A General Overview of Continuous Emission Monitoring Systems

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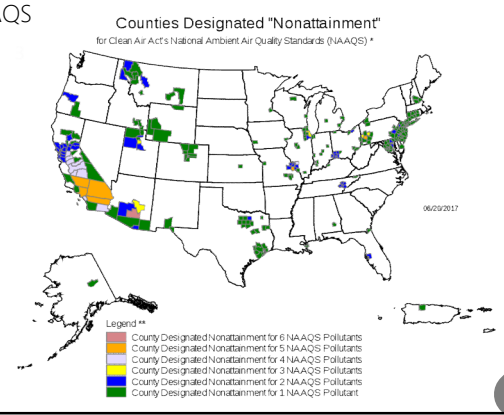
EPA REGULATIONS
CLEAN AIR ACT & AMENDMENTS

- The CAA and 1990 amendments requires the EPA to set National Ambient Air Quality Standards (NAAQS) for criteria pollutants and hazardous air pollutants emitted from stationary (industrial) sources and mobile sources deemed harmful to public health and the environment
  - Primary: Public Health
  - Secondary: Public Welfare
- EPA sets limits, for specific pollutants, on how much of each pollutant can be in the air anywhere in the U.S.
- Gives EPA, States, and Tribes enforcement powers
  - Authority is delegated to the States if they show that they have the ability to implement a program
- States do much of the work to carry out the Act
  - Planning, implementation, enforcement
  - More stringent … never less stringent
- Allows the public to participate in the process
- Requires EPA or States to take action against violators

EPA REGULATIONS
CLEAN AIR ACT & AMENDMENTS

- Non-Attainment Areas (NAAs)
  - Areas where the NAAQSs are not met
  - NAAQS are health standards for Carbon Monoxide, Lead, Ozone, Nitrogen Dioxide, Sulfur Dioxide, and Particulate Matter (PM-10 and PM-2.5)
  - Typically heavily populated areas, or areas of heavy industry
  - May be a NAA for one pollutant, but not another
  - The NAA require a plan to meet NAAQS
- State Implementation Plans (SIPs)
  - Emissions inventory on NAA
  - Issue permits to pollution sources
  - Define control measures
  - Plan to meet NAAQS after 10 years



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CLEAN AIR ACT
WHAT IS THE EPA'S ROLL IN THIS?

- Federal Implementation Plans
  - Air pollution reduction plan in absence of a state plan
- Development and oversight of monitoring plans
  - QA/QC of CEM (Performance Specifications)
  - Industry Specific Requirements (Subparts)
  - Enforcement oversight
  - Guidance for state regulators (DNR: Dept. of Natural Resources, DEP: Dept. of Environmental Protection, AQMD: Air Quality Management Districts, etc.)
- Creation of Reference Methods
  - Standards used for source testing and certification of CEM
  - Different from Performance Specifications for the monitoring system

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OVERVIEW OF EPA REGULATIONS

The U.S. EPA requires that each analyzer installed for Continuous Emission Monitoring (CEM) must be tested, following installation, to verify compliance with the applicable Federal Standards and Regulations:

- 40 CFR Part 60, Appendix B – Instrument Performance Specifications
- 40 CFR Part 60, Appendix F – Quality Assurance Procedures
- 40 CFR Part 60, 61, 63 – Reference Methods
- 40 CFR Part 60 – Industrial Subparts
- 40 CFR Part 75 – Continuous Emission Monitoring (Acid Rain)

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40 CFR PART 60
APPENDIX B

- Definition of CEM Performance Specifications
  - How an analyzer should be designed and operated
- Generally not technology specific
  - Performance specification for SO_2, NO_X, CO, or HCl … not for UV, CLD, NDIR or TDLS
  - One exception: PS15 is specific to FTIR Analyzers
- What functions should the analyzer system be able to perform
  - Where should the analyzer be mounted
  - Daily zero and span check
  - Maintenance
  - Calibration procedures
  - Outputs
- The EPA does not certify gas analyzers. It is the responsibility of the manufacturer and the operator to ensure compliance with the Performance Specification.

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40 CFR PART 60
APPENDIX B

Parameter	PS 2	PS 3	PS 4	PS 4a	PS 4b
Gas component	SO2 & NOx	CO2 & O2	CO 1000 ppm f.s.	CO < 200 ppm	CO + O2
Calibration drift (CD) test	at low level (zero or up to 20% of f.s.) + high level (50 - 100% of f.s.), [can be non-certified gas cells or optical filters] measured 1x per day for 7 consecutive days when facility is operating at > 50% of normal load	at low level (zero or up to 20% of f.s.) + high level (50 - 100% of f.s.) [can be non-certified gas cells or optical filters] measured 1x per day for 7 consecutive days when facility is operating at > 50% of normal load	at low level (zero or up to 20% of f.s) + high level (50 - 100% of f.s.), [can be non-certified gas cells or optical filters] measured 1x per day for 7 consecutive days when facility is operating at > 50% of normal load	at low level (zero or up to 20% of f.s) + high level (50 - 100% of f.s.) measured 1x per day for 7 consecutive days when facility is operating at > 50% of normal load	Same as PS 4a (CO) for both ranges and PS 3 (O2), measured 1x per day for 7 consecutive days when facility is operating at > 50% of normal load
Calibration drift specification	< or = 2.5% of f.s.	< or = 0.5% O2 or CO2	< or = 5% of f.s. for 6 out of 7 consecutive days	< or = 5% of f.s. for 6 out of 7 consecutive days	CO: < or = 3% of f.s. on both ranges for 6 out of 7 consecutive days, O2 < or = 0.5% O2
Measuring range(s)	f.s value is between 1.5x standard emission level and maximum allowed by the applicable subpart.	same as PS 2	span level 1000 ppm	Single Range analyzer, same as PS2. Dual Range analyzer - low range 1.5x standard emission level high range = 2000 ppm f.s.	O2: span = 25% CO low range span = 200 ppm, high range span = 3000 ppm, scale must record all readings within a measurement range with a resolution of 0.5%
Calibration error test procedure	not specified	not specified	not specified	not specified	Calibration gas (EPA protocol gas) must be injected at sample probe, through all CEMS components, three times at each measurement point and record responses.
Calibration error specification	not specified	not specified	not specified	not specified	mean difference between reference value and CEMS < or = 5% of f.s. for all 3 test points in Table 1
Calbration error concentration ranges	not specified	not specified	not specified	not specified	TABLE 1 CO Low range: 1: 0-40 ppm, 2: 60-80 ppm, 3: 140-160 ppm CO High range: 1:0-600 ppm, 2: 900-1200 ppm, 3: 2100-2400 ppm O2 1: 0-2 vol%, 2: 8-10 vol%, 3: 14-16 vol%

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40 CFR PART 60
APPENDIX B – PERFORMANCE SPECIFICATIONS

- PS 1 – Opacity Monitors (COMS)
- PS 2 – SO_2 and NO_X
- PS 3 – CO_2 and O_2
- PS 4 – CO (1000 ppm f.s.)
  - PS 4A – Low emission standard (< 200 ppm)
  - PS 4B – CO (dual range) and O_2 (specifically for Hazardous Waste Incinerators)
- PS 5 – Total Reduced Sulfur (TRS)
- PS 6 – Gas Flow Rate (CERMS)
- PS 8 – Volatile Organic Carbon
  - PS 8A – Total Hydrocarbons
- PS 11 – Particulate Matter
- PS 12A – Mercury
- PS 15 – FTIR
- PS 18 – HCl
  - Specific requirements for extractive and "integrated path" (in-situ) analyzers

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40 CFR PART 60
APPENDIX F

- Outlines the QA/QC requirements of a CEM
- Similar specification for criteria pollutants (CO, SO_2, NO_X, etc.)
- Calibration Drift Test (Daily)
  - Zero (0 - 20% f.s)
  - Span (50 - 100% f.s.)
  - Every 24 hours
  - "The reference value may be supplied by cylinder gas or optical filter and need not be certified"
- Adjustment made based on daily calibrations
  - Can they be made?
  - When?

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40 CFR PART 60
APPENDIX F

- Relative Accuracy Test Audit (RATA)
  - Compare to 3rd party CEM using Reference Methods
  - Use data from 9 of 12, 20 minute runs
  - "20 or 10"
  - Once a year
- Cylinder Gas Audit (CGA)
  - Quarterly (3 of 4 quarters, with Q4 being a RATA)
  - +/- 15% or 5ppm, whichever is greater
- Relative Accuracy Audit (RAA)
  - Alternative to Cylinder Gas Audit (CGA) when source emissions are <50% of emissions standard
  - Cylinder gas or certified calibration cells

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40 CFR PART 60
APPENDIX F

Parameter	Specification for Pollutant	Specification for Pollutant	Specification for diluent
	SO2, NOx	CO	CO2 or O2
CD	Must check calibration drift at two reference values (low and high) every 24 hrs. CD must be adjusted on the analyzer whenever the value is > 2x limit in PS 2, i.e. 5% of f.s.	Must check calibration drift at two reference values (low and high) every 24 hrs. CD must be adjusted on the analyzer whenever the value is > 2x limit in PS 4b, i.e. 6% of f.s.	Must check calibration drift at two reference levels (low and high) every 24 hrs. CD must be adjusted on the analyzer whenever the value is > 2x limit in PS 3, i.e. 1 vol%
Automatic adjustment	Can be made however, record of unadjusted value must be made or amt. of adjustment must be recorded.	Can be made however, record of unadjusted value must be made or amt. of adjustment must be recorded.	Can be made however, record of unadjusted value must be made or amt. of adjustment must be recorded.
Criteria for Excessive CD	Whenever the CD is > 2x limit for consecutive daily periods CEMS is "out-of-control", if CD is 4x limit in PS 2, i.e. 10% of f.s. on any day, the CEMS is "out-of-control"	Whenever the CD is > 2x limit for consecutive daily periods CEMS is "out-of-control", if CD is 4x limit in PS 4b, i.e. 12% of f.s. on any day, the CEMS is "out-of-control"	Whenever the CD is > 2x limit for consecutive daily periods CEMS is "out-of-control", if CD is 4x limit in PS 2, i.e. 4 vol% on any day, the CEMS is "out-of-control"
RATA (relative accuracy test audit)	same as RA test in Appendix B, must be done at least 1 of the 4 consecutive quarters	same as RA test in Appendix B, must be done at least 1 of the 4 consecutive quarters	same as RA test in Appendix B, must be done at least 1 of the 4 consecutive quarters
RATA specification	same as in Appendix B, < or = 20% when RM method results are < 50% of emission standard, < or = 10% when RM method results are > 50% of emission standard	same as in Appendix B, < or = 10% of RM average value	same as in Appendix B, < or = 20% when RM method results are < 50% of emission standard, < or = 10% when RM method results are > 50% of emission standard
RAA (relative accuracy audit)	same as RA test in Appendix B, only 3 sets of data required, can be done in 3 out of 4 consecutive quarters	same as RA test in Appendix B, only 3 sets of data required, can be done in 3 out of 4 consecutive quarters	same as RA test in Appendix B, only 3 sets of data required, can be done in 3 out of 4 consecutive quarters
RAA specification	+ or - 15% of 3 run average, or +/- 7.5% of the applicable emission standard, whichever is greater	+ or - 15% of 3 run average, or +/- 7.5% of the applicable emission standard, whichever is greater	+ or - 15% of 3 run average, or +/- 7.5% of the applicable emission standard, whichever is greater
CGA (cylinder gas audit)	challenge CEMS 3 times with each audit point: Audit point 1: 20 - 30% of span value, Audit point 2: 50 - 60% of span value, separate cylinders for audit points 1 and 2, cannot dilute gas before injecting in CEMS, Audit gas must be certified reference material (CRM).	challenge CEMS 3 times with each audit point: Audit point 1: 20 - 30% of span value, Audit point 2: 50 - 60% of span value, separate cylinders for audit points 1 and 2, cannot dilute gas before injecting in CEMS, Audit gas must be certified reference material (CRM).	challenge CEMS 3 times with each audit point: Audit point 1: CO2:5 - 8 vol%, O2: 4 - 6 vol% Audit point 2: CO2:10 - 14 vol %, O2: 8 - 12 vol% separate cylinders for audit points 1 and 2, cannot dilute gas before injecting in CEMS, Audit gas must be certified reference material (CRM).
CGA specification	+ or - 15% of average audit value, or +/- 5 ppm, whichever is greater	+ or - 15% of average audit value, or +/- 5 ppm, whichever is greater	+ or - 15% of average audit value, or +/- 5 ppm, whichever is greater

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EPA REFERENCE METHODS
"TEST METHODS"

- EPA defines reference methods for testing and measurement of specific criteria pollutants.
- Used by 3rd party stack testers for RATA comparisons and data gathering
- Do NOT offer any suggestion of a preferred measurement method by EPA
  - Up until 2006 CLD was the defined reference method for NO_X, but did not mean only this type of device could be used to measure NO_X in CEMS
- Notable Reference Methods:
  - Method 2 – Gas Flow Rate
  - Method 5 – Particulate Matter
    - Multiple variations within Method 5
    - Additional version (Method 17)
  - Method 6 – SO_2
  - Method 7 – NO_X
  - Method 8 – Acid Mist (SO_3)
  - Method 30 – Mercury

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40 CFR PART 75

- Promulgated to address "Acid Rain" concerns
- Specific to fossil fuel power generation units > 25 MW
  - Oil, Coal, Natural Gas
- Performance Specifications reference 40 CFR 60, Appendix B
- Primary differences are in QA/QC and record keeping
  - Daily calibrations required to be done with certified gas
  - Missing data substitution varies
- Currently dominated by dilution extractive CEMS
  - Historical reasons
  - Use of ambient air monitors after 50:1 / 100:1 dilution ratio
  - May be forced out eventually due to measurement constraints

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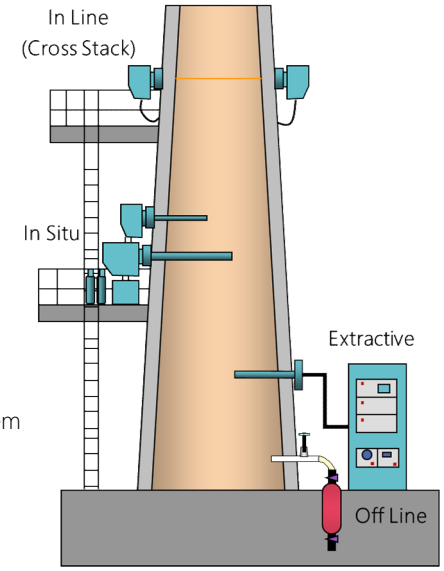
EMISSION MONITORING SYSTEMS
SAMPLING METHODOLOGIES

- In-Line / In-Situ
  - Cross Duct
  - Probe Style
- Close-Coupled Extractive (Ex-Situ)
- Cold / Dry Extractive
- Hot / Wet Extractive
- Dilution Extractive
  - With dilution at the sample probe
  - With dilution in the sample handling system
- Off-Line
  - Sample extracted and analyzed in a lab



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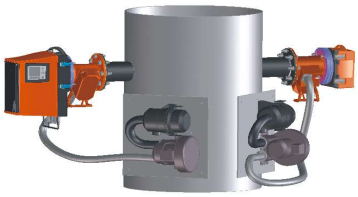
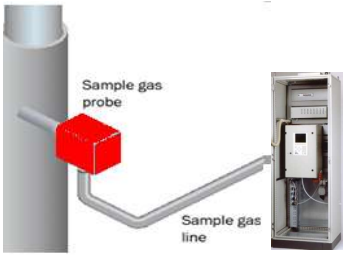
EMISSION MONITORING SYSTEMS
CHOOSING THE BEST SOLUTION

In-situ technology



Extractive technology



Both technologies are proven and state-of-the-art

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EMISSION MONITORING SYSTEMS
DESIGN CONSIDERATIONS

- Accessibility for Installation & Maintenance
- Reliability of Components
- Response Time Required
- Preventative Maintenance
  - Self-Diagnostics / Failure Protection
- Ambient Conditions for Operation & Maintenance
- Process Conditions
  - Dust Load
  - Moisture Content / Condensation
  - Corrosive / Reactive Components
  - Temperature / Pressure at Sample Point
- System Control
- Data Management
  - Analog / Digital / Modbus (RTU / TCP) / Profibus / Ethernet (OPC)

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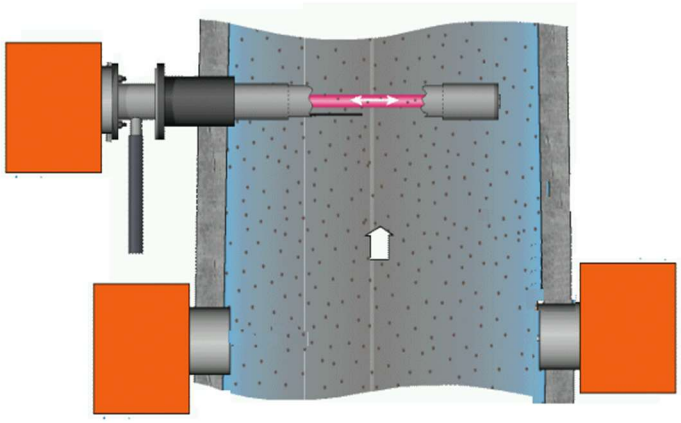
EMISSION MONITORING SYSTEMS
PRINCIPLES OF IN-LINE / IN-SITU MEASUREMENT



With Cross-Stack the process duct is the optical path
With In-Situ the reflector is mounted on the probe

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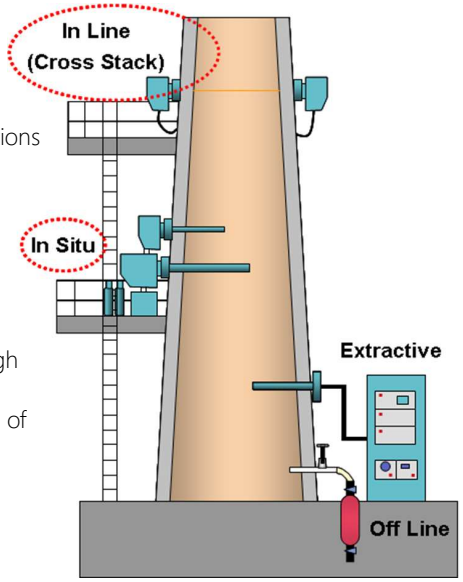
EMISSION MONITORING SYSTEMS
IN-LINE / IN-SITU

- Advantages
  - Direct installation into the process
  - Direct detection of changing concentrations
  - Almost no delay in measurement
  - Lower installation costs
- Disadvantages
  - Detector exposed directly to process temperature and pressure (measured)
  - Little or no protection from dust and high temperatures, or ambient conditions
  - Difficult for maintenance, e.g. at the top of the stack, ambient conditions, etc.
  - Compliance calibration issues



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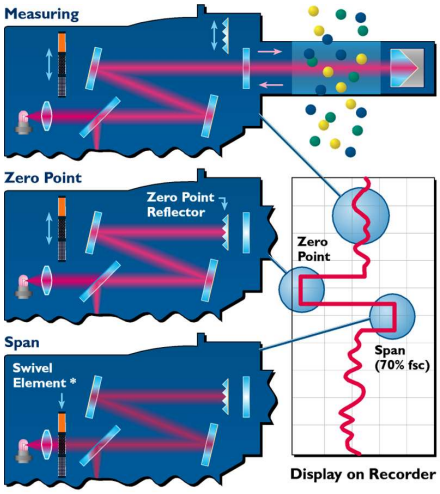
EMISSION MONITORING SYSTEMS
CALIBRATION REQUIREMENTS



- For compliance Daily Zero and Span measurements are required
- Zero measures the response of the analyzer with no process gas present
- Span measures the ability of the analyzer to respond correctly

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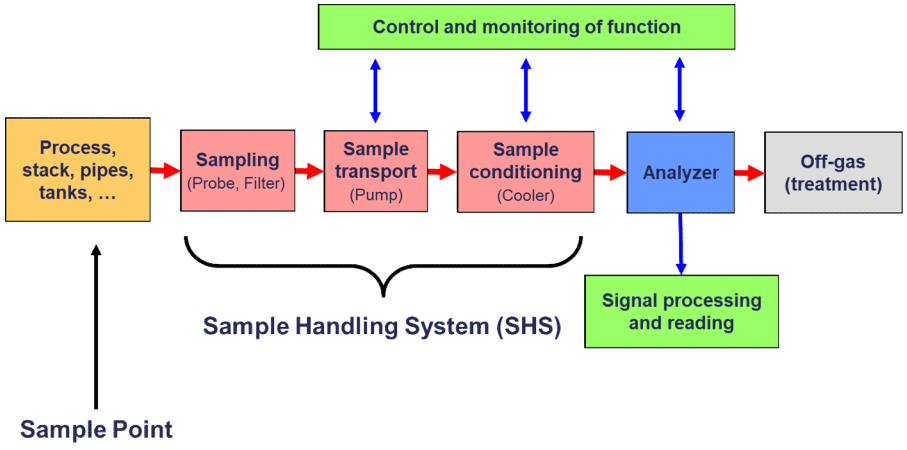
EMISSION MONITORING SYSTEMS
PRINCIPLES OF ON-LINE EXTRACTIVE SYSTEMS



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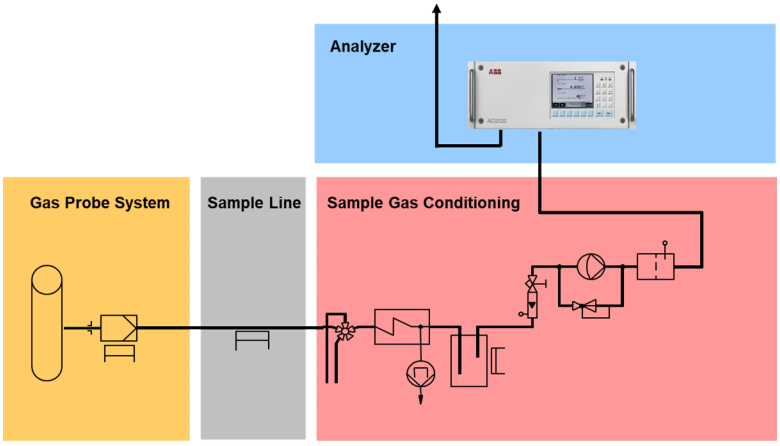
EMISSION MONITORING SYSTEMS
COMPONENTS OF ON-LINE EXTRACTIVE SYSTEMS



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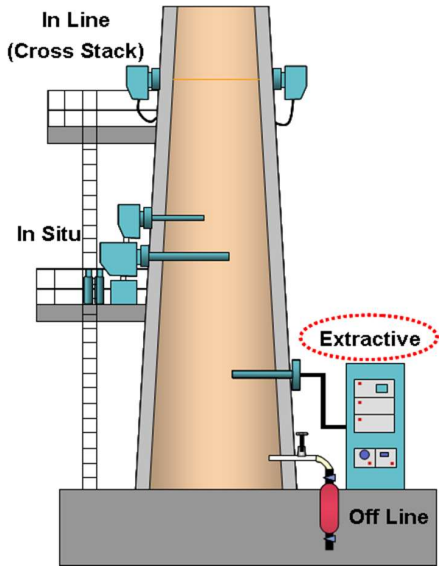
EMISSION MONITORING SYSTEMS
ON-LINE EXTRACTIVE

- Advantages
  - Easy maintenance at the analyzer
  - Multi-component measurement
  - Easy calibration with test gas
  - Sample gas conditioning possible
- Disadvantages
  - Additional effort for sampling handling and conditioning
  - Disposing of the sample gas
  - Leaks in sample line or system causing measurement errors
  - Potentially long response time
  - Higher installation costs



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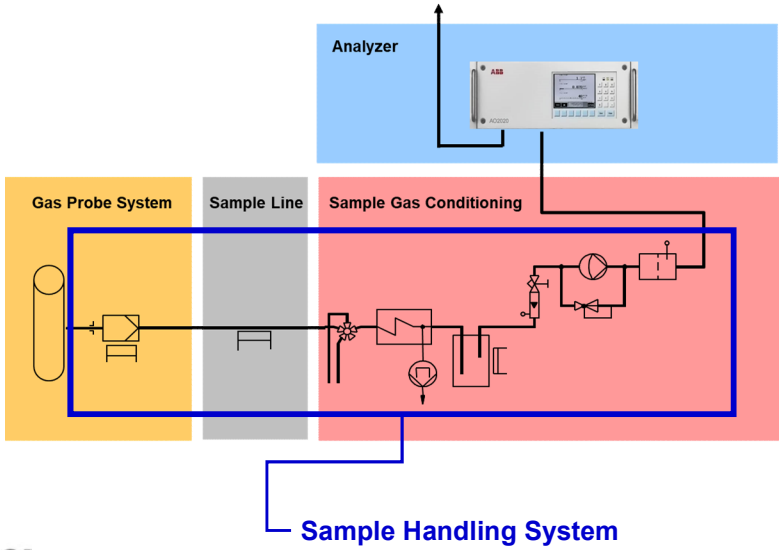
ON-LINE EXTRACTIVE SYSTEMS
COMPONENTS OF SAMPLING & CONDITIONING SYSTEM



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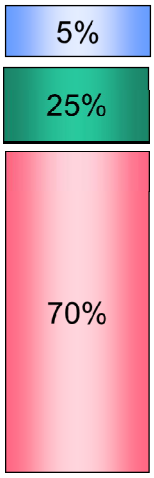
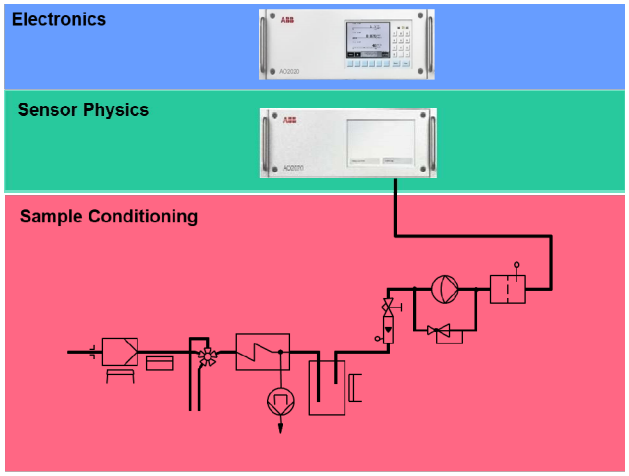
ON-LINE EXTRACTIVE SYSTEMS
IMPORTANCE OF SAMPLING SYSTEM





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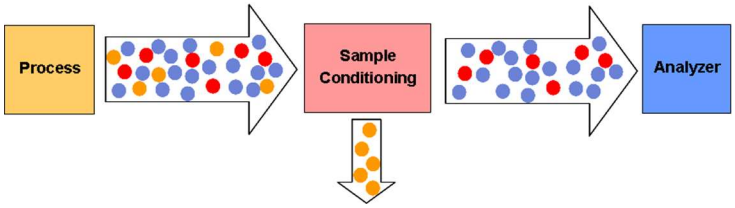
ON-LINE EXTRACTIVE SYSTEMS
SAMPLE HANDLING SYSTEM REQUIREMENTS



- Removal of solids (particulate, dust, etc.)
- Removal of condensable components (e.g. H_2O)
- Removal of corrosive components and interfering components
- Pressure / temperature reduction
- Sample transport

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ON-LINE EXTRACTIVE SYSTEMS
SAMPLE HANDLING SYSTEM CONCERNS

- Sample gas composition
  - Physical (temperature, pressure)
  - Chemical (corrosive, reactive) characteristics of the sample gas
  - Gas inlet conditions of the analyzers
- Control of temperature throughout the analysis system to prevent
  - Salt formation
  - Unwanted condensation
  - Chemical reactions
- Selection of suitable materials in contact with sample gas to prevent
  - Adsorption / Desorption
  - Off-gassing of tubing and seals
- Correct placement of dust filters and condensate traps
- Isolation of interfering or cross-sensitivity components in the sample gas

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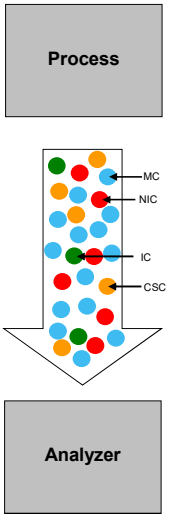
ON-LINE EXTRACTIVE SYSTEMS
SAMPLE GAS COMPOSITION



- Measured Component (MC)
  - Component of interest
  - Concentration measured by the analyzer
- Non-Interfering Component (NIC)
  - Not measured
  - Does not influence the SHS or analyzer
- Interfering Component (IC)
  - Influences the functionality of the SHS or analyzer
- Cross Sensitivity Component (CSC)
  - Causes a deviation of the analyzer reading due to similar physical characteristics to the measuring component

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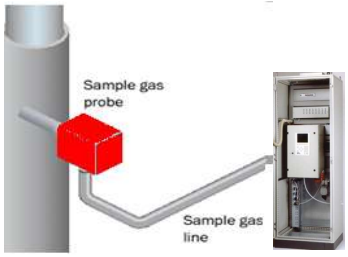
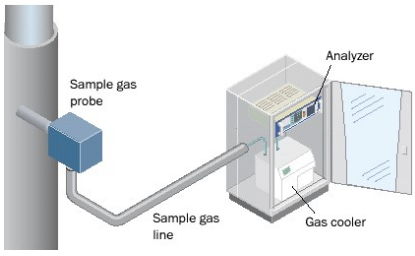
ON-LINE EXTRACTIVE SYSTEMS
CHOOSING THE BEST SOLUTION



Extractive Hot WET



Extractive Cold DRY

Consider the lifetime costs in relation to the initial investment

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ON-LINE EXTRACTIVE SYSTEMS
COLD / DRY SYSTEMS

- Sampling probe and line are kept hot (above sample gas dew point)
- Heated filter at the probe to remove particulate matter (dust)
- Flash cooler reduces the temperature to 35 … 40 °F
- Water vapor is condensed out of the sample gas stream
- "Dry" sample gas is measured by the analyzer

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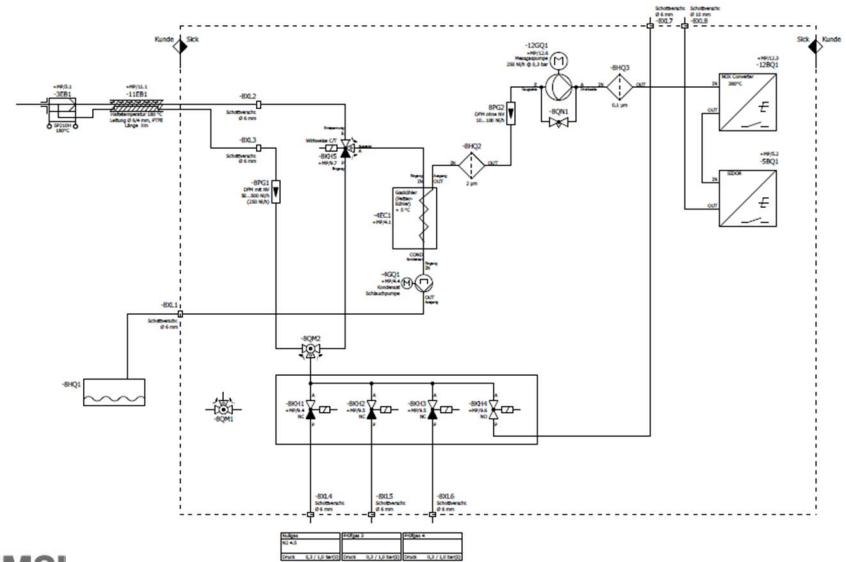
COLD / DRY EXTRACTIVE SYSTEM
TYPICAL FLOW DIAGRAM



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ON-LINE EXTRACTIVE SYSTEMS
WHY COLD / DRY ?

- Lower cost for analyzers
- Water vapor affects some measurements (particularly IR)
- Removal of corrosive gases
- Removal of cross interfering / condensable gases
- Improved sample conditioning and isolation of desired components
- Precise temperature control in sample handling system not as critical

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ON-LINE EXTRACTIVE SYSTEMS
HOT / WET SYSTEMS

- Sampling probe, sample line, pump, and analyzer are all heated
- Keeping sample gas hot prevents condensation – retains moisture content
- Approx. 40 °F above sample gas dew point (up to 200 C / 392 °F)
- Still need filters to remove particulate at the probe and analyzer
- "Wet" sample is measured by the analyzer

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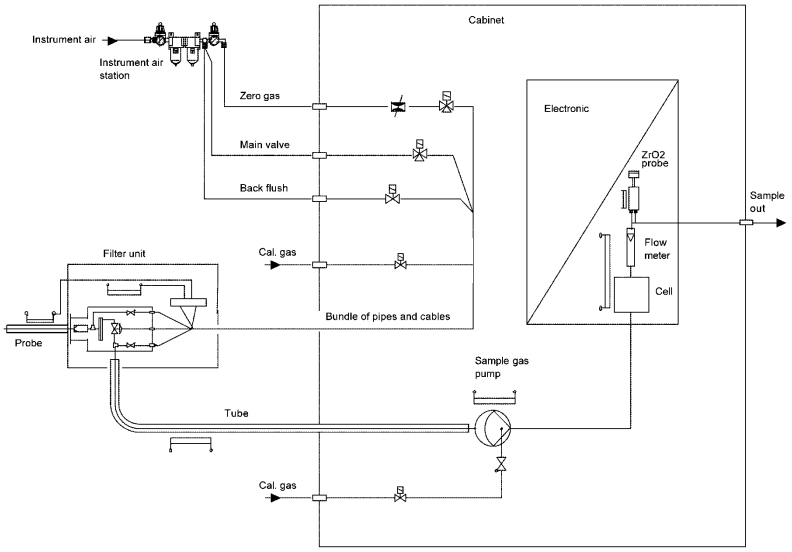
HOT / WET EXTRACTIVE SYSTEM
TYPICAL FLOW DIAGRAM



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ON-LINE EXTRACTIVE SYSTEMS
WHY HOT / WET ?

- Measurement of soluble gases (HCl, HF, NO_2 and NH_3)
- Requirement for water vapor measurement
- Reduced corrosion with high SO_2 / H_2SO_4 in the sample gas
- Lower maintenance costs due to less sampling components
- Typically lower cost for sample handling system, but analyzer costs more
- Commonly used in coal-fired power generation, incinerators & cement kilns
- Where there's an industry need for higher accuracy

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ON-LINE EXTRACTIVE SYSTEMS
DILUTION SYSTEMS

- Dilution can be done directly at the probe or in sample handling system
- Dilution system must be kept hot (above sample gas dew point)
- Diluting sample gas prevents condensation – retains moisture content
- Dilution ratios from 10:1 up to 500:1 can be achieved via critical orifice
- Higher dilution ratios require heated bypass injector to shorten response time
- Requires precision pressure and temperature control for accurate dilution
- Requires high sensitivity analyzer measurement (sub-ppm)

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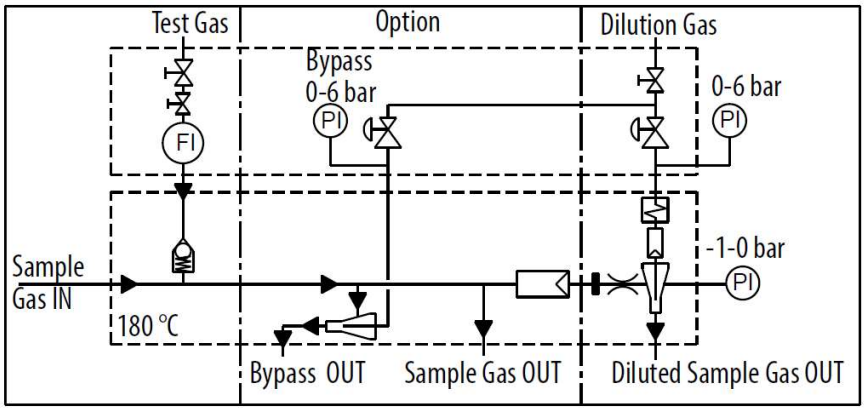
DILUTION EXTRACTIVE SYSTEM
TYPICAL FLOW DIAGRAM



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ON-LINE EXTRACTIVE SYSTEMS
WHY DILUTION ?

- Dilution at sampling probe may eliminate need for heated sample line
- Reduced corrosion with high SO_2 / H_2SO_4 in the sample gas
- Measurement of soluble gases and water vapor possible
- Lower maintenance costs due to less sampling components
- Typically lower cost for sample handling system and analyzers
- Utilizes same analyzer technologies as ambient air monitoring
- Historically used in coal-fired power generation industry

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MEASUREMENT TECHNOLOGIES
FOR GAS COMPONENTS

• NDIR / FTIR	CO / CO_2 / CH_4 / SO_2 / NO / NO_2 / NH_3 / HCl / HF
• NDUV	NO / NO_2 / SO_2
• TDLS / QCLS	NH_3 / HCl / HF / CO / CO_2 / CH_4 / O_2
• Paramagnetic	O_2
• Electrochemical	O_2
• Chemiluminesence	NO / NO_2
• UV Fluorescence	SO_2
• Flame Ionization	THC / VOC
• AAS / CVAF	Hg

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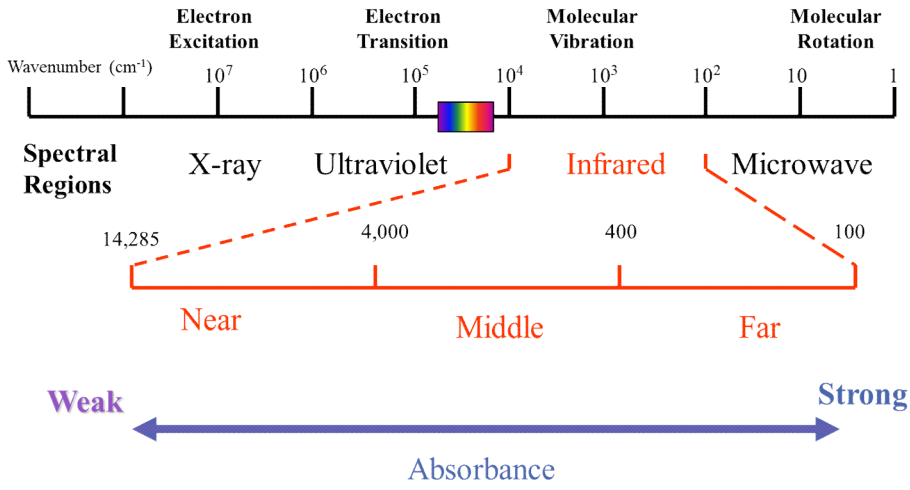
PHOTOMETRY BASICS
SPECTRAL REGIONS



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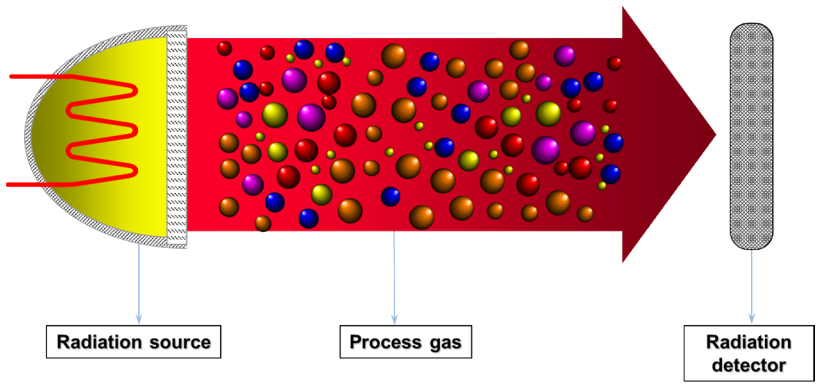
PHOTOMETRY BASICS
LAMBERT-BEER LAW



$$I = I_0 e^{-\varepsilon l c}$$

$$\frac{I_0 - I}{I_0} = A = 1 - e^{-\varepsilon l c}$$

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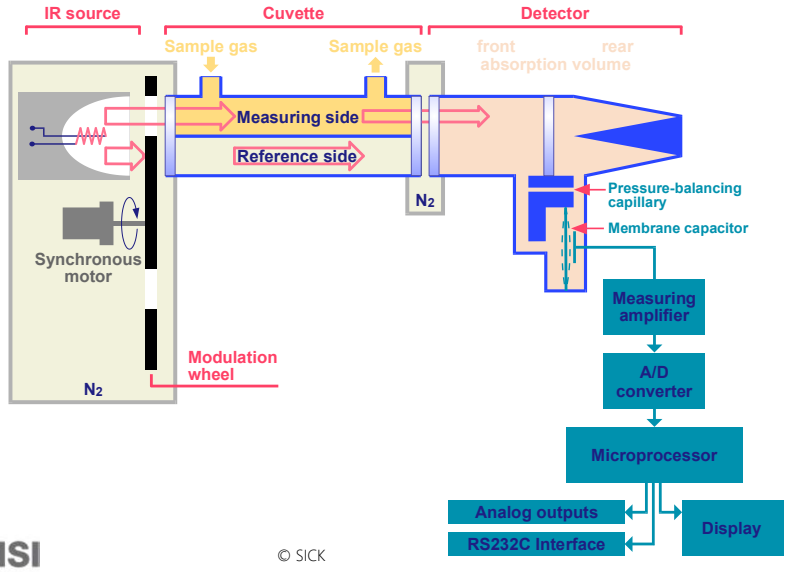
NON-DISPERSIVE INFRA-RED
MEASUREMENT PRINCIPLE (LUFT DETECTOR)



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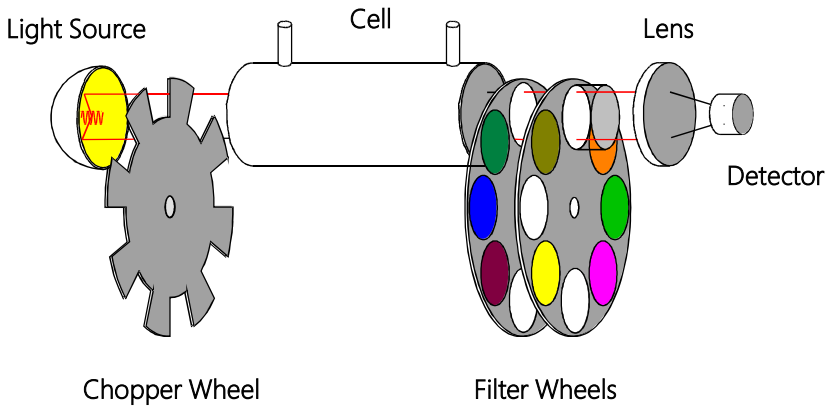
NDIR FILTER PHOTOMETER
MEASUREMENT PRINCIPLE



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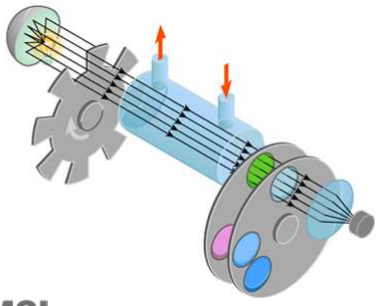
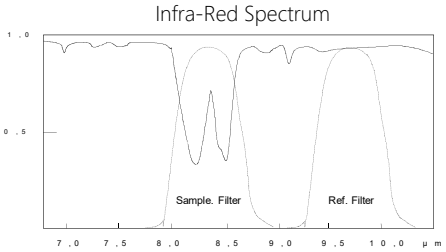
NDIR FILTER PHOTOMETER
DUAL WAVELENGTH TECHNIQUE

- Signal processing
  - Absorbance = – log (U Sample/U Ref)
  - Due to ratio measurement (Sample/Ref) all drift effects (source, detector, windows) are compensated
  - Typical components: SO_2, NO_2, CO_2, H_2O





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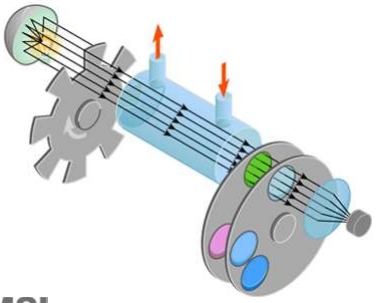
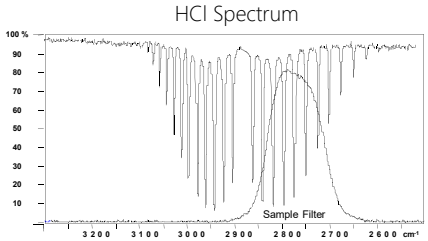
NDIR FILTER PHOTOMETER
GAS FILTER CORRELATION TECHNIQUE

- Signal processing
  - Absorbance = – log (U Sample/URef)
  - The gas filter eliminates the HCl spectrum to obtain a reference signal. The gas filter correlation technique suppresses interferences, because they are measured on both signal channels (sample and reference signal).
  - Typical components: HCl, NO, CO, NH_3





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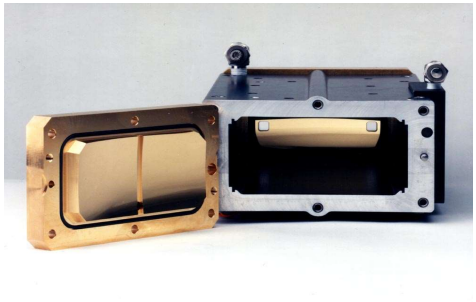
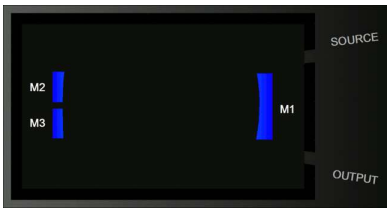
NDIR FILTER PHOTOMETER
WHITE GAS CELL

- Integrated mirrors
- Pre-adjusted optical path length of 3, 6, 12 m
- Working temperature 200°C (225°C optional)
- Gas filter at gas inlet
- Corrosion resistant
  - Gold covered mirrors with special surface coating





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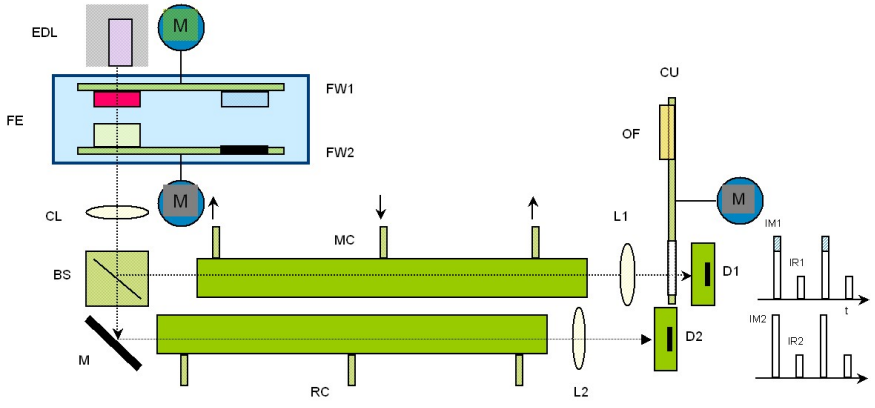
NDUV / UV-RAS
MEASUREMENT PRINCIPLE



EDL UV lamp
M Motor
FW1 Filter wheel 1
FW2 Filter wheel 2
FE Filter enclosure
CL Collimator lense

BS Beam splitter
M Mirror
MC Measuring cuvette
RC Reference cuvette
L1, L2 Lenses (collecting)
CU Calibration unit
OF Optical filter

D1, D2 Detectors

IM1 Intensity measurement detector 1
IR1 Intensity reference detector 1
IM2 Intensity measurement detector 2
IR2 Intensity reference detector 2

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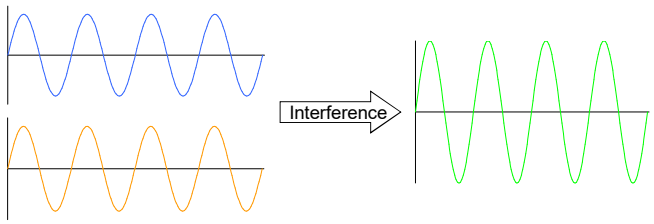
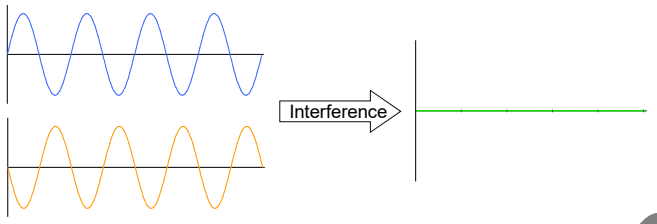
FOURIER TRANSFORM INFRA-RED
MEASUREMENT PRINCIPLE

- When coherent light waves are superimposed …
  - Constructive interference



  - Destructive interference



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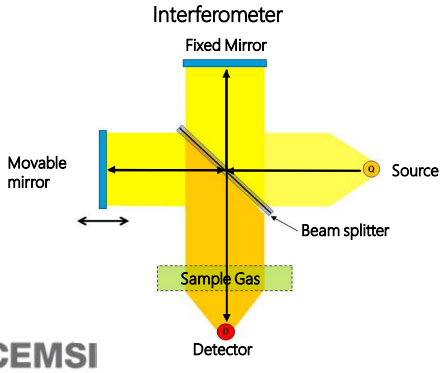
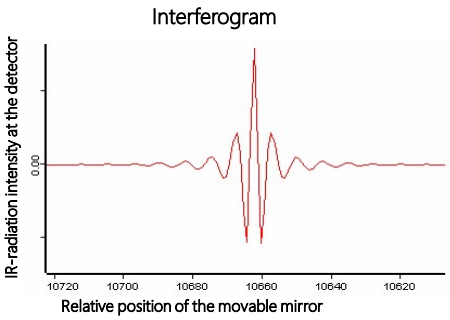
FOURIER TRANSFORM INFRA-RED
MICHELSON INTERFEROMETER

- The Interferometer splits the light beam emitted by an IR source into
  - a fixed part
  - and a part that is periodically phase-delayed
- When superimposing one partial beam on the other, an interferogram is formed, which is recorded by the detector





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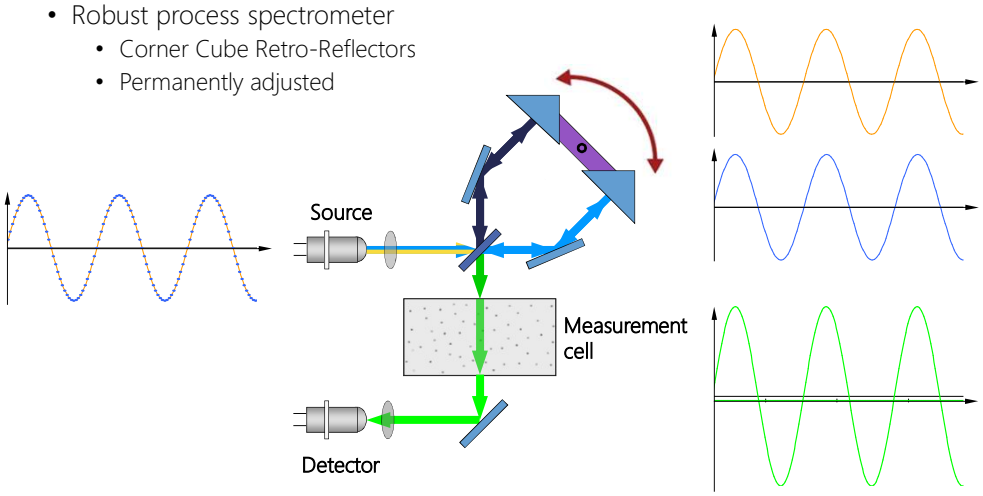
FOURIER TRANSFORM INFRA-RED
IR-CUBE INTERFEROMETER

- Robust process spectrometer
  - Corner Cube Retro-Reflectors
  - Permanently adjusted



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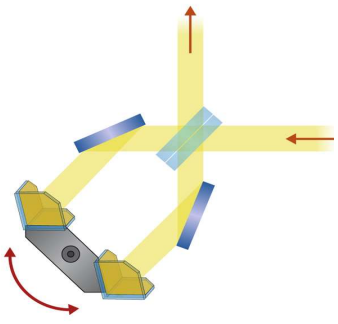
FOURIER TRANSFORM INFRA-RED
IR-CUBE INTERFEROMETER

- Based on the Corner Cube Technology with Retro-Reflectors
- Advantages of this technique
  - Insensitive to vibrations
  - Insensitive to temperature variations
  - Permanently adjusted
  - Reliable and robust technique, well-established in process chemistry
  - High spectral resolution
  - High measuring rate



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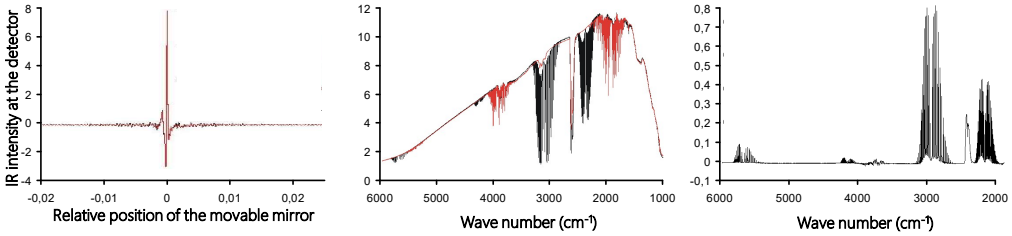
FOURIER TRANSFORM INFRA-RED
CALCULATING THE SPECTRUM

- Example
  - Sample gas with HCl
  - Reference gas

Interferogram → Fourier Transform → Raw Spectrum → Standardization → Absorbance Spectrum



- Absorbance spectrum
  - Selection of an appropriate spectral range for each measurement component => Calculation of gas concentration (proven PLS* method)
  - Considering thousands of reference spectra

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* PLS .... partial least square

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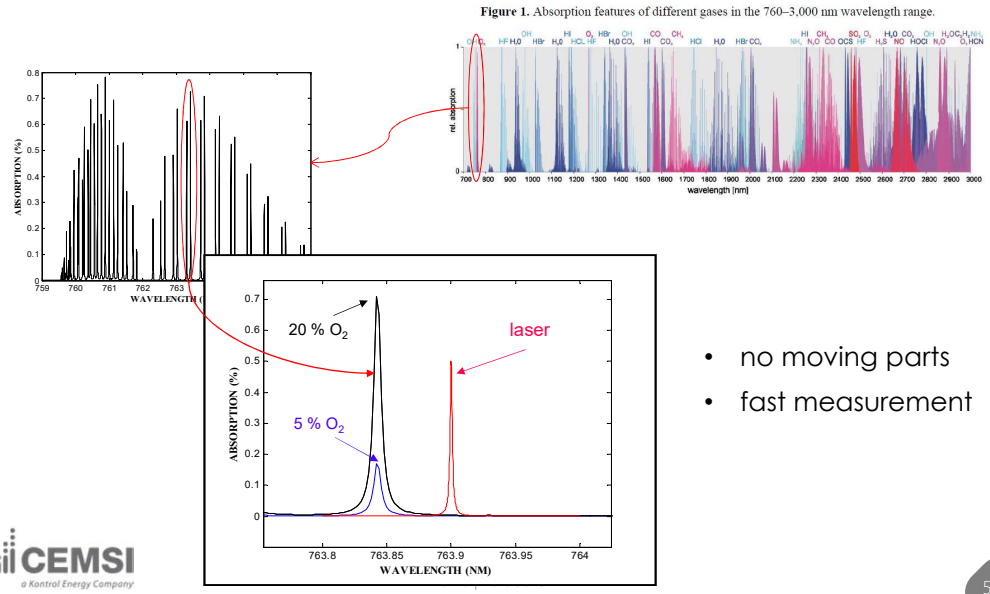
TUNEABLE DIODE LASER SPECTROSCOPY
MEASUREMENT PRINCIPLE



- no moving parts
- fast measurement

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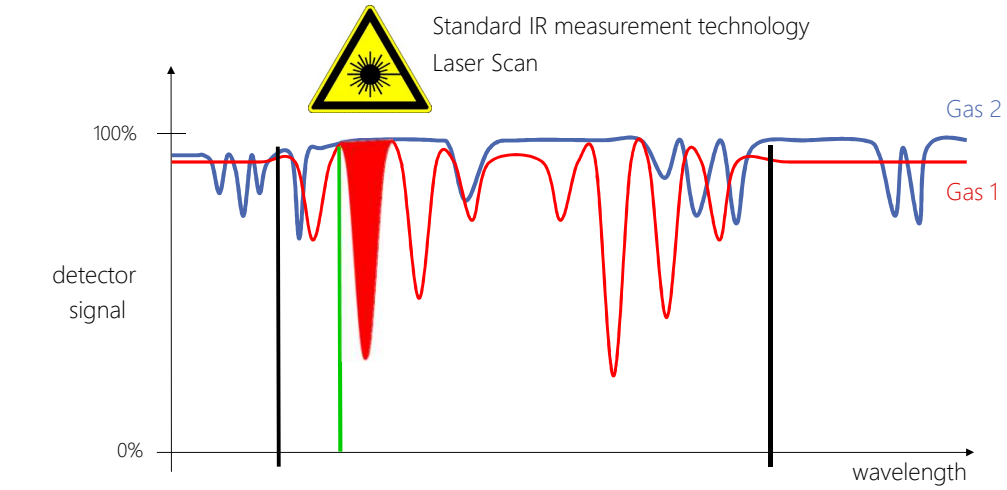
TUNEABLE DIODE LASER SPECTROSCOPY
MEASUREMENT PRINCIPLE



concentration ~ -log ($I_{meas}/I_{reference}$)

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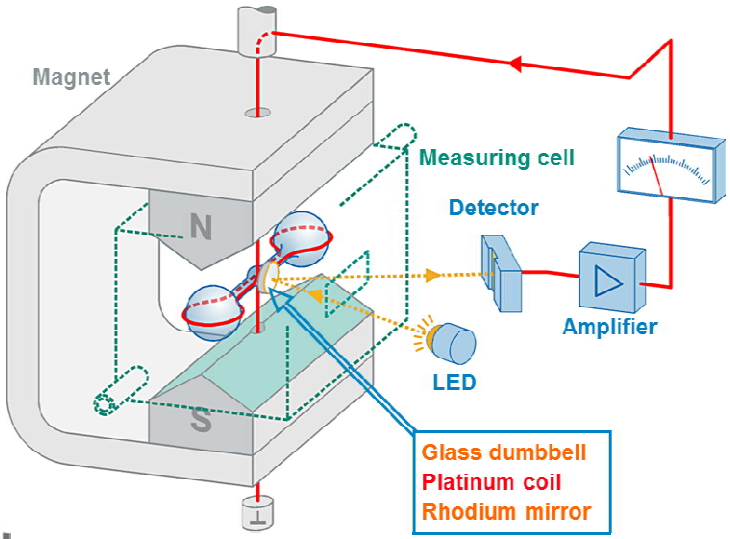
PARAMAGNETIC OXYGEN
MEASUREMENT PRINCIPLE (MAGNETOMECHANICAL)



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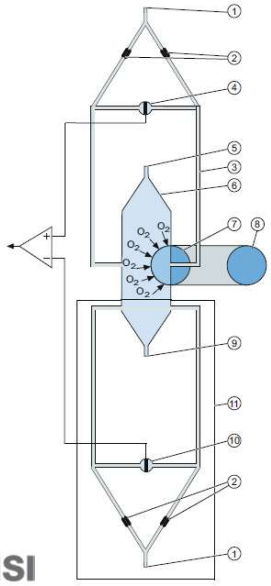
PARAMAGNETIC OXYGEN
MEASUREMENT PRINCIPLE (MAGNETOPNEUMATIC)



① Reference gas inlet
② Restrictors
③ Reference gas channels
④ Microflow sensor
⑤ Sample gas inlet
⑥ Measuring chamber
⑦ Paramagnetic measurement effect
⑧ Electromagnet with alternating current strength
⑨ Sample gas and reference gas outlet
⑩ Microflow sensor in the vibration compensation system (flow-type)
⑪ Vibration compensation system (optional)

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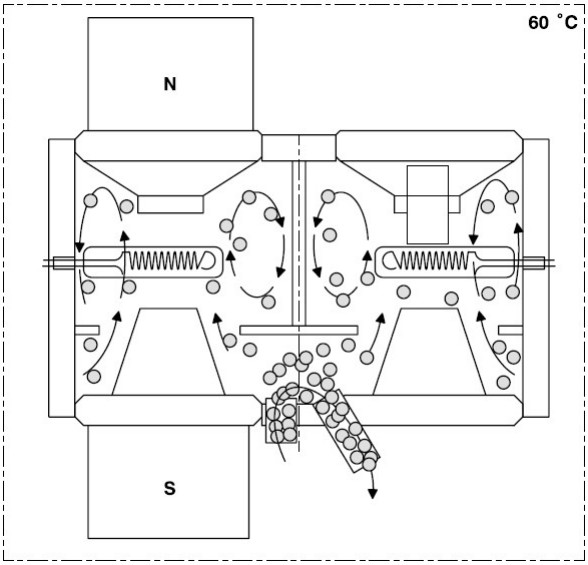
PARAMAGNETIC OXYGEN
MEASUREMENT PRINCIPLE (THERMOMAGNETIC)



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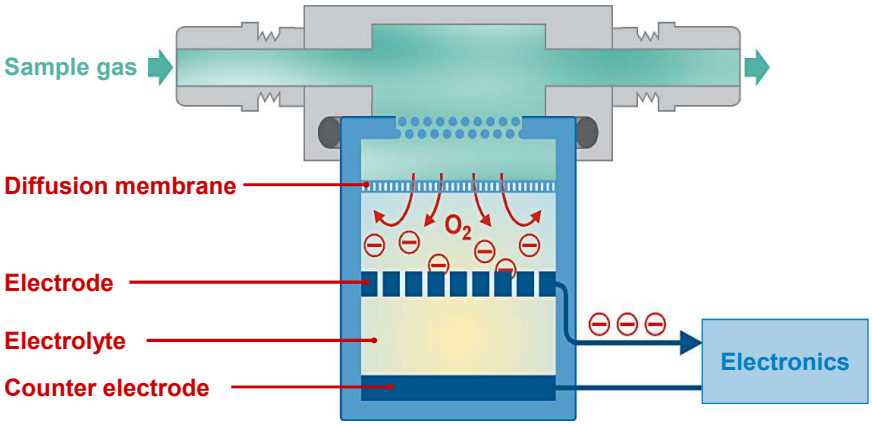
ELECTROCHEMICAL OXYGEN
MEASUREMENT PRINCIPLE (GALVANIC)



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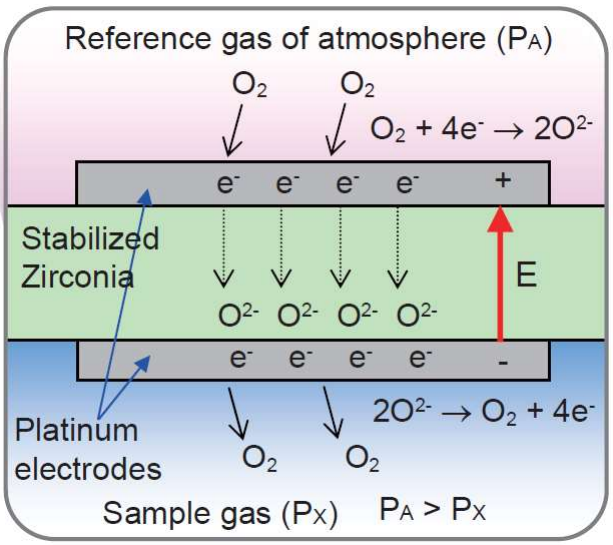
ELECTROCHEMICAL OXYGEN
MEASUREMENT PRINCIPLE (POTENTIOMETRIC)



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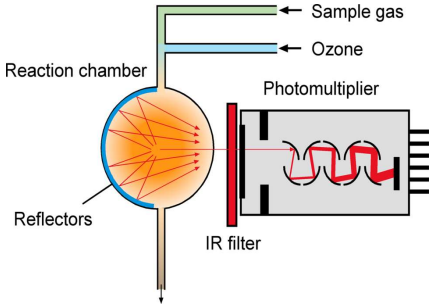
CHEMILUMINESCENCE
MEASURING PRINCIPLE

- Ozone produced from dry air is mixed with sample gas
- The mixture enters the reaction chamber, where NO in the sample gas reacts to NO_2 ($NO + O_3 \rightarrow NO_2 + O_2 + h\nu$)
- A proportion of the reaction energy is emitted as radiation ($h\nu$)
- The radiation is detected, enhanced and transformed into the detector signal by the photomultiplier



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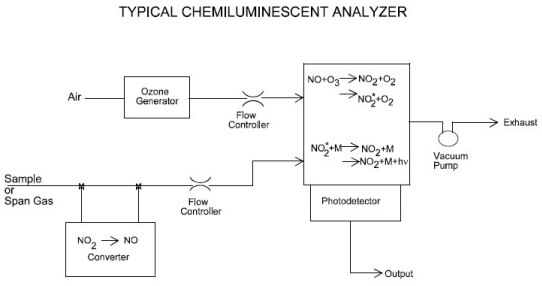
CHEMILUMINESCENCE
MEASURING PRINCIPLE

- To measure NO_2 …
- NO_2 in the sample gas is converted to NO by the integrated catalytic converter and then measured as NO the in the reaction chamber
- The difference between both measurements corresponds to the NO_2 content of the sample gas



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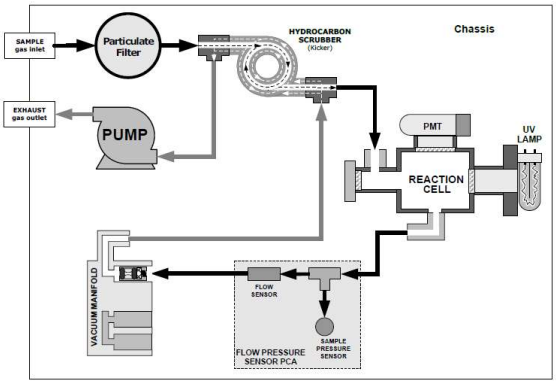
UV FLUORESCENCE
MEASURING PRINCIPLE

- Pulsating UV light excites the SO_2 in the sample gas
- As the excited SO_2 molecules decay to a lower energy state they emit UV light of a longer wavelength / lower energy
- A bandpass filter allows only the wavelength emitted by the excited SO_2 molecules to reach the photomultiplier tube (PMT)



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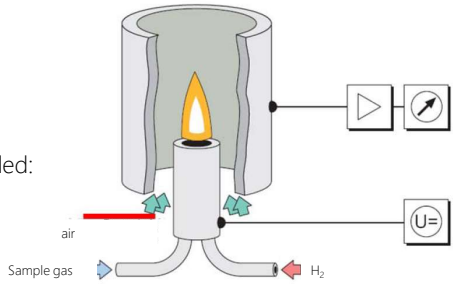
FLAME IONIZATION
MEASURING PRINCIPLE

- Name of the technology
  - FID = Flame Ionization Detector
- What is measured using an FID?
  - VOC = Volatile Organic Carbons, also called:
  - THC = Total HydroCarbons or
  - TOC = Total Organic Carbon



- What is the working principle of an FID?
  - continuously burning flame (H_2+O_2)
  - sample gas is lead into a flame
  - organic compounds are cracked to CH fragments
  - CH fragments are oxidized to CHO^+ ions
  - an electric current occurs (pA)
  - the current is proportional to the concentration of carbon

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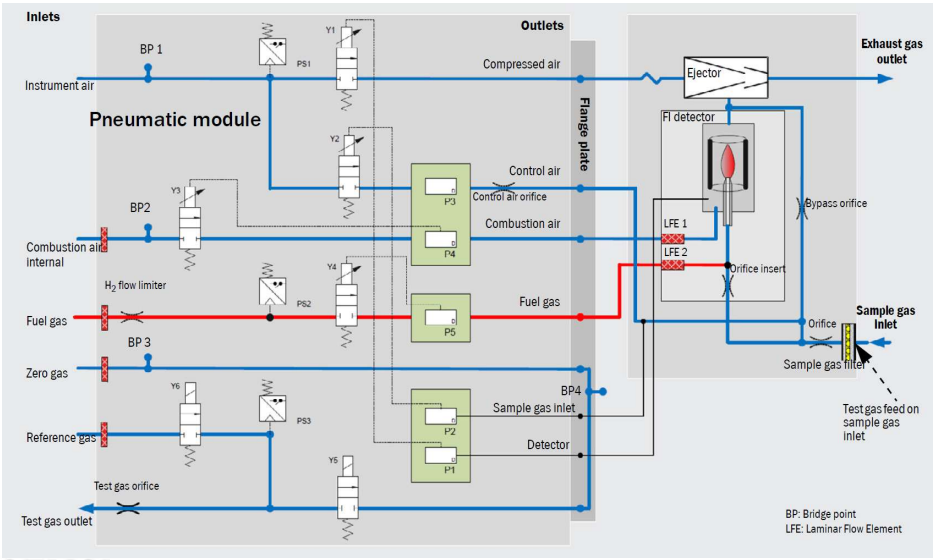
FLAME IONIZATION
TYPICAL GAS FLOW SCHEMATICS



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MEASUREMENT TECHNOLOGIES
FOR DUST / PARTICULATE MATTER

- Opacity / Transmissivity / Extinction
- Scattered Light (in-situ)
  - Backward scatter
  - Forward scatter
- Scattered Light (extractive)
- Probe Electrification / Triboelectric (charge transfer)
- Beta Attenuation
- Optical Scintillation
- Gravimetric (reference method)

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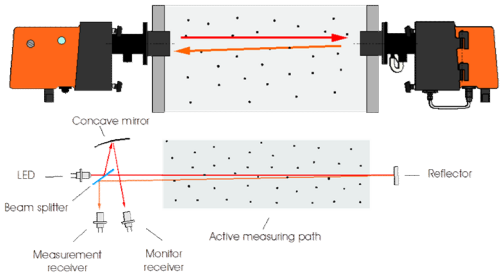
TRANSMISSION / OPACITY / EXTINCTION
MEASUREMENT PRINCIPLE

- A light beam is sent across the stack and measured on the opposite side (single path) or reflected back and measured on the sender side (double path)
- Measuring the amount of light received as a ratio of the amount of light emitted:
  - Transmission ($T = I / I_0$) is the percentage of light received
  - Opacity ($O = 1 - T$) is the percentage of light lost
  - Extinction ($E = \log [1 / T]$)
  - Dust concentration ($C = \ln [T] / [-k * L]$)



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TRANSMISSION / OPACITY / EXTINCTION
PERFORMANCE EVALUATION

- ADVANTAGES
  - Representative measurement cross-stack
  - Suitable for emission and process monitoring
  - Independent of gas velocity & particle charge
- DISADVANTAGES
  - Two-sided mounting (higher installation costs)
  - Continuous purge air necessary (both sides)
  - Physical detection limits for low concentrations
  - Initial "zero adjustment" in dust-free environment required

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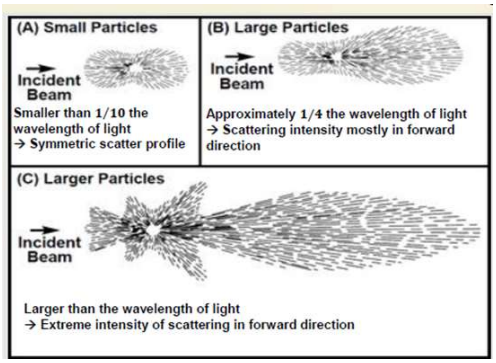
SCATTERED LIGHT
MEASUREMENT PRINCIPLE

- A modulated laser diode beams light onto the dust particles in the gas flow
- A highly sensitive detector register the light scattered by the particles
- Measured scattered light intensity is proportional to dust concentration



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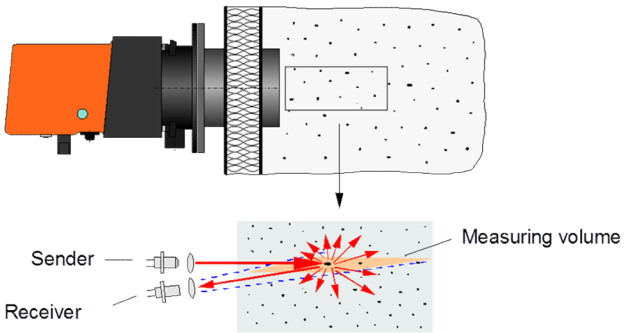
SCATTERED LIGHT - BACKWARD
MEASUREMENT PRINCIPLE

- The transmitter and receiver optics are located at the same side of the stack at a angle to one another which defines a specific measuring volume in the flue gas (e.g. 250 mm, 1000 mm)
- One-sided mounting saves installation and maintenance costs



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SCATTERED LIGHT - BACKWARD
PERFORMANCE EVALUATION

- ADVANTAGES
  - Sensitive for low to medium dust concentrations
  - One-sided installation (without light trap)
  - Wide application range with several penetration lengths
  - Independent of gas velocity & particle charge
  - Applicable in very high process temperatures
- DISADVANTAGES
  - Continuous purge air necessary
  - Influence of background and ambient light in very narrow stacks
  - May require a light trap mounted on opposite wall

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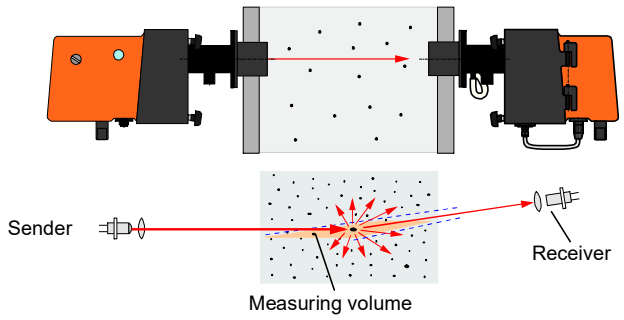
SCATTERED LIGHT - FORWARD
MEASUREMENT PRINCIPLE

- The transmitter and receiver optics are located at the opposite sides of the stack at a angle to one another which defines a specific measuring volume
- Very sensitive for low dust concentrations



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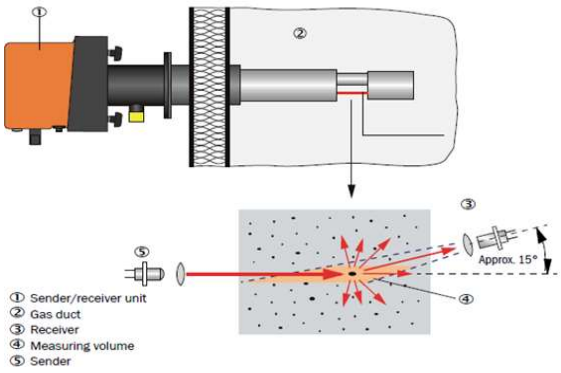
SCATTERED LIGHT - FORWARD
MEASUREMENT PRINCIPLE

- Probe design makes for easy installation and with a fixed measuring volume
- One-sided mounting saves installation and maintenance costs
- Well-suited for thick or double walled stacks



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SCATTERED LIGHT - FORWARD
PERFORMANCE EVALUATION

- ADVANTAGES
  - Very sensitive for low dust concentrations
  - One-sided installation (probe version)
  - Independent of gas velocity & particle charge
  - Applicable in very high process temperatures (cross-duct version)
- DISADVANTAGES
  - Continuous purge air necessary
  - Probe could get damaged in processes with corrosive gas matrix

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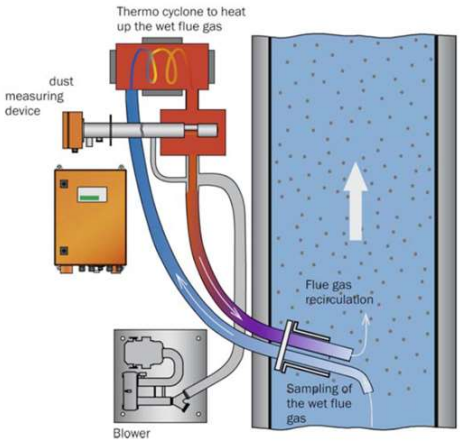
SCATTERED LIGHT - EXTRACTIVE
MEASUREMENT PRINCIPLE

- Extractive scattered light measurements are used when the stack gas is below the dew point and therefore contains water droplets, e.g. after a wet scrubber
- A probe extracts a partial volume of gas from the stack, which is then heated to evaporate water droplets and aerosols
- Dust in the dried gas dust is measured using a scattered light instrument in a special cuvette, before being returned to the stack



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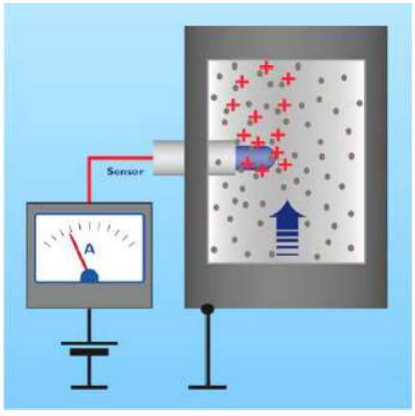
PROBE ELECTRIFICATION
MEASUREMENT PRINCIPLE

- Probe electrification measuring devices detect charge when a dust particle strikes or passes close to a conductor placed in the stack
- Striking the conductor generates a DC signal measured by most triboelectric devices
- Charged particles passing close to the conductor induce a charge of equal and opposite magnitude in the conductor, generating an AC signal measured by electrodynamic devices



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PROBE ELECTRIFICATION
PERFORMANCE EVALUATION

- ADVANTAGES
  - One-sided installation
  - Cost effective
  - No purge air necessary
- DISADVANTAGES
  - Measurement depends on gas velocity, moisture content of the particles, operating conditions of the separator, and contamination of the probe
  - No automatic function tests with zero and span value
  - The probe needs to be cleaned often as it get less sensitive with surface contamination, leading to high maintenance costs

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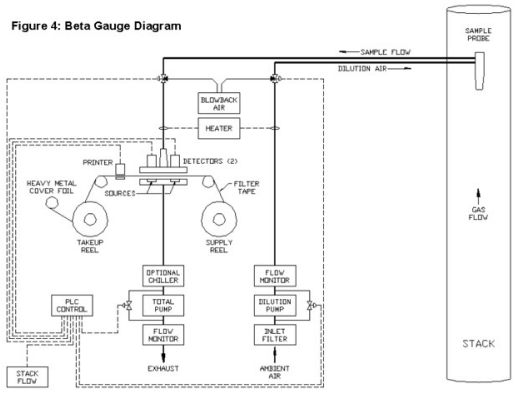
BETA RADIATION TECHNOLOGY
MEASUREMENT PRINCIPLE

- Alternative method for measuring in wet stack gas
- Dust particles are collected isokinetically on a filter paper tape and the change in transmission of beta-particles from a radioactive source is monitored

Figure 4: Beta Gauge Diagram



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BETA RADIATION TECHNOLOGY
PERFORMANCE EVALUATION

- ADVANTAGES
  - Output directly in dust concentration without correlation
  - Suitable for gases both above or below dew point
- DISADVANTAGES
  - Point measurement may not representative
  - Discontinuous measurement - only every ten minutes
  - High capital investment costs
  - High spare part consumption, especially filter paper
  - High maintenance effort
  - Beta radiation source requires qualified staff

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GRAVIMETRIC COMPARISON
FOR DUST / PARTICULATE MATTER

- No continuous method can measure dust concentration directly
- Gravimetric comparison measurement is required for calibration
- This measurement determines the dust concentration at the measurement site under different load conditions of the plant and different fuels
- A correlation curve results from comparison of the measured values from the online equipment and those determined by gravimetric measurements
  - At least 15 value pairs must be identified for the calibration
  - The procedure is defined by EPA standards PS 1 & PS 11
- Gravimetric measurement is based on following steps:
  - Isokinetic sampling of the gas flow at a representative measurement point
  - Collection of the particles in a filter element
  - Measurement of the gas velocity and gas temperature
  - Weighing of the filter before and after sampling and calculation of the particle mass
  - Calculation of dust concentration from particle mass and sample volume

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"When there's no room for error, trust the experts."

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