THE KNUDSEN COMPRESSOR AS AN ENERGY EFFICIENT MICRO-SCALE VACUUM PUMP

M. Young, E.P. Muntz, and G. Shiflett

University of Southern California

Los Angeles, CA 90089-1191

Amanda Green

Jet Propulsion Laboratory

2nd NASA/JPL Miniature Pumps Workshop
March 28 2002
Pasadena, CA

Overview

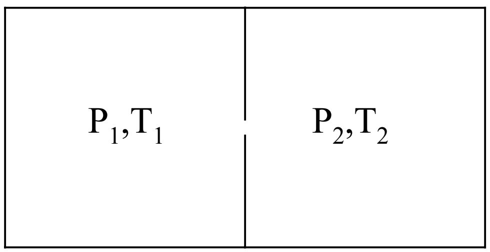
- Knudsen Compressor Description
- Advantages of Thermal Transpiration Pumps
- Thermal Transpiration Pump History at USC
- Transitional Flow Formulation and Results
- Sample Stage Sizing and Performance
- Special Considerations at the Low Pressure Limit
- Summary

Thermal Effusion and Creep

Rarefied gas phenomena (free-molecular flow driven by gas-surface interactions)

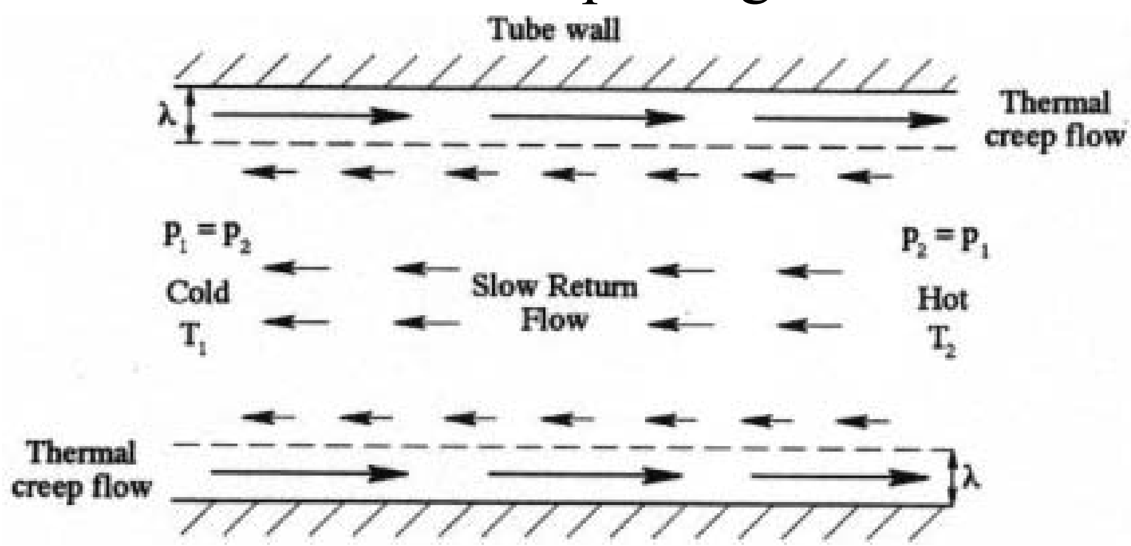
Thermal Effusion Through Orifice

$T_1 < T_2$



$$\frac{p_1}{p_2} = \sqrt{\frac{T_1}{T_2}}$$

Thermal Creep along surfaces



•Longitudinal Wall temperature gradient drives creep flow, counterbalanced by pressure driven return flow (Poiseuille flow)

•One of the driving mechanisms in Crooke's radiometer

Net effect is a flow from cold to hot side of tube

Knudsen Compressor Stage Operation

$$TMPD = \frac{\nabla P / P}{\nabla T / T}$$

Flow in a Knudsen Compressor is the difference between thermal creep and pressure driven return flows

FM equations

$$\dot{N}_T = \left\{ \frac{\sqrt{\pi}}{12} n_v v_o d^3 \right\} \frac{\nabla T}{T}$$

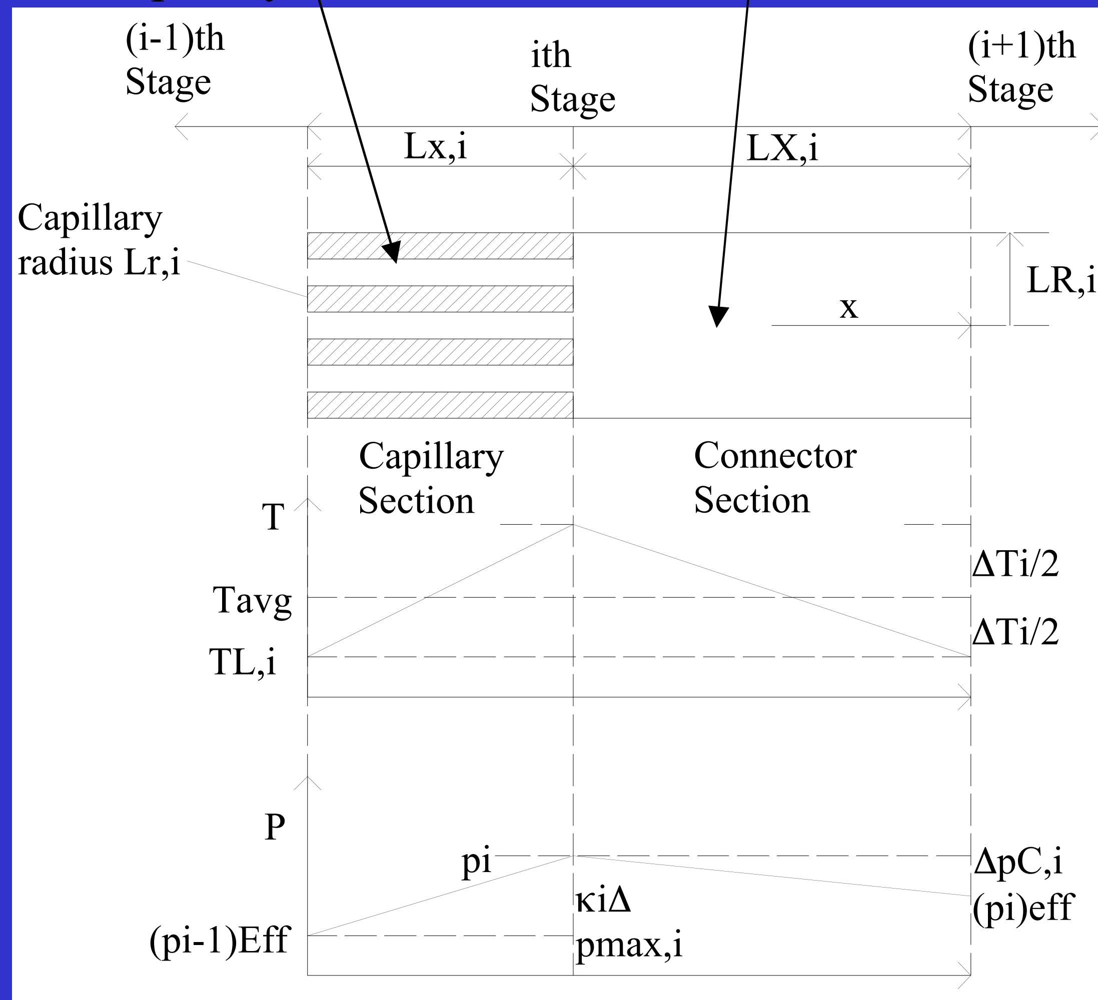
$$\dot{N}_p = \left\{ -\frac{\sqrt{\pi}}{6} n_v v_o d^3 \right\} \frac{\nabla p}{p}$$

$$\mathrm{TMPD}_{\mathrm{FM}} = \_$$

$$\mathrm{TMPD}_{\mathrm{Cont}} = 0$$

Rarefied flow in the capillary section

Continuum flow in the connector section

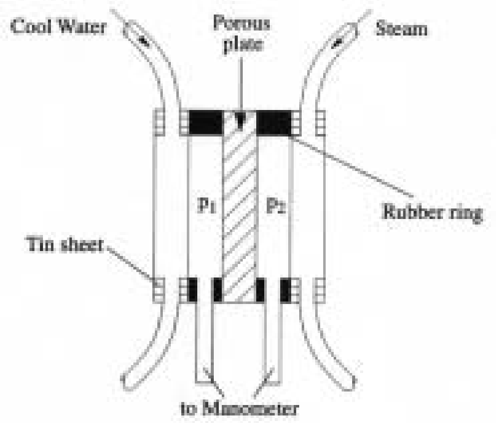


Why Thermal Transpiration Pumps?

- No moving parts.
- No oil or working fluids.
- Recent availability of small pore membrane materials with very low thermal conductivities.
- Can operate on waste heat from other equipment.
- MEMS fabrication allows for batch fabrication of the many required stages.
- Can operate over a wide range of pressures.
  - Roughing pump from 10 mTorr – 1 atm
  - High pressure gas source from 1 atm to 10 atm

Time-Line for Thermal Transpiration Pumps

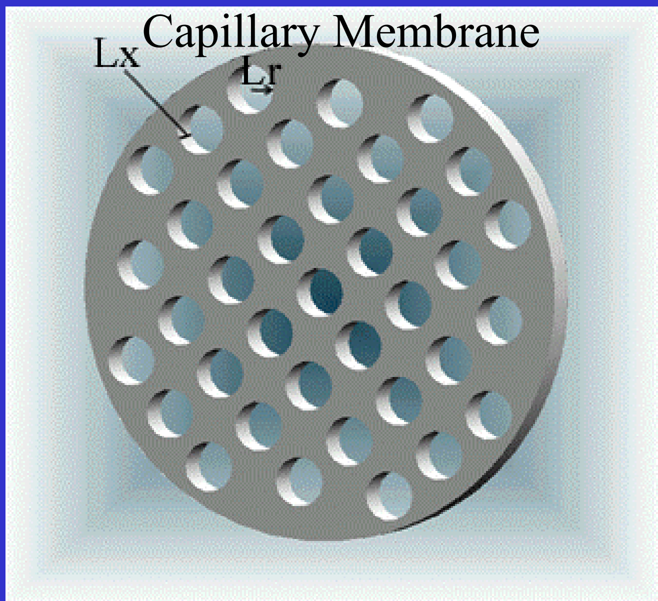
- Reynolds -- first explained thermal transpiration

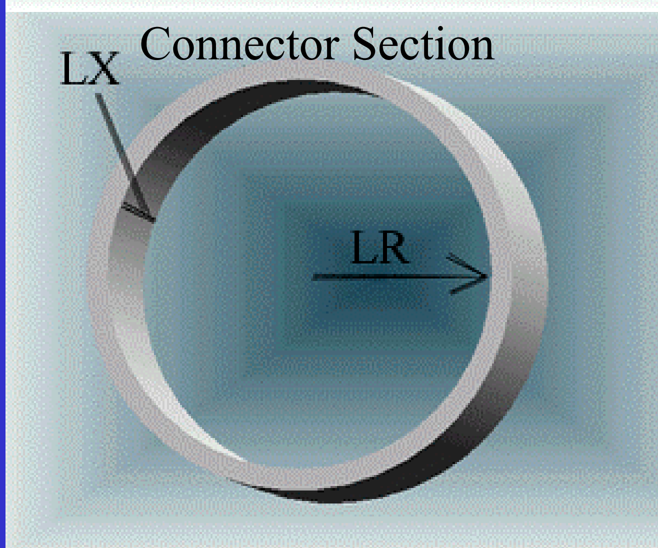


- Knudsen -- experimentally achieved pressure ratio of 10 with first multiple stage pump based on thermal transpiration.
- Pham-Van-Diep – Analysis of MEMS based pump
- Vargo – Demonstrated MEMS based vacuum pump stages
- MEMS Knudsen Pump – Optimize and Construct Multistage MEMS vacuum pump suitable for application

Reynolds	Knudsen	Pham-Van-Diep	Vargo	MEMS based Pump
1879	1910	1994	2000	Now

Transitional Flow Formulation

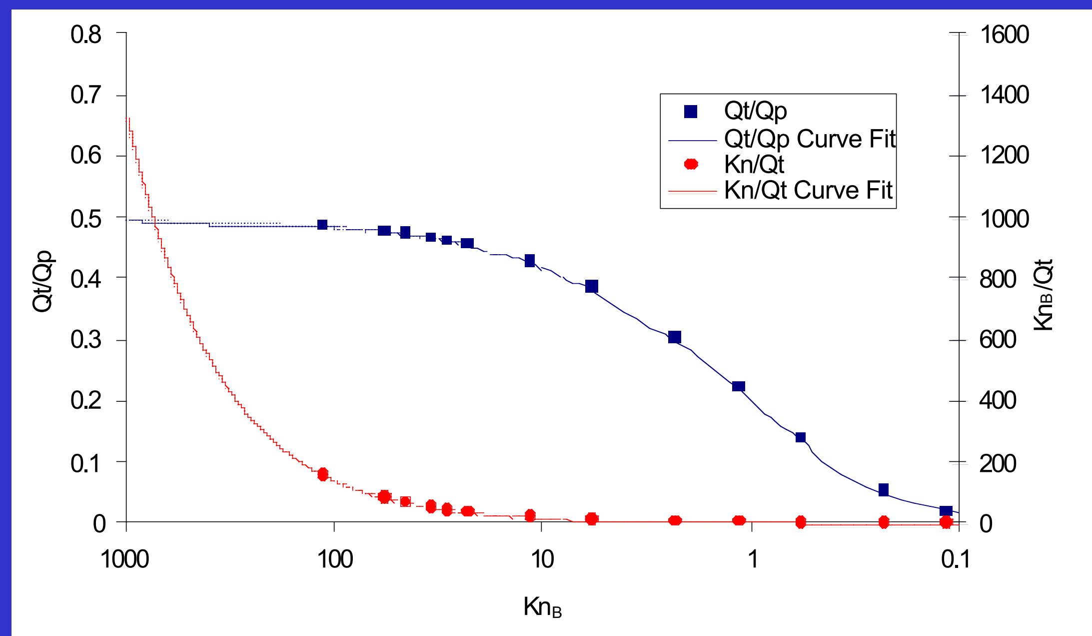




Transitional Flow Equations:

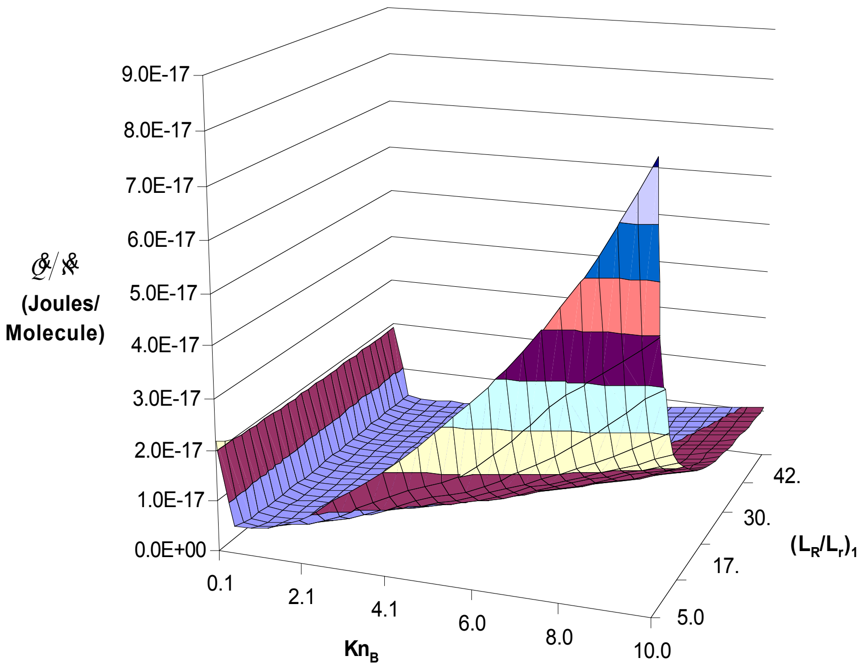
$$\Delta p = p_{AVG} \frac{\Delta T}{T_{AVG}} \frac{Q_T}{Q_P} \cdot \kappa$$

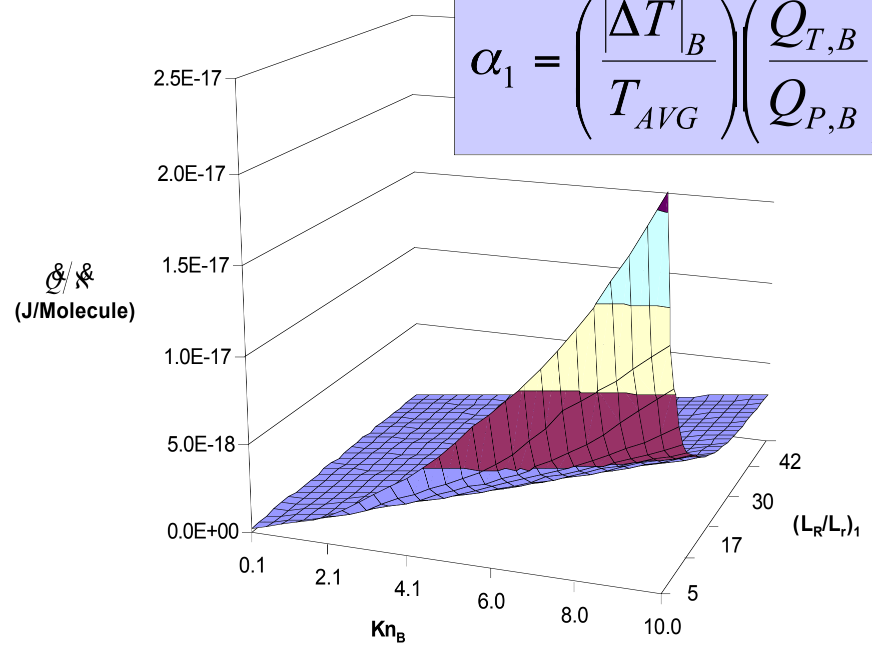
$$\dot{M}_i = \left[\frac{p_{AVG} F A}{\left(2(k/m)T_{AVG}\right)^{1/2}} \left(\frac{\Delta T}{T_{AVG}} \right) Q_T (1-\kappa) \left(\frac{L_r}{L_x} \right) \right]$$



Power Consumption Optimization Results

ΔT = constant | $\Delta P = 10$, $L_r = 500 \mu m$ | α_1 = constant





$$\alpha_1 = \left(\frac{|\Delta T|_B}{T_{AVG}}\right)\left(\frac{Q_{T,B}}{Q_{P,B}}\right)$$

Kn low: capillary section is not very efficient

Kn high: constant number of stages → energy consumption per unit number flux increases

L_R/L_r low: little difference between the capillary and connector sections

L_R/L_r high: constant number of stages → energy consumption per unit number flux constant

Kn low: inefficiency counteracted by increasing ΔT → no large increase in the number of stages

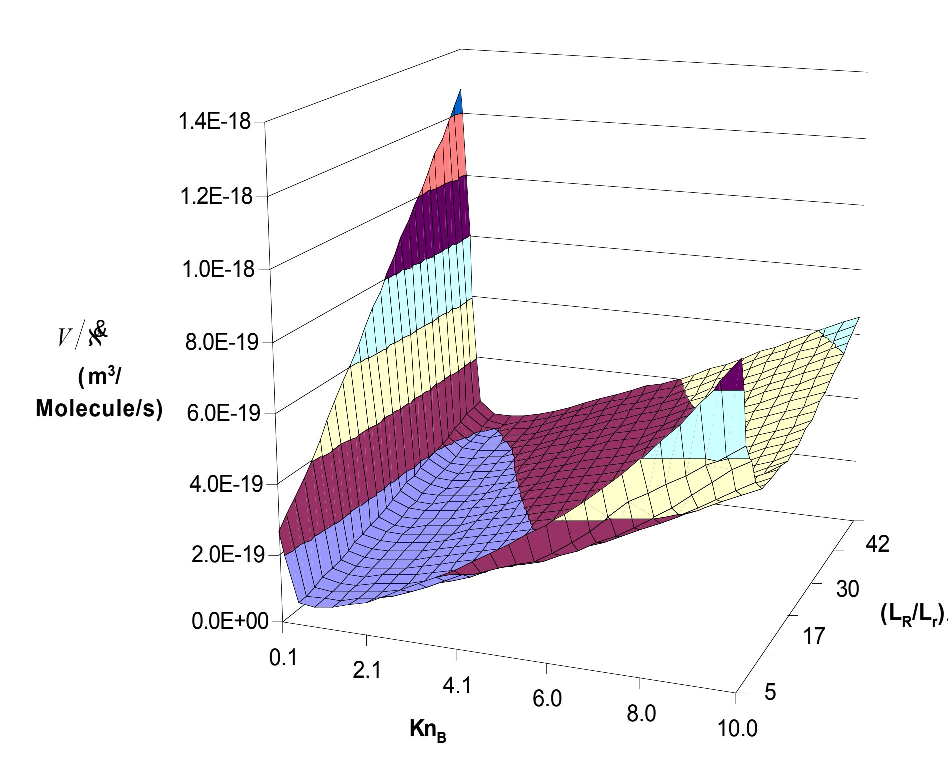
Kn high: same as ΔT = constant

L_R/L_r low:same as ΔT = constant

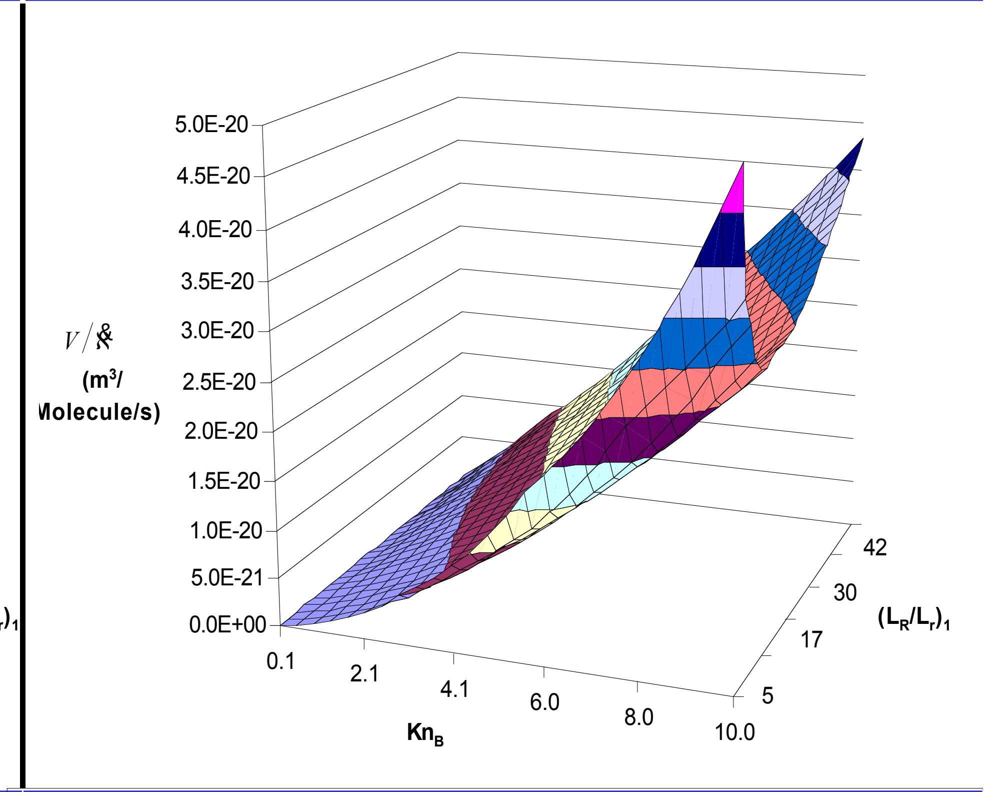
L_R/L_r high: same as ΔT = constant

Volume Optimization Results

ΔT = constant



α_1 = constant



Kn low: capillary section is not very efficient

Kn high: constant number of stages → volume per unit number flux increases linearly

L_R/L_r low: little difference between the capillary and connector sections

L_R/L_r high: length of the connector is increasing linearly with $(L_R/L_r)_1$ → increase linearly

Kn low: inefficiency counteracted by increasing the temperature difference → no large increase in the number of stages

Kn high: same as ΔT = constant

L_R/L_r low: same as ΔT = constant

L_R/L_r high: length of the connector is increasing linearly with $(L_R/L_r)_1$ → increase linearly

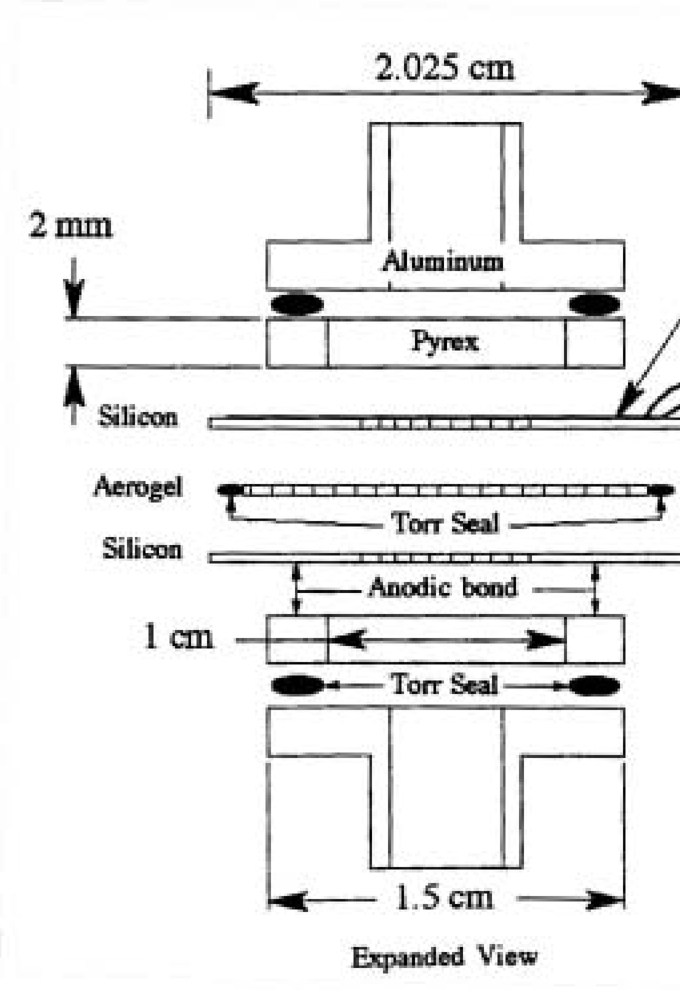
Previous Experimental Design

•Silicon Aerogel as Transpiration Membrane (0.6mm thick)

•Silicon wafer with DRIE holes and thin film gold heater used to apply temperature gradient

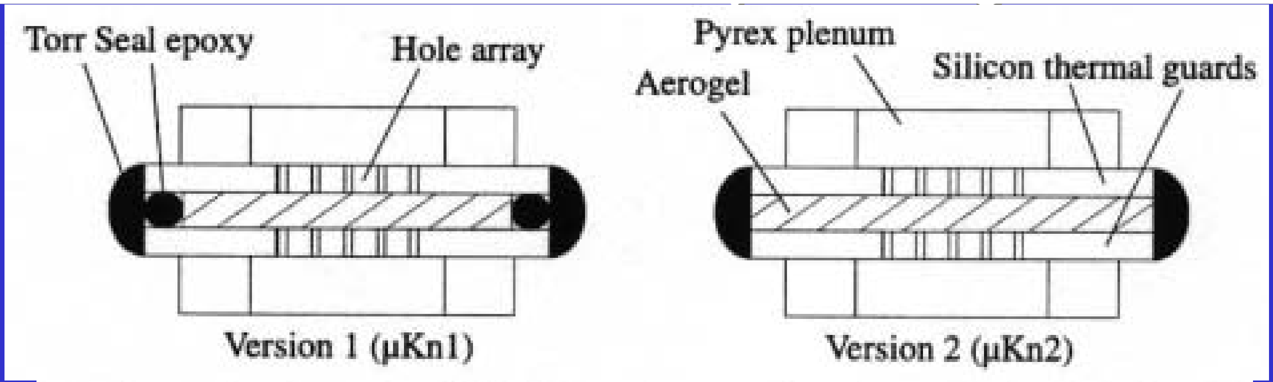
•Pyrex connector sections

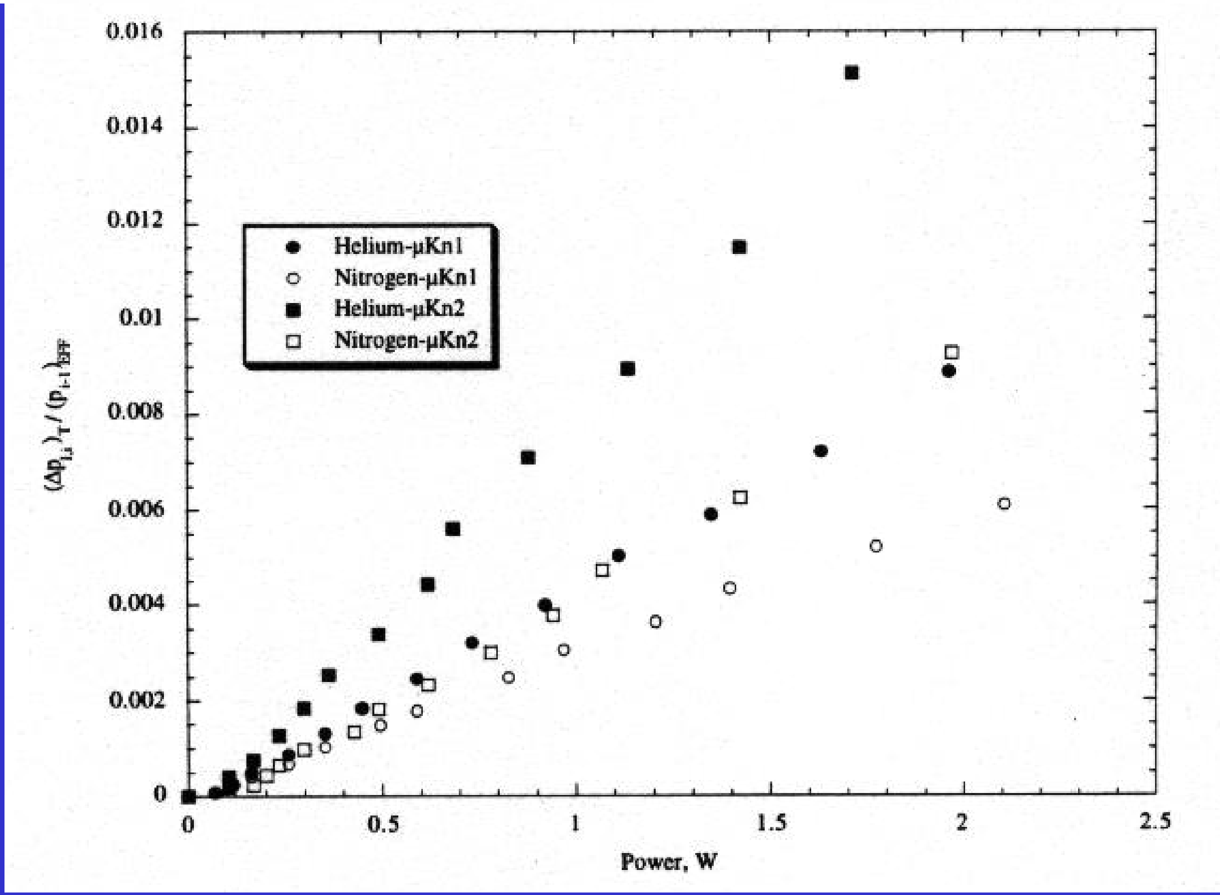
- Proof of concept for multiple stages
- Thermally efficient sealing identified as a major problem
- Transitional flow analysis validated
- Operation shown from atmospheric pressure down to several hundred Torr for several different working gases.



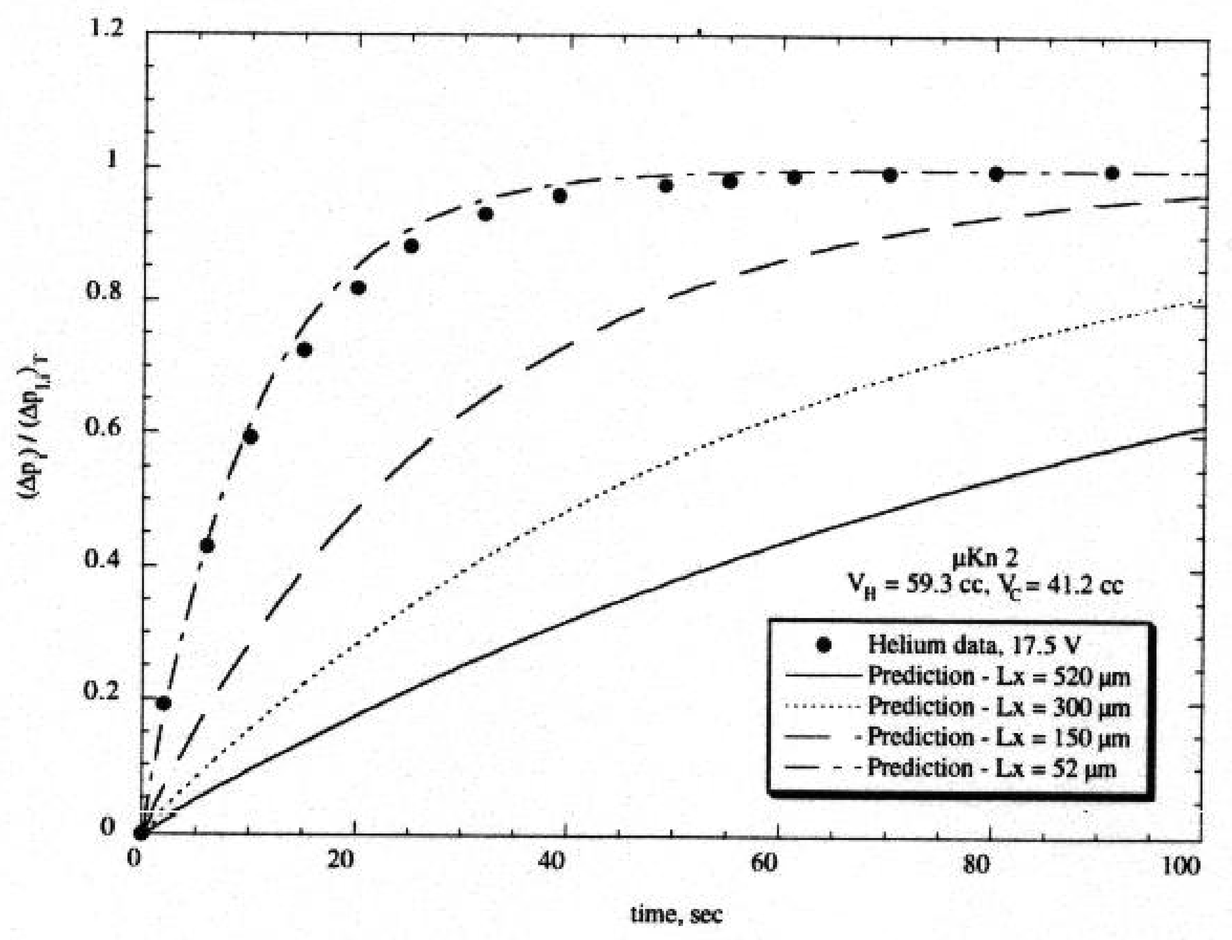
Vargo, 2000

Previous Results: Efficiently Sealing Membrane





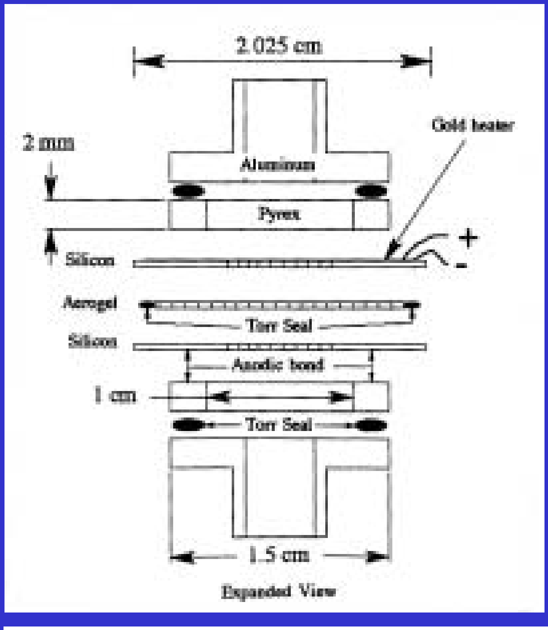
Previous Results: Validation of transitional flow model



vs.

- Model adequate for performance estimation using aerogel
- 10x better flowrate than predicted using nominal pore size and membrane thickness

Low Pressure Cascade Sizing Using L_r = 10nm



ΔT = 100K

L_r = 10nm

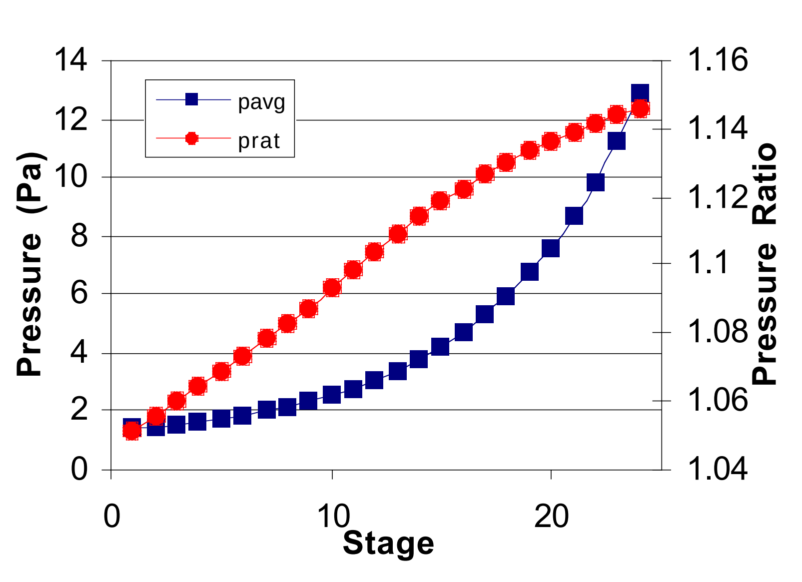
(2% carbon doped aerogel)

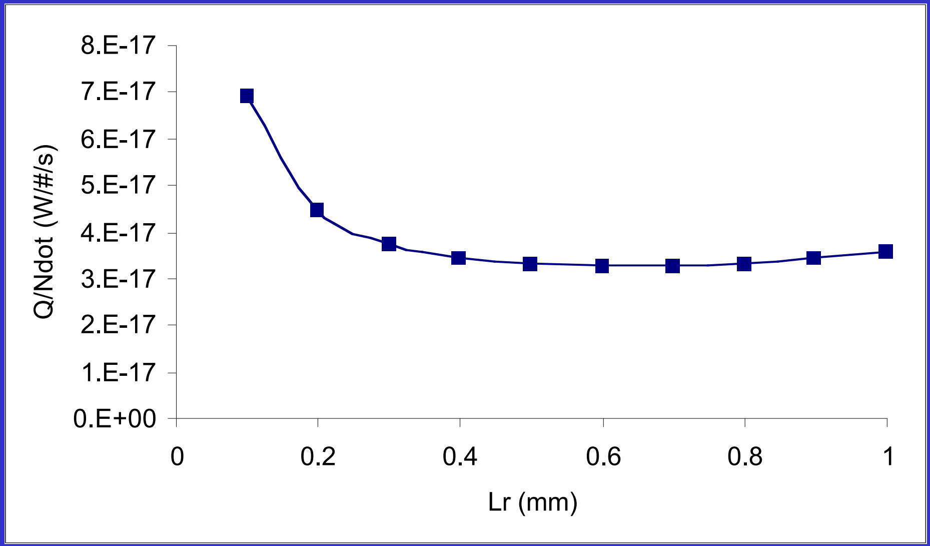
L_x = .55 mm

L_R = 5mm

L_X = 20mm

Number of Stages	24
Pressure Ratio	10 (10-100 mTorr)
Flow Rate	6E13 (#/s) or 0.186 ml/s
Volume	33 cm^3
Power Consumption	1.5 W
Energy Efficiency	2.5E-14 W/(#/s)
Volumetric Efficiency	5.5E-19 m^3/(#/s)



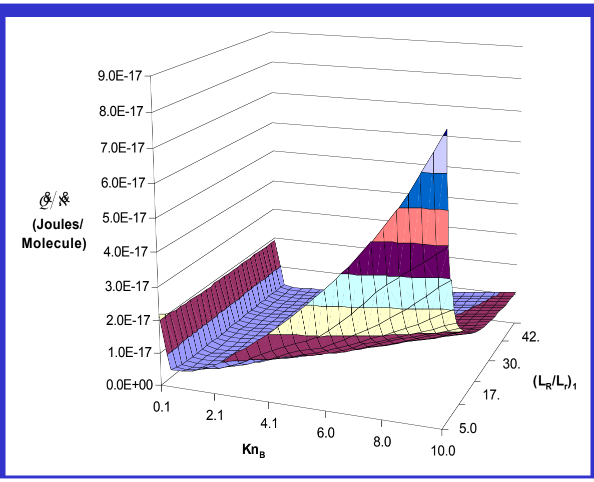


Considerations to Optimize Design for Low Pressure Applications

Optimize Capillary Pore Diameter

•Kn ~ 1 is optimum in capillary pores, using aerogel pores → Kn = 4.6E5

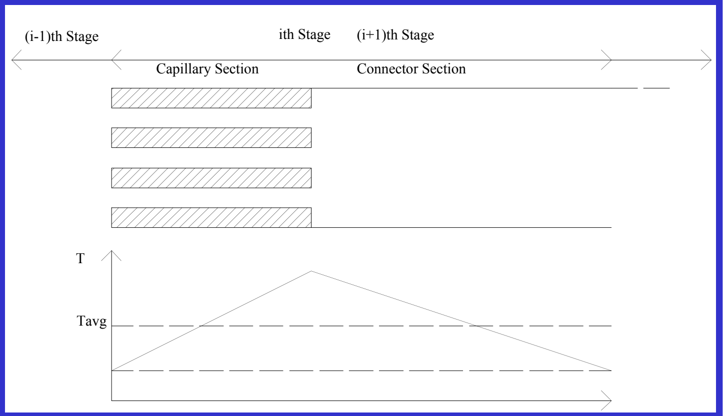
•By boring holes in the aerogel transpiration membrane the pore diameter can be optimally sized



Impose required temperature gradient

•At low connector Kn the gas is not uniformly hot at the hot side of the pores due to direct reflections from connector walls

•Add thermal adjustment material

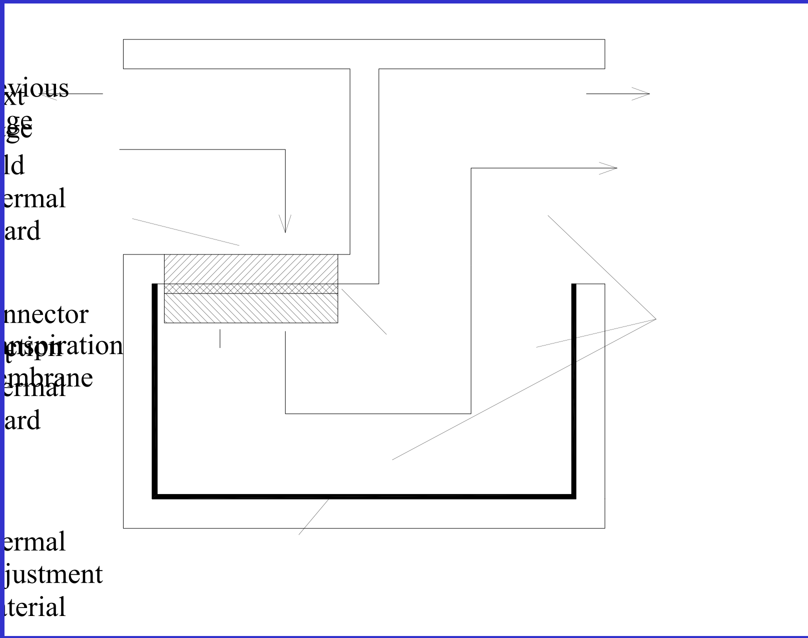


Performance Using Optimized Pore Diameters

Modifications:

1.) Bore Optimized Holes in Aerogel Substrate

2.) Add Thermal Adjustment Material



Cascade	L_r (m)	L_x (m)	L_R (m)	L_X (m)
10-100 mTorr	2.5E-04	5.0E-04	5.0E-03	2.0E-02
100 mTorr - 1Torr	2.5E-05	5.0E-04	2.8E-03	2.0E-02
1Torr-10Torr	2.5E-06	5.0E-04	2.7E-03	2.0E-02
10Torr-760 Torr	1.0E-08	5.0E-04	1.3E-03	5.0E-03

Low Pressure Performance Comparison

•Performance Increases Due to New Design

Number of Stages	24		Number of Stages	33
Pressure Ratio	10 (10-100 mTorr)		Pressure Ratio	10 (10-100 mTorr)
Flow Rate	6E13 (#/s)		Flow Rate	3E16 (#/s)
Volume	33 cm^3		Volume	45 cm^3
Power Consumption	1.5 W		Power Consumption	1.1 W
Energy Efficiency	2.5E-14 W/(#/s)		Energy Efficiency	7.E-17 W/(#/s)
Volumetric Efficiency	5.5E-19 m^3/(#/s)		Volumetric Efficiency	1.5E-21 m^3/(#/s)

•increased pore diameter → increased conductance

•increased conductance → increased mass flow

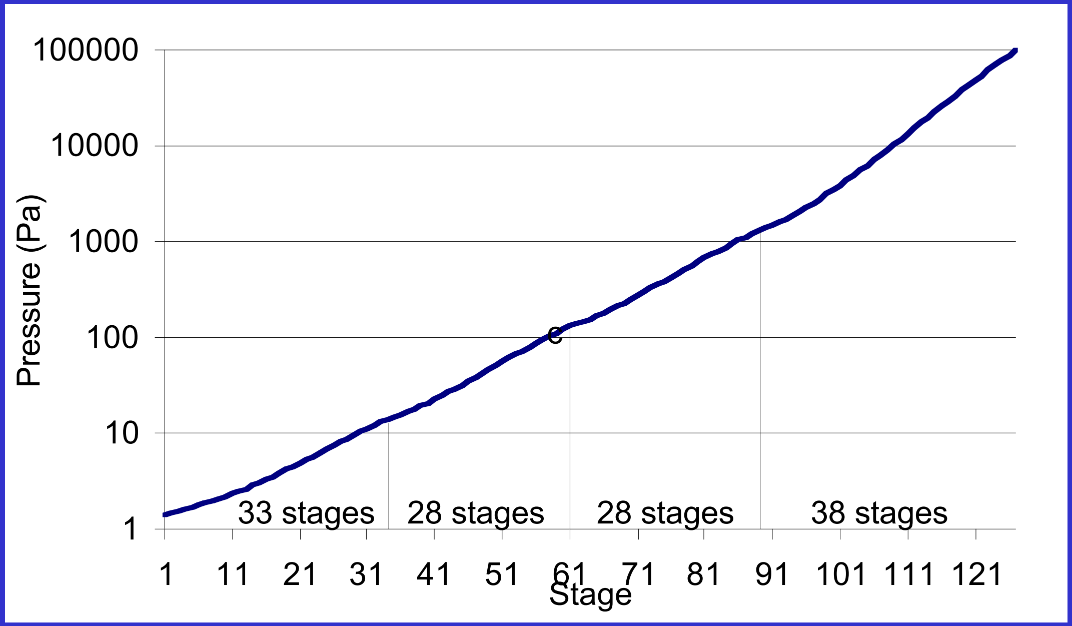
•decreased λ, Kn → decreased TMPD

•decreased pressure ratio → increased number of stages

•Net Results: more stages and volume, less power and volume/ upflow

Performance of New Design

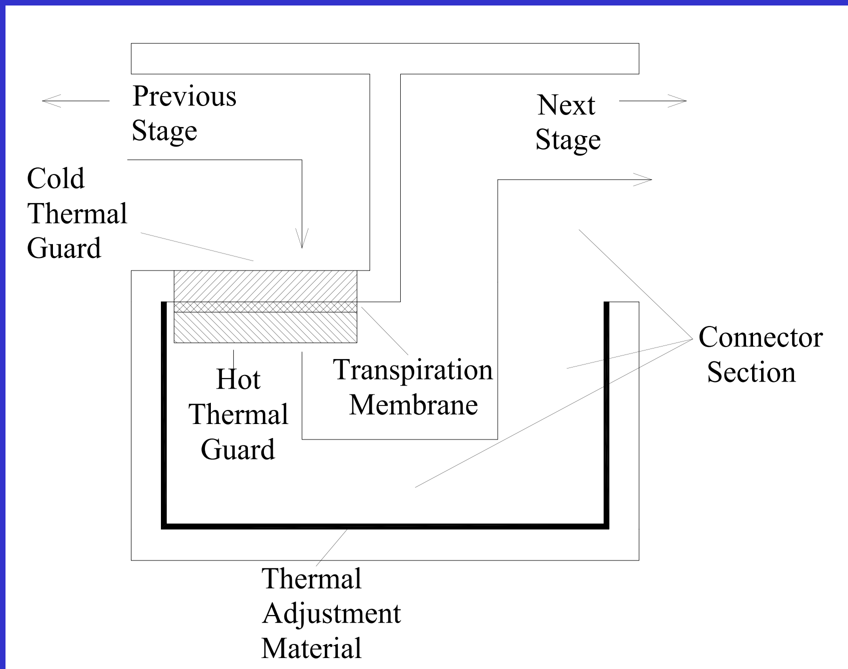
Cascade	Volume (cm^3)	Power (W)
10-100 mTorr	45.1	1.07
100mTorr-1Torr	13.0	0.297
1Torr-10Torr	11.8	0.268
10Torr-760Torr	5.26	0.92
Total	75.2	2.56

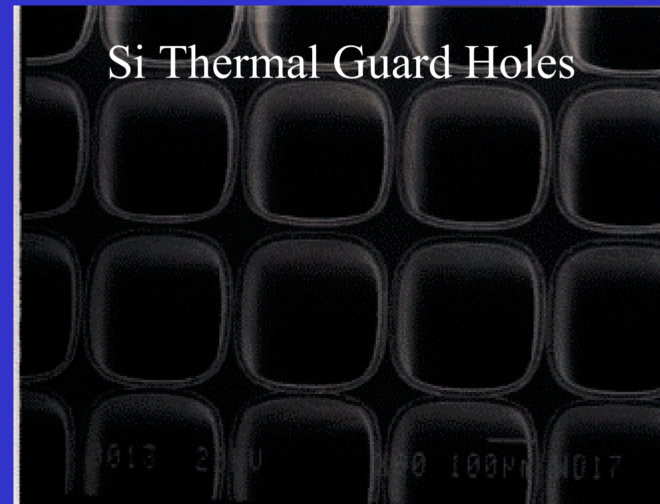


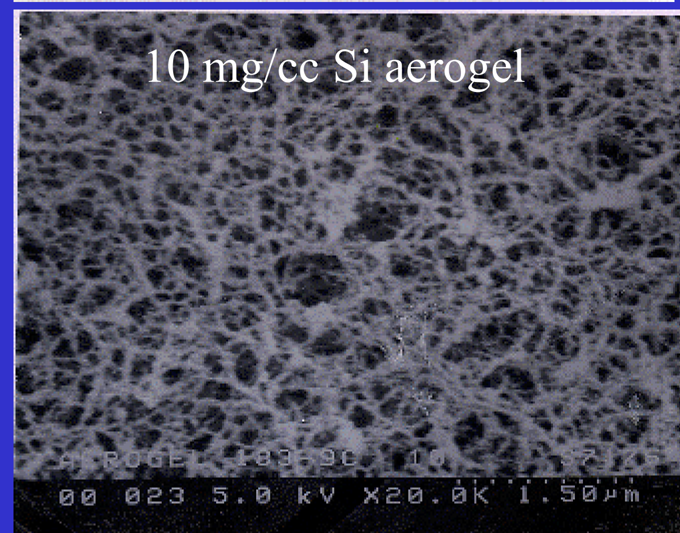
Power Efficiency	8.5E-17 W/(#/s)
Volumetric Efficiency	2.5E-21 m^3/(#/s)

Status of Experimental Work

- One stage device constructed and testing is ready to begin







Conclusions

- Optimum operation (based on thermal and volumetric efficiency) occurs at Capillary Kn ~ 1.
- Pore sizes must be optimized for low pressure application.
- Thermal adjustment material must be added at low pressures
- 10 mTorr identified as the lowest practical pressure attainable with a MEMS Knudsen Compressor.

This work is partially funded by NASA: award number NAG5-10399