Martian Atmospheric Dust Mitigation for ISRU Intakes via Electrostatic Precipitation

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JAMES R. PHILLIPS III

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James R. Phillips III[1], Jacob R. S. Pollard[2], Michael R. Johansen[1], Paul J. Mackey[1], J. Sid Clements[2], Carlos I. Calle[1]

[1]NASA KSC Mailcode UB-R2, Kennedy Space Center, FL 32899
[2]Appalachian State University, Dept. of Physics and Astronomy, Boone, NC 28608

Agenda

The Problem: Martian Atmospheric Dust

- Atmospheric In Situ Resource Utilization (ISRU)
- Atmosphere Requirements
- Atmospheric Dust Properties

The Solution: Electrostatic Precipitation

- Theory and Model
- Hardware and Software Prototype
- Difficulties and Results
- Conclusions
- Future Work

The Problem

DUST IN THE MARTIAN ATMOSPHERE

In Situ Resource Utilization (ISRU)

ISRU is creating consumables from resources available in the environment.

Particularly interested in Martian atmospheric ISRU:

- Oxygen needs to be produced for life support and propellant uses.
- Martian atmosphere is composed primarily of carbon dioxide (95.32%)[1].
- Carbon dioxide is easily converted into oxygen using a variety of methods.
- Full scale oxygen production of 2.2 kg/hr[2] is necessary for human exploration with six astronauts.

Since 2.2 kg/hr[2] is a very ambitious goal, two smaller benchmark missions will be flown:

- Mars 2020 aims for 1% full scale or 22 g/hr oxygen production rate over 50 sol.[2]
- Mars 2024 aims for 20% full scale or 440 g/hr oxygen production rate over 500 sol.[2]

[1] Williams, D. R. Mars Fact Sheet. *NASA Lunar and Planetary Science*, 2015.
[2] NASA SMD. Mars 2020 Investigations. NASA Solicitation and Proposal Integrated Review and Evaluation System, 2013.

Mars 2020

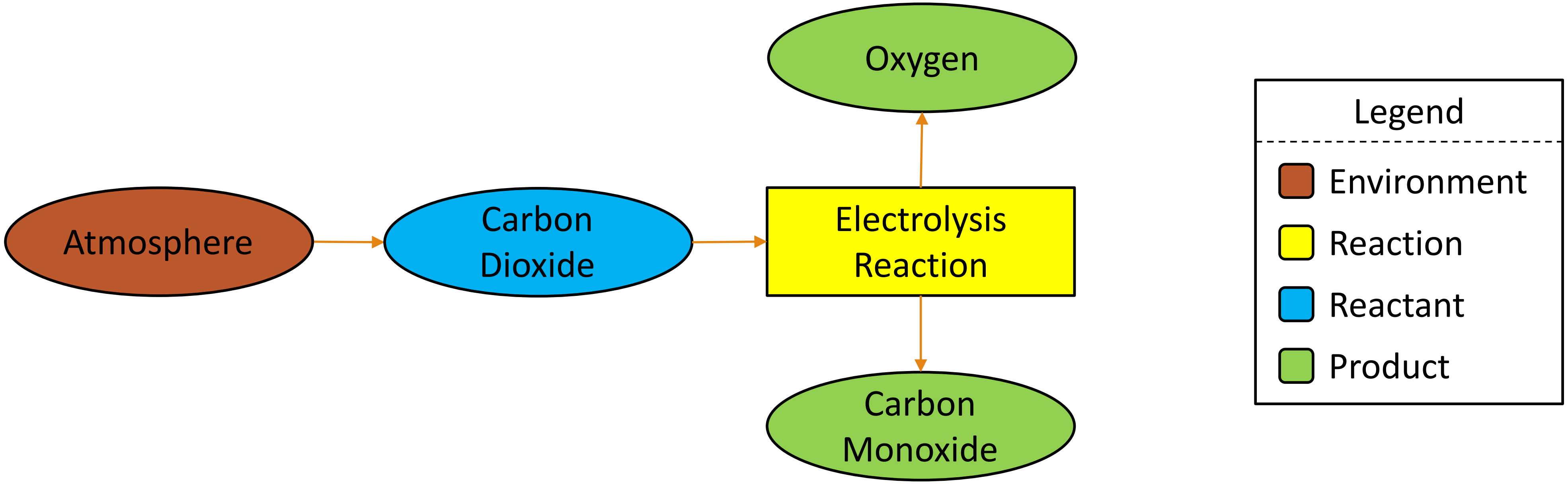
Solid Oxide Electrolysis (SOE)

- Reduce carbon dioxide: $CO_2 + 2e^- \rightarrow O^{2-} + CO$
- Recombine monatomic oxygen: $2O^{2-} \rightarrow 4e^- + O_2$
- **Net reaction:** $\mathbf{2CO_2 \rightarrow O_2 + 2CO}$

- Requires two moles of carbon dioxide for every one mole of oxygen.
- Will operate at 1% the rate of a full scale human exploration mission or 22 g/hr O_2.[1]
- Over mission length of 50 sol[1], 25.7 kg O_2 will be produced overall.

[1] NASA SMD. Mars 2020 Investigations. NASA Solicitation and Proposal Integrated Review and Evaluation System, 2013.

Solid Oxide Electrolysis Reaction



Mars 2024

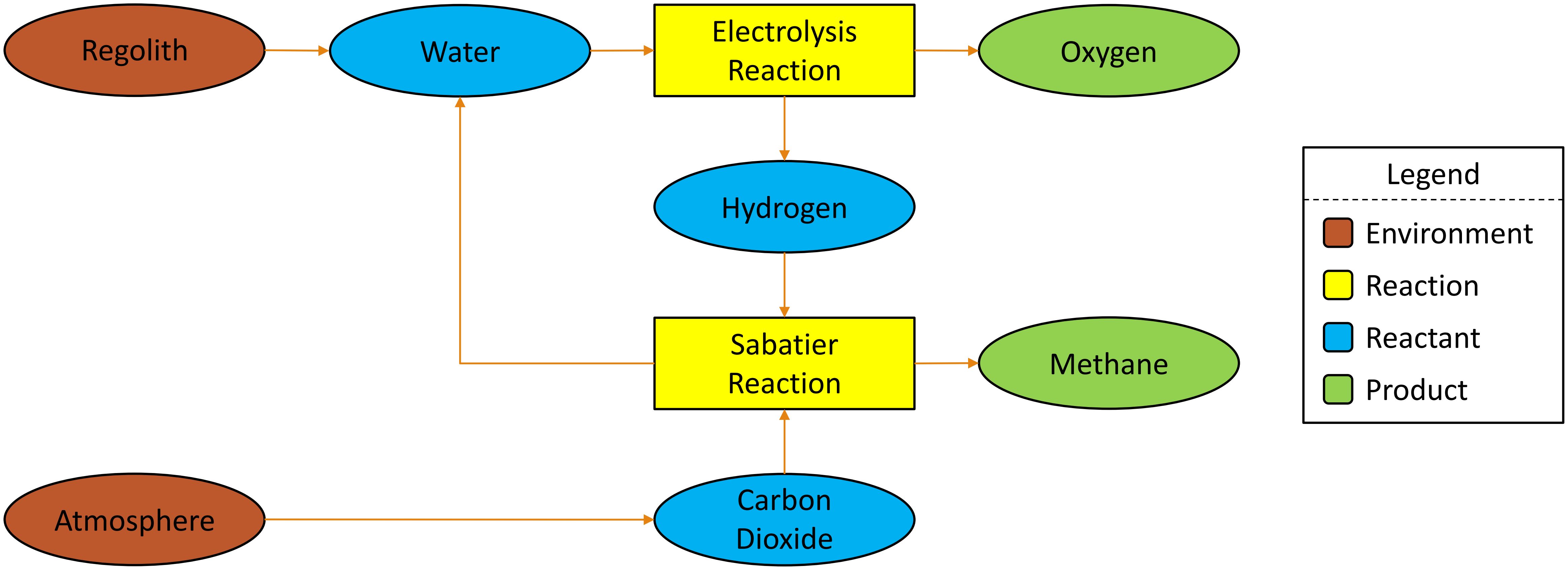
Sabatier Reactor

- Electrolyze water from regolith: $2H_2O \rightarrow 2H_2 + O_2$
- Sabatier reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
- **Net reaction:** $\mathbf{CO_2 + 2H_2O \rightarrow CH_4 + 2O_2}$

- Produces two moles of oxygen for every one mole of carbon dioxide.
- Will operate at 20% the rate of a full scale human exploration mission or 440 g/hr O_2.[1]
- Over mission length of 500 sol[1], 5140 kg O_2 will be produced overall.

[1] NASA SMD. Mars 2020 Investigations. NASA Solicitation and Proposal Integrated Review and Evaluation System, 2013.

Sabatier Reaction



ISRU Parameters

Parameter	Mars 2020	Mars 2024	Notes
Oxygen Production Rate	1% full scale 22 g/hr	20% full scale 440 g/hr	Mars 2020 AO[1] 20x higher O_2 rate
Primary Chemical Reaction	Electrolysis 1 O_2 per 2 CO_2	Sabatier 2 O_2 per 1 CO_2	4x more O_2 from CO_2
Operational Time	50 sol	500 sol	Mars 2020 AO[1] 10x longer operation
Total Oxygen Produced	25.7 kg	5140 kg	200x more O_2 total

[1] NASA SMD. Mars 2020 Investigations. NASA Solicitation and Proposal Integrated Review and Evaluation System, 2013.

Assumptions

Parameter	Value	Notes
Full Scale Oxygen Production Rate	2.2 kg/hr	Mars 2020 AO[1]
Carbon Dioxide Conversion Efficiency	60 %	Mars 2020 AO[1]
Martian Atmospheric Carbon Dioxide Composition	95.32 %	Williams, 2015[2]
Laboratory Atmospheric Mean Temperature	295 K	
Martian Atmospheric Mean Temperature	210 K	Williams, 2015[2] ~1.4x less than the lab
Laboratory Atmospheric Mean Pressure	1013.25 mbar	
Martian Atmospheric Mean Pressure	6.36 mbar	Williams, 2015[2] ~160x less than the lab

[1] NASA SMD. Mars 2020 Investigations. NASA Solicitation and Proposal Integrated Review and Evaluation System, 2013.
[2] Williams, D. R. Mars Fact Sheet. *NASA Lunar and Planetary Science*, 2015.

Martian Atmosphere Mass Intake

$$\dot{m}_{\text{mars}} = \dot{m}_{\text{CO}_2} \frac{1}{\eta} \frac{1}{w_{\text{CO}_2}} = \dot{m}_{\text{O}_2} \frac{M_{\text{CO}_2}}{M_{\text{O}_2}} \frac{n_{\text{CO}_2}}{n_{\text{O}_2}} \frac{1}{\eta} \frac{1}{w_{\text{CO}_2}}$$

$\dot{m}$: Mass flow rate

M: Molecular mass

w: Atmospheric composition

n: Number of moles

η: Conversion efficiency

Subscripts indicate oxygen or carbon dioxide.

Martian Atmosphere Volume Intake

$$\dot{V}_{\text{mars}} = \frac{\dot{m}_{\text{mars}}}{M_{\text{CO}_2}} R \frac{T}{P} = \frac{\dot{m}_{\text{O}_2}}{M_{\text{O}_2}} \frac{n_{\text{CO}_2}}{n_{\text{O}_2}} \frac{1}{\eta} \frac{1}{w_{\text{CO}_2}} R \frac{T}{P}$$

$\dot{V}$:	Volume flow rate	η:	Conversion efficiency
$\dot{m}$:	Mass flow rate	R:	Ideal gas constant
M:	Molecular mass	T:	Gas temperature
n:	Number of moles	P:	Gas pressure

Subscripts indicate oxygen or carbon dioxide.

Martian Atmospheric Requirements

Parameter	Mars 2020	Mars 2024	Notes
Mass Flow Rate	106 g/hr	529 g/hr	5x higher flow rate
Volume Flow Rate (Mars)	110 L/min	550 L/min	
Volume Flow Rate (Lab)	0.97 L/min	4.85 L/min	

Martian Atmospheric Dust

Dust storms cause surface regolith to become suspended in the atmosphere.

Continuous winds allow entrained dust to remain airborne indefinitely.

Any ISRU system utilizing Martian atmosphere will ingest dust along with the gas.

Dust will adversely affect ISRU systems, so it must be removed.

What do we know about this dust?

Martian Atmospheric Dust Properties

Parameter	Value	Note
Cross-Sectional Area Weighting Coefficient	6.875	Landis, 1996[1]
Mass Weighting Coefficient	9.75	
Cross-Sectional Area Weighted Mean Radius	1.6 µm	Tomasko, 1999[2]
Mass Weighted Mean Radius	2.27 µm	
Mean Cross-Sectional Area	$8.04\ \mu m^2$	
Mean Volume	$48.9\ \mu m^3$	
Mean Density	$1.52\ g/cm^3$	Hviid, 1997[3]
Mean Mass	74.4 pg	

[1] Landis, G. A. Dust Obscuration of Mars Solar Arrays. *Acta Astronautica*, 38(11): 885 – 891, 1996.
[2] Tomasko, M. G., et al. Properties of Dust in the Martian Atmosphere from the Imager on Mars Pathfinder. *Journal of Geophysical Research: Planets*, 104(E4): 8987–9007, 1999.
[3] Hviid, S. F., et al. Magnetic Properties Experiments on the Mars Pathfinder Lander: Preliminary Results. *Science*, 278(5344): 1768 – 1770, 1997.

Martian Atmospheric Dust Concentration

Parameter	Value	Notes
Atmospheric Optical Depth	0.5	Lemmon, 2004[1]
Atmospheric Scale Height	11.6 km	
Mean Surface Concentration (Linear Model)	5.36 $\text{particles}/\text{cm}^3$	
Mean Surface Concentration (Exponential Model)	8.48 $\text{particles}/\text{cm}^3$	~58% more than linear

[1] Lemmon, M. T., et al. Atmospheric Imaging Results from the Mars Exploration Rovers: Spirit and Opportunity. *Science*, 306(5702):1753–1756, 2004.

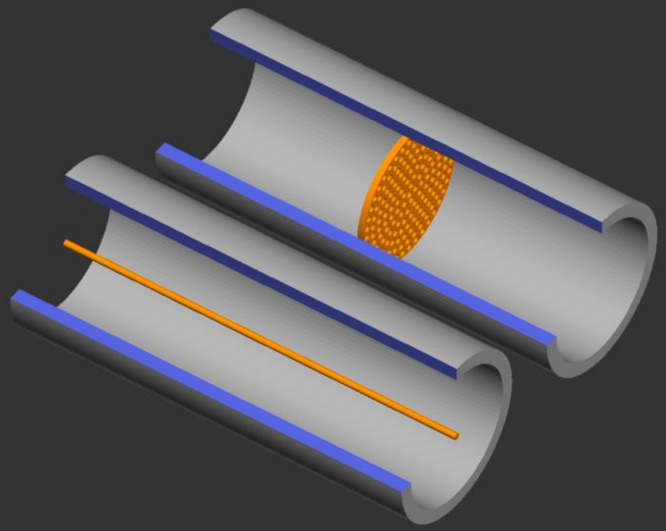
Martian Atmospheric Dust Ingestion

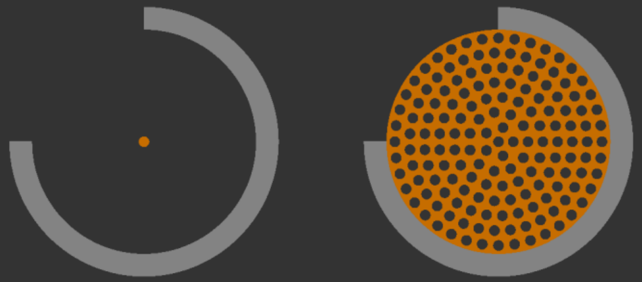
Parameter	Mars 2020	Mars 2024	Notes
Dust Ingestion Rate	9.33×10^{5} particles/s	6.54×10^{10} particles/s	
	69.4 μg/min	347 μg/min	5x higher flow rate
Total Dust Ingested	$3.20\ \mathrm{cm}^{3}$	$160\ \mathrm{cm}^{3}$	50x more dust total
	4.86 g	243 g	

The Solution

MARTIAN ENVIRONMENT ELECTROSTATIC PRECIPITATOR

Precipitator vs. Conventional Filter





Electrostatic Precipitator Reasoning

Conventional filter limits flow due to high pressure drop and clogs quickly.

Precipitator has very low pressure drop due to open geometry.

One of the only viable possibilities for Martian atmosphere filtration available.

Terrestrial precipitators are commonplace and achieve efficiencies upward of 99%.

Electrostatic Precipitator Theory

$$E(r) = \frac{V}{r \ln\frac{R}{a}} \qquad E(r) = \sqrt{\frac{I}{2\pi\varepsilon_0 Lb} + \left(\frac{a}{r}\right)^2 \left[\left(\frac{V}{\ln\frac{R}{a}}\right)^2 - \frac{I}{2\pi\varepsilon_0 Lb}\right]}$$

E:	Electric field	V:	Applied voltage
r:	Distance from electrode	R:	Precipitator radius
a:	Electrode diameter	L:	Precipitator length
I:	Ion current	b:	Ion mobility
ε_0:	Permittivity of free space		

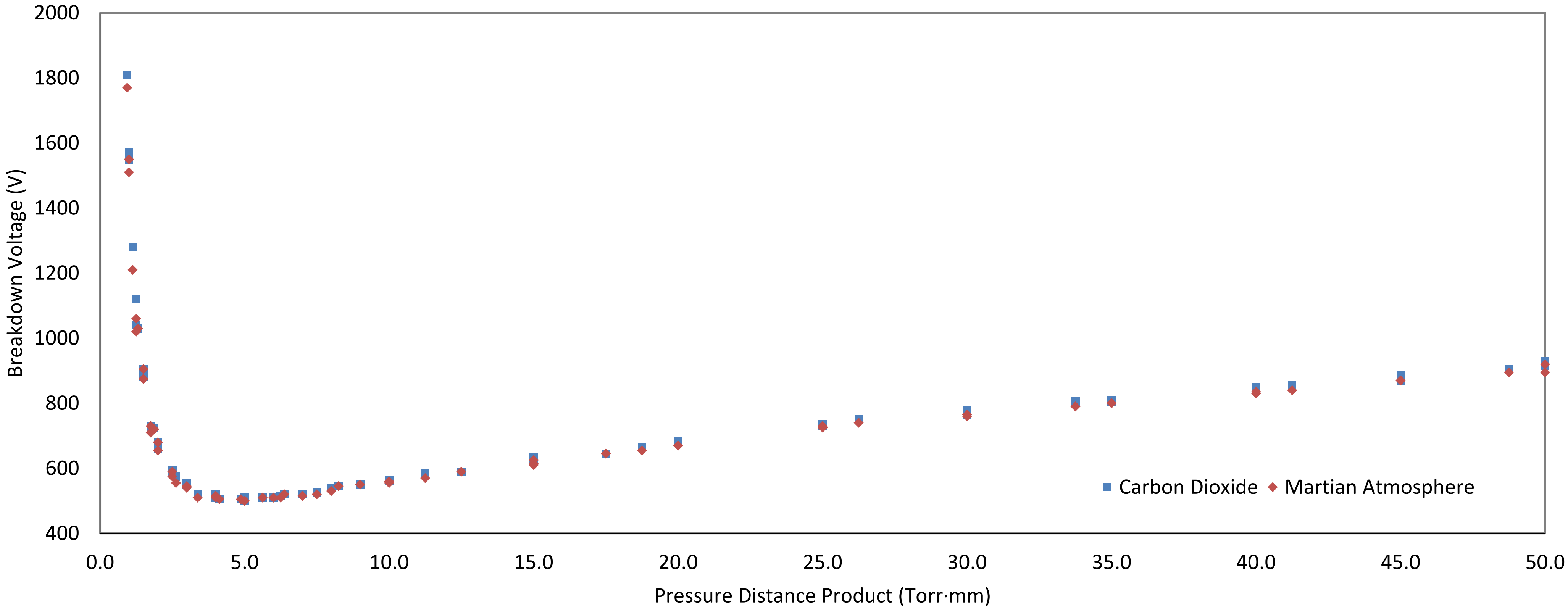
Generalized Paschen's Law

$$V_B(pd) = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1+\frac{1}{\gamma}\right)\right]} \qquad V_{\mathrm{B,\,min}} = \frac{B}{A} e \ln\left(1 + \frac{1}{\gamma}\right)$$

V_B:	Breakdown voltage	p:	Gas pressure
d:	Electrode separation	A:	Saturation ionization constant
B:	Ionization energy constant	γ:	Secondary electron emission constant

Pressure and separation govern maximum voltage attainable before spark.

Paschen's Law in Martian Atmosphere



Breakdown at Martian Conditions

Precip. Radius (mm)	P-D Product (Torr-mm)	Breakdown Voltage (V)	Notes
1.05	5	500	10x radius yields only 1.8x voltage
2.10	10	555	
3.14	15	610	
4.19	20	670	
5.24	25	725	
6.29	30	760	
7.34	35	800	
8.39	40	835	
9.43	45	870	
10.5	50	920	

6.36 mbar ≈ 4.77 Torr

Paschen’s Law in Martian Atmosphere

Increase maximum voltage by increasing gas pressure:

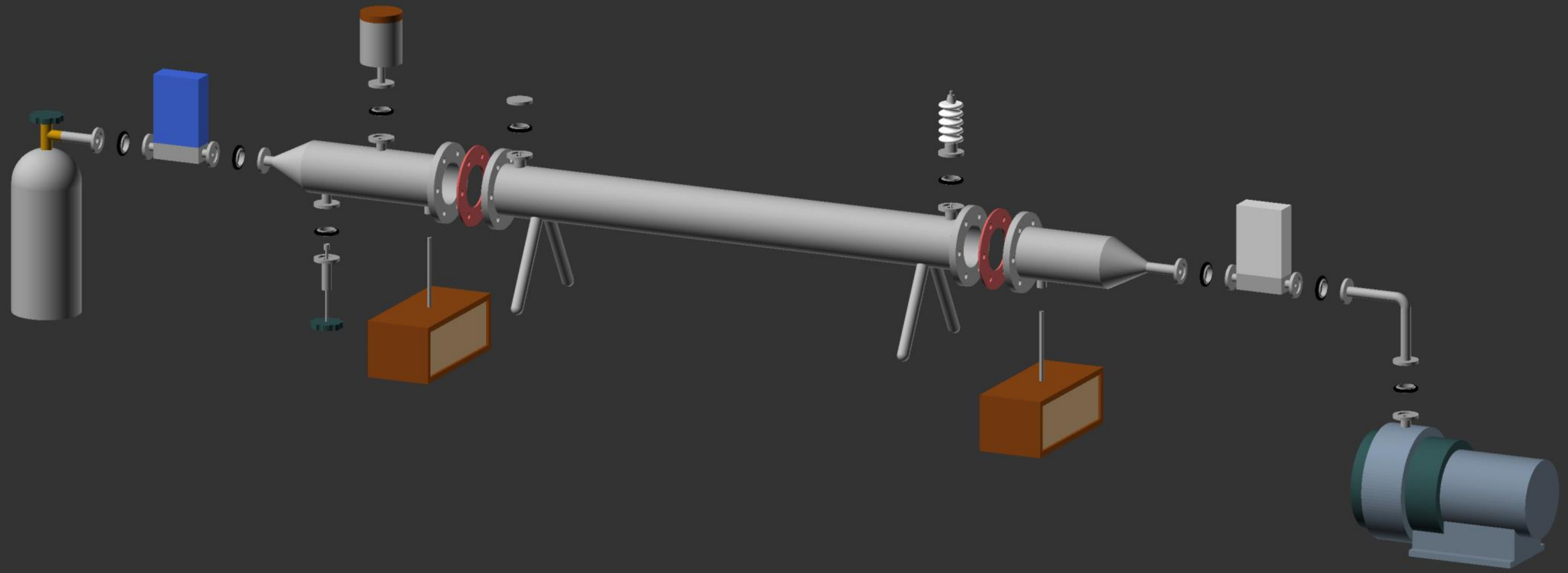
- Need system upstream of precipitator to compress gas
- Compression system will be damaged by dust, so a filter will be needed

Increase maximum voltage by increasing precipitator radius:

- Electric field from electrode decreases with increasing radius faster than maximum voltage increases
- Precipitator system becomes much larger and more massive

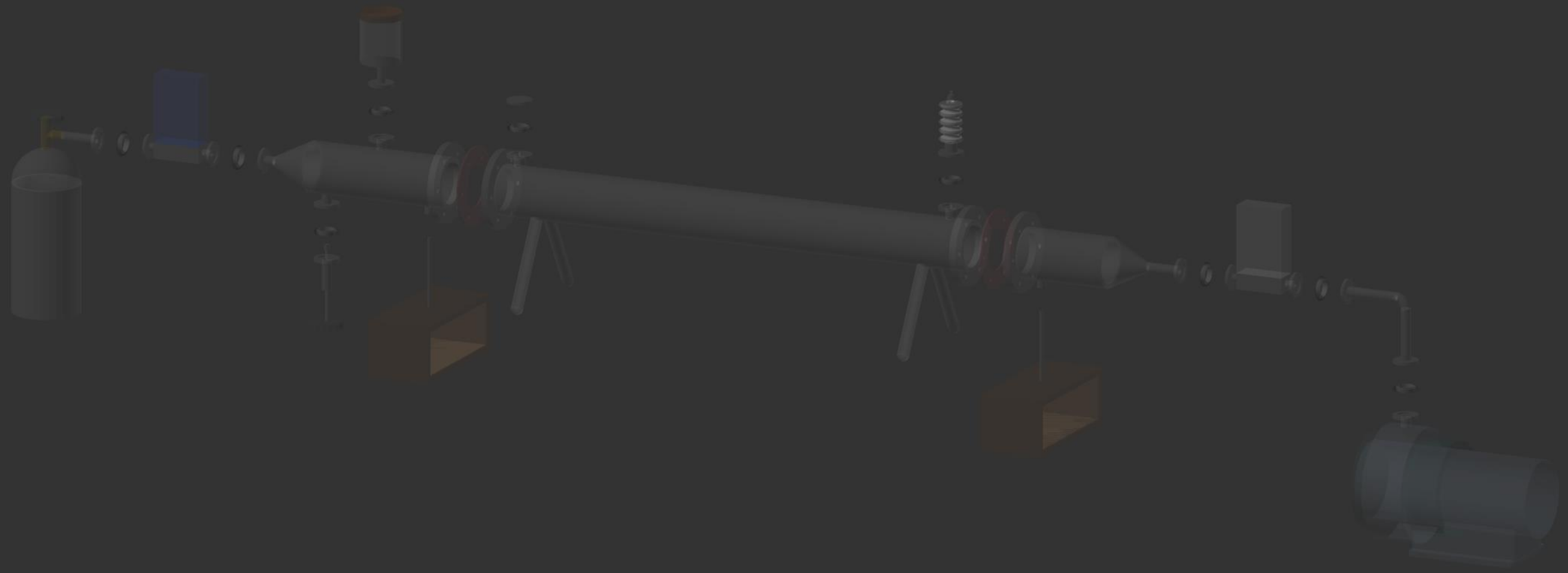
Electrostatic Precipitator Model

EXPLODED SYSTEM



Electrostatic Precipitator Model

EXPLODED SYSTEM



Electrostatic Precipitator Model

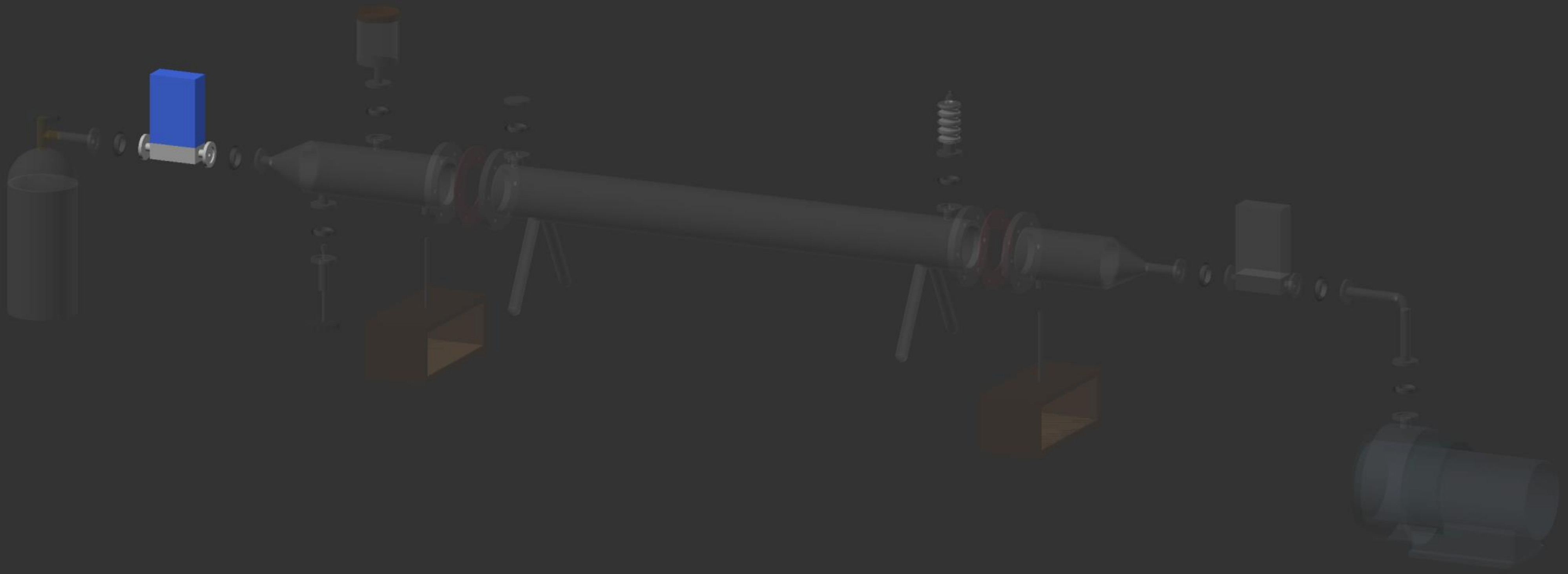
Carbon Dioxide Gas Bottle

Electrostatic Precipitator Model

KF25 O-Ring

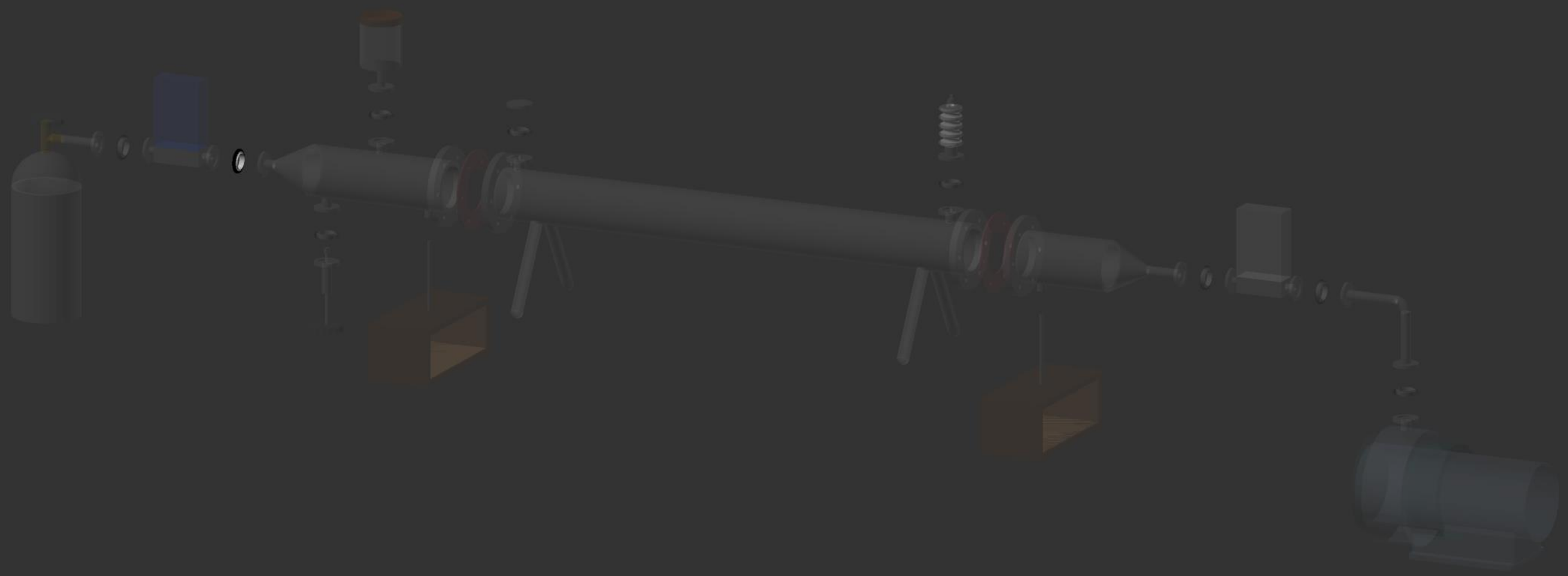
Electrostatic Precipitator Model

Mass Flow Controller



Electrostatic Precipitator Model

KF25 O-Ring



Electrostatic Precipitator Model

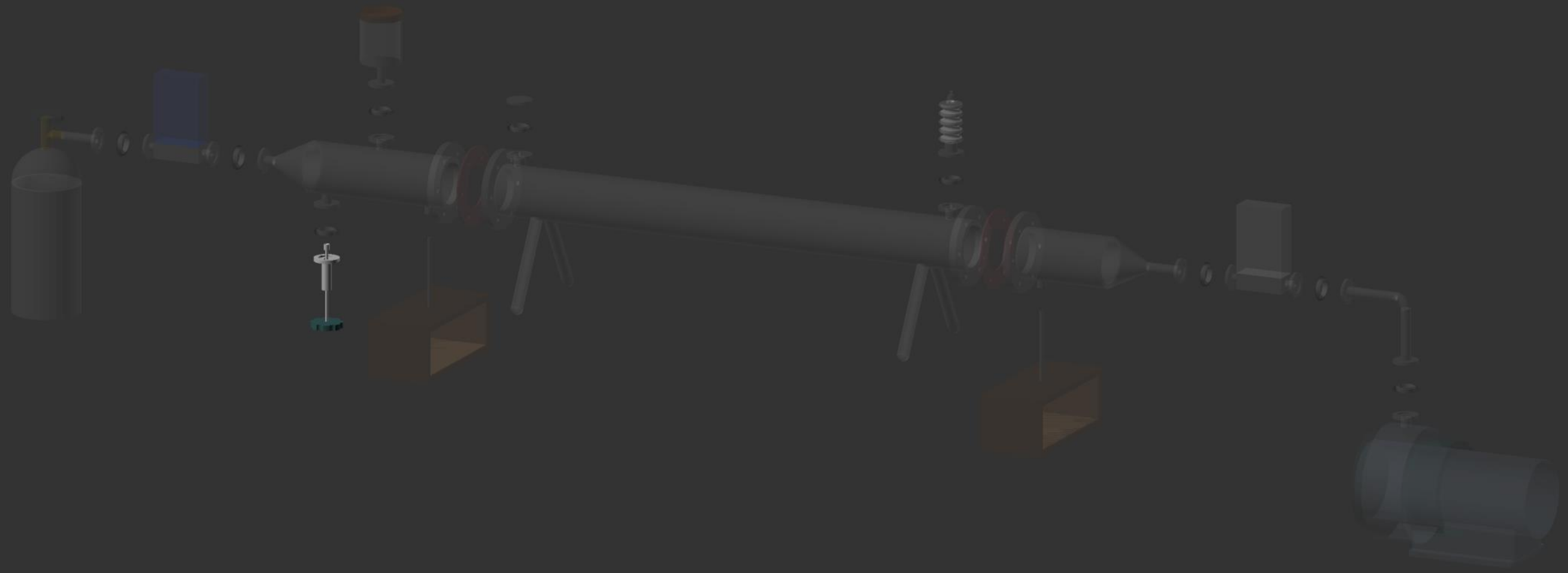
Upstream Segment

Electrostatic Precipitator Model

KF25 O-Ring

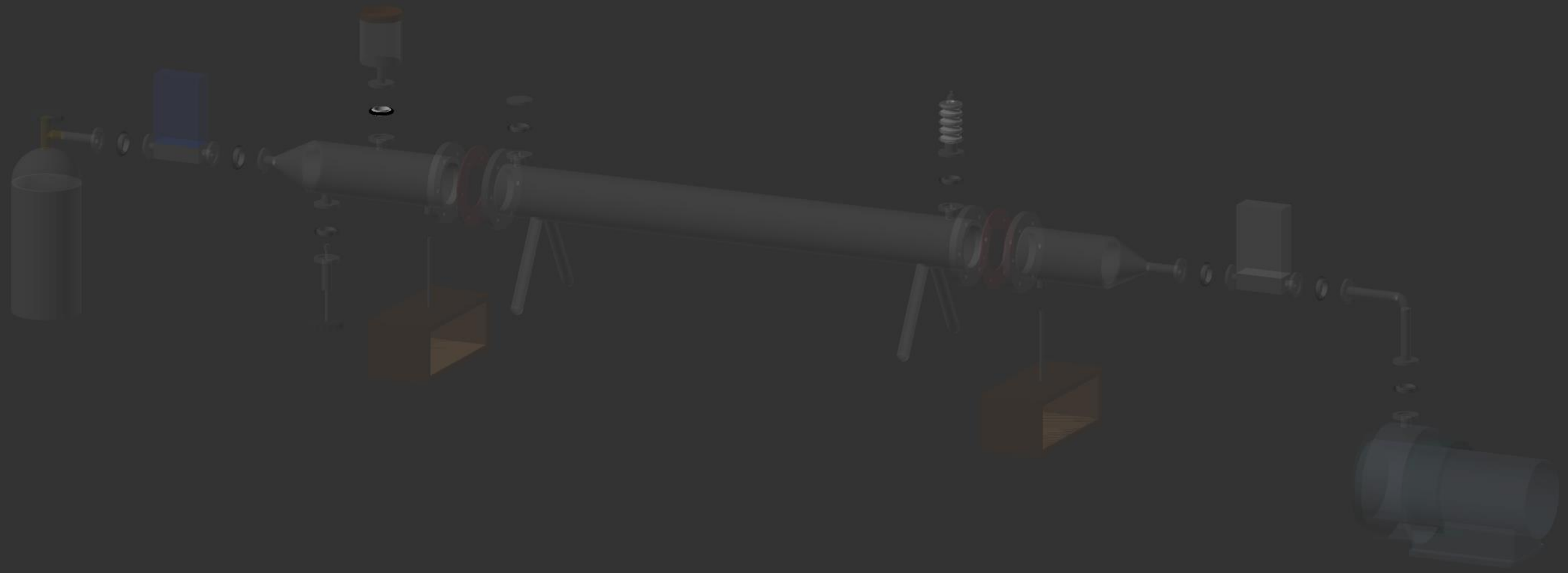
Electrostatic Precipitator Model

Dust Feedthrough



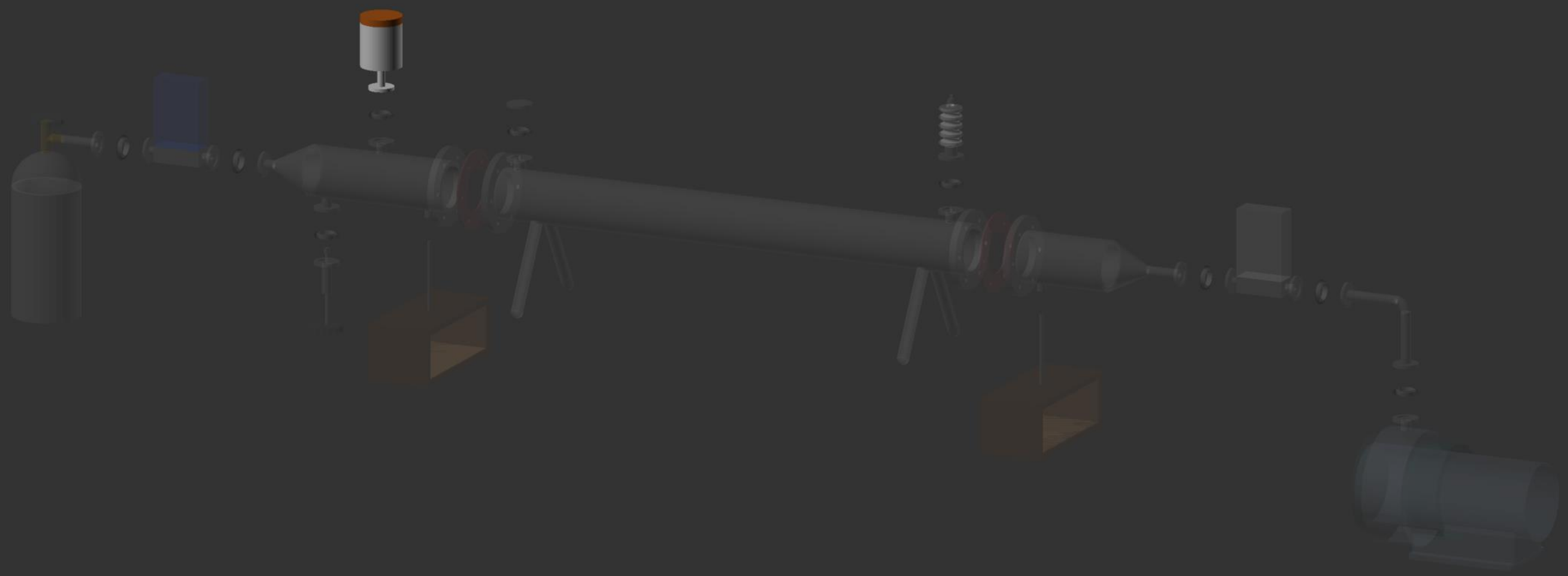
Electrostatic Precipitator Model

KF25 O-Ring



Electrostatic Precipitator Model

PRESSURE TRANSDUCER



Electrostatic Precipitator Model

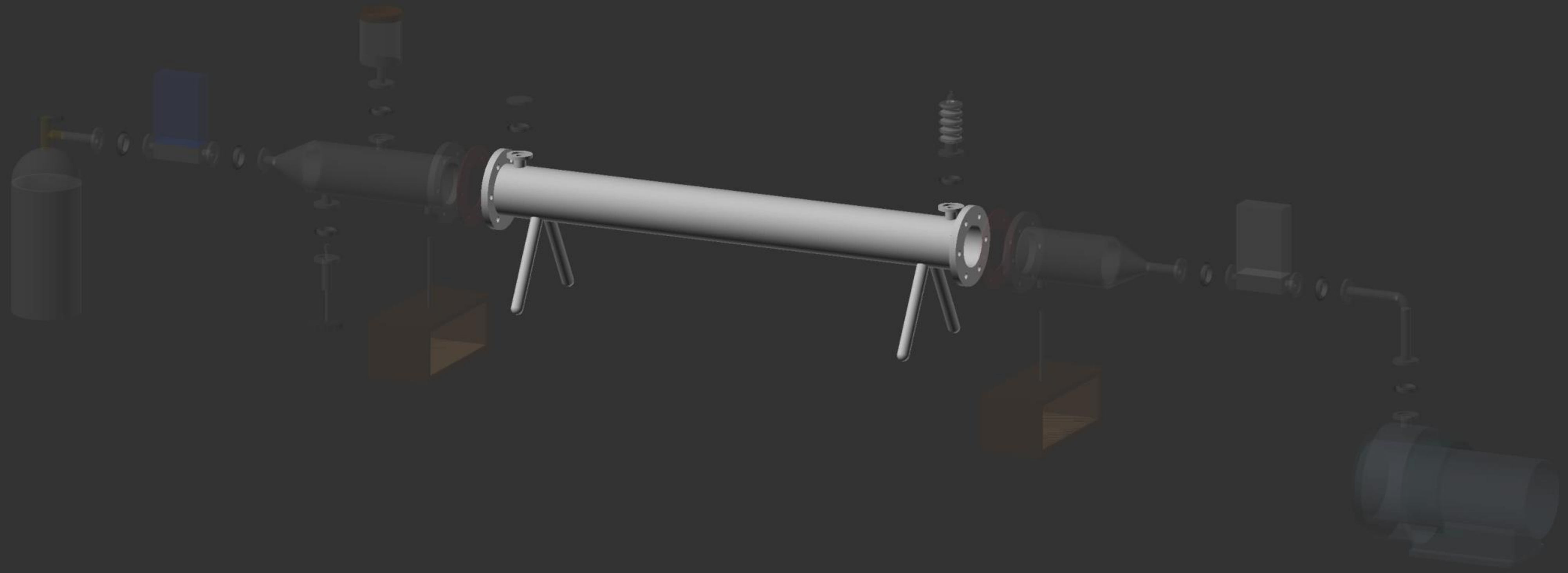
UPSTREAM PARTICLE COUNTER

Electrostatic Precipitator Model

GASKET

Electrostatic Precipitator Model

PRECIPITATOR BODY



Electrostatic Precipitator Model

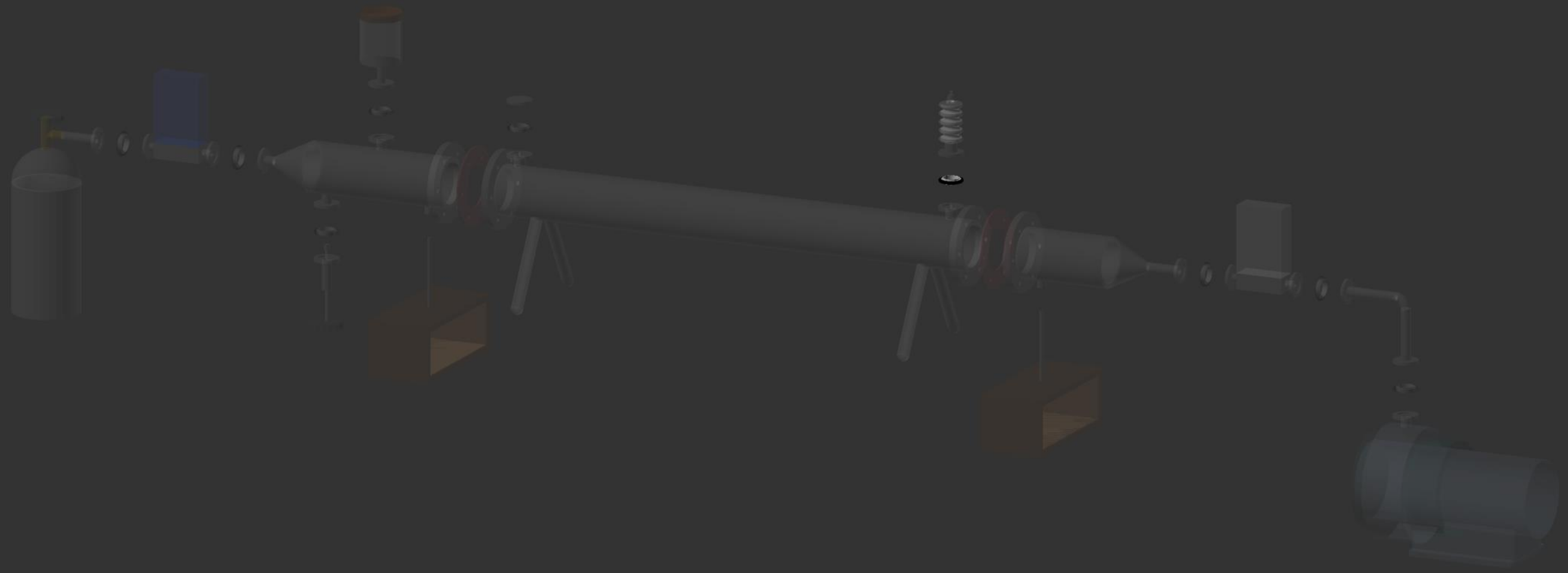
KF25 O-RING

Electrostatic Precipitator Model

ELECTRODE TERMINATOR

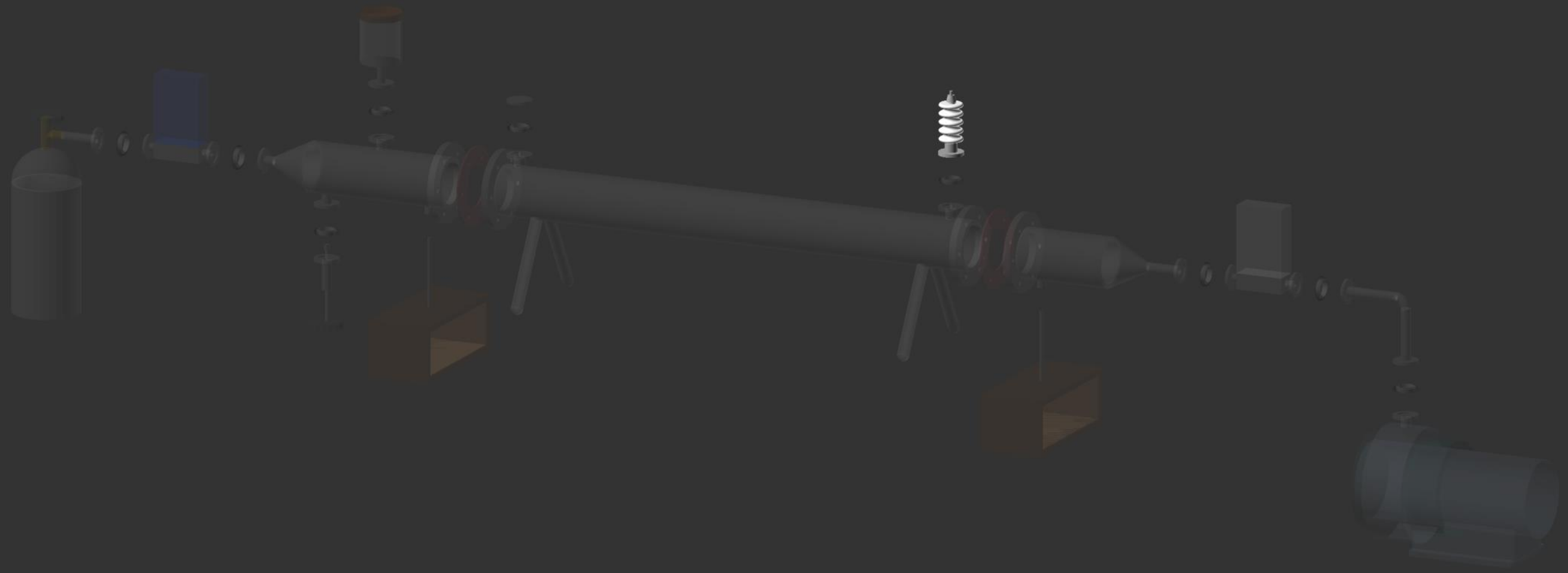
Electrostatic Precipitator Model

KF25 O-Ring



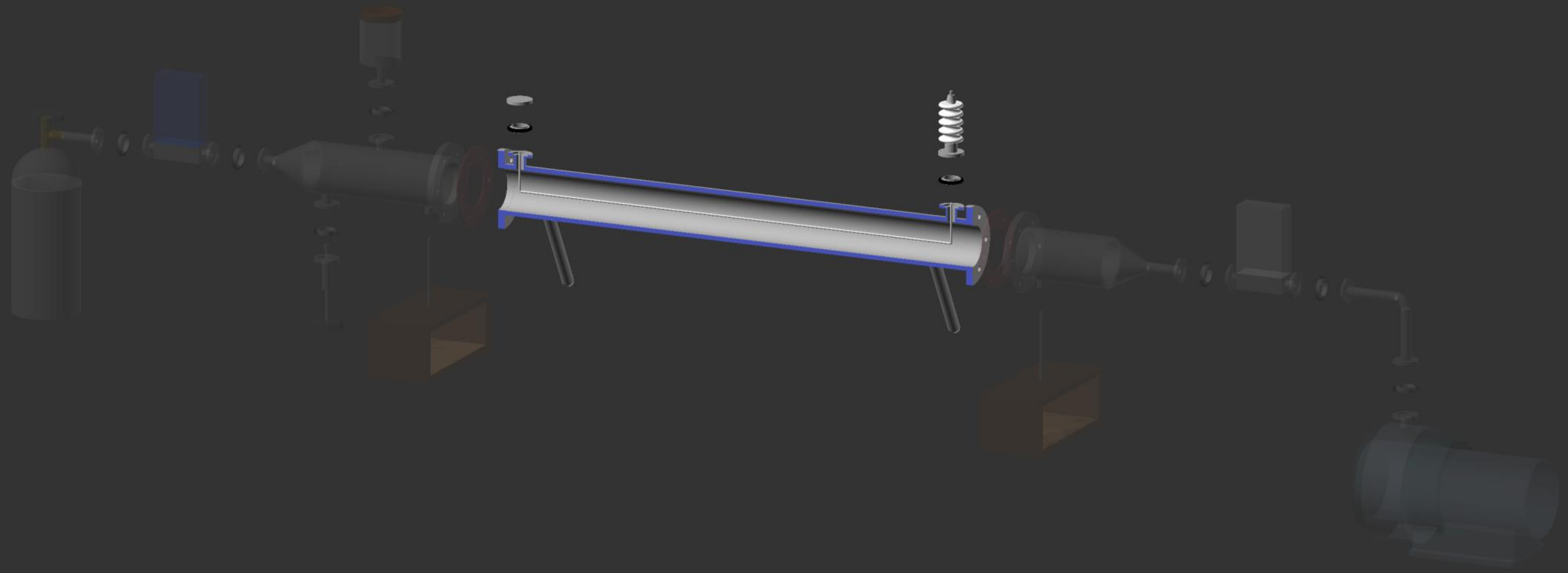
Electrostatic Precipitator Model

HIGH VOLTAGE FEEDTHROUGH



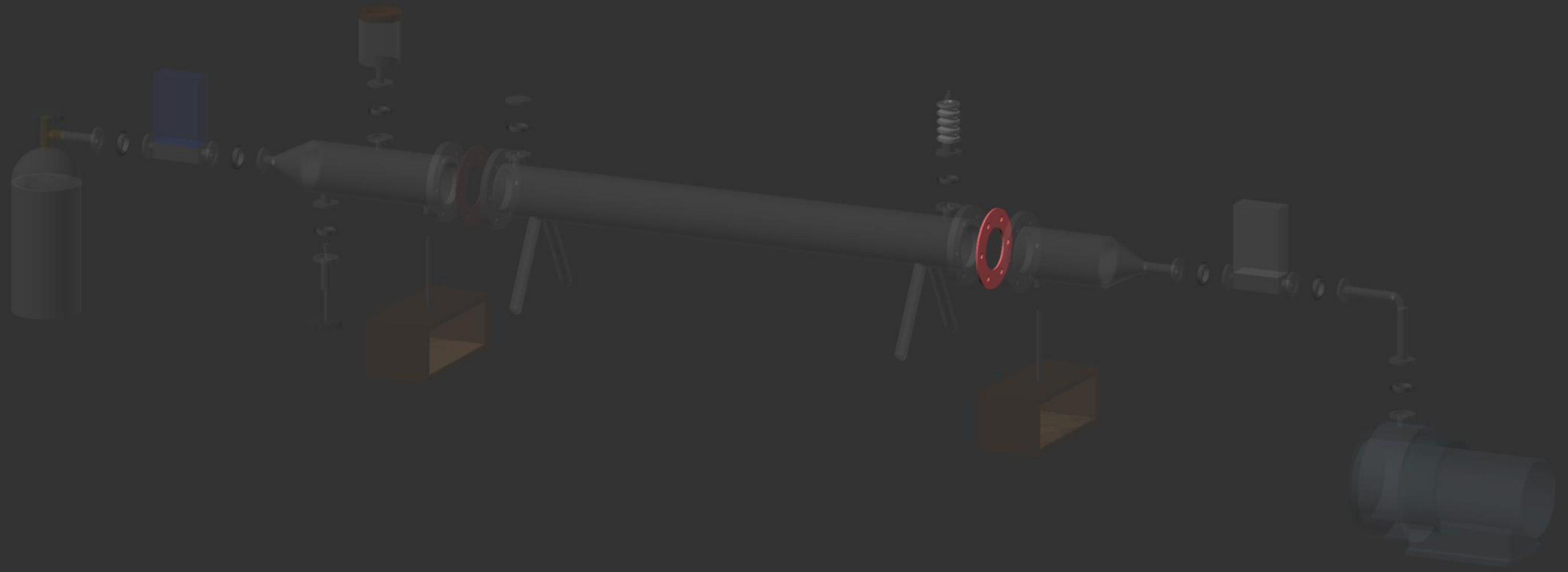
Electrostatic Precipitator Model

PRECIPITATOR BODY CUTAWAY



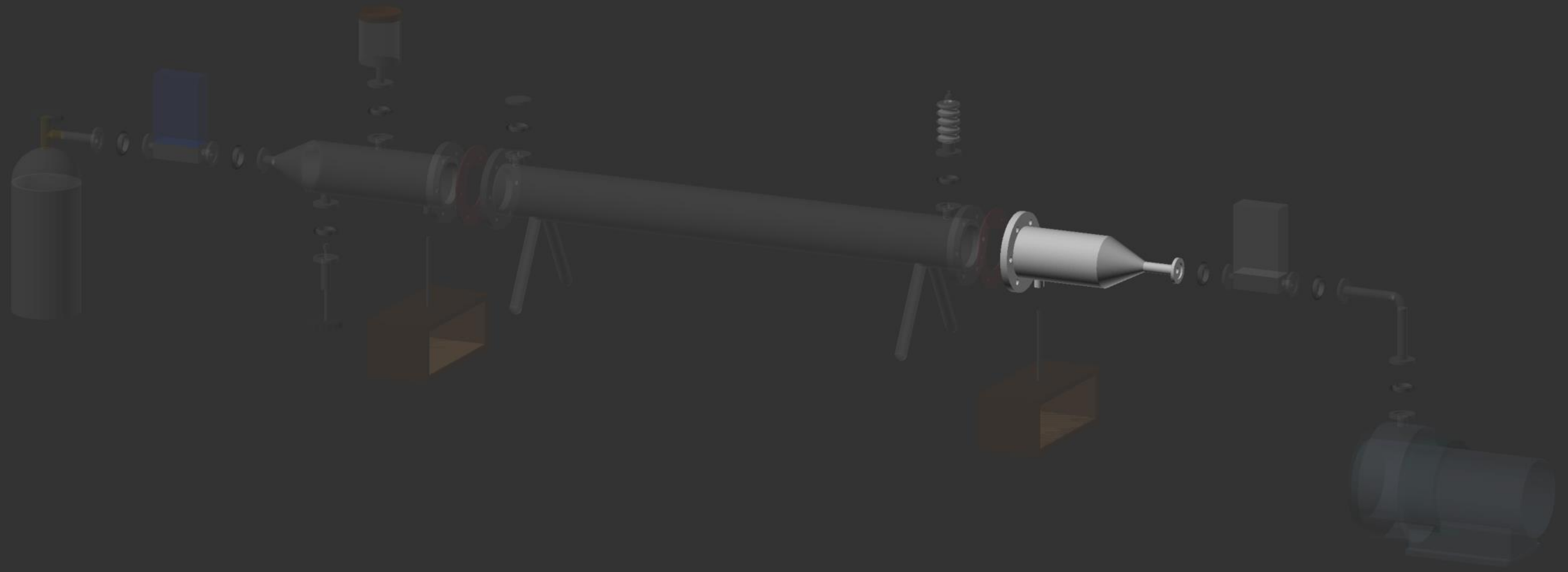
Electrostatic Precipitator Model

GASKET



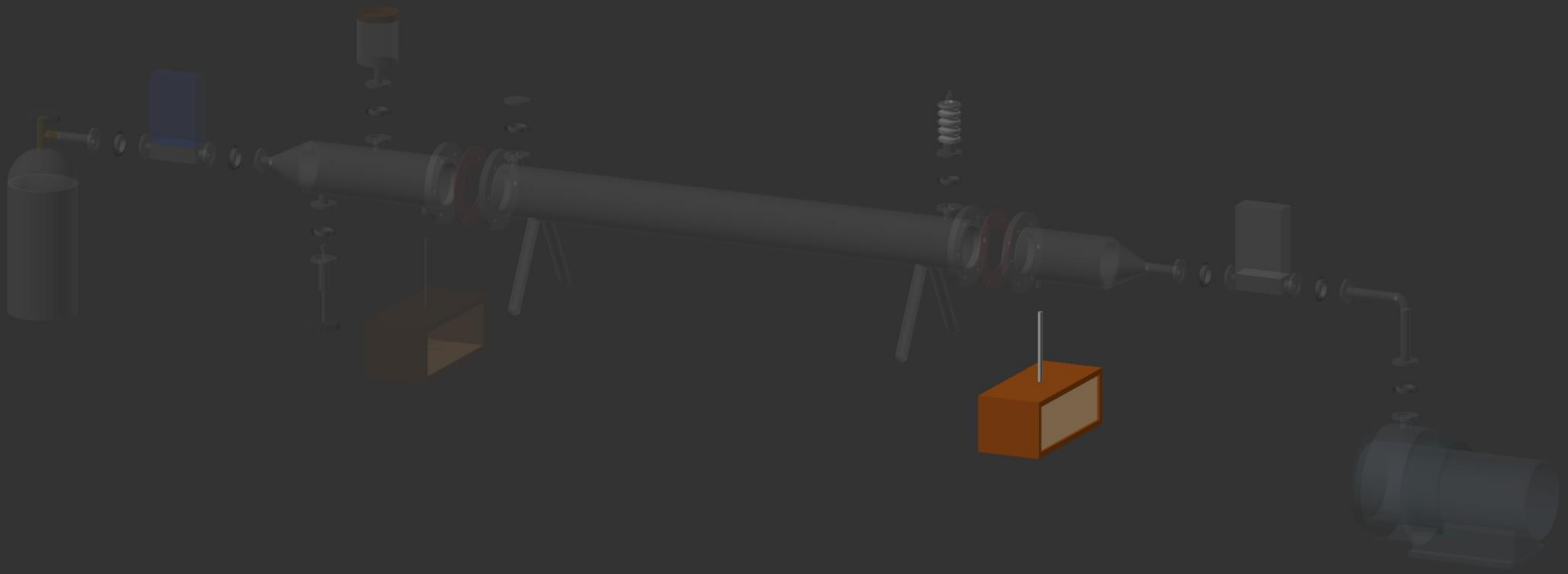
Electrostatic Precipitator Model

Downstream Segment



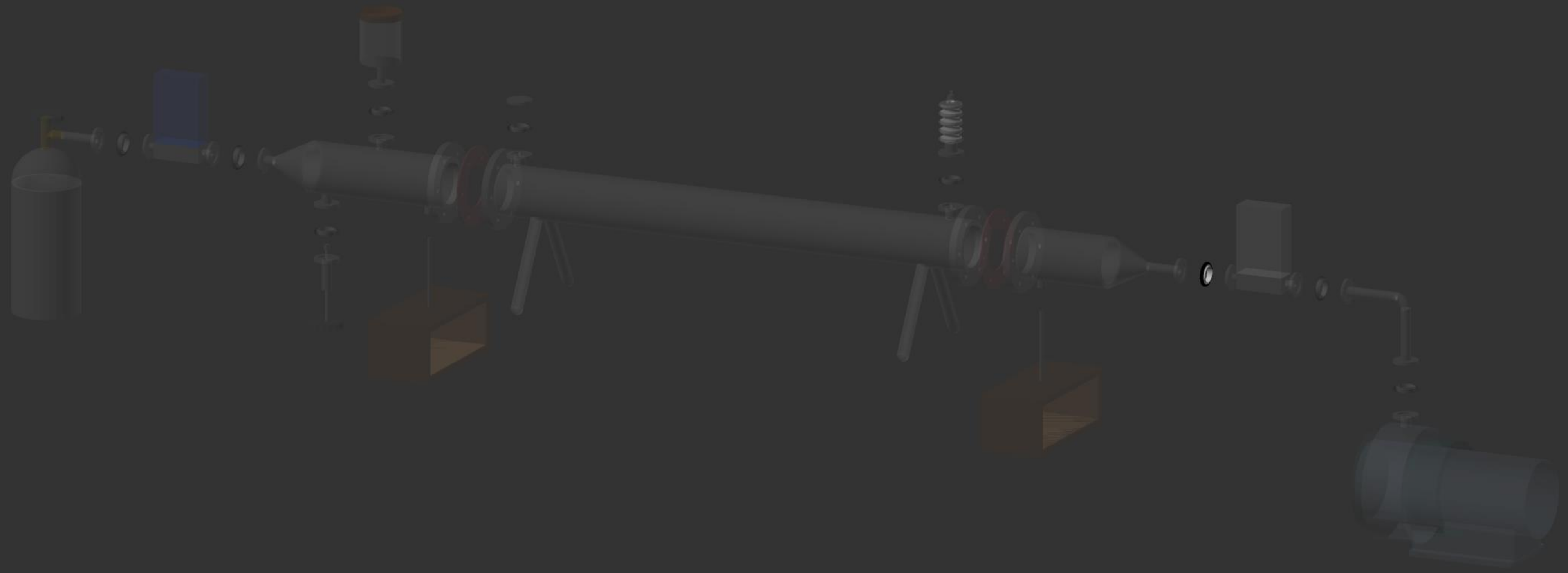
Electrostatic Precipitator Model

DOWNSTREAM PARTICLE COUNTER



Electrostatic Precipitator Model

KF25 O-Ring



Electrostatic Precipitator Model

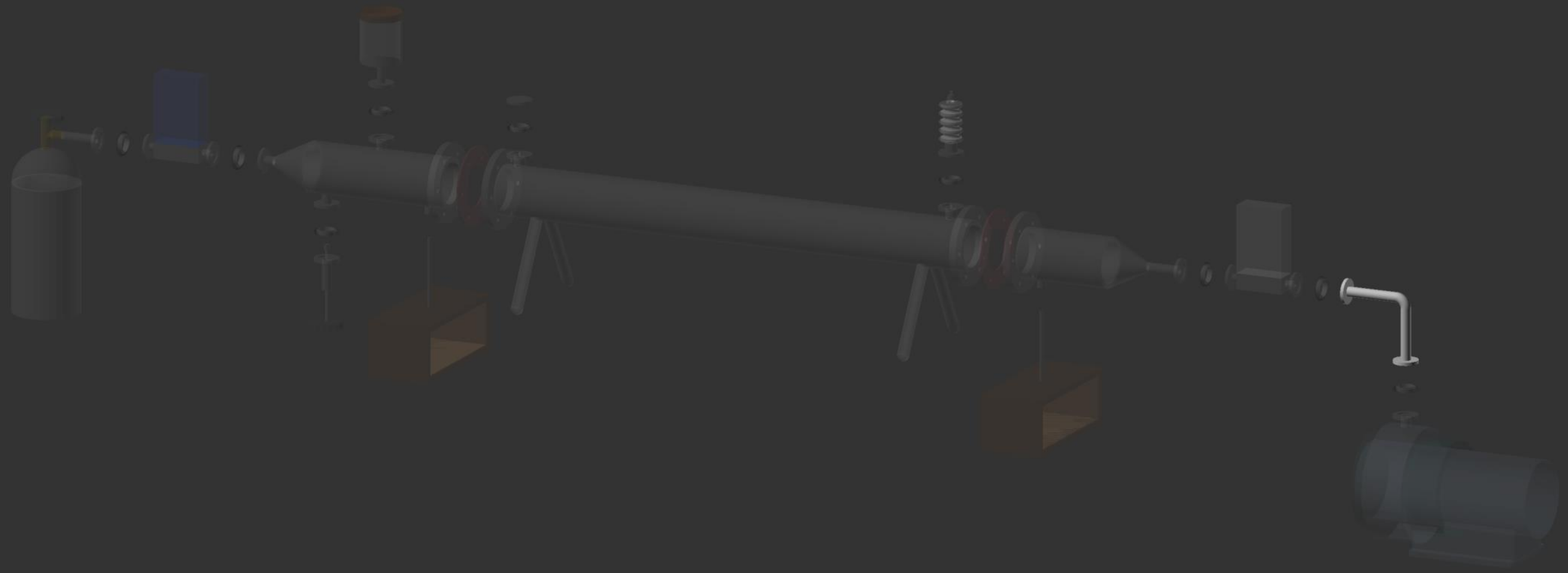
PRESSURE CONTROLLER

Electrostatic Precipitator Model

KF25 O-Ring

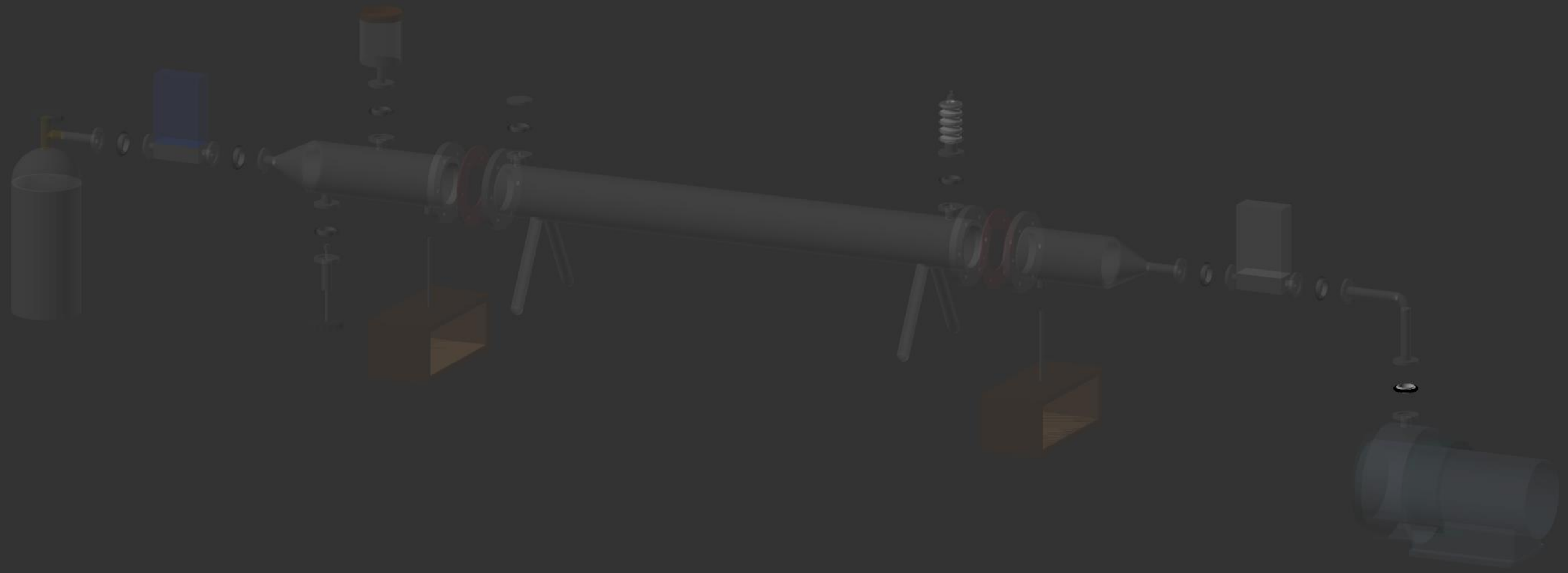
Electrostatic Precipitator Model

VACUUM HOSE



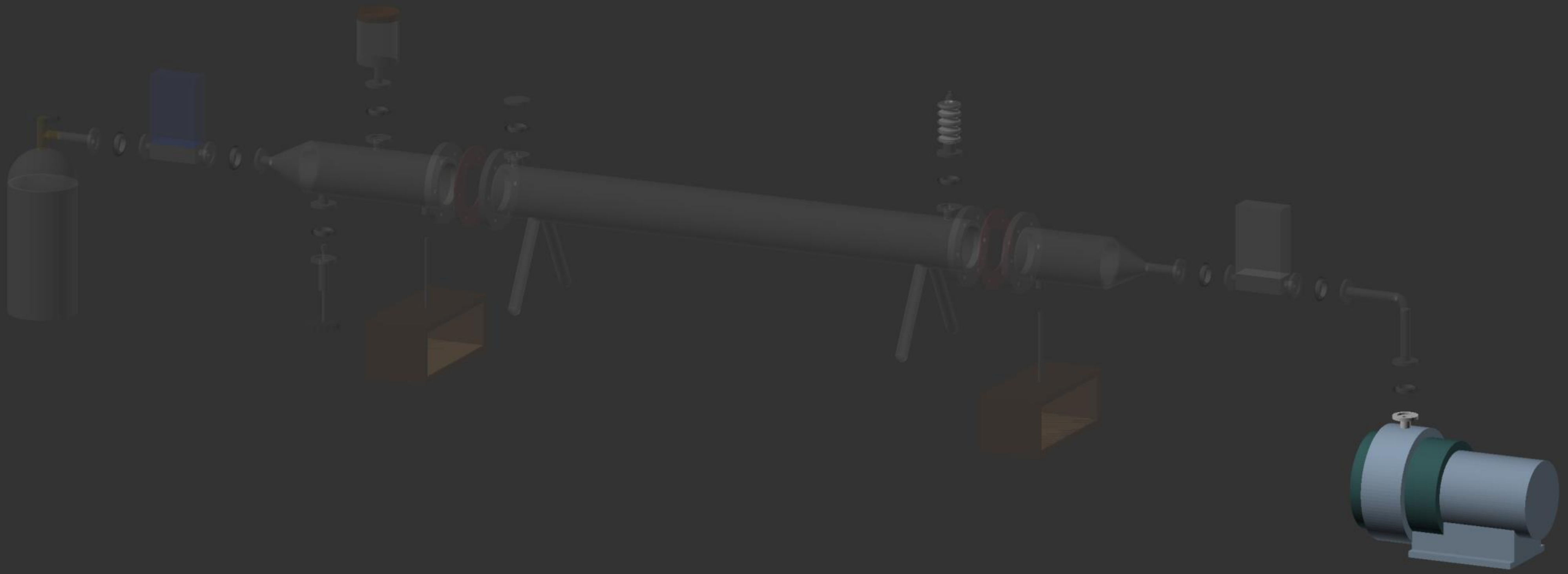
Electrostatic Precipitator Model

KF25 O-Ring



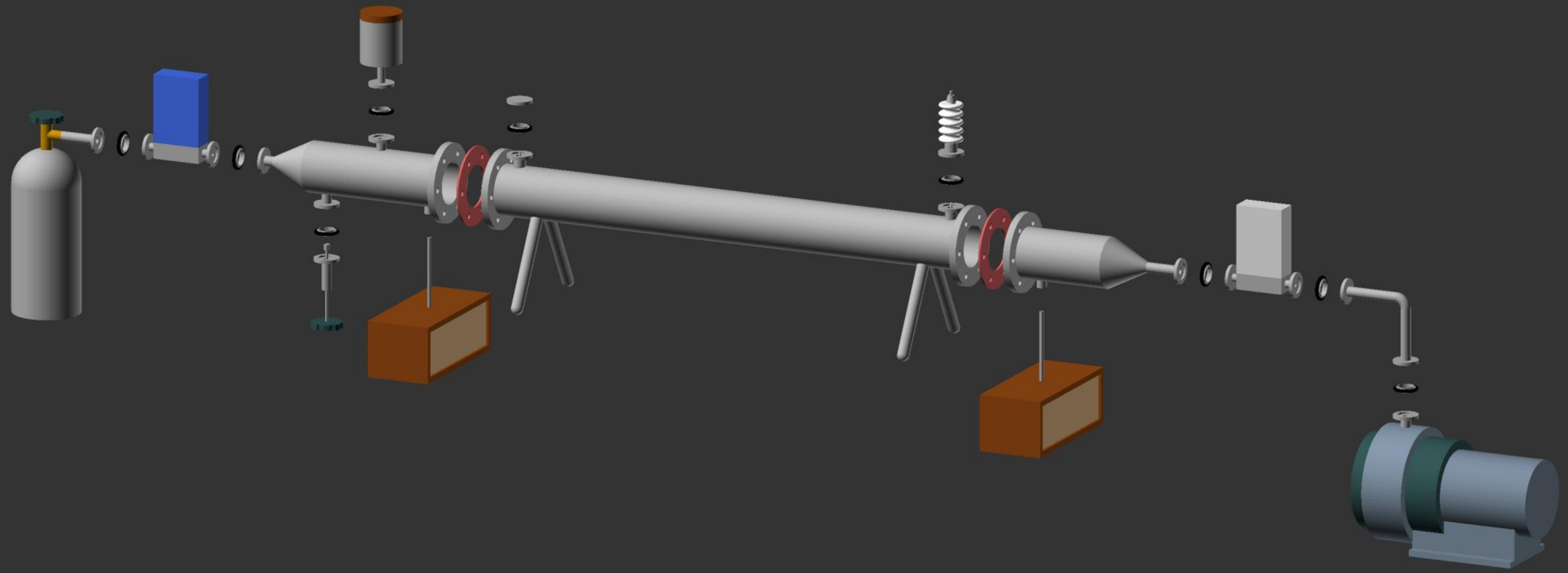
Electrostatic Precipitator Model

Vacuum Pump



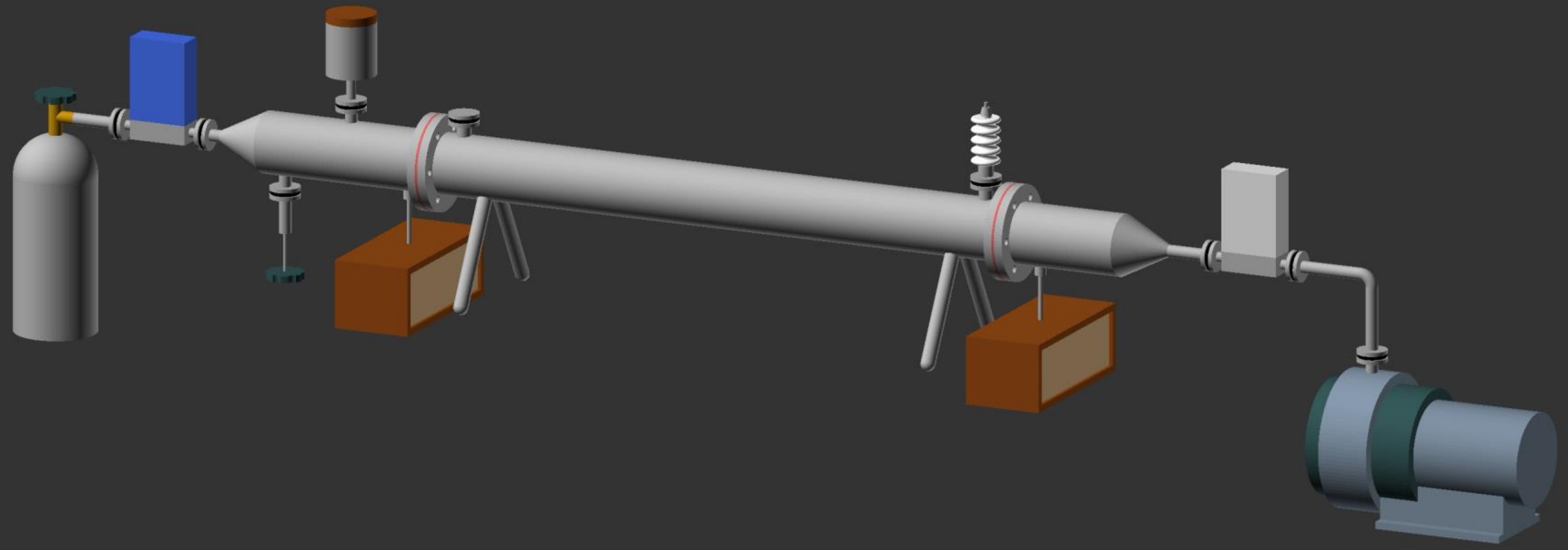
Electrostatic Precipitator Model

Exploded System

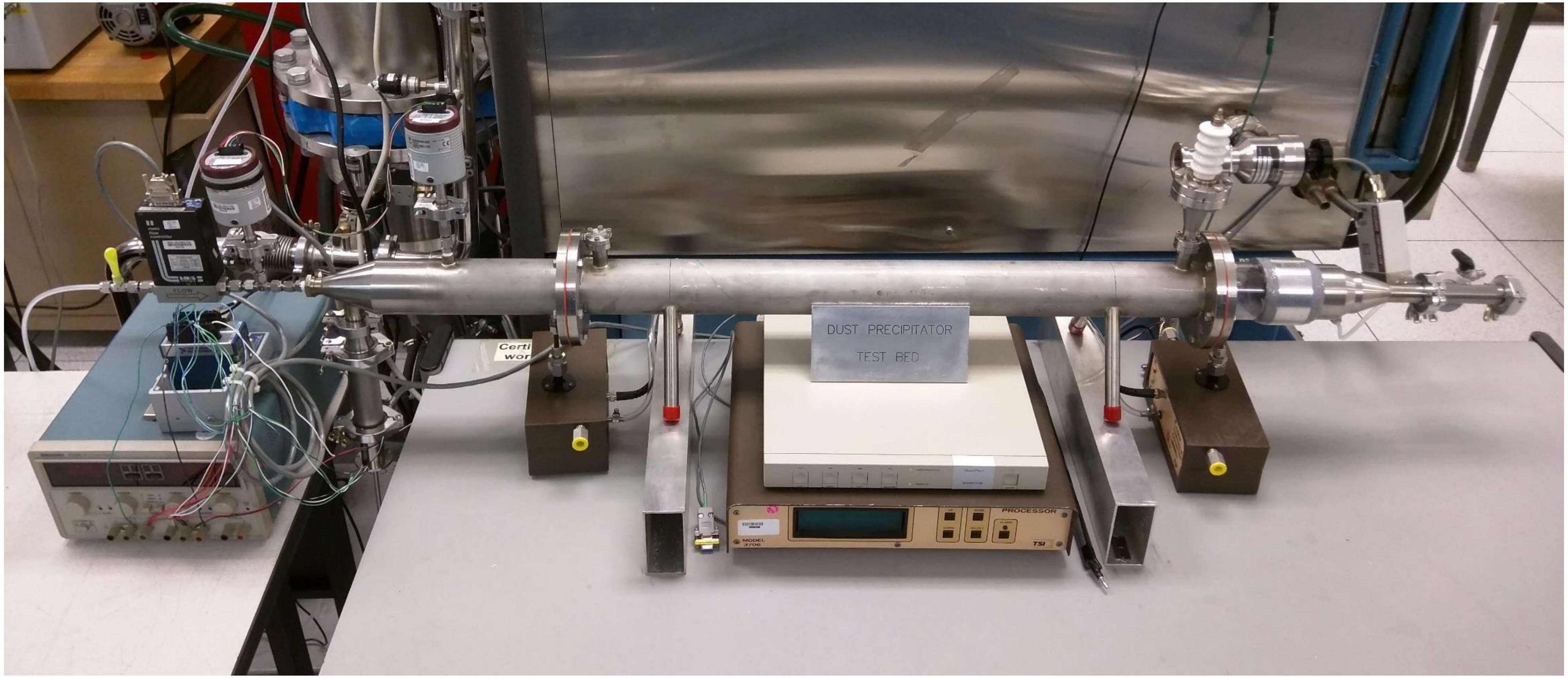


Electrostatic Precipitator Model

Assembled System



Electrostatic Precipitator Prototype



Electrostatic Precipitator Software

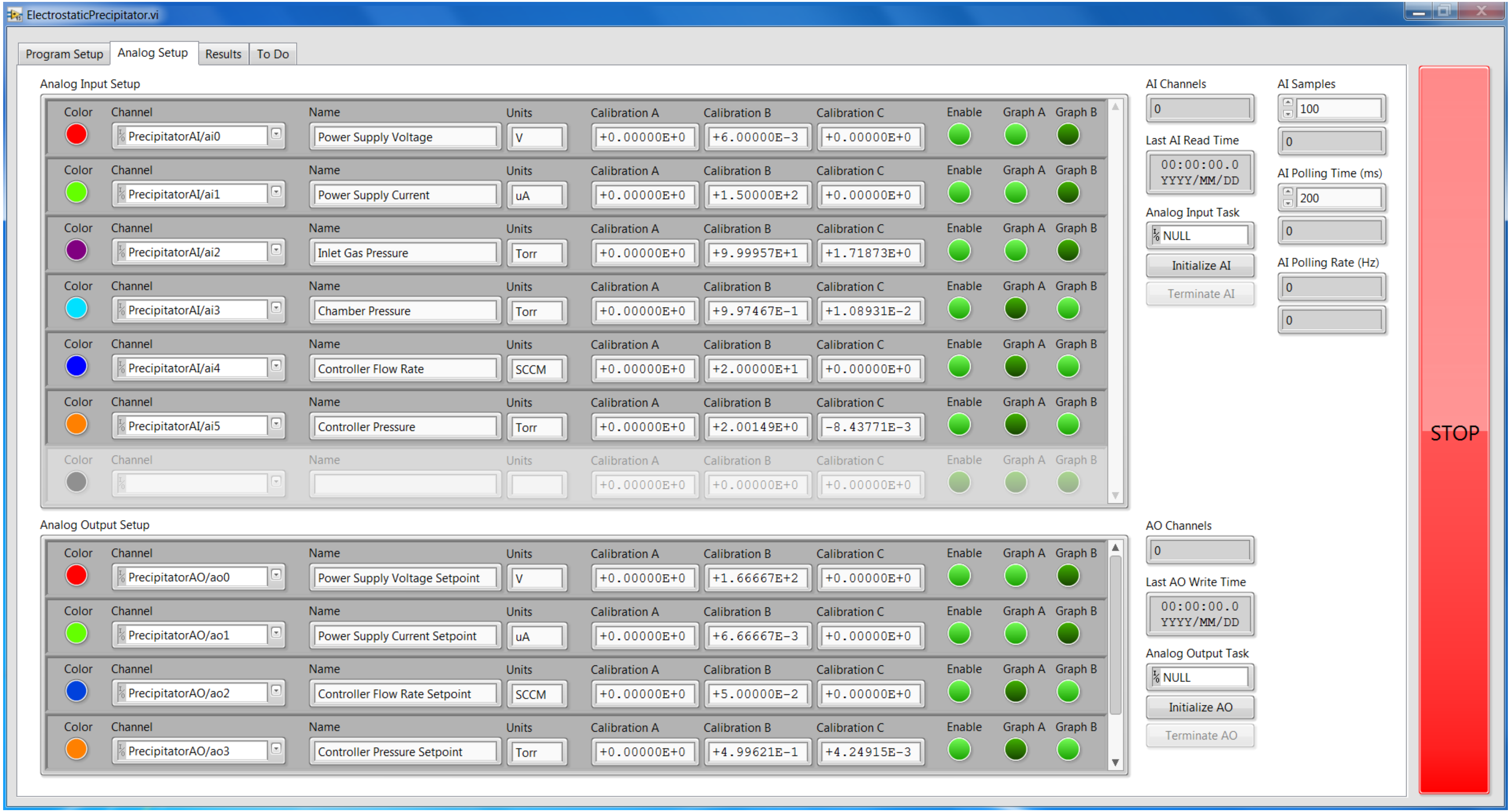
Developed robust LabVIEW program utilizing analog data acquisition cards.

Software generalized to allow for quickly adding and calibrating new analog inputs and outputs.

- Program is now used to automate all vacuum chambers in lab for Martian conditions.

Software features:

- Add/calibrate/remove analog inputs and outputs easily
- Interact with inputs and outputs in actual units rather than voltages
- Plot and record all inputs and outputs in real time
- Automatically sweep through the values of an output and monitor inputs
- Manually output individual values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Program Setup
Analog Setup
Results
To Do
Analog Input Setup
Color Channel Name Units Calibration A Calibration B Calibration C Enable Graph A Graph B
PrecipitatorAI/ai0 Power Supply Voltage V +0.00000E+0 +6.00000E-3 +0.00000E+0
PrecipitatorAI/ai1 Power Supply Current uA +0.00000E+0 +1.50000E+2 +0.00000E+0
PrecipitatorAI/ai2 Inlet Gas Pressure Torr +0.00000E+0 +9.99957E+1 +1.71873E+0
PrecipitatorAI/ai3 Chamber Pressure Torr +0.00000E+0 +9.97467E-1 +1.08931E-2
PrecipitatorAI/ai4 Controller Flow Rate SCCM +0.00000E+0 +2.00000E+1 +0.00000E+0
PrecipitatorAI/ai5 Controller Pressure Torr +0.00000E+0 +2.00149E+0 -8.43771E-3
+0.00000E+0 +0.00000E+0 +0.00000E+0
AI Channels
0
Last AI Read Time
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YYYY/MM/DD
Analog Input Task
NULL
Initialize AI
Terminate AI
AI Samples
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0
AI Polling Time (ms)
200
0
AI Polling Rate (Hz)
0
0
STOP
Analog Output Setup
Color Channel Name Units Calibration A Calibration B Calibration C Enable Graph A Graph B
PrecipitatorAO/ao0 Power Supply Voltage Setpoint V +0.00000E+0 +1.66667E+2 +0.00000E+0
PrecipitatorAO/ao1 Power Supply Current Setpoint uA +0.00000E+0 +6.66667E-3 +0.00000E+0
PrecipitatorAO/ao2 Controller Flow Rate Setpoint SCCM +0.00000E+0 +5.00000E-2 +0.00000E+0
PrecipitatorAO/ao3 Controller Pressure Setpoint Torr +0.00000E+0 +4.99621E-1 +4.24915E-3
AO Channels
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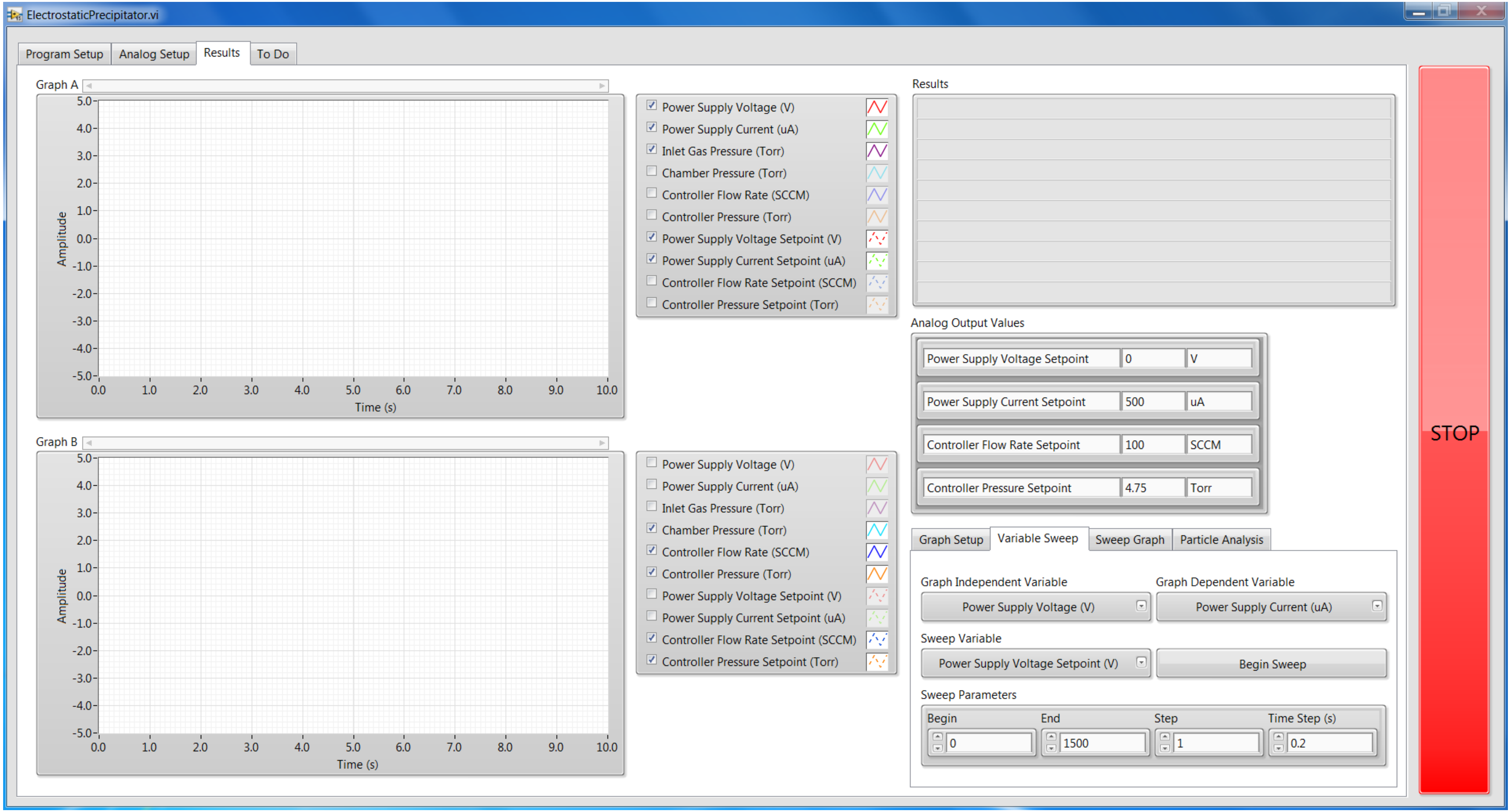
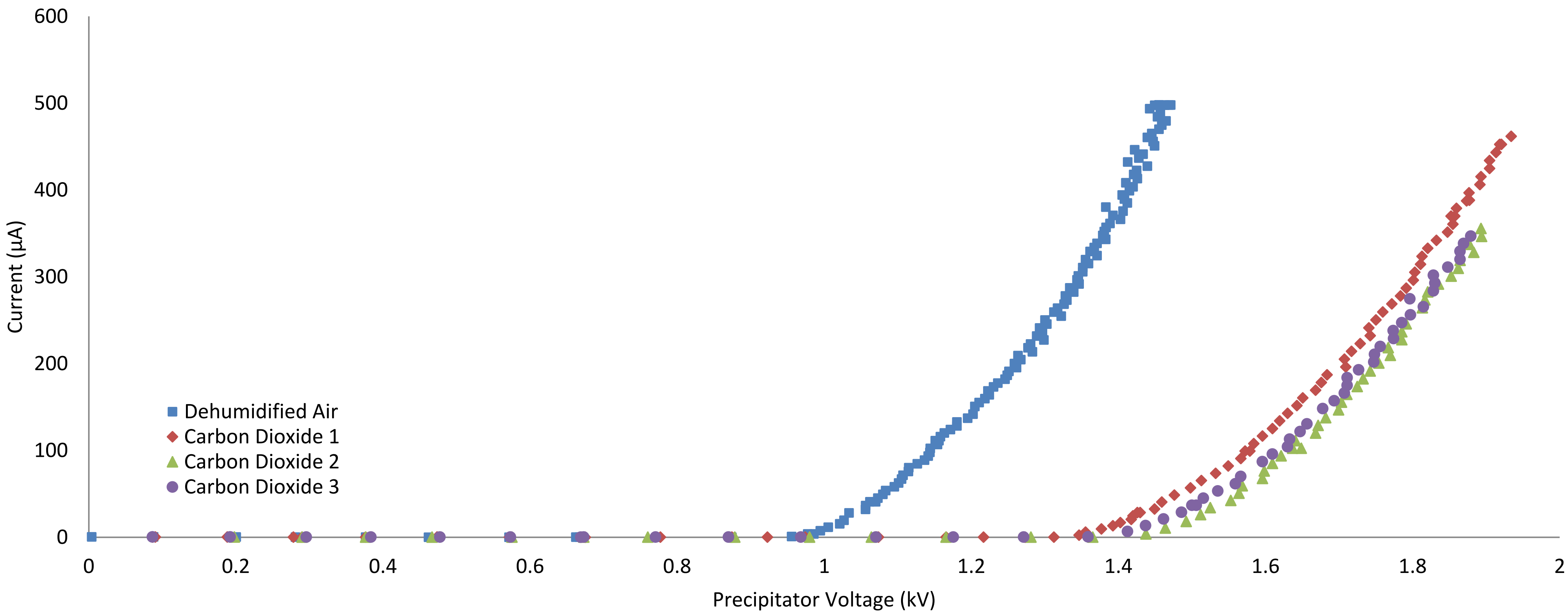
Initialize AO
Terminate AO


ElectrostaticPrecipitator.vi
Program Setup
Analog Setup
Results
To Do
Graph A
Amplitude
Time (s)
Power Supply Voltage (V)
Power Supply Current (uA)
Inlet Gas Pressure (Torr)
Chamber Pressure (Torr)
Controller Flow Rate (SCCM)
Controller Pressure (Torr)
Power Supply Voltage Setpoint (V)
Power Supply Current Setpoint (uA)
Controller Flow Rate Setpoint (SCCM)
Controller Pressure Setpoint (Torr)
Results
Analog Output Values
Power Supply Voltage Setpoint 0 V
Power Supply Current Setpoint 500 uA
Controller Flow Rate Setpoint 100 SCCM
Controller Pressure Setpoint 4.75 Torr
STOP
Graph B
Amplitude
Time (s)
Graph Setup
Variable Sweep
Sweep Graph
Particle Analysis
Graph Independent Variable
Power Supply Voltage (V)
Graph Dependent Variable
Power Supply Current (uA)
Sweep Variable
Power Supply Voltage Setpoint (V)
Begin Sweep
Sweep Parameters
Begin 0
End 1500
Step 1
Time Step (s) 0.2

Preliminary Results



9 mbar ≈ 6.75 Torr

Preliminary Results

	Upstream	Downstream	Efficiency
Disabled	282	784	N/A
Operating	467	1	99.83%

Low counts because terrestrial pressure particle counters were used.

Precipitator Difficulties

Keeping transducers safe from high voltage transients

- Large resistor on the order of GΩ used to limit current to safe levels

Developing control system that can maintain flow rate and pressure

- Currently works very well at 1% full scale use case
- Will require modifications to accommodate 20% full scale use case

Achieving characteristic quantity and size distribution of dust

- Investigating separate dust aerosolization chamber rather than dust cup

Particle counters in use are not calibrated for use at Martian pressures

- Will look into removing internal orifice to increase flow rate and number of counts

Conclusions

Martian atmosphere intake was calculated for two future missions:

- Mars 2020 will intake 110 L/min on Mars, but only 0.97 L/min when simulated in the lab
- Mars 2024 will intake 550 L/min on Mars, but only 4.85 L/min when simulated in the lab

Martian atmospheric dust intake was calculated for two future missions:

- Mars 2020 will intake 3.20 cm^3 or 4.86 g of Martian dust
- Mars 2024 will intake 160 cm^3 or 243 g of Martian dust

Electrostatic precipitator prototype operational voltages were measured:

- Dehumidified air undergoes stable corona between 950V and 1500V
- Carbon dioxide undergoes stable corona between 1350V and 1900V

Electrostatic precipitator prototype showed encouraging particle removal efficiencies.

Future Work

Model precipitator system in COMSOL to optimize parameters

Quantify collection efficiency as a function of:

- Voltage and corona current
- Electrode length and diameter
- Simulated atmospheric flow rate

More precisely control dust injection to match the particle size distribution on Mars

Determine a way to better interpret particle counts at pressures lower than terrestrial

After determining optimal geometry, build larger prototype capable of full scale flows

Choose a minimum efficiency and work to minimize mass and volume of final prototype

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