Electrical Mobility Particle Sensor with Micrometers Spacing Between Electrodes

SOUTHWEST RESEARCH INSTITUTE®

Imad Khalek and Maher Dayeh, Southwest Research Institute

OSAR Conference, CE-CERT, March 30-31, 2023

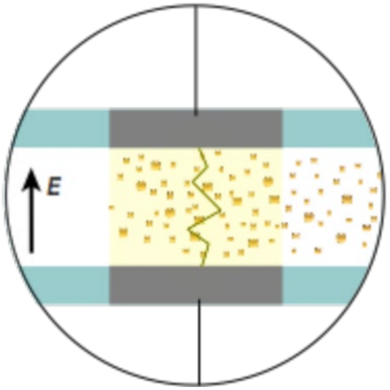
Background: Exhaust Particle Sensors

- As a part of SwRI PSPD consortium (2011-2023), we have evaluated three classes of sensing technologies and cover them in this conference earlier:
  - **Cumulative Sensors** (e.g Bosch)
    - Relate change in electric resistance to particle mass
    - Relies on the fact that soot is electrically conductive
    - It takes minutes to get a measurement depending on particle concentrations
  - **Real Time Sensors**
    - Emisense
      - Relate current induced by charge particles deposition and release to particle mass or number
      - Relies on the fact that particles carry charge on their surface
      - Second by second measurement
    - NGK-NTK
      - Actively charge particles via a corona needle with a monopolar charge
      - Relate particle net escaping current in a faraday cage to particle mass or number
      - Second by second measurement or better

- There is a continuous interest in particle sensing technologies that can measure low particle concentration for various applications

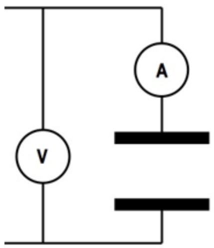
Program Objective

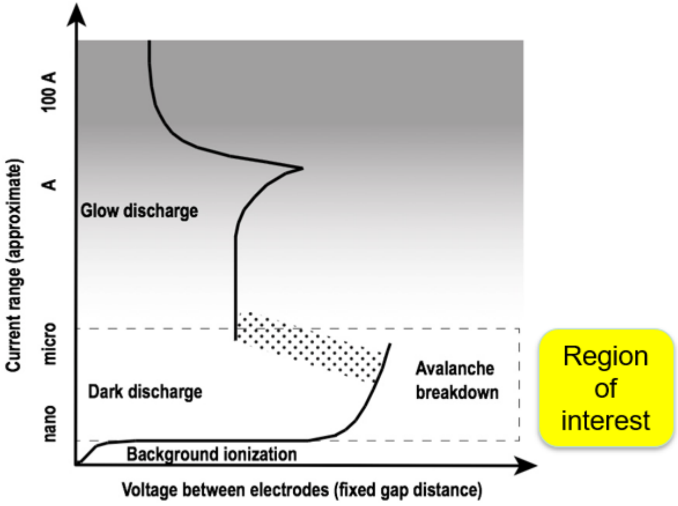
- The original objective of this work was to develop a particle sensor based on voltage breakdown between two electrodes
  - The basic concept was to measure differences in the onset of voltage breakdown (VB) as a function of particle concentration by monitoring electric current
  - Other elements include the rapid rise in current to identify any unique features that can be linked to particle concentration



Background-Paschen Curve

- Paschen's law is an equation that gives the breakdown voltage, which is the voltage necessary to start a discharge or electric arc, between two electrodes in a gas as a function of pressure (p) and gap length (d).





$$V_B = \frac{Bpd}{\ln(Apd) - ln[ln(1 + \frac{1}{\gamma_{se}})]}$$

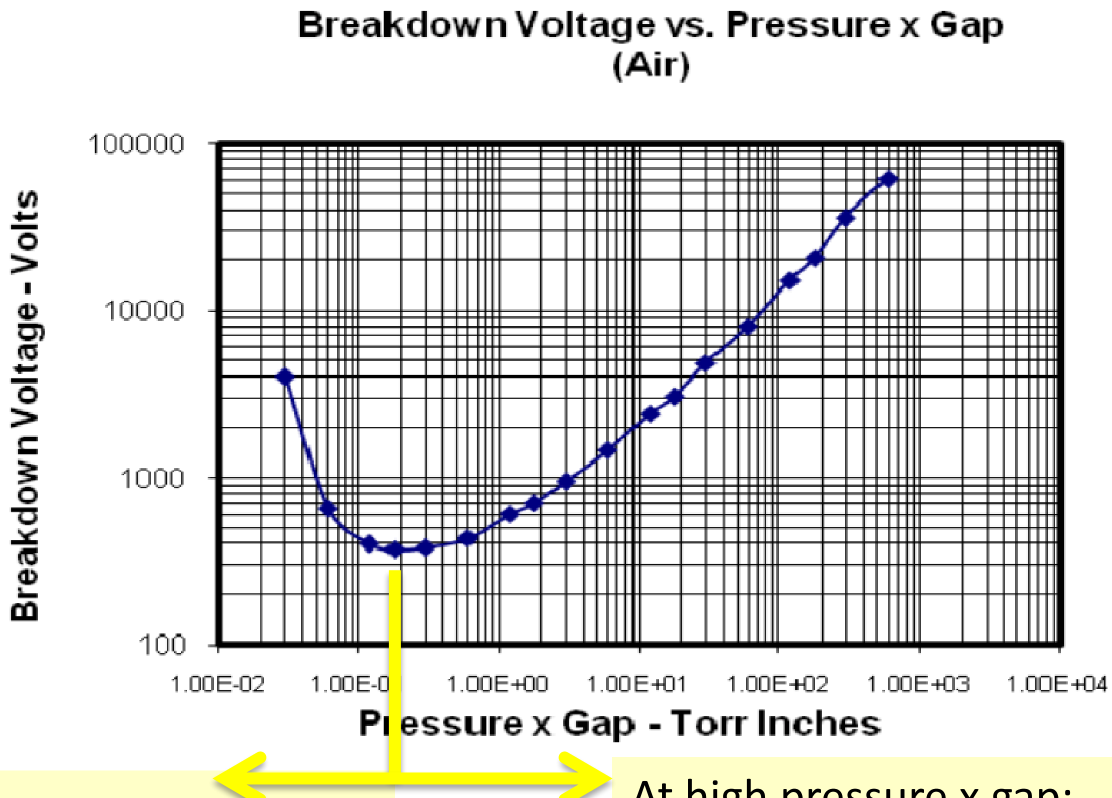
* VB: voltage breakdown

* A, B: constants related to the ionization energies of the gas

* Gamma: secondary ionization constant at the cathode

Differentiating the above equation and setting it to zero determines the minimum VB

Paschen Curve



At low pressure x gap:

- longer e- mean free path → less collisions
- More gained energy, but fewer collisions
- High voltages are required to assure ionization

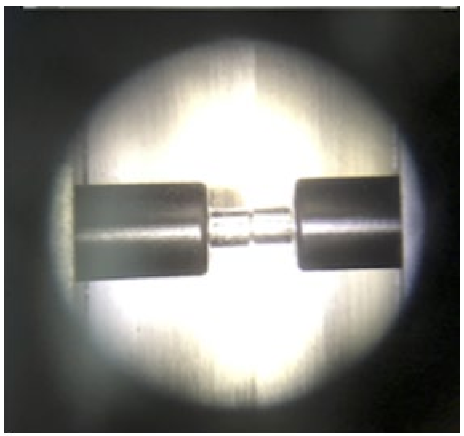
At high pressure x gap:

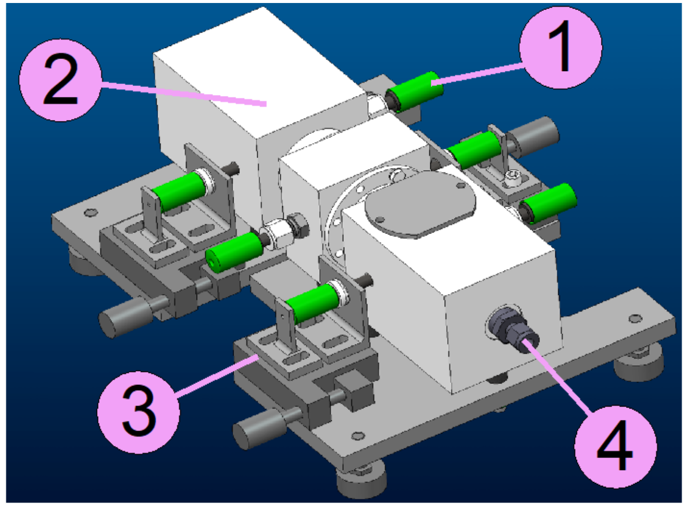
- Shorter e- mean free path → more collisions
- Less gained energy → harder ionizations
- Energy losses would require higher voltages

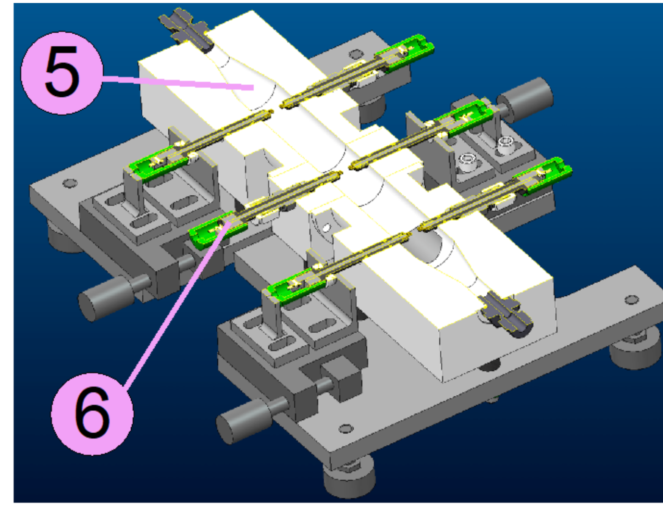
Program Approach

- We used several highly polished electrode materials to study voltage breakdown
  - Nickel, Copper, Alumina, Copper-Tungsten alloy
- The breakdown stability of each electrode was studied in clean air by a voltage sweep and a gap distance sweep
- The most stable electrode was chosen to carry the voltage sweep in the presence of particles

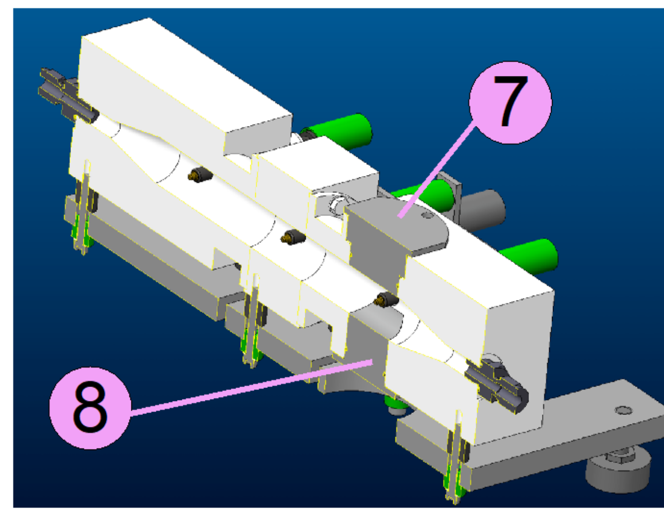
Apparatus with a Piezoelectric Actuator to Change Distance between Electrodes





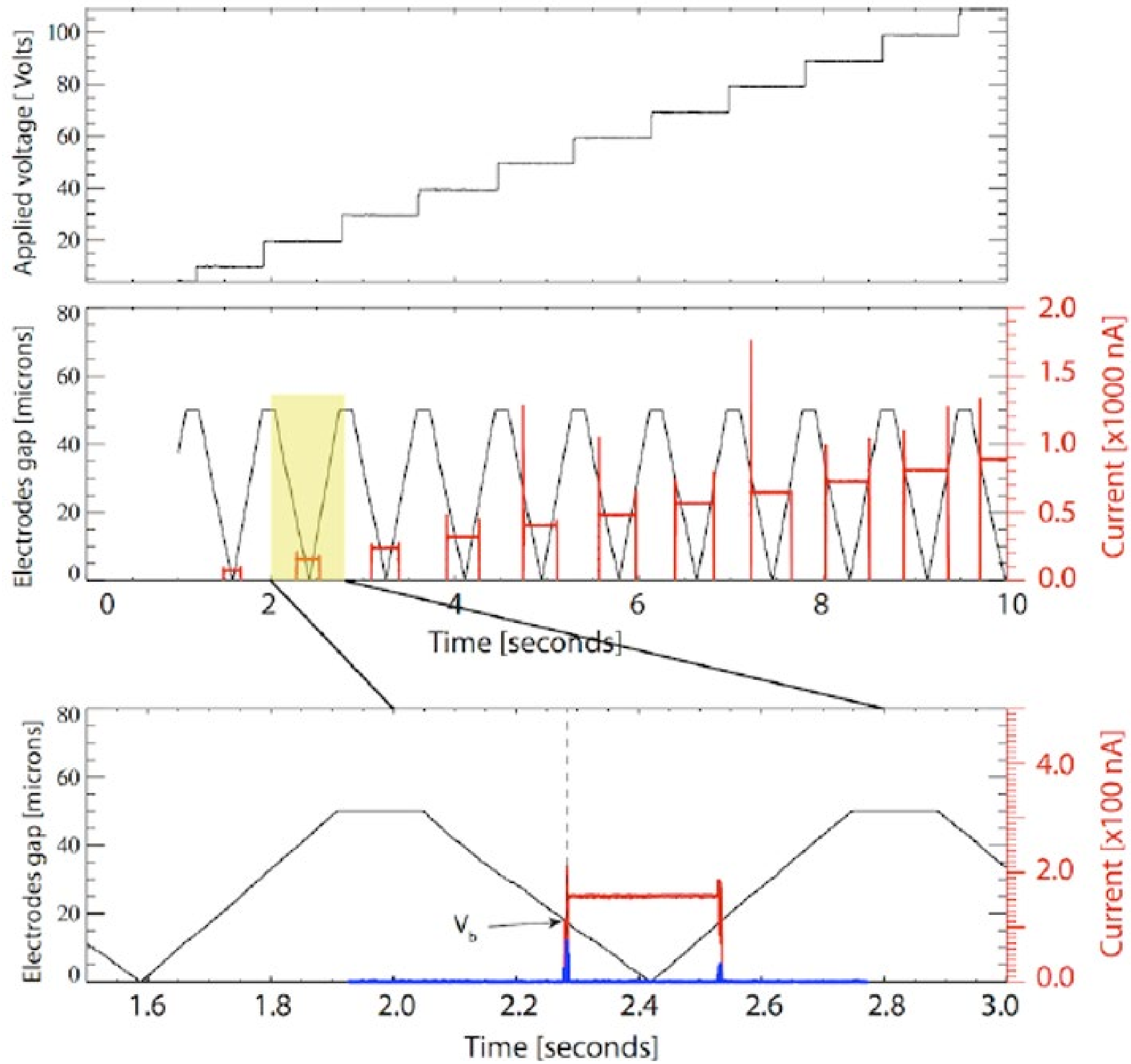


(1) Movable electrode extender with sub-microm eter resolution
(2) External body of the sensor
(3) Movable linear stage that will connect to an automated actuator
(4) Gas inlet
(5) sensor space from the inside
(6) high-voltage feed-through electrode wire
(7) Fitting for a high-speed camera
(8) Fitting for a photomultiplier tube



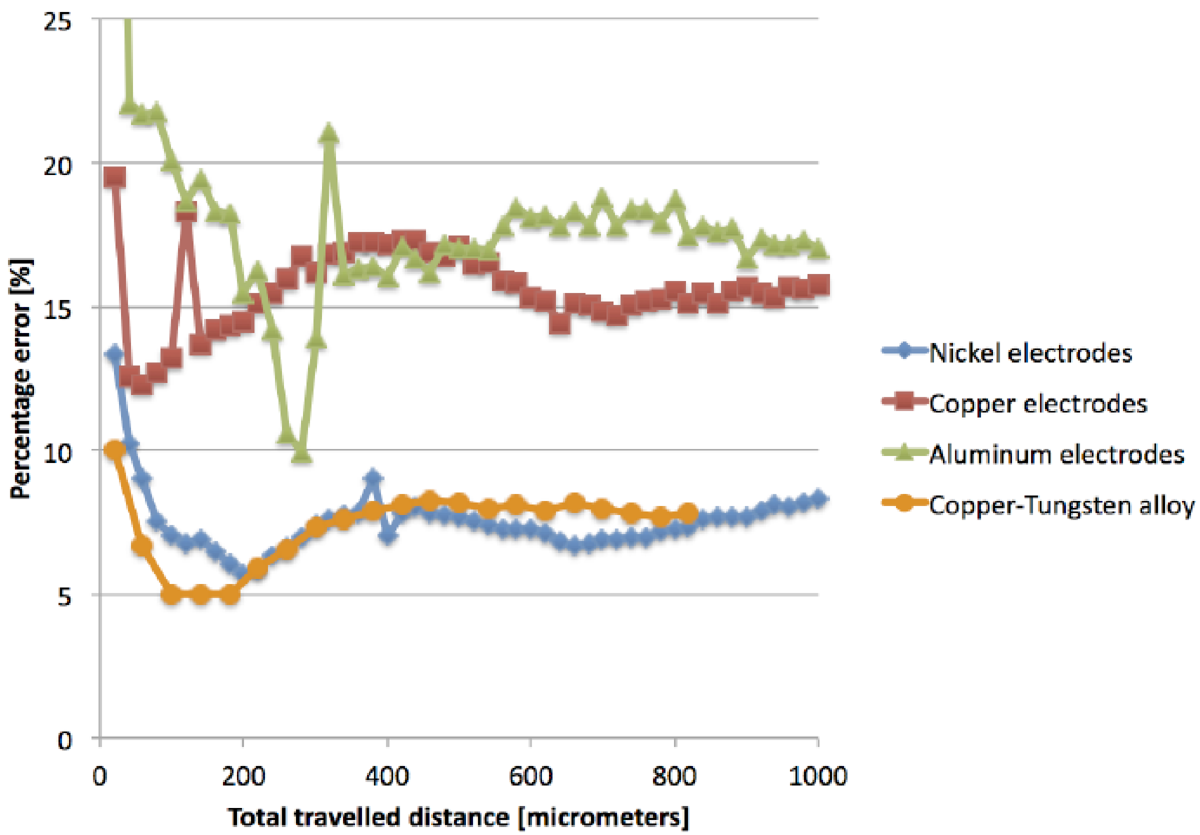
Voltage Breakdown (VB) Sweep Example

- The voltage was maintained constant and the distance between the two electrodes was changed until a sudden rise
- VB was identified at the onset of current rise



Electrode Stability

- The Copper-Tungsten alloy was the most stable with the lowest and VB error



VB with and w/o particles

- Voltage breakdown was sensitive to CO_2 concentration and to H_2O
- **VB was not sensitive to particle concentration**
- We were interested in seeing a unique signature in current rise during VB, but a higher data acquisition speed was needed to observe any signature in this region

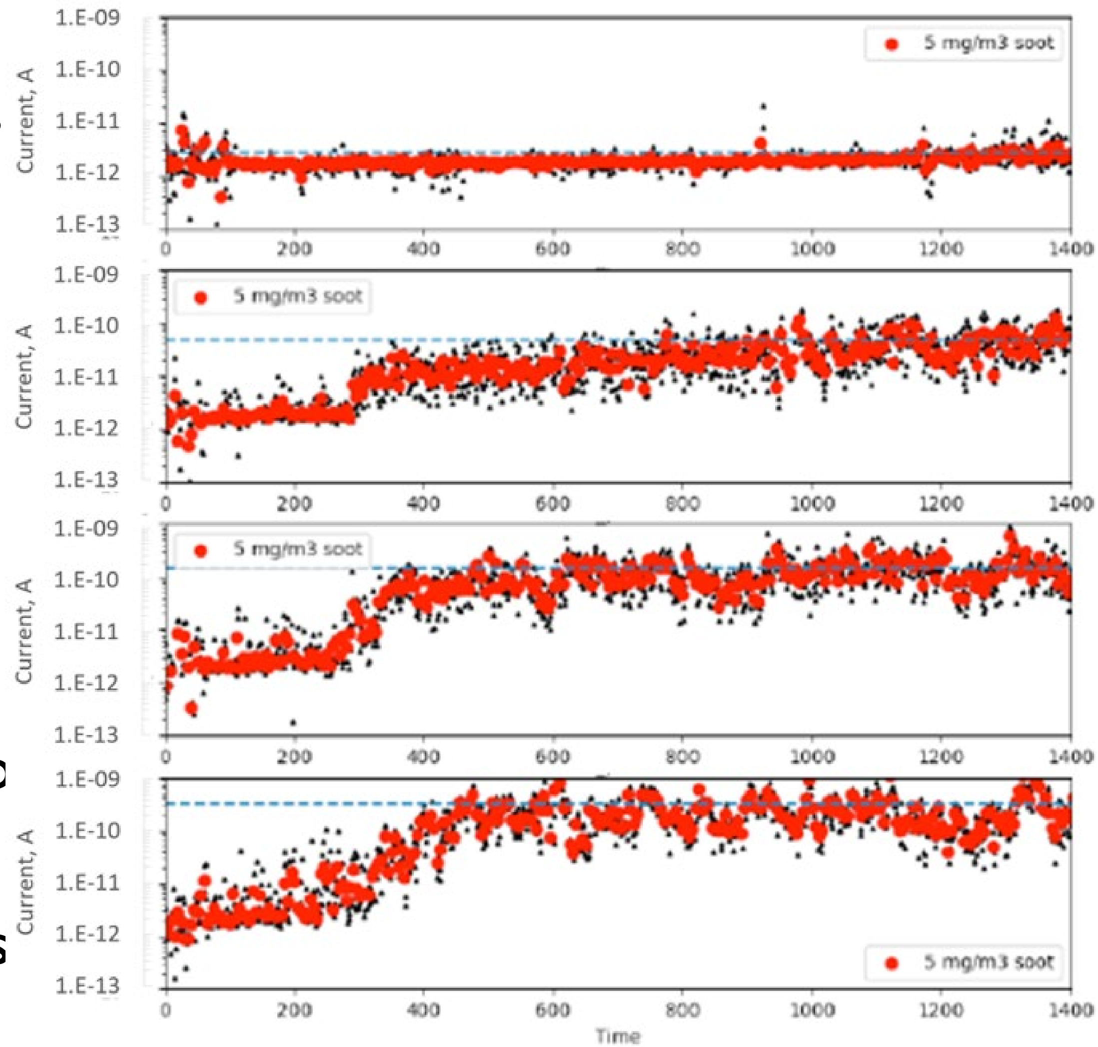
Medium	Average, V	Stdev, V	COV
N_2 baseline	891.7	22.1	2.5%
14.11% CO2	1021.7	44.2	4.3%
N_2 baseline	924.5	20.8	2.2%
7.05% CO2	1011.2	26.9	2.7%
N_2 baseline	913.7	48.8	5.3%
3.03% CO2	972.4	20.1	2.1%
N_2 baseline	917.1	53.4	5.8%

Medium	Average, V	Stdev, V	COV
N_2 baseline	874.5	26.0	3.0%
Dry Air, 18 % RH	906.1	27.7	3.1%
N_2 baseline	916.7	49.8	5.4%
Air, 62% RH	865.0	11.7	1.3%

Medium	Average, V	Stdev, V	COV
N_2 baseline	934.2	80.0	8.6%
1 mg/m^3 soot	917.0	16.7	1.8%
N_2 baseline	889.3	68.3	7.7%
5 mg/m^3 soot	883.2	28.9	3.3%
N_2 baseline	871.9	31.4	3.6%
100 mg/m^3 soot	839.5	8.0	0.9%
N_2 baseline	870.0	46.9	5.4%
220 mg/m^3 soot	900.7	40.3	4.5%

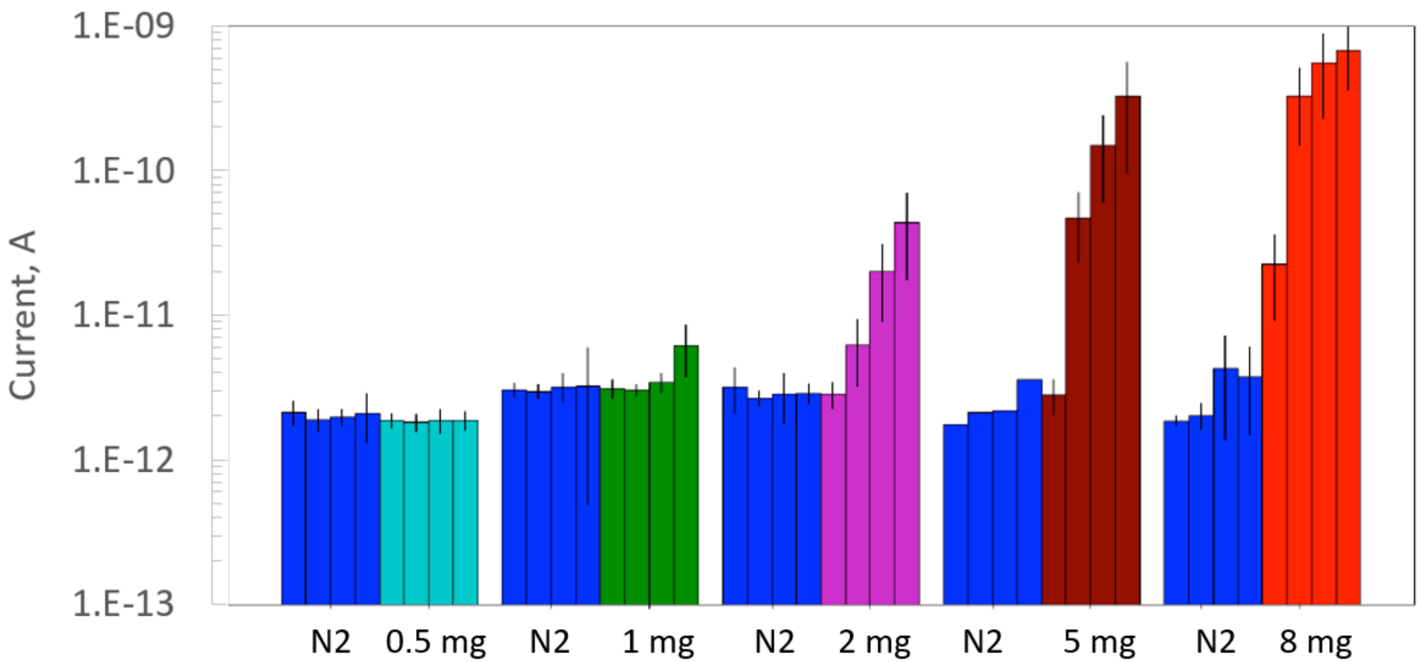
Sensor Performance Below VB

- Below VB, the sensor responded to soot particles using mini-CAST/Stripper particle generator at 5 mg/m^3
- Initially, it took about 28 minutes for the current to increase by 2 order of magnitude using 2 lpm, with 70 µm spacing between two electrodes at 700 V
- After that, it took 4 minutes for the current to respond



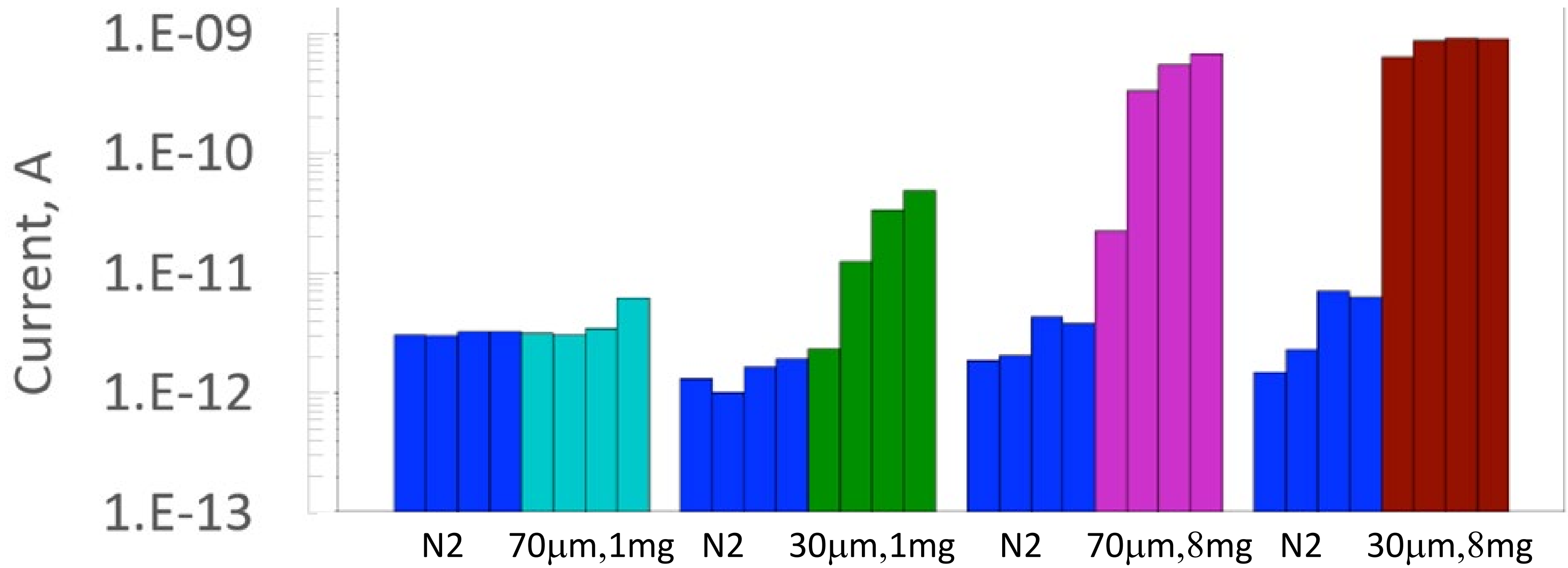
Summary of Sensor Performance as a Function of Soot Concentration (700 V, 70 μm, 2 lpm)

- Sensor was sensitive down to a particle concentration of 1 mg/m^3
- Close to 3 orders of magnitude rise in electric current was observed at 8 mg/m^3
- Sensor response was quicker at high concentration



Summary of Sensor Performance as a Function of Soot Concentration (700 V, 70 μm), (500 V, 30 μm), 2 lpm

- Reducing the gap from 70 μm to 30 μm, led to more sensitivity at 1 mg/m3, but at a higher to voltage to gap ratio.
- The voltage to gap ratio is an important parameter



Summary of Parameters and Their Effects Below VB

Parameter changed	Effect on current
4 L/min[1]	Overall decreased amount of time to reach stable current
alternate with turning off voltage[1]	Overall increased amount of time to reach stable current
	Noisier data set when voltage is turned off
alternate with shutting off soot flow[1]	Similar slow decay of current between shutting off soot flow and flowing N_2
	Faster gain in current upon reintroducing soot flow
	Noisier data set when flow is shut off
30 um, 500V[2]	Increased stable current value by 1 order of magnitude
	Noisier data set
750V[2]	Increased stable current value by 1 order of magnitude
	Noisier data set
30 um, 500V[3]	Decreased time to reach stable current when switching to soot
750V[3]	Decreased time to reach stable current when switching to soot
	Overall decreased time to reach stable current
Change soot concentration from 5 mg/ m^3 to 10 mg/m^3 to 5 mg/ m^3	Decreased time to stabilize current when changing from 5 mg to 10 mg/m^3 concentration
	Decreased time to stabilize current from 10 mg to 5 mg
	Noisier data set when switching from 10 mg to 5 mg

[1]*Compare to 5 mg/m^3, 700V, 70 microns gap, alternate with N_2 at 2 lpm*

[2]*Compare to 1 mg/m^3, 700V, 70 microns gap, alternate with N_2 at 2 lpm*

[3]*Compare to 8 mg/m^3, 700V, 70 microns gap, alternate with N_2 at 2 lpm*

Overall Summary

- We have developed a sensor apparatus to study VB in the presence of particles
  - VB was insensitive to particle concentration
- The apparatus was used to investigate the current between two parallel plates electrodes below VB
  - The sensor showed two to three order of magnitude rise in current as a function of particle concentration, as a result of particle deposition and release similar to that of the Emisense sensor
- The apparatus provides us with the opportunity to do fundamental research on electrode surfaces, materials and flow rates to accelerate the response time and improve sensor sensitivity

Acknowledgements

- This work was funded by Southwest Research Institute Internal Research and Development (IR&D) Program

Southwest Research Institute®

Imad A. Khalek, Ph.D., Sr. Program Manager
Ikhalek@swri.org