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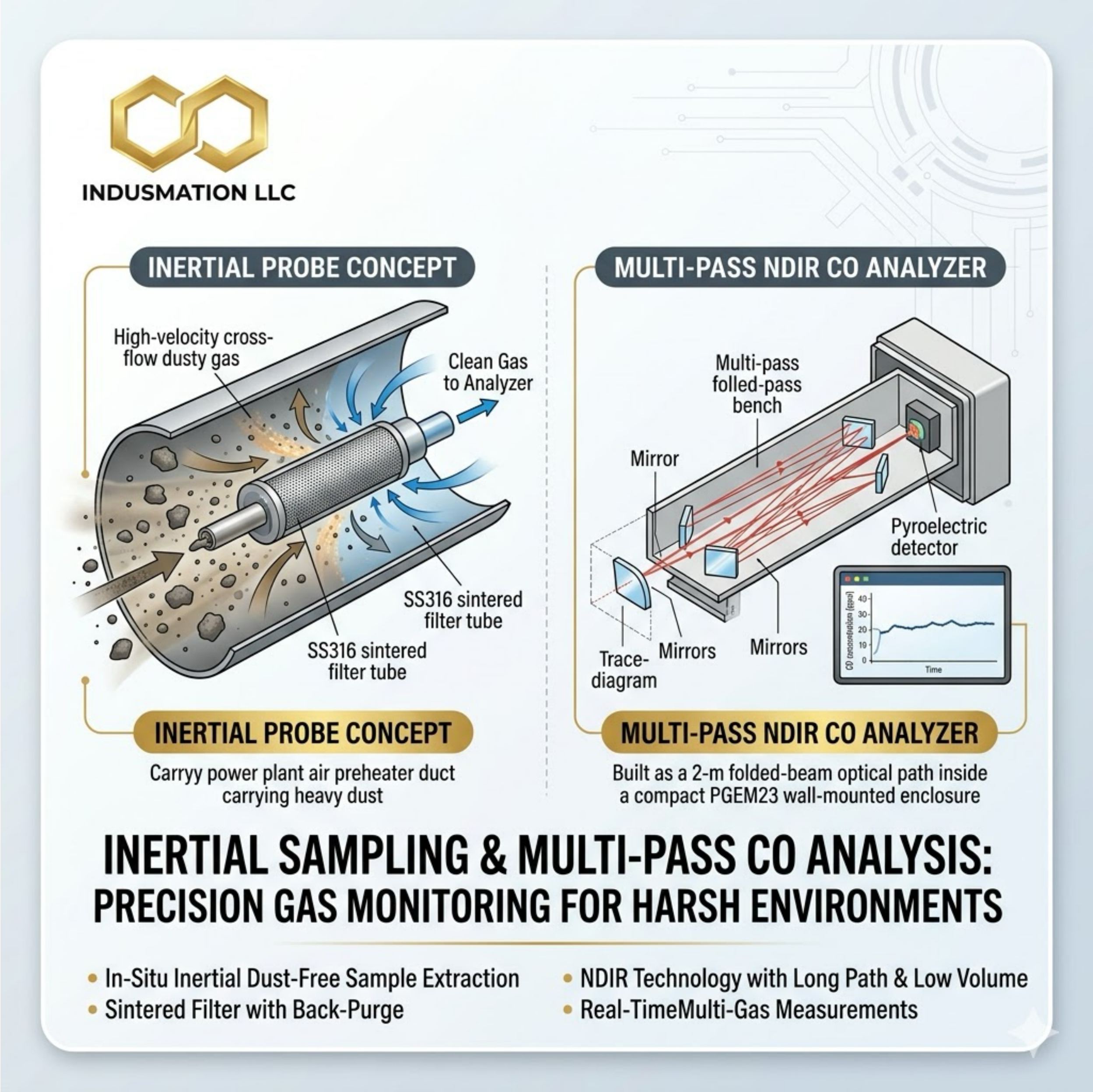

Inertial Probe-Based CO Analysis for Ultra-Severe, High-Dust Combustion Environments

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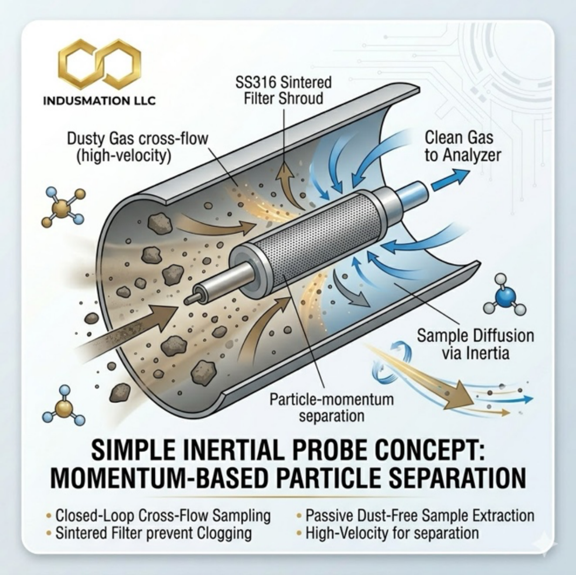
1. Executive Summary

Industrial flue gas ducts carrying massive particulate loads present severe operational challenges for continuous emissions monitoring systems (CEMS). In coal-fired utility plants, the inlet to the air preheater (APH) is the ideal process location for Carbon Monoxide (CO) monitoring. Implementing a closed-loop combustion trim system at this stage minimizes the excess oxygen setpoint, maximizing thermal efficiency while suppressing nitrogen oxide (NOx) formation.

While a nominal **0.5% to 1.5%** boiler efficiency improvement translates to immense annual fuel savings, fly ash loading at this stage regularly exceeds **50 g/m³**. Traditional cross-duct optical paths or standard in-situ porous probes suffer from rapid erosion, window obscuration, and catastrophic filter cake blinding.

To overcome these failure modes, this design combines a proprietary sintered metal **Inertial Gas Sampling (IGS)** probe with a high-sensitivity **2.5-meter multi-pass NDIR cell** integrated within a compact, wall-mounted analyzer enclosure.



2. Evaluative Analysis of Extraction Methods

Isolating a representative gas sample from a process stream running 50 g/m³ of fly ash requires a departure from standard mechanical filtration. Conventional barrier methods rely on surface or depth filtration, which inevitably leads to cake compaction and flow restriction.

Inertial extraction operates on a fluid-momentum vector principle. By keeping the process stream moving at ultra-high axial linear velocities through the core of a porous matrix, particulates are forced by momentum to bypass the radial extraction pores entirely.

The following matrix compares the primary methodologies evaluated for severe service gas extraction:

Table 1: Comparative Engineering Analysis of Sampling Methods

Technical Parameter	**Sintered Inertial Gas Sampling (IGS)**	**Cyclone Centrifugal Separators**	**Conventional Barrier Filters**
Separation Physics	High-velocity axial boundary layer bypass with low-velocity radial gas diffusion	Centrifugal vortex generation driving high-mass particles to walls	Direct interception, inertial impaction, and cake accumulation on a physical barrier
Particulate Capture Efficiency	Extremely high gas-phase separation; enhanced by a dynamic sub-micron boundary layer	Poor efficiency for sub-micron particulate matter; highly velocity-dependent	Highly variable; standard elements leak fine dust over time, leading to bench fouling
Clogging & Blinding Resistance	**Excellent**; continuous self-cleaning via boundary layer shear stress; clearable via blowback	High resistance, but suffers from severe abrasive erosion of internal mechanical boundaries	**Low**; rapid surface blinding and cake compaction require frequent manual change-outs

INERTIAL PROBE MECHANICAL DESIGN & FLUID DYNAMICS

3. Inertial Separation Architecture

The proprietary inertial probe utilizes momentum-driven boundary layer separation. The dusty flue gas enters the inner diameter (D_i) of an isostatically cold-pressed and vacuum-sintered stainless steel porous tube at a high axial linear velocity (V_a). This velocity is maintained either by the natural positive pressure of the process duct or via a downstream high-velocity venturi jet eductor.

Concurrently, a low-capacity sample pump draws the gas sample radially outward through the porous matrix wall into the outer sample housing annulus at a low radial filtration velocity (V_r). Because the ratio of axial velocity to radial velocity is exceptionally high:

$$\frac{Va}{Vr} \gg 100$$

The momentum of the fly ash particles forces them to maintain their axial trajectory, carrying them right past the radial pores. Over the first few hours of operation, a thin, highly permeable dynamic boundary layer of superfine particles forms on the inner surface. This layer acts as an integrated ultra-filtration membrane, enhancing sub-micron separation efficiency without inducing a significant differential pressure drop.

4. Mechanical Sizing & Material Specifications

For standard coal-fired fly ash environments, the primary porous media is selected as **Media Grade 0.5**, providing an optimal balance of microparticle rejection and gas permeability. For extreme applications containing elevated sulfur compounds (SO_2) or extreme temperatures, the porous tube material can be upgraded from **316L Stainless Steel** to **Inconel 600** or **Hastelloy X** to eliminate intergranular corrosion.

Core Probe Specifications:

- **Tube Dimensions:** Inside Diameter (D_i) of 0.75 in; Outside Diameter (D_o) of 1.00 in; Porous Length (L) of 36 in.
- **Porosity Parameters:** Nominal pore size of 0.5 μm.
- **Filtration Efficiency:** 99.9% initial collection efficiency under dry gas flow for all particle sizes down to 0.5 μm.
- **Sample Flow Generation:** Designed to deliver a continuous, representative sample flow rate (Qs) of 1 to 2 L/min to the analyzer conditioning system while operating comfortably within low surface flux limits to prevent particulate entrainment.

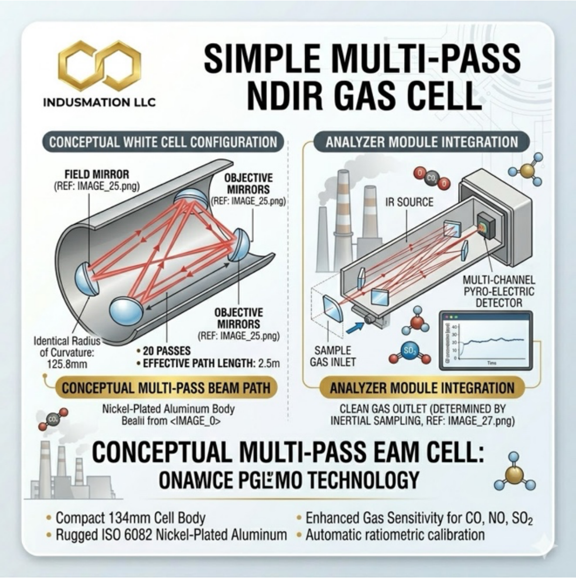
To counter sticky organic ash or process upsets, a high-pressure automated reverse blowback system is integrated directly into the probe assembly, periodically purging the inner element with dry instrument air.

OPTOMECHANICAL DESIGN OF THE MULTI-PASS NDIR CELL

5. Optical Cavity & White Cell Geometry

Once a clean, dust-free sample is extracted by the inertial probe, it is routed to the multi-pass optical cavity within the analyzer enclosure. To measure low ppm levels of CO with high precision, an extended optical path length is mandatory. The system achieves a **2.5-meter effective optical path length** (L_{eff}) within a physical cell length of only **134 mm** using a classic 3-mirror **White Cell configuration**.

The optical bench comprises two spherical objective mirrors mounted at one end of a rigid cell body and a single T-shaped field mirror mounted at the opposite end. The cell body is CNC-machined from **ISO 6082 Aluminum** and finished with **electroless nickel plating** to provide robust corrosion resistance against aggressive acid gases (SOx, NOx).



3D ray-trace modeling showing the infrared beam entering the entrance aperture, forming 9 non-overlapping reflection spots on the gold-coated field *mirror, and exiting via the symmetrical exit aperture.*

6. Mirror Coordinates & Aperture Tolerances

All three mirrors are fabricated with an identical radius of curvature (R) of **125.8 mm**, with the physical spacing between the mirror apexes set precisely equal to R.

- **Aperture Design:** The field mirror features two precise laser-cut apertures: an entrance aperture (A_{in}) and a symmetrical exit aperture (A_{out}).
- **Reflection Density:** The infrared beam enters the cell and is redirected by the objective mirrors to form exactly **9 distinct, non-overlapping, and equidistant reflection spots** on the gold-coated reflective surface of the field mirror, completing **20 passes** through the sample gas.
- **Clipping Prevention:** A strict minimum distance of 1.5 mm is maintained from any reflection spot to the edge of the adjacent apertures, completely eliminating beam clipping and stray-light interference.

ELECTRO-OPTICS & EMBEDDED SIGNAL PROCESSING

7. Electro-Optics Architecture

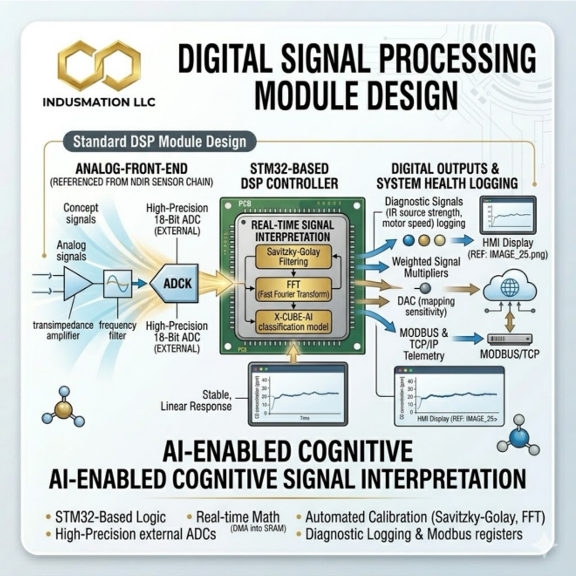
The electro-optics chain is engineered for high energy throughput and spectral selectivity:

- **Infrared Source:** A high-intensity broadband thermal source utilizing a Ni-Chrome filament operates continuously, backed by a gold-coated parabolic reflector to collimate forward emission.
- **Transfer Optics:** High-grade Calcium Fluoride (CaF_2) bi-convex lenses focus the collimated beam directly through the cell apertures.
- **Detection System:** A multi-channel pyroelectric detector (such as the LRM-278) features integrated narrow bandpass interference filters specifically tuned to the primary absorption band of Carbon Monoxide.

8. Embedded Lock-In DSP Firmware

To isolate the tiny absorption signals from intense industrial background thermal noise, the signal processing electronics run on an **STM32F4 series microcontroller**.

The raw analog output from the pyroelectric detector channels is digitized via high-resolution ADCs. The microcontroller's DSP core executes a highly optimized **Goertzel algorithm** operating as a digital lock-in filter tuned exactly to the optical modulation frequency. This processing isolates the true ratiometric signal amplitude while completely rejecting low-frequency thermal drift and ambient electronic noise.

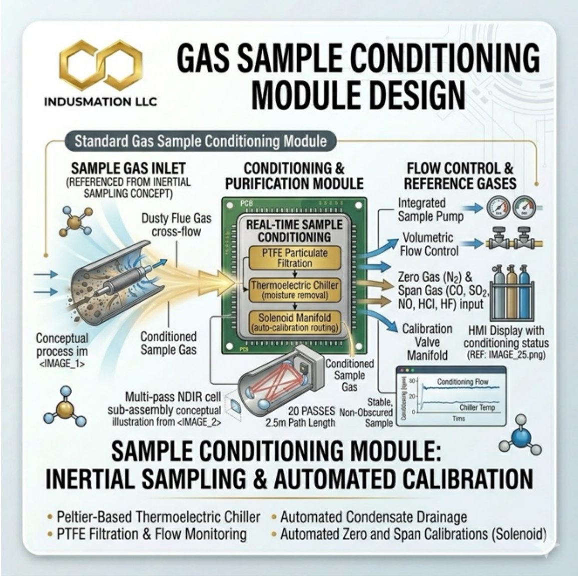


Block diagram detailing the processing path: Pyroelectric Detector $\rightarrow$ Preamplification $\rightarrow$ High-Res ADC $\rightarrow$ STM32F4 Goertzel Lock-In Filter $\rightarrow$ Linearized Gas Concentration Output.

9. Sample Conditioning & Automation

Housed inside a rugged wall-mounted or 19-inch rack enclosure, the system contains an automated gas conditioning subsystem:

- **Thermoelectric Chiller:** Rapidly condenses and removes flue gas moisture to prevent spectral interference from water vapor bands.
- **Pneumatic Manifold:** An integrated manifold handles automated daily **Zero and Span calibrations** once every 24 hours. The microcontroller switches internal solenoids to isolate the probe sample line, floods the multi-pass cell with zero-grade nitrogen, and subsequently injects a certified CO span gas to verify ratiometric accuracy and system linearity.



TOTAL BILL OF MATERIALS & MASTER MILESTONES

10. Comprehensive Core Analyzer Cost Summary

The core system is structured into modular sub-assemblies to simplify manufacturing localization and support local procurement initiatives. The estimated core material breakdown is detailed below:

Table 2: Estimated Core Cost Breakdown

- **Multi-Pass Cell Sub-Assembly:** $1,989 (Includes nickel-plated aluminum cell body, gold-coated spherical mirrors, mounts, and CaF_2 windows).
- **Electro-Optics Chain:** $715 (Includes broadband IR source, parabolic reflector, bi-convex

lenses, and multi-channel pyroelectric detector).

- **Sample Conditioning & Pneumatics:** $1,185 (Includes KNF Neuberger PTFE-head sample pump, calibration solenoids, manifold blocks, and filters).
- **Control Electronics & Enclosure:** $890 (Includes custom STM32 processing board, power supplies, local HMI screen, and industrial rack enclosure).
- **Sintered Inertial Probe & Options:** $1,475 (Includes 36" 316L SS Grade 0.5 porous tube, outer jacket assembly, blowback valves, and high-velocity venturi eductor).

Total Estimated Core Manufacturing Material Cost: $6,254

11. Master 15-Month Development Timeline

The technology transfer and localized commercialization roadmap is divided into three distinct phases:

- **Phase I: Bench Development & Fluid Modeling (Months 1–9)**

  Focuses on optical ray-tracing, fluid dynamics modeling of the boundary layer velocities across the custom probe, CNC machining the mechanical cell assemblies, and thermal profiling inside environmental chambers.

- **Phase II: Electronics & DSP Firmware Optimization (Months 10–12)**

  Integration of the STM32F4 microcontroller board, programming the digital lock-in filtering algorithm, and finalizing the automatic ratiometric baseline calibration software.

- **Phase III: Field Trial & Environmental Certification (Months 13–15)**

  Deploying prototypes at an operational air preheater utility duct to validate the anti-clogging performance of the inertial probe over extended timelines and securing regulatory compliance certifications.