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Technologies for clean air & pure water

Numerical Engineering Evaluation of ESP Modernization Strategies

Dr. Henry V. Krigmont, Ph.D.
Allied Environmental Technologies, Inc.

James J. Ferrigan
Fuel Tech, Inc.



HOW DO YOU DETERMINE THE OPTIMUM ESP MODERNIZATION STRATEGY BEFORE SPENDING MILLIONS OF DOLLARS?

ENGINEERING DIAGNOSIS

INFORMED DECISIONS

REDUCED RISK

MAXIMUM VALUE

Why ESP Modernization Decisions Are Difficult

The same symptom — high particulate emissions — can result from very different limitations within the precipitation process.

ELECTRICAL

Inadequate power delivery or distribution limits charge and collection efficiency.

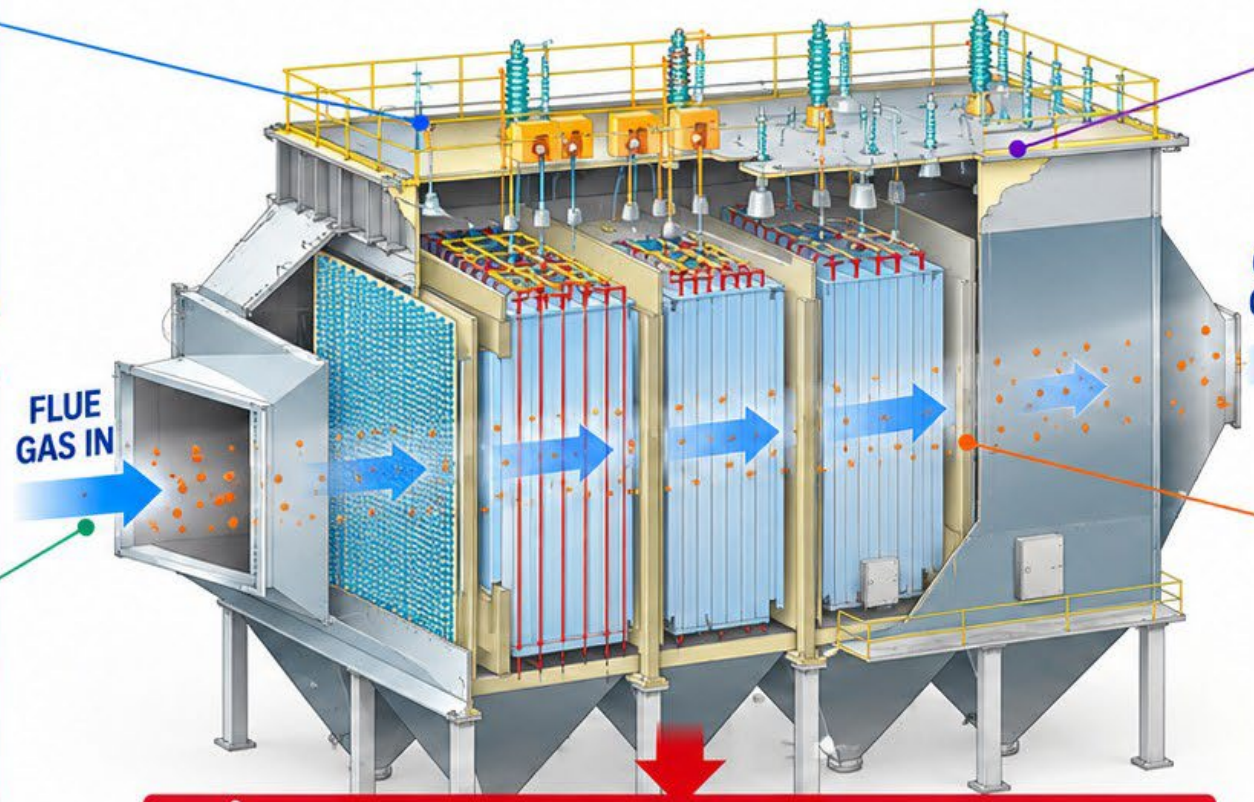
- Power supply
- Voltage / current
- Sparking / back corona

PROCESS / FLOW

Operating conditions affect gas properties and particle behavior.

- Temperature
- Gas distribution
- Loading
- Operating conditions

MULTIPLE LIMITATIONS CAN LEAD TO THE SAME OUTCOME



MECHANICAL

Mechanical condition and alignment affect collecting efficiency.

- Rappers / clearances
- Internal condition
- Plate alignment

PARTICULATE

Particle characteristics control how easily charge is acquired and dissipated.

- Resistivity
- PSD / size distribution
- Chemistry
- Cohesivity
- Re-entrainment

Modernization should begin with diagnosis of the controlling mechanism — **not with selection of a preferred technology.**

Identify the limiting factor → Target the root cause → Implement the right solution

From Symptoms to Root Cause

The existing ESP must first be reproduced numerically before modernization alternatives can be compared.

1 PLANT DATA

Geometry + process
PSD / resistivity + V–I

- Collect site measurements
- Characterize fly ash
- Capture ESP operating data

2 CALIBRATE

Reproduce measured emissions + field behavior

- Build baseline model
- Calibrate to plant data
- Validate model accuracy
- Establish confidence in baseline

3 DIAGNOSE

Identify the actual controlling limitation

- Resistivity limitation?
- Electrical limitation?
- Mechanical limitation?
- Process / flow limitation?

4 EVALUATE

Test competing modernization strategies

- SO_3 conditioning
- Dual FGC (SO_3 + NH_3)
- HFPS energization
- Other configuration options

5 DECIDE

Compare performance, cost, outage, reliability, risk

- Emission reduction
- Capital & O&M cost
- Outage / implementation
- Reliability & risk

ROOT-CAUSE ENGINEERING

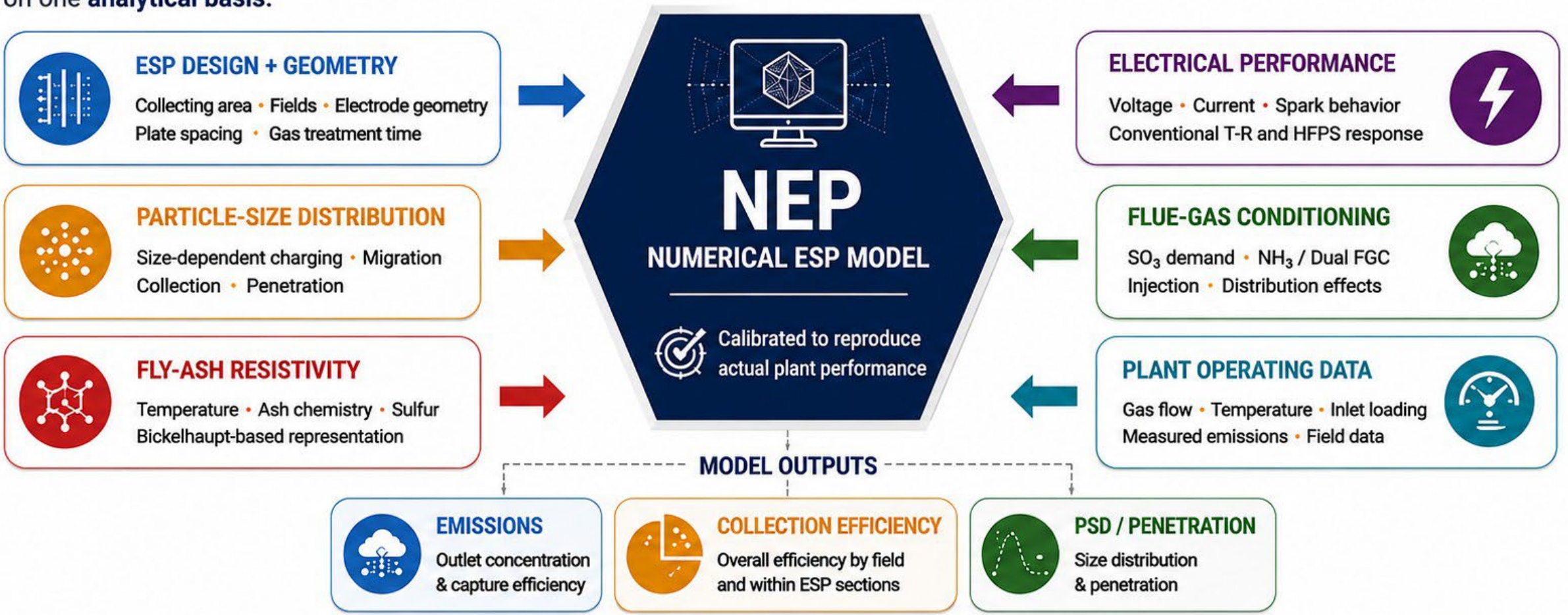
Treat the limitation — not merely the symptom.

Calibration converts a generic ESP calculation into a plant-specific engineering decision tool.

The calibrated baseline becomes the reference for every proposed modification.

What Is the NEP Model?

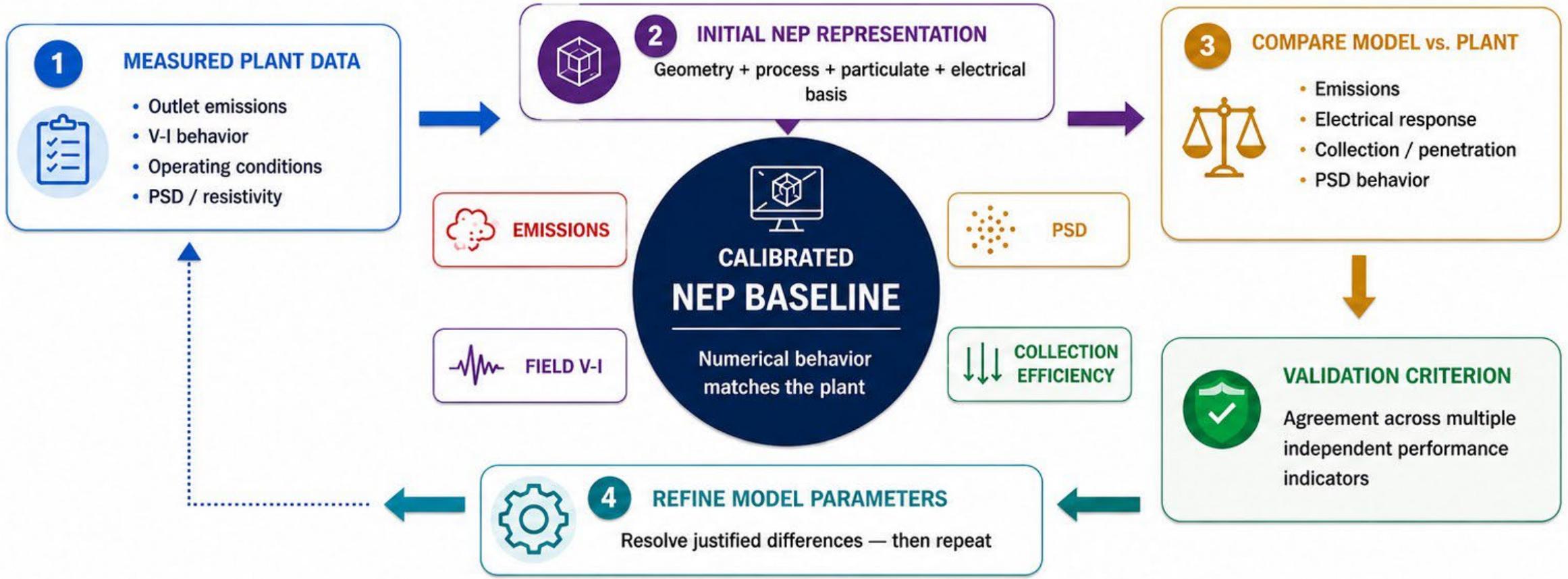
A calibrated numerical representation of the **operating ESP** that integrates particle, electrical, process and equipment behavior on one **analytical basis.**



Once calibrated, the same model becomes a controlled what-if environment for evaluating modernization alternatives before physical changes are made.

Calibration & Validation — Establishing the Baseline

The NEP model is refined until it reproduces the measured behavior of the existing ESP — creating a defensible reference for every subsequent what-if case.

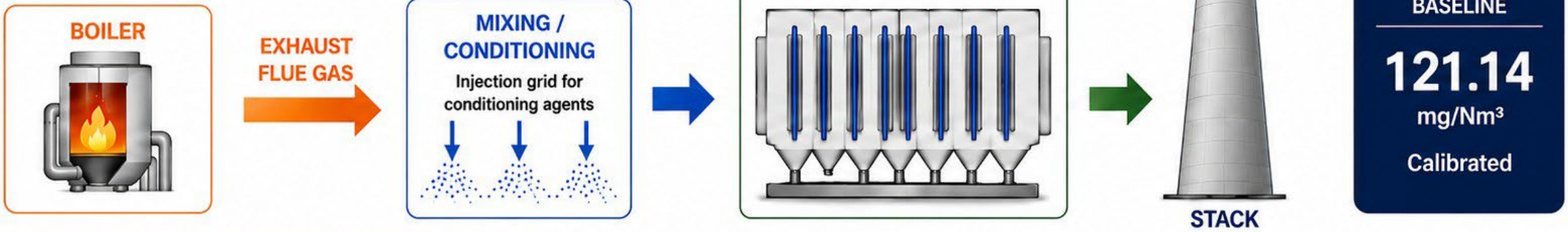


Matching a single outlet-emissions value is not enough.
Confidence increases when the model also reduces electrical and particle-size-dependent behavior.

Representative Industrial Case Study

One calibrated ESP baseline was used to evaluate progressively more comprehensive modernization strategies under the same operating basis.

REPRESENTATIVE FLUE-GAS PATH



CALIBRATED BASELINE

121.14 mg/Nm³

Calibrated

CONTROLLED WHAT-IF MODERNIZATION CASES

Same Operating Basis • Same Load • Same Fuel • Same ESP Design

A — BASELINE
Existing ESP
Conventional T-R

121.14 mg/Nm³

REFERENCE

B — + SO_3 FGC
Resistivity Control

53.84 mg/Nm³
56% below baseline

RESISTIVITY CONTROL

C — + DUAL FGC
SO_3 + NH_3 conditioning

33.65 mg/Nm³
72% below baseline

RESISITIVITY + SURFACE EFFECTS

D — + HFPS
Dual FGC + advanced electrical energization

8.75 mg/Nm³
93% below baseline

MAXIMUM PERFORMANCE

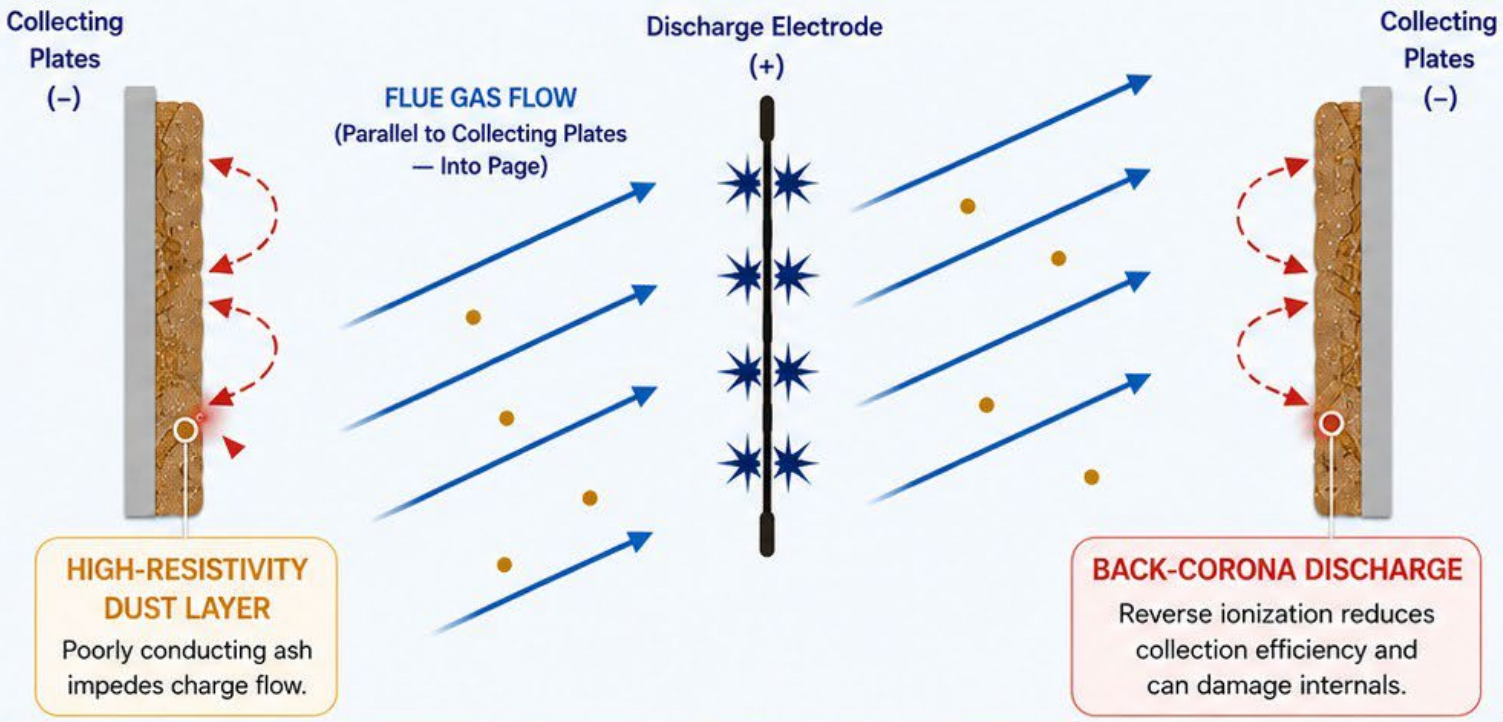
Each case changes selected variables while preserving the calibrated operating basis — **allowing the incremental benefit of each measure to be isolated.**

Quantified Improvements | Isolated Benefits | Reduced Risk Decision-Making

The Controlling Limitation – High Fly-Ash Resistivity

In the calibrated baseline, very high particulate resistivity restricts useful ESP energization.
The resulting dust-layer voltage can initiate back corona and limit the benefit of simply applying more electrical power.

SIMPLIFIED ESP COLLECTION PASSAGE (ONE FIELD)



RESULT: High resistivity causes high dust-layer voltage and back corona, ***limiting useful energization and collection performance.***

WHY PERFORMANCE IS LIMITED

1. **VERY HIGH RESISTIVITY**
   Charge does not dissipate readily through the deposited ash layer.
2. **DUST-LAYER VOLTAGE RISES**
   The electrical field develops across the resistive deposit.
3. **BACK CORONA DEVELOPS**
   Reverse ionization interferes with normal particle charging/current.
4. **USEFUL ENERGIZATION LIMITED**
   Additional applied voltage does not translate directly into collection.

ENGINEERING IMPLICATION:
Electrical modernization alone cannot remove an intrinsic fly-ash resistivity limitation.

Resistivity control is a prerequisite for realizing any electrical upgrade benefit.

Case B — SO_3 Flue-Gas Conditioning

SO_3 conditioning addresses the controlling particulate-resistivity limitation by promoting formation of a conductive sulfuric-acid layer on the fly-ash surface.

FROM SO_3 INJECTION TO IMPROVED ESP PERFORMANCE

1 — SO_3 INJECTION



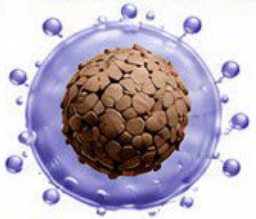
SO_3 introduced into the flue-gas stream.

2 — H_2SO_4 FORMATION



SO_3 combines with available water vapor to form sulfuric acid (H_2SO_4).

3 — SURFACE CONDENSATION



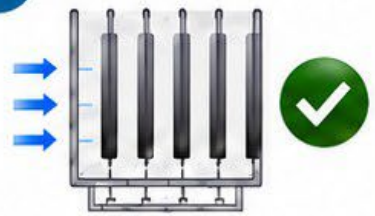
H_2SO_4 condenses on fly-ash particle surfaces, creating a liquid film.

4 — LOWER RESISTIVITY



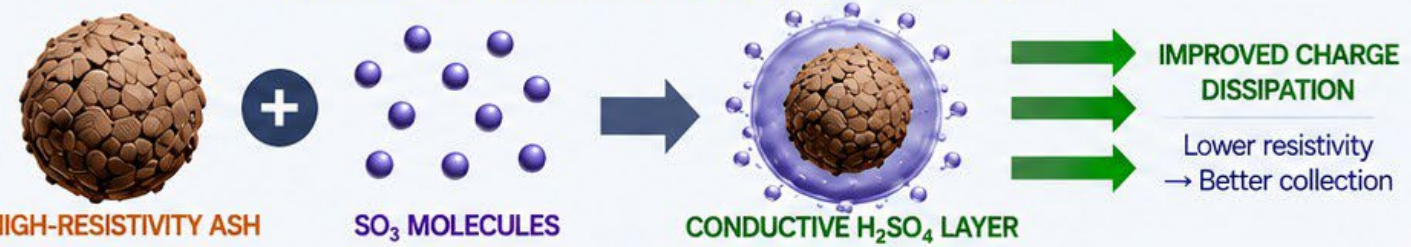
The conductive molecular layer improves charge dissipation and lowers resistivity.

5 — BETTER ESP USE



Reduced back-corona tendency allows stronger, more stable and useful energization.

PARTICLE-SURFACE CONDITIONING MECHANISM



CASE B — CALCULATED RESULT

53.84 mg/Nm³

56% BELOW CALIBRATED BASELINE



Note: Bar lengths are proportional to the values.

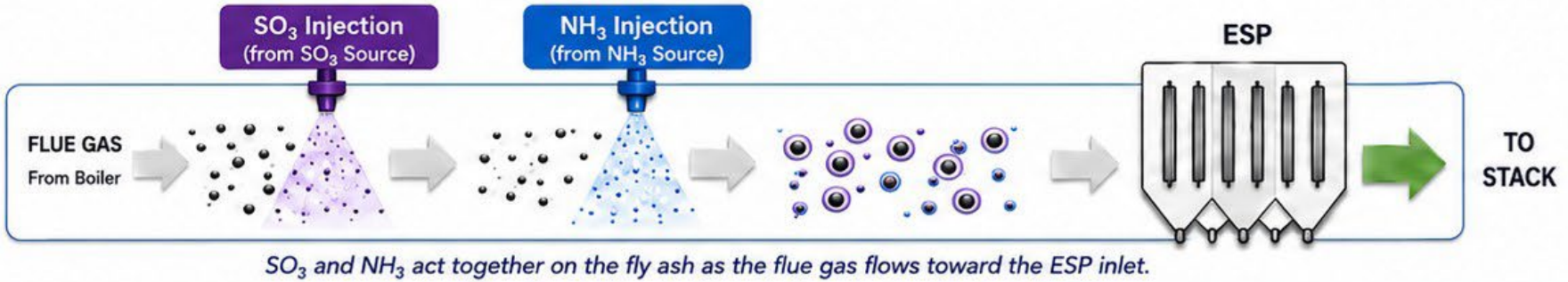
Key Point: SO_3 FGC improves ESP performance by changing the particulate condition — not by increasing the installed collecting area or electrical equipment.

ENGINEERING IMPLICATION: SO_3 flue-gas conditioning addresses the **underlying resistivity limitation,** enabling improved ESP collection performance without increasing the installed collecting area or electrical capacity.

Case C — Dual Flue-Gas Conditioning

Dual FGC combines SO_3 and NH_3 conditioning to address both fly-ash resistivity and particle-surface behavior, extending the benefit beyond SO_3 conditioning alone.

DUAL CONDITIONING — TWO REAGENTS, ONE CONTROLLED ENVIRONMENT



SO_3 and NH_3 act together on the fly ash as the flue gas flows toward the ESP inlet.

1 SO_3 EFFECT — RESISTIVITY IMPROVEMENT



High Resistivity (Ω·cm)

Acid Layer Formation (Lower Resistivity)

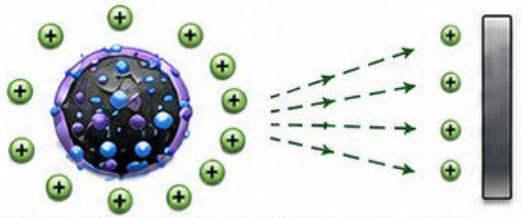
SO_3 forms H_2SO_4, which condenses on the fly-ash surface, creating a conductive liquid layer and lowering resistivity.

2 NH_3 EFFECT — SURFACE MODIFICATION



NH_3 reacts with the acid layer to form ammonium sulfates, attaching to the acid layer on the surface and also combining in-flight with H_2SO_4 vapor and fine acids, forming ammonium sulfates in-fiight.

3 COMBINED EFFECT — ENHANCED COLLECTION



Lower resistivity + improved surface properties produce stronger electrical response and significantly better fine-particle capture.

EMISSIONS PROGRESSION

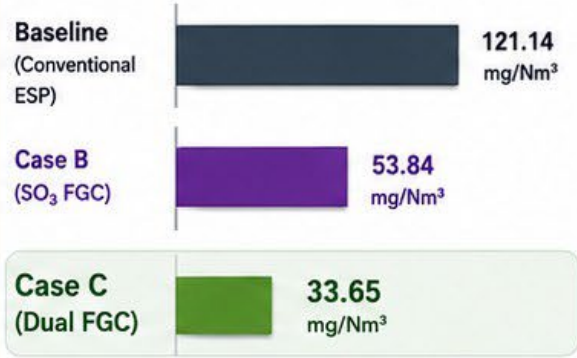
Baseline (Conventional ESP)	Case B (SO_3 FGC)	Case C (Dual FGC)
121.14 mg/Nm³	53.84 mg/Nm³	33.65 mg/Nm³

CASE C — CALCULATED RESULT

33.65 mg/Nm³

72% BELOW CALIBRATED BASELINE

PROGRESSIVE IMPROVEMENT



IMPROVEMENT vs. BASELINE ↓ **72%**

Note: Bar lengths are proportional to the values.

Dual FGC delivers **additional benefit** beyond SO_3 conditioning alone by combining **resistivity reduction** with **improved particle-surface behavior**, resulting in **superior fine-particle collection**.

Cleaner Emissions · Higher Reliability · Lower Risk

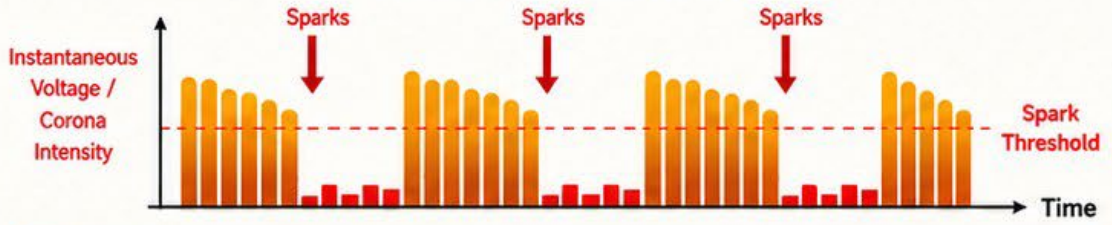
Advanced Electrical Energization — Why HFPS Matters

Once the resistivity limitation is controlled, the ESP can better use advanced power delivery to maintain effective particle charging.

Same ESP hardware — different power-delivery behavior under operating electrical conditions

CONVENTIONAL T–R ENERGIZATION

Intermittent power with slow recovery



Spark → voltage collapse → **slower recovery** → **lower average useful energization**

Slower Response
Longer time to re-establish stable corona.

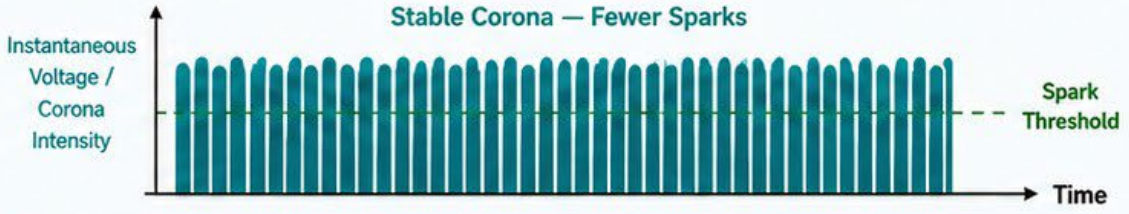
Greater Spark Recovery Loss
More frequent interruptions reduce average power.

More Time Below Optimum
Less time at effective energization levels.

VS

HIGH–FREQUENCY POWER SUPPLY (HFPS)

Continuous, stable power with fast control



Fast control maintains stable voltage → **higher average useful energization**

Faster Voltage Control
Rapid adjustment maintains stability.

Reduced Spark / Re-strike Severity
Fewer interruptions improve reliability.

Greater Useful Charging Energy
More consistent power improves collection.

HFPS improves how electrical power is delivered — ***it does not change*** the intrinsic resistivity of the fly ash.

Therefore, **Case D** evaluates HFPS **after Dual FGC** has addressed the dominant particulate limitation.

ROLE IN MODERNIZATION
HFPS maximizes the benefit of chemical conditioning by delivering cleaner, more stable electrical power.

ENGINEERING IMPLICATION:
Electrical modernization alone cannot remove an intrinsic fly-ash resistivity limitation.

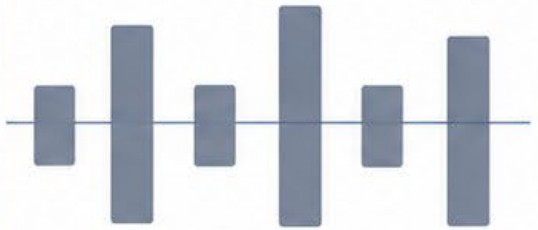
Resistivity control is a prerequisite for realizing any electrical upgrade benefit.

Case D — Dual FGC + High-Frequency Power Supply

Once particulate resistivity is controlled by Dual FGC; advanced high-frequency energization can be used more effectively to increase useful ESP power input.

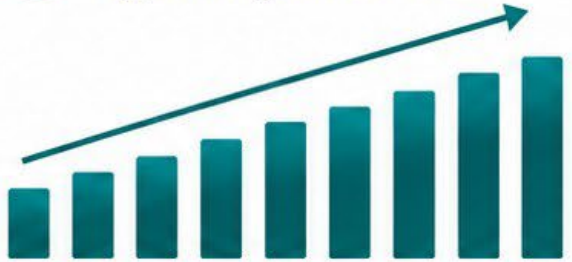
WHY THE COMBINATION WORKS

1 CONVENTIONAL T-R
Baseline electrical behavior:



Lower average useful voltage/current under severe resistivity limitation

2 HIGH-FREQUENCY POWER SUPPLY
Applied along with Dual FGC:



Higher, more stable useful energization with improved electrical control

3 COMPARISON MODEL vs. PLANT:

- Emissions
- Electrical response
- Collection / penetration behavior
- PSD behavior

VALIDATION CRITERION

Agreement across multiple independent performance indicators

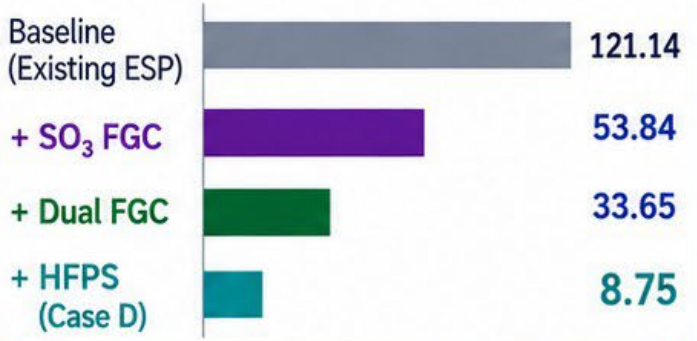
DUAL FGC: Controls resistivity (conditions particles) + **HFPS** Delivers advanced electrical energization = **PARTICULATE CONTROL + ELECTRICAL OPTIMIZATION** Maximizes useful ESP power

CASE D — CALCULATED RESULT

8.75 mg/Nm³

93% below calibrated baseline

INCREMENTAL PERFORMANCE (mg/Nm³)



HFPS improves energization — it does not change intrinsic ash resistivity.

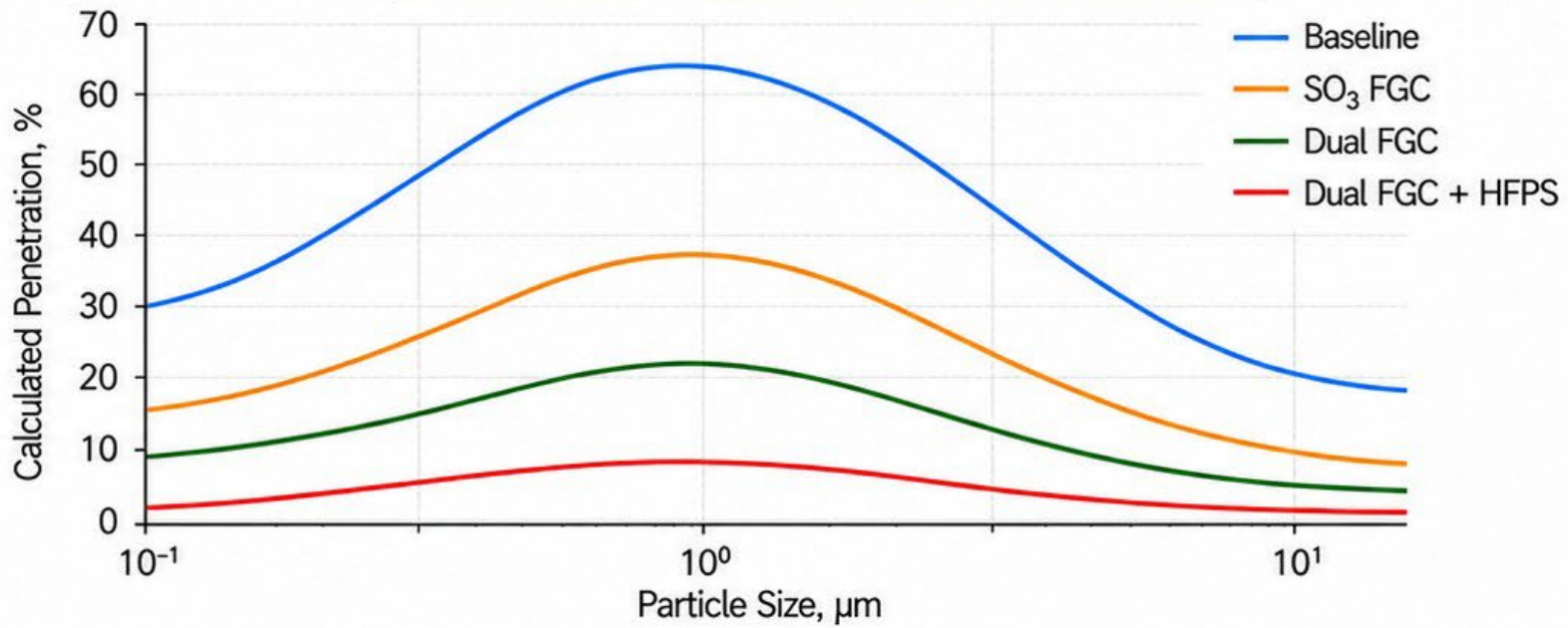
The strongest modeled result occurs when the particulate limitation is **corrected first** and **advanced electrical energization** is then applied to the conditioned ESP.

KEY TAKEAWAY: Dual FGC establishes favorable resistivity conditions, and HFPS enables higher and more stable useful energization, resulting in substantially lower particulate emissions.

Particle-Size-Dependent Performance

Overall outlet concentration does not show which particle-size ranges are responsible for the remaining emissions.
The NEP evaluation therefore examines penetration across the full particle-size spectrum.

CALCULATED PENETRATION vs. PARTICLE SIZE



Penetration typically peaks in the fine-particle range (~0.3–2 µm), driving the majority of residual emissions.

ENGINEERING INTERPRETATION

Baseline
Highest penetration across the critical size range.

SO_3 FGC
Large reduction after resistivity control.

Dual FGC
Additional improvement, particularly in the fine-particle range.

Dual FGC + HFPS
Lowest calculated penetration after particulate and electrical limitations are addressed together.

The combination delivers the lowest penetration across the **entire particle-size spectrum.**

Particle-size-dependent analysis demonstrates why ESP modernization alternatives with similar overall collection efficiencies can produce substantially different residual emissions.

ENGINEERING IMPLICATION: Proper characterization of particle-size-dependent penetration is essential for selecting and optimizing ESP modernization strategies, as fine-particle control is the primary determinant of overall emission performance.

From Performance Prediction to Modernization Decision

The lowest calculated emissions do not automatically define the best project. The technical result must be considered together with cost, outage, reliability and implementation risk.

1 — TECHNICAL PERFORMANCE
Calculated emissions and PSD response

2 — OPERATING MARGIN
Margin below the required limit

3 — CAPITAL + RECURRING COST
Equipment, FGC, power and O&M

4 — OUTAGE + IMPLEMENTATION
Installation scope and outage duration

5 — RELIABILITY + TECHNICAL RISK
Complexity, maturity and long-term operation

The Same Calibrated Model Can Support Different Project Objectives

MINIMUM COMPLIANCE
Meet the required limit with adequate margin
Lowest justified scope

BALANCED MODERNIZATION
Performance + reliability with practical operating margin
Often the economic optimum

MAXIMUM PERFORMANCE
Lowest technically achievable emissions for the evaluated basis
Highest performance margin

→ **SELECT BEST VALUE**

The objective is not simply to maximize collection efficiency — it is to select the level of modernization justified by the project's **technical, economic** and **operational value**.

ENGINEERING IMPLICATION: The NEP model provides a quantitative basis to compare modernization options on a consistent basis, supporting a balanced decision that meets performance, operational and economic objectives.

What the Evaluation Provides

The principal value of **Advanced** Numerical Engineering Evaluation is not a single **calculated** emissions number.
It is a defensible engineering basis for deciding what **should—and should not—be** changed.

1 DIAGNOSE

Identify the mechanism actually controlling ESP performance.

2 QUANTIFY

Estimate the incremental benefit of individual and combined modernization measures.

3 COMPARE

Evaluate competing alternatives on the same calibrated operating basis.

4 SELECT

Choose the modernization level justified by performance, cost and risk.

A Cause-and-Effect Framework for ESP Modernization

Existing ESP → **Calibrated Baseline** → **Controlling Limitation** → **What-If Alternatives** → **Defensible Decision**

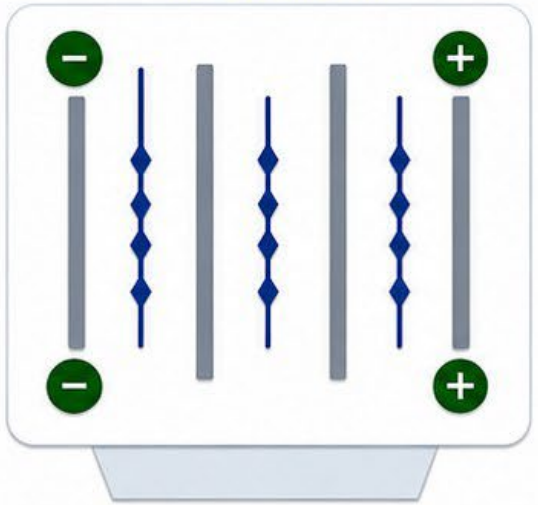
Modernization decisions can therefore be based on **demonstrated engineering need** rather than technology preference.

ENGINEERING IMPLICATION: The NEP evaluation provides a transparent and quantitative basis for prioritizing modernization options, reducing uncertainty and supporting technically and economically sound decision making.

Future Development — Toward an AI-Enabled ESP Digital Twin

The envisioned next step extends the calibrated NEP model from a project-specific engineering tool toward a dynamic representation of the operating ESP.

PHYSICAL ESP



Voltage • Current • Sparks • Temperature
Gas Flow • Emissions • FGC • Rapping

REAL-TIME + HISTORICAL DATA

ESP DIGITAL TWIN

Continuously Evolving Engineering Representation

- **PHYSICS-BASED NEP MODEL** — Calibrated, high-fidelity physics and electrical response
- **PLANT OPERATING DATA** — Real-time and historical operating conditions and measurements
- **AI-ASSISTED ANALYSIS** — Pattern recognition, anomaly detection, and root-cause insights
- **CONTINUOUS LEARNING** — Model updates and validation with measured performance

PREDICTIVE DECISION SUPPORT

- **TREND RECOGNITION** — Identify developing performance limitations before emissions impact increases
- **WHAT-IF EVALUATION** — Predict response to process and electrical changes
- **CORRECTIVE ACTIONS** — Evaluate alternatives before implementation
- **OPERATING OPTIMIZATION** — Improve energization, FGC, rapping and other controls

CLOSED-LOOP DEVELOPMENT PATH

MONITOR — Collect and validate operating data → **PREDICT** — Forecast performance and responses → **EVALUATE** — Compare alternatives and risks → **OPTIMIZE** — Implement and refine for continuous improvement

Objective: progress from periodic performance evaluation toward predictive, continuously informed ESP optimization.

ENGINEERING IMPLICATION:
The calibrated NEP Model provides the physics-based foundation for evolving from periodic engineering studies toward continuous, data-informed ESP optimization.

MODEL + PLANT DATA + AI
From engineering evaluation to an evolving ESP Digital Twin.

The most effective ESP modernization begins by identifying the limitation — not by selecting the technology.

1

DIAGNOSE

Establish a calibrated representation of the existing ESP

2

EVALUATE

Quantify modernization alternatives before implementation

3

OPTIMIZE

Select the combination that provides performance, margin, reliability and value

A calibrated numerical model transforms ESP modernization from an equipment-selection exercise into a defensible engineering decision.

Thank You

Questions & Discussion

Dr. Henry V. Krigmont, Ph.D.

Allied Environmental Technologies, Inc.