgK)	750	830	140	490
Melting Point (°C)	2600	2030	2996	1460
Maximum Use Temperature (°C)	2300	1800	N/A	N/A

Table 3-2. Properties of Selected Solids at Room Temperature.

4. SOURCE GAS FLOW CHARACTERISTICS

4.a. Source Gas Velocity and Reynolds Number in the Heater

In order to assess the heat transfer characteristics of this device, the source gas flow must be analyzed. An extreme condition of maximum pressure and maximum outlet temperature is considered here.

At the heater inlet, the source gas is at ambient temperature (300 K) and under 2000 psi pressure. Using air as a typical source gas, assume a mass flow rate of 0.0001 kg/s, the density will be 160.2 kg/m^3, and the kinematic viscosity 1.152×10^{-7} m^2/s. The flow velocity at the inlet is therefore:

$$V = 4*m / \rho*\pi*D^2$$

$$= 4*(0.0001 \text{ kg/s}) / (160.2 \text{ kg/m}^3)*(3.1416)*(0.005 \text{ m})^2$$

$$= 0.0318 \text{ m/s} = 0.104 \text{ ft/s} \qquad \text{(inlet)}$$

The local Reynolds number is:

$$Re = V*D/\nu$$

$$= 0.0318 \text{ m/s}*(0.005 \text{ m})/(1.152 \times 10^{-7} \text{ m}^2/\text{s})$$

$$= 1380 \qquad \text{(inlet)}$$

At the heater outlet, just before entry into the nozzle, the source gas is at 2000 K and 2000 psi pressure. Again using air as an example, this gives a density of 23.97 kg/m^3, and a kinematic viscosity of 2.711×10^{-6} m^2/s. For flow inside a cylindrical tube, the flow velocity is given by:

$$V = 4*m / \rho*\pi*D^2$$

$$= 4*(0.0001 \text{ kg/s}) / (23.97 \text{ kg/m}^3)*(3.1416)*(0.005 \text{ m})^2$$

$$= 0.21 \text{ m/s} = 0.69 \text{ ft/s} \qquad \text{(outlet)}$$

So the average flow velocity at the hot end of the tube is about 8 1/4 inches per second.

The Reynolds number of this flow is small:

$Re = V*D/\nu$

$= 0.21\ m/s*(.005\ m)/(2.711x10^{-6}\ m^2/s)$

$= 387$ (outlet)

Since the Reynolds number of the flow never exceeds 2000, the flow is laminar.

Many first-order calculations depend on properties of the flow through the heater evaluated at the mean fluid temperature (T_m). Note that the use of mean properties is not accurate for large changes in fluid properties over the temperature range, but is merely designed to give an estimate. Taking T_m to be 1150 K (the mean of 300 K inlet temperature and 2000 K outlet temperature), the typical source gas (air) at 2000 psi has a density of 41.85 kg/m^3 and kinematic viscosity of $1.091x10^{-6}\ m^2/s$, leading to a velocity of:

$V = 4*(0.0001\ kg/s) / (41.85\ kg/m^3)*(3.1416)*(0.005\ m)^2$

$= 0.122\ m/s = 0.399\ ft/s$ (mean temp.)

The Reynolds number of the mean temperature flow is:

$Re = V*D/\nu$

$= 0.122\ m/s*(.005\ m)/(1.091x10^{-6}\ m^2/s)$

$= 559$ (mean temp.)

4.b. Heater Exit Conditions and Nozzle Diameter

As the source gas flows through the heater, it accelerates slowly from about 30 mm/s to 200 mm/s. At the end of the heater, it is forced in a very short (< 1 mm) distance to sonic velocity, then expands out a nozzle into the wind tunnel. The conditions that determine the diameter of the nozzle needed for sonic conditions are:

1. Gas Type. Specifically, the gas's molecular weight (M) and ratio of specific heats (γ).
2. The stagnation temperature of the gas, T_o.
3. The mass flow rate out of the heater, *m*.

4. The pressure inside the heater, P_o.

Assuming the source gas is accelerated isentropically, the relationship among the five variables just described is given by Ashkenas & Sherman (1964) as:

$$D = [0.75*(R*T_0)^{1/4}*((\gamma+1)/2)^{\{0.25*(\gamma+1)/(\gamma-1)\}}*(m/P_o)^{1/2}] / [0.67*\gamma]$$

where: D is the sonic diameter

R is the specific gas constant = R_u/M

R_u = Universal gas constant = 8315 J/(kgmol*K)

The axial location of the Mach disk, x_m, depends on the pressure in the wind tunnel, P_1:

$$x_m/D = 0.67*(P_o/P_1)^{1/2}$$

For typical conditions of air (M = 28.97, γ = 1.4) at P_o = 2000 psi, P_1 = 200 mm of Hg, m = 0.0001 kg/s, and T_o = 2000 K, this yields:

D = 0.078 mm = 0.0031"

x_m = 0.0375 m

An extensive parametric study of minimum throat diameter D as a function of all of these variables appears in Appendix 2. The parameters covered include:

1. Source gases are N2, Air, Nitric Oxide (NO), 80% Helium (He) with 20% Oxygen (O_2), 95% Helium with 5% Oxygen, and pure Oxygen.
2. Each gas has four graphs, for mass flow rates of 0.05 g/s, 0.10 g/s, 0.50 g/s, and 1.0 g/s.
3. Each plot has five curves, for pressures of 100, 500, 1000, 1500, and 2000 psi.
4. Each curve has five data points, for stagnation temperatures from 1000 K to 2000 K.

5. HEAT TRANSFER CONSIDERATIONS

5.a. Convection inside the heater tube

The flow inside the heater was established to be laminar in Section 4. The heating filament consumes a constant amount of power per unit length, so the flow of the source gas has a constant heat flux boundary condition. From Kays & Crawford (1980), the criterion for fully developed flow is:

$$x^+ = 2.0*x / D*Re*Pr > 0.1$$

$$x > 0.05*D*Re*Pr$$

Using the properties at the mean fluid temperature, this yields fully-developed flow for:

$$x \geq 0.05*(0.005 \text{ m})*(559)*(.70) = 0.098 \text{ m} = 98 \text{ mm}$$

Since the heater tube is of the order 400 mm long, the flow can not be safely considered fully developed everywhere.

5.b. Energy Requirement of Source Gas for Given Outlet Temperature

Consider the heater now as a black box. The rate at which energy (in the form of the source gas) enters the box is $m*c_p*T_{in}$. The energy of the source gas leaves the heater at a rate of $m*c_p*T_{out}$. Hence the power requirement for the source gas is:

$$P_{source\ gas} = m*c_p*T_{out} - m*c_p*T_{in}$$

Allowing the heat capacity of the gas to vary with temperature, this becomes:

$$P_{source\ gas} = m[c_p*T_{out} - c_p*T_{in}]$$

Assuming air is the source gas, for the conditions of:

$T_{in} = 300$ K

$T_{out} = 2000$ K

$m = 0.0001$ kg/s

and using $c_{p_{air}} = 1000$ J/kgK at the inlet, 1240 J/kgK at the outlet, this yields the design 'requirement' of:

$P_{source\ gas} = m[(c_p)T_{out} - (c_p)T_{in}]$

$P_{source\ gas} = 0.0001$ kg/s[(1240 J/kgK)2000 K - (1000 J/kgK)300 K]

$P_{source\ gas} = 218$ W.

Hence no matter what losses occur elsewhere in or from the heater, for this worst case example the source gas needs to receive 218 W of power in order to reach the design temperature.

5.c. Axial Conduction in the Heater Tube

According to Kays & Crawford (1980), axial conduction in a pipe flow is negligible if the Peclet number of the flow is greater than 100. Here, using the lowest Reynolds number in the flow,

$$Pe = Re*Pr = 387*0.70 > 100$$

So axial conduction is negligible.

5.d. Constant heat flux analysis

It was established in Section 2 that the heat source for this heater was to be some sort of filament with an electrical current running through it. Assuming a constant cross-section filament, wound uniformly along the length of the heater, the power consumed by it per unit length will be constant. Hence it is logical to analyze the heater as a constant heat flux supplying the zirconia tube.

Assuming for the moment that the flow of the source gas in the heater is fully developed everywhere, the expected temperature profile along the length of the heater is linear, and the temperature difference between the inside wall of the zirconia tube (T_w) and the mean source gas temperature (T_m) is a constant. The required temperature gradient along the heater is:

$$d(T_m)/dx = (T_{out} - T_{in})/L$$

to get $$d(T_m)/dx = (2000 - 300\ K)/0.4\ m = 4250\ K/m$$

And the difference between local wall and mean temperatures is:

$$T_w - T_m = 4.0*q / [D*\rho*c_p*V*A]$$

where: q = Total heat flux to source gas, from Section 5.b (W)

D = Zirconia tube inside diameter (0.005 m)

ρ = source gas mean density (kg/m^3)

c_p = source gas mean heat capacity (J/kg)

V = source gas mean velocity (m/s)

A = tube inner surface area (m^2) = π*D*L

to get:

$$T_w - T_m = 4.0*(218\ W) / [(0.005m)*(41.85\ kg/m^3)*(1170\ J/kgK)*0.122\ m/s)*(6.28x10^{-3}\ m^2)] = 4650\ K$$

Clearly this is not achievable, since the source gas mean temperature, T_m, needs to reach 2000 K. Since the source gas mean velocity is inversely proportional to the tube diameter squared, $T_w - T_m$ is independant of the tube diameter, and a substantial increase in the heater length would be needed to bring the wall temperature down to an acceptable level. This redesign gives opportunity for reconsideration of whether this analysis is appropriate. Since this heater is to operate as a steady-state device, the strong axial temperature gradient (4250 K/m) will drive heat flow toward the cooler end of the device. It was already shown that this gradient is not important in the source gas, but the rest of the device has a much larger area for heat flow. Therefore it was speculated that, over time, this heater would become isothermal axially. Then, except for end effects, the temperature in the heater would only be a function of radius, and the appropriate analysis for heat flux to the source gas is that of a constant temperature boundary condition.

This speculation was confirmed by conversation with engineers at heater companies (see Appendix 1). They indicated that, even with constant heat flux per unit length powering the heater, the net effect was to generate a constant temperature heat source. The internal temperature profile of the source gas confirms this; they claim the source gas nearly reaches the output temperature immediately, then rises very slowly along the rest of the heater. This profile is characteristic of a constant temperature boundary condition, where the source gas temperature rises exponentially, then asymptotically approaches the wall temperature.

5.e. Constant Temperature Analysis

Neglecting for the time being that the heat transfer characteristics are not fully developed, consider the heat transfer to the source gas due to a constant wall temperature, T_w. The heat flux at any point along the heater is given by

$$q(x) = Nu*k/D *(T_w - T_{in})\exp(-\alpha*Nu*x/[r^2V])$$

where $r = D/2$ = zirconia tube inner radius

x = axial coordinate

Recall for fully developed flow, the Nusselt number is a constant, 3.66. Integrate the last equation over the effective heater tube length, L, assuming constant properties, to get

$$q/L = r^2*V*k/(\alpha*D)*(T_w - T_{in})*[1 - \exp(-\alpha*Nu*L/(r^2*V))]$$

or, in more consistent variables

$$q/L = D*V*k/(4*\alpha)*(T_w - T_{in})*[1 - \exp(-4*\alpha*Nu*L/(D^2*V))]$$

Using gas properties for air evaluated at the mean temperature, the exponent is:

$$-4*(1.546\times10^{-6}\ m^2/s)*(3.66)*L / [(0.005\ m)^2*(0.122\ m/s) = -7.42*L$$

and the other constant is

$$D*V*k/(4*\alpha) = (0.005\ m)*(0.122\ m/s)*(0.0757\ W/mK) / [4*(1.546\times10^{-6}\ m^2/s)]$$

$$= 7.467\ W/mK$$

so the equation becomes

$$q/L = (7.467\ W/mK)*(T_w - T_{in})*[1 - \exp(-7.42*L)]$$

Let $T_w - T_{in} = 2000$ K, $q = 218$ W to get

$$L = 0.0146\ m / [1 - \exp(-7.42*L)]$$

Iterate to get the result L = 0.048 m. Hence for a constant wall temperature boundary condition, the source gas will approach the wall temperature only 2 inches inside the heater. Again, this does not allow for the flow being thermally developing.

5.f. Free Convection Around Outside of Heater

In order to assess the thermal losses from the heater, it is important to consider all ways heat can be dissipated. In this Section, we evaluate whether free convection is a significant source of heat loss from the heater.

Consider the ambient gas in the wind tunnel to be at a temperature of 300 K, and a pressure of 0.2 Torr. The free convection flow characteristics are determined by the product of the Graetz and Prandtl numbers. Assume for now that outer surface of heater is at 450 K.

$$GrPr = g*\beta*\Delta T*D^3*Pr/\nu^2$$

where D = diameter of the heater = 0.1 m

$\beta = 1/T_f = 2.0/(300+450) = 1/375$ K

$\Delta T = 450 - 300$ K = 150 K

$\nu = \mu/\rho = (1.846\text{x}10^{-5}$ kg/m s) / $(3.01\text{x}10^{-4}$ kg/m$^3) = 0.0596$ m^2/s

to get

$$GrPr = (9.81 \text{ m/s2})/(375 \text{ K})*(150 \text{ K})*(0.1 \text{ m})^3*(0.708)/(0.0596 \text{ m}^2/\text{s})^2$$

$$GrPr = 0.78$$

This indicates laminar flow, as could be expected. Holman (1981) gives the resulting heat flow from a cylinder as:

$$Nu_D = h*D/k = 0.36 + 0.518*(GrPr)^{0.25} / [1 + (0.559/Pr)^{9/16}]^{4/9}$$

$$Nu_D = 0.728$$

$$h = 0.728*k/D = 0.728*(0.02624 \text{ W/mK})/(0.1 \text{ m}) = 0.191 \text{ W/m}^2\text{K}$$

$$q = h*A*\Delta T$$

where A = outer surface area of heater = $\pi*D*L = 0.134$ m^2

to get $q = (0.191 \text{ W/m}^2\text{K})*(0.134 \text{ m}^2)*(150 \text{ K}) = 3.84$ W

Hence free convection is not a significant heat transfer mode from the heater.

5.g. Heat Transfer Resistances

Because the heater will become axially isothermal (except for end effects), the temperature profile will become only a radial function. Knowing how much power needs to be delivered to the source gas, and the dimension and properties of the heater, we can uniquely determine the power input required. This will provide all data needed to find the temperature profile in the heater.

Assume a total of three heat shields will be used outside of the heating element (wire), and that only the zirconia tube is inside of the wire. Define nodes to represent key radial locations:

Node	Diameter (mm)	Significance
0	0	Centerline
1	5	Inner surface of zirconia tube
2	8	Outer surface of zirconia tube
3	9.25	Location of heating element (wire)
4	25	Inner surface of alumina tube
5	30	Outer surface of alumina tube
6	60	Inner surface of 2nd heat shield
7	70	Outer surface of 2nd heat shield
8	80	Inner surface of 3rd heat shield
9	90	Outer surface of 3rd heat shield
10	139.7	Inner surface of pressure vessel
11	203.2	Outer surface of pressure vessel
12	∞	Infinity

The second and third heat shields shown above are based on alumina tubes available from Johnson-Matthey. They are quite expensive, about $850 for the two of them in 400 mm lengths.

A material called Mullite from Coors Ceramics Co. may be a good option for low-cost heat shields. Thin-walled cast tubes, in diameters from 1.5" to 5.0" cost from $28 to $150 in a 16" length. Mullite is rated to tolerate 1700 °C under no-load conditions. Various grades of alumina can also be used for heat shields, but many are more expensive than Mullite.

Our heat transfer analysis follows the electrical analogy, with a heat flow input at node 3 of Q Watts. The total Q input splits into two directions: Q1, which flows inward radially, and eventually heats the source gas, and Q2, which flows outward and is dissipated. From Section 5.b., a Q1 of 218 W is a boundary condition on this problem.

From Siegel & Howell (1981), this situation allows the equivalent resistances due to conduction and radiation to be calculated separately, then added like resistors in parallel for the total thermal resistance.

The equivalent resistance for conduction between two cylinders is given by Kreith (1973) as:

$$R_{cond} = \ln(r_o/r_i) / [2*\pi*L*k]$$

where r_o = outer cylinder radius

r_i = inner cylinder radius

To apply this here, define R_{c_i} as the conduction resistance between nodes i and i+1, which is:

$$R_{c_i} = \ln(D_{i+1}/D_i) / [2*\pi*L*k_i]$$

where k_i = conductivity of material between nodes i and i+1.

Then, for conduction alone, the heat flux between any two nodes is given by:

$$q'' = q/A = (T_i - T_{i+1})/R_{c_i}$$

where q is defined positive flowing from node i to node i+1.

The radiation resistance between any two nodes is based on the grey body assumption. All nodes (surfaces) are assumed to have an emissivity (ε) that describes the net absorption and reflection of radiation over all frequencies and temperatures. The materials' emissivity is averaged to account for changes over frequency; changes of emissivity with temperature; are accounted for by selecting a mean emissivity based on a typical temperature seen by the material.

The radiation resistance between nodes i and i+1 is given by;

$$R_{r_i} = (1-\varepsilon_i)/\varepsilon_i + 1/(F_{i\,i+1}*A_i) + (1-\varepsilon_{i+1})/\varepsilon_{i+1}$$

The heat flow due to radiation is

$$q = \sigma*(T_i^4 - T_{i+1}^4)/R_{r_i}$$

where σ is the universal constant 5.669×10^{-8} W/m^{2}K^4

This is also expressed as

$$q = (E_{b_i} - E_{b_{i+1}})/R_{r_i}$$

where $E_{b_i} = \sigma*T_i^4$.

Note that R_{c_i} and R_{r_i} have very different dimensions; K/W for the former, and m^{-2} for the latter.

The radiation heat transfer increases with the fourth power of temperature, so for a device with an output temperature of 2000 K, it is expected that radiation heat transfer will dominate, and conduction will play a relatively small role.

5.h. Temperature Profile Algorithm and Results

1. Separately sum the conduction and radiation resistances for the inner problem (from the wire inward) and the outer problem (from the wire outward). This will yield: R_{c_I} (total conduction resistance for the inner problem), R_{c_O} (total conduction resistance for the outer problem), R_{r_I} (total radiation resistance, inner problem), R_{r_O} (total radiation resistance, outer problem).

2. Use the Q1 requirement from Section 5.b. to determine the wire node temperature, T_3, assuming only radiation heat transfer. Realize that this temperature is not the actual wire's temperature, since the wire is not a cylindrical sheet (as it is being modeled). The temperature T_3 is an artifact of the one-dimensional modeling used here.

3. Once T_3 is known, find Q2 using radiation only.

4. Find equivalent conduction resistances for the inner and outer problems.

$$R_I = (T_3 - T_0)/Q1 \qquad\qquad R_O = (T_3 - T_{12})/Q2$$

5. Sum results of step 4 with original conduction resistances like parallel resistors to get the total equivalent resistance.

6. Use Q1 requirement again to get new T_3.

7. Find Q2 using T_3 and results of step 5.

8. Knowing Q1 and Q2, can repeat steps 4 and 5 for intermediate points to get local total equivalent resistances, and hence find their temperatures.

This algorithm, and calculation of the resistances that preceded it, have been put on a spreadsheet (Figure 5-1). This method is reported by Siegel & Howell (1981) to be accurate for finding heat fluxes, but less reliable for temperatures. Accordingly, consider temperatures to be approximate only.

Notice on Figure 5-1 that the conduction resistance for all solid bodies is negligible compared to that for the argon gaps. For most cases, all conduction effects will only change the temperature profile slightly (under 50 K).

5.i. Total Power Requirements of Heater

In order to get the total power requirements for the heater, radiation losses from the ends of the heater need to be accounted for. The one-dimensional analysis in the previous Section yields the power requirement Q1 + Q2 = 1350 W. Add to this the conduction/radiation losses from the ends.

An estimate of the losses from the ends of the heater can be found from considering the following 1-D analysis. Let the end plates each be modeled as an infinite plate of area A. One side of the plate has a known temperature, To, given by the local temperature in the profile just generated in the last Section. Going through the end plate, an unknown heat flux Q" passes through a known conduction resistance Rc, which may consist of the sum of two or more resistances from various materials. After the unknown Q" reaches the other side, it is at the outer surface temperature, T1. Between T1 and T∞ there is a radiation resistance Rr. See Figure 5-2. Equating the heat fluxes of conduction and radiation yields a unique value for Q". Similarly, find Q" at other points along each plate, then integrate them over the local area of the plate to get the total Q for one end plate. Multiply the result by two to get the total heat loss due to end effects.

For one-dimensional conduction in Cartesian coordinates, the heat flux is given by

$q'' = q/A = k/t*\Delta T$

where k is the thermal conductivity

t is the plate thickness

ΔT is the temperature difference across the plate

For this case, allowing for multiple materials between To and T1, it becomes

$q'' = \Sigma(k/t)*\Delta T$

where (k/t) is summed for each material (e.g. zirconia and steel).

Let $S = \Sigma(k/t)$, so $q'' = S*\Delta T$.

For one-dimensional radiation in Cartesian coordinates between two 'grey' objects, the resistance is

$$Rr = (1-\varepsilon_1)/A_1*\varepsilon_1 + 1/(A_1*F_{12}) + (1-\varepsilon_2)/A_2*\varepsilon_2$$

Model the heater radiating into the wind tunnel as a flat plate radiating into an infinite area. Then A_2 goes to infinity, and the last term is zero. Furthermore, F_{12} is unity, since all energy leaving the plate reaches the wind tunnel. The resistance simplifies to

$$Rr = 1/\varepsilon_1*A_1$$

In the context of radiation heat transfer, recall that the resistance is used in the formula

$q = (Eb1-Eboo)/Rr$

where $Ebi = \sigma*Ti**4$.

To solve for T1, let q(radiation) = q(conduction). This gives a cubic equation, solved iteratively using

$$T1 = To + \varepsilon_1 * \sigma / S * (Too**4 - T1**4)$$

Let $K = \varepsilon_1 * \sigma / S$ to get

$$T1 = To + K*(Too**4 - T1**4).$$

This usually converges rapidly, as seen in Figure 5-3. Once T1 is known, the local q" can be found, and multiplied by the area represented by the original heater temperature, To. The sum of all of these q's gives an estimate for the total heat loss from one end of the heater. Added to a similar calculation for the other end of the heater gives the total heat loss due to end effects, 900 W.

The power requirement of the heater is estimated to be 1350 W + 900 W = 2250 W. Add 20% to this as margin for error, to get the **total power requirement of 2700 W.**

6. MECHANICAL DESIGN

6.a. Mechanical Design Goals

The shape of the heater is basically cylindrical, and must perform several tasks.

1. It must contain the noble gas, argon, which surrounds the tantalum wire and the heat shields.
2. It must keep the source gas and the argon separate.
3. It must allow for standard fittings to supply the source gas(es) and argon.
4. It must have provision for cooling the joints in case it is needed.
5. It must be inexpensive.
6. The device must be easy to disassemble for changing the heating wire, heat shields, *etc.*

6.b. Pressure Vessel Material and Properties

The basic cylinder itself must be a pressure vessel, that will retain strength at 1000 ^{o}F, and safely contain 2000 psi. The high temperature precludes the use of heat-treated materials, since they might lose their temper. Of common (and inexpensive) materials, either low-grade steel or aluminum would seem suitable. To help insure the vessel is not weakened by the thermal environment, seems wise to rule out the use of aluminum. This leaves low-grade steel as the prime candidate for the pressure vessel material.

To insure compatability as the temperature rises, it is recommended that the end plates be of the same material as the pressure vessel cylinder.

A reasonable estimate of the yield strength of mild steel is 35,000 psi. This is the minimum strength to meet ASTM A 106 (1988), Grade B, which applies to seamless carbon steel for high-temperature service.

6.c. Pressure Vessel Design

Having defined the pressure vessel material and basic configuration, the interfaces between the cylinder and the end plates are now considered. Several options exist for connecting the three major pieces of the pressure vessel. Keep in mind that the axial load that this joint has to safely hold is about 2000 psi*π*(3 in)^2 = 57,000 lbs.

1. Flanges can be welded around the ends of the cylinder, and the endplates made oversized, so bolts can go through the endplates and the flange (Figure 6-1).

2. The endplates can be welded directly to the cylinder (Figure 6-2).

3. The endplates can be made like large nuts. Thread the outside of the cylinder, and screw the endplates onto the cylinder (Figure 6-3).

4. Make the cylinder very thick-walled, and bolt the endplates onto the cylinder walls (Figure 6-4).

The first two options have major problems for this design. A welded flange joint six inches in diameter to withstand a nearly thirty ton load has to be carefully designed, very well made, and welded from both sides of the joint. This discourages using the first option. The weld isn't removable, so the second option doesn't meet the sixth mechanical design requirement (Section 6.a.).

The third option is possible, but would place high shear loads on the zirconia disk during assembly. For this reason it seems wise to avoid this option.

This leaves the fourth option. It has the drawback of requiring a thick wall for the cylinder, but meets all of the design requirements. Since weight of the heater is not critical, the fourth option is selected.

6.d. Bolt Design

The bolts to hold the endplates in place will be mild steel. To be safe, assume they have a yield strength of only 30,000 psi. Assume for now that 1/2" diameter bolts will be used, and see if this yields a reasonable number of bolts. Use a stress concentration factor of

1.5, and a safety factor of 3.0, to get a usable stress level of 6,670 psi. For a load of 57,000 lbs, this means the total cross-sectional area of bolts must be 57,000 lb/6,670 psi = 8.55 in^2. Each bolt has an area of π*(1/4")^2 = 0.196 in^2, so the number of bolts needed is 8.55/0.196 = 44 bolts. The diameter of the bolt pattern is the diameter of the zirconia disk (6.0"), plus two bolt diameters (2*0.5"). This allows an arc of length π*(7")/44 = 0.50" per bolt - not acceptable for the heads of 1/2" bolts! Either try larger bolts or stagger the bolt pattern so there are two bolt pattern radii. The minimum arc length acceptable is the bolt head maximum diameter (from Marks' (1978)) plus an arbitrary 1/16" clearance. The bolt head maximum diameter is that for an internal cap screw head (also from Marks'). The criterion for best design is the one that allows the least wall thickness to hold the given load. For cases where the minimum arc length is not sufficient for one row of bolts, the wall thickness is calculated as follows:

Let d = diameter of each bolt

A = cross-sectional area of bolts (in^2) = π*d^2/4

n = number of bolts needed = 8.55"^{2}/A

r1 = inner bolt pattern radius = 3.0" + d

r2 = outer bolt pattern radius = r1 + z

x = minimum arc length between bolts = max. bolt head dia. + 1/16" clearance

y = arc length available between bolts = 2*π*r1/n

z = difference in bolt pattern radii = r2 - r1 = (x^2 - y^2)**0.5

t = wall thickness = z + 2*d

The procedure to find the wall thickness is:

1. For given d, look up x, find A, r1and y.
2. If $x \leq y$, there is only one bolt pattern diameter, and z=0.

   If $x > y$, there are two bolt pattern diameters, and z = (x^2 - y^2)**0.5.
3. Find t = z + 2*d.

This procedure was followed for bolt diameters of 1/2" through 7/8" diameter. The results are shown in Table 6-1. *On this basis it is recommended to use twenty (20) 3/4" bolts to secure the endplates of the heater.*

Bolt Dia., d (")	1/2	5/8	**3/4**	7/8
Bolt Area, A ("^{2})	0.196	0.307	0.442	0.601
Number of Bolts Req'd, n	44	28	**20**	15
Inner Bolt Pattern Radius, r1 (")	3.5	3.625	3.75	3.875
Min. Arc Length, x (")	13/16	15/16	17/16	19/16
Arc Length Available, y (")	0.500	0.813	1.178	1.623
Bolt Pattern Radii Difference, z (")	0.641	0.467	0	0
Wall Thickness, t (")	1.641	1.717	**1.5**	1.75

Table 6-1. Selection of bolt size to minimize pressure vessel wall thickness.

For maximum strength, it is recommended to use internal cap screws (e.g. Allen head bolts), as previously noted. Use of flat washers will help prevent added stresses on the endplate. There is not adequate clearance between bolts for full size washers, which are 2" in diameter for the size bolts recommended, so they wil have to be trimmed to 9/8" diameter to fit.

To keep the threads from being pulled off of the bolts, the shear strength of the bolts must not be exceeded. Using the rule of thumb that the maximum shear strength is one third of the tensile strength, and assume (as before) that the tensile strength is 30,000 psi, a maximum shear stress of 10,000 psi is obtained.

τ_{max} = 10,000 psi

The stress in the bolts is given by:

$\tau = 2*F / (\pi*d*h)$

where F is the force on the bolt (lbs.)

d is the bolt diameter (nominal) = 3/4"

and h is the depth of engagement of the bolt.

The bolt needs to be engaged at least 7 threads. For coarse (UNC) thread, there are 10 threads per inch, so let:

h = 3/4".

The force per bolt is 57,000 lb/20 bolts = 2850 lbs/bolt. Hence the maximum shear stress on the threads is:

$\tau = 2*F / (\pi*d*h)$

τ = 2*(2850 lbs/bolt) / [π*(0.75")*(0.75")]

τ = 3230 psi << τ_{max}

Since the actual shear stress on the threads is much less than the maximum shear stress, there is no problem with the threads holding.

6.e. Endplate Thicknesses

The endplate at the inlet side of the heater is modeled as a cylindrical disk of constant thickness with a constant force per unit area, q, on one side of it. The only concern for this part of the analysis is to make the plate thick enough to keep the maximum stress below acceptable levels.

From Roark (1989), the maximum stress under these conditions is:

$\sigma_{max} = 6*q*a^2*(3 + \nu) / [16*t^2]$

where q = load per unit area = 2000 psi

a = disk radius = 3"

ν = Poisson ratio = 1/3

t = disk thickness

Assuming the endplate to be of the same material as the pressure vessel cylinder, the yield strength is 35,000 psi. Use a stress concentration factor of 1.5, and a safety factor of 3, the usable maximum stress is 7770 psi. Solve for the endplate thickness:

$$t^2 = 6*q*a^2*(3 + \nu) / [16*\sigma_{max}]$$

$$t^2 = 6*(2000\text{ psi})*(3")^2*(3 + 1/3) / [16*7770\text{ psi}]$$

$$t^2 = 2.90\text{ in}^2$$

$$t = 1.70\text{ inches}$$

Rounding this up to a common size, *the endplate for the inlet end should be 1.75 inches thick.*

For the outlet end of the heater, the zirconia disk should be unsupported as far (in radius) as possible, to avoid exposing the endplate to excessive temperature. The zirconia disk is one inch thick (25.4 mm), and according to Ceramic Source (1987) has a strength of 143 MPa. (Apologies for the switch to SI units.) For lack of data to the contrary, assume ν = 1/3. Assume a stress concentration factor of 1.0, and a safety factor of 3.0. The maximum usable stress is then 47.7 MPa = 47.7 N/mm^2. The load per unit area, q, becomes 13.74 N/mm^2. The maximum radius the disk can remain unsupported is:

$$a^2 = 16*\sigma_{max}*t^2 / [6*q*(3 + \nu)]$$

$$a^2 = 16*(47.7\text{ N/mm}^2)*(25.4\text{ mm})^2 / [6*(13.74\text{ N/mm}^2)*(3.3333)]$$

$$a^2 = 1792\text{ mm}^2$$

$$a = 42.3\text{ mm}$$

Hence the diameter of the hole in the outlet endplate can be no more than 3.333".

The outlet endplate bears the same total load as the inlet endplate, but has the load distributed closer to the supports (i.e. the bolts). Hence the maximum moment generated by the load is less, so the outlet endplate could be thinner than the inlet endplate. For ease of manufacture, however, they will be left the same thickness, 1.75".

6.f. Seals

Ceramic-to-Ceramic

The primary concern in sealing the heater is between the outlet between the zirconia tube and the steel pressure vessel. The original concept for the seal was a several-fold mechanical ground taper joint (Figure 6-5). The first joint would be from the zirconia tube to a zirconia disk, then another joint from the zirconia disk to, for example, a high-purity (99.5%) alumina disk, then to a low-purity (85%) alumina disk. Finally, the last alumina disk would be bonded to the steel pressure vessel. The sequence of materials was to correspond to the maximum temperature they would see. Several ceramics manufacturers expressed concern over the amount of leakage the joints would have, however, so the seal was simplified to a single ceramic-to-ceramic joint.

The joint consists of a 6" diameter zirconia disk, with the center ground out to a 3-5^{o} angle cone (Figure 6-6). The 0.3" diameter zirconia tube is machined at the closed end to the same angle, and left slightly oversized (Figure 6-7). The two parts are ground together with zirconia powder as the medium, then fired to help make a good seal. The zirconia disk size, 6" diameter by 1" thick, was chosen as the most suitable production-made zirconia product. It cost about $300, compared to a custom-made zirconia disk, which would cost at least $1000 each in small quantities.

An extensive and fruitless search was conducted for a cement that could help seal the mechanical ceramic joints. The closest candidate was an Aremco product, designed for zirconia-zirconia bonds (see Appendix 1). No product could meet both pressure and temperature requirements (2000 psi and 2000 K). Accordingly, it is hoped that the leakage of gases through the ceramic joint will not interfere appreciably with the desired wind tunnel conditions.

The possibility of making a custom zirconia tube with a flange at one, sealed end was also investigated. The nozzle would have been machined into the end after the part was formed. A few ceramics companies said they could do the job, but wouldn't for such a small production run (up to 5 pieces total) for financial reasons. One company bid to do it in alumina for a little over $1300 per part, provided they could increase the outside diameter of the tube to 22 mm, instead of the specified 8 mm. They gave structural reasons for requiring the design change.

Ceramic-to-Metal

There are two ceramic-to-metal joints in the heater, one from the zirconia disk to the steel pressure vessel and the outlet endplate, the other from the zirconia tube to the inlet endplate.

The former is sealed by a steel annular disk pressing the zirconia disk against an O-ring in the wall of the pressure vessel. Seals between the outer edge of the zirconia disk and the pressure vessel were ruled out because there is no way to press against the O-ring without using a relatively complicated backup rings. This left putting the seal against the inside or outside surface of the zirconia disk; using the former prevents the need for a seal between the pressure vessel and the steel disk. The design chosen is shown in Figure 6-8. More complex seals, such as those used in pressure vessels to study rock mechanics and geology, are shown in Figures 6-9 and 6-10. The latter Figure brings up the subject of backup rings, which are discussed extensively in the Parker catalog. Backup rings prevent extrusion of the O-ring at high pressure. Their use is recommended for applications using pressures higher than 1500 psi, so they should be considered for this heater. The seals in Figures 6-9 and 6-10 were not chosen because:

1) They are much more expensive to implement

2) They are designed for much higher pressures than this heater requires (ca. 10,000 psi), and 3) They would require further machining of the zirconia disk, which is good to avoid since it is the weakest part of the structure.

To prevent the annular disk from damaging the zirconia disk, a buffer material of ceramic fiber paper is recommended. Cerametek makes such a paper from alumina in thicknesses of 1/32 and 1/16" (and larger). This paper is very inexpensive, about $1 per square foot, and should help prevent local stress concentrations in the zirconia disk. The only problem with its use is that the crushing of the paper will affect pre-compression of the O-rings. It will have to be determined experimentally how much pre-compression is needed to achieve a good seal. NOTE: the ceramic paper can not be reused, so a new paper gasket will have to be used every time the outlet endplate is installed.

The latter joint is handled with a two-piece fitting from Conax (Model PG4-312-B). A stainless steel fitting is screwed into a hole through the inlet endplate. The zirconia tube slides through the middle of the fitting. A Teflon seal is slipped over the end of the zirconia tube, and the other piece of the fitting is screwed on. The second piece of the fitting has standard gas hose threads on it, which connect to the source gas. Teflon is used for the seal because it can be easily scraped off to allow removal of the zirconia tube.
In use, the argon is prevented from escaping by threads on the first part of the fitting and the Teflon seal. Likewise, the source gas is contained by the hose threads and the Teflon seal. This arrangement has the added advantage that the Teflon seal does not see a very big pressure difference, since in operation the argon and source gas are at nearly the same pressure (the argon slightly higher to prevent its contamination and oxidation of the tantalum wire).

The Teflon seal can only withstand 500 ^{o}F, so the inlet endplate of the heater may require cooling, such as a copper water line, in order to keep the Teflon intact. The need for this (or not) will have to be determined experimentally. The inlet end of the heater can also be sized to allow for a couple inches of zirconia insulation before the heating element starts. This will be taken up further in Section 9.

Metal-to-Metal

The only metal-to-metal seal, excluding threaded surfaces, is between the pressure vessel and the inlet endplate. The same bolt pattern derived in Section 6.d is used here, with a Viton O-ring at a diameter of around 5 3/4".

7. ELECTRICAL DESIGN

Using the result of Section 5.i., and allowing an extra 20% for unforeseen losses, the heater needs 2700 Watts of electrical power input. As discussed in Section 2, the means to introduce this power to the heater is Direct Current through a tantalum wire.

To maintain adequate flexibility, the wire should not be more than about 0.060" in diameter. Allowing 10 mm spacing between revolutions of the doubled wire, the usable zirconia tube length of 150 mm has room for no more than 15 wrappings of wire. These constraints help form the design of the heating element.

7.a. Resistivity as a Function of Temperature

Tantalum's electrical resistivity changes rapidly with temperature, as shown in Figure 7-1 (courtesy of Fansteel Metals). During the experiment described in Section 8, this resulted in the change of voltage in the power supply over time with a fixed input current. When the current was raised for a given voltage, the wire heated up, its resistivity (and hence resistance) went up, and so a higher voltage was required to maintain the given current.

For design purposes of the heater, the wire is expected to be essentially isothermal. Accordingly, its resistivity can be assumed constant, equal to the value for the output temperature.

$$\rho = 80\text{x}10^{-6}\ \Omega\text{*cm}$$

The resistance of the wire is given by:

$$R = \rho * l\ /\ (\pi * D^2/4) = 4 * \rho * l\ /\ (\pi * D^2)$$

The voltage, current, and power across, through, and consumed by the wire are related by:

$$I = V/R$$

$$P = I^2 * R$$

Set the power requirement at 2700 W, and the wire diameter at 0.050", and solve for the wire length.

$$P = I^2 * R = 4*\rho*l*I^2 / (\pi*D^2)$$

$$l*I^2 = P*\pi*D^2 / (4*\rho) = (2700\ W)*\pi*(0.127\ cm)^2 / (4*80*10^{-6}\ \Omega*cm)$$

$$l*I^2 = 427{,}534\ A^2cm$$

At 28 Amps (the highest value achieved during the test described in Section 8), this means a wire length of 5.45 m is required. Clearly a higher current is called for, since it would be very difficult to get that much wire in the heater without shorting itself. If 40 Amps were obtained, the wire length would have to be 2.67 m. This is much more realistic.

The resistivity of zirconia drops at high temperatures, so it was a concern that the zirconia tube would become a significant electrical resistance. The resistivity function is shown in Figure 7-2, courtesy of Zircar Products. Using similar formulas to those above, treating the zirconia tube as a resistor at 2000 K, it is determined that the zirconia has an electrical resistance 1300 times greater than the tantalum wire. Accordingly, very little current will flow through the zirconia, and its electrical effect on the heater can be neglected.

8. DESIGN VALIDATION TEST

In order to see first-hand how tantalum wire and a zirconia tube interact, a brief experiment was conducted in Room 245 of Hesse Hall (UC Berkeley) on August 15, 1990.

Materials used for the experiment were:

1. Four feet of 0.050" (1.27 mm) diameter tantalum wire.
2. A Sorensen DCR 40-40B (Raytheon) power supply, able to deliver up to 50 amps DC at 50 V.
3. Leads from the power supply were 8 Ga, 7 strand copper wire, type TW 600V E14656K, with two inches of the ends stripped for connecting to the tantalum wire.
4. A zirconia tube, both ends open, 8 mm outisde diameter, 5 mm inside diameter, 170 mm long, made of ZR23 from Johnson-Matthey (see Appendix 1).
5. Two cinder blocks.

8.a. Test Setup

The wire was folded in half (Figure 8-1), with a 10 mm diameter loop at the end. The wire was then wrapped manually 12 1/2 times around the zirconia tube in a space of 135 mm, for an average of 10.8 mm per wrap. Spacing between the wires was very irregular, ranging from 1 mm (slightly less than one wire diameter) in the middle, to 10 mm near the ends of the tube. The tantalum wire leads connected to the copper wires from the power supply about 115 mm from the tube. Hence the length of wire actually wrapped around the tube was about 990 mm (4 feet minus 2*115 mm). The tube and tantalum wire rested on the cinder blocks, about 1 foot from the power supply.

8.b. Test Data

Data were collected over a 26-minute test. No quantitative temperature measurements were made, but the changing color of the tantalum wire and the zirconia tube provided qualitative temperature information. Unless otherwise specified, all references to 'wire' or 'lead' refer to tantalum.

Time	Volts	Amps	Watts	Notes
1:45	1	5	5	Power turned on. Voltage control does not seem to have an effect except to turn the supply on/off. Only amperage is controlled.
1:48	2	10.5	21	
1:50	7	24	168	Wire clearly getting warm. Light oxidation on wire. Middle 3 coils dark red.
1:53	9	24	216	No change to controls, yet voltage went up.
1:54	"	"	"	4 middle coils red
1:56	8.5	24	204	Voltage settling down
1:59	11	28	308	Wires getting orange where close spacing. Red colder. Leads getting dark red.
2:02	11.5	28	322	Blowing on wire darkens it, and drops voltage 0.5 V temporarily.
2:05	"	"	"	Wires in middle bright orange.
2:06	12	28	336	Copper leads noticably warm (due to conduction?)
2:09	13.5	28	378	Middle wires yellow. Zirconia tube glowing in proportion to wire color.
2:11	"	"	"	Power surge, possibly due to arcing between close wires. Power shut down.

8.c. Post-test Notes

1. Thick white oxidation coating on closest wires, with axial cracks in the oxidation; thinner, greyish coating on cooler parts. Most severe oxidation crumbled off easily.

2. Wire much more brittle; broke instead of bending when pulled on. When compared to unheated wire, 3/4 of wire's cross-section was noticably lighter color (i.e. oxidation affected much of the wire).

3. Dark mark on zirconia tube in center where hottest wire was. Mark is intermittent, but nearly 2 revolutions long.

8.d. Conclusions from Testing

1. Power supply is only controlled by output amperage. Voltage not directly controllable at all.

2. Spacing of wires is critical in determining wire temperature. Need to control wire spacing very carefully in heater.

3. Wires wrapped around ungrooved tube can wander by about 1 wire diameter during heating, perhaps to relieve residual bending stresses. This is important to consider when planning how tightly to space the wire.

4. No sagging of the wire was evident during the experiment.

5. Oxidation of the wire must be avoided. It makes the wire much more brittle, and forces larger wire spacing due to the oxidation build-up.

6. The change of resistivity of tantalum has a substantial impact on its use as a heating element. A noticable amount of time (e.g. 10 minutes) must be allowed for the wire to reach a steady state, even when the heat transfer from the wire responds quickly. Accordingly, in use, the heater will require a long time (1-2 hours?) to reach steady state before it is used.

9. PRELIMINARY HEATER DESIGN

Finally, it is time to put all of this information together to describe what this heater could be like. First, examine what elements of the heater will be encountered as one progresses from the inlet (to the heater) to the outlet. This will also describe the overall dimensions of the heater in the process. See Figure 9-1.

9.a. Heater Length

The source gas hose is connected to the free threads of the Conax fitting (Section 6.f.), which are estimated to be 1" long. Allowing another inch for the Teflon seal and its joint, then the inlet endplate, which is 2" thick. Entering the heater core now, allow 2" for zirconia insulation to protect the Teflon and other weak materials. Then half-an-inch for clearance before the tantalum wire starts wrapping around the zirconia tube.

Allow six inches of wrapped tube, consisting of four inches to achieve fully developed flow (Section 5.a.) and two inches for heating the source gas (Section 5.e.). Realize that this is a very conservative estimate, because a transient constant temperature boundary condition heat transfer analysis could be done to show less than six inches is adequate. It is much preferred to allow too much time for heating the source gas than too little.

The last half inch of tube before the zirconia disk can't be wrapped with wire, to allow for clearance. Then the zirconia disk is an inch thick, and the annular steel disk (outlet endplate) is 1.75" thick. All of this makes for a heater with a overall length of:

$$L_{overall} = 1" + 1" + 2" + 2" + 0.5" + 6" + 0.5" + 1" + 1.75" = \underline{15.75"} \text{ long}$$

The zirconia tube has a length of (assuming 1" sticks out of inlet endplate, and the other end is flush with the outside surface of the zirconia disk):

$$L_{zirc\ tube} = 1" + 2" + 2" + 0.5" + 6" + 0.5" + 1" = 13" \text{ long}$$

The cylindrical part of the pressure vessel extends from inside the inlet endplate to inside the outlet endplate, for a length of:

$$L_{cylinder} = 2" + 0.5" + 6" + 0.5" + 1" = 10" \text{ long.}$$

The overall diameter of the heater is 6" for the zirconia disk, plus two times 1.5" for the bolt pattern derived in Section 6.d., for an overall diameter of 9". Note that the heater overall length and diameter fit within the constraints set forth in Section 2.

9.b. Parts Requirements

A summary of the parts needed for the heater is shown in Table 9-1. Not included on the list are:

1. Two fittings to pass a wire from outside the heater to inside the alumina tube. Since the zirconia tube's fitting is so big, the wire can't be passed directly through the inlet endplate. Instead, the tantalum wire will probably have to be welded to a large copper wire inside the heater, then have the copper wire pass out of the heater through another pair of (Conax) fittings.

2. A safety valve system needs to be developed to detect the presence of oxygen outside of the zirconia tube (i.e. anywhere it could build up that it doesn't belong). The heat shield region of the heater should always contain only argon, so it could be constantly sampled for oxygen content, with the source gas shut off automatically if oxygen is detected. An alternate scheme would be to monitor the mass flow rates of the source gas and of the wind tunnel. If the source gas has a higher mass rate than the tunnel, the source gas must be leaking, and the system is shut off.

3. Other fittings (such as Conax's) could be used to put thermocouple probes through the inlet endplate at various radial locations to monitor the temperature profile in the heater. Thermocouples surface-mounted on the outside of the heater should be used near key joints to insure the O-rings aren't overheating. The heat transfer analysis showed the conduction

resistance through metal to be negligible, so the inside and outside temperatures of the steel parts should be about the same.

4. As an alternative to items 'e' in Table 9-1 for heat shields, it has been suggested to fill the core of the heater, from the 30 mm OD alumina tube to the steel pressure vessel, with zirconia powder. This is an interesting concept. With each grain of powder radiating to and from neighboring grains, it could provide a very effective radiation heat shield. Analysis of this configuration is beyond the scope of this report, however.

---

a. Zirconia tube, 5 mm ID by 8 mm OD by 13" long, one end closed except for nozzle as shown in Figure 6-7.

b. Zirconia disk, 6" diameter by 1" thick, modified as shown in Figure 6-6.

c. Conax PG4-312-B fitting with Teflon seal.

d. First heat shield: alumina tube, 25 mm ID by 30 mm OD by 9" long.

e. Other heat shields: alumina tubes, 9" long by (1 ea.):

60 mm ID by 70 mm OD

80 mm ID by 90 mm OD (from Section 5.g.)

f. Inlet endplate: mild steel disk, 9" diameter by 2" thick, machined per Figure 9-1.

g. Outlet Endplate: mild steel disk, 9" OD by 3.3" ID (from Section 6.e.) by 1.75" thick, drilled to accomodate twenty 3/4" bolts in a 7.5" diameter pattern.

h. Padding: Cerametek ceramic (alumina) paper, to pad zirconia disk per Figure 9-1.

i. Tantalum wire: 0.050" diameter by 3.5 m long (per Section 7.a.).

j. Forty (40) 3/4" bolts (length?) and forty (40) 9/8" OD diameter flat washers.

k. O-rings to fit as shown in Figure 9-1.

Table 9-1. Parts list for heater. See text for more information.

9.c. Summary

A design has been developed for a stagnation heater for the rarefied wind tunnel at the University of California, Berkeley. It will operate at up to 2000 psi internal pressure, and deliver a low flow rate of gas at up to 2000 K. It meets all of the structural, materiel, and heat transfer characteristics required, can be made for a reasonably low cost, and fits well in the wind tunnel's constraints. The heater consumes 2700 W of electricity, and consists primarily of a mild steel pressure vessel, a zirconia tube, a zirconia disk, and tantalum wire.

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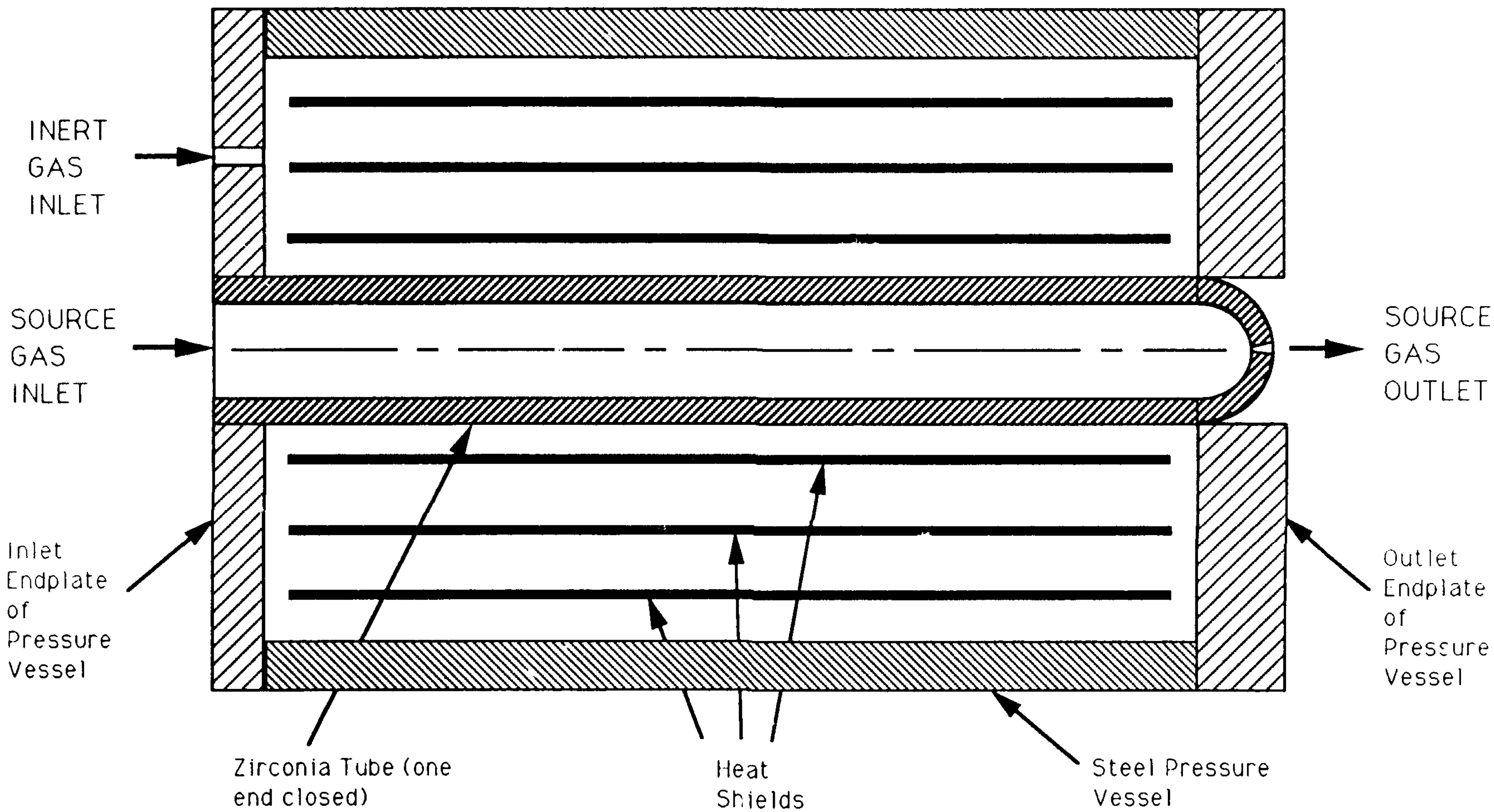


Figure 2-1. Schematic of Heater Design.
(Tantalum Heating Wire, wrapped around zirconia tube, not shown)

	A	B	C	D	E	F	G	H	I
1	**Robert Booker**				**PROPERTIES**	(Average values)			
2	**ME299**				Material	k (W/(mK))	Emissivity		
3	**Summer 1990**				Argon	0.065	0		
4	**Prof. Hurlbut, Advisor**				Air	0.06	0		
5	12/5/90				Zirconia	2.1	0.45		
6	Spreadsheet to find the temp profile in isothermal heater.				Alumina	29	0.5		
7	Heavy wall (9.5/5.5") configuration with 3 heat shields.				Steel	30	0.4		
8	End effects added.								
9		Heated length (L) :	0.1524	m					
10		pi	3.14159265						
11		Two * pi	6.28318531			**TOTAL CONDUCTION RESISTANCES**			
12		R c 0 = 1/hA =	7.97680854	K/W		Node	Sum of R k i		
13	**LOCAL CONDUCTION RESISTANCES**					2	2.3326	K/W	
14	Node	Diameter (mm)	R k i (K/W)	Notes		4	15.9742		
15	1	5	0.2337	inner zirconia		6	27.1172		
16	2	8	2.3326	outer zirconia		10	36.3366		
17	3	9.25	15.9742	"wire"		Inner	10.5431	(includes R c 0)	
18	4	25	0.0066	inner alumina		Outer	36.3557		
19	5	30	11.1365	outer alumina					
20	6	60	0.0056	1st H.S. inner					
21	7	70	2.1454	1st H.S. outer		**TOTAL RADIATION RESISTANCES**			
22	8	80	0.0042	2nd H.S. inner		Node	Sum of R r i		
23	9	90	7.0642	2nd H.S. outer		2	805.9796	m^-2	
24	10	139.7	0.0190	Steel inner		4	648.0452		
25	11	241.3	0	Steel outer		6	822.0992		
26	12	99999999999		infinity		10	976.7238		
27						Inner	805.9796		
28			where			Outer	998.3633		
29			R k i =LN(Di+1/Di)/(2*pi*ki*L)						
30									
31									
32									
33									

Figure 5-1. Radial Heat Transfer Analysis Spreadsheet. Page 1 of 3.

	A	B	C	D	E	F	G	H	I
34	**TEMPERATURE PROFILE**			**Air properties:**					
35	Mass Rate =	0.0001	kg/s	Temp (K)	Air Cp (J/kgK)				
36	inlet T =	300	K	300	1000				
37	and outlet T =	2000	K	2000	1240				
38	Ambient T =	300	K						
39	sigma =	5.669E-08	W/(m^2K^4)						
40									
41	Then To =	2000.00	K						
42	q 1	218	W = (m dot)*Cp*(delta T)						
43	q 2 =	1084.06	W (rad. only)	q 2 =	1131.14	W (rad & cond)			
44	Determine T3 from known q I, the given resistances, and known T0 and T16.								
45									
46		RADIATION ONLY				**RAD and COND.**			
47	Node	Temp (K)	E b i (W/m^2)	R bar i (K/W)	R eq i (K/W)	**Temp. (K)**	E b i (W/m^2)		
48	0	2000.00	907040.00	0.4152	0.3995	**2000.00**	907040.00		
49	2	2000.00	907040.00	0.4152	0.3525	**2010.25**	925776.45		
50	3	2090.52	1082743.55	0.0000	0.0000	**2087.09**	1075654.79		
51	4	1609.29	380224.50	0.4439	0.4319	**1598.53**	370163.96		
52	6	1355.78	191539.79	0.6778	0.6612	**1339.13**	182305.73		
53	10	805.94	23917.71	1.1850	1.1476	**789.05**	21975.20		
54	12	300.00	459.19	1.6517	1.5799				
55									
56			(T2=T0 for radiation-only analysis)						
57									
58			**Q total =**	**1349.14**	**W (does not include end losses)**				
59									
60			Max. Steel Temp	960	deg F				
61									
62									
63									
64									
65									
66									

Figure 5-1. Page 2 of 3.

	A	B	C	D	E	F	G	H	I
100									
101	**LOCAL RADIATION RESISTANCES**								
102	Surface	Epsilon i	Epsilon i+1	1/A i	((1-E)/AE)i	1/Ai+1	((1-E)/AE)i+1	R r i	
103	2	0.45	0.5	261.0809	319.0989	225.7997	225.7997	805.9796	
104	3	0.4	0.5	225.7997	338.6996	83.5459	83.5459	648.0452	
105	5	0.5	0.5	69.6216	69.6216	34.8108	34.8108	174.0540	
106	7	0.5	0.5	29.8378	29.8378	26.1081	26.1081	85.7837	
107	9	0.5	0.4	23.2072	23.2072	14.9509	22.4264	68.8408	
108	11	0.4	0.4	8.6558	12.9837	0.0000	0.0000	21.6395	
109									
110			A i = pi*Di*L/1000 (m^2)		R r i = ((1-E)/AE)i + 1/Ai + ((1-E)/AE)i+1				
111									
112	Alumina (AL23) open end tubes from Johnson-Matthey								
113	d2/d1 (mm)	price ($)							
114	30/25	104							
115	35/29	123							
116	40/34	139							
117	45/38	163							
118	50/42	193							
119	55/47	198							
120	60/50	229							
121	65/55	264							
122	70/60	289							
123	80/70	352							
124	90/80	562							
125	100/85	634							
126	110/95	692							
127	130/110	856							
128	140/120	969							
129	150/130	1060							
130									
131									
132									

Figure 5-1. Page 3 of 3.

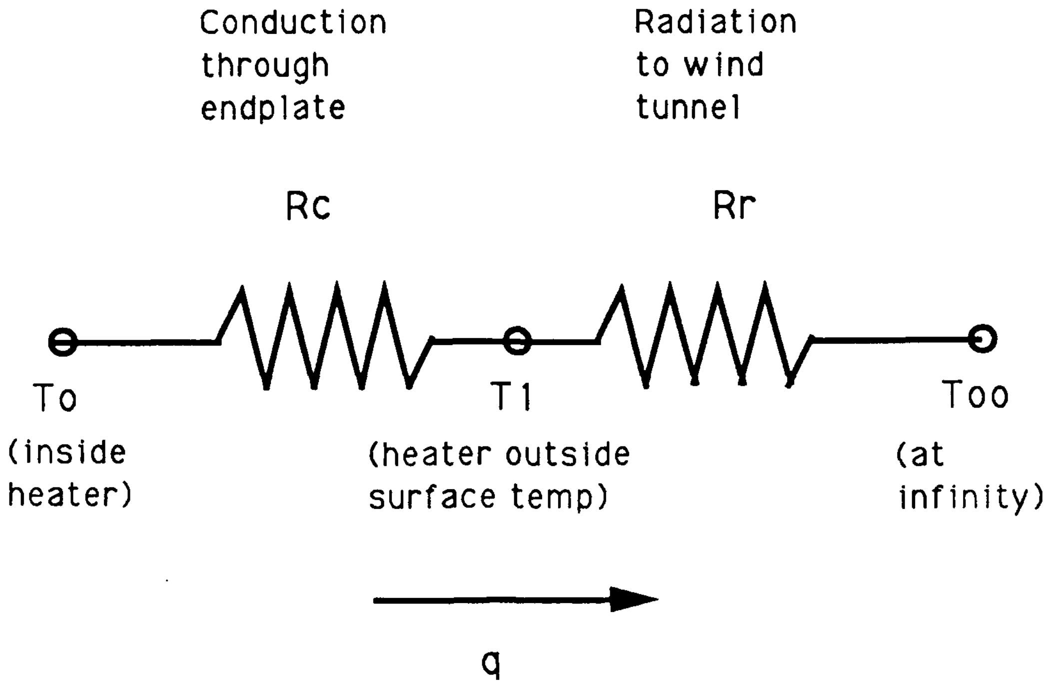


Figure 5-2. End Effects Heat Transfer Model.

$$q = A*(To - T1)/Rc \quad \sigma*(T1^4 - Too^4)/Rr$$

	A	B	C	D	E	F	G	H	I
133	End losses due to combined conduction-radiation problem								
134						Final			
135	Node	Diameter (mm)	Area (m^2)	To	K	T1	q" (W/m^2)	Local q (W)	
136	2	8	0.0000503	2010.25	1.8222E-11	1812.89	276298.65	13.888	
137	3	9.25	0.0000169	2087.09	3.0856E-10	2086.93	13.10	0.000	
138	4	25	0.0004237	1598.53	3.0856E-10	1200.00	32949.67	13.960	
139	6	60	0.0023366	1339.13	3.0856E-10	1000.00	28038.49	65.514	
140	10	139.7	0.0125005	789.05	2.9932E-11	778.31	8137.29	101.720	
141	11	241.3	0.0304024	789.05	2.9932E-11	778.31	8137.29	247.393	
142									
143	Node	epsilon	sum of (k/t)	1st T1 (K)	2nd T1 (K)	3rd T1 (K)	4th T1 (K)	5th T1 (K)	
144	2	0.45	1400.0000	1800	1819.11	1810.86	1814.45	1812.89	##
145	3	0.45	82.6772	1800	-1149.50	1550.86	304.65	2086.93	##
146	4	0.45	82.6772	1100	1149.28	1062.72	1207.47	945.13	##
147	6	0.45	82.6772	1000	1033.08	990.18	1045.02	973.65	##
148	10	0.4	757.5928	800	777.04	778.38	778.31	778.31	##
149	11	0.4	757.5928	800	777.04	778.38	778.31	778.31	##
150									
151			Dimensions of "sum of (k/t)" are W/(m^2K)						
152			Dimensions of "K" are 1/K^3						
153									
154			Total power loss at one end of the heate			442.48	W		
155									
156			**Total Heater Power Requirements are**				**2234.09**	**Watts**	
157									
158									
159									

Figure 5-3. End Effects Heat Transfer Spreadsheet.

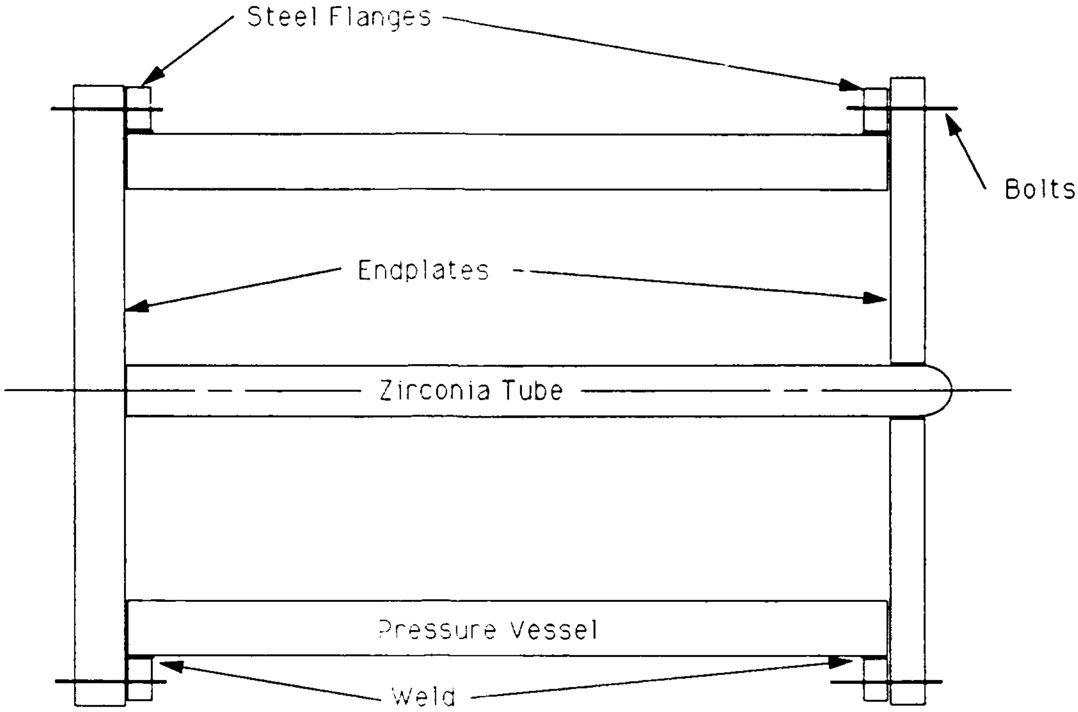


Figure 6-1. First Pressure Vessel Design Option

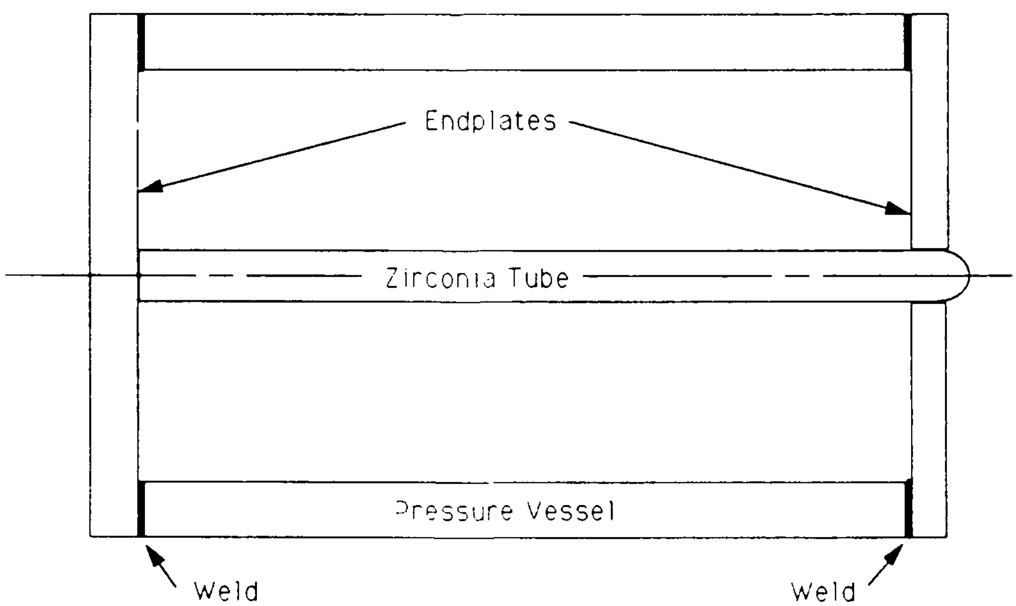


Figure 6-2. Second Pressure Vessel Design Option

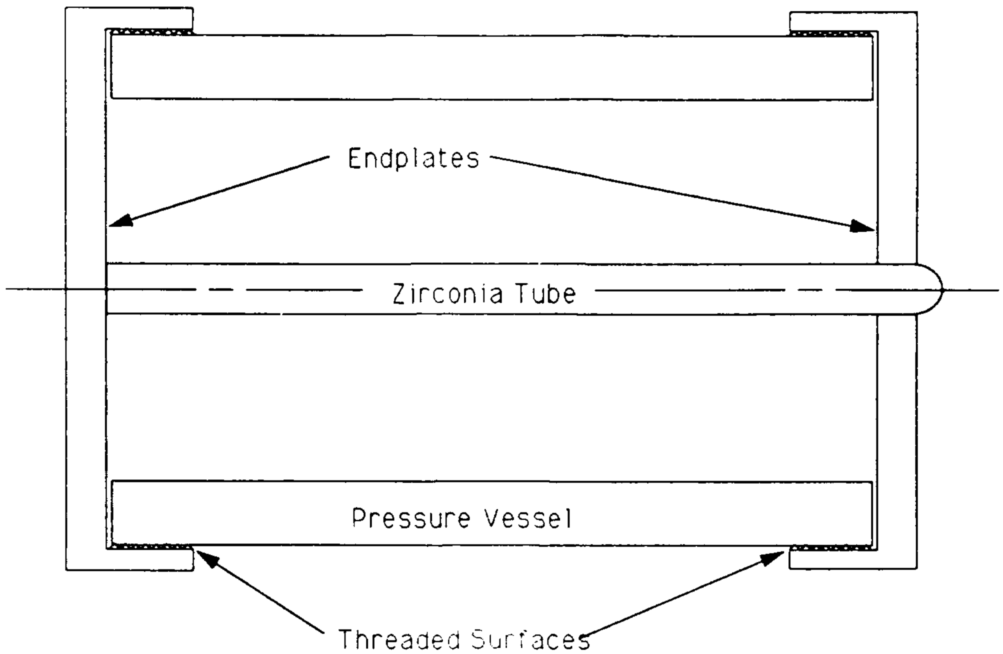


Figure 6-3. Third Pressure Vessel Design Option

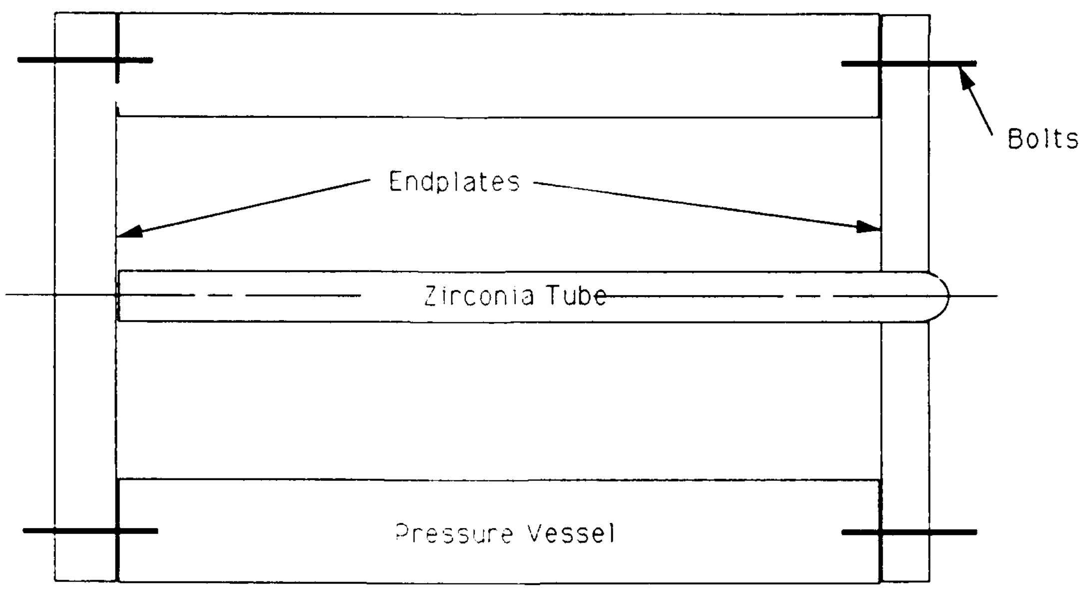


Figure 6-4. Fourth Pressure Vessel Design Option

NOT TO SCALE

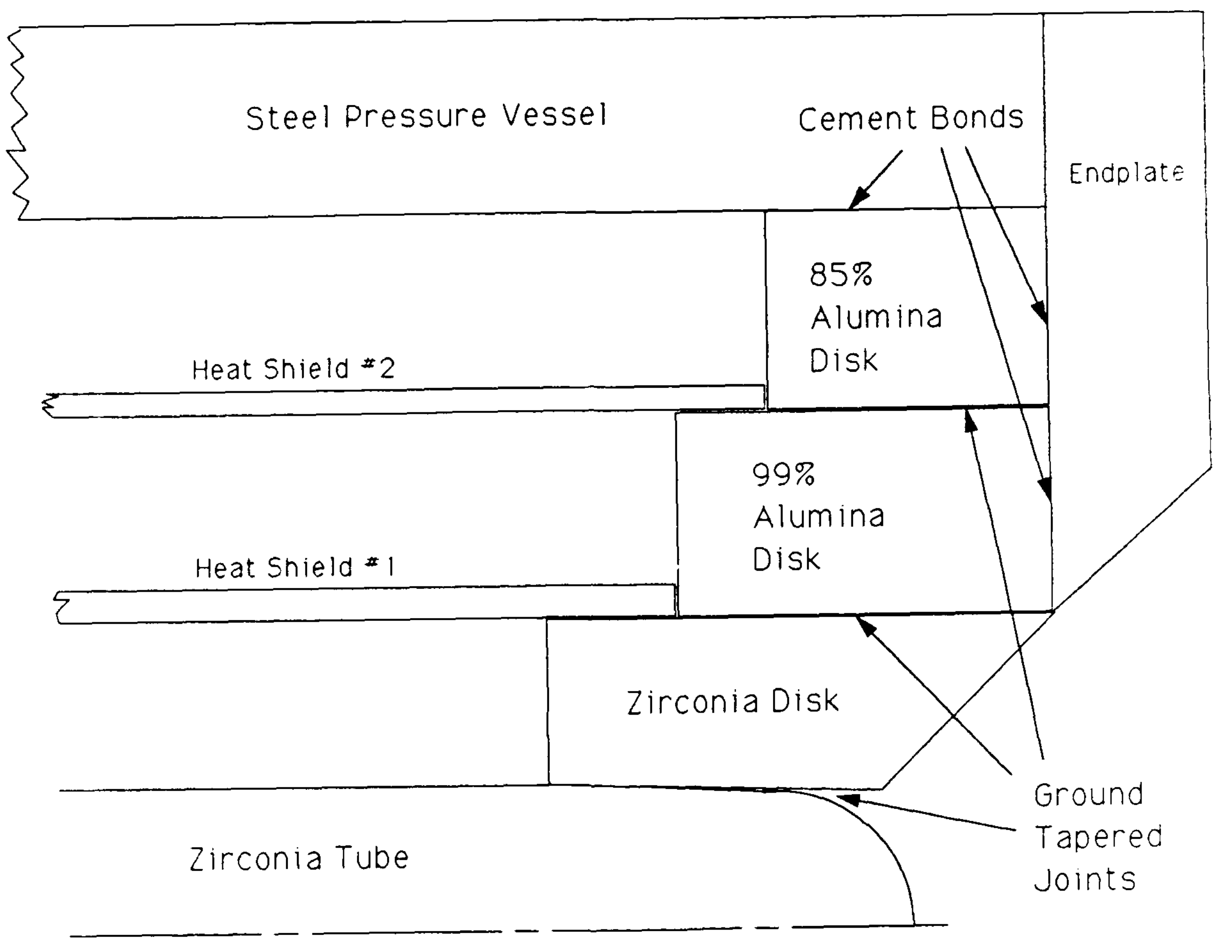


Figure 6-5. Multiple Ground Tapered Joint. Original concept for ceramic-metal joint near heater outlet. Overall diameter was expected to be 3-4". Endplate joint to pressure vessel not shown.

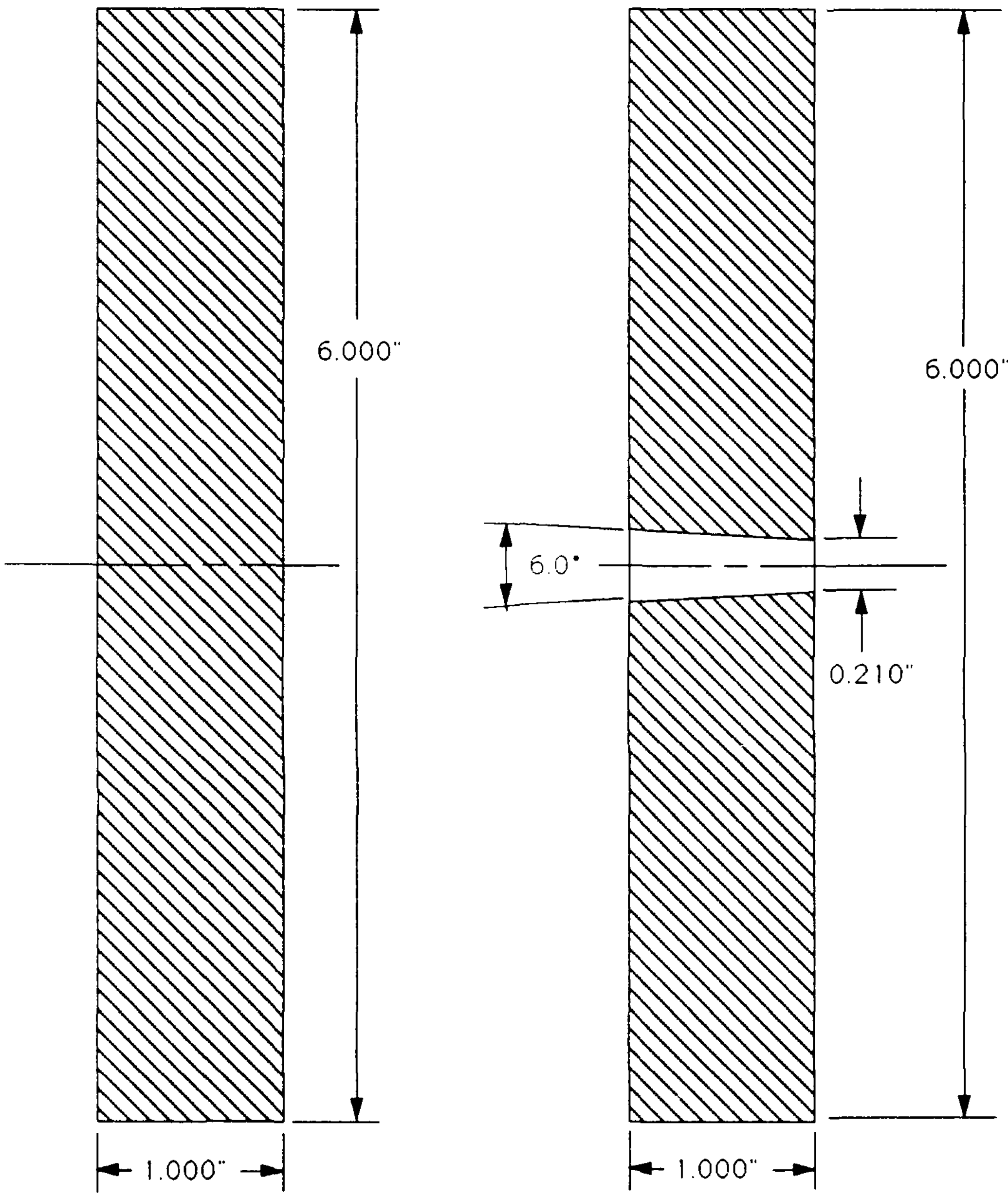


Figure 6-6. Zirconia Disk Cross-section Views. Left drawing is disk as received from supplier. Right drawing is disk ready to be joined to the zirconia tube.

RGB 12/2/90

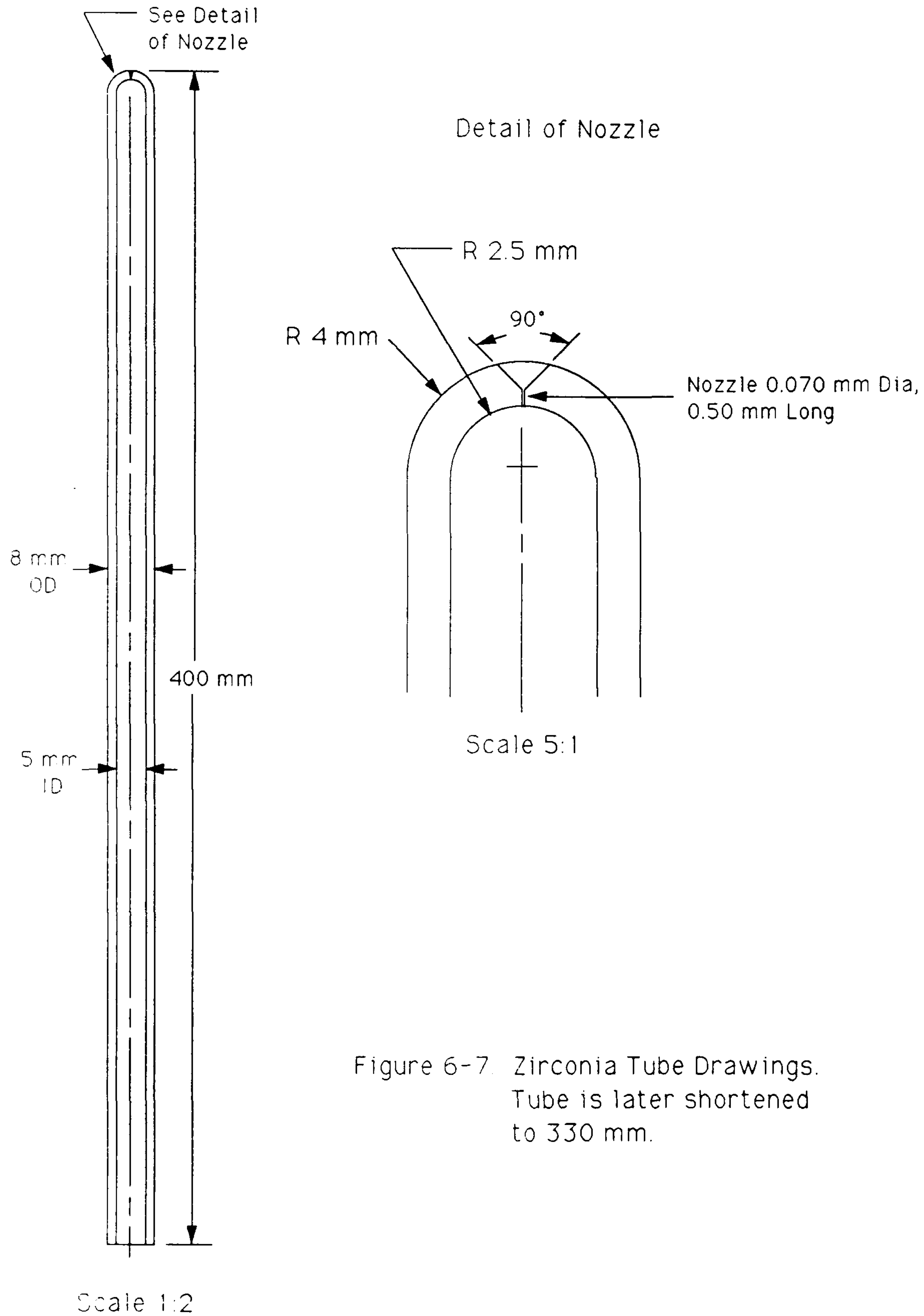


Figure 6-7. Zirconia Tube Drawings.
Tube is later shortened
to 330 mm.

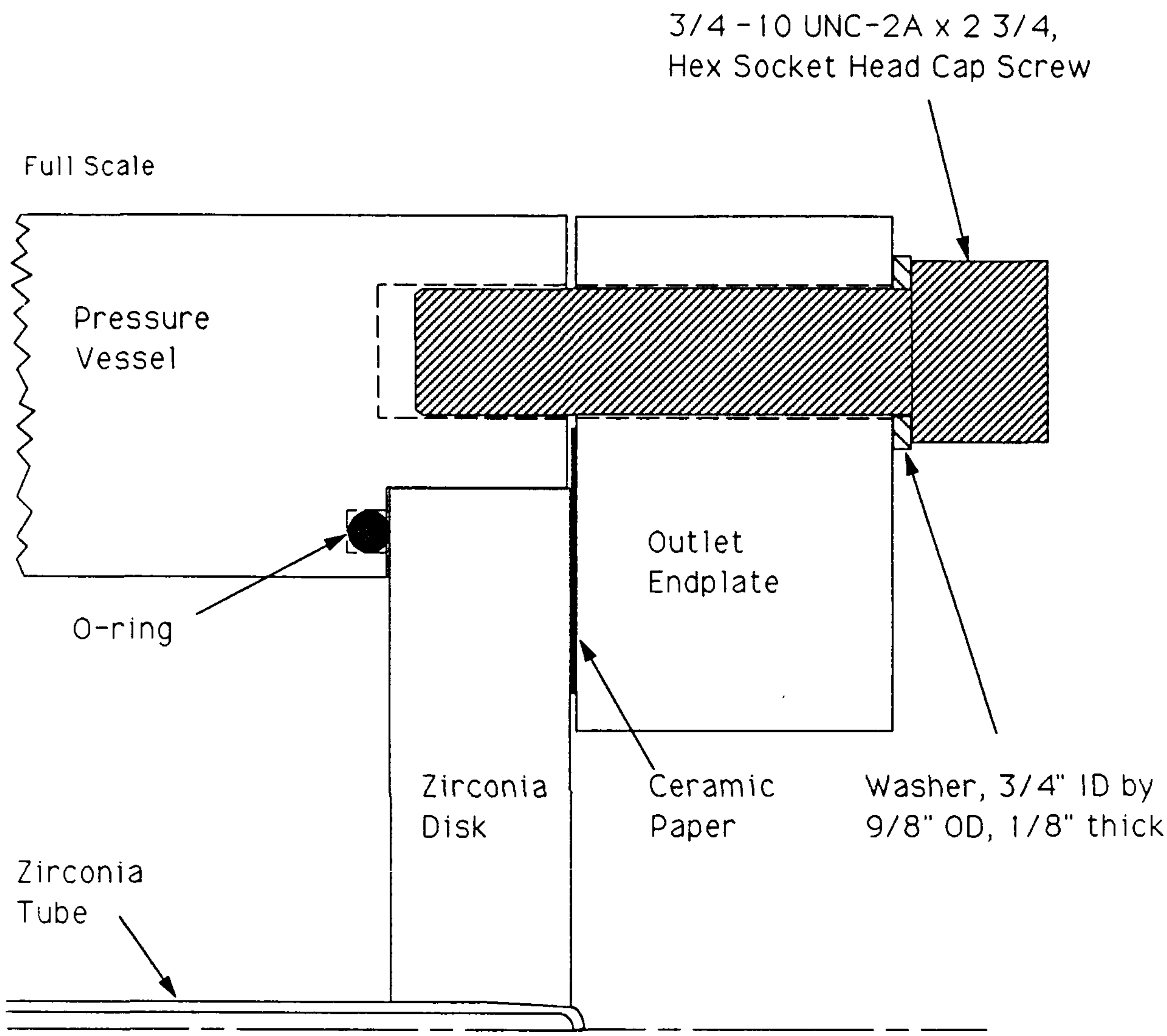


Figure 6-8. Zirconia-Metal Joint Design. Heat shields omitted for clarity.

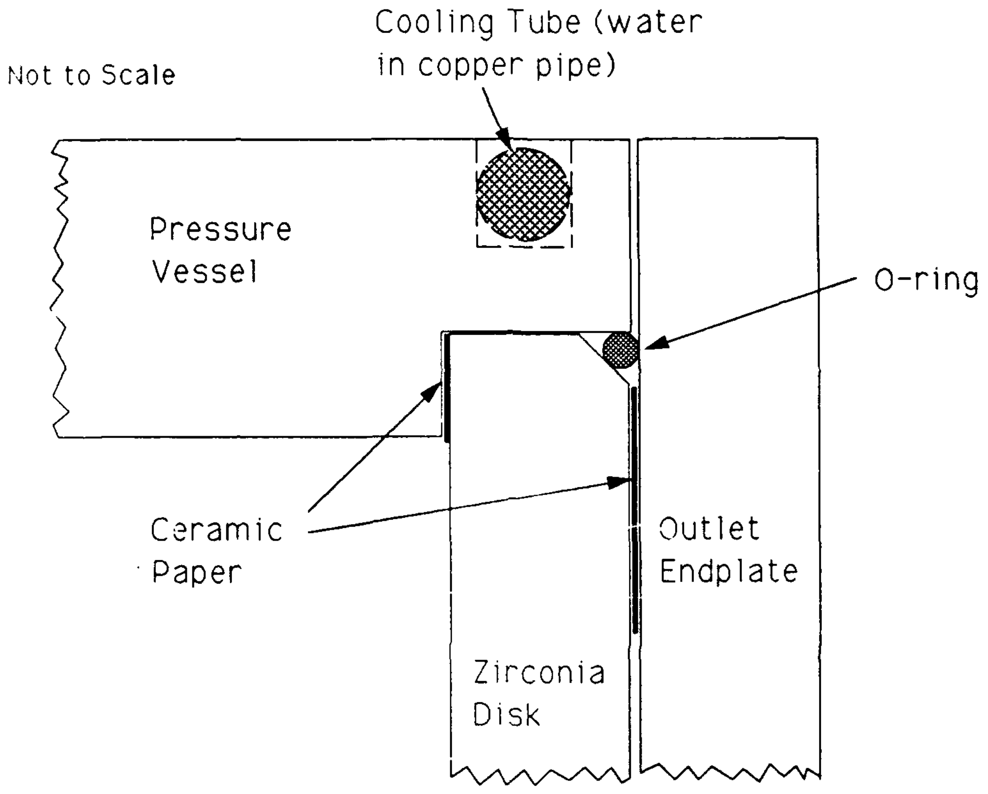


Figure 6-9. Advanced Zirconia-Metal Joint, Design A. Attachment of Endplate to Pressure Vessel not shown.

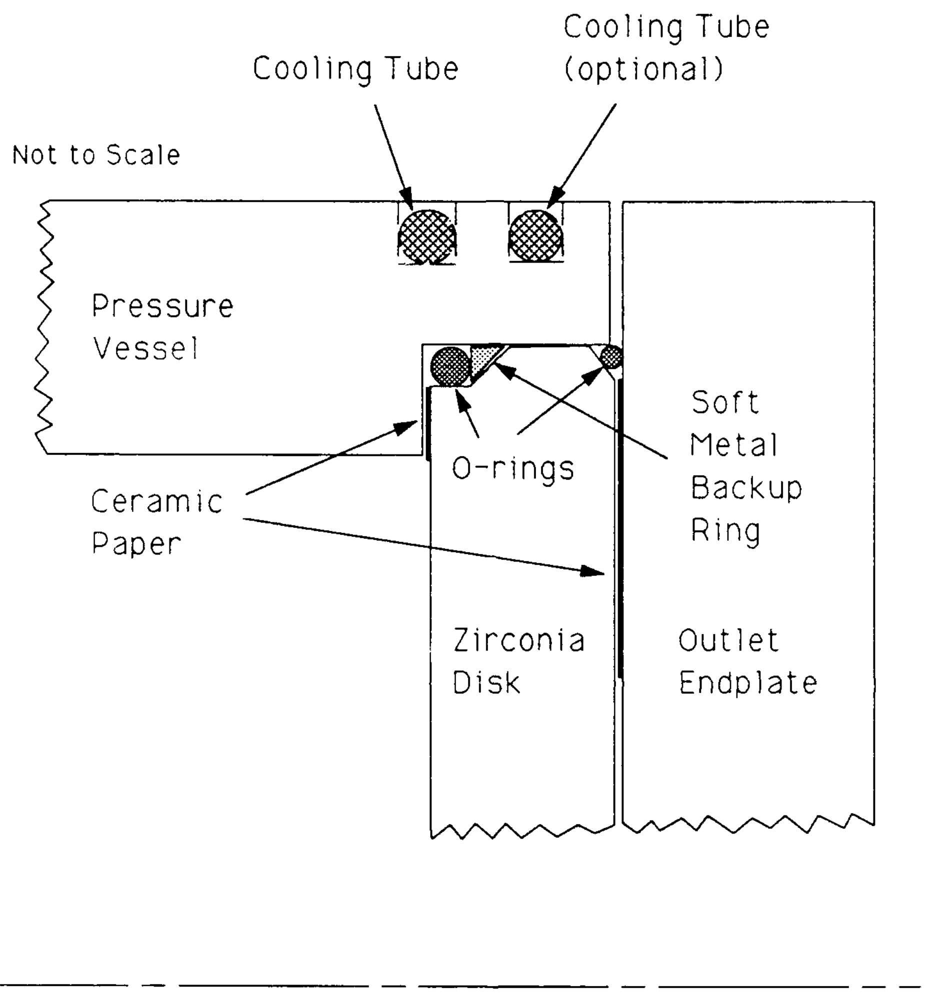


Figure 6-10. Advanced Zirconia-Metal Joint, Design B. Attachment of Endplate to Pressure Vessel not shown. The Backup Ring is typically made of copper, and is used to prevent extrusion of the O-ring.

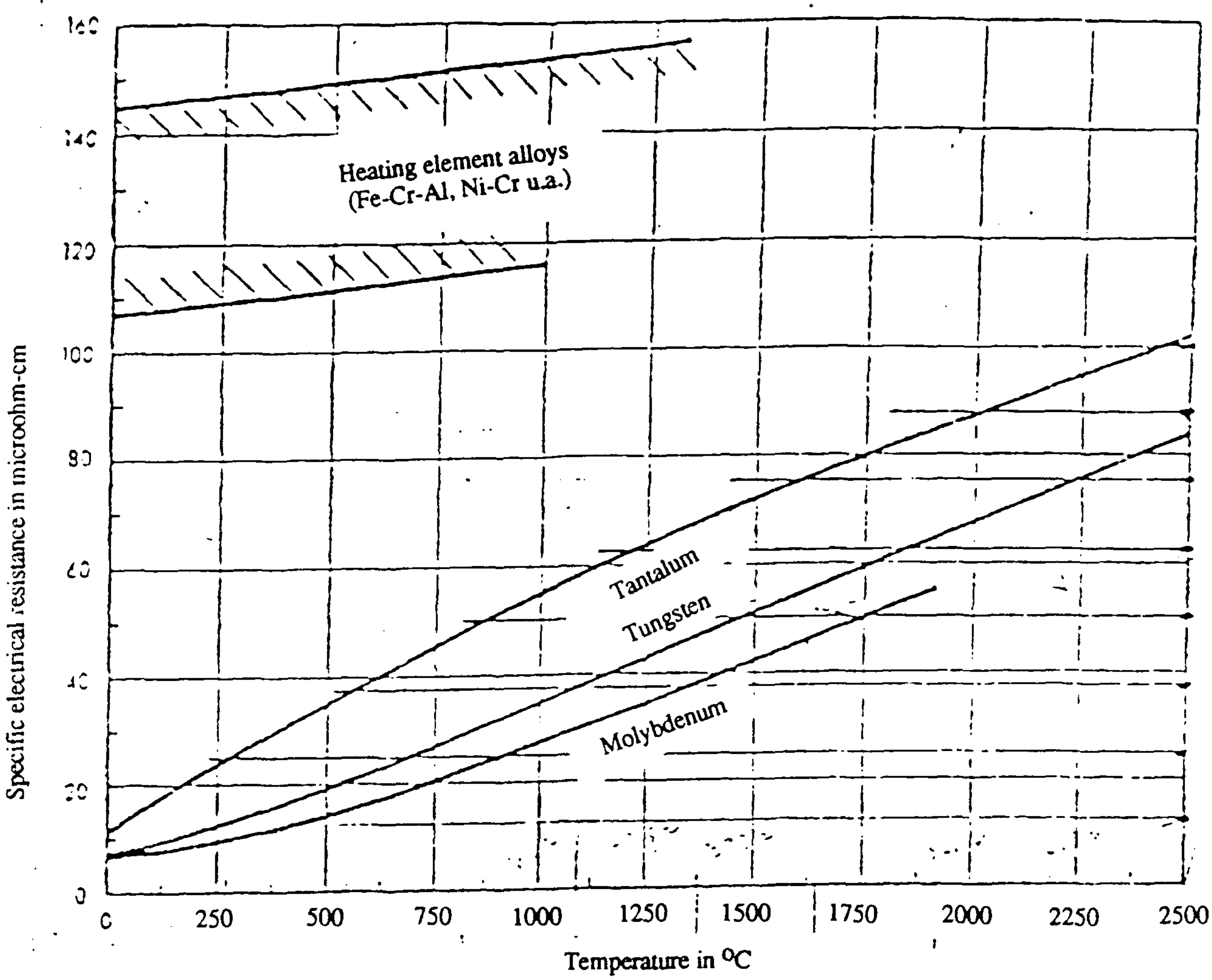


Figure 7-1. Resistivity of tantalum and other metals.

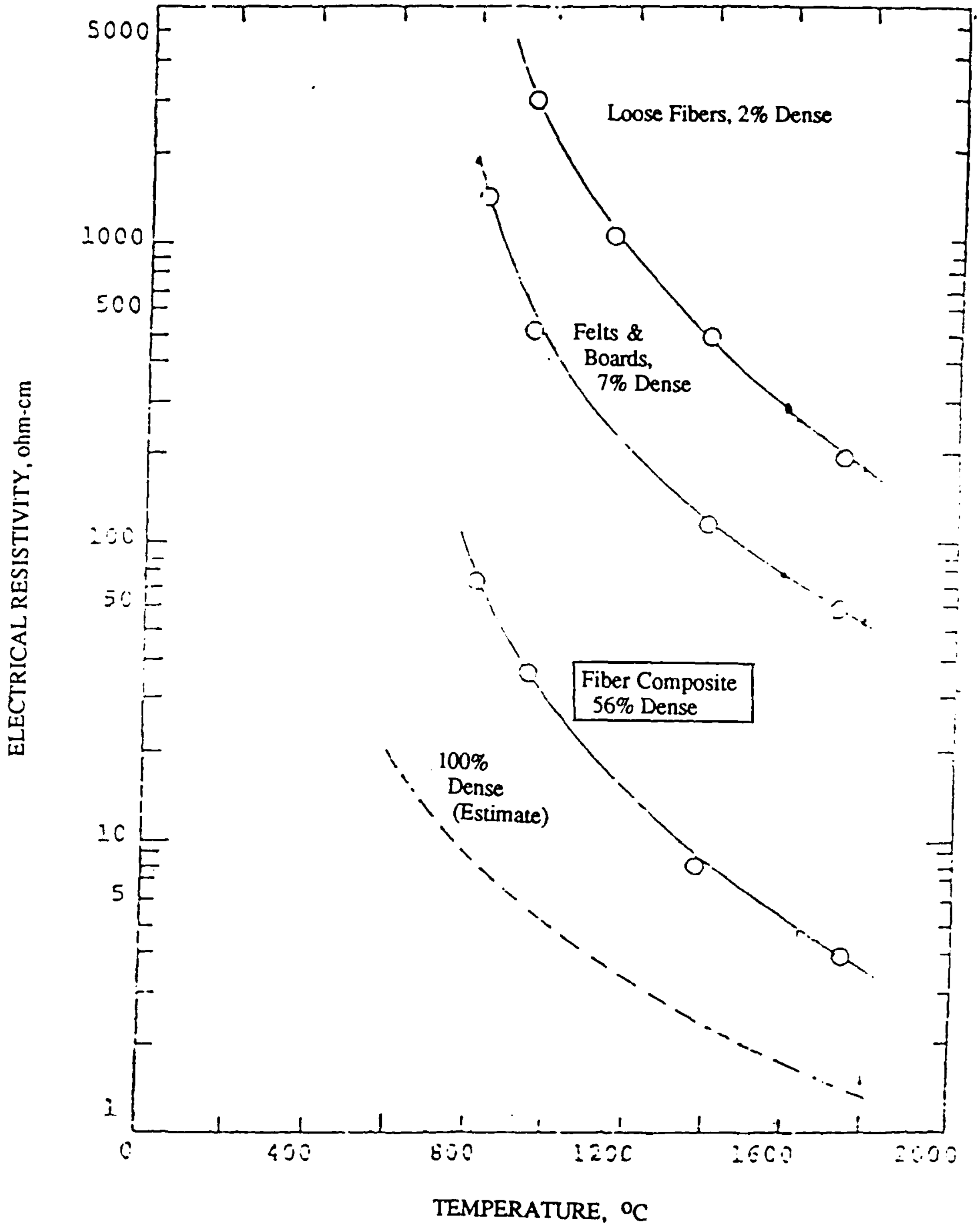
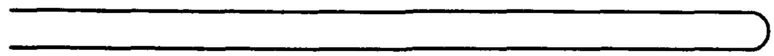


Figure 7-2. Resistivity of zirconia composites.



Tantalum wire is recurved (ideally) as shown above, then wrapped around the zirconia tube. Ends on the left become the leads, and the loop on the right is snug against the zirconia tube.

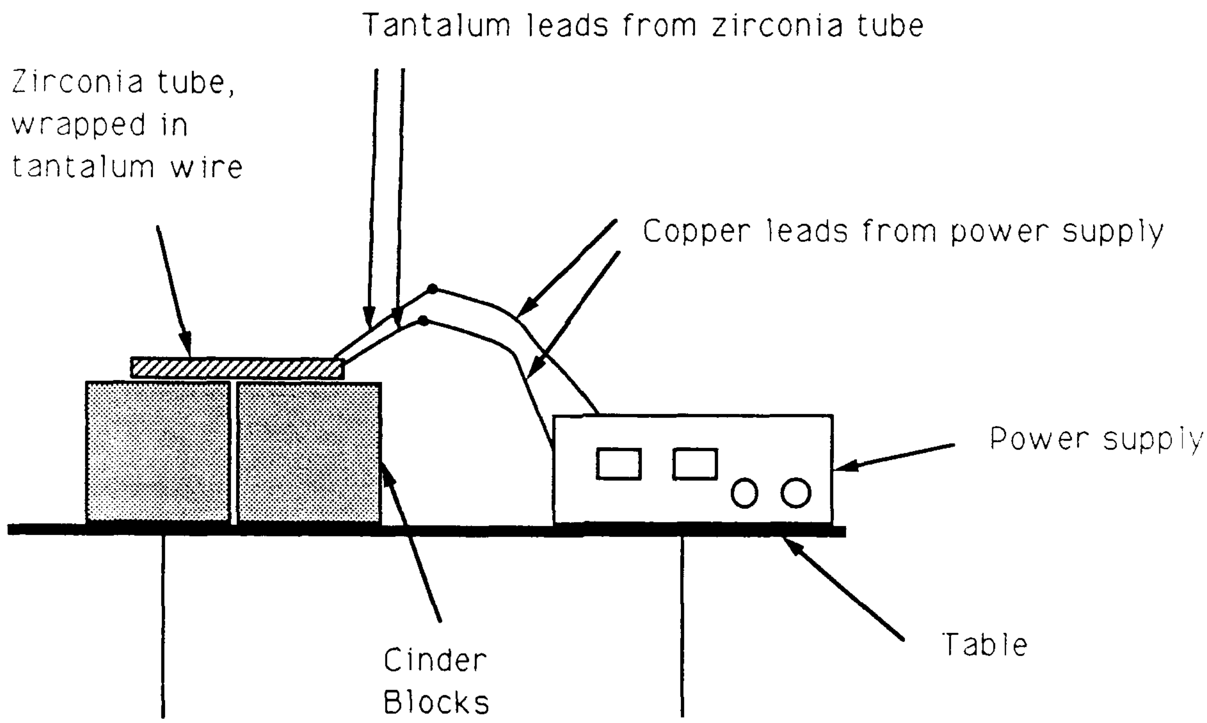


Figure 8-1. Experiment Setup.

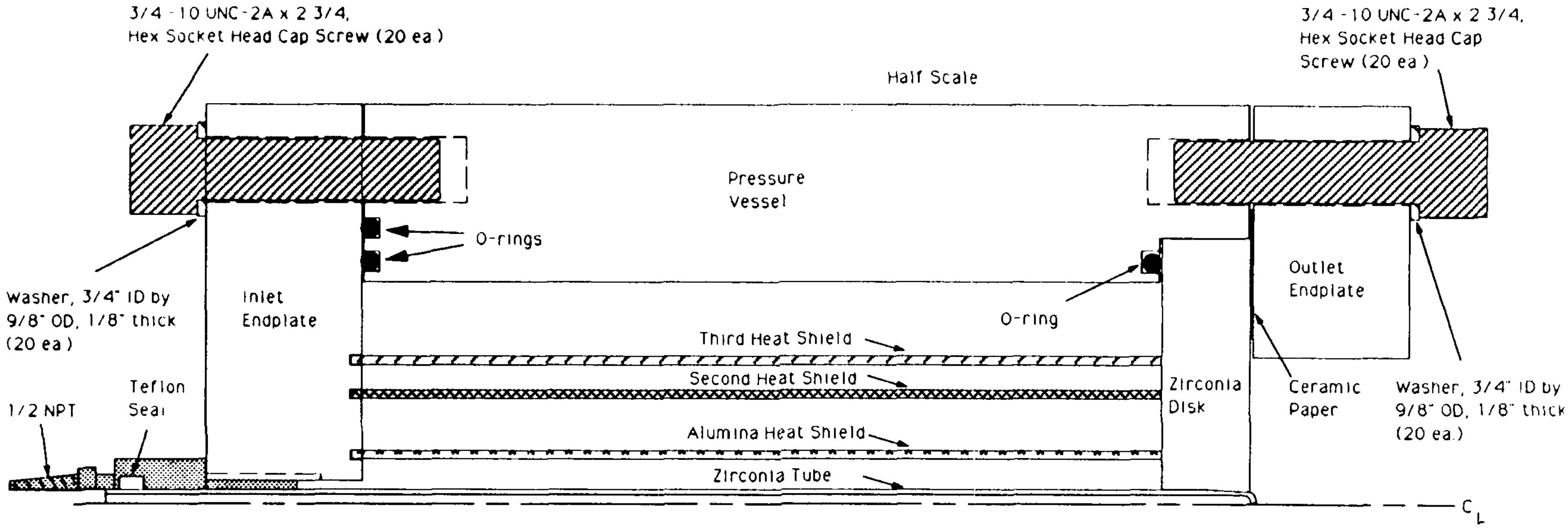


Figure 9-1. Preliminary Heater Design.

Appendix 1: Industry Contacts

In the course of this project, many companies were contacted. This Appendix first lists those from which services were obtained or componants purchased, then those that were contacted but not used. All dates were in 1990.

Major topics included:
"1-piece design" = Attempt to get bids for the custom manufacture of a single piece zirconia tube with a large flange at the end. This was to avoid a mechanical ceramic joint at high temperature and pressure.
"disk" = Search for bids on a zirconia disk to be fitted to the end of the Johnson-Matthey zirconia tube. Both custom and off-the-shelf items were considered.
"wire" = Search for manufacturer of tantalum wire for the heating element; 0.050" diameter desired.
"cement" = Search for ceramic cement that could help bond zirconia tube and disk; none of the candidates proved suitable, hence the use of the mechanical ground tapered joint. Cement was obtained for bonding the alumina heat shields to the pressure vessel.
"steel cylinder" = Search for materials for the cylindrical pressure vessel. Eventually decided on carbon steel that meets ASTM SA 106 Grade B.

"zirconia powder" = Wanted powder with a 30-50 μm grain size to help make the ground tapered joint between the zirconia tube and disk.
"drilling" = Wanted subcontractor to make hole in end of zirconia tube. Some proposed laser, ultrasonic, waterjet, or other means.

Part 1: Companies used to obtain services and/or parts.

Aremco (914) 762-0685 Local Rep.: Colin Raufer or Frank
23 Snowden Ave. (714) 948-9592
Ossining, NY 10562 9816 Cresent Center Dr.
Unit #704
Rancho Cucamonga, CA
91730

Ceramic cement source. Claim their 516 Ultratemp is for bonding zirconia to zirconia, but they admit it wouldn't hold up under both high temp and pressure; costs $80/pint. They recommended 571 Ceramabond for securing heat shields, but Larry Gochberg thought 569 Ceramabond cement more appropriate; cost for either is $85 per pint.

Conax Corp. (716) 684-4500 Local Rep.: QCON, Inc.
2300 Walden Ave FAX (716) 684-7433 (415) 682-2020
Buffalo, NY 14225 Concord, CA

Source of fitting to seal zirconia tube and inlet endplate. Also can use their parts for getting the wire connection through the inlet endplate, and for letting thermocouple probes into the heater. Later found out they're the Cadillac of such fittings, and that others may have good parts for less money. Order placed 8/13 through Instrument Laboratory, 830 Charcot Ave., San Jose, CA 95131, (408) 858-1161, Sue, 3 week delivery expected.

Fansteel Metals (708) 689-4900 John Ralsh, Tech. Dir.
Jerry O'Grady, sales rep.

Wire data source. Sold their wire sales to NRC Corp., but John sent data (6/22 and 7/24/90) on the change of resistivity of Ta with temperature (Figure 7-1).

HDE Systems (408) 735-7272 Dan Fritschen
615 N. Merry Ave.
Sunnyvale, CA 94404

Claim 7/3 they can do hole .003+-.001" to a depth of .020-.025". Water jet can only go to .005" diameter. Quoted $450 to do trial piece and a couple of real ones. Received advertisement stuff from them 8/16.

Johnson-Matthey (800) 343-0660 Bobbie (sales)
(508) 777-1970 Paul Zubiel, ext. 433
FAX (800) 322-4757

Source for zirconia tube. Sent FAX 7/3 for 1-piece design; said can't do it 7/17. Also have zirconia and alumina disks in stock, but none usable for this heater. J-M was horribly slow to send catalogs, but was quick to respond to orders.

JL Becker (313) 591-6036
Livonia, MI

Heater company, contacted by Larry Gochberg to help determine proper temperature profile model in heater.

National Element Inc. (313) 362-0950 Lorn Best
Troy, MI

Heater company, contacted by Larry Gochberg to help determine proper temperature profile model in heater.

Parker Seal Group (606) 269-2351
O-ring Division
2360 Palumbo Dr.
PO Box 11751
Lexington, KY 40512

Local Rep.: Nor-Cal Seal Co.
840 Doolittle Dr.
San Leandro, CA
94577
(415) 569-7371

Source of O-rings and backup rings (Parbak). Very informative catalog, number ORD 5700. Outlet endplate seal may use a silicone ring in size 2-356 or 2-357; this is a 0.210" diameter ring. Silicone is rated for a 10-hour life at 500 °F, or one hour at 600 °F.

Specialty Pipe and Tube (216) 394-2512 Jerry
Akron, OH Norm Mansfield

Source for heavy-walled pipe for high-temperature service (per ASME SA 106). Quoted 8/7 prices for 2' of pipe: 8" OD, 1.25" wall thickness $350; 8.5" OD, 1.5" wall $400; 8" OD, 1.5" wall $405. A call on 12/3 got a quote of $330 (delivered) for one foot of 9.5" OD by 5.5" ID pipe. Local distributor is Tubesales (Hayward, CA) at (800) 545-5000, but they must order from Specialty to get the stuff anyway. (It isn't kept in stock) True Pipe only goes to about 0.9" wall thickness (Schedule 160), so that can't be used for the heater.

TAM Ceramics (716) 278-9400
New York 278-9453, Dan Rooney

Only make ceramic powders. Sent free sample (5 lb.) of 70 µm calcia stabilized zirconia powder. Sell it in 100 lb. lots.

Thermo Shield (415) 941-5230 Bernard
722 Orange Ave.
Los Altos, CA 94022

Wire source. First contact 6/21/90. Have Ta wire in .010, .015, .020, .025, .030, .040, .050, .060, 3/32" sizes. 15 feet of .050" wire was $5.38/ft.

Western Industrial Ceramics (415) 782-2087 Janine
Hayward, CA

Local distributor of ceramic fiber paper. Paper is 52% alumina, 48% silica, and has a density of 10 lb/cu ft. Is rated to use at 1533 K. Heater will use 970-series paper; 970-F is 1/16" thick, and costs $122 for a one-foot by 200 foot roll of it. Manufacturer of the paper is Carborundum Co., Fibers Division, POB 808, Niagra Falls, NY 14302, (716) 278-6221; their Los Angeles office is at (213) 723-4866.

Zircar Products, Inc. (914) 651-4481 Blake Emmerick (engr)
110 No. Main St. Debbie Wright (sales)
Florida, NY 10921

Source of 6" dia x 1" zirconia disk, and (on 7/18) of information on zirconia resistivity as a function of temperature. Disk was of FBD zirconia, with flexure strength of 1200 psi, and compressive strength of 1500 psi, and cost $325. Their ZYZ ceramics are not stable at high temperature, and the FBC material is weaker than FBD. They claim steel/carbide tools will work on it. Also have alumina sheets available: Sali2 material is good to 1800 °C, and 9x12x1.5" is $305. A sheet 9x12x1" is $220. Sali1 material is good to 1700 °C, a 9x12x0.5" sheet is $85.
Composition of FBD is 92% ZrO_2, 0.5% Hf, 8% Yittria (stabilizer). Note that the zirconia tube and powder obtained are calcia stabilized, so they are yellow. Zircar's zirconia is white.

Part 2: Companies contacted but not used for this project.

AD McKay (203) 655-7401
10 No. Broadway FAX (203) 655-6234
Red Hook, NY 12571

Wire source. Have Ta wire in .040, 1/16" sizes; either is $17.40/ft, about three times the cost of Thermo Shield's wire.

Aeroquip/Kayser Co., Inc. (415) 483-9917
14306 Wicks Blvd.
San Leandro, CA 94577

Might be a cheaper source of tube fittings than Conax, but after repeated attempts they still wouldn't send the correct catalog (#260A).

Applied Ceramics, Inc. (404) 448-6888 Allen Carroll
Georgia FAX (404) 368-8261

Contacted many times regarding a quote for a one-piece zirconia tube/disk, but never got specific response. Claimed they do a lot of special shapes in zirconia, though.

Astro Met, Inc. (513) 772-1242 Michael Shepherd
9974 Springfield Pike
Cincinnati, OH 45215

Gave quote 7/19 for custom zirconia disk (without tube), 4" OD by 1.25" thick, of $525 each for two. Length limit of 8" or 9" precluded them from doing the disk/tube one-piece design.

Atomergic Chemical Corp. (516) 694-9000 Gary Newman
New York FAX (516) 694-9177

Contacted regarding the one-pice zirconia tube/disk. Their work is done in Europe, so if they could do it, it would be pricey. "Consider as a last chance option."

Bolt Technical Ceramics (409) 539-2552 Juergen Ruchhoeft
P.O. Box 718
Conroe, TX 77305-0718

Claimed 98% alumina good to 1500 °C. Recrystallized silicon carbide may go to 1650 °C, but is too porous. Suggested to cement flange (disk) onto tube while green. Screw-on flange idea suggested too. FAX on 7/11 said they can't do it in silicon carbide. Gave quote 7/30 for one-piece extruded tube/disk in alumina with tube OD of 22 mm of $898 per piece, plus one-time tooling charge of $235.

Carborundum (716) 278-6228
Advanced Ceramics (716) 278-6022, John Devilacqua, Structural Division
Niagra Falls, NY (716) 731-9281, Dr. Vish

Recommended 7/12 making the one-piece tube/disk out of sintered a silicon carbide only. Has higher thermal conductivity than zirconia, so would have to increase disk radius. Would perform better at high temperature than alumina, though alumina is a much better known material than zirconia or silicon carbide. Silicon carbide good to 1400 °C. Not interested in low volume production. Emphasized that zirconia needs to be stabilized in order to retain its structure as it cools below 1600 °C.

Ceradyne, Inc. (714) 549-0421 Doug Brown
California FAX (714) 549-5787 (Diana, secretary)

Received quote 7/18 for custom zirconia disk (no tube) of $2000/part, with 10-12 week delivery.

Cerametek (801) 972-2455 Raymond Cutler
Salt Lake City, UT FAX (801) 972-1925

Contacted regarding 1-piece zirconia disk/tube. Claimed that zirconia will creep, starting at 1200-1300 °C, and that silicon carbide would be better. They would add an oxidation resistant, and could do it themselves. They referred to 3 other companies. The silicon carbide idea was scrapped due to fire danger. Yes, this is the supplier of the ceramic fiber paper.

Coors Ceramics Co. (303) 278-4000 Kathleen Hartman
Structural Division FAX (303) 277-4453 Dick Rannie, mgr
600 9th St. (303) 278-4043
Golden, CO 80401

First contact 6/28. Sent FAX for 1-piece zirconia disk/tube design bid. They questioned whether design is slip-castable. Concluded 7/3 that flange a major problem for casting; injection molding may work better. Gave three other references. Can't cast as 1 big piece since 1.25" maximum thickness allowable, for cooling reasons.

On 8/17 received information on Mullite tubes, which may make a good, cheap heat shield material. Mullite is 60% alumina, 40% silica, will stand 1700 °C, and is formed by casting.

Coors Ceramics (303) 277-4914 Richard Okupniak
Colorado FAX (303) 277-4990

1-piece design source. Coors injection molding, primarily in alumina. Sent FAX 7/5. Said 7/24 they wouldn't do it.

Coors Oak Ridge (800) 331-2401 Kevin Sullivan
Oak Ridge, TN (615) 481-8021 John Ghinazzi, ext. 210
FAX (615) 481-8022

1-piece design source. Sent FAX 7/5. Suggested alternate designs 7/11.

Corning Glass Works (607) 974-4262
New York

Ceramics. Referred to their subsidiary, Zircoa.

Diamond Devices (916) 823-3333 Robert [illegible]

Diamond drill bit source. Claim 7/16 that cobalt bits won't work on zirconia. Can custom make bits at $35 each (for a dozen) to +-.0003" or for $70 each (for a dozen) to +-.0001". Depth to .030" if drill fast enough (200-300,000 rpm); 4-6 weeks for delivery. Bits in stock typically down to 0.006" diameter.

Ebtec West (800) EB-LASER Mark Rubcich
(714) 895-2725

Laser drilling source. Claim 7/11 their laser does a "perfect circle." No zirconia experience, but think it "possible." $250 minimum job (2 hours). Have 2 Yag lasers, but think CO_2 better to use.

GTE, Wesgo Division (415) 592-9440 Harry Bell
Howard Mizuhara, Tech. Dir.

Have no zirconia experience. Gave advice on zirconia tube-disk combination: Recommend max use temperature equal to 70% of melting point. For bonding ceramics, use paste of sintering aid (silica?). Use 5 degree taper maximum to avoid stress cracks, and fire the bond vertically. Said "bonding bigger headache than 1-piece design."

Laserfab, Inc. (415) 676-2238 Conrad

Laser drilling source. Claimed 7/5 they could do .003" hole to depth of .030-.035"; $250 for a couple of holes, but need green ceramic to do it.

Laseronics (213) 320-3700 Bob Harsh
Torrence, CA

Laser drilling contact. Warned of toxicity of zirconia vapor. Preferred working with very thin materials (0.010") for small holes. Could do hole 0.003" diameter to depth of 0.040"; diameter plus or minus 0.001", maybe 0.0005" for shallower hole. Minimum order $270, estimated our job would be $350. Need sample to make sure they can drill zirconia.

L.T.D. Ceramics (415) 366-8781 Mladen Vukic
FAX (415) 366-0946

To get hole in zirconia tube, recommends pushing a wire through green ceramic (a lost metal technique). Claim this doesn't work well for small diameter holes - they close up during firing.

McDanel Refractory (412) 843-8300 Renald Bartoe, sales mgr
Pennsylvania FAX (412) 843-5644 Chric Rogowski

Sent for quote on 1-piece zirconia disk/tube. They "not comfortable with the design," can't manufacture it. Could do custom zirconia disk (alone). Was to send quote; never did.

Midland Materials Research (517) 835-7604 Frank Fonzi
Michigan

Was referred to by Cerametek; contacted 7/11. Could use ATJ graphite from Union Carbide to make tube/disk as one piece, then CVD (Chemical Vapor Deposition) coat it with silicon carbide. Claim it is good to 1400 ^{o}C. Cost would be $1000 to $1500 for the finished piece.

New Castle Refractories (412) 654-7711 Jack Campbell
Pennsylvania FAX (412) 654-6322

Inquired regarding the 1-piece zirconia disk/tube. They don't do anything in zirconia.

Nilcra Ceramics, Inc. (800) 356-8171 Jim Sufka
180 West Park Ave. FAX (312) 941-7983
Elmhurst, IL 60126-3307

Claimed 7/11 that a green hole in ceramics will close if under 0.015" diameter. Yttria is a worse stabilizer for this application than magnesium. Their facility length constrained to 13" maximum. Recommend isopress the part instead of extruding it. Claimed 7/30 that they can't do one-piece zirconia disk/tube, but quoted $955/pair for custom disks 4" OD by 1.25" thick. Original phone numbers for Jim of (800) 356-8171, (708) 941-0221, FAX (708) 941-7983; those above from the 7/30 FAX.

Precision Technologies (415) 373-8324 Mark

Wire source. Contacted 6/21. Gave Ta properties as: resistivity = 0.124 Ohm*mm^2/m at 20 ^{o}C, c_p = 0.14 J/gK at 100 ^{o}C. Suggested to use 2 mm diameter stranded cable instead of solid wire; it could be bent easily above transition temperature of 600 ^{o}F.

Saureisen Cements Co. (412) 963-0303 Local Rep.: JA Crawford Co.
Pittsburgh, PA 15238 (213) 698-0901
Santa Fe Springs, CA

Ceramic cement source. Theirs are quite weak (100's of psi strength), and the highest temperature limit is 2600 ^{o}F (1700 K).

So. California Laser Products, Inc. (714) 676-8083 Ted Levin

Laser drilling. Not sure if can do zirconia; would need to try sample. Can do .003" hole +-.0005" to depth of .040" or less. $500 minimum job.

Texramics (800) 367-0547 Dr. Bill Corbett
Technical Ceramics Lab (404) 475-5371 Kent Kohnken

1-piece zirconia disk/tube design source. Sent FAX 7/3. FAX response 7/16 - they could do either design, but won't (not profitable enough). Could do custom disk too, but won't.

Titex Tools, Inc. (413) 774-6561
189 Laurel St. FAX (413) 774-2110
Greenfield, MA 01301

Source of very small diameter cobalt drill bits ('micro drills'). Other claim that cobalt won't handle fired zirconia - only green zirconia. Diamond bits preferred for this application. They didn't know if it would work.

Vesuvius McDanel Co. (412) 843-8300 Chris Rogowski
510 Ninth Ave FAX (412) 843-5644
PO Box 560
Beaver Falls, PA 15010-0560

Claimed 7/26 that they can't do one-piece zirconia disk/tube, or disk alone. Their work is all slip-cast, and the disk would have to be pressed.

Zircoa, Inc. (216) 248-0500 Connie Houghtaling
31501 Solon Rd. FAX (216) 248-8864 Barb Nemeier
Solon, OH 44139

FAX sent 6/29 for 1-piece design quote. By 7/6 rec'd FAX saying it wasn't worth their while. Also tried to get zirconia powder info, but the only type they carry is too coarse (2 mm to 150 μm).

??? (408) 432-6133 Richard Walker, and others.
San Jose, CA (800) 729-0292

Laser drilling source. 7/3 thought ruby laser best for ceramic, but 500 sW Yag might do it. No other details.

Part 3: Other contacts.

Andrew (415) 486-7462 (lab)
LBL Ceramics Shop (415) 486-5901 (sec'y)

Prime advisor on machinability of ceramics. He can make tapered hole in zirconia disk. Can also machine outside of zirconia tube to make groove for tantalum wire. Can not drill small hole in end of zirconia tube; their drills only go from 25 to 40 krpm; need 200 to 300 krpm for fine diamond bits.
Can mate and fire the disk and tube. Kiln can accomodate the 400 mm tube, and can provide up to 2800 F for firing. Suggested to secure end of zirconia tube during fifring, to prevent misalignment; might use alumina plate with hole in it, supported by several 9x4.5x2.5" kiln bricks. If hole drilling fails, could machine a tantalum insert for the end of the tube, which would have the nozzle in it.
tube/disk mating instructions, page 65.

Prof. Gary Chapman (415) 642-5300
6107 Etcheverry Hall

Helped with questions on the gas' material properties and equation of state.

Prof. Finnie (415) 642-1496
5135 Etcheverry Hall

Gave recommendations 7/12 for stress concentration factors (2-4); referenced Roark's formulas and Timeschenko (plates and shells). Important to round edges of ceramic to avoid stress concentrations.

Prof. Andy Glaser (415) 486-7262
LBL Material Science Lab

Was very skeptical 7/6 of Aremco's (cement) performance claims, later confirmed by their catalog: terms like 'temperature limit 3200 F,' 'temperature resistance,' seemed to admit no strength left at those temperatures.

Dr. Paul Hed (415) 422-9991
Lawrence Livermore Nat. Lab FAX (415) 422-7098

Quoted $1200 (16 hours at $75/hr) on 8/6 for precise laser hole drilling and cone formation in the end of the zirconia tube. Decided that precision not critical for now, and to go with cheaper laser drilling.

Prof. Pisano
Etcheverry Hall

Structures/mechanical design contact. Conversation 8/3. See Section 6.

Meg St. Hill (415) 486-6565

LBL Subcontracting contact.

Prof. Seth Sanders (415) 643-6680

EE contact. Said need to account for heat transfer to find wire temperature; current and material properties not enough. Mainly convection is important.

Al Shaw (415) 642-4585
2113 Etcheverry Hall

Contact for electrical feed-through into heater, and for gas safety shut-off valve.

John Souza (415) 642-3314
1168 Etcheverry Hall

Contact in machine shop, to determine capabilities to make the pressure vessel and endplates.

APPENDIX 2:

PARAMETRIC STUDIES OF HEATER THROAT SIZE

	A	B	C	D	E	F	G	H	I
1	ROBERT BOOKER								
2	10/3/90		GAS	J					
3	ME 299		N2	4.3627					
4	Summer, 1990		Air	4.7104					
5	Prof. Hurlbut, Advisor		NO	4.2883					
6			Ar	3.4012					
7			80/20 He/O2	5.0146					
8			95/5 He/O2	5.6604					
9			O2	4.2197					
10									
11	The pressures correspond to 500, 1000, 1500, 2000 and 100 psi, respectively.								
12	Extremes for D are: 3.64e-5 (for Argon at 2000 psi, 1000K, m dot .05 g/s)								
13	1.44e-3 (for 95/5 He/O2 at 100 psi, 2000K, m dot 1 g/s)								
14	Nominal mass flow rate is 0.1 g/s; range is from .05 to 1.0 g/s.								
15	Area ratio (Dmax/Dmin)^2 =		1566.78						
16									
17	GAS: N2					GAS: N2			
18	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
19	0.00005	3444200	1000	9.3475E-05		0.0001	3444200	1000	0.00013219
20	0.00005	3444200	1250	9.8838E-05		0.0001	3444200	1250	0.00013978
21	0.00005	3444200	1500	0.00010345		0.0001	3444200	1500	0.0001463
22	0.00005	3444200	1750	0.00010751		0.0001	3444200	1750	0.00015204
23	0.00005	3444200	2000	0.00011116		0.0001	3444200	2000	0.00015721
24	0.00005	6888400	1000	6.6097E-05		0.0001	6888400	1000	9.3475E-05
25	0.00005	6888400	1250	6.9889E-05		0.0001	6888400	1250	9.8838E-05
26	0.00005	6888400	1500	7.3148E-05		0.0001	6888400	1500	0.00010345
27	0.00005	6888400	1750	7.6022E-05		0.0001	6888400	1750	0.00010751
28	0.00005	6888400	2000	7.8603E-05		0.0001	6888400	2000	0.00011116
29	0.00005	10332600	1000	5.3968E-05		0.0001	10332600	1000	7.6322E-05
30	0.00005	10332600	1250	5.7064E-05		0.0001	10332600	1250	8.0701E-05
31	0.00005	10332600	1500	5.9725E-05		0.0001	10332600	1500	8.4464E-05
32	0.00005	10332600	1750	6.2072E-05		0.0001	10332600	1750	8.7783E-05
33	0.00005	10332600	2000	6.4179E-05		0.0001	10332600	2000	9.0763E-05
34	0.00005	13776800	1000	4.6738E-05		0.0001	13776800	1000	6.6097E-05
35	0.00005	13776800	1250	4.9419E-05		0.0001	13776800	1250	6.9889E-05
36	0.00005	13776800	1500	5.1724E-05		0.0001	13776800	1500	7.3148E-05
37	0.00005	13776800	1750	5.3756E-05		0.0001	13776800	1750	7.3022E-05
38	0.00005	13776800	2000	5.5581E-05		0.0001	13776800	2000	7.8603E-05
39	0.00005	688840	1000	0.00020902		0.0001	688840	1000	0.00029559
40	0.00005	688840	1250	0.00022101		0.0001	688840	1250	0.00031255
41	0.00005	688840	1500	0.00023132		0.0001	688840	1500	0.00032713
42	0.00005	688840	1750	0.0002404		0.0001	688840	1750	0.00033998
43	0.00005	688840	2000	0.00024856		0.0001	688840	2000	0.00035152
44									
45	GAS: N2					GAS: N2			
46	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
47	0.0005	3444200	1000	0.00029559		0.001	3444200	1000	0.00041803
48	0.0005	3444200	1250	0.00031255		0.001	3444200	1250	0.00044202
49	0.0005	3444200	1500	0.00032713		0.001	3444200	1500	0.00046263
50	0.0005	3444200	1750	0.00033998		0.001	3444200	1750	0.00048081
51	0.0005	3444200	2000	0.00035152		0.001	3444200	2000	0.00049713
52	0.0005	6888400	1000	0.00020902		0.001	6888400	1000	0.00029559
53	0.0005	6888400	1250	0.00022101		0.001	6888400	1250	0.00031255
54	0.0005	6888400	1500	0.00023132		0.001	6888400	1500	0.00032713
55	0.0005	6888400	1750	0.0002404		0.001	6888400	1750	0.00033998
56	0.0005	6888400	2000	0.00024856		0.001	6888400	2000	0.00035152
57	0.0005	10332600	1000	0.00017066		0.001	10332600	1000	0.00024135
58	0.0005	10332600	1250	0.00018045		0.001	10332600	1250	0.0002552
59	0.0005	10332600	1500	0.00018887		0.001	10332600	1500	0.0002671
60	0.0005	10332600	1750	0.00019629		0.001	10332600	1750	0.00027759
61	0.0005	10332600	2000	0.00020295		0.001	10332600	2000	0.00028702
62	0.0005	13776800	1000	0.0001478		0.001	13776800	1000	0.00020902

	A	B	C	D	E	F	G	H	I
63	0.0005	13776800	1250	0.00015628		0.001	13776800	1250	0.00022101
64	0.0005	13776800	1500	0.00016356		0.001	13776800	1500	0.00023132
65	0.0005	13776800	1750	0.00016999		0.001	13776800	1750	0.0002404
66	0.0005	13776800	2000	0.00017576		0.001	13776800	2000	0.00024856
67	0.0005	688340	1000	0.00066097		0.001	688840	1000	0.00093475
68	0.0005	688840	1250	0.00069889		0.001	688840	1250	0.00098838
69	0.0005	688840	1500	0.00073148		0.001	688840	1500	0.00103447
70	0.0005	688840	1750	0.00076022		0.001	688840	1750	0.00107512
71	0.0005	688840	2000	0.00078603		0.001	688840	2000	0.00111161
72									
73									
74	GAS: Air					GAS: Air			
75	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
76	0.00005	3444200	1000	0.00010092		0.0001	3444200	1000	0.00014273
77	0.00005	3444200	1250	0.00010672		0.0001	3444200	1250	0.00015092
78	0.00005	3444200	1500	0.00011169		0.0001	3444200	1500	0.00015796
79	0.00005	3444200	1750	0.00011608		0.0001	3444200	1750	0.00016416
80	0.00005	3444200	2000	0.00012002		0.0001	3444200	2000	0.00016973
81	0.00005	6888400	1000	7.1365E-05		0.0001	6888400	1000	0.00010092
82	0.00005	6888400	1250	7.5459E-05		0.0001	6888400	1250	0.00010672
83	0.00005	6888400	1500	7.8978E-05		0.0001	6888400	1500	0.00011169
84	0.00005	6888400	1750	8.2081E-05		0.0001	6888400	1750	0.00011608
85	0.00005	6888400	2000	8.4867E-05		0.0001	6888400	2000	0.00012002
86	0.00005	10332600	1000	5.8269E-05		0.0001	10332600	1000	8.2405E-05
87	0.00005	10332600	1250	6.1612E-05		0.0001	10332600	1250	8.7133E-05
88	0.00005	10332600	1500	6.4485E-05		0.0001	10332600	1500	9.1196E-05
89	0.00005	10332600	1750	6.7019E-05		0.0001	10332600	1750	9.4779E-05
90	0.00005	10332600	2000	6.9294E-05		0.0001	10332600	2000	9.7996E-05
91	0.00005	13775800	1000	5.0462E-05		0.0001	13776800	1000	7.1365E-05
92	0.00005	13776800	1250	5.3358E-05		0.0001	13776800	1250	7.5459E-05
93	0.00005	13776800	1500	5.5846E-05		0.0001	13776800	1500	7.8978E-05
94	0.00005	13776800	1750	5.804E-05		0.0001	13776800	1750	8.2081E-05
95	0.00005	13776800	2000	6.001E-05		0.0001	13776800	2000	8.4867E-05
96	0.00005	688840	1000	0.00022568		0.0001	688840	1000	0.00031915
97	0.00005	688840	1250	0.00023862		0.0001	688840	1250	0.00033746
98	0.00005	688840	1500	0.00024975		0.0001	688840	1500	0.0003532
99	0.00005	688840	1750	0.00025956		0.0001	688840	1750	0.00036708
100	0.00005	688840	2000	0.00026837		0.0001	688840	2000	0.00037954
101									
102	GAS: Air					GAS: Air			
103	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
104	0.0005	3444200	1000	0.00031915		0.001	3444200	1000	0.00045135
105	0.0005	3444200	1250	0.00033746		0.001	3444200	1250	0.00047724
106	0.0005	3444200	1500	0.0003532		0.001	3444200	1500	0.0004995
107	0.0005	3444200	1750	0.00036708		0.001	3444200	1750	0.00051913
108	0.0005	3444200	2000	0.00037954		0.001	3444200	2000	0.00053675
109	0.0005	6888400	1000	0.00022568		0.001	6888400	1000	0.00031915
110	0.0005	6888400	1250	0.00023862		0.001	6888400	1250	0.00033746
111	0.0005	6888400	1500	0.00024975		0.001	6888400	1500	0.0003532
112	0.0005	6888400	1750	0.00025956		0.001	6888400	1750	0.00036708
113	0.0005	6888400	2000	0.00026837		0.001	6888400	2000	0.00037954
114	0.0005	10332600	1000	0.00018426		0.001	10332600	1000	0.00026059
115	0.0005	10332600	1250	0.00019483		0.001	10332600	1250	0.00027554
116	0.0005	10332600	1500	0.00020392		0.001	10332600	1500	0.00028839
117	0.0005	10332600	1750	0.00021193		0.001	10332600	1750	0.00029972
118	0.0005	10332600	2000	0.00021913		0.001	10332600	2000	0.00030989
119	0.0005	13776800	1000	0.00015958		0.001	13776800	1000	0.00022568
120	0.0005	13776800	1250	0.00016873		0.001	13776800	1250	0.00023862
121	0.0005	13776800	1500	0.0001766		0.001	13776800	1500	0.00024975
122	0.0005	13776800	1750	0.00018354		0.001	13776800	1750	0.00025956
123	0.0005	13776800	2000	0.00018977		0.001	13776800	2000	0.00026837
124	0.0005	688840	1000	0.00071365		0.001	688840	1000	0.00100925
125	0.0005	688840	1250	0.00075459		0.001	688840	1250	0.00106715

	A	B	C	D	E	F	G	H	I
126	0.0005	688840	1500	0.00078978		0.001	688840	1500	0.00111692
127	0.0005	688840	1750	0.00082081		0.001	688840	1750	0.0011608
128	0.0005	688840	2000	0.00084867		0.001	688840	2000	0.00120021
129									
130									
131	GAS: NO					GAS: NO			
132	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
133	0.00005	3444200	1000	9.1881E-05		0.0001	3444200	1000	0.00012994
134	0.00005	3444200	1250	9.7152E-05		0.0001	3444200	1250	0.00013739
135	0.00005	3444200	1500	0.00010168		0.0001	3444200	1500	0.0001438
136	0.00005	3444200	1750	0.00010568		0.0001	3444200	1750	0.00014945
137	0.00005	3444200	2000	0.00010927		0.0001	3444200	2000	0.00015452
138	0.00005	6888400	1000	6.497E-05		0.0001	6888400	1000	9.1881E-05
139	0.00005	6888400	1250	6.8697E-05		0.0001	6888400	1250	9.7152E-05
140	0.00005	6888400	1500	7.1901E-05		0.0001	6888400	1500	0.00010168
141	0.00005	6888400	1750	7.4726E-05		0.0001	6888400	1750	0.00010568
142	0.00005	6888400	2000	7.7262E-05		0.0001	6888400	2000	0.00010927
143	0.00005	10332600	1000	5.3048E-05		0.0001	10332600	1000	7.5021E-05
144	0.00005	10332600	1250	5.6091E-05		0.0001	10332600	1250	7.9325E-05
145	0.00005	10332600	1500	5.8707E-05		0.0001	10332600	1500	8.3024E-05
146	0.00005	10332600	1750	6.1013E-05		0.0001	10332600	1750	8.6286E-05
147	0.00005	10332600	2000	6.3085E-05		0.0001	10332600	2000	8.9215E-05
148	0.00005	13776800	1000	4.5941E-05		0.0001	13776800	1000	6.497E-05
149	0.00005	13776800	1250	4.8576E-05		0.0001	13776800	1250	6.8697E-05
150	0.00005	13776800	1500	5.0842E-05		0.0001	13776800	1500	7.1901E-05
151	0.00005	13776800	1750	5.2839E-05		0.0001	13776800	1750	7.4726E-05
152	0.00005	13776800	2000	5.4633E-05		0.0001	13776800	2000	7.7262E-05
153	0.00005	688840	1000	0.00020545		0.0001	688840	1000	0.00029055
154	0.00005	688840	1250	0.00021724		0.0001	688840	1250	0.00030722
155	0.00005	688840	1500	0.00022737		0.0001	688840	1500	0.00032155
156	0.00005	688840	1750	0.0002363		0.0001	688840	1750	0.00033418
157	0.00005	688840	2000	0.00024433		0.0001	688840	2000	0.00034553
158									
159	GAS: NO					GAS: NO			
160	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
161	0.0005	3444200	1000	0.00029055		0.001	3444200	1000	0.0004109
162	0.0005	3444200	1250	0.00030722		0.001	3444200	1250	0.00043448
163	0.0005	3444200	1500	0.00032155		0.001	3444200	1500	0.00045474
164	0.0005	3444200	1750	0.00033418		0.001	3444200	1750	0.00047261
165	0.0005	3444200	2000	0.00034553		0.001	3444200	2000	0.00048865
166	0.0005	6888400	1000	0.00020545		0.001	6888400	1000	0.00029055
167	0.0005	6888400	1250	0.00021724		0.001	6888400	1250	0.00030722
168	0.0005	6888400	1500	0.00022737		0.001	6888400	1500	0.00032155
169	0.0005	6888400	1750	0.0002363		0.001	6888400	1750	0.00033418
170	0.0005	6888400	2000	0.00024433		0.001	6888400	2000	0.00034553
171	0.0005	10332600	1000	0.00016775		0.001	10332600	1000	0.00023724
172	0.0005	10332600	1250	0.00017738		0.001	10332600	1250	0.00025085
173	0.0005	10332600	1500	0.00018565		0.001	10332600	1500	0.00026254
174	0.0005	10332600	1750	0.00019294		0.001	10332600	1750	0.00027286
175	0.0005	10332600	2000	0.00019949		0.001	10332600	2000	0.00028212
176	0.0005	13776800	1000	0.00014528		0.001	13776800	1000	0.00020545
177	0.0005	13776800	1250	0.00015361		0.001	13776800	1250	0.00021724
178	0.0005	13776800	1500	0.00016078		0.001	13776800	1500	0.00022737
179	0.0005	13776800	1750	0.00016709		0.001	13776800	1750	0.0002363
180	0.0005	13776800	2000	0.00017276		0.001	13776800	2000	0.00024433
181	0.0005	688840	1000	0.0006497		0.001	688840	1000	0.00091881
182	0.0005	688840	1250	0.00068697		0.001	688840	1250	0.00097152
183	0.0005	688840	1500	0.00071901		0.001	688840	1500	0.00101683
184	0.0005	688840	1750	0.00074726		0.001	688840	1750	0.00105678
185	0.0005	688840	2000	0.00077262		0.001	688840	2000	0.00109266
186									
187									
188	GAS: Argon					GAS: Ar			

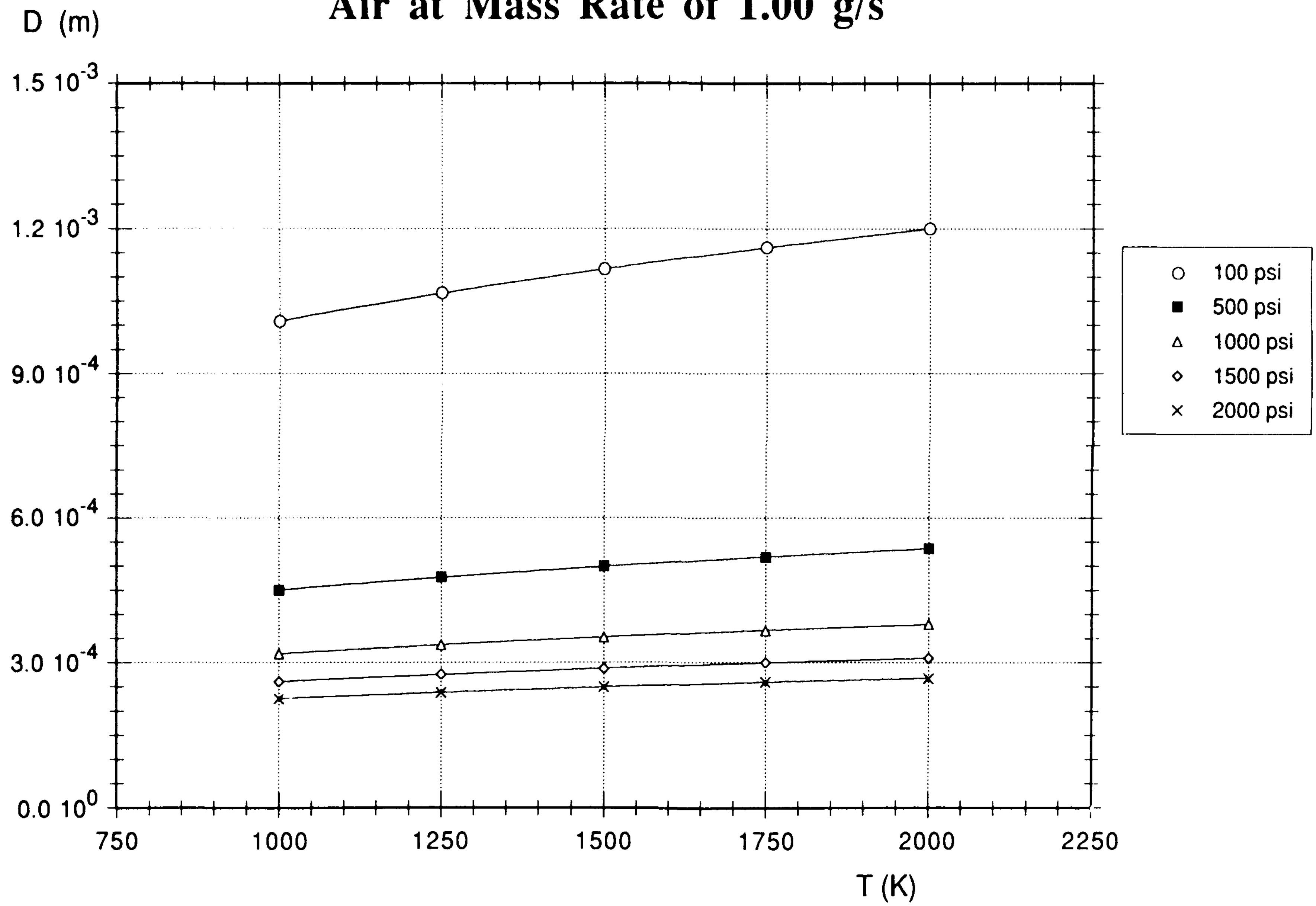
	A	B	C	D	E	F	G	H	I
189	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
190	0.00005	3444200	1000	7.2874E-05		0.0001	3444200	1000	0.00010306
191	0.00005	3444200	1250	7.7055E-05		0.0001	3444200	1250	0.00010897
192	0.00005	3444200	1500	8.0648E-05		0.0001	3444200	1500	0.00011405
193	0.00005	3444200	1750	8.3817E-05		0.0001	3444200	1750	0.00011854
194	0.00005	3444200	2000	8.6662E-05		0.0001	3444200	2000	0.00012256
195	0.00005	6888400	1000	5.153E-05		0.0001	6888400	1000	7.2874E-05
196	0.00005	6888400	1250	5.4486E-05		0.0001	6888400	1250	7.7055E-05
197	0.00005	6888400	1500	5.7027E-05		0.0001	6888400	1500	8.0648E-05
198	0.00005	6888400	1750	5.9268E-05		0.0001	6888400	1750	8.3817E-05
199	0.00005	6888400	2000	6.128E-05		0.0001	6888400	2000	8.6662E-05
200	0.00005	10332600	1000	4.2074E-05		0.0001	10332600	1000	5.9501E-05
201	0.00005	10332600	1250	4.4488E-05		0.0001	10332600	1250	6.2915E-05
202	0.00005	10332600	1500	4.6562E-05		0.0001	10332600	1500	6.5849E-05
203	0.00005	10332600	1750	4.8392E-05		0.0001	10332600	1750	6.8436E-05
204	0.00005	10332600	2000	5.0035E-05		0.0001	10332600	2000	7.076E-05
205	0.00005	13776800	1000	3.6437E-05		0.0001	13776800	1000	5.153E-05
206	0.00005	13776800	1250	3.8527E-05		0.0001	13776800	1250	5.4486E-05
207	0.00005	13776800	1500	4.0324E-05		0.0001	13776800	1500	5.7027E-05
208	0.00005	13776800	1750	4.1909E-05		0.0001	13776800	1750	5.9268E-05
209	0.00005	13776800	2000	4.3331E-05		0.0001	13776800	2000	6.128E-05
210	0.00005	688840	1000	0.00016295		0.0001	688840	1000	0.00023045
211	0.00005	688840	1250	0.0001723		0.0001	688840	1250	0.00024367
212	0.00005	688840	1500	0.00018034		0.0001	688840	1500	0.00025503
213	0.00005	688840	1750	0.00018742		0.0001	688840	1750	0.00026505
214	0.00005	688840	2000	0.00019378		0.0001	688840	2000	0.00027405
215									
216	GAS: Ar					GAS: Ar			
217	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
218	0.0005	3444200	1000	0.00023045		0.001	3444200	1000	0.0003259
219	0.0005	3444200	1250	0.00024367		0.001	3444200	1250	0.0003446
220	0.0005	3444200	1500	0.00025503		0.001	3444200	1500	0.00036067
221	0.0005	3444200	1750	0.00026505		0.001	3444200	1750	0.00037484
222	0.0005	3444200	2000	0.00027405		0.001	3444200	2000	0.00038757
223	0.0005	6888400	1000	0.00016295		0.001	6888400	1000	0.00023045
224	0.0005	6888400	1250	0.0001723		0.001	6888400	1250	0.00024367
225	0.0005	6888400	1500	0.00018034		0.001	6888400	1500	0.00025503
226	0.0005	6888400	1750	0.00018742		0.001	6888400	1750	0.00026505
227	0.0005	6888400	2000	0.00019378		0.001	6888400	2000	0.00027405
228	0.0005	10332600	1000	0.00013305		0.001	10332600	1000	0.00018816
229	0.0005	10332600	1250	0.00014068		0.001	10332600	1250	0.00019896
230	0.0005	10332600	1500	0.00014724		0.001	10332600	1500	0.00020823
231	0.0005	10332600	1750	0.00015303		0.001	10332600	1750	0.00021641
232	0.0005	10332600	2000	0.00015822		0.001	10332600	2000	0.00022376
233	0.0005	13776800	1000	0.00011522		0.001	13776800	1000	0.00016295
234	0.0005	13776800	1250	0.00012183		0.001	13776800	1250	0.0001723
235	0.0005	13776800	1500	0.00012752		0.001	13776800	1500	0.00018034
236	0.0005	13776800	1750	0.00013253		0.001	13776800	1750	0.00018742
237	0.0005	13776800	2000	0.00013703		0.001	13776800	2000	0.00019378
238	0.0005	688840	1000	0.0005153		0.001	688840	1000	0.00072874
239	0.0005	688840	1250	0.00054486		0.001	688840	1250	0.00077055
240	0.0005	688840	1500	0.00057027		0.001	688840	1500	0.00080648
241	0.0005	688840	1750	0.00059268		0.001	688840	1750	0.00083817
242	0.0005	688840	2000	0.0006128		0.001	688840	2000	0.00086662
243									
244									
245	GAS: 80/20 He/O2					GAS: 80/20			
246	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
247	0.00005	3444200	1000	0.00010744		0.0001	3444200	1000	0.00015195
248	0.00005	3444200	1250	0.00011361		0.0001	3444200	1250	0.00016066
249	0.00005	3444200	1500	0.0001189		0.0001	3444200	1500	0.00016816
250	0.00005	3444200	1750	0.00012358		0.0001	3444200	1750	0.00017476
251	0.00005	3444200	2000	0.00012777		0.0001	3444200	2000	0.0001807

	A	B	C	D	E	F	G	H	I
252	0.00005	6888400	1000	7.5973E-05		0.0001	6888400	1000	0.00010744
253	0.00005	6888400	1250	8.0332E-05		0.0001	6888400	1250	0.00011361
254	0.00005	6888400	1500	8.4078E-05		0.0001	6888400	1500	0.0001189
255	0.00005	6888400	1750	8.7382E-05		0.0001	6888400	1750	0.00012358
256	0.00005	6888400	2000	9.0348E-05		0.0001	6888400	2000	0.00012777
257	0.00005	10332600	1000	6.2032E-05		0.0001	10332600	1000	8.7727E-05
258	0.00005	10332600	1250	6.5591E-05		0.0001	10332600	1250	9.276E-05
259	0.00005	10332600	1500	6.865E-05		0.0001	10332600	1500	9.7085E-05
260	0.00005	10332600	1750	7.1347E-05		0.0001	10332600	1750	0.0001009
261	0.00005	10332600	2000	7.3769E-05		0.0001	10332600	2000	0.00010433
262	0.00005	13776800	1000	5.3721E-05		0.0001	13776800	1000	7.5973E-05
263	0.00005	13776800	1250	5.6803E-05		0.0001	13776800	1250	8.0332E-05
264	0.00005	13776800	1500	5.9452E-05		0.0001	13776800	1500	8.4078E-05
265	0.00005	13776800	1750	6.1788E-05		0.0001	13776800	1750	8.7382E-05
266	0.00005	13776800	2000	6.3886E-05		0.0001	13776800	2000	9.0348E-05
267	0.00005	688840	1000	0.00024025		0.0001	688840	1000	0.00033976
268	0.00005	688840	1250	0.00025403		0.0001	688840	1250	0.00035926
269	0.00005	688840	1500	0.00026588		0.0001	688840	1500	0.00037601
270	0.00005	688840	1750	0.00027633		0.0001	688840	1750	0.00039078
271	0.00005	688840	2000	0.00028571		0.0001	688840	2000	0.00040405
272									
273	GAS: 80/20					GAS: 80/20			
274	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
275	0.0005	3444200	1000	0.00033976		0.001	3444200	1000	0.0004805
276	0.0005	3444200	1250	0.00035926		0.001	3444200	1250	0.00050807
277	0.0005	3444200	1500	0.00037601		0.001	3444200	1500	0.00053176
278	0.0005	3444200	1750	0.00039078		0.001	3444200	1750	0.00055265
279	0.0005	3444200	2000	0.00040405		0.001	3444200	2000	0.00057141
280	0.0005	6888400	1000	0.00024025		0.001	6888400	1000	0.00033976
281	0.0005	6888400	1250	0.00025403		0.001	6888400	1250	0.00035926
282	0.0005	6888400	1500	0.00026588		0.001	6888400	1500	0.00037601
283	0.0005	6888400	1750	0.00027633		0.001	6888400	1750	0.00039078
284	0.0005	6888400	2000	0.00028571		0.001	6888400	2000	0.00040405
285	0.0005	10332600	1000	0.00019616		0.001	10332600	1000	0.00027742
286	0.0005	10332600	1250	0.00020742		0.001	10332600	1250	0.00029333
287	0.0005	10332600	1500	0.00021709		0.001	10332600	1500	0.00030701
288	0.0005	10332600	1750	0.00022562		0.001	10332600	1750	0.00031907
289	0.0005	10332600	2000	0.00023328		0.001	10332600	2000	0.00032991
290	0.0005	13776800	1000	0.00016988		0.001	13776800	1000	0.00024025
291	0.0005	13776800	1250	0.00017963		0.001	13776800	1250	0.00025403
292	0.0005	13776800	1500	0.00018801		0.001	13776800	1500	0.00026588
293	0.0005	13776800	1750	0.00019539		0.001	13776800	1750	0.00027633
294	0.0005	13776800	2000	0.00020202		0.001	13776800	2000	0.00028571
295	0.0005	688840	1000	0.00075973		0.001	688840	1000	0.00107443
296	0.0005	688840	1250	0.00080332		0.001	688840	1250	0.00113607
297	0.0005	688840	1500	0.00084078		0.001	688840	1500	0.00118905
298	0.0005	688840	1750	0.00087382		0.001	688840	1750	0.00123577
299	0.0005	688840	2000	0.00090348		0.001	688840	2000	0.00127772
300									
301									
302	GAS: 95/5 He/O2					GAS: 95/5			
303	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
304	0.00005	3444200	1000	0.00012128		0.0001	3444200	1000	0.00017152
305	0.00005	3444200	1250	0.00012824		0.0001	3444200	1250	0.00018136
306	0.00005	3444200	1500	0.00013422		0.0001	3444200	1500	0.00018981
307	0.00005	3444200	1750	0.00013949		0.0001	3444200	1750	0.00019727
308	0.00005	3444200	2000	0.00014423		0.0001	3444200	2000	0.00020397
309	0.00005	6888400	1000	8.5758E-05		0.0001	6888400	1000	0.00012128
310	0.00005	6888400	1250	9.0678E-05		0.0001	6888400	1250	0.00012824
311	0.00005	6888400	1500	9.4906E-05		0.0001	6888400	1500	0.00013422
312	0.00005	6888400	1750	9.8635E-05		0.0001	6888400	1750	0.00013949
313	0.00005	6888400	2000	0.00010198		0.0001	6888400	2000	0.00014423
314	0.00005	10332600	1000	7.0021E-05		0.0001	10332600	1000	9.9024E-05

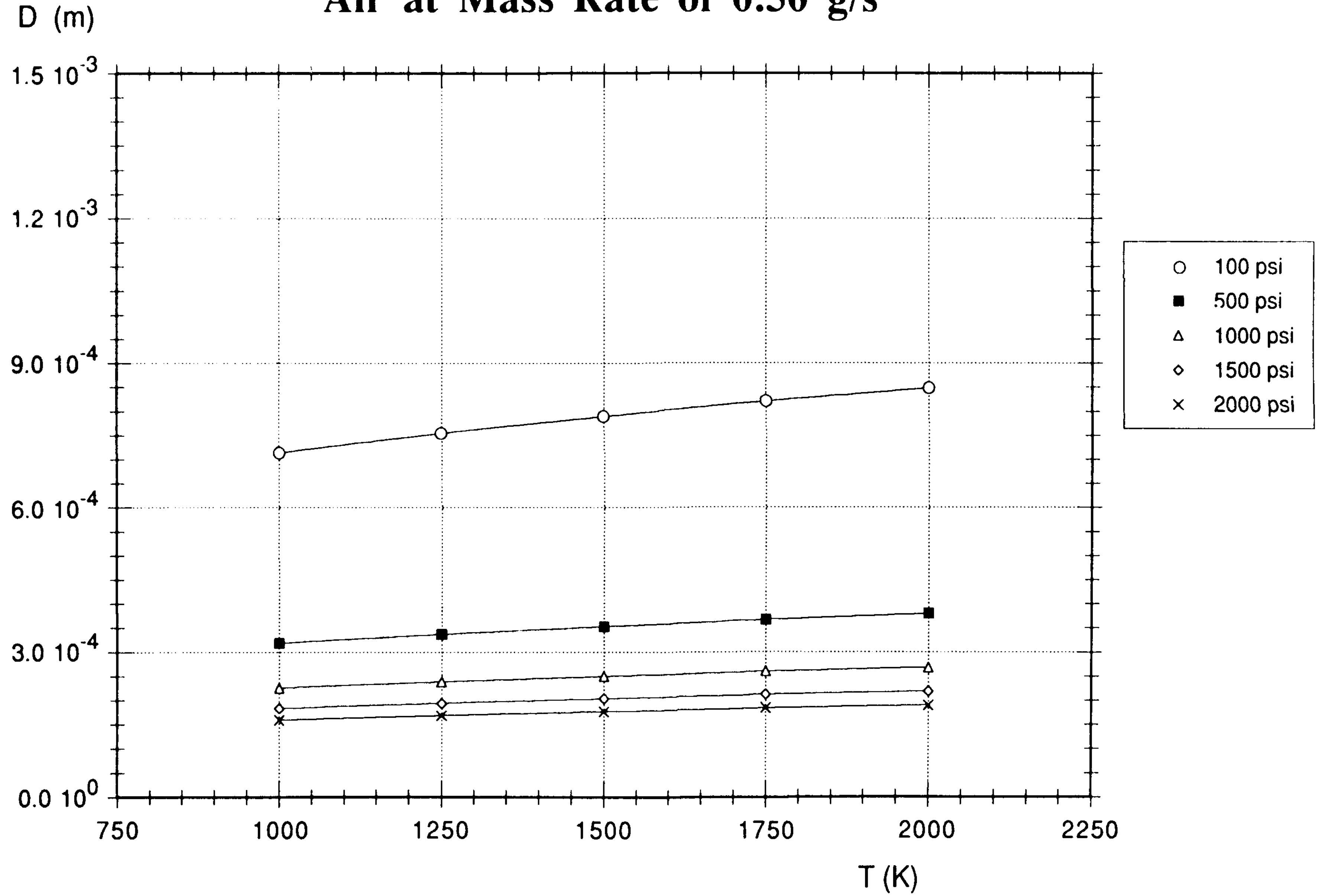
	A	B	C	D	E	F	G	H	I
315	0.00005	10332600	1250	7.4038E-05		0.0001	10332600	1250	0.00010471
316	0.00005	10332600	1500	7.7491E-05		0.0001	10332600	1500	0.00010959
317	0.00005	10332600	1750	8.0535E-05		0.0001	10332600	1750	0.00011389
318	0.00005	10332600	2000	8.3269E-05		0.0001	10332600	2000	0.00011776
319	0.00005	13776800	1000	6.064E-05		0.0001	13776800	1000	8.5758E-05
320	0.00005	13776800	1250	6.4119E-05		0.0001	13776800	1250	9.0678E-05
321	0.00005	13776800	1500	6.7109E-05		0.0001	13776800	1500	9.4906E-05
322	0.00005	13776800	1750	6.9746E-05		0.0001	13776800	1750	9.8635E-05
323	0.00005	13776800	2000	7.2113E-05		0.0001	13776800	2000	0.00010198
324	0.00005	688840	1000	0.00027119		0.0001	688840	1000	0.00038352
325	0.00005	688840	1250	0.00028675		0.0001	688840	1250	0.00040552
326	0.00005	688840	1500	0.00030012		0.0001	688840	1500	0.00042443
327	0.00005	688840	1750	0.00031191		0.0001	688840	1750	0.00044111
328	0.00005	688840	2000	0.0003225		0.0001	688840	2000	0.00045608
329									
330	GAS: 95/5					GAS: 95/5			
331	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
332	0.0005	3444200	1000	0.00038352		0.001	3444200	1000	0.00054238
333	0.0005	3444200	1250	0.00040552		0.001	3444200	1250	0.0005735
334	0.0005	3444200	1500	0.00042443		0.001	3444200	1500	0.00060024
335	0.0005	3444200	1750	0.00044111		0.001	3444200	1750	0.00062382
336	0.0005	3444200	2000	0.00045608		0.001	3444200	2000	0.000645
337	0.0005	6888400	1000	0.00027119		0.001	6888400	1000	0.00038352
338	0.0005	6888400	1250	0.00028675		0.001	6888400	1250	0.00040552
339	0.0005	6888400	1500	0.00030012		0.001	6888400	1500	0.00042443
340	0.0005	6888400	1750	0.00031191		0.001	6888400	1750	0.00044111
341	0.0005	6888400	2000	0.0003225		0.001	6888400	2000	0.00045608
342	0.0005	10332600	1000	0.00022143		0.001	10332600	1000	0.00031314
343	0.0005	10332600	1250	0.00023413		0.001	10332600	1250	0.00033111
344	0.0005	10332600	1500	0.00024505		0.001	10332600	1500	0.00034655
345	0.0005	10332600	1750	0.00025468		0.001	10332600	1750	0.00036017
346	0.0005	10332600	2000	0.00026332		0.001	10332600	2000	0.00037239
347	0.0005	13776800	1000	0.00019176		0.001	13776800	1000	0.00027119
348	0.0005	13776800	1250	0.00020276		0.001	13776800	1250	0.00028675
349	0.0005	13776800	1500	0.00021222		0.001	13776800	1500	0.00030012
350	0.0005	13776800	1750	0.00022056		0.001	13776800	1750	0.00031191
351	0.0005	13776800	2000	0.00022804		0.001	13776800	2000	0.0003225
352	0.0005	688840	1000	0.00085758		0.001	688840	1000	0.0012128
353	0.0005	688840	1250	0.00090678		0.001	688840	1250	0.00128238
354	0.0005	688840	1500	0.00094906		0.001	688840	1500	0.00134218
355	0.0005	688840	1750	0.00098635		0.001	688840	1750	0.00139491
356	0.0005	688840	2000	0.00101984		0.001	688840	2000	0.00144227
357									
358									
359	GAS: O2					GAS: O2			
360	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
361	0.00005	3444200	1000	9.0411E-05		0.0001	3444200	1000	0.00012786
362	0.00005	3444200	1250	9.5598E-05		0.0001	3444200	1250	0.0001352
363	0.00005	3444200	1500	0.00010006		0.0001	3444200	1500	0.0001415
364	0.00005	3444200	1750	0.00010399		0.0001	3444200	1750	0.00014706
365	0.00005	3444200	2000	0.00010752		0.0001	3444200	2000	0.00015205
366	0.00005	6888400	1000	6.393E-05		0.0001	6888400	1000	9.0411E-05
367	0.00005	6888400	1250	6.7598E-05		0.0001	6888400	1250	9.5598E-05
368	0.00005	6888400	1500	7.0751E-05		0.0001	6888400	1500	0.00010006
369	0.00005	6888400	1750	7.353E-05		0.0001	6888400	1750	0.00010399
370	0.00005	6888400	2000	7.6026E-05		0.0001	6888400	2000	0.00010752
371	0.00005	10332600	1000	5.2199E-05		0.0001	10332600	1000	7.382E-05
372	0.00005	10332600	1250	5.5194E-05		0.0001	10332600	1250	7.8056E-05
373	0.00005	10332600	1500	5.7768E-05		0.0001	10332600	1500	8.1696E-05
374	0.00005	10332600	1750	6.0037E-05		0.0001	10332600	1750	8.4906E-05
375	0.00005	10332600	2000	6.2075E-05		0.0001	10332600	2000	8.7788E-05
376	0.00005	13776800	1000	4.5206E-05		0.0001	13776800	1000	6.393E-05
377	0.00005	13776800	1250	4.7799E-05		0.0001	13776800	1250	6.7598E-05

	A	B	C	D	E	F	G	H	I
378	0.00005	13776800	1500	5.0028E-05		0.0001	13776800	1500	7.0751E-05
379	0.00005	13776800	1750	5.1994E-05		0.0001	13776800	1750	7.353E-05
380	0.00005	13776800	2000	5.3759E-05		0.0001	13776800	2000	7.6026E-05
381	0.00005	688840	1000	0.00020217		0.0001	688840	1000	0.00028591
382	0.00005	688840	1250	0.00021376		0.0001	688840	1250	0.00030231
383	0.00005	688840	1500	0.00022373		0.0001	688840	1500	0.00031641
384	0.00005	688840	1750	0.00023252		0.0001	688840	1750	0.00032884
385	0.00005	688840	2000	0.00024042		0.0001	688840	2000	0.00034
386									
387	GAS: O2					GAS: O2			
388	Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)		Mass Rate (kg/s)	P (N/m^2)	T (K)	D (m)
389	0.0005	3444200	1000	0.00028591		0.001	3444200	1000	0.00040433
390	0.0005	3444200	1250	0.00030231		0.001	3444200	1250	0.00042753
391	0.0005	3444200	1500	0.00031641		0.001	3444200	1500	0.00044747
392	0.0005	3444200	1750	0.00032884		0.001	3444200	1750	0.00046505
393	0.0005	3444200	2000	0.00034		0.001	3444200	2000	0.00048083
394	0.0005	6888400	1000	0.00020217		0.001	6888400	1000	0.00028591
395	0.0005	6888400	1250	0.00021376		0.001	6888400	1250	0.00030231
396	0.0005	6888400	1500	0.00022373		0.001	6888400	1500	0.00031641
397	0.0005	6888400	1750	0.00023252		0.001	6888400	1750	0.00032884
398	0.0005	6888400	2000	0.00024042		0.001	6888400	2000	0.00034
399	0.0005	10332600	1000	0.00016507		0.001	10332600	1000	0.00023344
400	0.0005	10332600	1250	0.00017454		0.001	10332600	1250	0.00024683
401	0.0005	10332600	1500	0.00018268		0.001	10332600	1500	0.00025834
402	0.0005	10332600	1750	0.00018985		0.001	10332600	1750	0.0002685
403	0.0005	10332600	2000	0.0001963		0.001	10332600	2000	0.00027761
404	0.0005	13776800	1000	0.00014295		0.001	13776800	1000	0.00020217
405	0.0005	13776800	1250	0.00015115		0.001	13776800	1250	0.00021376
406	0.0005	13776800	1500	0.0001582		0.001	13776800	1500	0.00022373
407	0.0005	13776800	1750	0.00016442		0.001	13776800	1750	0.00023252
408	0.0005	13776800	2000	0.00017		0.001	13776800	2000	0.00024042
409	0.0005	688840	1000	0.0006393		0.001	688840	1000	0.00090411
410	0.0005	688840	1250	0.00067598		0.001	688840	1250	0.00095598
411	0.0005	688840	1500	0.00070751		0.001	688840	1500	0.00100056
412	0.0005	688840	1750	0.0007353		0.001	688840	1750	0.00103988
413	0.0005	688840	2000	0.00076026		0.001	688840	2000	0.00107518

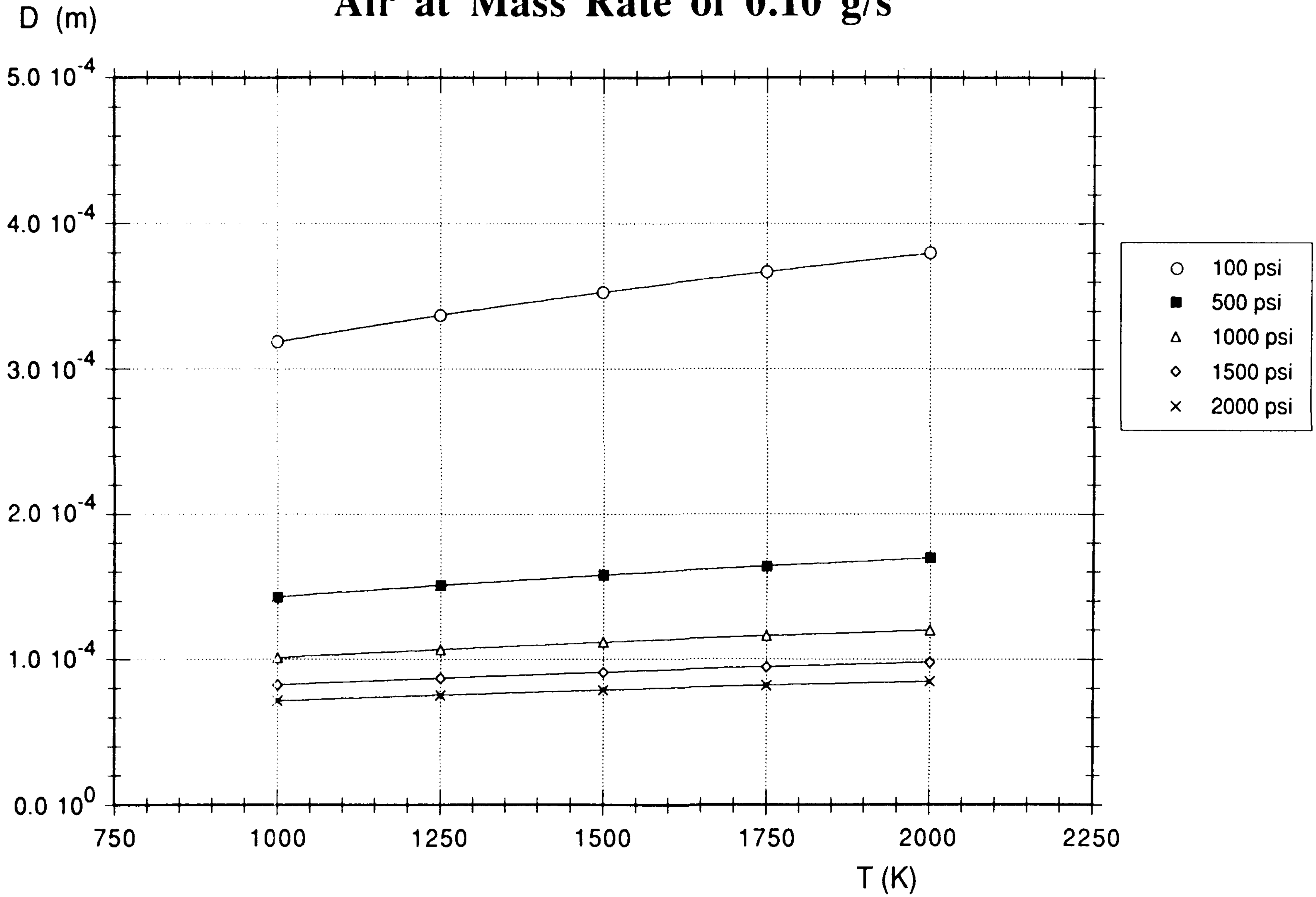
Air at Mass Rate of 1.00 g/s



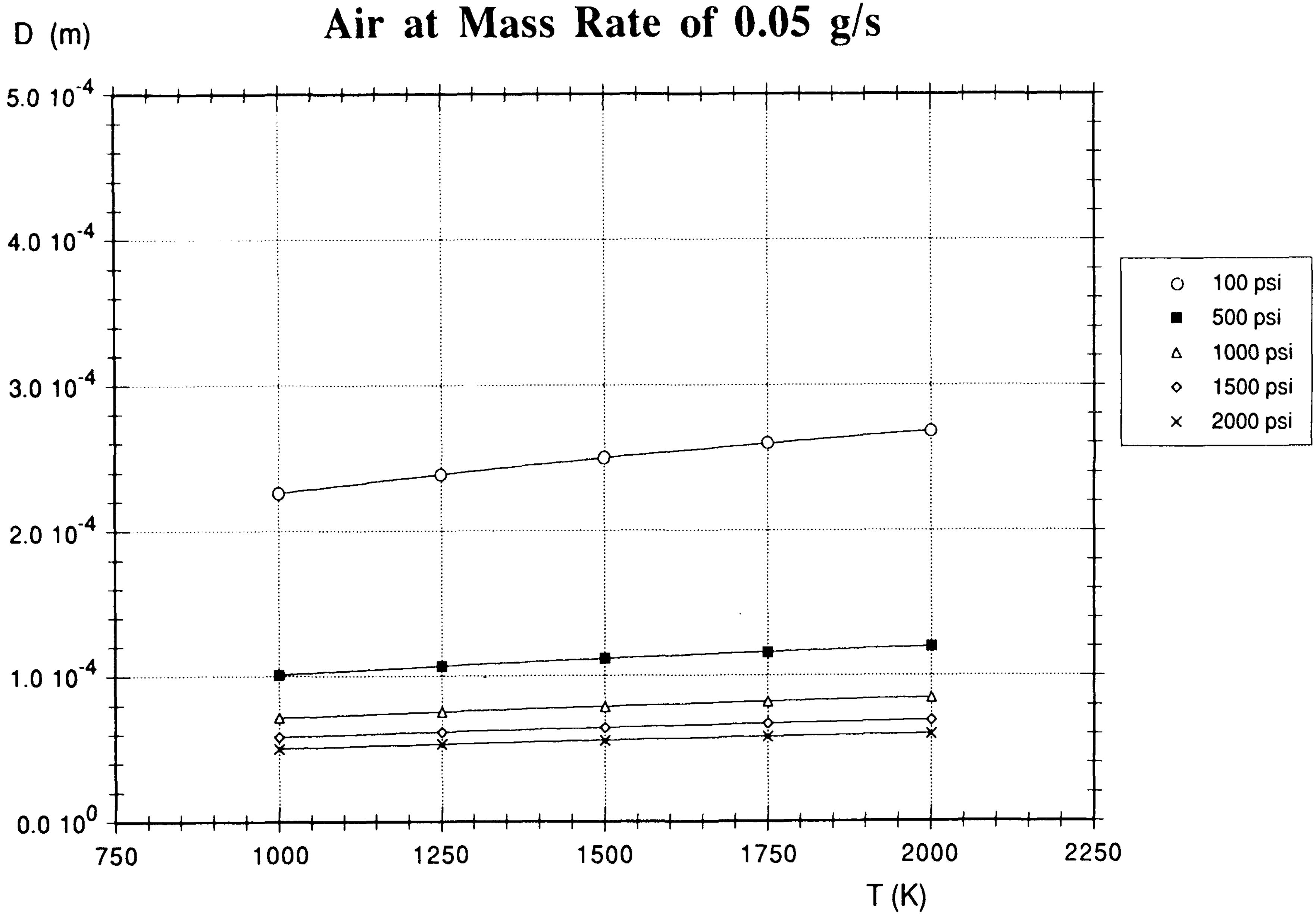
Air at Mass Rate of 0.50 g/s



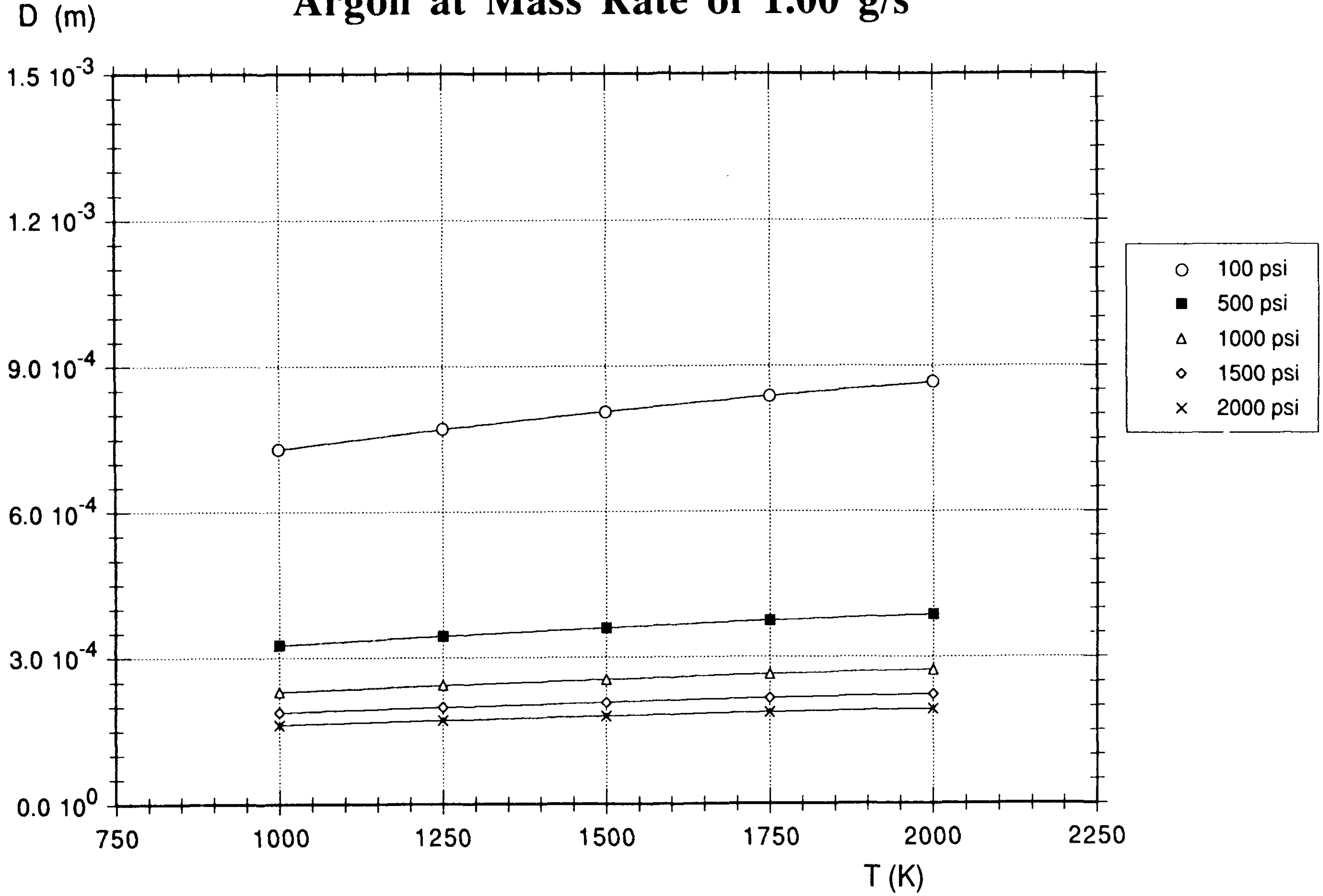
Air at Mass Rate of 0.10 g/s



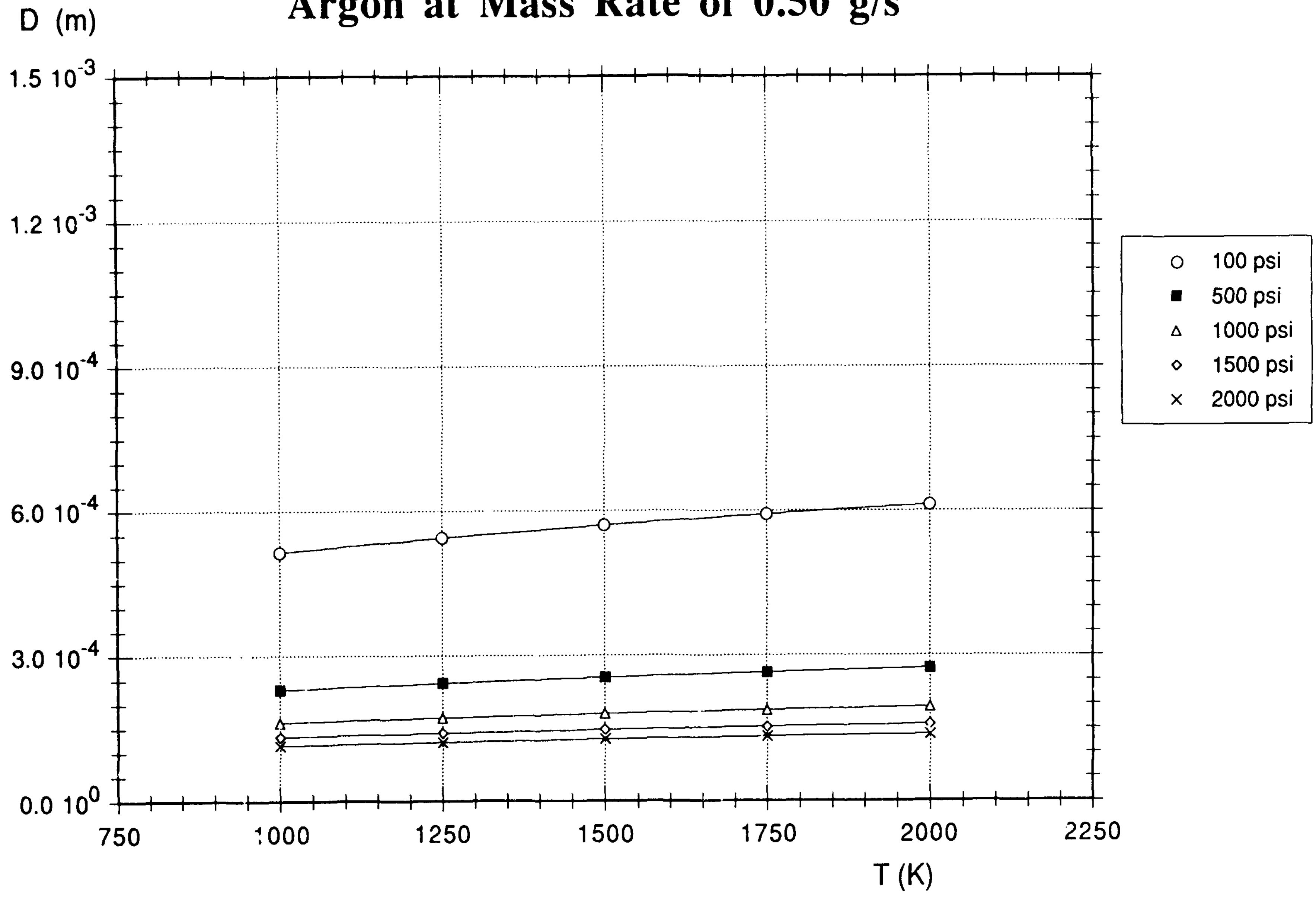
Air at Mass Rate of 0.05 g/s



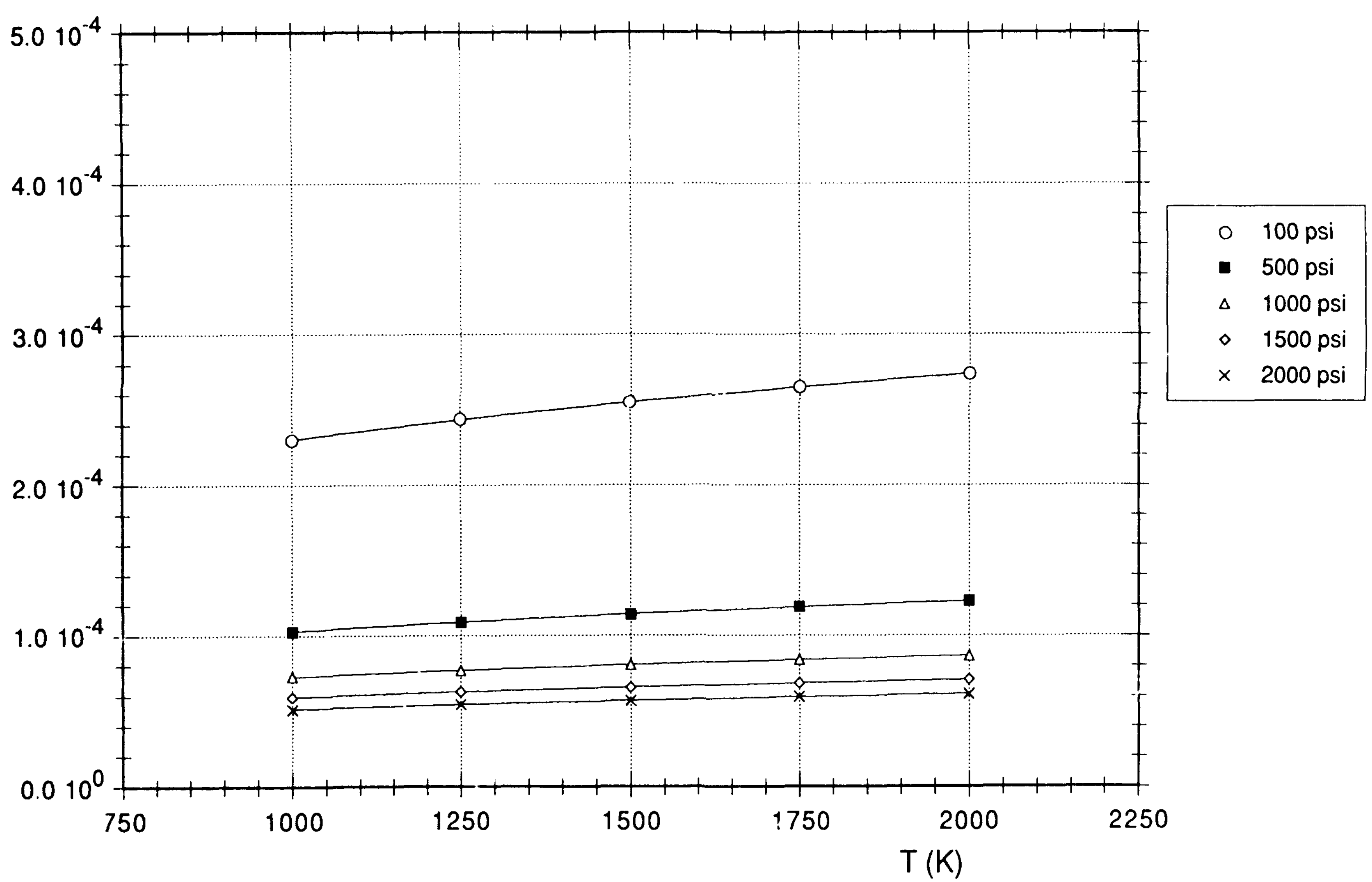
Argon at Mass Rate of 1.00 g/s



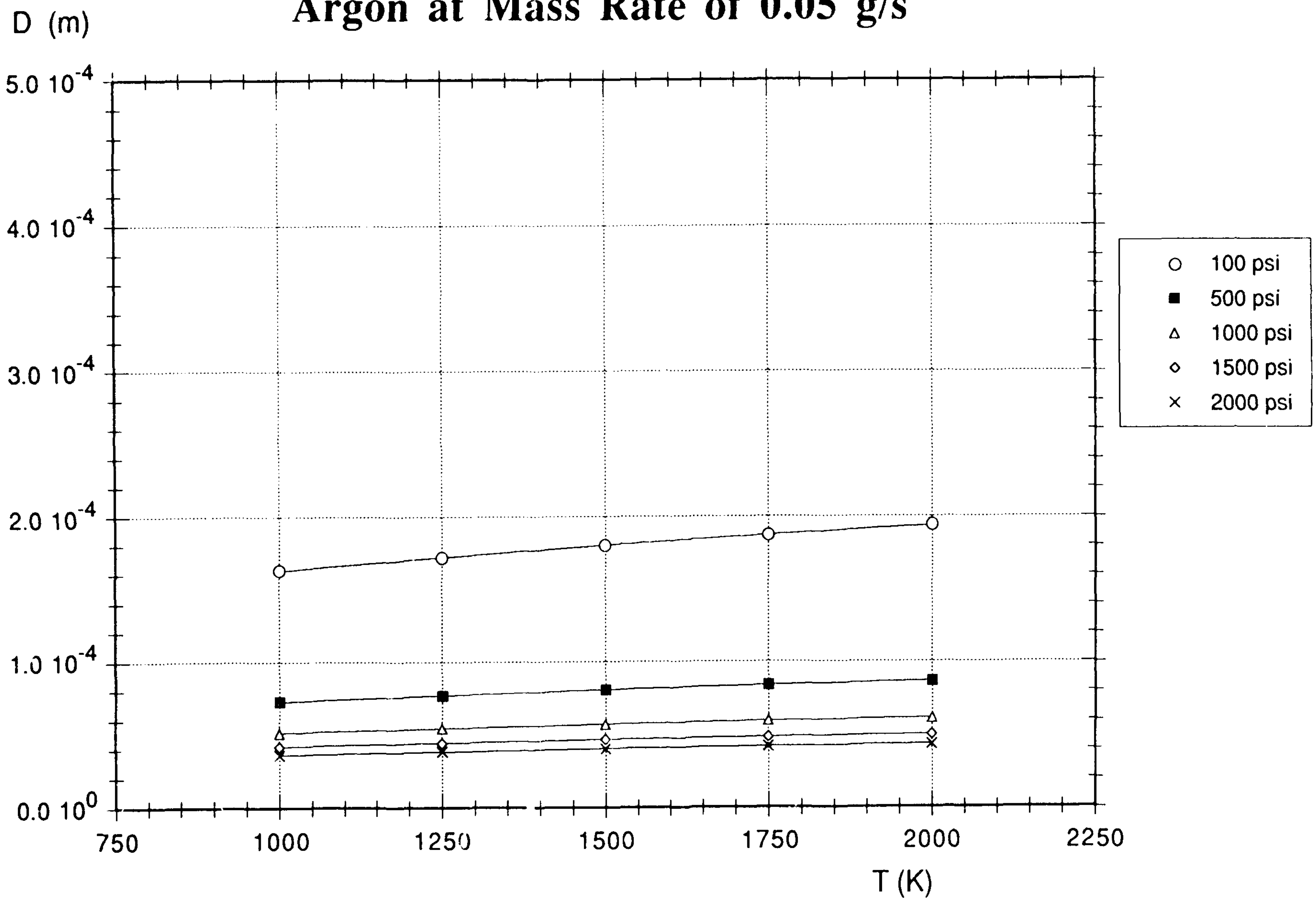
Argon at Mass Rate of 0.50 g/s



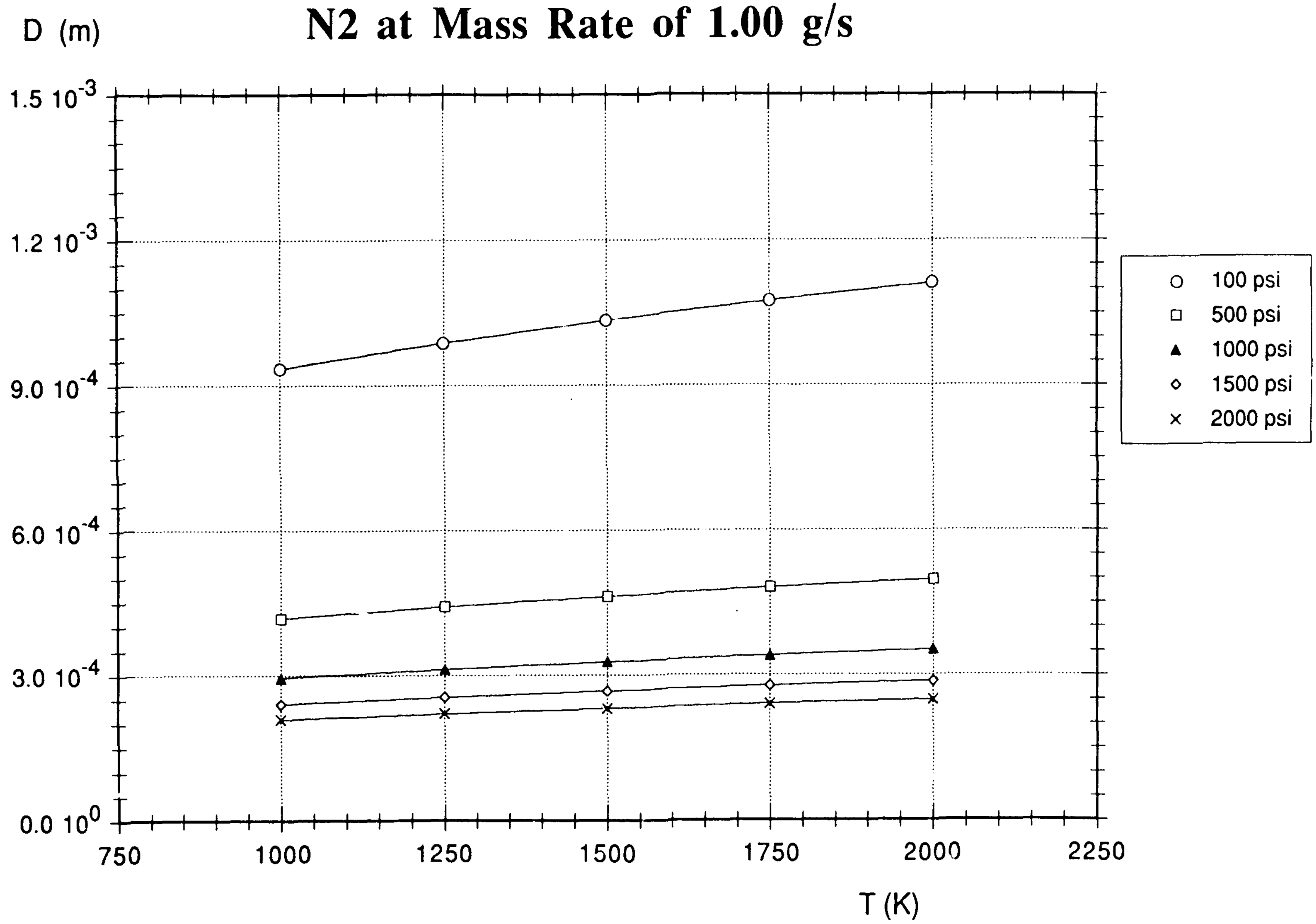
Argon at Mass Rate of 0.10 g/s



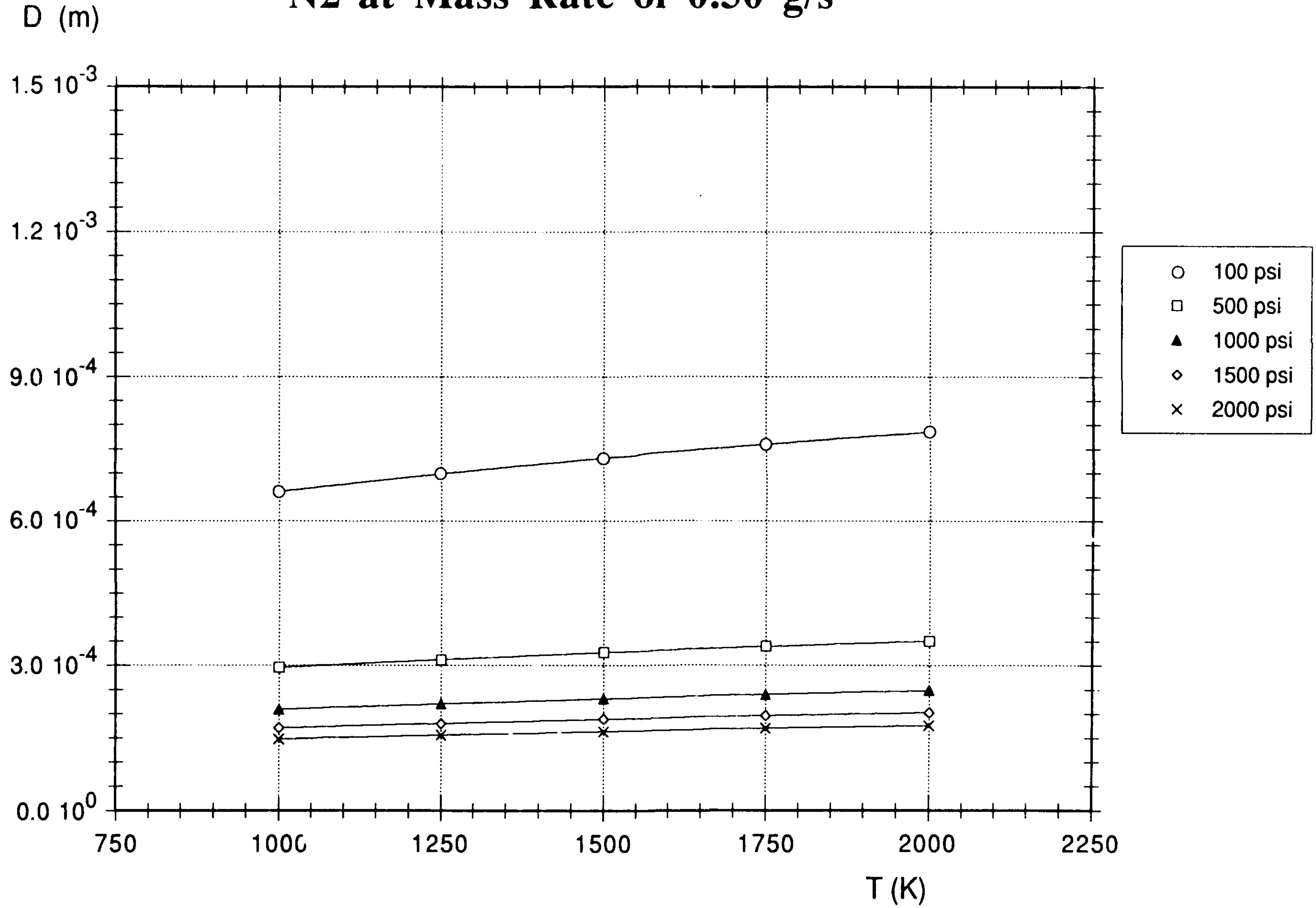
Argon at Mass Rate of 0.05 g/s



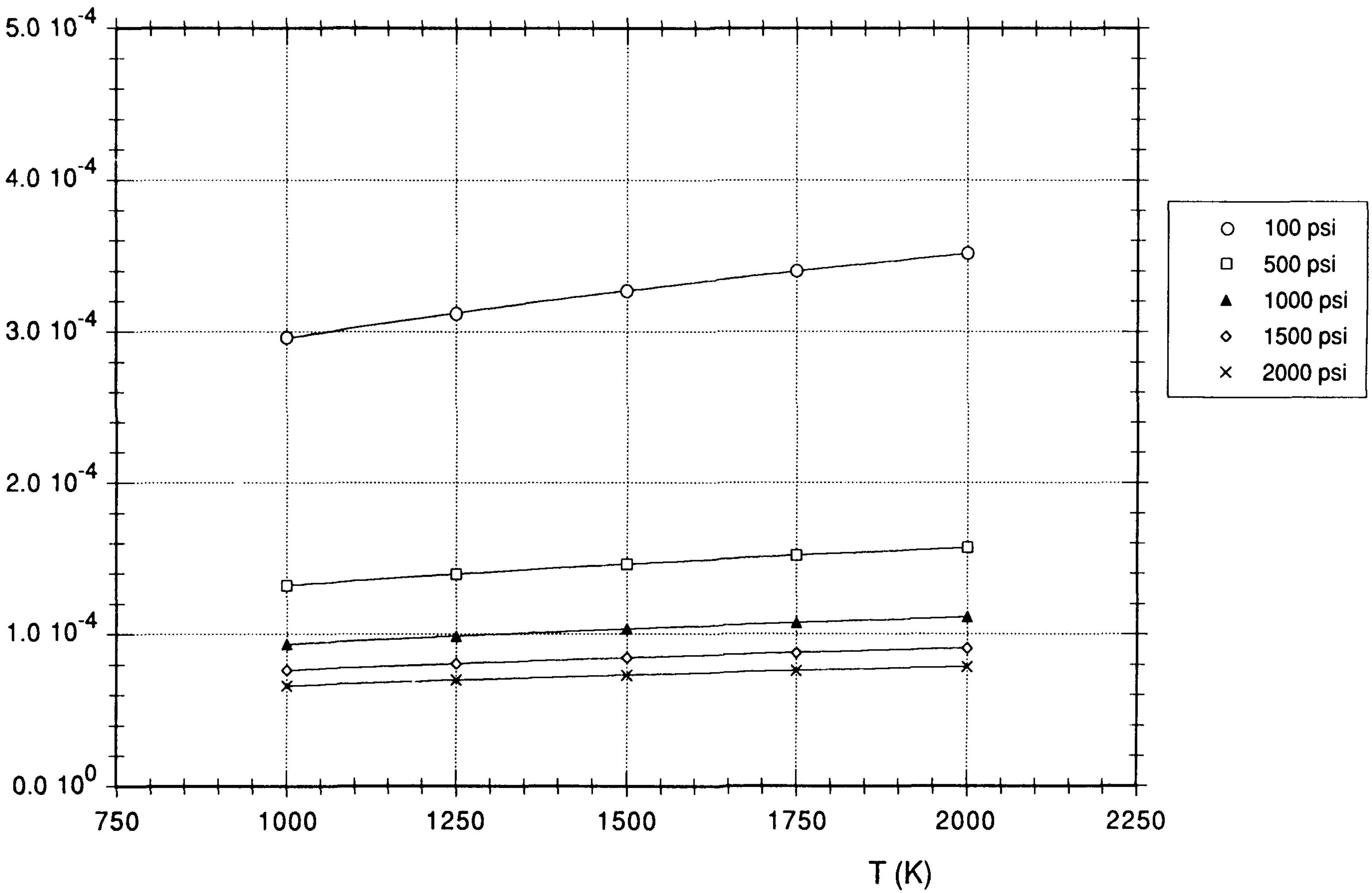
N2 at Mass Rate of 1.00 g/s



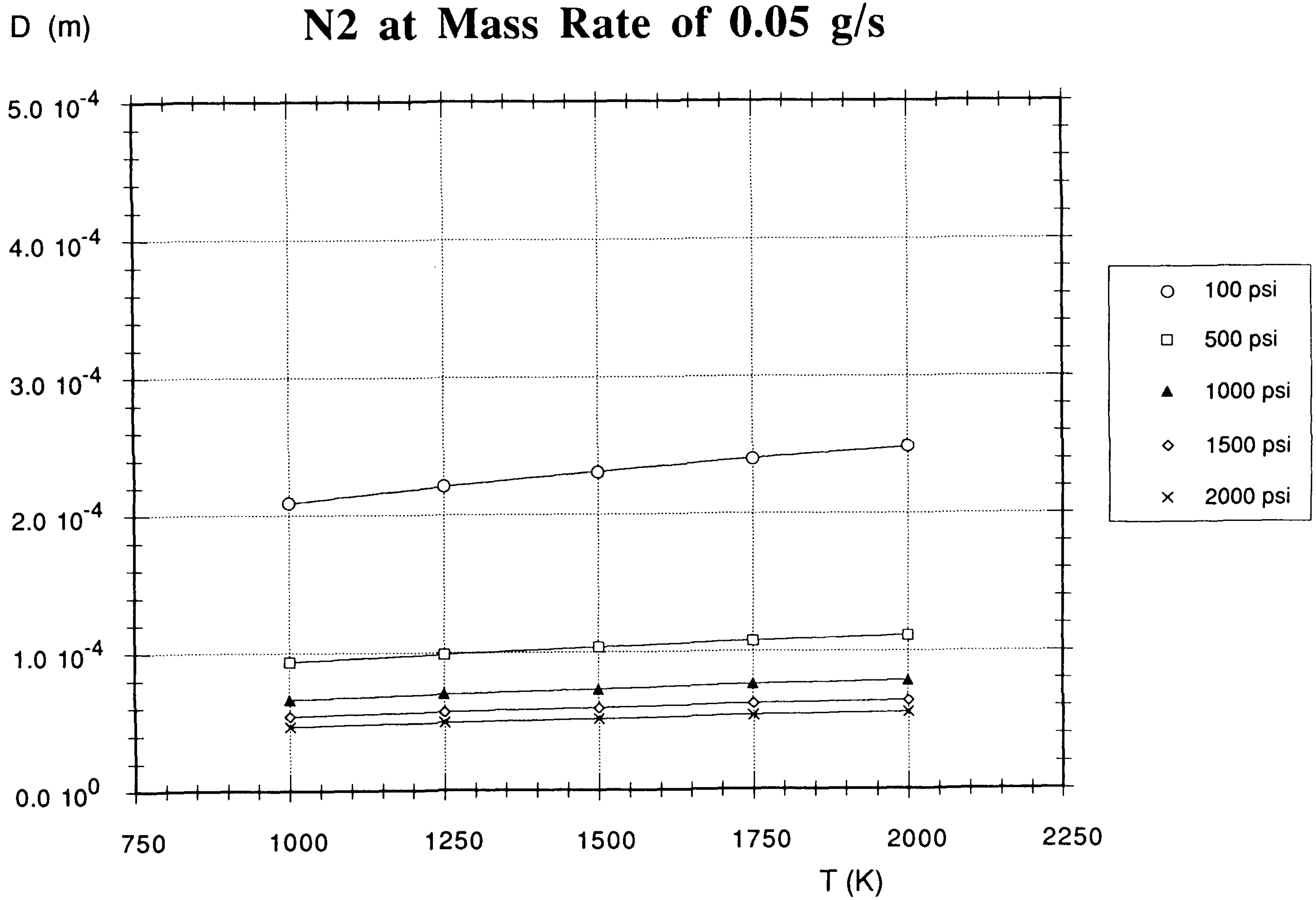
N2 at Mass Rate of 0.50 g/s



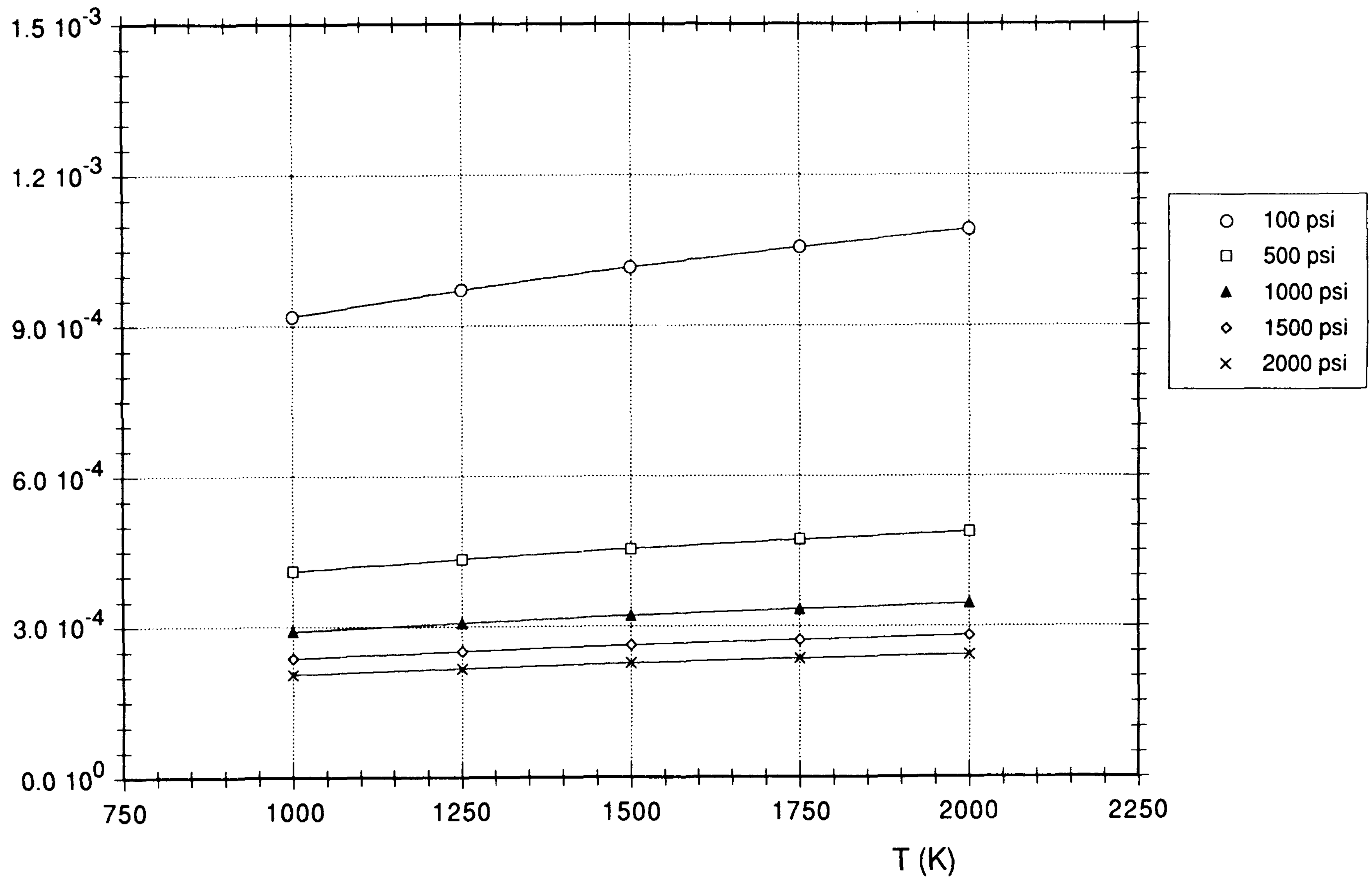
N2 at Mass Rate of 0.10 g/s



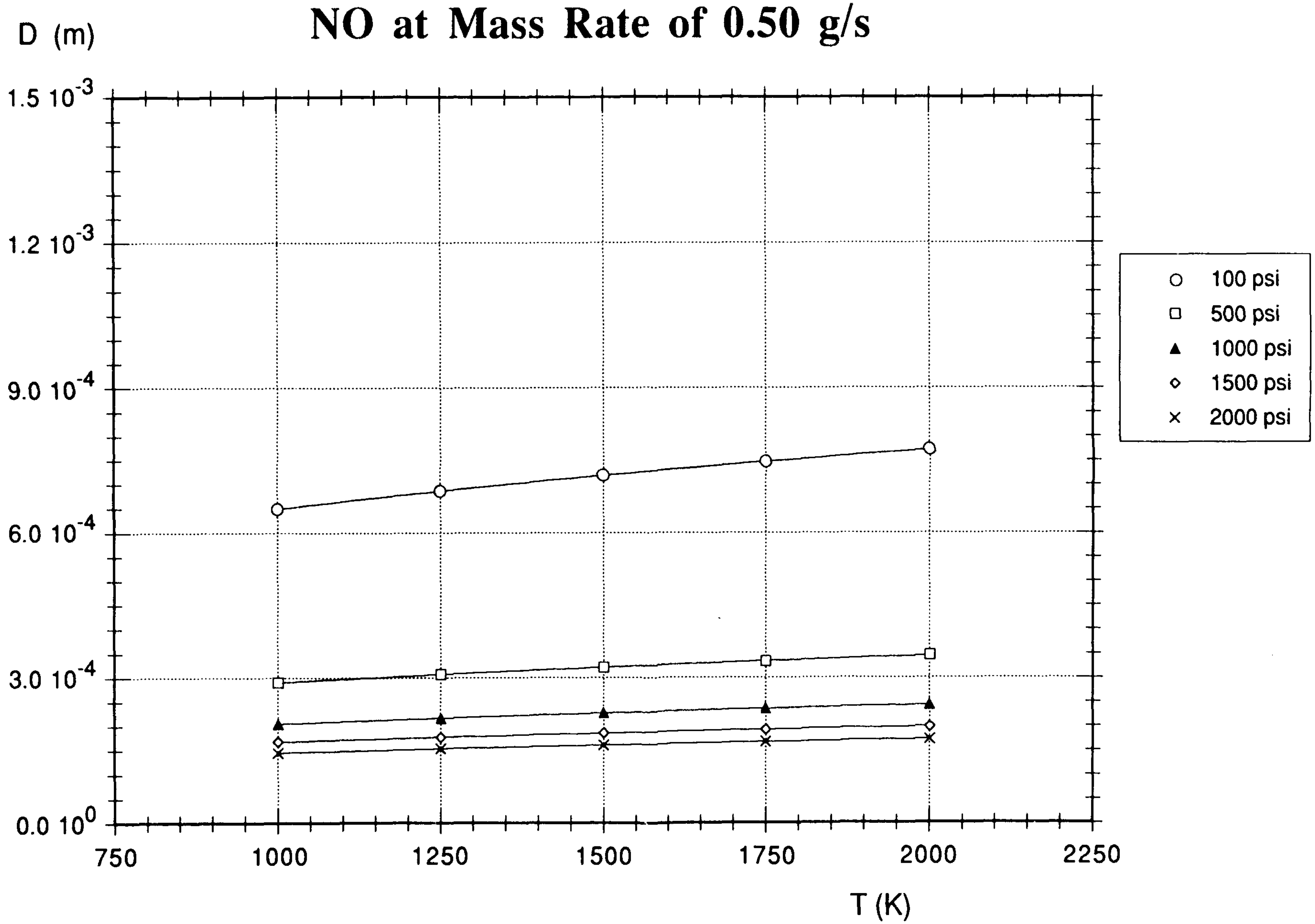
N2 at Mass Rate of 0.05 g/s



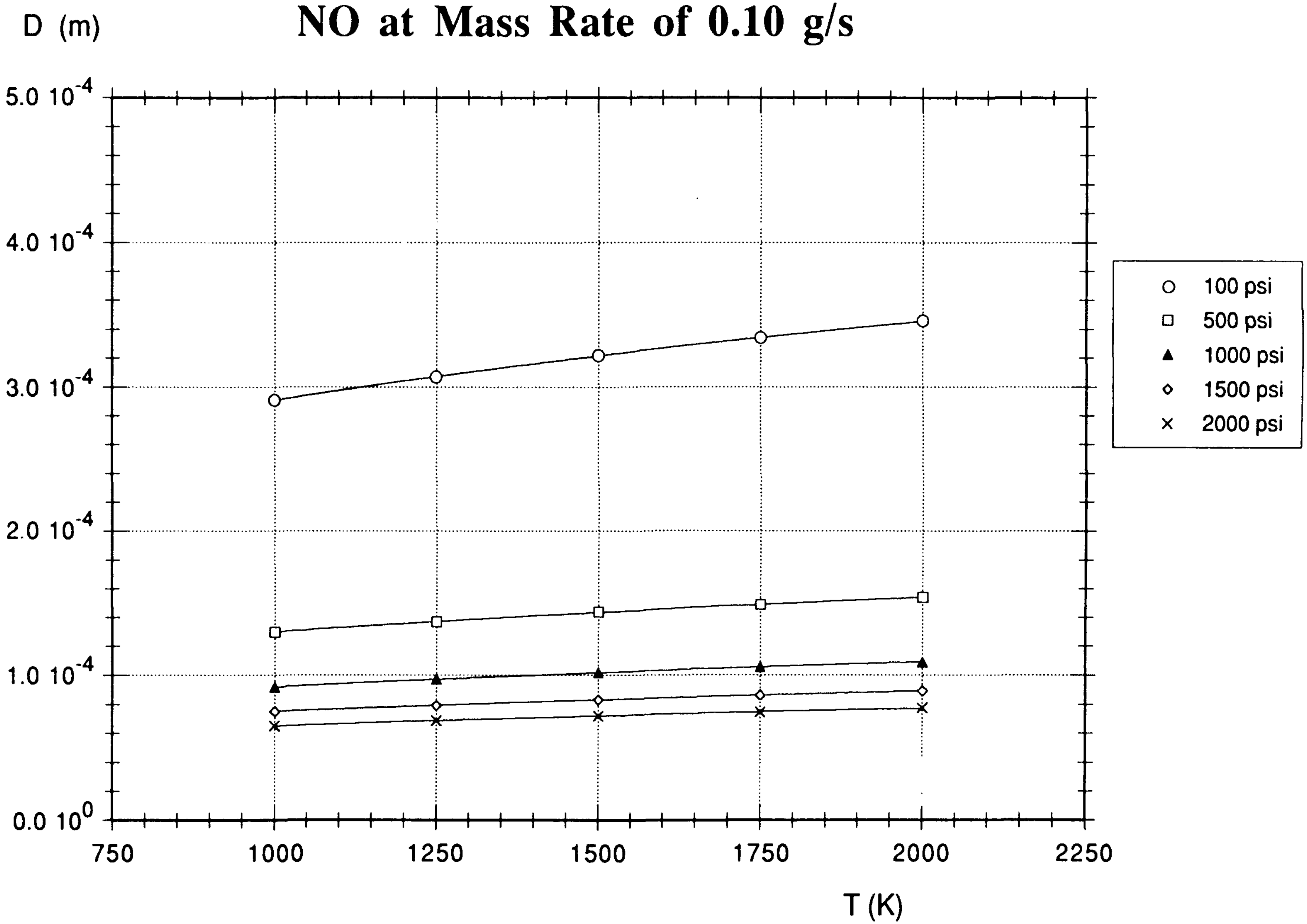
NO at Mass Rate of 1.00 g/s

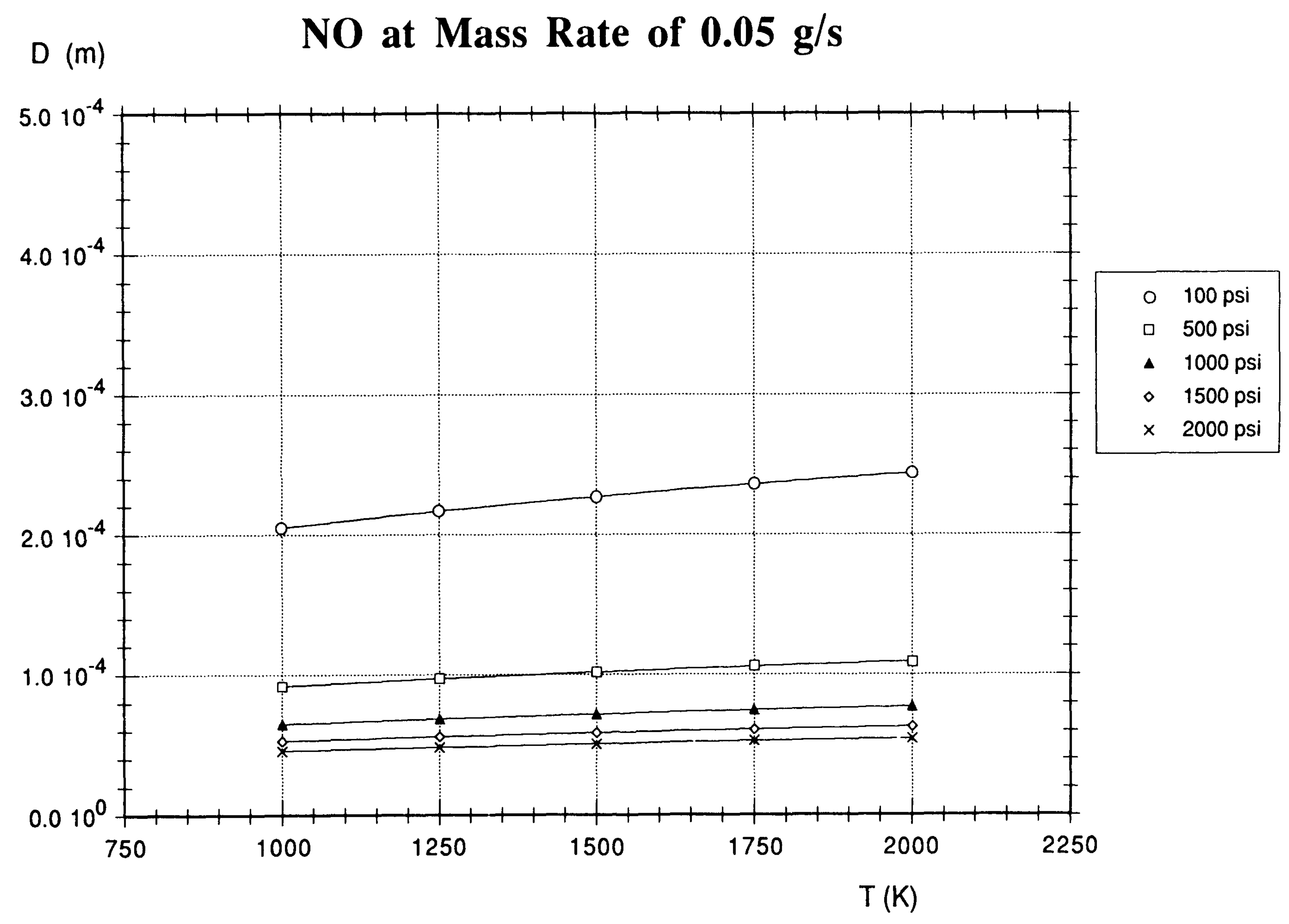


NO at Mass Rate of 0.50 g/s



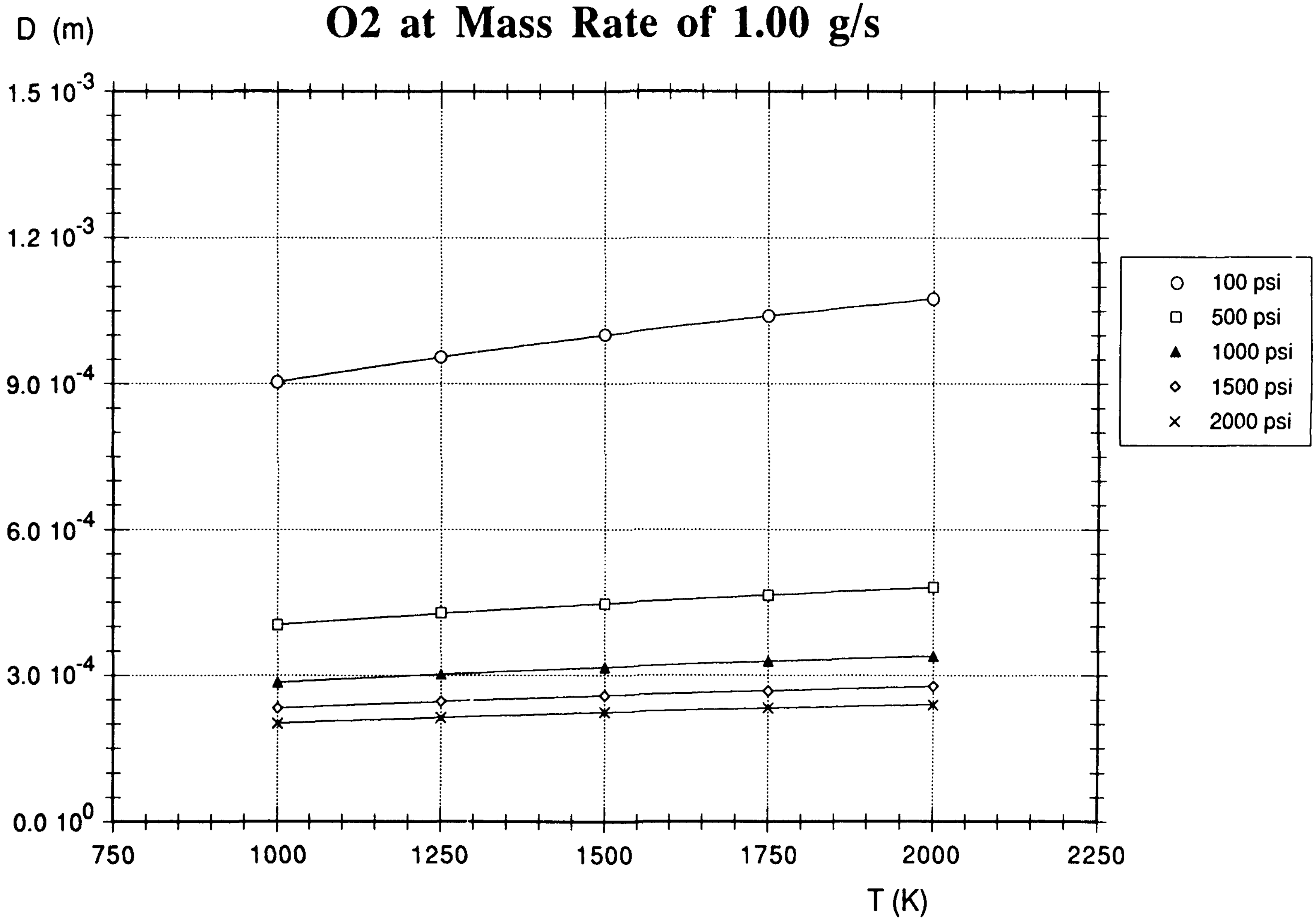
NO at Mass Rate of 0.10 g/s

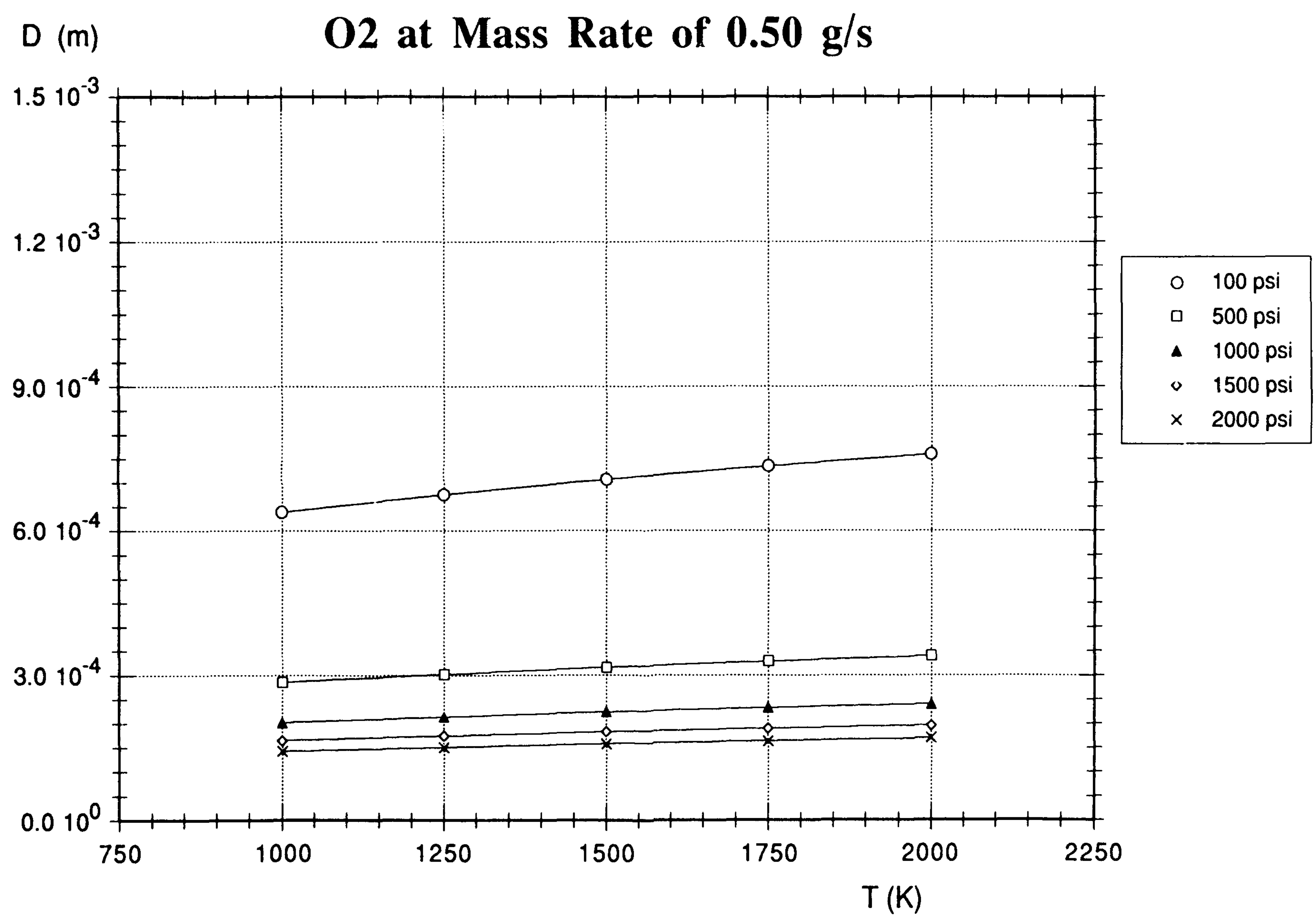




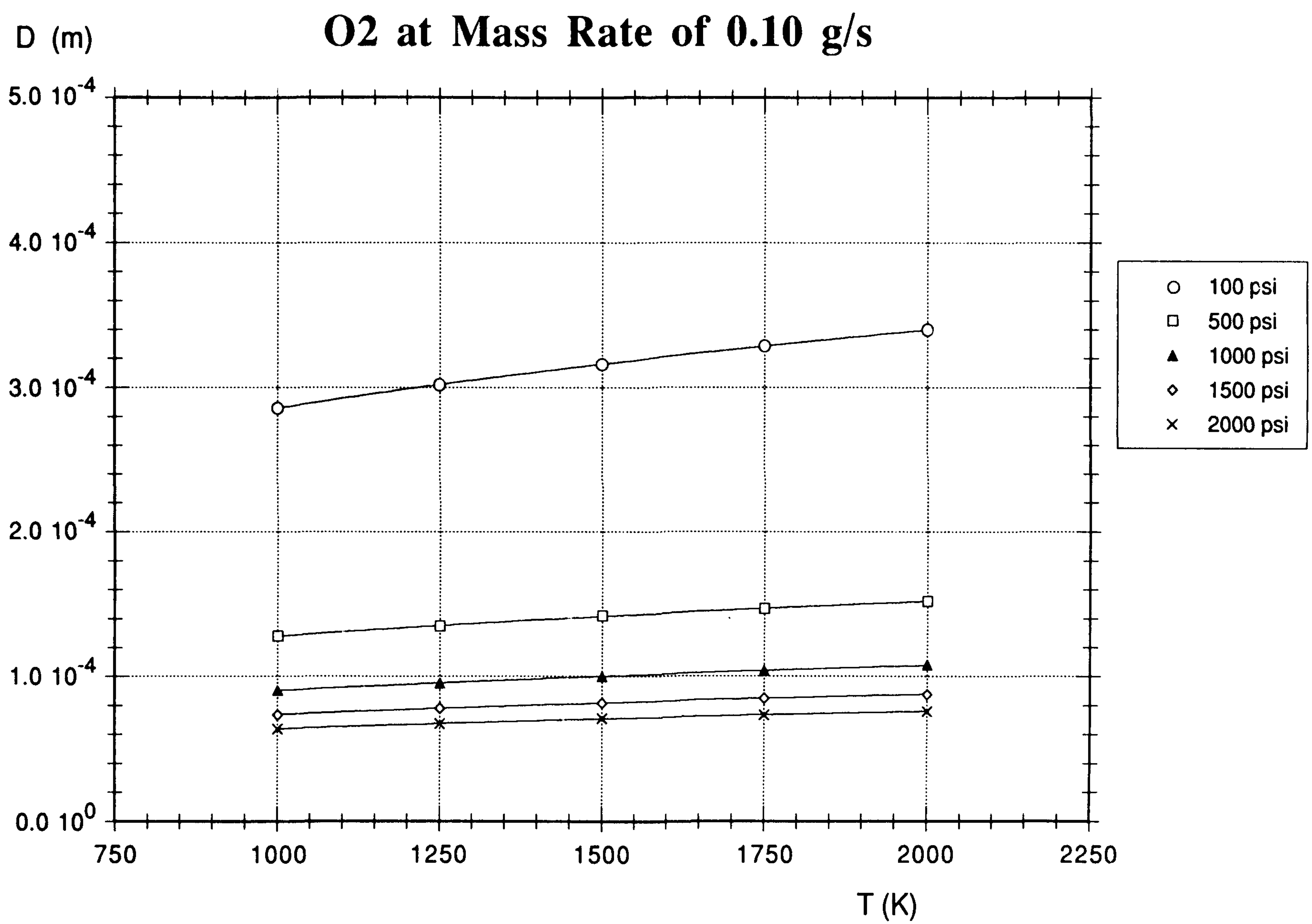
NO at Mass Rate of 0.05 g/s
D (m)
5.0 10-4
4.0 10-4
3.0 10-4
2.0 10-4
1.0 10-4
0.0 100
750
1000
1250
1500
1750
2000
2250
T (K)
100 psi
500 psi
1000 psi
1500 psi
2000 psi

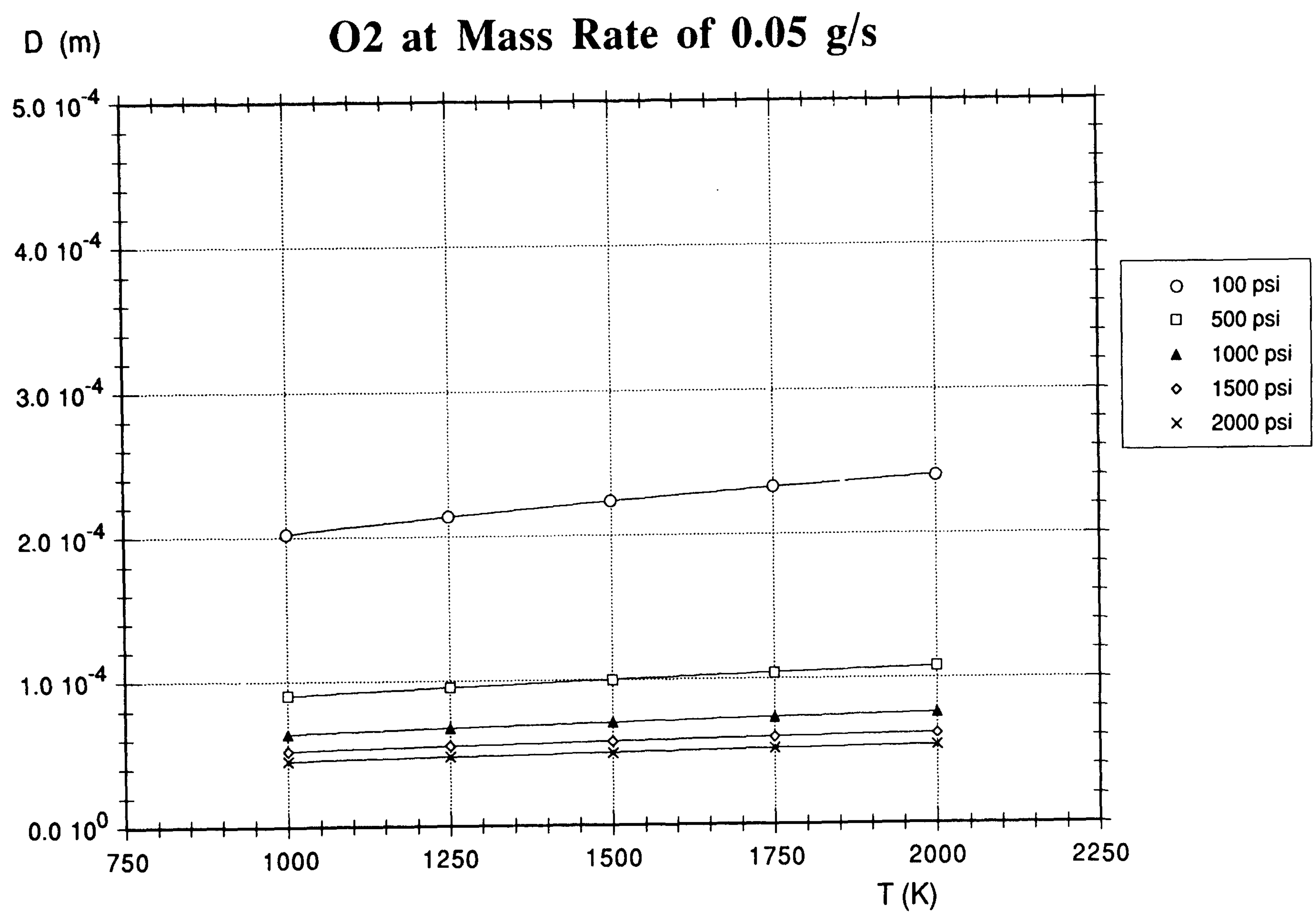
O2 at Mass Rate of 1.00 g/s



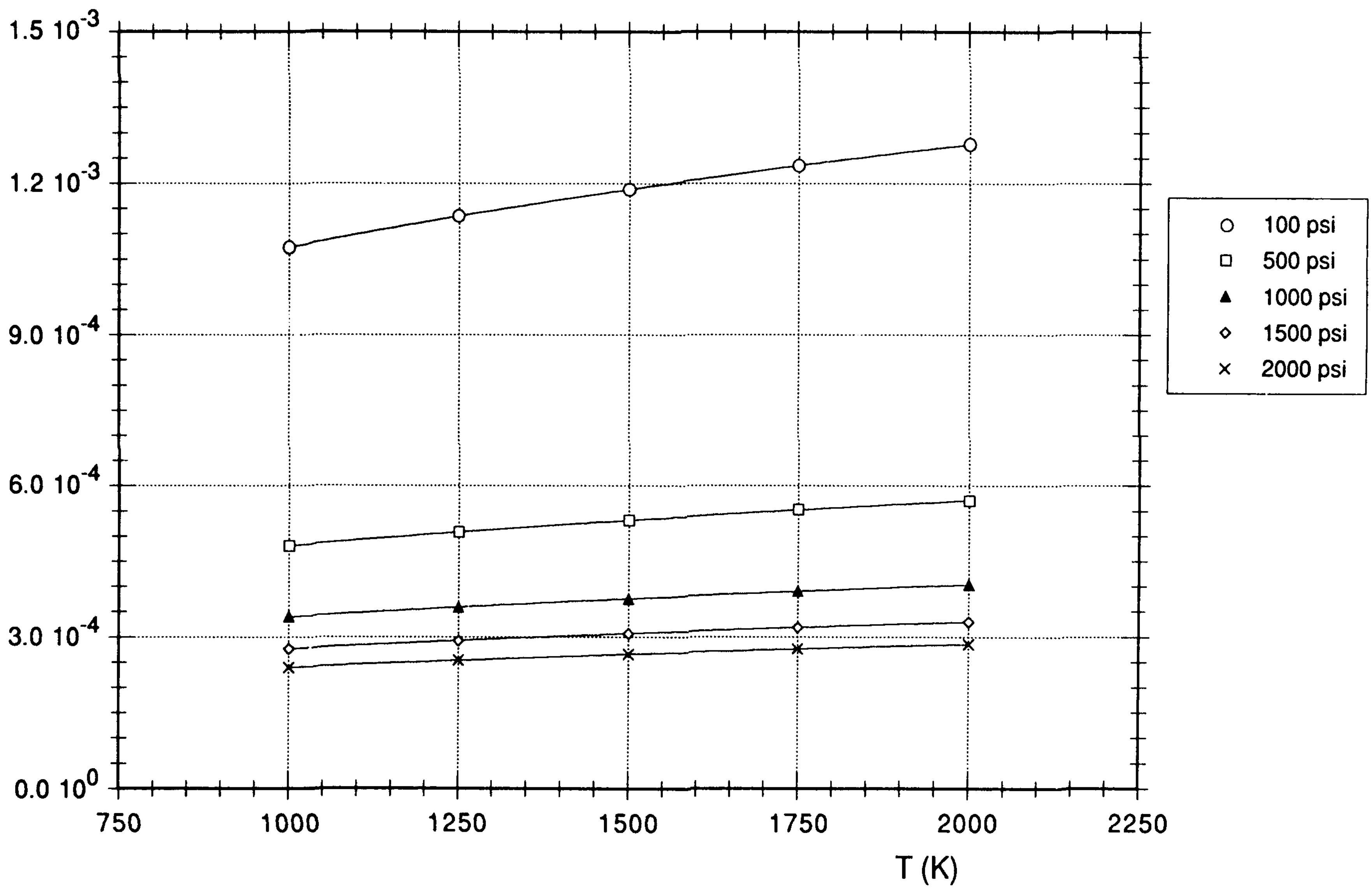


O2 at Mass Rate of 0.50 g/s
D (m)
1.5 10^-3
1.2 10^-3
9.0 10^-4
6.0 10^-4
3.0 10^-4
0.0 10^0
750
1000
1250
1500
1750
2000
2250
T (K)
100 psi
500 psi
1000 psi
1500 psi
2000 psi

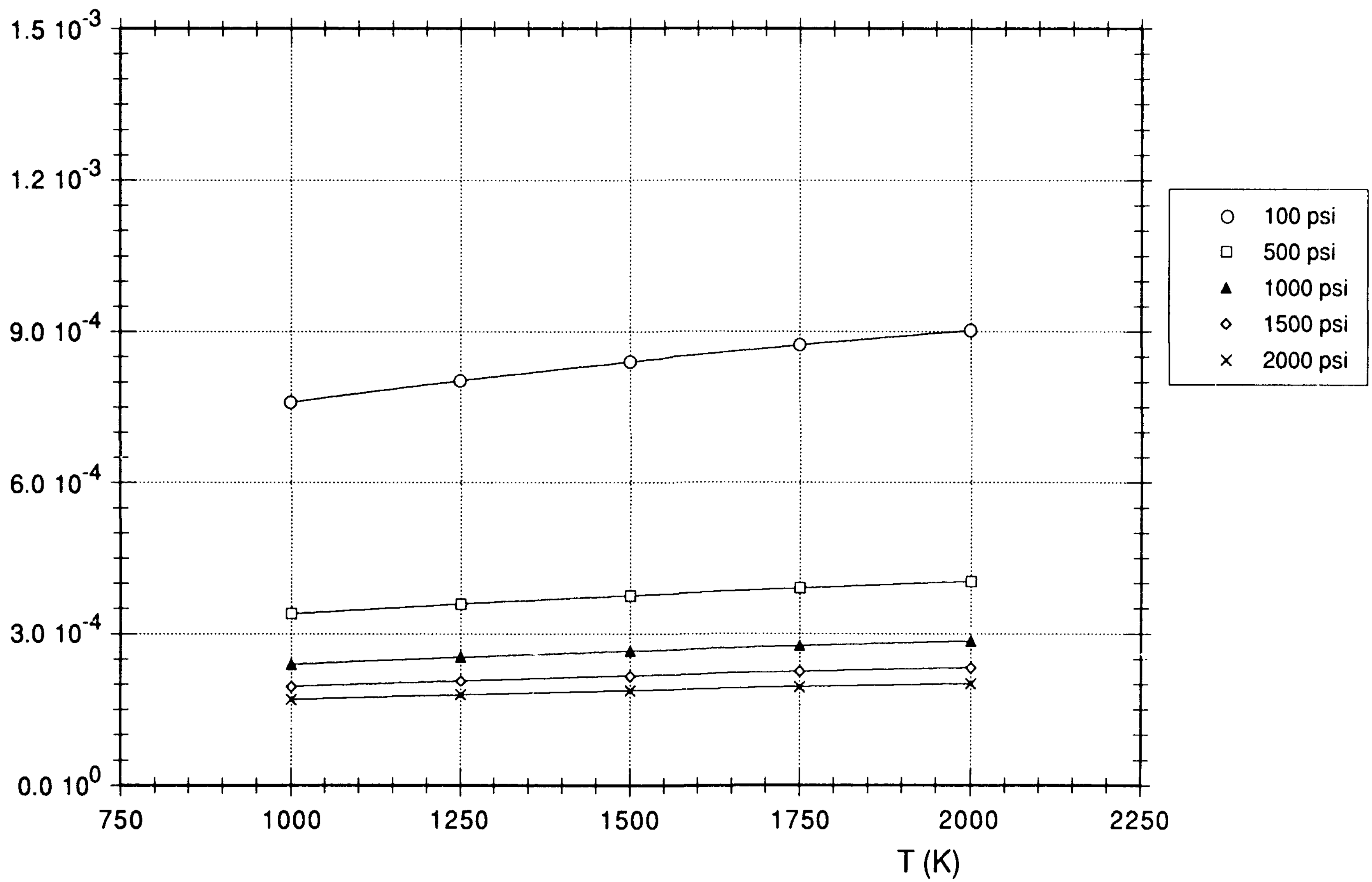

O2 at Mass Rate of 0.10 g/s
D (m)
5.0 10^-4
4.0 10^-4
3.0 10^-4
2.0 10^-4
1.0 10^-4
0.0 10^0
750
1000
1250
1500
1750
2000
2250
T (K)
100 psi
500 psi
1000 psi
1500 psi
2000 psi


O2 at Mass Rate of 0.05 g/s
D (m)
5.0 10^-4
4.0 10^-4
3.0 10^-4
2.0 10^-4
1.0 10^-4
0.0 10^0
750
1000
1250
1500
1750
2000
2250
T (K)
100 psi
500 psi
1000 psi
1500 psi
2000 psi

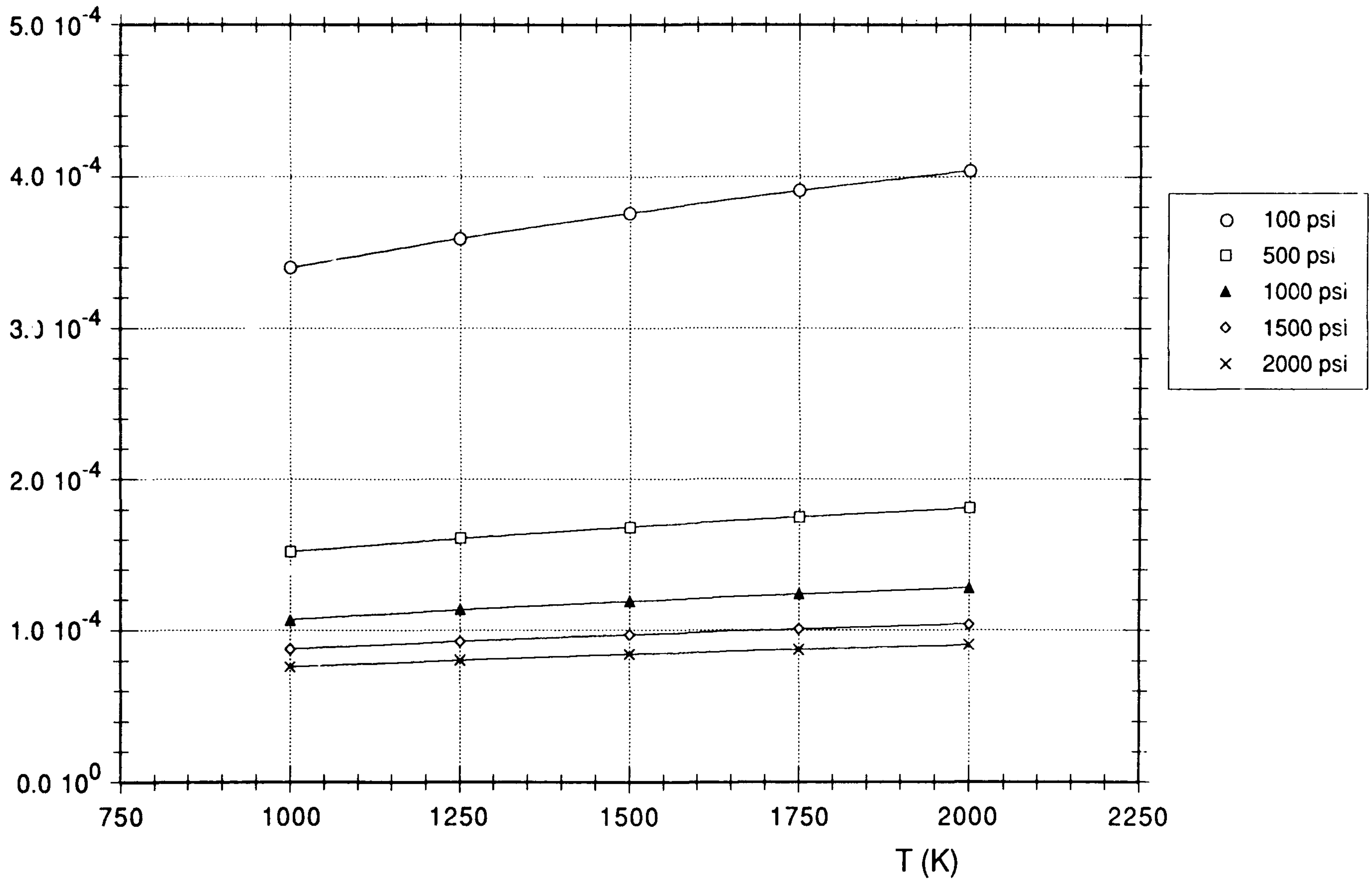
80% He / 20% O2 at Mass Rate of 1.00 g/s



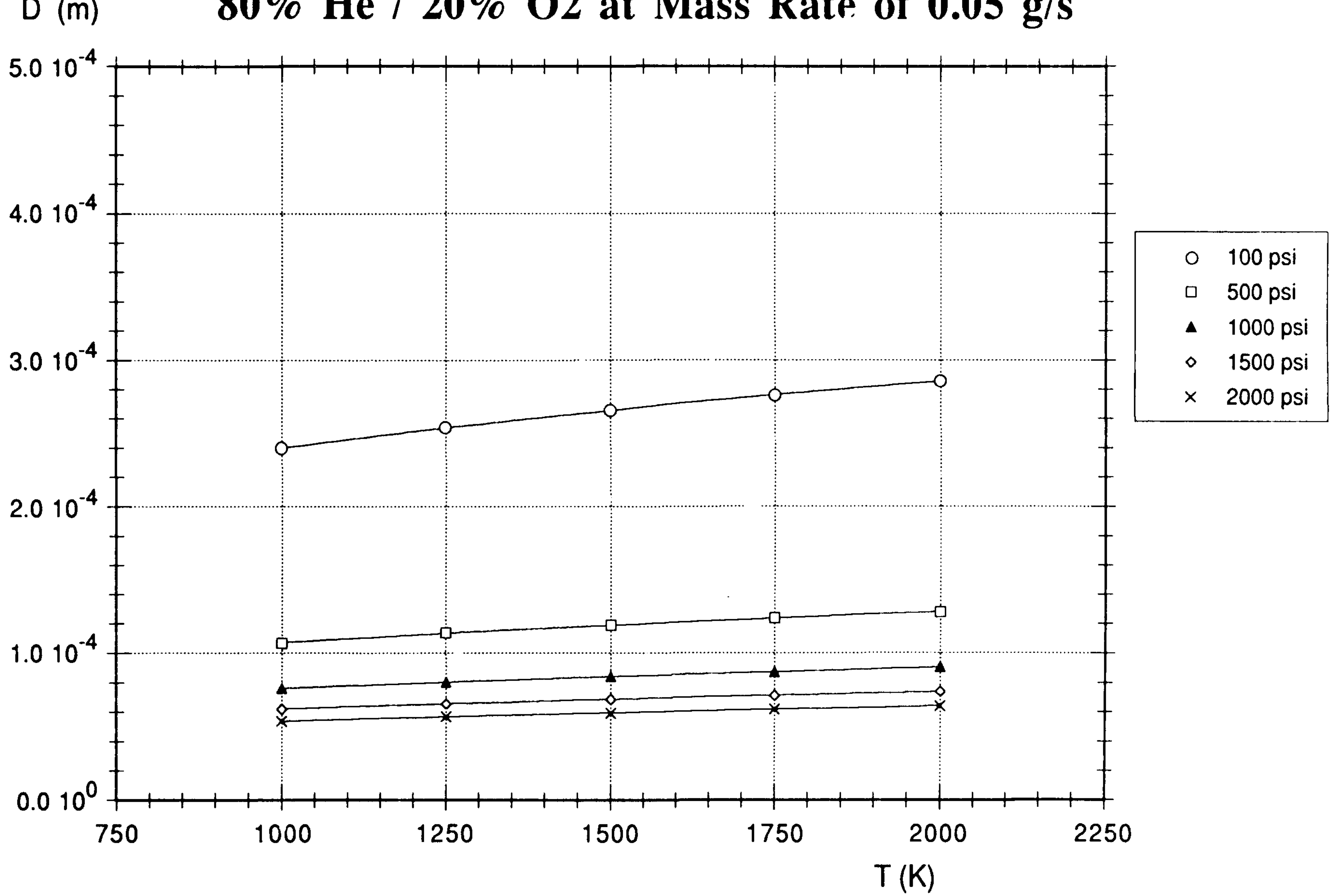
80% He / 20% O2 at Mass Rate of 0.50 g/s



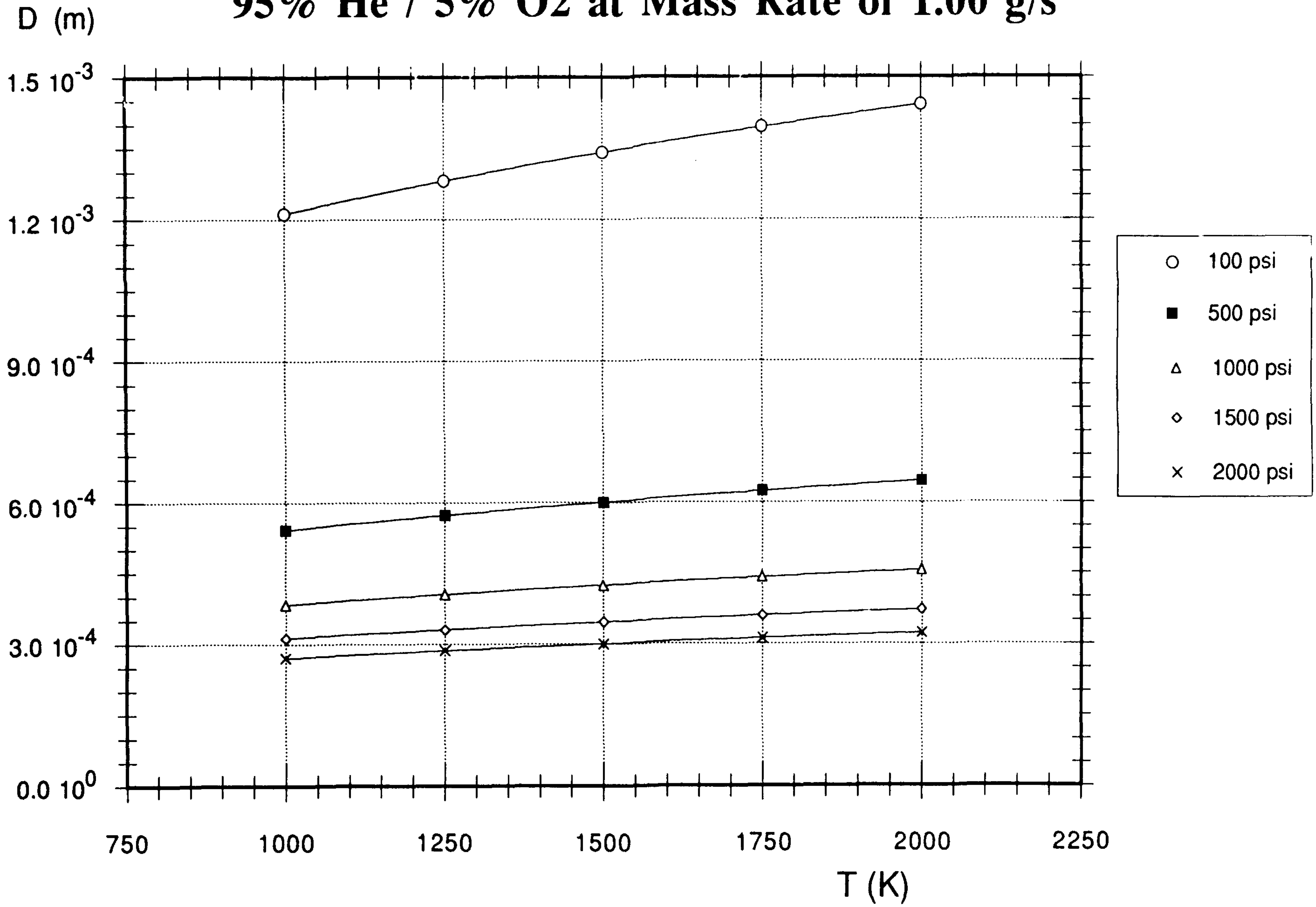
80% He / 20% O2 at Mass Rate of 0.10 g/s



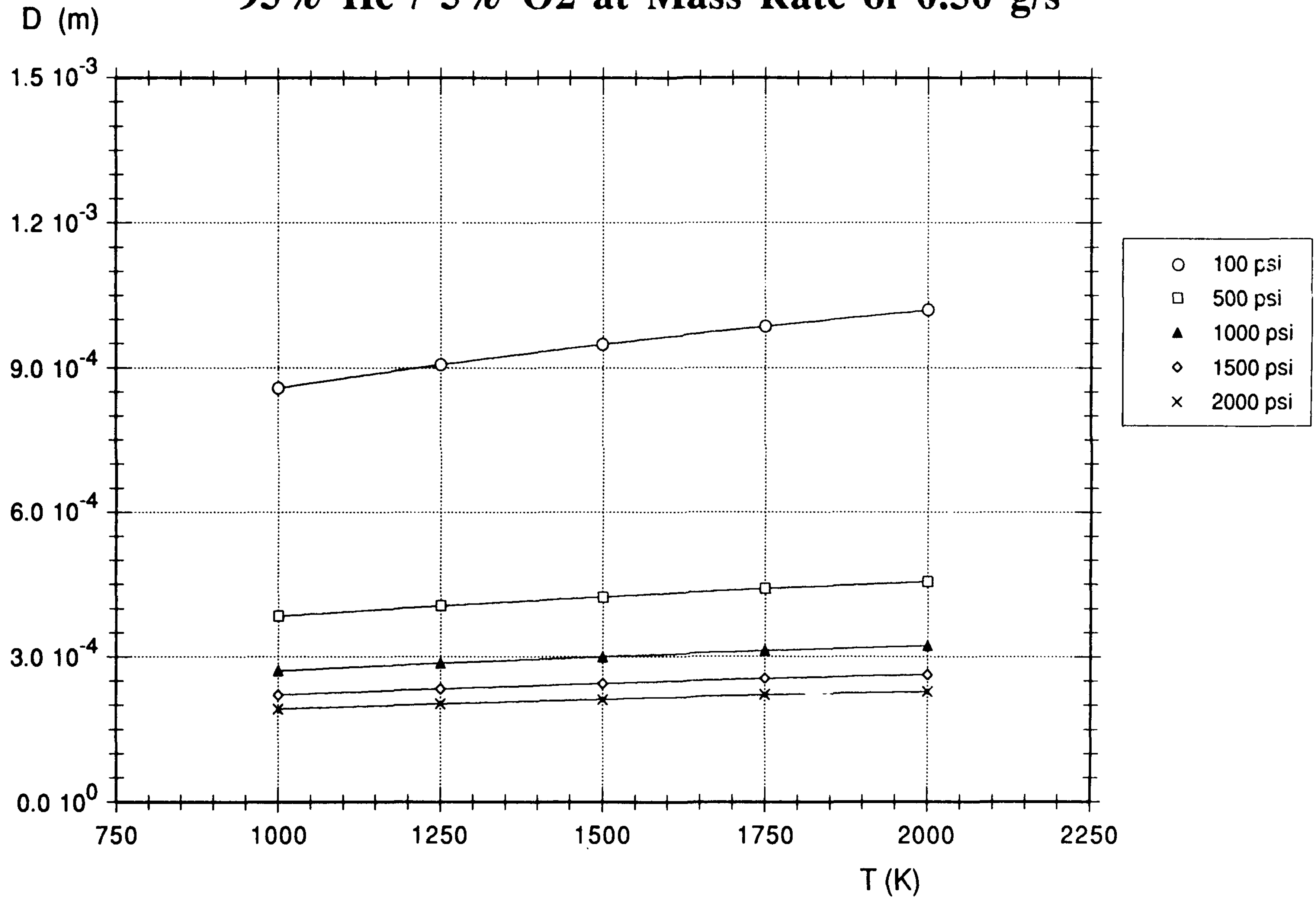
80% He / 20% O2 at Mass Rate of 0.05 g/s



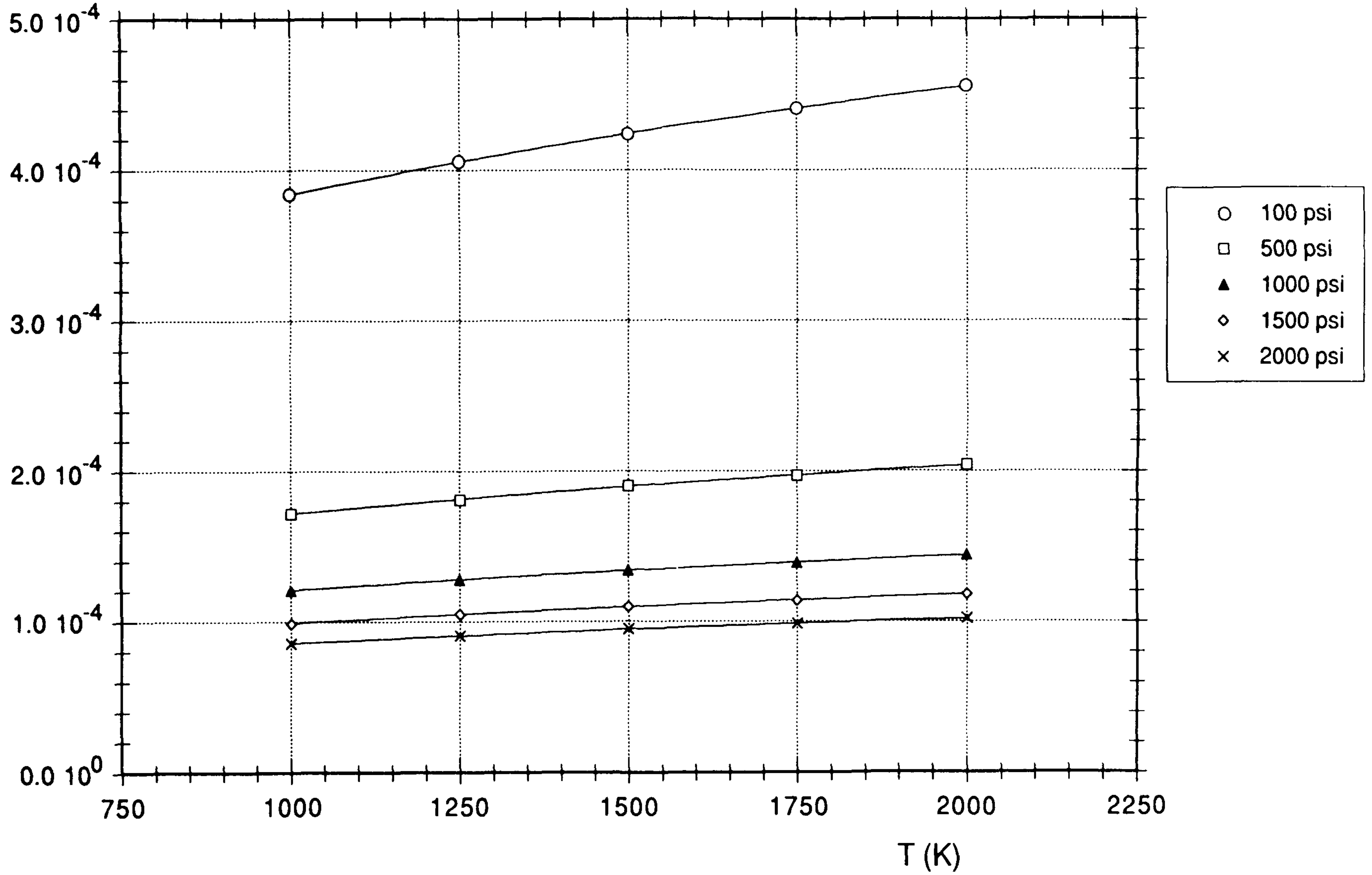
95% He / 5% O2 at Mass Rate of 1.00 g/s



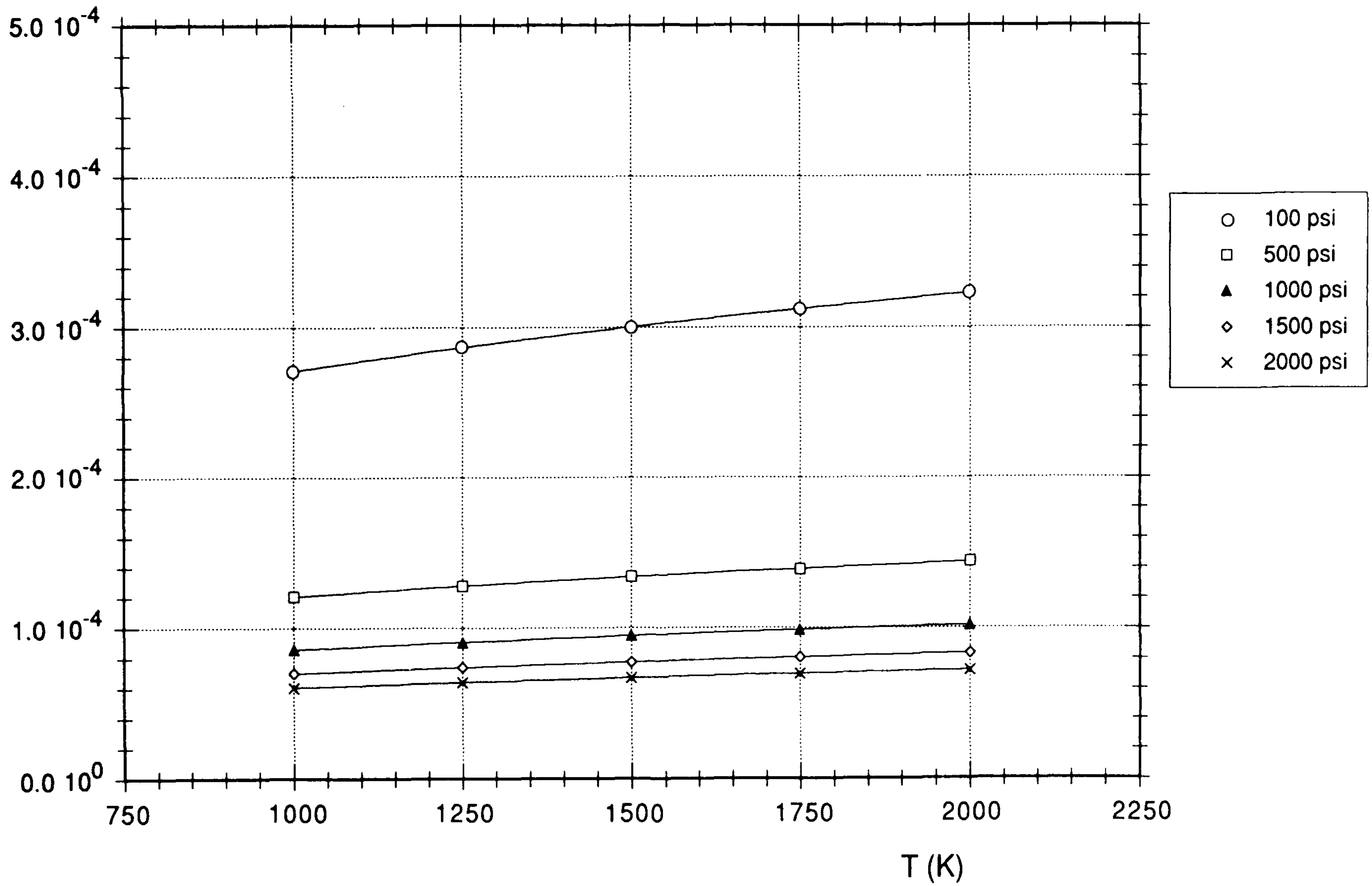
95% He / 5% O2 at Mass Rate of 0.50 g/s



95% He / 5% O2 at Mass Rate of 0.10 g/s



95% He / 5% O2 at Mass Rate of 0.05 g/s



APPENDIX 1:

INDUSTRY CONTACTS