SAND2019-9947PE

FEMA Deposition Model Work for the Assessment Working Group

August 28th 2019

PRESENTED BY

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Request and Initial Steps

In 2017, I was asked by Assessment Working Group if I would be willing to perform a literature review of available deposition models and propose a path forward for updating the model used by the AWG and within Turbo FRMAC to a more advanced and modern model.

I accepted to the work and began to review the available literature in the summer of 2018.

Over the course of the summer I reviewed approximately 80 literature papers from the 1960's up to 2016. I would follow up by reading approximately 20 more papers in early 2019.

Initial Conclusions.

- As the phrase goes, all models are wrong, some models are useful.
- General consensus of literature was all models struggle greatly in the submicron to a tenish micron range.
- All models contain conceptual terms with fitting parameters that require laboratory or field data to ascertain.
- General consensus was all field data suffers greatly from uncertainty and inconsistent application of adjustment factors.
  - Data has more a noise to signal ratio, than a signal to noise ratio.
  - Data fits are for specific surfaces where the upwind fetch is long and uniform.
  - Assume homogeneity in time and space, and no ongoing source of pollutant.
  - Critical parameters of particle size, shape, density are difficult to determine and highly uncertain due to available instrumentation.
  - Generally data is limited to neutral conditions where collection of data is simplest.
  - Corrections made to data on the same order of magnitude or more of the data collected.
  - Because of limitations of field data, applicability is generally restricted to less than 1 um.
- Hence, review paper of Hicks 2016 says in paraphrase, All our models suck, we need to rethink our science, some models appear to do ok, but we honestly don’t know why.

Initial Conclusions, Next Steps

The literature universally agreed that key values for determining deposition velocity were particle size and friction velocity with particle density and shape factor of secondary importance and vegetative properties of third order significance.

The literature stated consistently that resistive models performed very poorly or were inappropriate to the Urban Environment.

At the conclusion of 2018 a SAND report was written Titled - Deposition Velocity Modeling for Turbo FRMAC, SAND2018-8192.

The report represented a comprehensive summary of the literature that was reviewed, the results of a similar investigation by NARAC, and a discussion of best of breed models.

Of these it was recommended in the paper that the Feng Model and the Petroff and Zhang model should be investigated further with the greater simplicity and easier extensibility of Feng potentially making it the preferential choice.

Model Implementation and Further Investigation

In 2019 the two models were implemented starting with Petroff and Zhang.

The actual Fortran implementation was acquired directly from Zhang and Environment Canada.

This code was converted to Java for use by Turbo FRMAC.

To validate the implementation of the Java code, the Fortran code was augmented with print statements to print of the value of every sub term and collection of sub terms for every surface type available in the model for particle size of 1 micron and a density of 1500 kg / m^3.

This process was repeated up to the full deposition velocity calculation.

Numbers between the two codes were verified to agree within 1 hundredth to 1 millionth of a percent depending on the test.

During the process it was uncovered that the Fortran code (particularly when the vertical flux of sensible heat was zero, e.g. at night) would divide by zero or calculate infinity in places, and yet return a finite "reasonable" result.

In the Java the same concept as L'Hoptial's rule of limits was used to catch division by zero's and infinite results and return the limit in these cases.

Petroff and Zhang were e-mailed about these cases, but never replied.

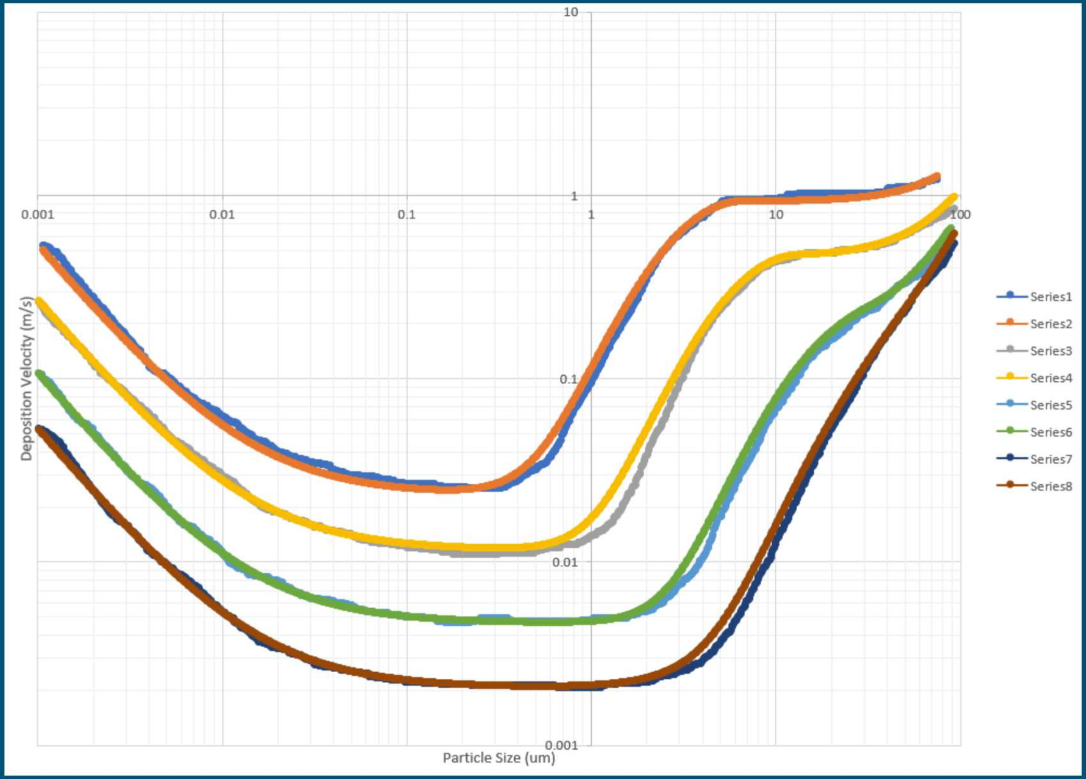
Model Implementation and Further Investigation

Although Feng (a colleague of Zhang) was also e-mailed for source code, no response was received.

Equations were thus directly coded up from Feng 2008 paper which thankfully had a complete listing of all terms in his model.

All charts of model results from Feng were scanned in and digitized to reproduce the curves.

Using the stated input values for each chart test cases were run for the 20 odd curves provided in the Feng paper.



Comparison to Field Data

Plots from Petroff and Zhang's 2010 paper which contained field data points against which P&Z and a few other models had been compared were then digitized and for the conditions stated in the paper (not fully specified so reasonable guesses were made on particle density for example).

Petroff and Zhang as well as Feng were then calculated over the particle size range and surface type specified to compare the models to the data. Since the actual roughness length of the surface was not specified, the P & Z roughness length was assumed for Feng.

Calculated P & Z was first compared to the chart in their paper to further ensure the implementation was "correct" and limit assumptions had not drastically changed the answer.

Results of comparison follows.

Validation Data Set

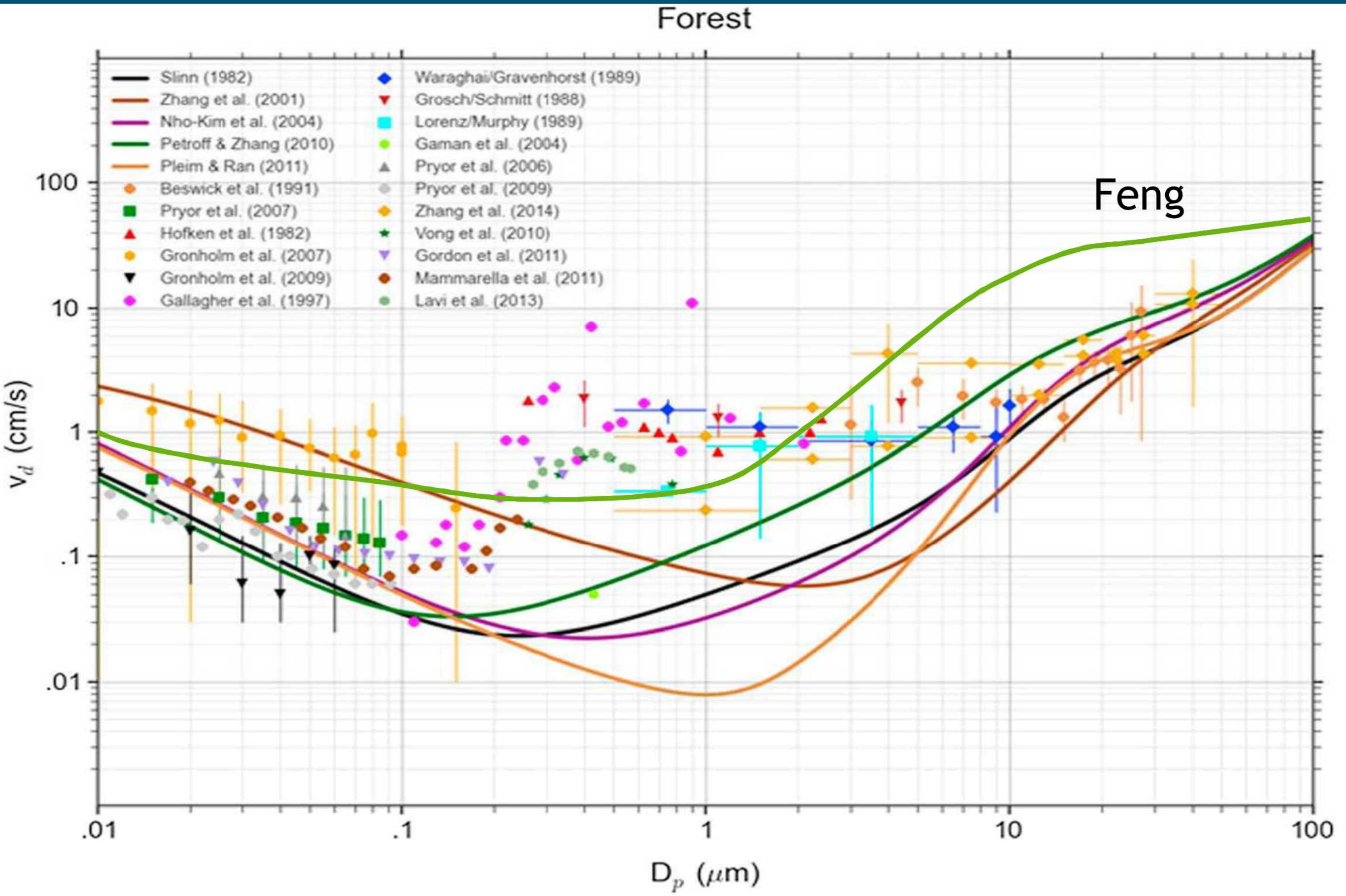
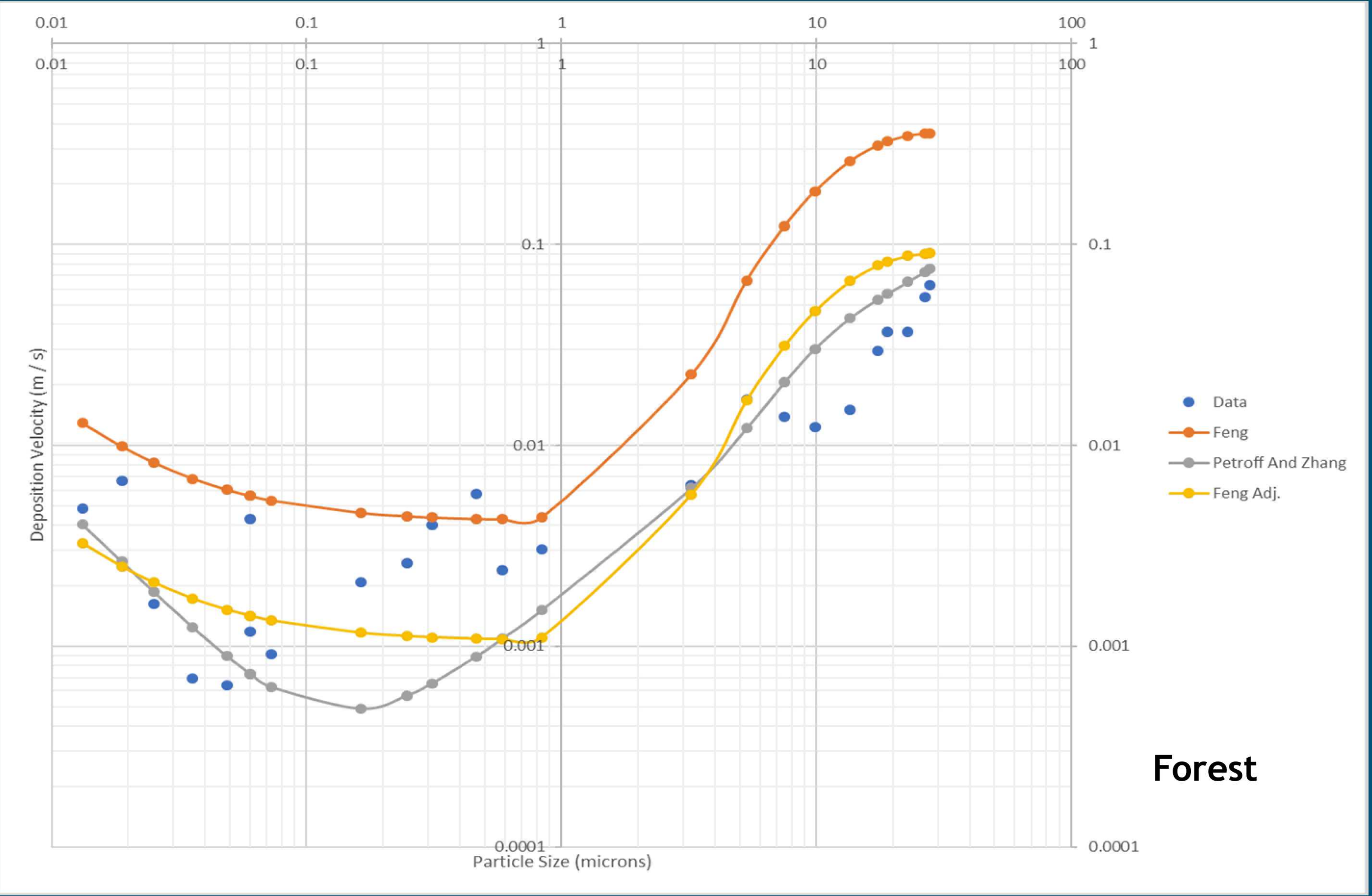


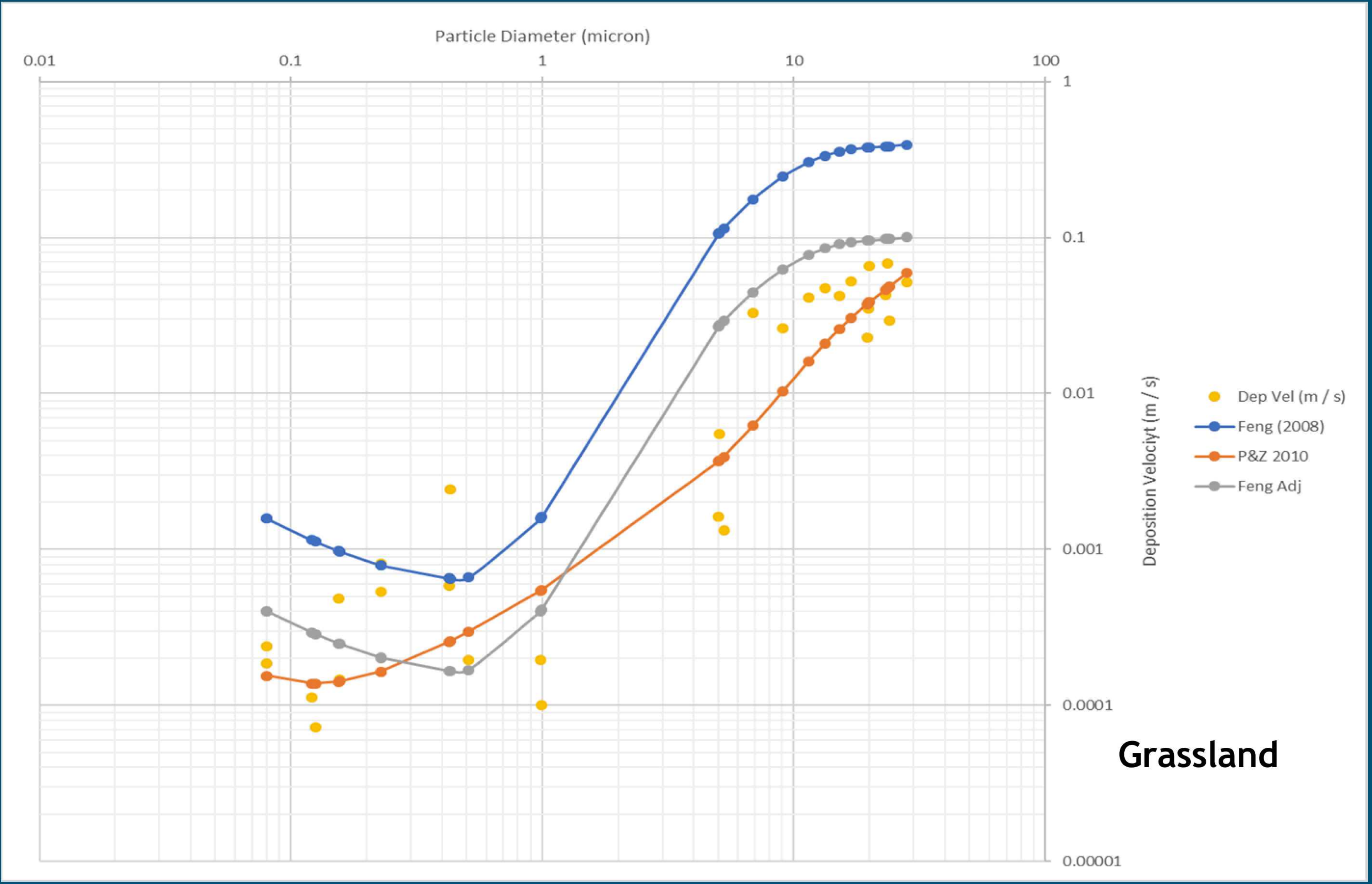
Figure 7. The dependence of the particle deposition velocity from the air to forest canopies, as predicted by several modeling schemes (the lines) and as determined by field experiments (the points). Note that the models seem to share the familiar "well" in the curve, whereas almost all of the experimental data do not.

Best of Breed Model Comparison

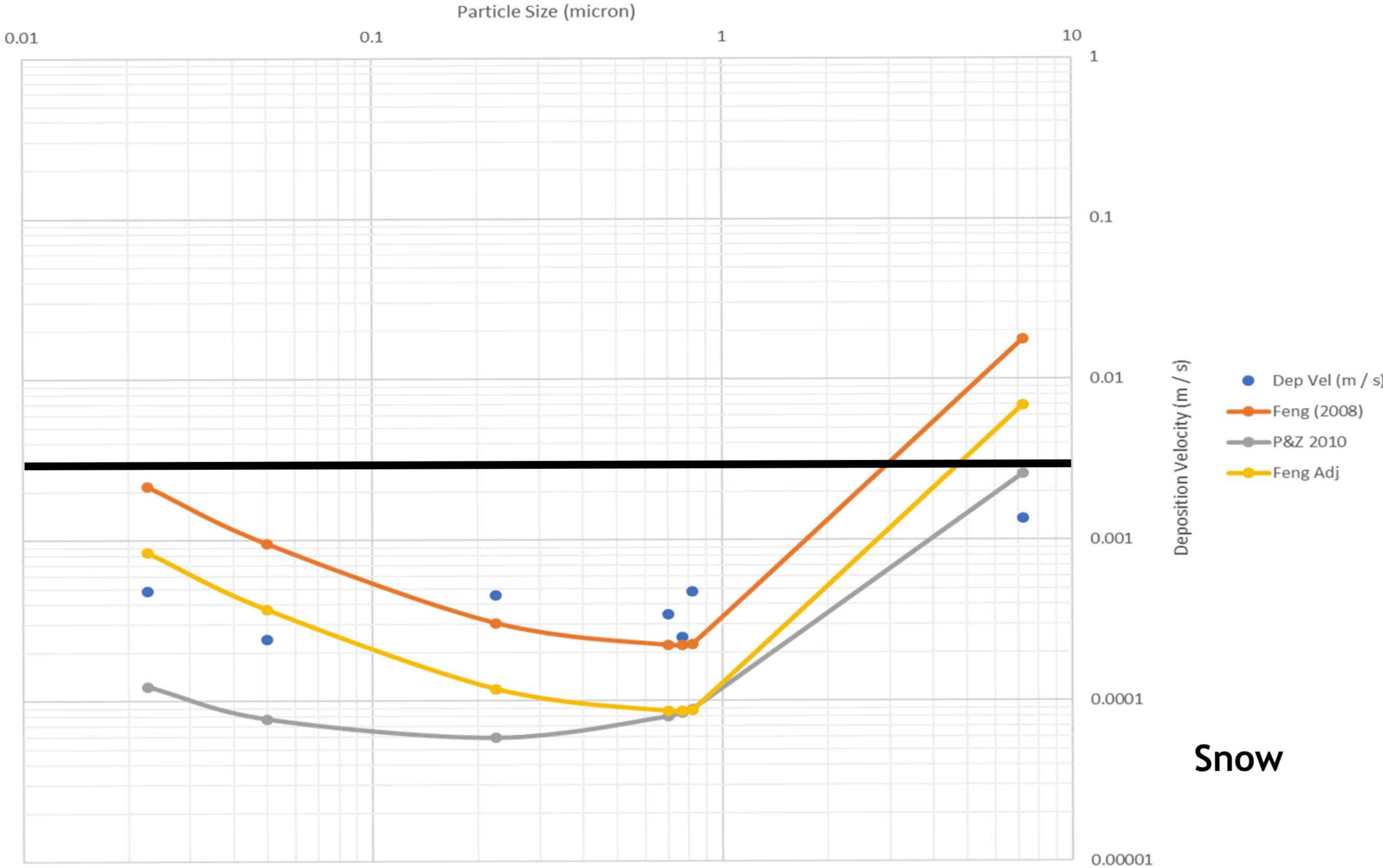


Forest

Best of Breed Model Comparison

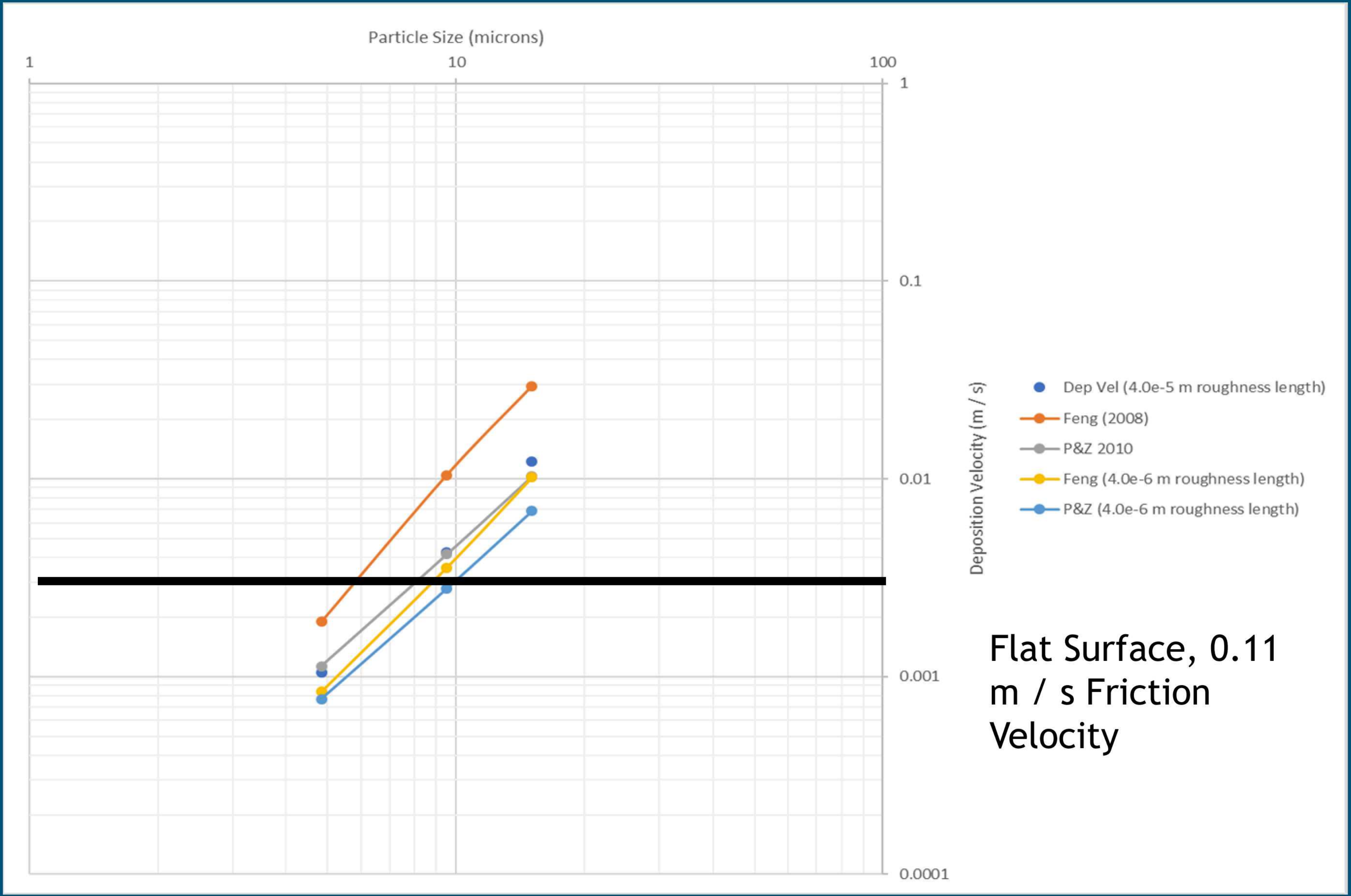


Best of Breed Comparison



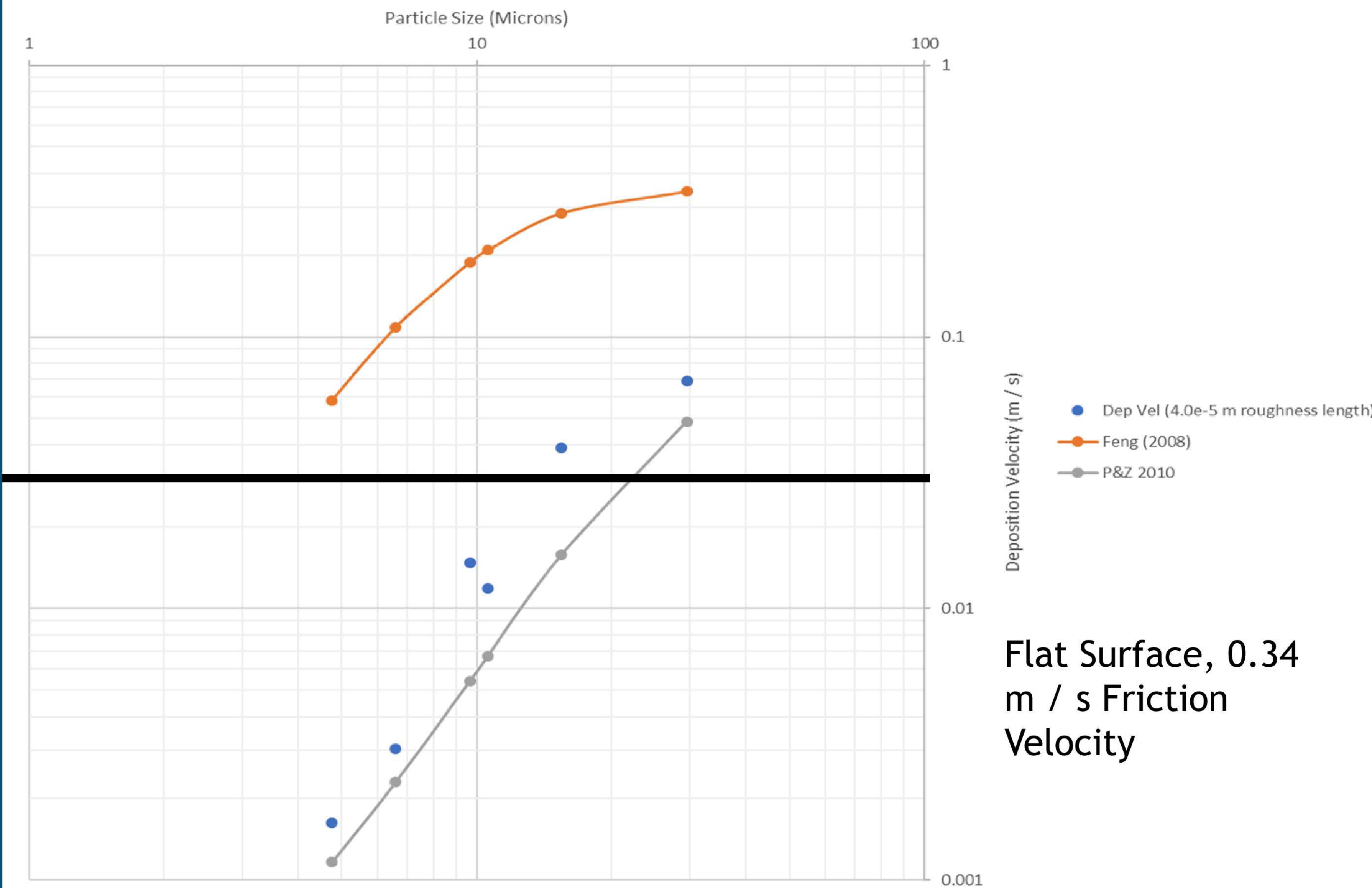
Snow

Best of Breed Comparison



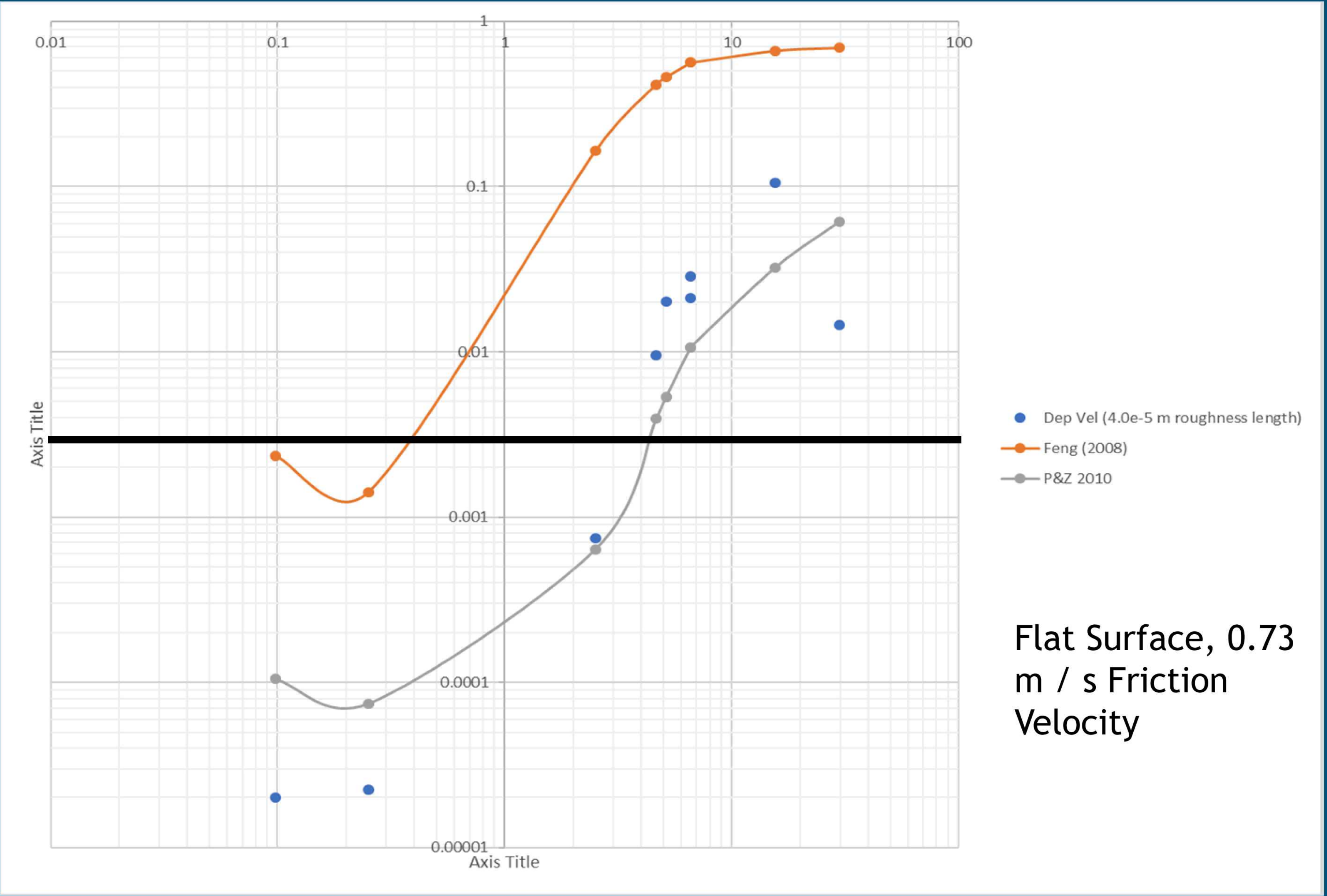
Flat Surface, 0.11 m / s Friction Velocity

Best of Breed Comparison



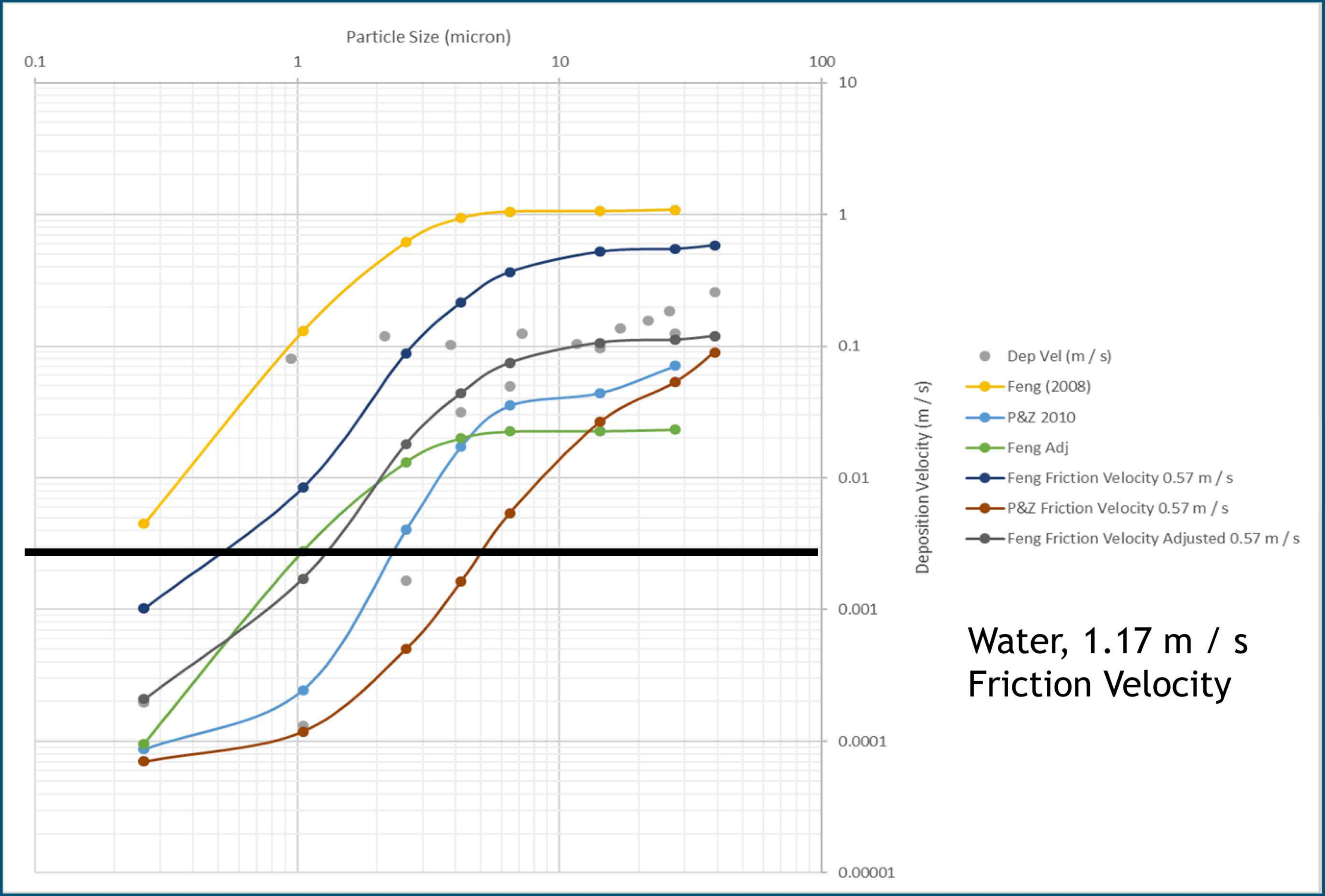
Flat Surface, 0.34 m / s Friction Velocity

Best of Breed Comparison



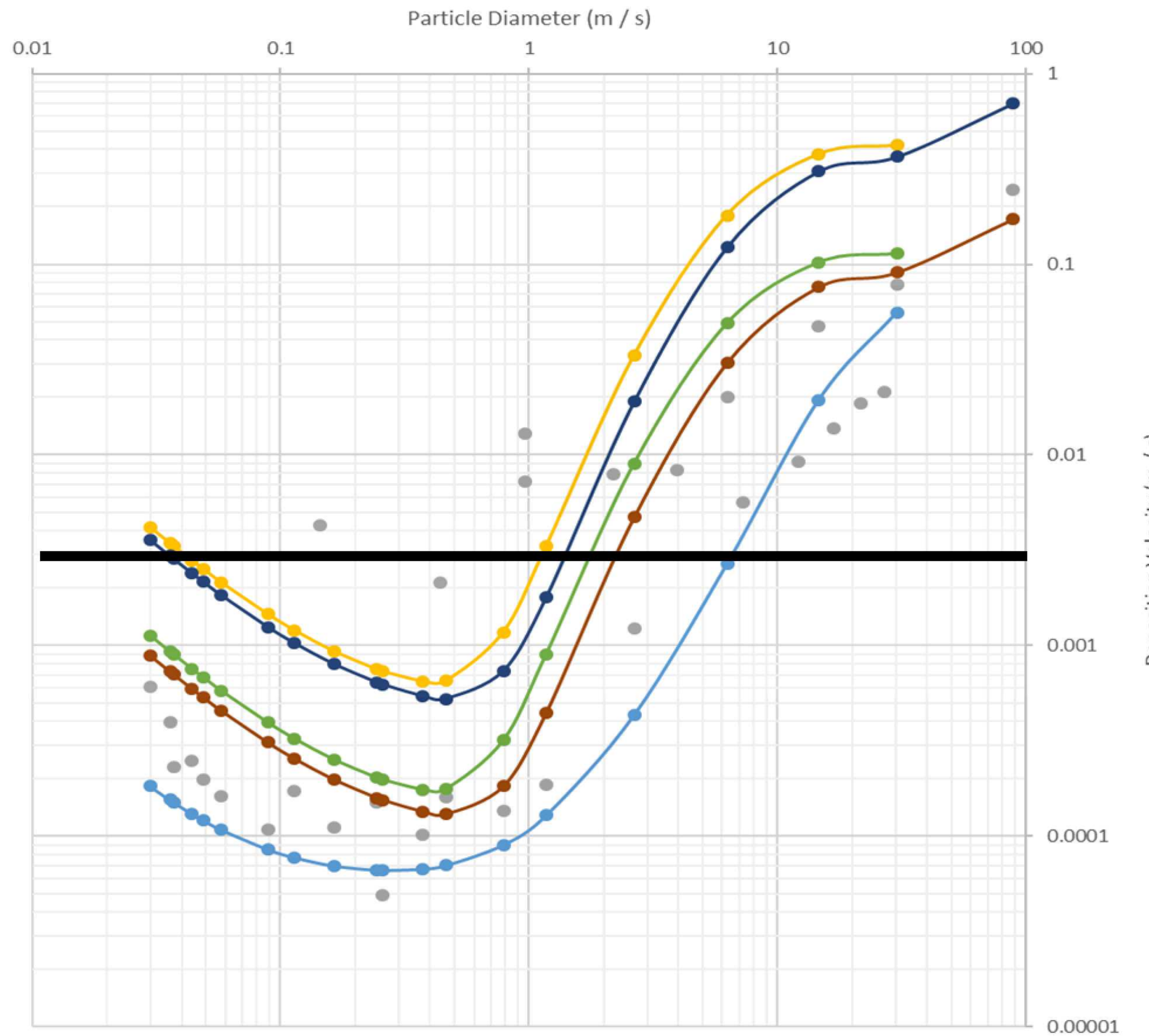
Flat Surface, 0.73 m / s Friction Velocity

Best of Breed Comparison



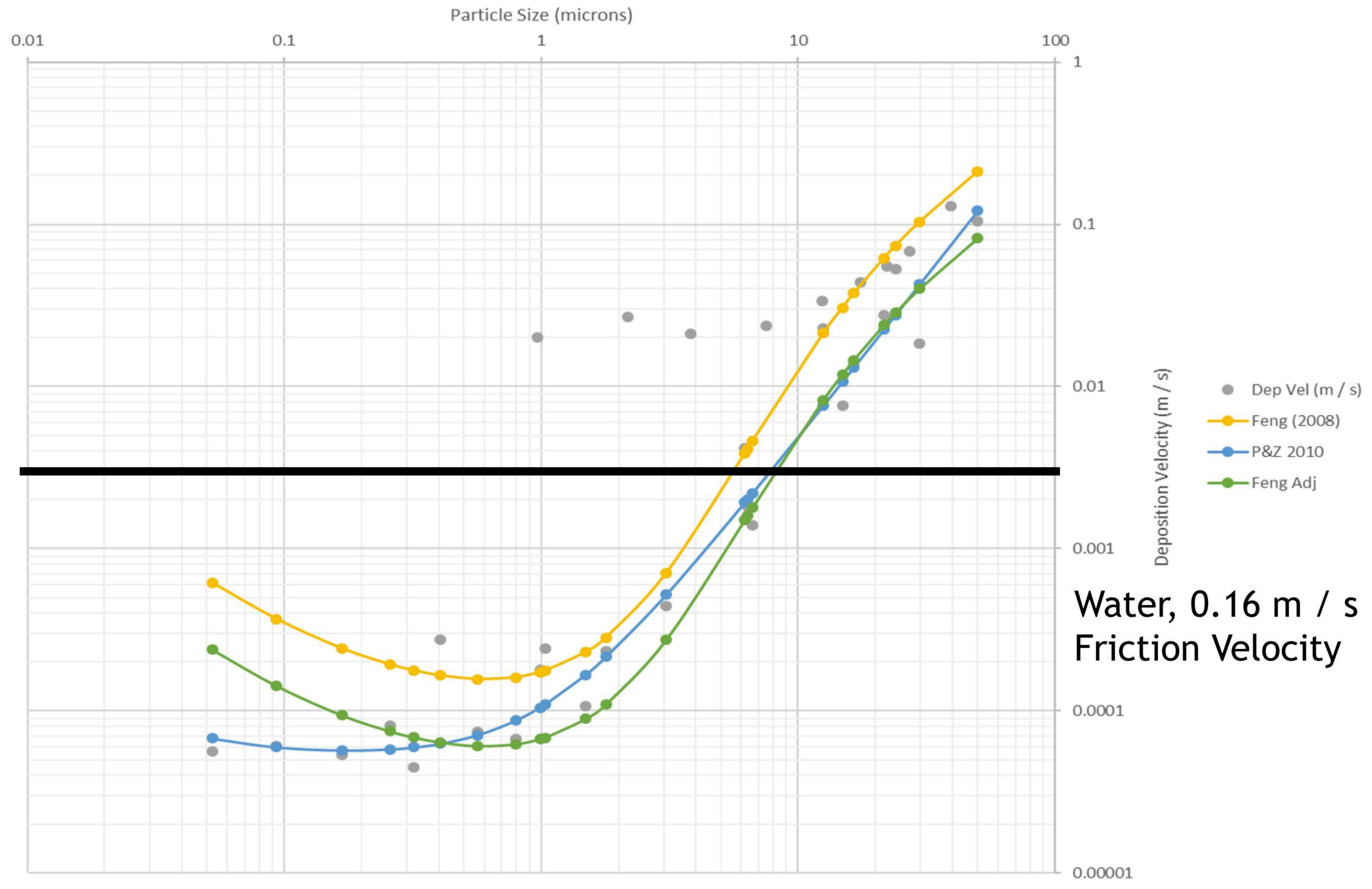
Water, 1.17 m / s
Friction Velocity

Best of Breed Comparison



Water, 0.42 m / s
Friction Velocity

Best of Breed Comparison



Water, 0.16 m / s Friction Velocity

Further Action

The AWG requested that a sensitivity study be performed to assess the impact of the two models upon calculated results.

The following plots are the results of running calculations from Turbo FRMAC over a range of particle size distributions that are reasonable.

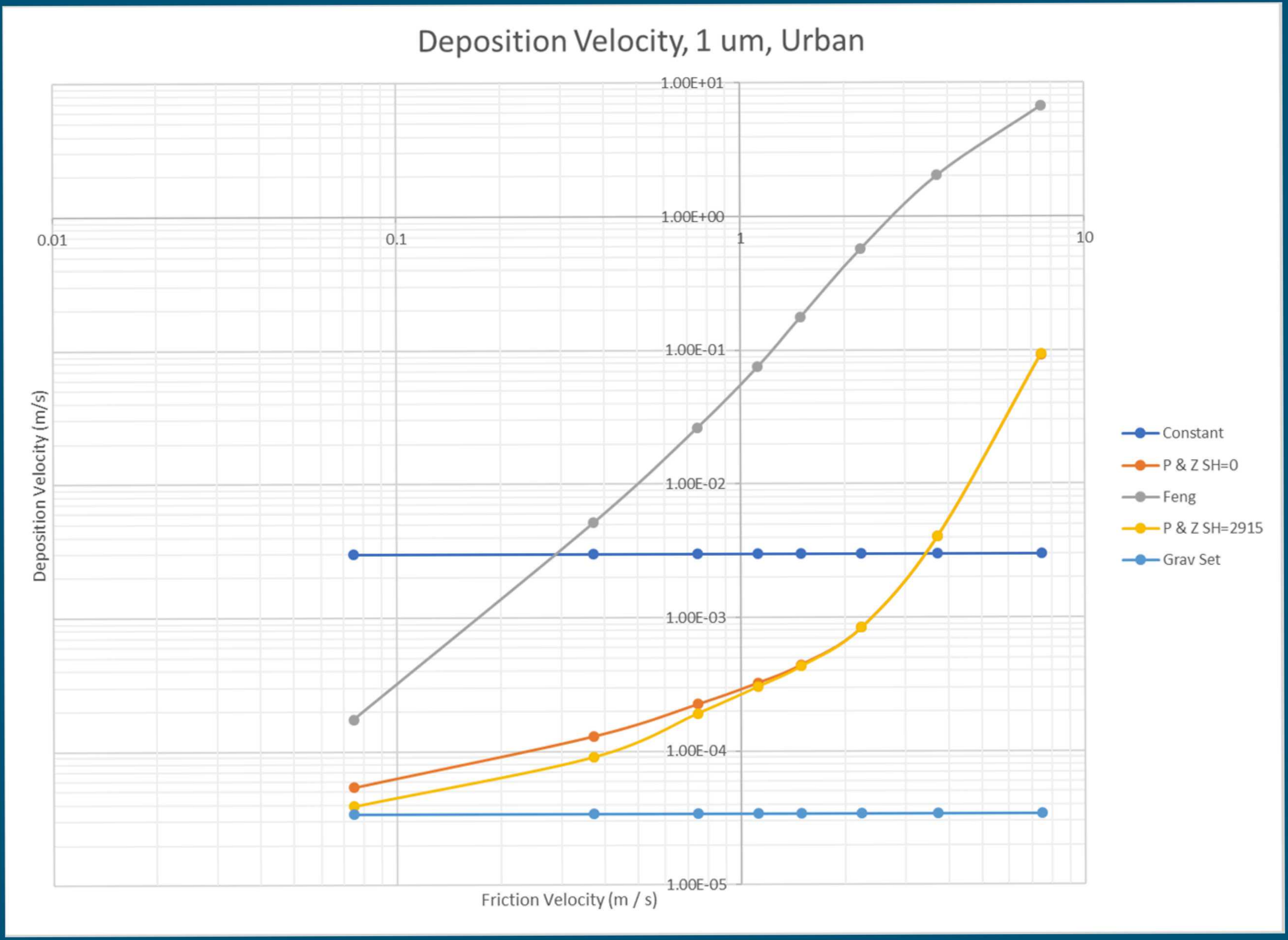
The Urban Deciduous, Broadleaf Forest, Desert, and Crop surface types were selected to cover the range of reasonable surface roughnesses.

Logarithmic Wind Profile, Friction Velocity, And Roughness Length

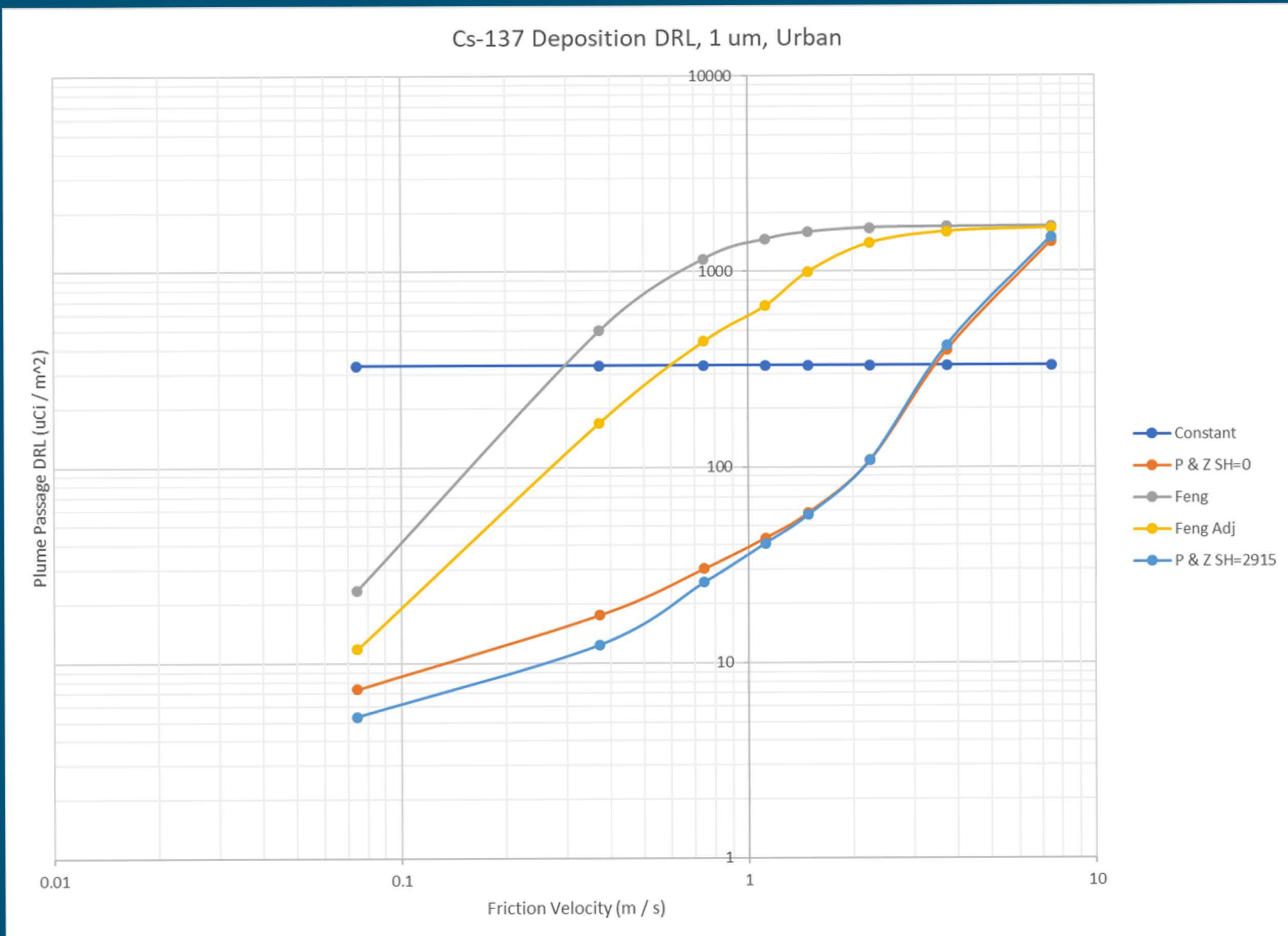
$U_* = (.4*U)/\ln((Z + D) / Z_o)$

Where

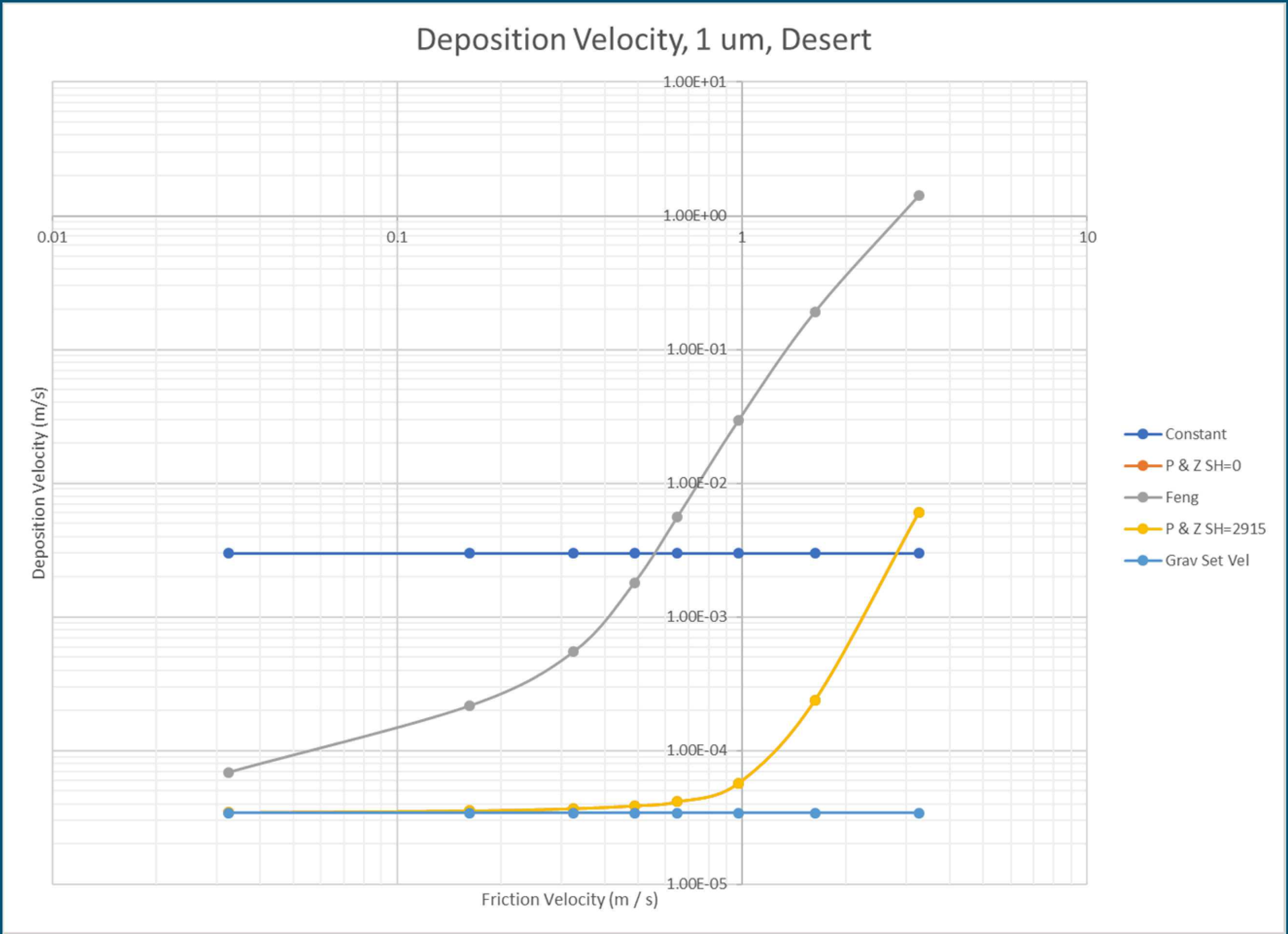
- U is the wind speed at height Z
- Z_o is the roughness length of the surface (roughly 1/30th the height of surrounding roughness elements)
- D is a displacement height, sometimes set to 0, or Z_o, or some other reference height such as top of the forest canopy.



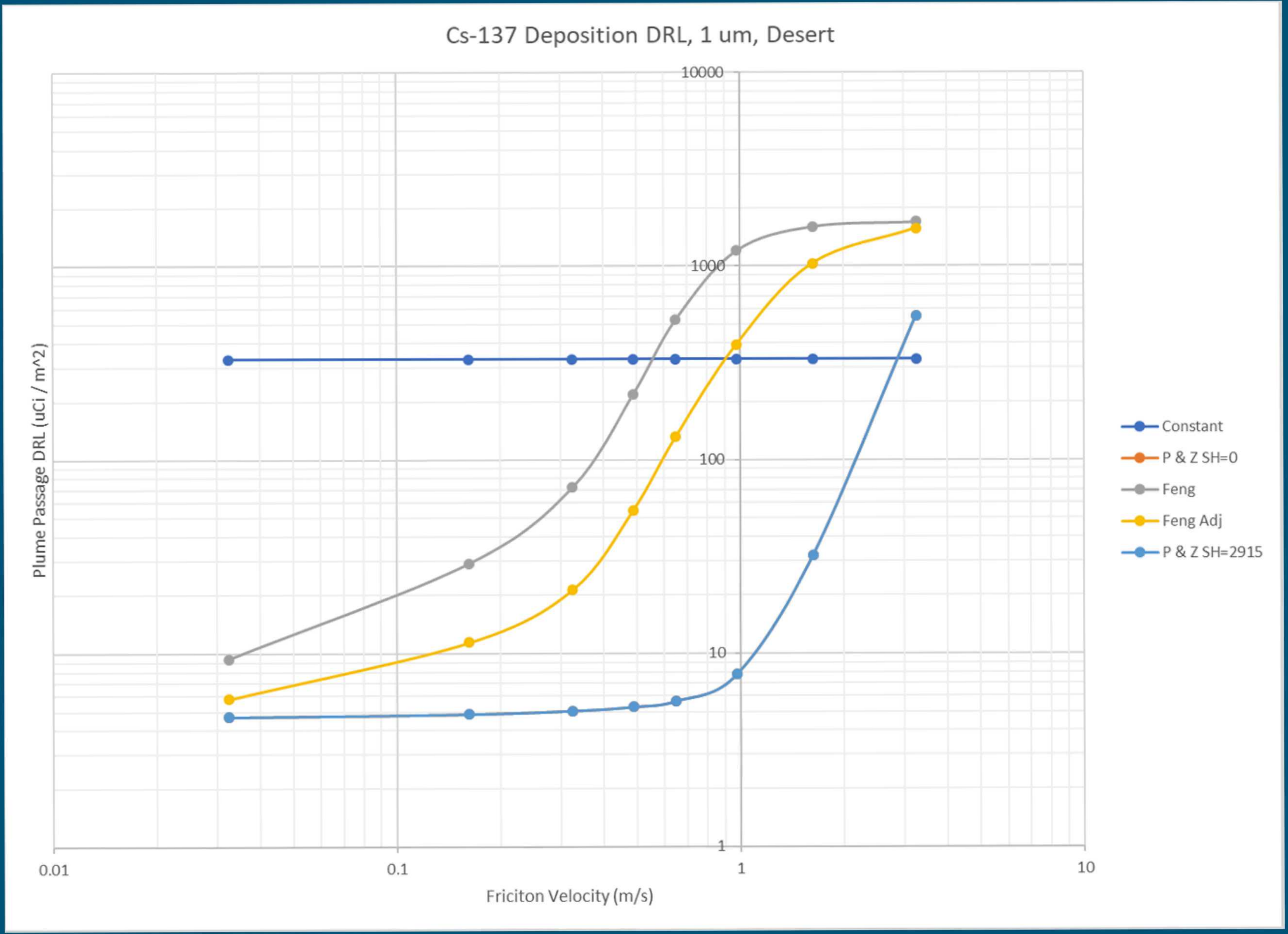
Deposition Velocity, 1 um, Urban
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
0.01
0.1
1
10
Deposition Velocity (m/s)
Friction Velocity (m / s)
Constant
P & Z SH=0
Feng
P & Z SH=2915
Grav Set

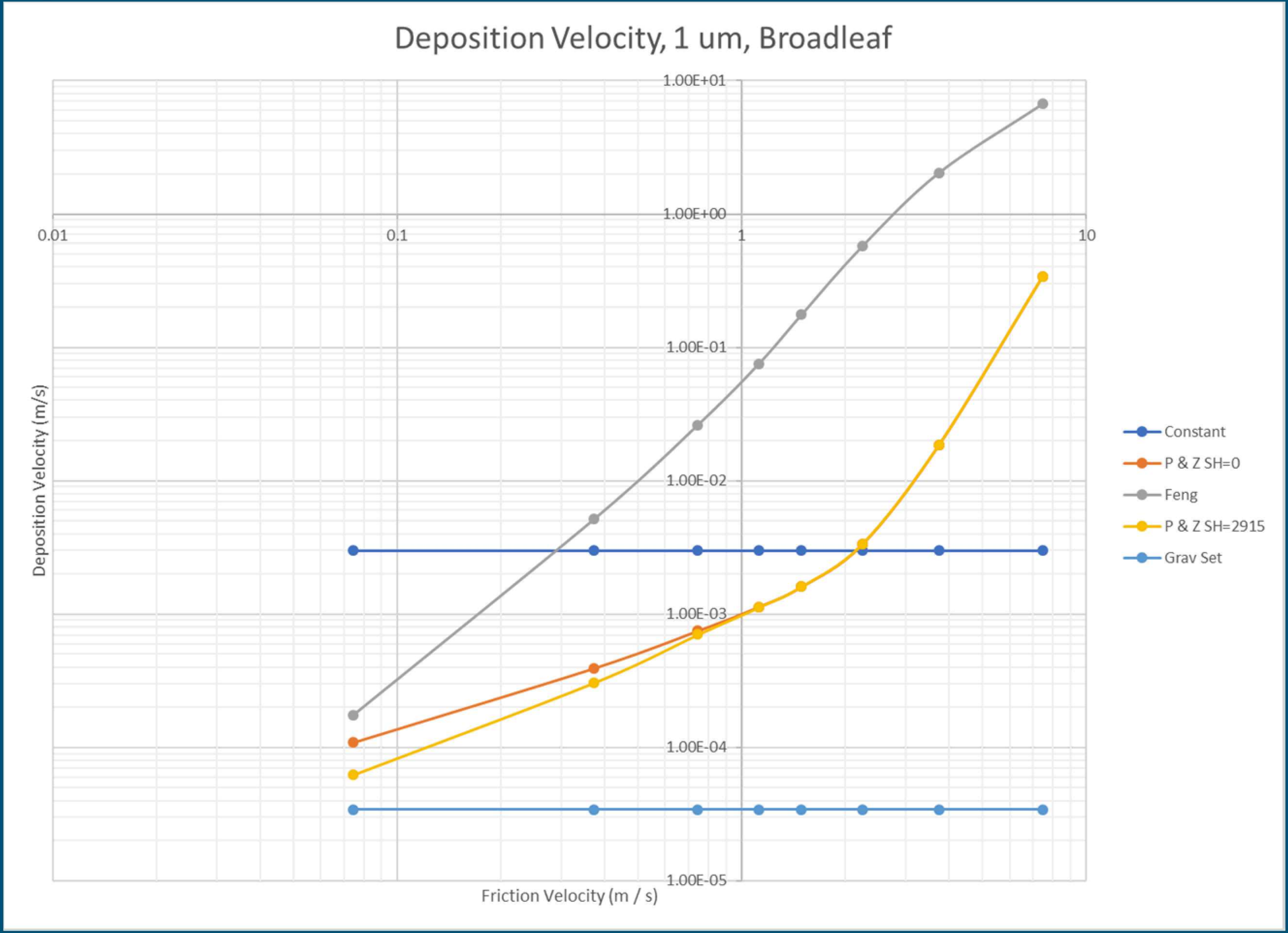


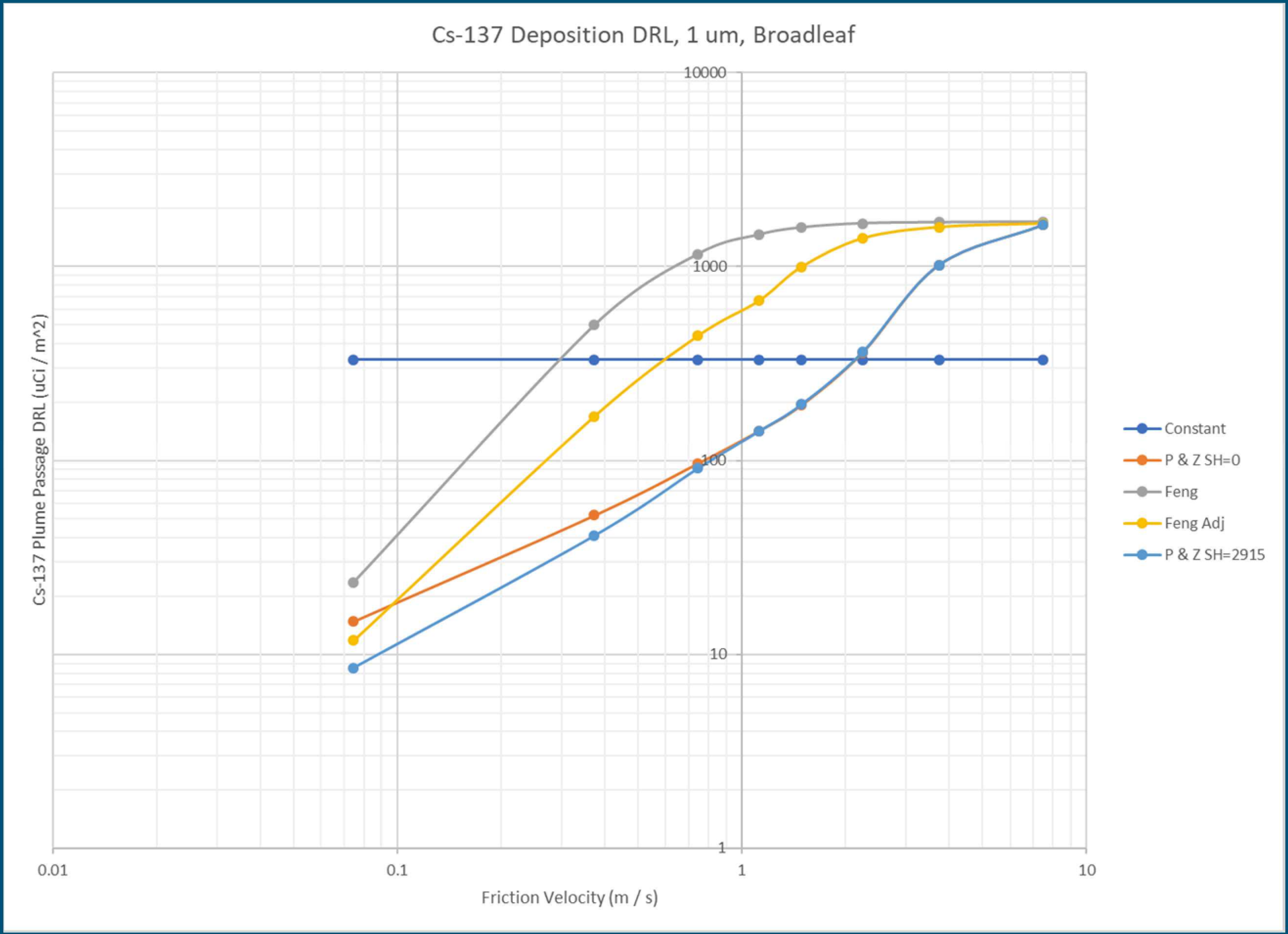
Cs-137 Deposition DRL, 1 um, Urban
Plume Passage DRL (uCi / m^2)
10000
1000
100
10
1
0.01
0.1
1
10
Friction Velocity (m / s)
Constant
P & Z SH=0
Feng
Feng Adj
P & Z SH=2915

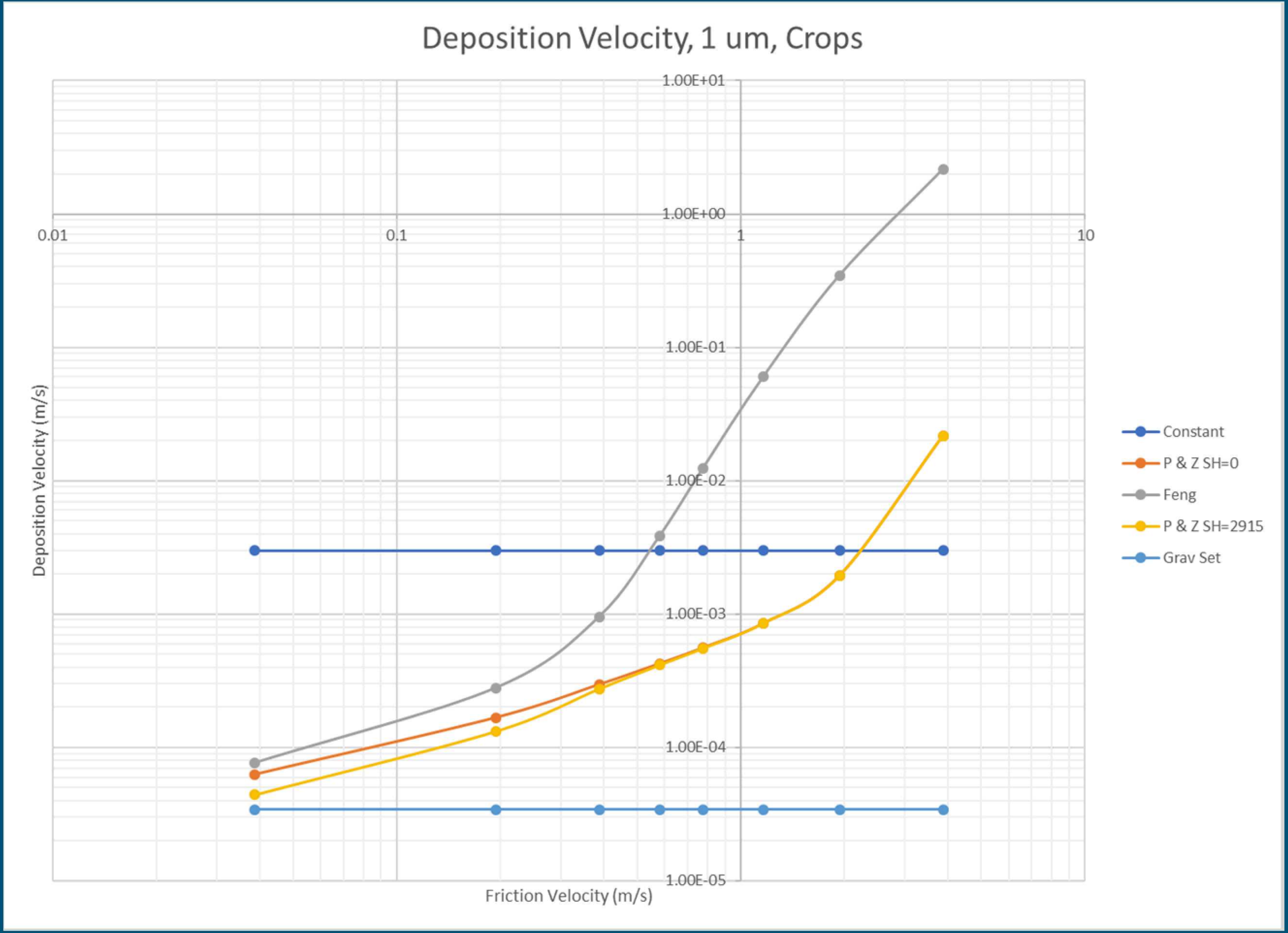


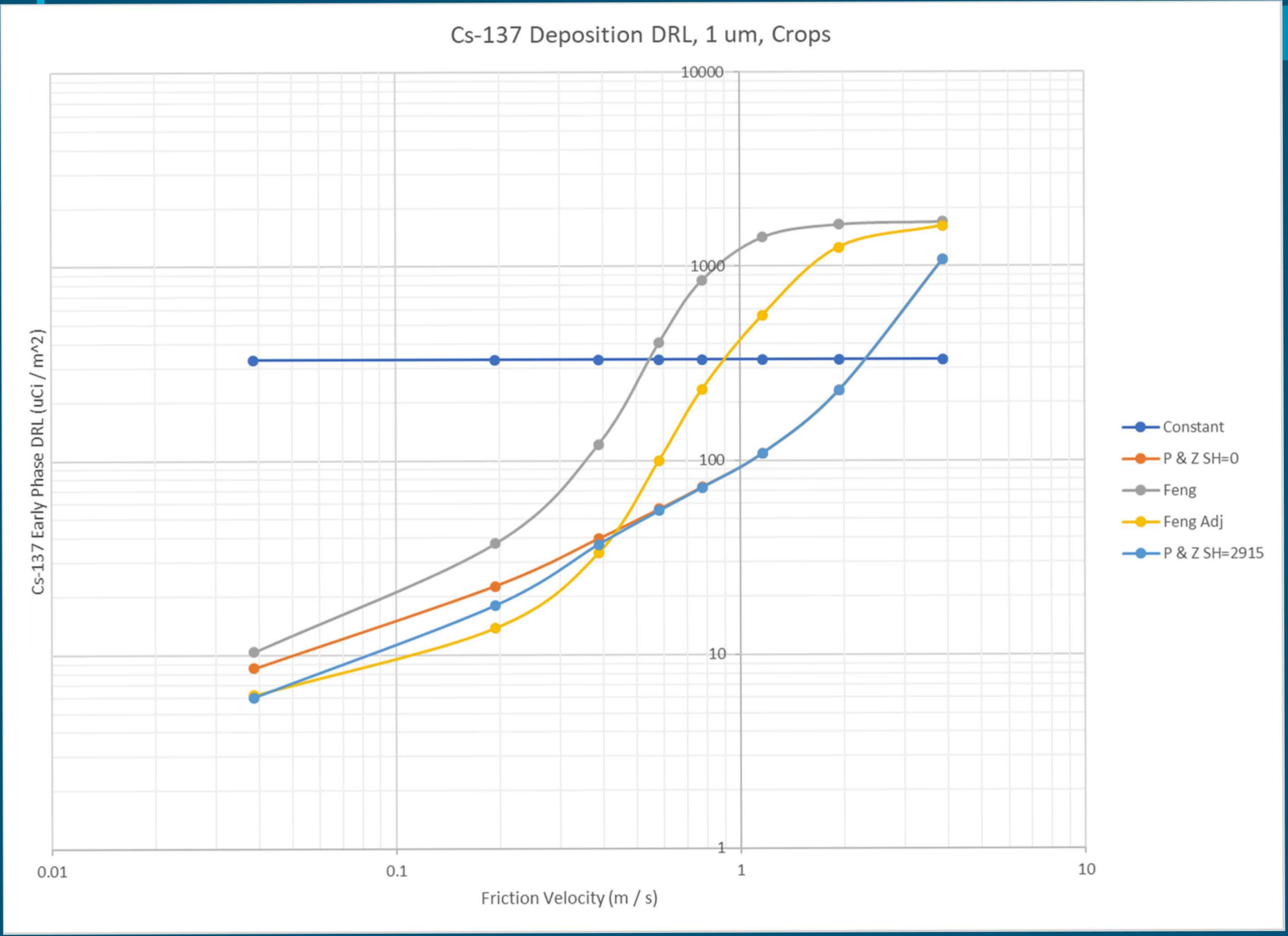
Deposition Velocity, 1 um, Desert
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
0.01
0.1
1
10
Deposition Velocity (m/s)
Friction Velocity (m / s)
Constant
P & Z SH=0
Feng
P & Z SH=2915
Grav Set Vel


Cs-137 Deposition DRL, 1 um, Desert
10000
1000
100
10
1
0.01
0.1
1
10
Plume Passage DRL (uCi / m^2)
Friciton Velocity (m/s)
Constant
P & Z SH=0
Feng
Feng Adj
P & Z SH=2915


Deposition Velocity, 1 um, Broadleaf
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
0.01
0.1
1
10
Deposition Velocity (m/s)
Friction Velocity (m / s)
Constant
P & Z SH=0
Feng
P & Z SH=2915
Grav Set


Cs-137 Deposition DRL, 1 um, Broadleaf
10000
1000
100
10
1
0.01
0.1
1
10
Friction Velocity (m / s)
Cs-137 Plume Passage DRL (uCi / m^2)
Constant
P & Z SH=0
Feng
Feng Adj
P & Z SH=2915


Deposition Velocity, 1 um, Crops
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
0.01
0.1
1
10
Deposition Velocity (m/s)
Friction Velocity (m/s)
Constant
P & Z SH=0
Feng
P & Z SH=2915
Grav Set



Cs-137 Deposition DRL, 1 um, Crops
10000
1000
100
10
1
0.01
0.1
1
10
Friction Velocity (m / s)
Cs-137 Early Phase DRL (uCi / m^2)
Constant
P & Z SH=0
Feng
Feng Adj
P & Z SH=2915

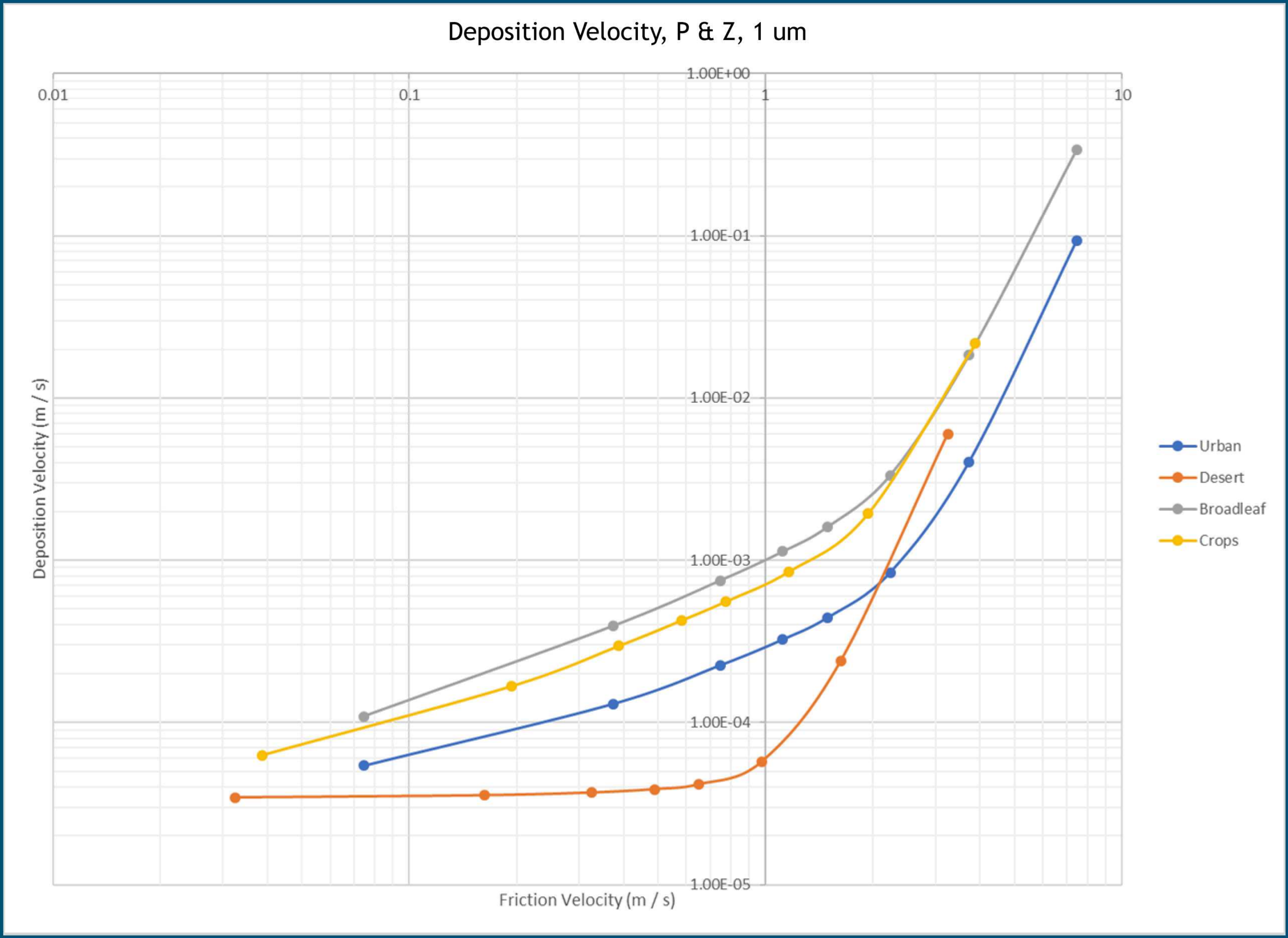
The Ho-Ho Test

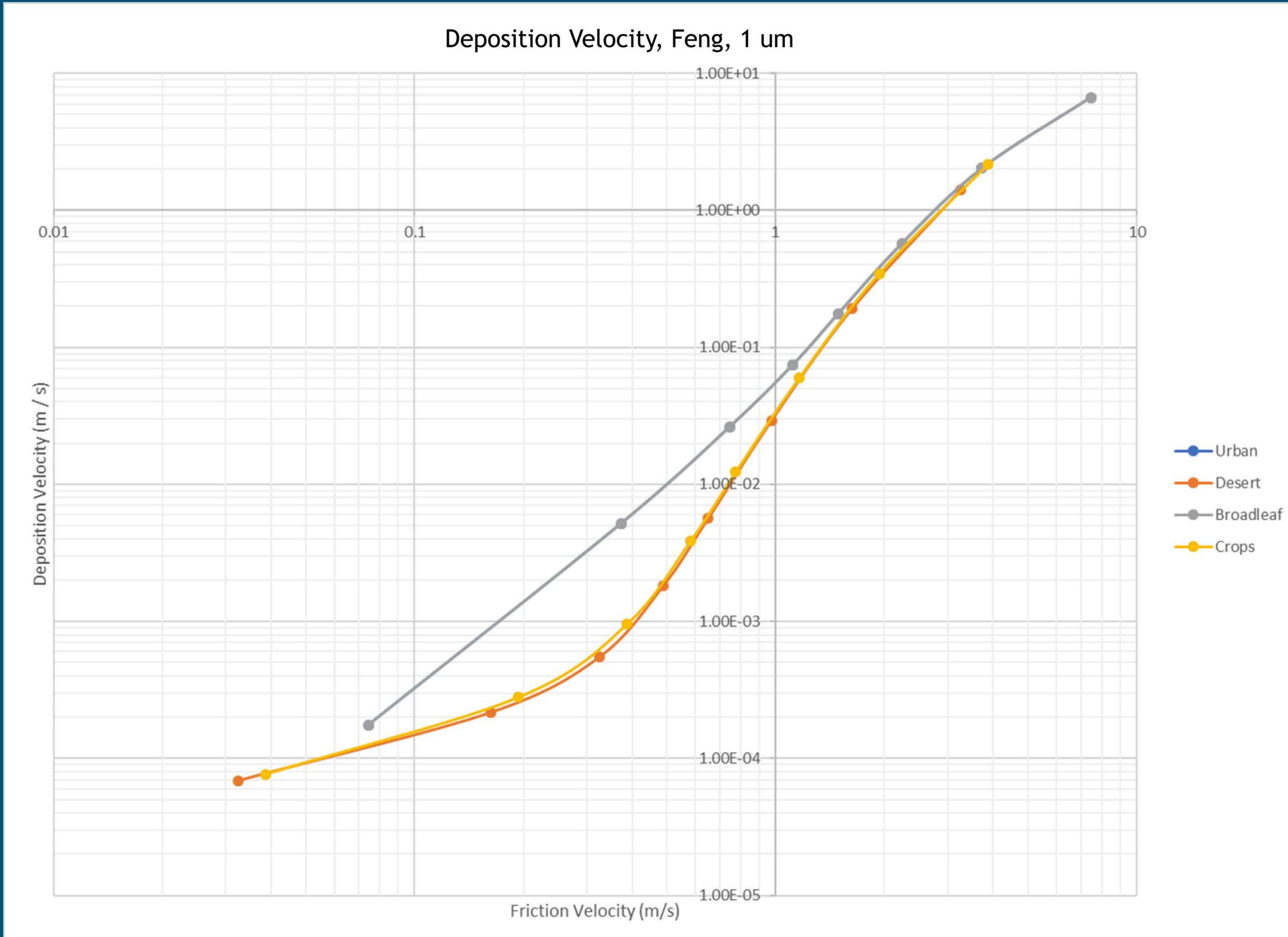
Your out for a walk in the country side, which do you fear more?

Expected Trends.

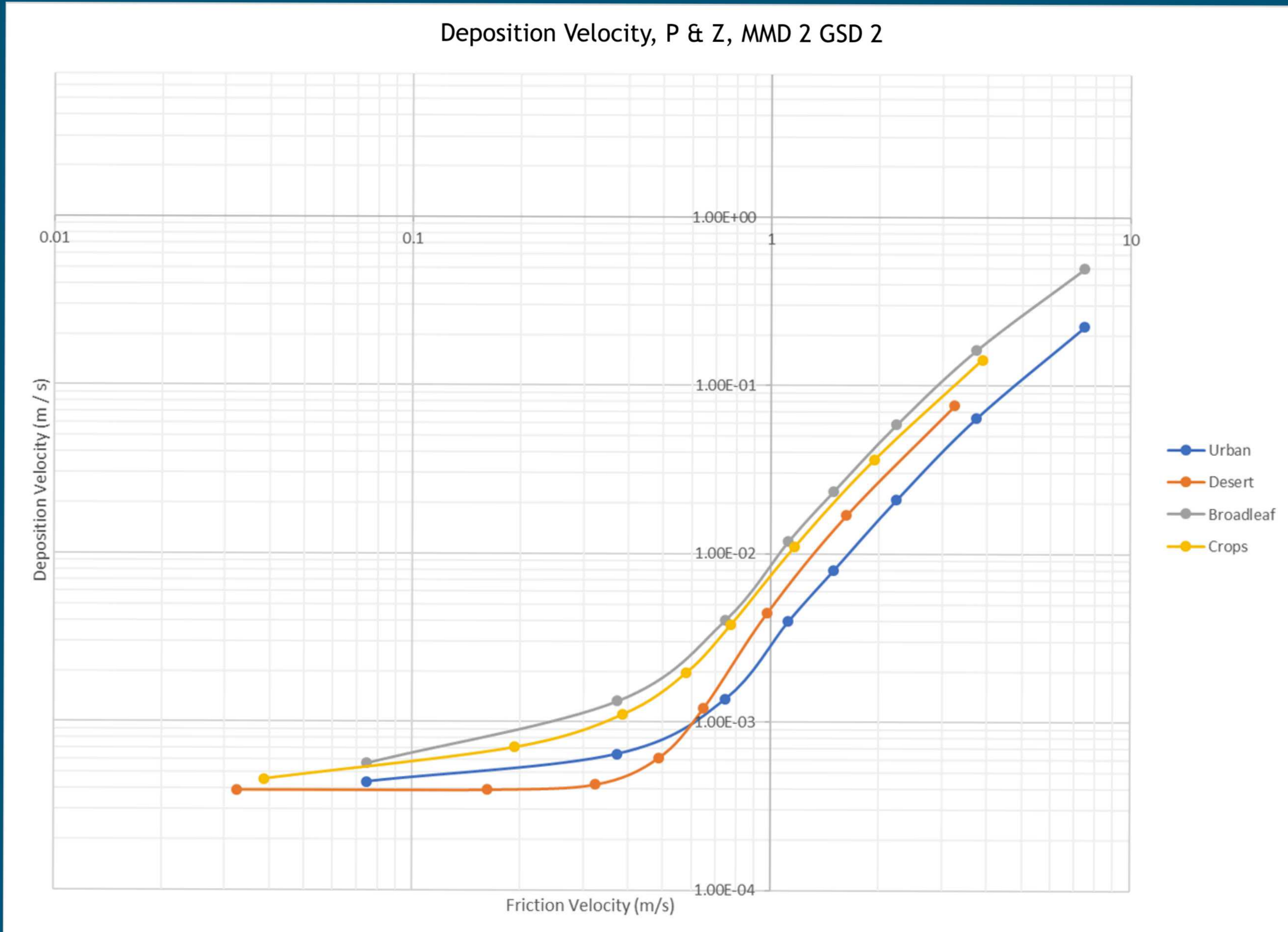
- Now,
- $V_d \propto U_*$, where $U_* \propto (U, Z_o)$
- So
  - For a given model, plotting the deposition velocity of different surfaces (different Z_o) as a function of U_* should produce 1 line.
  - For small particle sizes (<~ a couple um) other effects that do not scale by U_* may drive deviations from this expectation.
  - Since $V_d \propto U_* \propto Z_o$, greater surface roughness equates to greater deposition velocity and thus the deposition velocity of the surfaces considered should rank as follows from greatest to least.
  - Furthermore, lines of deposition velocity of one surface to another should never cross when plotted as a function of U_*

Surface	Friction Velocity
Urban	1.00 m
Broadleaf	1.00 m
Crops	0.11 m
Desert	0.04 m

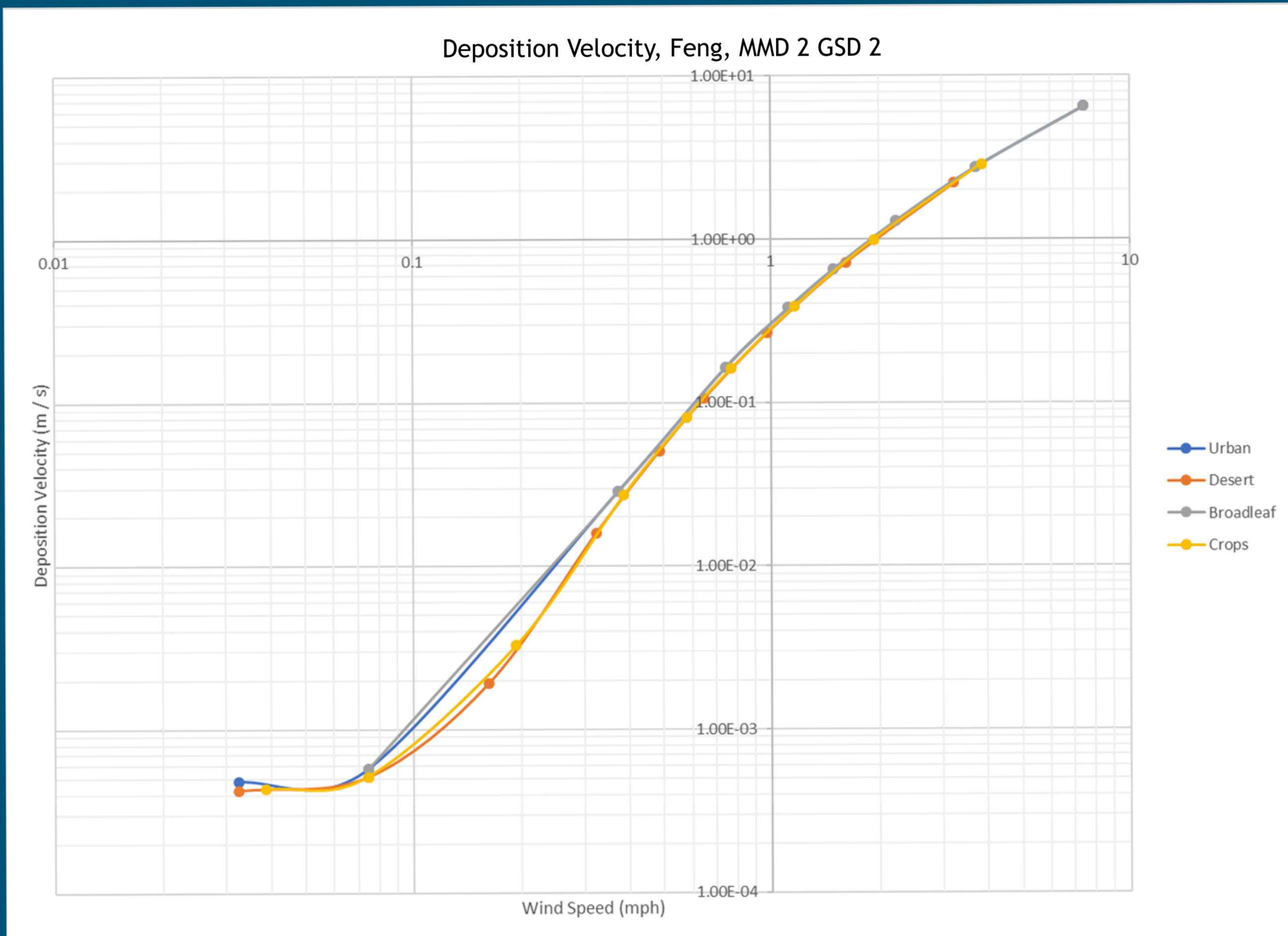

Deposition Velocity, P & Z, 1 um
0.01
0.1
1
10
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
Deposition Velocity (m / s)
Friction Velocity (m / s)
Urban
Desert
Broadleaf
Crops



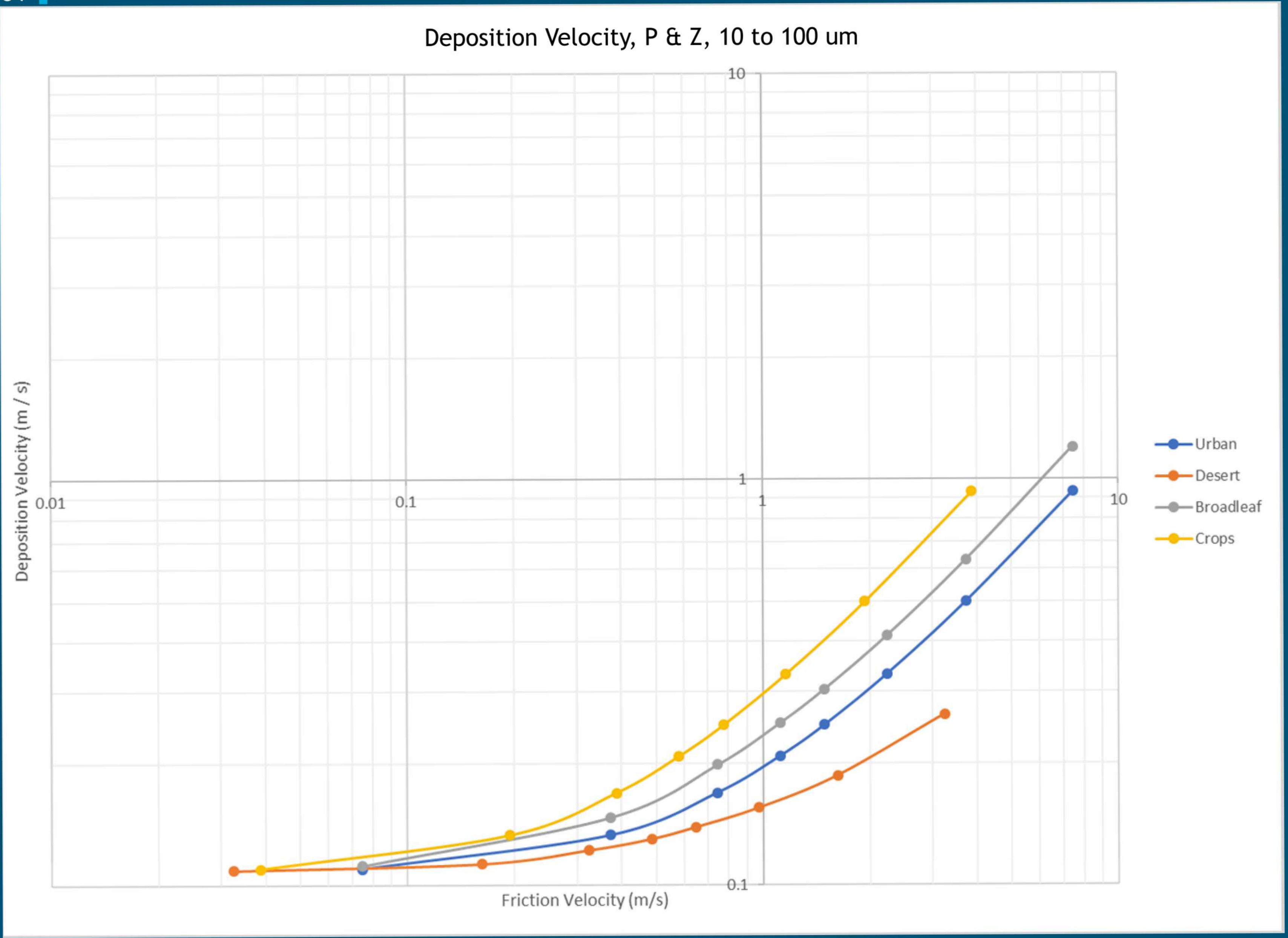
Deposition Velocity, Feng, 1 um
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
0.01
0.1
1
10
Deposition Velocity (m / s)
Friction Velocity (m/s)
Urban
Desert
Broadleaf
Crops



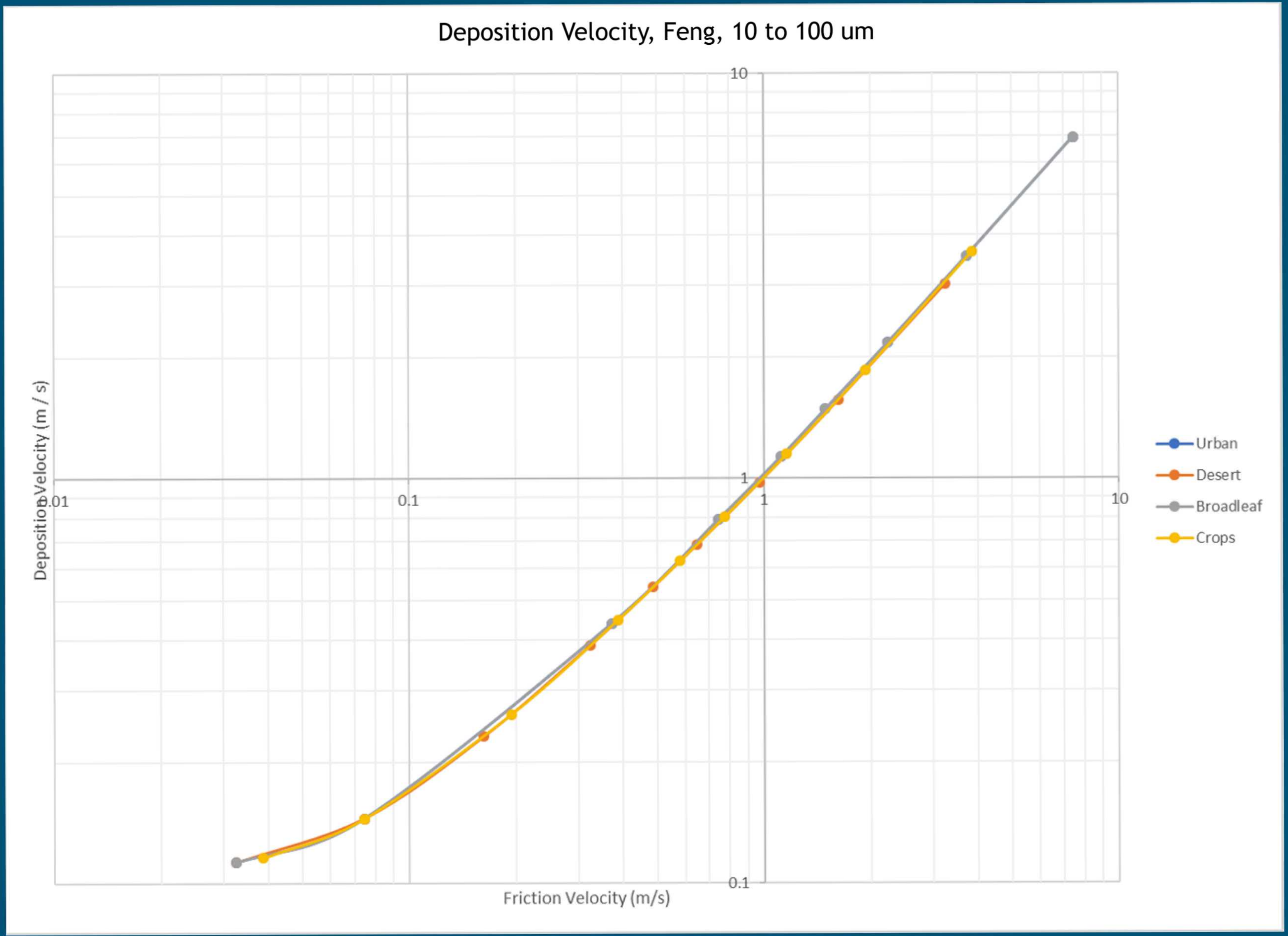
Deposition Velocity, P & Z, MMD 2 GSD 2
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
0.01
0.1
1
10
Deposition Velocity (m / s)
Friction Velocity (m/s)
Urban
Desert
Broadleaf
Crops



Deposition Velocity, Feng, MMD 2 GSD 2
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
0.01
0.1
1
10
Deposition Velocity (m / s)
Wind Speed (mph)
Urban
Desert
Broadleaf
Crops



Deposition Velocity, P & Z, 10 to 100 um
Deposition Velocity (m / s)
Friction Velocity (m/s)
10
1
0.1
0.01
0.1
1
10
Urban
Desert
Broadleaf
Crops


Deposition Velocity, Feng, 10 to 100 um
10
1
0.1
0.01
0.1
1
10
Deposition Velocity (m / s)
Friction Velocity (m/s)
Urban
Desert
Broadleaf
Crops

The simplest explanation that fits the facts is usually the correct one.

The Deposition Velocity Equation of P&Z.

$$
\begin{cases}
V_s + V_{phor} + \dfrac{1}{\dfrac{1}{k u_*}\left(\ln\left(\dfrac{Z_r - d_c}{z_0 - d_c}\right) - \psi_h\left(\dfrac{Z_r - d_c}{L_m}\right) - \psi_h\left(\dfrac{z_0 - d_c}{L_m}\right)\right) + \dfrac{1}{u_*\left(\dfrac{\left(\dfrac{Sc^{-\frac{2}{3}}}{14.5}\right)}{\left(\frac{1}{6}\ln\left(\frac{(1+F)^2}{1-F+F^2}\right) + \frac{1}{\sqrt{3}}\arctan\left(\frac{2F-1}{\sqrt{3}}\right) + \frac{\pi}{6\sqrt{3}}\right)} + E_B\right)\dfrac{\left(1 + \left(\dfrac{\frac{\frac{h^* LAI^* V_t}{k u_* (h-d)}}{\phi_h\left(\frac{h-d}{L_m}\right)}}{\frac{\frac{h V_d}{k u_* (h-d)}}{\phi_h\left(\frac{h-d}{L_m}\right)}} - \dfrac{\left(\frac{k_x LAI}{12k^2\left(1-\frac{d}{h}\right)^2}\right)^{\frac{1}{3}} \phi_m^{\frac{2}{3}}\left(\frac{h-d}{L_m}\right)}{2}\right)\right)\left(\dfrac{\tanh\left(\sqrt{\frac{\left(\left(\frac{k_x LAI}{12k^2\left(1-\frac{d}{h}\right)^2}\right)^{\frac{1}{3}} \phi_m^{\frac{2}{3}}\left(\frac{h-d}{L_m}\right)\right)^2}{4} + \frac{\frac{h^* LAI^* V_t}{k u_* (h-d)}}{\phi_h\left(\frac{h-d}{L_m}\right)}}\right)}{\sqrt{\frac{\left(\left(\frac{k_x LAI}{12k^2\left(1-\frac{d}{h}\right)^2}\right)^{\frac{1}{3}} \phi_m^{\frac{2}{3}}\left(\frac{h-d}{L_m}\right)\right)^2}{4} + \frac{\frac{h^* LAI^* V_t}{k u_* (h-d)}}{\phi_h\left(\frac{h-d}{L_m}\right)}}}\right)}{\left(1 + \left(\dfrac{\frac{h V_d}{k u_* (h-d)}}{\phi_h\left(\frac{h-d}{L_m}\right)} - \dfrac{\left(\frac{k_x LAI}{12k^2\left(1-\frac{d}{h}\right)^2}\right)^{\frac{1}{3}} \phi_m^{\frac{2}{3}}\left(\frac{h-d}{L_m}\right)}{2}\right)\right)\left(\dfrac{\tanh\left(\sqrt{\frac{\left(\left(\frac{k_x LAI}{12k^2\left(1-\frac{d}{h}\right)^2}\right)^{\frac{1}{3}} \phi_m^{\frac{2}{3}}\left(\frac{h-d}{L_m}\right)\right)^2}{4} + \frac{\frac{h^* LAI^* V_t}{k u_* (h-d)}}{\phi_h\left(\frac{h-d}{L_m}\right)}}\right)}{\sqrt{\frac{\left(\left(\frac{k_x LAI}{12k^2\left(1-\frac{d}{h}\right)^2}\right)^{\frac{1}{3}} \phi_m^{\frac{2}{3}}\left(\frac{h-d}{L_m}\right)\right)^2}{4} + \frac{\frac{h^* LAI^* V_t}{k u_* (h-d)}}{\phi_h\left(\frac{h-d}{L_m}\right)}}}\right)}}} & \text{Vegetated} \\
V_s + V_{phor} + \dfrac{1}{\dfrac{1}{k u_*}\left(\ln\left(\dfrac{Z_r - d_c}{z_0}\right) - \psi_h\left(\dfrac{Z_r - d_c}{L_m}\right) - \psi_h\left(\dfrac{z_0}{L_m}\right)\right) + \dfrac{1}{\left(\dfrac{\left(\dfrac{Sc^{-\frac{2}{3}}}{14.5}\right)}{\left(\frac{1}{6}\ln\left(\frac{(1+F)^2}{1-F+F^2}\right) + \frac{1}{\sqrt{3}}\arctan\left(\frac{2F-1}{\sqrt{3}}\right) + \frac{\pi}{6\sqrt{3}}\right)} + E_B\right) u_*}} & \text{Non-Vegetated}
\end{cases}
$$

Fitted parameters include h, z_o, d, LAI, L, C_b, C_{in}, C_{im}, $Beta_{im}$, $C_{it,}$ k_x, … for 11 fitted parameters times 28 surface types for a total of at least 308 fitted parameters with many assumed functional forms.

The Deposition Velocity Equation of Feng

$$V_d = V_t + u_* \left(Sc^{-0.6} + 0.0226 e^{-0.5\left(\frac{\left(\frac{u_* z_o}{\mu} - 40300\right)}{15330}\right)^2} + 0.8947 e^{-0.5\left(\frac{\left(\left(\frac{\rho_p d^2}{18\mu}\right)\left(\frac{u_*^2}{\nu}\right) - 18\right)}{1.7}\right)^2} \right)$$

Fitted parameters include a_1, a_2, a_3, b_1, b_2, b_3, for a total of six fitted parameters with two assumed functional forms.

Why do I favor Feng.

It doesn't calculate nan or division by zero and then spit out a finite result.

It fits basic trends you would expect from first order principles.

6 fitted parameters versus 308.

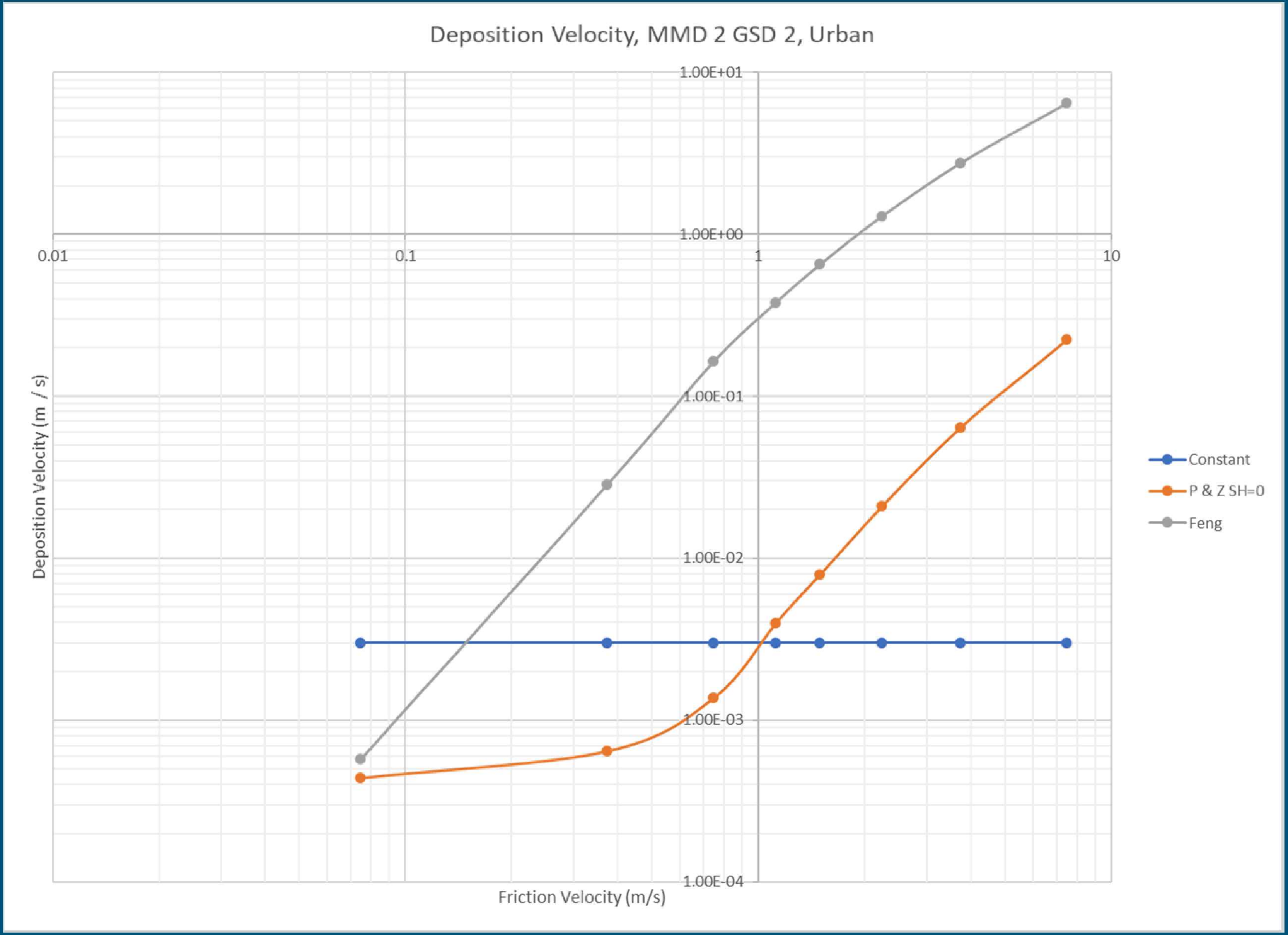
Although vastly simpler than P&Z it fits the data at least as well as any other model and actually shows predictive capability to surfaces and data that were never used to fit it.

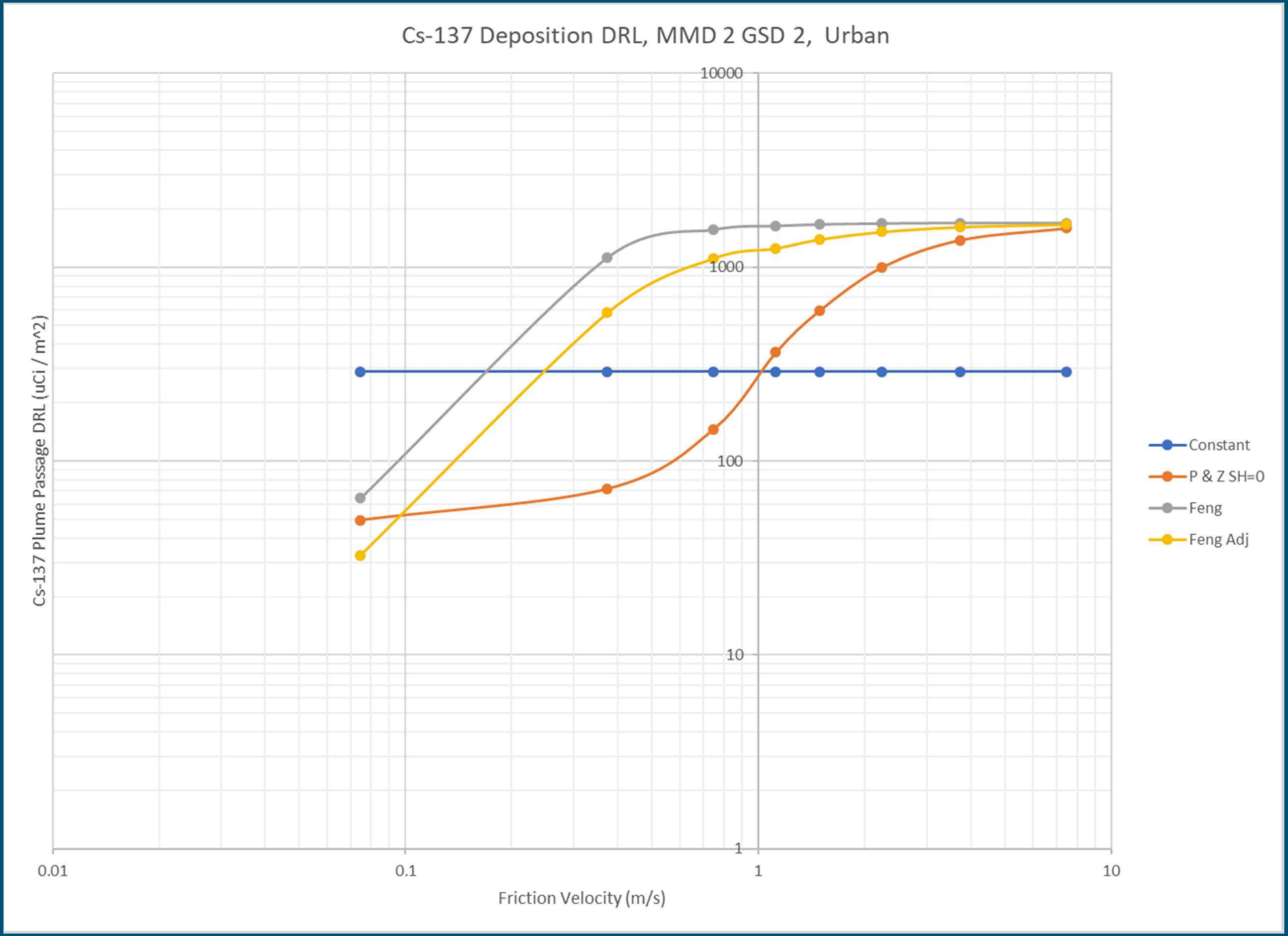
It is trivial to expand to any surface. P&Z would require a field study in the affected region.

HOWEVER

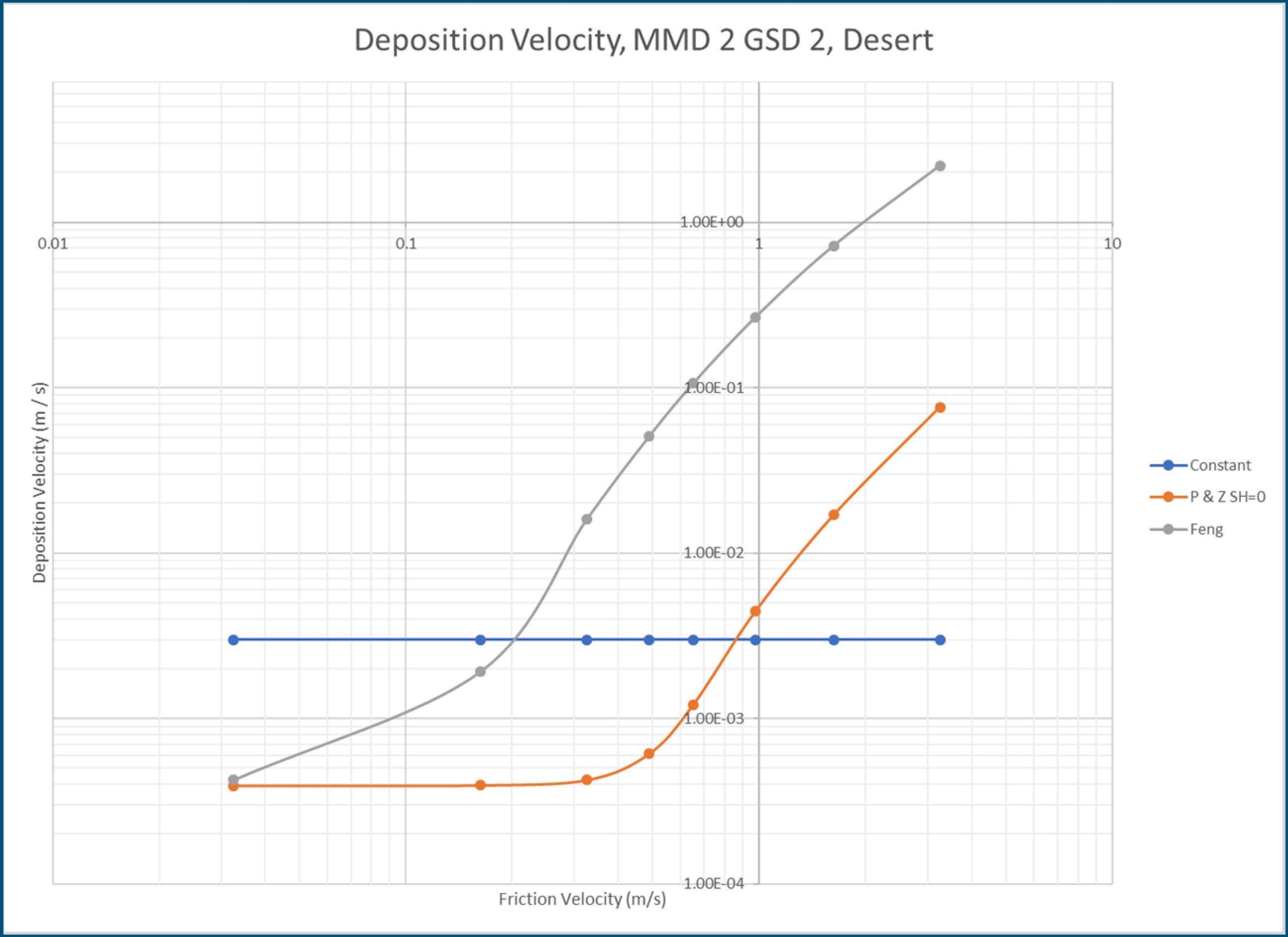
It is not currently a model used operationally by weather centers.

Backup Material

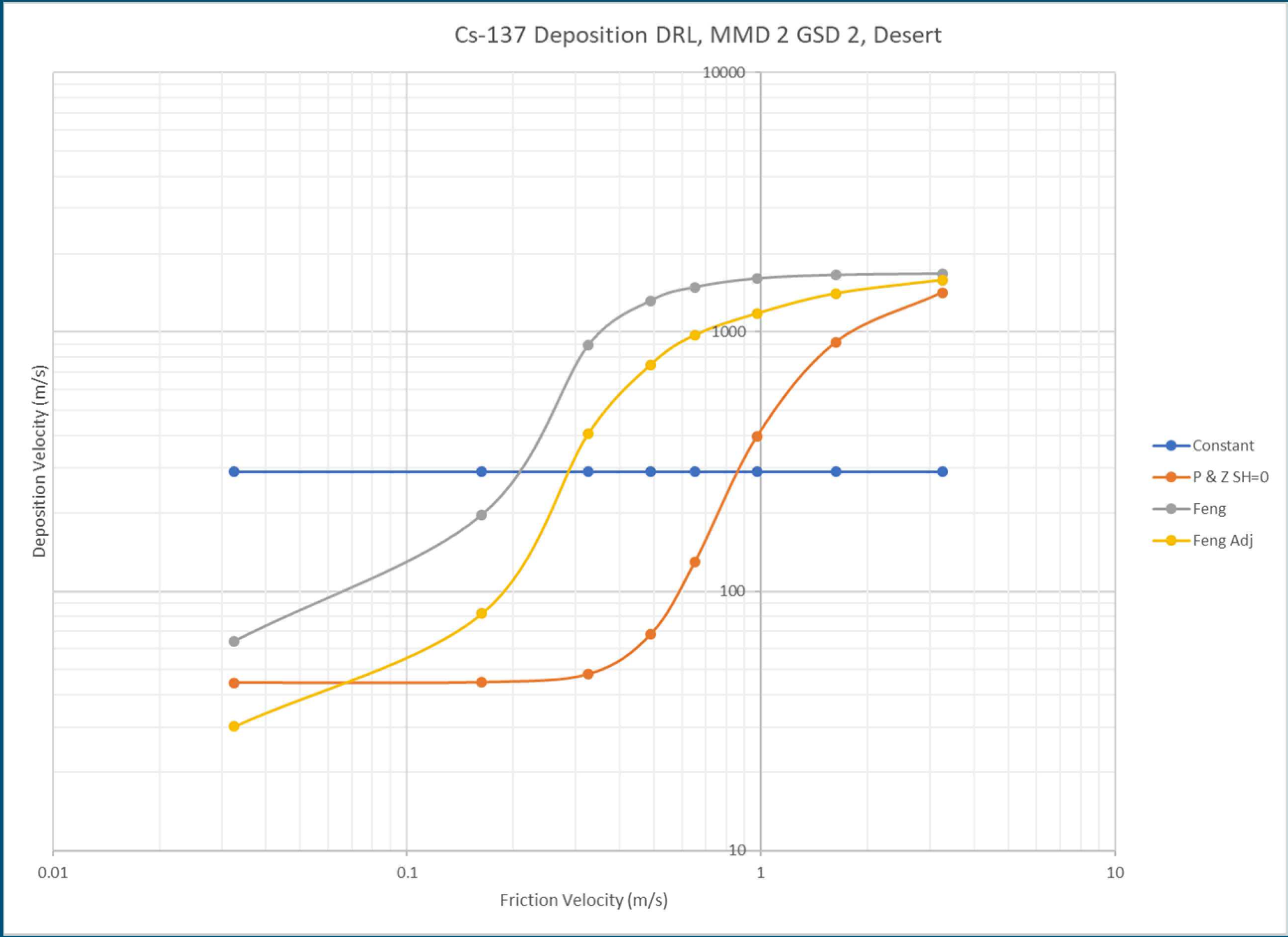

Deposition Velocity, MMD 2 GSD 2, Urban
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
0.01
0.1
1
10
Deposition Velocity (m / s)
Friction Velocity (m/s)
Constant
P & Z SH=0
Feng

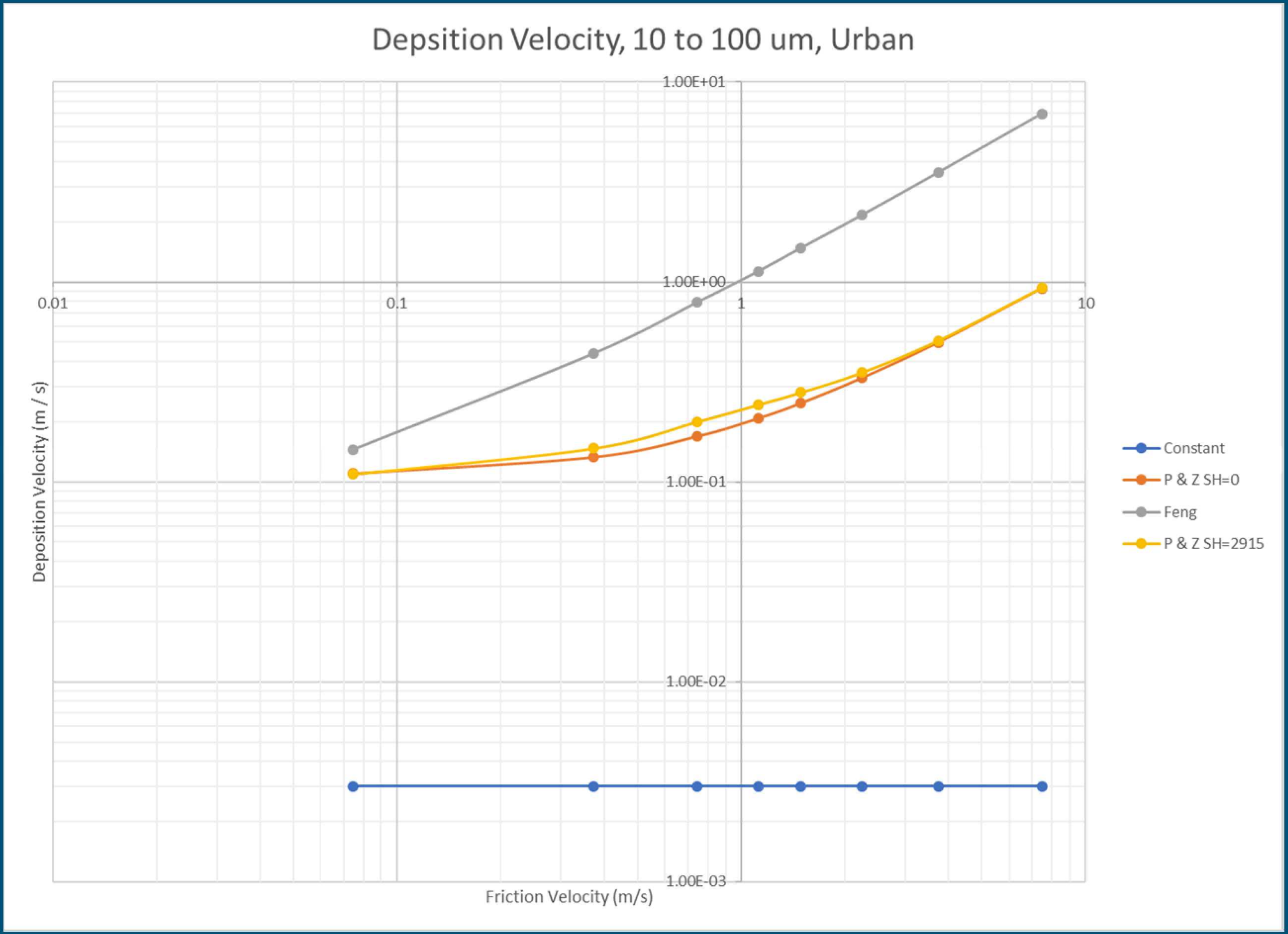


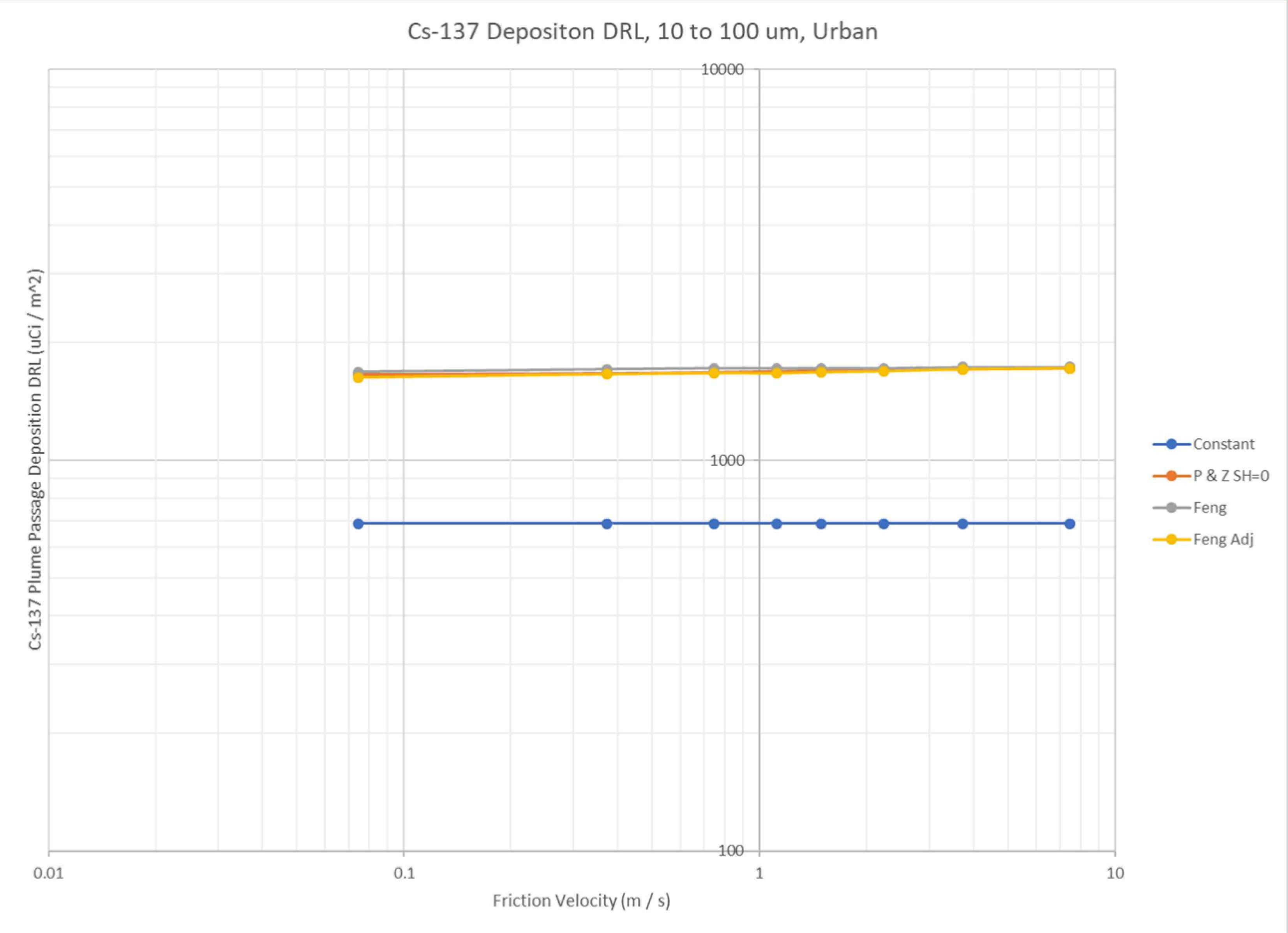
Cs-137 Deposition DRL, MMD 2 GSD 2, Urban
10000
1000
100
10
1
0.01
0.1
1
10
Friction Velocity (m/s)
Cs-137 Plume Passage DRL (uCi / m^2)
Constant
P & Z SH=0
Feng
Feng Adj

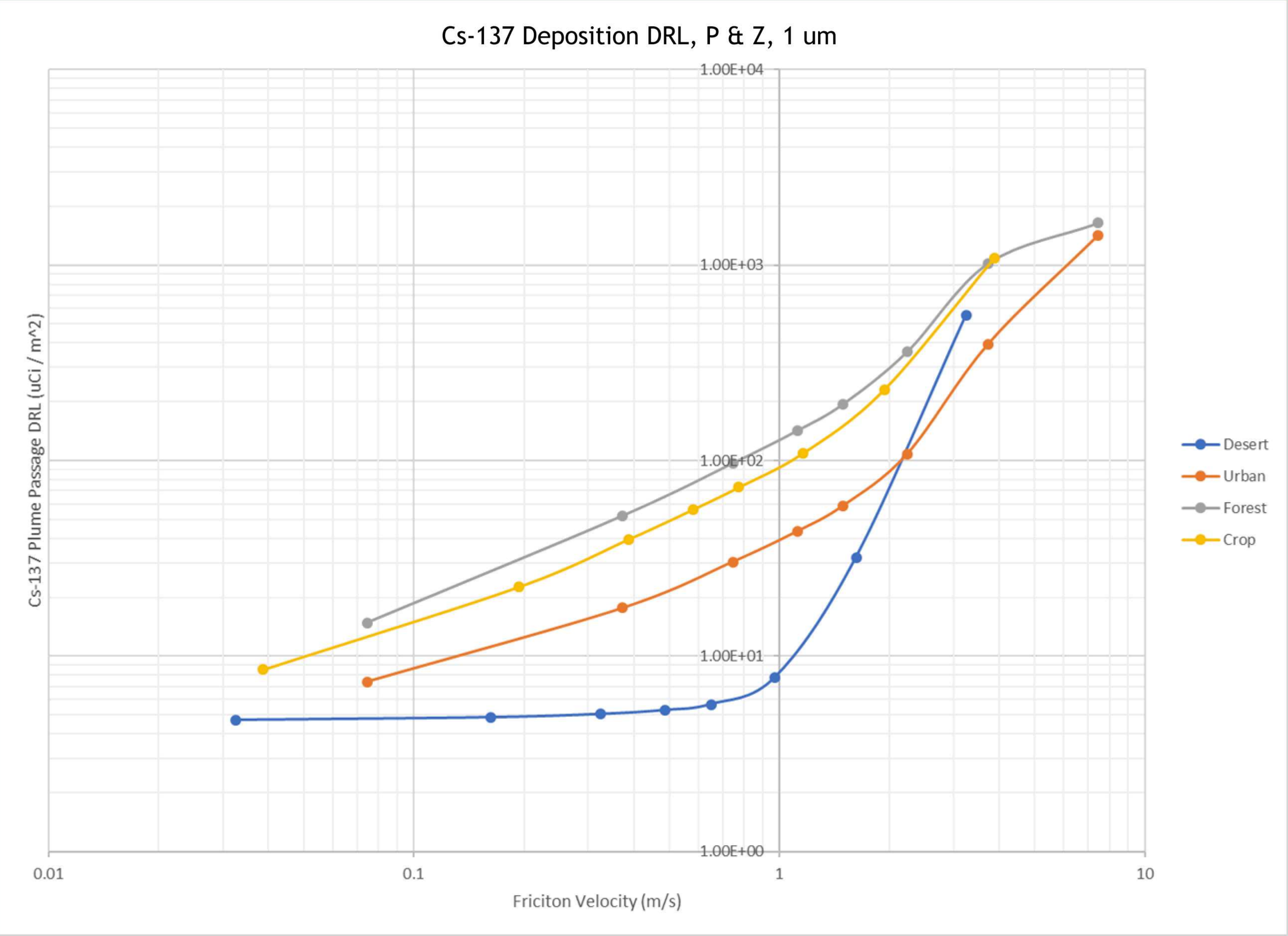


Deposition Velocity, MMD 2 GSD 2, Desert
Deposition Velocity (m / s)
Friction Velocity (m/s)
0.01
0.1
1
10
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
Constant
P & Z SH=0
Feng

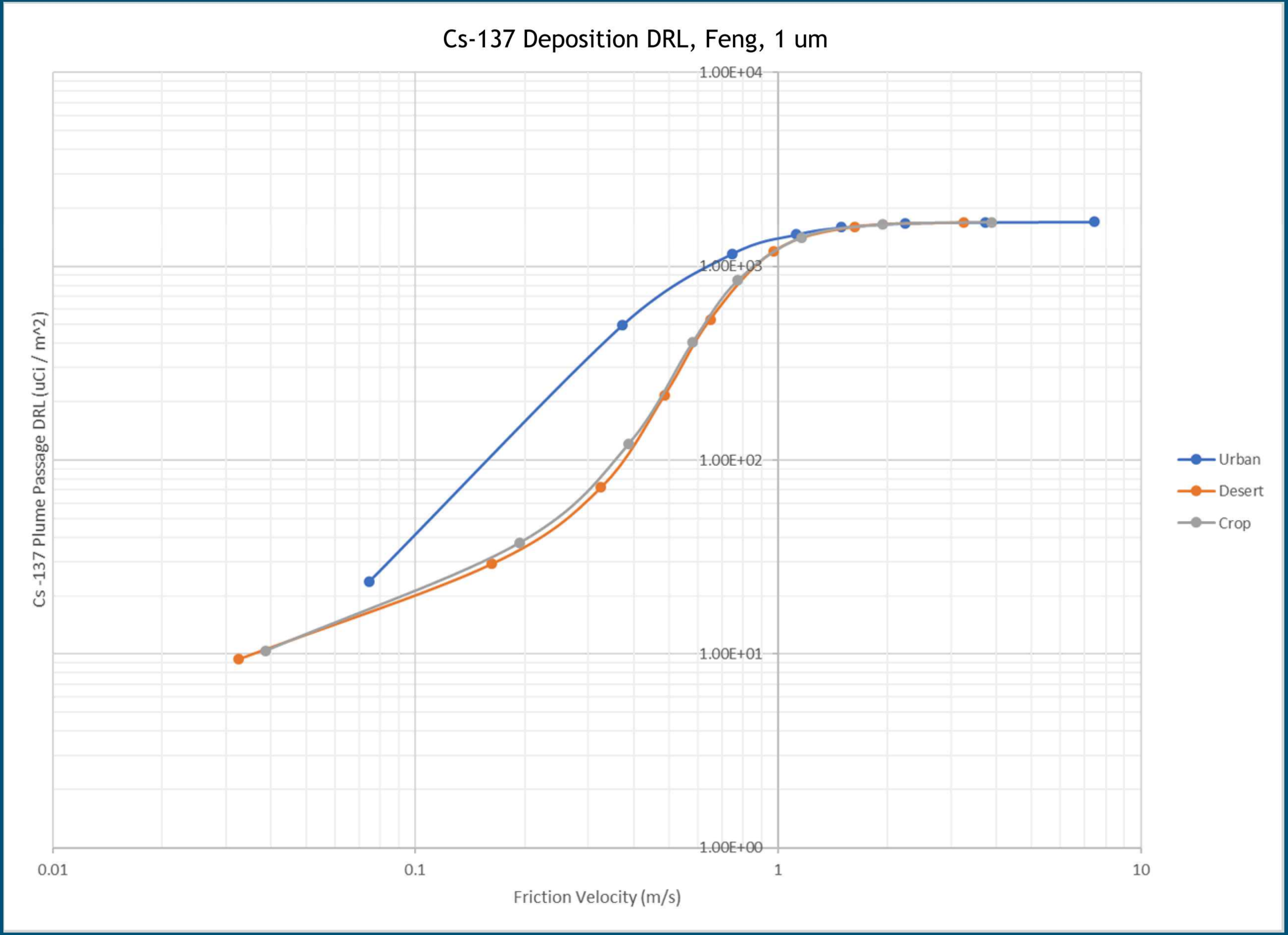

Cs-137 Deposition DRL, MMD 2 GSD 2, Desert
Deposition Velocity (m/s)
10000
1000
100
10
0.01
0.1
1
10
Friction Velocity (m/s)
Constant
P & Z SH=0
Feng
Feng Adj


Depsition Velocity, 10 to 100 um, Urban
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
0.01
0.1
1
10
Deposition Velocity (m / s)
Friction Velocity (m/s)
Constant
P & Z SH=0
Feng
P & Z SH=2915


Cs-137 Depositon DRL, 10 to 100 um, Urban
Cs-137 Plume Passage Deposition DRL (uCi / m^2)
10000
1000
100
0.01
0.1
1
10
Friction Velocity (m / s)
Constant
P & Z SH=0
Feng
Feng Adj



Cs-137 Deposition DRL, P & Z, 1 um
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Cs-137 Plume Passage DRL (uCi / m^2)
0.01
0.1
1
10
Friciton Velocity (m/s)
Desert
Urban
Forest
Crop



Cs-137 Deposition DRL, Feng, 1 um
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0.01
0.1
1
10
Friction Velocity (m/s)
Cs -137 Plume Passage DRL (uCi / m^2)
Urban
Desert
Crop