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Engineering Solutions

DESIGN DOCUMENT

PGEM23 Hybrid Gas Analyzer System with Multi-Pass NDIR Gas Sample Cell (MPC)

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Prepared by Indusmation for potential manufacturing partners and licensees.

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Document Control

Revision History

Rev	Date	Description	Author
A	May 2026	Initial Draft - Complete system design	Indusmation Engineering

Distribution

This document is proprietary to Indusmation and is provided to qualified manufacturing partners and licensees under appropriate non-disclosure agreements.

Introduction

Purpose

This design document provides the complete technical specification for the PGEM23 Hybrid Gas Analyzer System incorporating a multi-pass NDIR (Non-Dispersive Infrared) gas sample cell. The document is intended to enable qualified manufacturing partners to produce the multi-pass cell sub-assembly and the complete PGEM23 analyzer under license from Indusmation.

Scope

The document covers the following major subsystems:

- Multi-Pass Cell (MPC) - White Cell optical configuration with field mirror and objective mirrors
- Electro-Optics Assembly - IR source, transfer optics, CaF₂ lenses, and IR detector
- Sample Conditioning System - gas pump, filters, flow control, and calibration manifold
- Signal Processing Electronics - detector amplification, signal processing, and data output
- Analyzer Enclosure - panel-mounted /19-inch rack housing with thermal management
- Bill of Materials with estimated component costs

Target Application

The PGEM23 is designed for continuous emission monitoring (CEM) and process gas analysis in industrial stack applications. Target analyte gases include CO, CO₂, NO, NO₂, SO₂, and H₂O (moisture), measured using NDIR absorption spectroscopy across wavelengths in the 2 to 15 micrometer infrared band.

Design Philosophy

The multi-pass cell design is based on the White Cell configuration (developed by John U. White), which uses three spherical mirrors of identical radius of curvature to achieve extended optical path lengths within a compact volume. The PGEM23 design targets a 2.5-meter effective optical path length using 20 passes (9 reflections on the field mirror) within a cell body approximately 134 mm long. This provides sufficient absorption path length for sensitive detection of stack emission gases while maintaining a compact form factor suitable for panel mounting.

The design leverages the Cyclone C2 gas cell geometry as its optical baseline, with mirrors having a radius of curvature of 125.8 mm. The cell body is constructed from aluminium (ISO 6082) with electroless nickel plating for corrosion resistance, and all wetted surfaces are compatible with aggressive stack gas environments.

Reference Documents

Ref	Document	Description
R1	D16-0006_A001	Gas Cell Requirements Specification

R2	20-3 / 20-7bis	Optical ray-trace simulation (Zemax/OpticStudio)
R3	LC-P03 Rev 3	Main Body mechanical drawing
R4	LC-P04 Rev 3	Objective Mirrors Holder drawing
R5	LC-M02 Rev 4b	Gas Cell Field Mirror Housing drawing
R6	Beam Requirements	Simulation of Multi-Pass Gas Cell - optical analysis
R7	Assembly v03	Gas Cell Assembly 3D model (IGES)

System Architecture Overview

PGEM23 Analyzer Functional Block Diagram

The PGEM23 analyzer comprises four primary functional blocks arranged within a 19-inch rack-mount enclosure (up to 6U height):

1. Gas Sample Conditioning Module - receives raw stack gas, filters particulates, removes excess moisture, regulates temperature and flow rate, and delivers conditioned sample gas to the measurement cell.
2. Multi-Pass Cell and Electro-Optics Module - the core measurement engine consisting of the White Cell optical cavity, IR source, transfer optics, CaF2 windows, and IR detector (LRM-278).
3. Signal Processing and Control Electronics - amplifies the detector signal, performs spectral analysis, calculates gas concentrations, and manages calibration routines.
4. Pneumatics and Calibration Module - manages gas flow paths, houses solenoid valves for zero/span calibration gas switching and includes the sample pump.

Key System Specifications

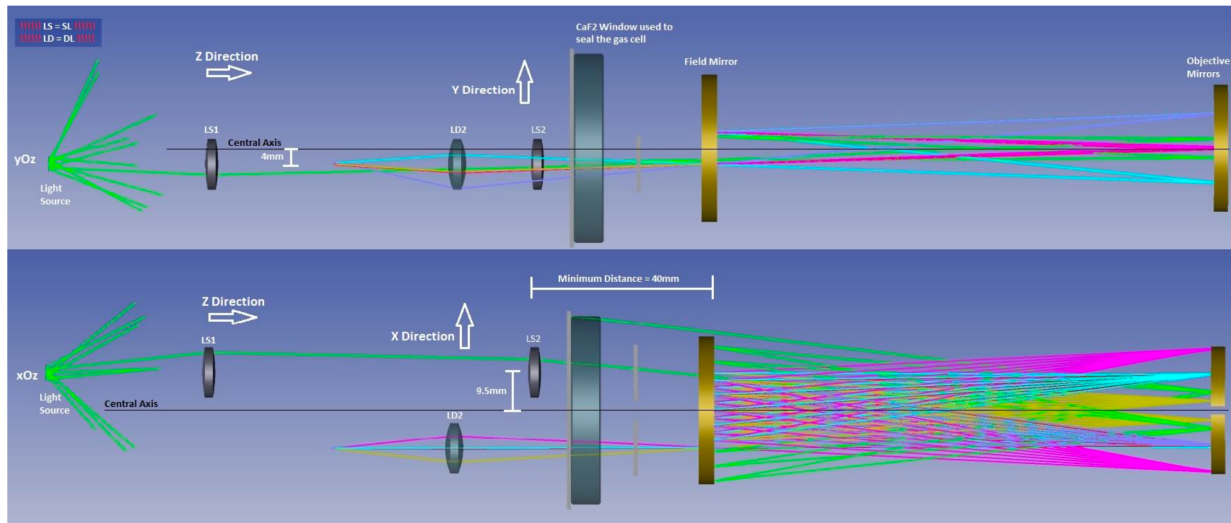
Parameter	Specification
Measurement Principle	NDIR (Non-Dispersive Infrared) absorption spectroscopy
Cell Configuration	White Cell (multi-pass, 3-mirror)
Optical Path Length	2.5 m (fixed, non-adjustable), tolerance +/- 0.1 m
Number of Passes	20 (9 reflections on field mirror)
Target Gases	CO, CO2, NO, NO2, SO2, H2O
IR Source	IR-18 Ni-Chrome wire emitter (~20W), Boston Electronics
IR Detector	LRM-278 (pyroelectric or thermopile, 2 x 2 mm active area)
Sample Flow Rate	2 L/min nominal
Sample Gas Temperature	1 to 140 deg C (cell heatable to 140 deg C)
Sample Gas Pressure	80,000 to 120,000 Pa (0.8 to 1.2 bar abs)
Ambient Operating Range	10 to 50 deg C
Enclosure	19-inch rack mount, max 482.6 x 304.8 x 266.7 mm (19 x 12 x 10.5 in, 6U) / Panel mount
Wetted Materials	Nickel, Gold, Stainless Steel, Viton, Calcium Fluoride (CaF2)
Gas Connections	1/4-inch OD push-fit fittings

Multi-Pass Cell (MPC) Design

White Cell Optical Principle

The multi-pass cell employs the White Cell configuration, which consists of two objective mirrors and one field mirror (T-shaped), all with identical radius of curvature ($R_c = 125.8 \text{ mm}$). The mirrors are positioned such that the distance between the field mirror and the objective mirror pair equals the radius of curvature. The objective mirror images the entrance source onto the field mirror surface, and the field mirror reflects the beam from the first objective mirror onto the second. This bouncing continues until the image of the entrance beam falls outside the field mirror aperture at the designated exit position.

For the PGEM23 design, the mirrors are oriented to achieve 20 passes, which corresponds to 9 images on the field mirror (labeled N1 through N9). The entrance beam position P2 is set at coordinates $x = +9.5 \text{ mm}$, $y = -4 \text{ mm}$ relative to the central axis, and the exit beam E1 is at $x = -9.5 \text{ mm}$, $y = -4 \text{ mm}$. The positions P1/E1 and the field mirror reflection spots N1 through N9 are equidistant on the field mirror surface.



Mirror Design and Specifications

Field Mirror (T-Shape Mirror)

The field mirror is a concave spherical mirror with a T-shaped profile, housed in a dedicated housing (part LC-M02). It is positioned at the entrance end of the gas cell.

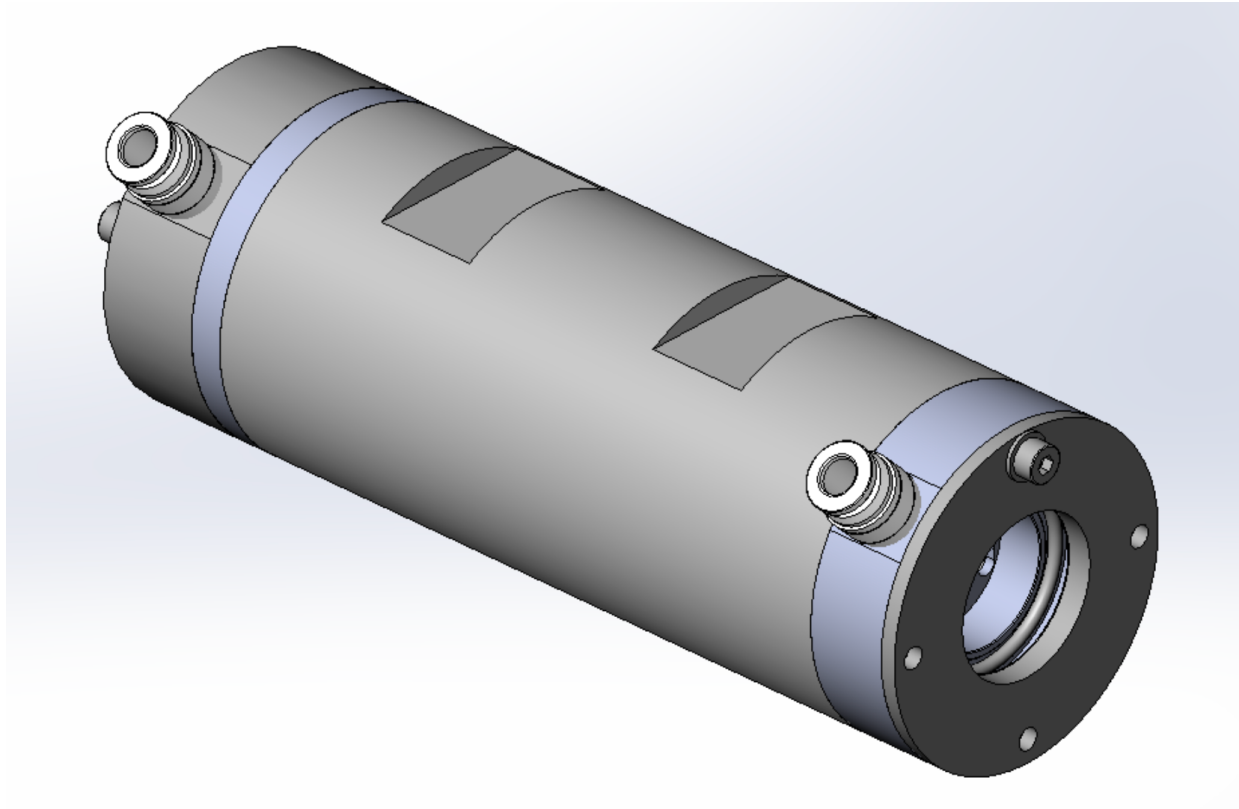
Parameter	Value
Type	Concave spherical, T-shaped profile
Radius of Curvature	125.8 mm
Material	Aluminium ISO 6082 substrate
Surface Finish	Electroless nickel plate to 0.015 mm thickness all over
Optical Coating	Protective gold coating ($R > 98\%$ over 2 to 20 micrometer wavelength range)

Curved Surface Roughness	Less than 20 Angstroms RMS (scratch/dig 60/40)
Entrance Aperture Diameter	4 mm (positioned at +9.5 mm from center on X axis)
Exit Aperture Diameter	4 mm (positioned at -9.5 mm from center on X axis)
Aperture Y-offset from Center	-4 mm (both entrance and exit)
Min. Distance from Mirror Edge	3.8 mm (closest light bounce, for 9 passes on field mirror)
Housing Part Number	LC-M02 Rev 4b
Housing Material	Aluminium ISO 6082, electroless nickel plated
Mounting	6 holes drill dia. 4.3, C/bore dia. 8 x 4.4 deep, Equi spaced on 54.0 PCD

Objective Mirrors (Pair)

Two objective mirrors are mounted on a common holder (part LC-P04) at the far end of the gas cell from the field mirror. They share the same radius of curvature as the field mirror.

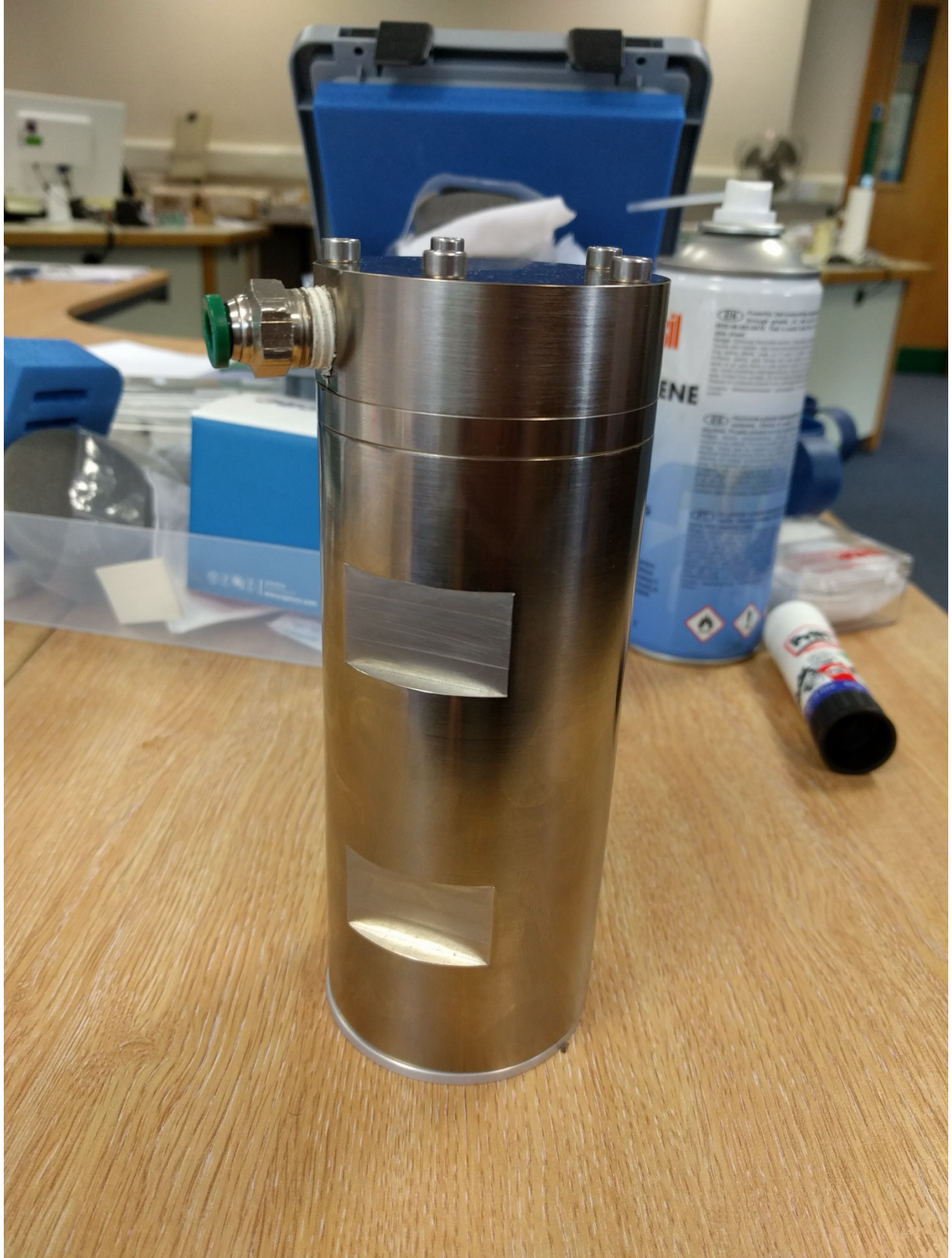
Parameter	Value
Type	Concave spherical (matched pair)
Radius of Curvature	125.8 mm
Material	Aluminium ISO 6082 substrate
Surface Finish	Electroless nickel plate to 0.015 mm thickness
Optical Coating	Protective gold coating (R > 98% over 2 to 20 micrometer range)
Mirror Holder Outer Diameter	63.0 mm
Holder Part Number	LC-P04 Rev 3
Holder Material	Aluminium ISO 6082, electroless nickel plated
Mounting Holes (cell side)	5 holes drill and tap M4 x 8 deep, Equi spaced on 54.0 PCD
Mounting Holes (mirror side)	6 holes drill and tap M3
Mirror Tilt Angle	Approximately 5 degrees (set during alignment for 20-pass configuration)



Cell Body (Main Body)

The main body (part LC-P03) is a cylindrical tube that forms the sealed gas volume between the field mirror housing and the objective mirror holder.

Parameter	Value
Part Number	LC-P03 Rev 3
Overall Length	134.36 mm
Outer Diameter	63.0 mm (at flanges)
Inner Bore Diameter (field end)	46.56 / 46.40 mm step bore
Inner Bore Diameter (objective end)	38.1 mm / 39.0 mm step bore
Material	Aluminium ISO 6082
Surface Finish	Electroless nickel plate to 0.015 mm thickness all over
Field Mirror End Flange	6 holes drill and tap M4 x 8 deep, Equi spaced on 54.0 PCD
Objective Mirror End Flange	5 holes drill and tap M4 x 8 deep, Equi spaced on 54.0 PCD
Viewing Windows	Three cutouts along body (for inspection/alignment)
Gas Ports	Two 1/4-inch NPT threaded ports (tap drill dia. 11.1 x 10.0 deep, flat bottom)
Sealing	O-ring grooves at both ends; seals designed for positive gauge pressure
Internal Volume	Approximately 200 mL (estimated)



CaF2 Optical Windows

Calcium Fluoride (CaF₂) windows are used to seal the gas cell at the field mirror end while maintaining optical transparency across the infrared measurement band (2 to 20 micrometers). CaF₂ is chosen for its wide IR transmission range, chemical inertness, and mechanical hardness.

Parameter	Value
Material	Calcium Fluoride (CaF ₂), optical grade
Transmission Range	0.13 to 10 micrometers (usable to ~12 micrometers)
Window Diameter	Matched to cell aperture (nominally 12.7 mm / half-inch)
Surface Quality	40/20 scratch-dig or better
Mounting	Sealed into field mirror housing with Viton O-ring
Function	Seals gas cell while transmitting IR source and return beams

Gas Path Design

The gas sample enters and exits the cell body through two 1/4-inch NPT ports located on the cylindrical wall of the main body. The ports are positioned to promote even gas distribution and minimize dead volume. Push-fit fittings accepting 1/4-inch OD plastic tubing are used for connection to the sample conditioning system. The cell is designed to operate with positive sample gas pressure (gauge) at flow rates up to 2 L/min. All internal surfaces in contact with the gas sample are either nickel-plated aluminium, gold-coated mirror surfaces, stainless steel fittings, Viton elastomer seals, or CaF₂ windows, ensuring compatibility with corrosive stack gases including SO₂ and NO₂.

Thermal Design

The gas cell must be heatable to 140 deg C to prevent condensation of moisture and acid gases within the optical path. Heating is accomplished via external band heaters or cartridge heaters mounted on the cell body, with a temperature sensor (thermocouple or RTD) providing feedback to a PID controller in the electronics module. Thermal insulation is applied around the cell to minimize heat loss and maintain temperature uniformity. The cell assembly including heating elements must operate within an ambient temperature range of 10 to 50 deg C.

Electro-Optics Design

Optical System Overview

The electro-optics system comprises the IR source, source-side transfer optics, the multi-pass cell, detector-side transfer optics, and the IR detector. The optical path begins at the IR source, is collimated and focused through a CaF₂ lens into the entrance aperture of the field mirror, traverses the 20-pass White Cell cavity, exits through the exit aperture, and is then collected and focused onto the IR detector through a second CaF₂ lens and wavelength-selective filter.

The minimum distance from the CaF₂ window (cell outermost wall) to the center of the nearest transfer lens is 40 mm, constrained by mechanical clearances at the field mirror housing.

IR Source

The PGEM23 uses the IR-18 broadband infrared source from Boston Electronics (or equivalent). This is a Ni-Chrome wire filament emitter mounted on a ceramic post, providing approximately 20 watts of broadband IR emission.

Parameter	Value
Source Model	IR-18 (Boston Electronics) or equivalent
Emitter Type	Ni-Chrome wire on ceramic post
Emitter Dimensions	3.6 x 3.0 mm (active area)
Power Consumption	Approximately 20 W
Emission Type	Broadband thermal (near-Lambertian, 3D emission)
Operating Voltage	Typically 6 to 12 V DC (model-dependent)
Reflector	Recommended: parabolic or elliptical reflector behind source to increase forward efficiency
Modulation	Mechanical chopper or electronic pulsing for AC detection

Note: The earlier prototype design used the IR-12 source (3.6 x 3 mm Ni-Chrome wire). The IR-18 was selected for the PGEM23 to provide higher radiant power (~20W) for improved signal-to-noise ratio in stack gas applications with longer path lengths (greater than 2.5 m if the design is scaled).

Source-Side Transfer Optics

The source-side transfer optics image the IR source filament at the entrance aperture (P2) of the field mirror with a magnification of $M = 1$ (1:1 imaging). This is implemented as a 4f relay system using a CaF₂ bi-convex lens.

Parameter	Value
Lens Type	CaF ₂ bi-convex (Thorlabs LB5922 or equivalent)
Focal Length	20 mm
Diameter	12.7 mm (1/2 inch)
Magnification	$M = 1.0$ (source side)

Source-to-Lens Distance	40 mm (2f)
Lens-to-Image Distance	40 mm (2f)
Numerical Aperture	~0.16
Lens Designation	LS2 (in optical schematic)
Position (X, Y from center)	X = -4 mm, Y = +9.5 mm

A second lens (LS1) may be placed between the IR source and LS2 to improve collection efficiency, particularly if a reflector is not used behind the source. The choice of LS1 depends on the source-to-first-lens distance and the desired collection NA.

Detector-Side Transfer Optics

The detector-side transfer optics collect the exit beam from the cell and focus it onto the detector active area. Since the detector (LRM-278) has a 2 x 2 mm active area and the source image at the exit is approximately 3.6 x 3 mm, a demagnification of at least $M = 0.5$ (1:2) is required.

Parameter	Value
Lens Type	CaF2 bi-convex (Thorlabs LB5922 or equivalent)
Focal Length	20 mm
Diameter	12.7 mm (1/2 inch)
Magnification	$M = 0.5$ or lower (detector side)
Lens-to-Cell Distance	~40 mm minimum from CaF2 window
Numerical Aperture (at $M=0.5$)	~0.11
Lens Designation	LD2 (in optical schematic)
Position (X, Y from center)	X = -4 mm, Y = -9.5 mm

IR Detector

The PGEM23 uses the LRM-278 infrared detector for measuring the transmitted IR intensity after the multi-pass cell.

Parameter	Value
Model	LRM-278
Active Area	2 x 2 mm
Type	Pyroelectric / Thermopile (application-dependent)
Spectral Range	Compatible with 2 to 15 micrometer measurement band
Window	Matched to target gas absorption wavelength (bandpass filter integrated or separate)
Responsivity	Per manufacturer datasheet
Mounting	On detector transfer optics mounting bracket, aligned to exit optical axis

Wavelength Selection

Wavelength discrimination is achieved using narrow bandpass interference filters placed between the cell exit and the detector. For multi-gas measurement, a rotating filter wheel is positioned in the collimated beam path between the detector lens and the detector. The filter wheel carries individual bandpass filters for each target gas absorption band, plus a reference channel filter at a non-absorbing wavelength. The beam is bent at 90 degrees on both sides of the filter wheel to reduce the overall width of the analyzer optical bench.

Gas	Absorption Band (micrometers)	Typical Filter Center Wavelength
CO	4.5 to 4.8	4.64 micrometer
CO ₂	4.2 to 4.4	4.26 micrometer
NO	5.2 to 5.4	5.26 micrometer
NO ₂	6.1 to 6.3	6.23 micrometer
SO ₂	7.3 to 7.5	7.35 micrometer
H ₂ O	2.5 to 2.8	2.59 micrometer
Reference	3.8 to 4.0	3.91 micrometer (non-absorbing)

Optical Efficiency Budget

Based on the Zemax/OpticStudio ray-trace simulations performed during the prototype phase, the following efficiency budget was established for the optical system:

Stage	Efficiency	Cumulative
IR Source emission (forward hemisphere)	~50%	50%
Source-side lens collection (NA = 0.16)	~0.72%	0.36%
Gas cell throughput (20 passes, gold mirrors)	~28%	0.10%
Detector-side lens collection	~95%	~0.095%
Filter transmission	~80%	~0.076%
Overall system efficiency	-	~0.08% of total source power

The system efficiency can be improved by adding a parabolic or elliptical reflector behind the IR source to redirect backward-emitted radiation into the optical path. This could potentially double the effective source power entering the cell.

Sample Conditioning System

Overview

The sample conditioning system prepares the raw stack gas for optical measurement by removing particulates, controlling moisture, regulating temperature and pressure, and managing flow rate. Proper sample conditioning is critical for accurate and reliable NDIR measurements, and for protecting the optical surfaces within the multi-pass cell from contamination and corrosion.

Sample Gas Flow Path

The gas flow path through the PGEM23 analyzer follows this sequence:

5. Sample probe (external) extracts gas from the stack or duct.
6. Heated sample line (external, maintained at 180 deg C typical) transports gas to the analyzer.
7. Coalescing filter removes particulates and liquid droplets.
8. Sample cooler/dryer (Peltier-type or Nafion) reduces moisture to a controlled dew point.
9. Fine particulate filter (sintered stainless steel, 2-micrometer nominal).
10. Flow control valve regulates flow to 2 L/min.
11. Sample pump (diaphragm type, chemically resistant) draws sample through the system.
12. Multi-pass cell (measurement volume).
13. Exhaust vent (returned to stack or safely vented).

Calibration Gas Manifold

The calibration manifold enables automated zero and span calibration by switching between sample gas, zero gas (typically nitrogen or clean dry air), and span gas (certified reference gas mixtures). Solenoid valves (3-way, chemically resistant) are used to select the gas source. The calibration sequence is controlled by the electronics module and can be triggered manually or on a programmed schedule.

Component	Specification
Zero Gas	Nitrogen (N2) or clean dry instrument air
Span Gas	Certified reference mixture for each target gas at known concentration
Switching Valves	3-way solenoid valves, PTFE/Viton wetted parts, 24 VDC coil
Number of Valve Positions	Minimum 3: Sample, Zero, Span (expandable for multi-span)
Calibration Trigger	Automatic (timed) or manual command

Sample Pump

A chemically resistant diaphragm pump is used to draw sample gas through the conditioning train and measurement cell. The pump is located downstream of the measurement cell to maintain the cell at a slight positive pressure relative to ambient, minimizing the risk of ambient air ingress.

Parameter	Value
Type	Diaphragm pump, chemically resistant
Flow Rate	0 to 5 L/min (adjustable), nominal 2 L/min
Wetted Materials	PTFE head, FFKM/Viton valves
Power	24 VDC, typically 10 to 15 W
Pressure Rating	0.8 to 1.2 bar abs at cell



Signal Processing and Control Electronics

Overview

The electronics module processes the raw detector signal, performs gas concentration calculations using Beer-Lambert Law relationships, manages calibration routines, controls the sample conditioning system, and provides output interfaces for data communication and system integration.

Detector Signal Chain

The signal processing chain for the LRM-278 detector output consists of:

14. Pre-amplifier: low-noise transimpedance amplifier located close to the detector to minimize noise pickup.
15. Bandpass filter: matched to the chopper/modulation frequency to reject DC drift and low-frequency noise.
16. Synchronous demodulator (lock-in amplifier): extracts the AC signal at the chopper frequency for maximum signal-to-noise ratio.
17. ADC: 16-bit or higher analog-to-digital converter for digitizing the demodulated signal.
18. Microprocessor: performs Beer-Lambert calculations, temperature/pressure compensation, linearization, and calibration correction.

Concentration Calculation

Gas concentration is determined using the Beer-Lambert Law: $I = I_0 * \exp(-\alpha * C * L)$, where I is the measured intensity at the gas absorption wavelength, I_0 is the reference intensity (measured at a non-absorbing wavelength or with zero gas), α is the absorption coefficient for the specific gas at the filter wavelength, C is the gas concentration, and L is the optical path length (2.5 m). The ratio I/I_0 eliminates common-mode variations due to source aging, window contamination, and detector drift.

Control Functions

Function	Description
Cell Temperature Control	PID controller for cell heater, setpoint 60 to 140 deg C (application-dependent)
Chopper/Filter Wheel Motor	Speed control for rotating filter wheel or mechanical chopper
Pump Speed Control	Flow rate regulation via pump voltage/PWM
Calibration Sequencing	Automated valve switching for zero/span calibration cycles
Alarm Management	Fault detection for source failure, low flow, over-temperature, calibration drift
Data Logging	Internal storage of measurement data, calibration history, and fault logs

Communication Interfaces

Interface	Specification
Analog Output	4-20 mA (one per gas channel), isolated, into 750 ohm max load
Digital Output	RS-485 Modbus RTU (standard), optional RS-232
Relay Outputs	Programmable alarm relays (SPDT, 250 VAC / 5A rating)
Optional	Ethernet TCP/IP (Modbus TCP), USB for service/configuration
Display	Front panel LCD/LED for concentration readout and status (optional)

Power Supply

The PGEM23 analyzer operates from a universal AC power input (100 to 240 VAC, 50/60 Hz). An internal switch-mode power supply provides regulated DC rails for the various subsystems. Estimated total power consumption is 80 to 120 W depending on cell heater setpoint and number of gas channels.

Analyzer Enclosure Design

Mechanical Envelope

The PGEM23 analyzer is housed in a panel-mounted 19-inch rack enclosure conforming to the following maximum dimensions:

Dimension	Value
Length (depth)	482.6 mm (19 inches)
Width	304.8 mm (12 inches)
Height	266.7 mm (10.5 inches, 6U)
Mounting	Standard 19-inch rack ears, panel mount compatible
Material	Powder-coated sheet steel or aluminium
Ingress Protection	IP20 minimum (indoor use)

Internal Layout

The internal layout is organized to separate the optical measurement section from the pneumatic and electronic sections, minimizing thermal and electromagnetic interference:

- Front zone: Front panel with display, indicator LEDs, and gas connection ports.
- Left compartment: Multi-pass cell assembly with electro-optics, mounted on a precision optical bench plate. The cell is thermally insulated from the enclosure walls.
- Right compartment: Sample conditioning components including pump, filters, valves, and calibration manifold.
- Rear zone: Electronics boards (signal processing, power supply, communication interfaces), rear panel connectors for power, communications, and analog outputs.

Thermal Management

Heat generated by the IR source (~20 W), cell heater (up to 50 W), pump motor, and electronics is managed through a combination of natural convection, internal fans, and thermal isolation. The optical bench plate provides thermal mass to stabilize the cell temperature. Ventilation openings on the rear and side panels allow airflow without compromising the IP rating.

Bill of Materials and Cost Estimate

Multi-Pass Cell Assembly

Item	Description	Qty	Est. Unit Cost (USD)	Est. Total (USD)
1	Main Body LC-P03 (Al 6082, Ni plated, machined)	1	\$350	\$350
2	Field Mirror Housing LC-M02 (Al 6082, Ni + Au coated)	1	\$400	\$400
3	Objective Mirrors Holder LC-P04 (Al 6082, Ni plated)	1	\$250	\$250
4	Field Mirror (spherical, Rc=125.8mm, Au coated)	1	\$300	\$300
5	Objective Mirrors (spherical pair, Rc=125.8mm, Au coated)	2	\$200	\$400
6	CaF2 Windows (12.7mm dia, optical grade)	2	\$80	\$160
7	Viton O-rings (assorted sizes for sealing)	1 set	\$15	\$15
8	M3/M4 SS fasteners, dowel pins	1 set	\$20	\$20
9	Gas port fittings (1/4-inch push-fit, SS)	2	\$12	\$24
10	Band heater or cartridge heaters (140 deg C rated)	1 set	\$45	\$45
11	Temperature sensor (thermocouple or RTD)	1	\$25	\$25
			Subtotal	\$1,989

Electro-Optics Assembly

Item	Description	Qty	Est. Unit Cost (USD)	Est. Total (USD)
12	IR-18 Source (Boston Electronics, ~20W Ni-Chrome)	1	\$120	\$120
13	Source reflector (parabolic, gold coated)	1	\$85	\$85
14	CaF2 Bi-convex lens, f=20mm, 12.7mm dia (Thorlabs LB5922)	2	\$95	\$190
15	Lens mounting brackets (machined Al, source side)	1	\$40	\$40
16	Lens mounting brackets (machined Al, detector side)	1	\$40	\$40
17	LRM-278 IR Detector	1	\$250	\$250
18	Rotating filter wheel assembly (motor + encoder)	1	\$200	\$200

19	Narrowband IR filters (per gas channel, 6 channels + ref)	7	\$150	\$1,050
20	Optical bench mounting plate (machined Al)	1	\$80	\$80
21	Mechanical chopper or electronic modulator	1	\$75	\$75
			Subtotal	\$2,130

Sample Conditioning and Pneumatics

Item	Description	Qty	Est. Unit Cost (USD)	Est. Total (USD)
22	Diaphragm sample pump (PTFE head, 2 L/min)	1	\$180	\$180
23	Coalescing filter housing + element	1	\$60	\$60
24	Fine particulate filter (sintered SS, 2 micron)	1	\$45	\$45
25	Solenoid valves 3-way (calibration manifold)	3	\$65	\$195
26	Flow sensor/controller	1	\$90	\$90
27	1/4-inch PTFE tubing and fittings (internal)	1 set	\$40	\$40
28	Pressure sensor (cell pressure monitoring)	1	\$55	\$55
			Subtotal	\$665

Electronics and Enclosure

Item	Description	Qty	Est. Unit Cost (USD)	Est. Total (USD)
29	Signal processing PCB (pre-amp, lock-in, ADC, MCU)	1	\$350	\$350
30	Power supply (100-240VAC to multi-rail DC, 150W)	1	\$80	\$80
31	I/O board (4-20mA outputs, relays, RS-485)	1	\$120	\$120
32	Cell heater PID controller module	1	\$60	\$60
33	19-inch rack enclosure (6U, sheet metal)	1	\$150	\$150
34	Front panel (display, indicators, connectors)	1	\$100	\$100
35	Rear panel (power inlet, comms connectors)	1	\$50	\$50
36	Internal wiring harness and connectors	1 set	\$60	\$60
37	Cooling fan(s)	2	\$12	\$24
38	Thermal insulation (cell area)	1 set	\$25	\$25
			Subtotal	\$1,019

Total Estimated Cost Summary

Assembly	Estimated Cost (USD)
Multi-Pass Cell Assembly	\$1,989
Electro-Optics Assembly	\$2,130
Sample Conditioning and Pneumatics	\$665
Electronics and Enclosure	\$1,019
Assembly, Testing, and QC Labor (estimated 8 hours)	\$600
Total Estimated Unit Cost	\$6,403

Note: All costs are preliminary estimates for budgetary purposes and are subject to change based on supplier quotations, volume pricing, and detailed design finalization. The figures above reflect component-level estimates for a complete analyzer system.

Manufacturing and Quality Notes

Critical Tolerances

The following tolerances are critical to optical performance and must be maintained during manufacturing:

- Mirror radius of curvature: $R_c = 125.8$ mm with tolerance per optical drawing (typically ± 0.5 mm or better for White Cell performance).
- Mirror surface roughness: less than 20 Angstroms RMS on all optical surfaces (scratch/dig 60/40).
- Mirror alignment: The tilt angle of the objective mirrors must be adjustable during assembly to achieve the 20-pass configuration. Shim or fine-adjustment screw provisions are recommended.
- Bore concentricity: Machined diameters on the main body to be concentric to within 0.1 mm (per drawing tolerance block).
- Surface finish: 1.6 micrometers Ra all over machined surfaces (per drawing tolerance block).
- Electroless nickel plating: 0.015 mm (15 micrometers) thickness uniformly over all specified parts.
- Gold coating on mirrors: $R > 98\%$ reflectivity over 2 to 20 micrometer range, applied over electroless nickel on curved surfaces only (Surface X on LC-M02).

Assembly and Alignment Procedure

Final assembly of the multi-pass cell requires optical alignment to achieve the designed 20-pass beam pattern. The alignment procedure involves:

19. Install the field mirror into its housing (LC-M02) and verify the mirror surface curvature and position.
20. Install the objective mirror pair into the holder (LC-P04) with adjustable tilt hardware.
21. Assemble the main body (LC-P03) with CaF₂ windows, O-ring seals, and gas port fittings.
22. Mount the field mirror housing and objective mirror holder onto the main body.
23. Using a visible alignment laser directed through the entrance aperture (P2 position), adjust the objective mirror tilt angles until 9 reflection spots are visible on the field mirror surface in the correct pattern.
24. Verify the exit beam exits through the exit aperture (E1 position) and reaches the detector optical axis.
25. Lock mirror adjustments and perform a gas leak test at 1.2 bar abs with nitrogen.

Quality Control and Testing

Each assembled multi-pass cell and complete PGEM23 analyzer unit should undergo the following acceptance tests:

- Optical throughput test: Measure IR transmission through the cell with zero gas (N₂) and verify throughput efficiency is within specification.
- Gas leak test: Pressurize the cell to 1.2 bar abs and verify leak rate is below the acceptable threshold.
- Heated cell test: Ramp cell to 140 deg C and verify temperature uniformity and seal integrity.
- Calibration verification: Introduce certified span gases and verify concentration readings are within specified accuracy.
- Long-term stability test: Run the analyzer for a minimum of 24 hours and verify zero and span drift are within specification.

Appendices

Appendix A: Optical Coordinate System

The optical coordinate system used throughout this document and the referenced drawings is defined as follows:

- Z-axis: Along the central optical axis of the cell (from field mirror toward objective mirrors).
- X-axis: Horizontal, perpendicular to Z. The entrance beam LS2 is at X = +9.5 mm, the exit beam LD2 is at X = -9.5 mm from center.
- Y-axis: Vertical, perpendicular to both X and Z. Both LS2 and LD2 are at Y = -4 mm from the central axis.

The apertures on the field mirror have a 4 mm diameter and cannot be larger because the closest light bounce on the field mirror needs to be approximately 3.8 mm from the entrance or exit of the gas cell to allow for 9 passes and achieve the 2.5 m path length.

Appendix B: Key Supplier References

Component	Supplier	Part Number / Notes
CaF2 Bi-convex Lens	Thorlabs	LB5922 (f=20mm, dia=12.7mm)
IR Source (~20W)	Boston Electronics	IR-18 Ni-Chrome emitter
IR Detector	TBD	LRM-278 (or equivalent pyroelectric/thermopile)
IR Bandpass Filters	Spectrogon / Northumbria Optical	Custom per gas channel
Gold Mirror Coating Service	Optical coating vendor	R > 98%, 2-20 micrometer range
Electroless Nickel Plating	Metal finishing vendor	0.015 mm uniform thickness
CaF2 Window Blanks	Crystran / ISP Optics	Optical grade, 12.7mm dia

Appendix C: Drawing List

Drawing No.	Title	Revision
LC-P03	Main Body	Rev 3
LC-P04	Objective Mirrors Holder	Rev 3
LC-M02	Gas Cell Field Mirror Housing	Rev 4b
Assembly v03	Gas Cell Assembly (3D IGES)	v03

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