Quantifying Leak Rates and Vacuum Impact on Granular Soil Column Pneumatic Seal

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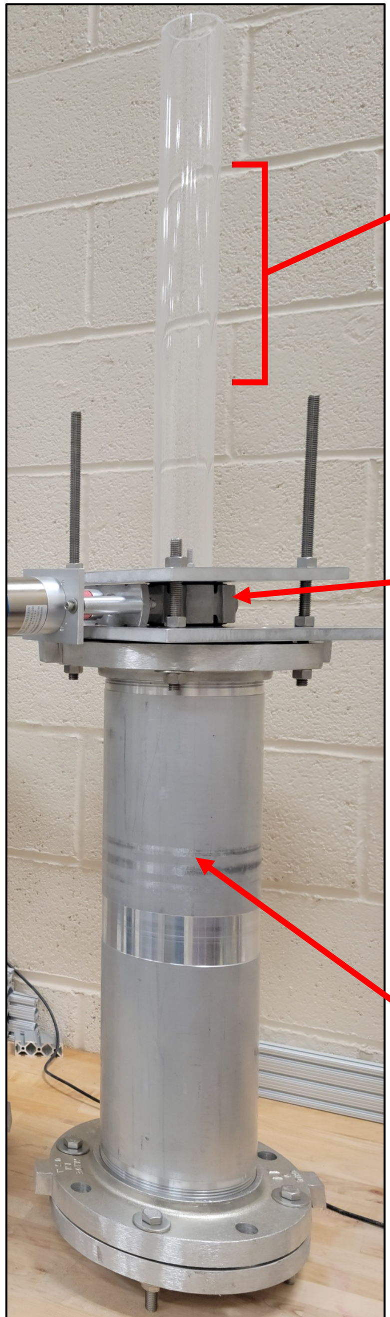
Space Resources Roundtable 2023

Test Hardware Setup



Soil filled both to 8” and 16” heights

2”, 4”, and 6” diameter columns tested

Butterfly valve flows gas into bottom of soil

OB-1a regolith simulant used

Lower plenum filled with gaseous nitrogen to apply pressure to underside of soil column

GRC’s VF-13 vacuum chamber (opened)

Running an Experiment

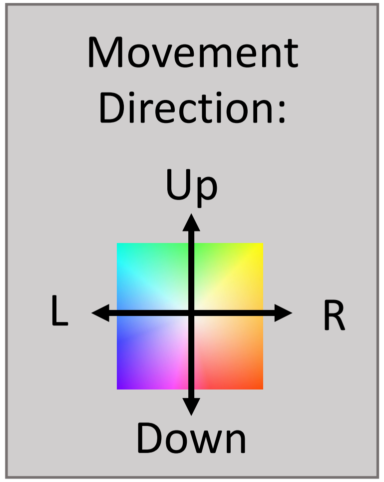
Increasing gas pressures eventually cause visual soil disruption (shown right), but there is significant gas flow through the regolith prior to tunneling

This presentation focuses on quantifying the leak rate of the soil seal below this threshold pressure, where regolith remains undisturbed

4” diameter, 6” height

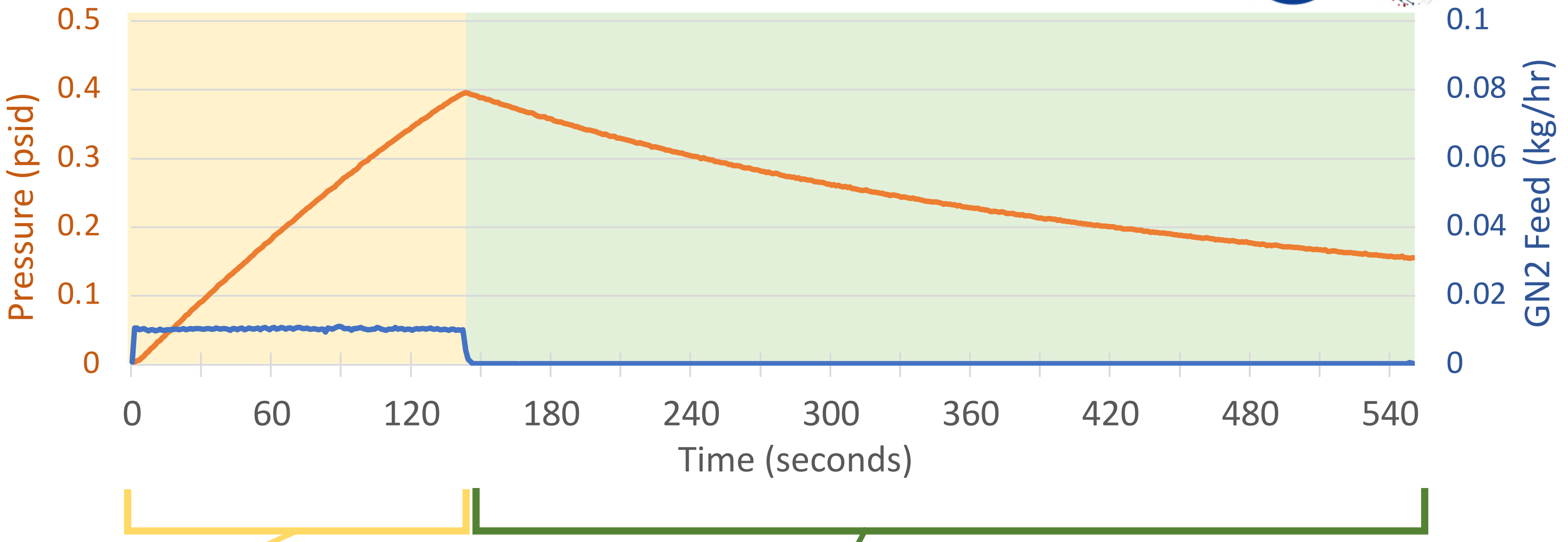
Nitrogen gas fed from lower plenum

Real-time optical flow footage of soil column ‘failure’ under high pressure in ambient conditions



Generating Data:

Simplified test run



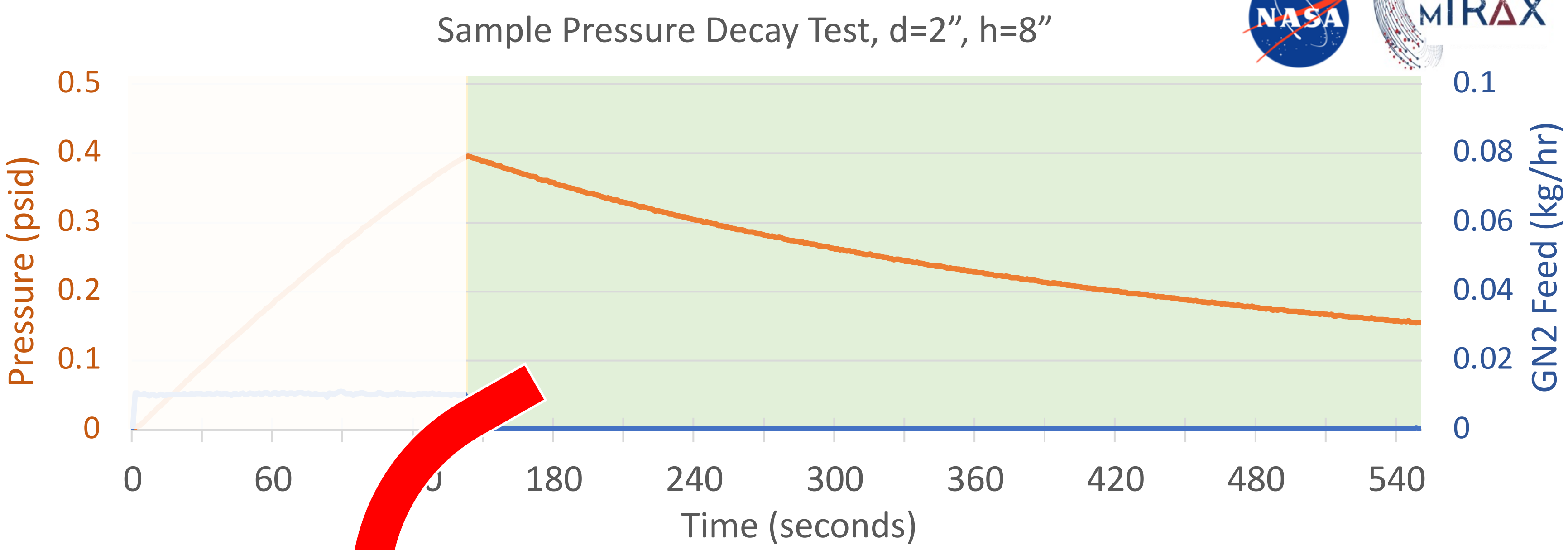
GN2 fed into lower plenum at constant ~0.01 kg/hr

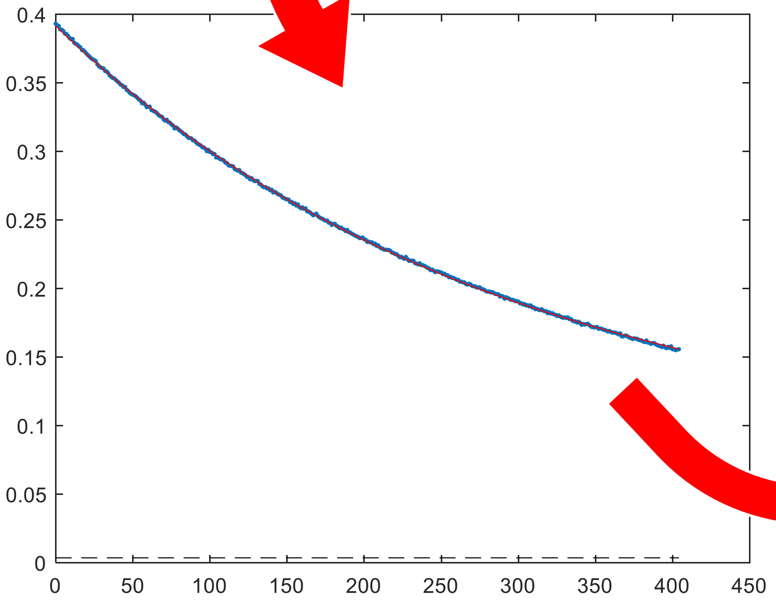
GN2 feed turned off and pressure in plenum allowed to diffuse through the column into the chamber

Generating Data:

Extracting parameters

Diffusion rate through column is modeled by generic exponential decay, and curve fit in Matlab





General exponential decay:

$$y = a - b \cdot e^{-c \cdot x}$$

	Nominal
a	0.0775
b	-0.314
c	0.0034
R^2	0.99989

Curve-fitting coefficient interpretation:

a: equilibrium pressure (absolute)

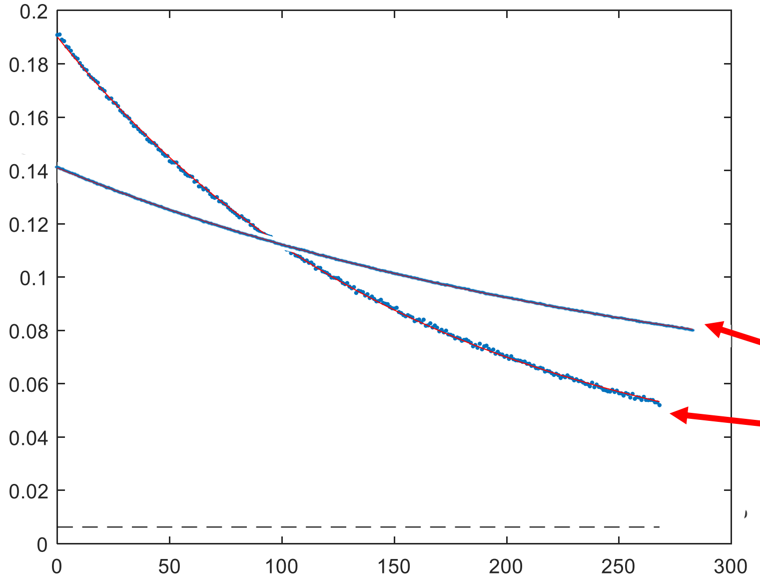
b: decay rate (weak)

c: decay rate (strong)

Generating Data:
Comparing values

Soil seal performance is inversely proportional to decay coefficient c!

Unitless c parameter describing decay speed allows comparison of soil seal performance regardless of initial delta-pressure



The 'c' coefficient is the dominant term governing decay rate

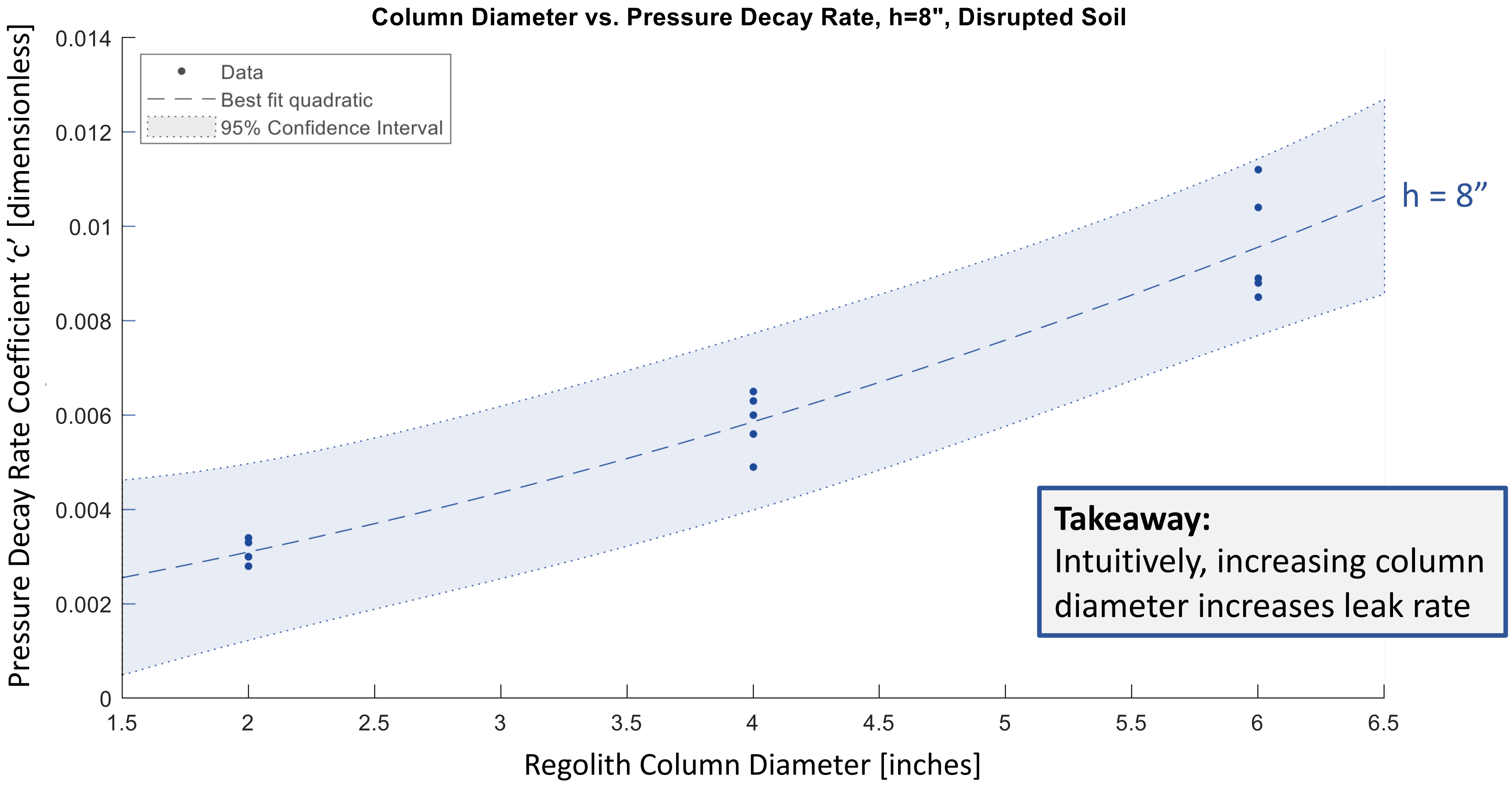
Low c: smaller leak rate; better soil 'seal'
High c: larger leak rate; worse soil 'seal'

General exponential decay:

$$y = a - b \cdot e^{-c \cdot x}$$

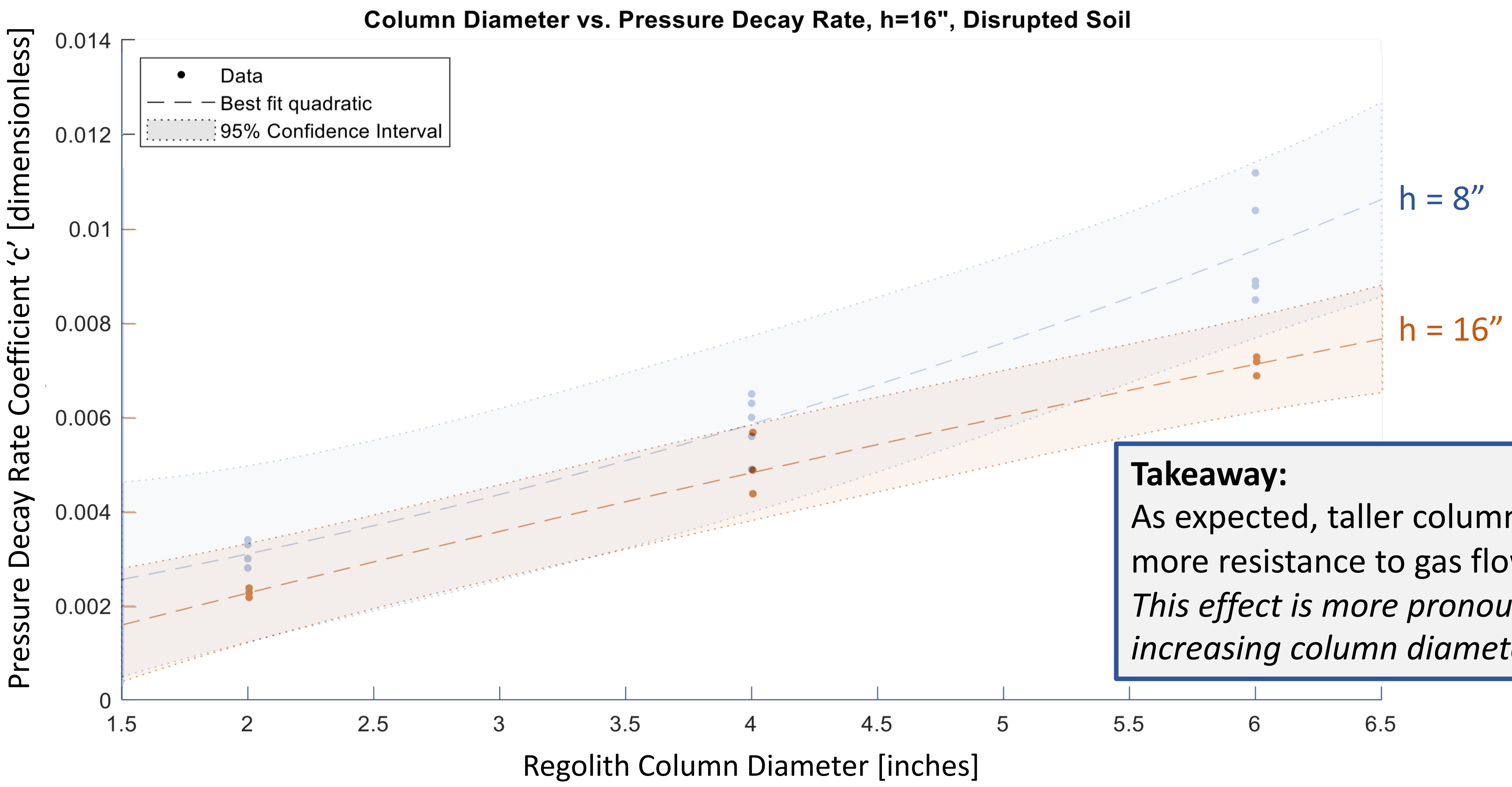
	Nominal
a	0.0775
b	-0.314
c	0.0034
R^2	0.99989

Column **Diameter** Impacting Leak Rate



Takeaway:
Intuitively, increasing column diameter increases leak rate

Column **Height** Impacting Leak Rate



Takeaway:
As expected, taller columns provide more resistance to gas flow
This effect is more pronounced with increasing column diameter

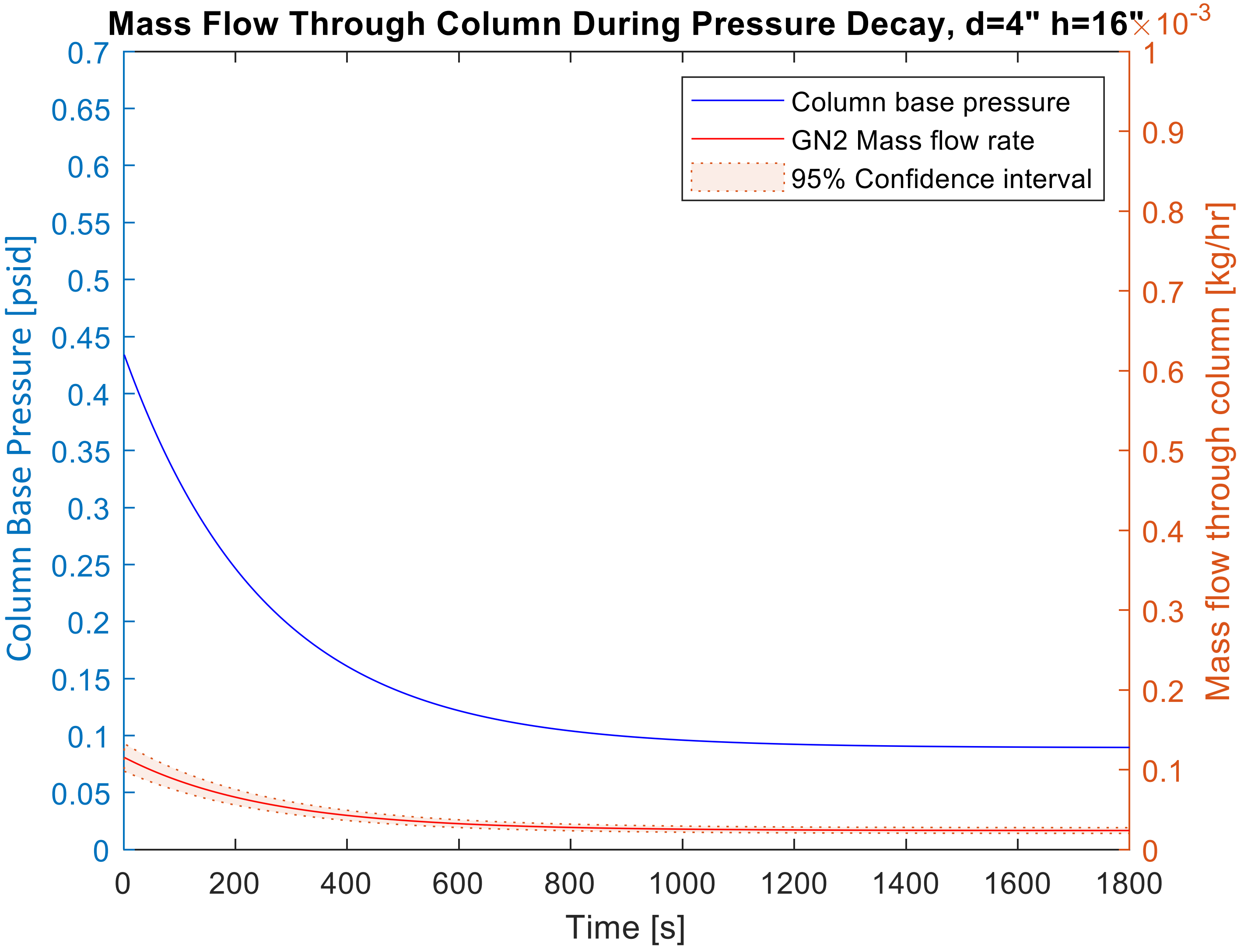
Dusty-Gas Model Adaptation: **Time dependence**

Model describes molar flow rate of gas through porous media

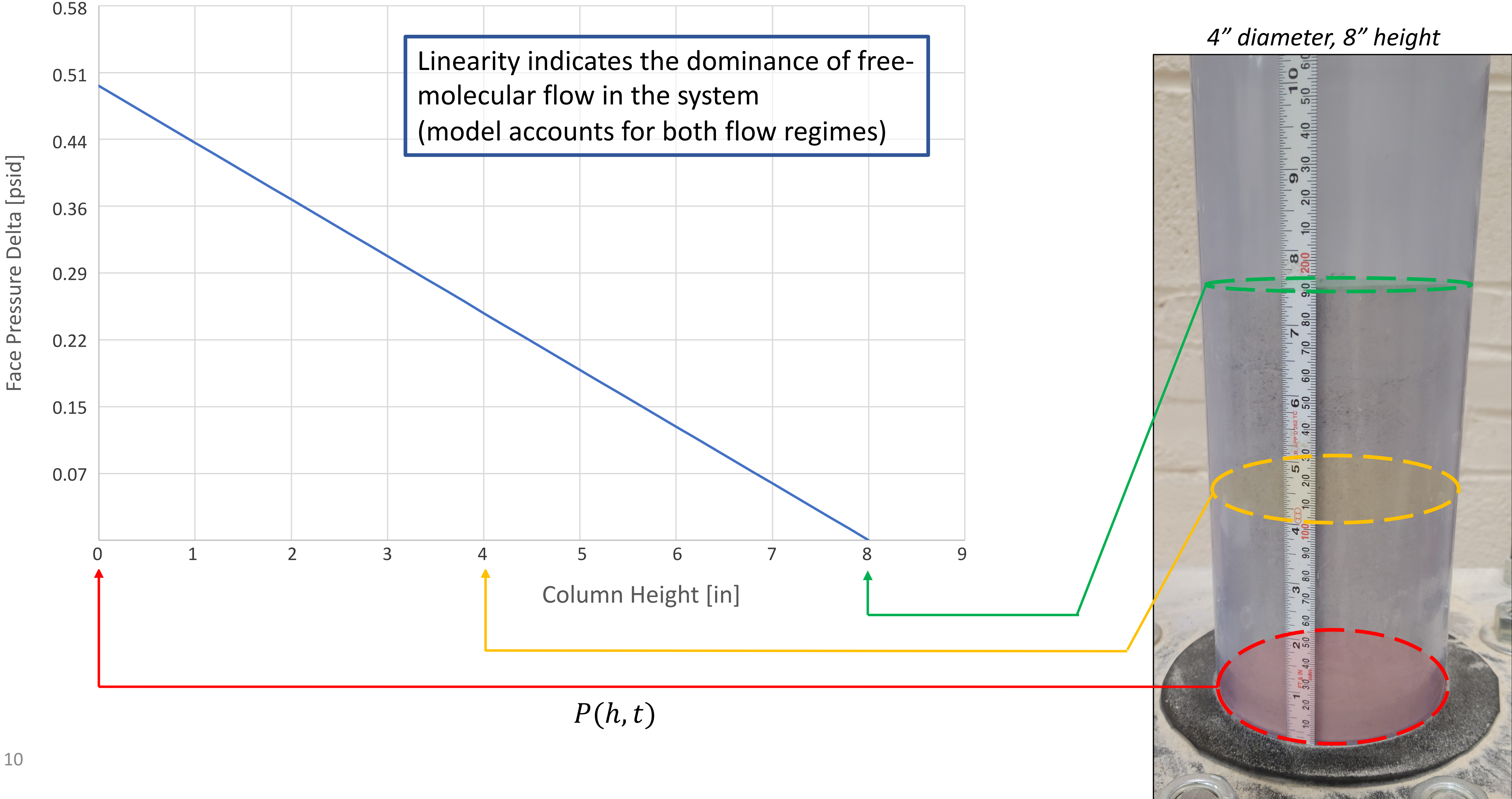
By substituting time-series pressure data, time-dependent pressure gradient and mass flux can be determined

Column pressure
Gas pressure is predicted for every point in space and time

Mass flux
Determine how much gas is escaping the system



Dusty-Gas Model Adaptation: **Location dependence**



Dusty-Gas Model Adaptation: Assumptions and Extensions

Modelling Assumption	Testing Mitigation	Expanded Upon in Report?
Non-reacting gas flow	Pure, dry GN2 used with OB-1 mechanical simulant	**No**
Pure gas flow	Pure, dry GN2 used	**Yes** Report includes generalized model which accounts for viscosity effects of gas mixtures
Constant ambient pressure	Vacuum chamber volume much larger than pressurized plenum; chamber pressure monitored	**Yes** Referenced work of Shugard and Robinson detailing applications of variable ambient pressure
Regolith spatially uniform	Soil columns drained and regolith mixed between tests to prevent gradual size beneficiation	**No** Existing model could be applied in discrete segments to approximate continuously variable regolith properties

Conclusions

- Intuitive design trades have been empirically quantified:
  - Minimize column diameter for given regolith feed requirement
  - Maximize column height for given loading architecture
- Adapted model describes gas pressure at any point in location and time
- Vacuum testing is critical for tortuous path-type pneumatic seals
  - Comparable ambient tests report significantly higher leak rates
  - Ensuring free molecular flow minimizes gas leak rate
- More comprehensive information available upon request, and later in technical memo (found in NASA STI program: https://www.sti.nasa.gov/)

Backup

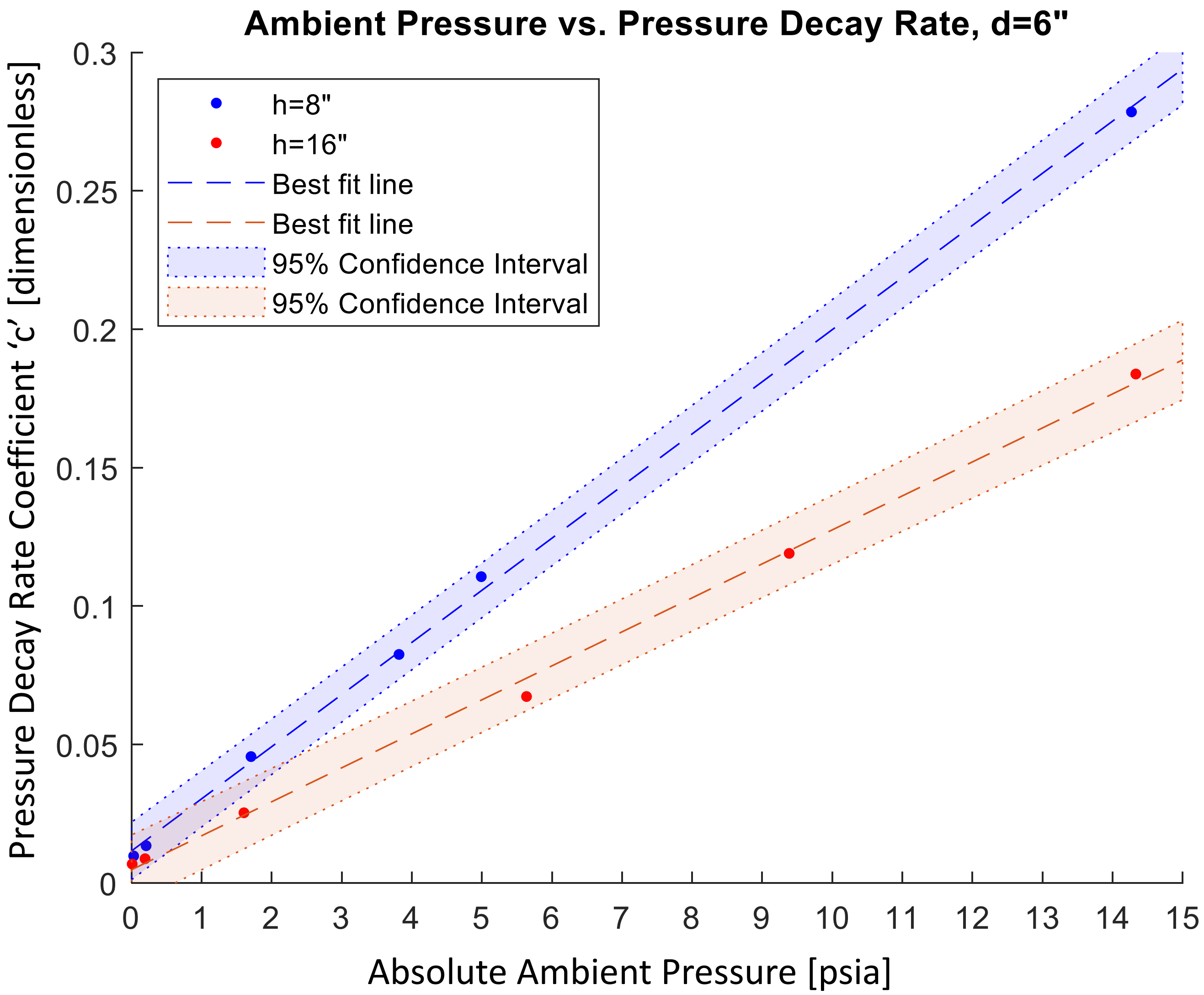
Relevant Resources

'Dusty-Gas Model' Origin

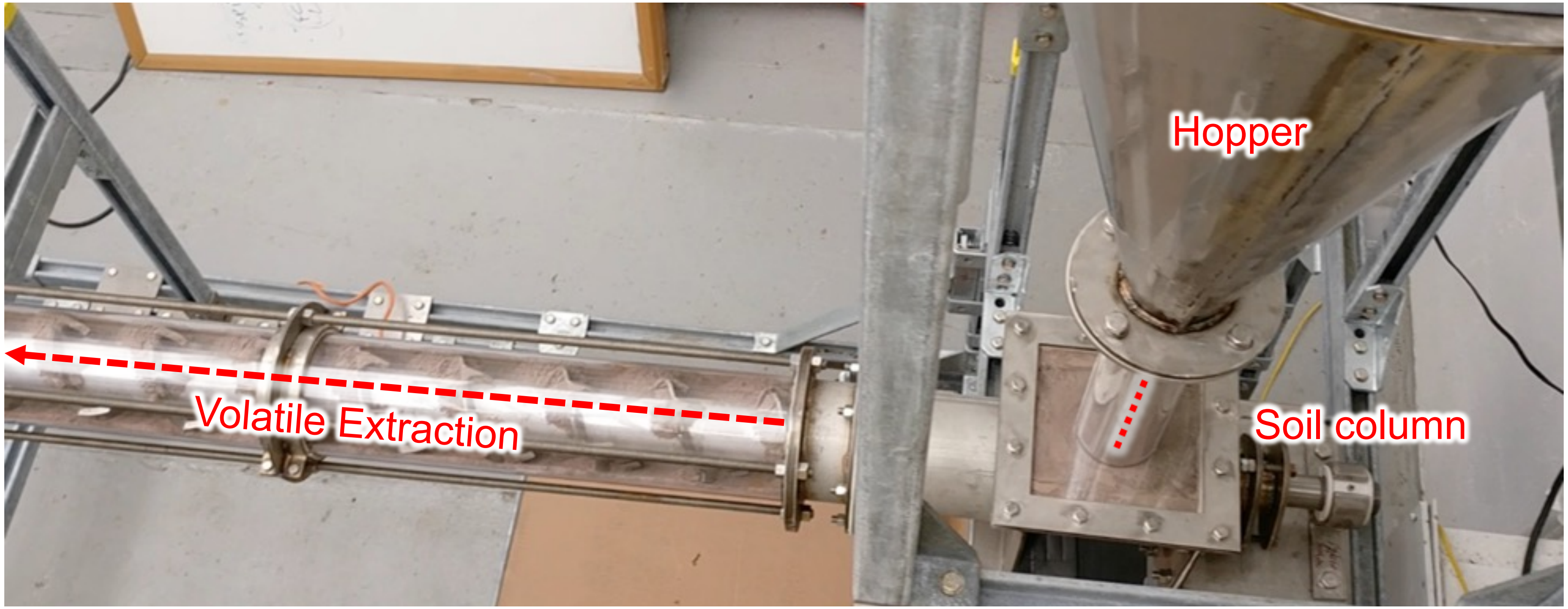
Dusty-Gas Model overview and applications

1. Evans, R. B., et al. "Gaseous Diffusion in Porous Media at Uniform Pressure." The Journal of Chemical Physics, vol. 35, no. 6, 1961, pp. 2076–2083., https://doi.org/10.1063/1.1732211.
2. Evans, R. B., et al. "Gaseous Diffusion in Porous Media. II. Effect of Pressure Gradients." The Journal of Chemical Physics, vol. 36, no. 7, 1962, pp. 1894–1902., https://doi.org/10.1063/1.1701287.
3. Mason, E. A., et al. "Gaseous Diffusion in Porous Media. III. Thermal Transpiration." The Journal of Chemical Physics, vol. 38, no. 8, 1963, pp. 1808–1826., https://doi.org/10.1063/1.1733880.
4. Mason, E. A., and A. P. Malinauskas. "Gaseous Diffusion in Porous Media. Iv. Thermal Diffusion." The Journal of Chemical Physics, vol. 41, no. 12, 1964, pp. 3815–3819., https://doi.org/10.1063/1.1725819.
5. Mason, E. A., et al. "Flow and Diffusion of Gases in Porous Media." The Journal of Chemical Physics, vol. 46, no. 8, 1967, pp. 3199–3216., https://doi.org/10.1063/1.1841191.
6. Shugard, A., & Robinson, D. "A simple model of gas flow in a porous powder compact." 2014, https://doi.org/10.2172/1127097
7. Davies, C.N. "Gas Transport in Porous Media: The Dusty-Gas Model." Journal of Aerosol Science, vol. 15, no. 1, 1984, p. 81., https://doi.org/10.1016/0021-8502(84)90058-2.

Ambient Pressure Impacting Leak Rate

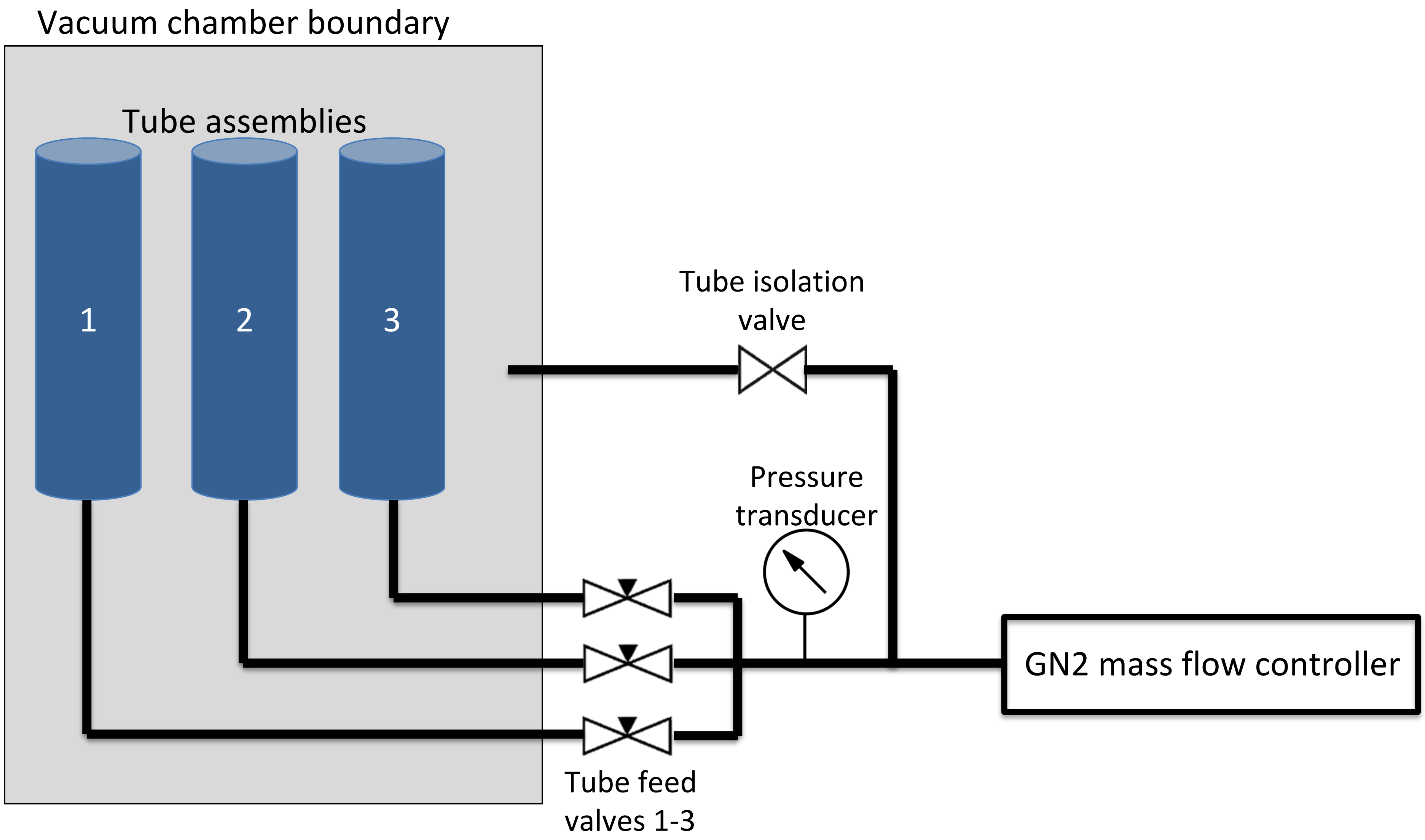


Takeaway:
Decreasing absolute ambient pressure decreases soil seal leak rate
Transition from primarily viscous to free-molecular flow increases the amount of time it takes for gas to travel through the regolith



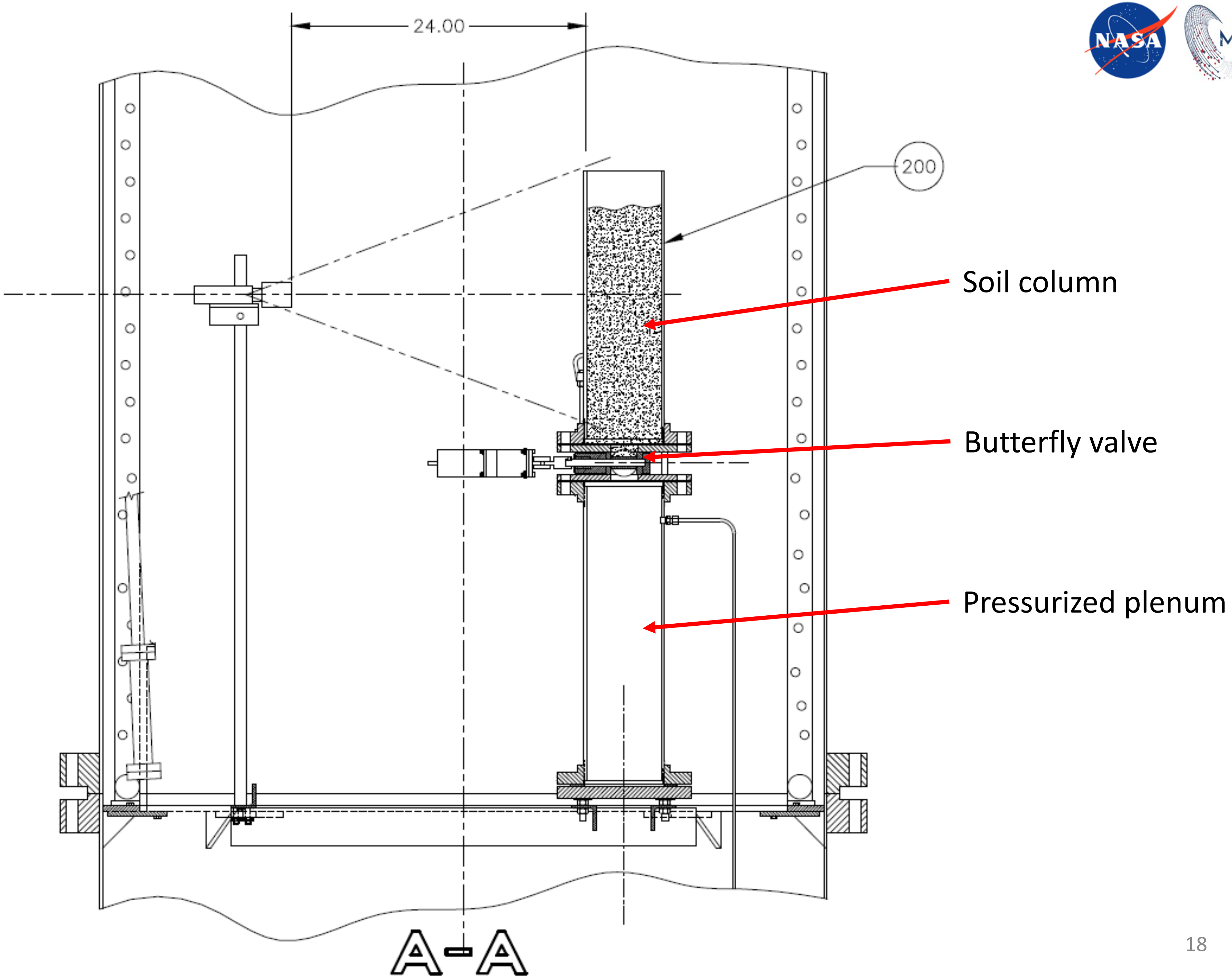
Lunar Auger Dryer ISRU (LADI) breadboard prototype shown with regolith feed hopper and columnated soil seal

P&ID



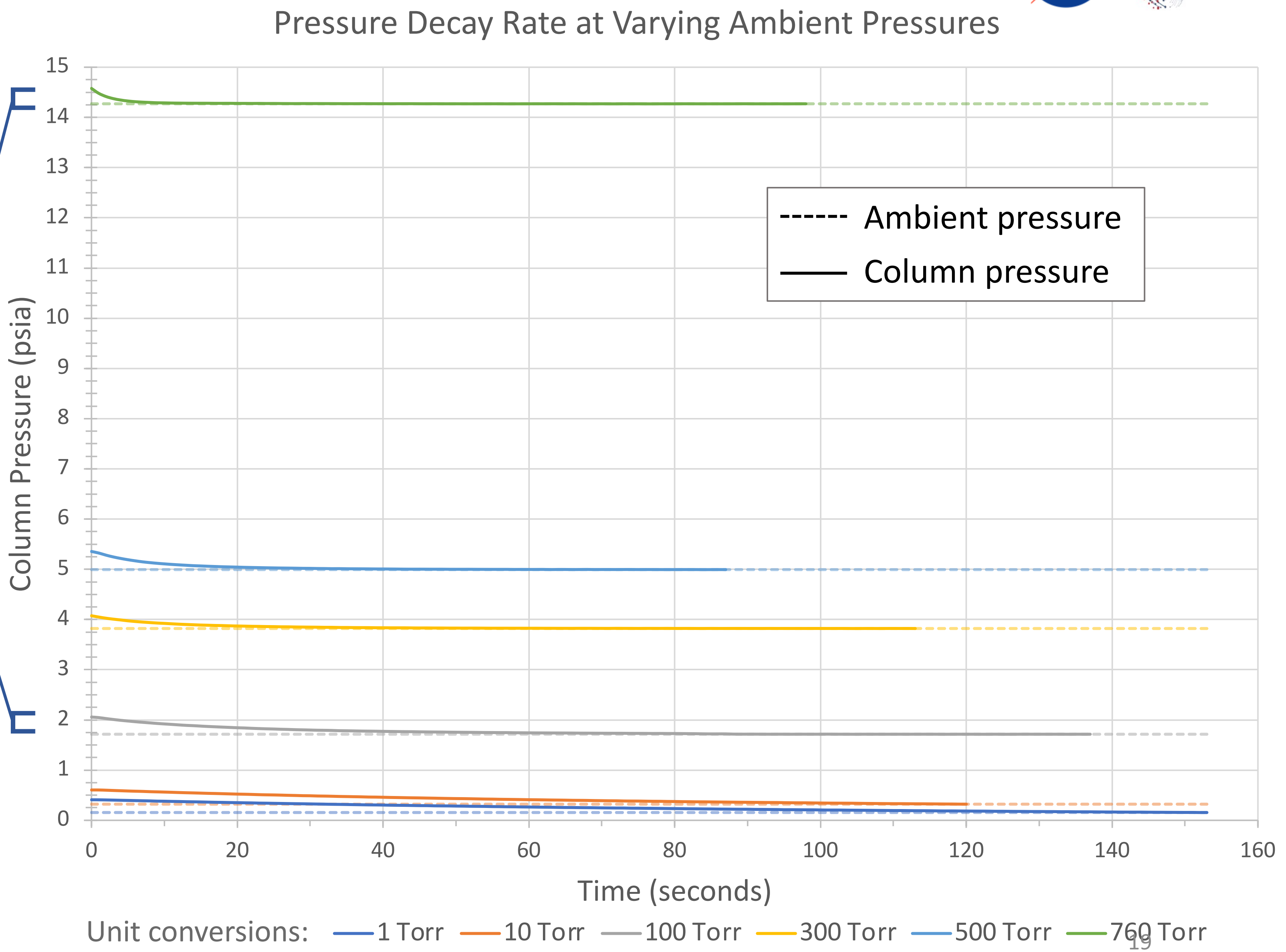
Vacuum chamber boundary
Tube assemblies
1
2
3
Tube isolation valve
Pressure transducer
GN2 mass flow controller
Tube feed valves 1-3

Section view



Ambient Pressure Tests

Similar pressure differential (~0.5 psid) applied to identical column configurations at different levels of absolute ambient pressure



Dusty-Gas Model Adaptations

Molar flux of pure, nonreacting gas through porous media: $N = \frac{-BP_1}{\mu RT}\nabla P - \frac{D^K}{RT}\nabla P = N_v + N_m$

Free-molecular flow dominance condition: $\frac{BP_1}{\mu D^K} \ll 1$

Instantaneous pressure gradient: $P(z) = \frac{-D^K\mu}{B} + P_1\sqrt{1-\left(1-\frac{{P_2}^2}{{P_1}^2}\right)\frac{z}{h}+\frac{2D^K\mu}{BP_1}\left[1-\left(1-\frac{P_2}{P_1}\right)\frac{z}{h}\right]+\left(\frac{D^K\mu}{BP_1}\right)^2}$

Time-dependent mass flow: $\dot{m}(t) = \frac{3.6\cdot MA_c}{2RTh\mu}\left[B(a-b\cdot e^{-c\cdot t})^2 + 2D^K\mu(a-b\cdot e^{-c\cdot t}) - BP_2 - 2D^K\mu P_2\right]$

Nomenclature

Symbol	Units	Description
A_c	cm^2	Sectional area of simulant column
a	-	Exponential function constant offset
B	cm^2	Effective permeability of regolith simulant
b	-	Exponential function weak coefficient
c	-	Exponential function strong coefficient
D^K	cm^2/s	Effective Knudsen diffusion coefficient
d	m	Mean pore diameter of regolith simulant
h	cm	Regolith simulant column height
M	kg/mol	Molar mass of gas
$\dot{m}$	kg/hr	Mass flow rate through simulant column
$\dot{n}$	$mmol/s$	Molar flow rate through simulant column
P_1	MPa	Lower plenum pressure
P_2	MPa	Ambient pressure
P_{AVG}	MPa	Average simulant face pressure
ΔP_{BED}	MPa	Pressure differential across simulant column
R	$J/mol \cdot K$	Universal gas constant
T	K	Gas temperature
x	-	Mole fraction of gas
ε	-	Void fraction of regolith simulant
μ	$MPa \cdot s$	Gas viscosity
$\bar{\mu}$	$MPa \cdot s$	Mean viscosity of gas mixture