Tracer Gas Inleakage Testing Experience In Korean Nuclear Power Plants

(한국 원자력 발전소에서 추적가스를 이용한 Inleakage 시험 경험)

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Terms

- CRE: Control Room Envelope
- CREEVS: Control Room Envelope Emergency Ventilation System
- MER: Mechanical Equipment Room
- Inleakage: The entrance of untreated air into the CRE *by any means* when the CREEVS is operating

Lagus Applied Technology, Inc. (LAT)

- Founded in 1990
- Primary business is tracer gas testing of complex ventilation systems, contaminant migration studies in the built environment, and manufacture of specialized tracer gas analyzers
- Senior staff posses *in excess* of 120 person-years experience in all aspects of tracer gas testing

LAT History

- LAT principals authored ASTM Standard E741.
- LAT principals developed ASTM Standard E2029.
- LAT principals taught the US NRC about tracer gas testing technology.
- LAT performed first tracer gas inleakage tests in US, Japan, Korea, China, and the UAE.

KFTL Expertise

- KOLAS Certification
  - In-place testing of air and gas filters
  - In-place testing of air cleaning units

- Expertise in design, performance, construction and testing
  - HEPA Filter systems
  - Charcoal Adsorber systems
  - HVAC Systems
  - Control Room Habitability

KFTL & LAT Partnership

- Since 2011, KFTL and LAT have partnered to provide quality tracer gas inleakage measurement services to the Korean Nuclear Power Industry.
- LAT has provided over 100 hours of classroom
  - Training in the theory and practice of tracer gas inleakage testing.
- KFTL/LAT have performed over 25 inleakage tests.
  - 7 KOREAN nuclear power plants
  - Significant experience applying classroom principles

Why measure inleakage?

- Nuclear power plants require accurate assessment of inleakage during emergency operation.
  - Assess control room dose during radiation accident
  - Evaluate toxic gas hazard
- Demonstrate compliance with GDC 19, i.e. less than 5 rem (0.05 Sievert) during a Design Basis Accident.
- Explicitly required in US NRC Reg Guide 1.197

Advantages of a Tracer Gas Test?

- Directly *measures* Air Inleakage into Control Room Envelope (CRE) under *actual* operating conditions.
  - Makes no assumptions about leak site distribution or system performance.
- Also can directly measure component leakage, i.e. dampers, ducts, shaft seals.
- Often can locate actual in (or out) leakage sites as an aid in sealing CRE or Emergency Ventilation System.

Major Issues with *any* Tracer Gas Test

- Injecting tracer gas into a CRE, *ALWAYS* results in a tracer gas concentration *in* the CRE.
- Experimentally measure average concentration in CRE
  - Uncertainty in this value is a major factor in the total uncertainty of the measurement of inleakage
- Well mixed gas concentration in the CRE obeys the solution to a first order differential equation.
- Entering concentration data into this solution always yields a numerical result.

Numerical Inleakage Test Result

- **Detailed technical knowledge and experience are required to ensure that the resulting numerical values reflect actual system performance.**
  - Heart surgery by reading a book is dangerous!
  - The same holds true for inleakage testing.

Inleakage for Pressurization Systems

Inleakage is the difference between the Total amount of air flowing into the CRE and the air supplied by the CREEVS to the CRE

$$Q_{inleak} = Q_{tot} - Q_{mu}$$

Pressurization Mode Inleakage

- Plants with low allowable inleakage and large pressurization (make-up) flow rates need high precision measurements of Q_{tot} and Q_{mu}
  - Modern Korean plant design Q_{mu} = 3000 CFM
  - Allowable Inleakage = 25 CFM

Therefore, Total Inflow = 3025 CFM

- Precisely and Accurately measuring the difference between two large numbers (3025 and 3000) is DIFFICULT.

- This difficulty is the fundamental measurement problem for tracer gas inleakage testing.
  - Use ANSI/ASME PTC 19.1 to assess accuracy and uncertainty.

Test using ASTM Standard E741

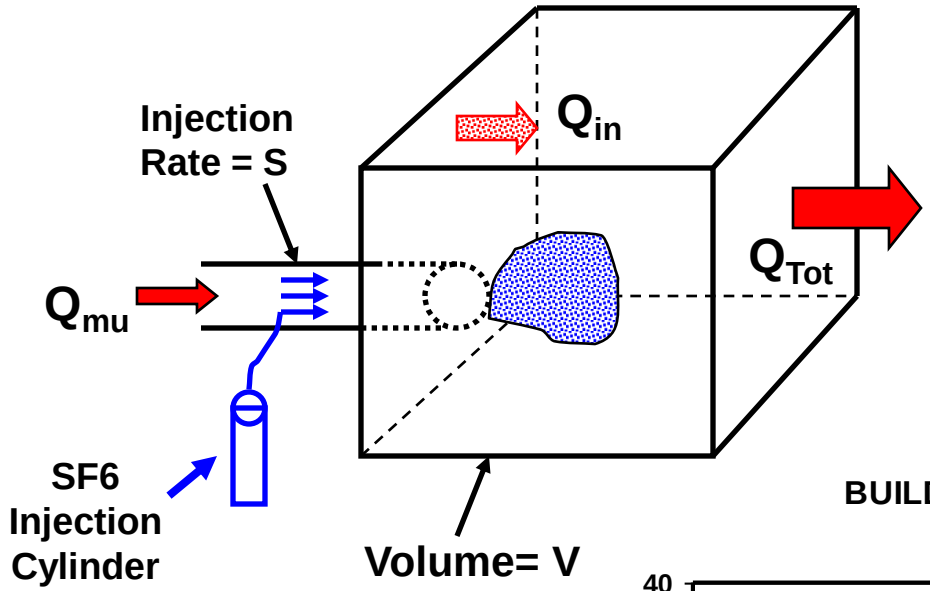
- Developed during the Energy Crisis in 1970's
  - Primarily used to improve energy conservation in single family or small multi-unit dwellings
  - Did not place limits on accuracy but requires it to be reported
  - Required concentration uniformity of 10% for valid test
    - For Inleakage testing need +/-2% uniformity.
- ASTM E741 does not obligate GC usage.
  - Nevertheless, GC is specifically mentioned and is considered the "Gold Standard" for E741 measurements.
- The techniques described in ASTM E741 are ideally suited to measure inleakage into Nuclear Power Plant control rooms.

ASTM Standard E741

- Use Tracer Gas Techniques to Measure Total Air Inflow
  - Based on Conservation of Mass

- Standard describes three distinct tracer gas tests that can be used to measure inleakage
  - Constant Injection Test
    - Most useful for Pressurization CREEVS
  - Concentration Decay Test
    - Most useful for Recirculation CREEVS
  - Constant Concentration Test
    - Primarily a research type test

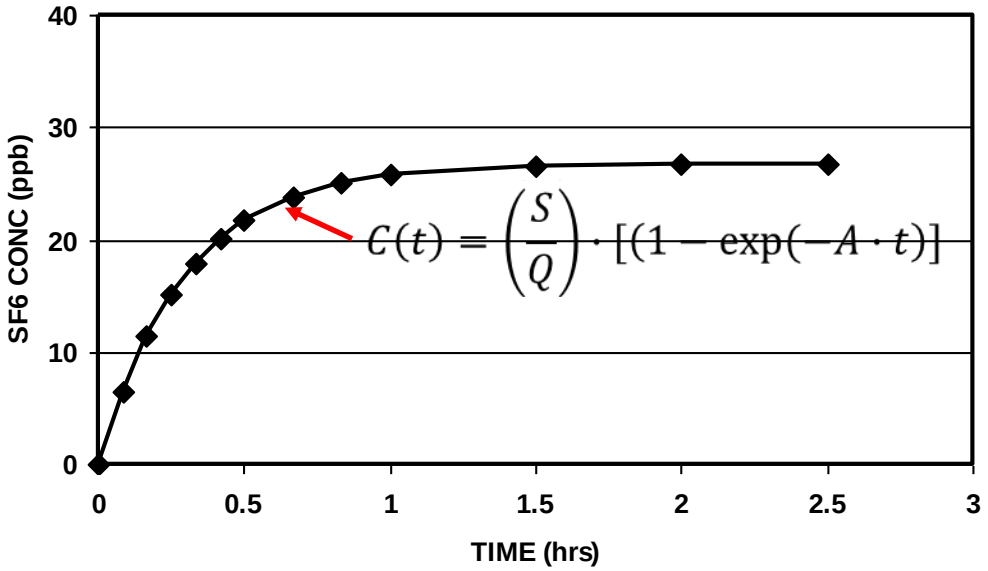
Constant Injection Test



1. Inject SF6 at Constant Rate
2. Mix SF6 throughout Volume
3. Measure concentration in Volume
4. At equilibrium, calculate Total Inflow

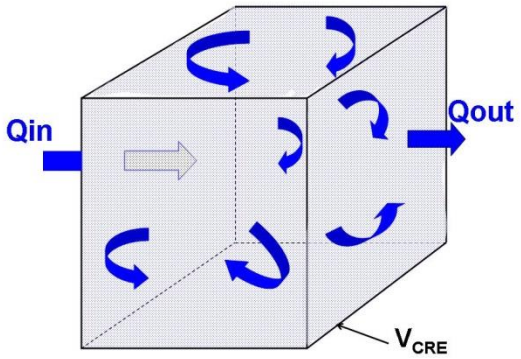
$$Q_{Tot} = S/(C_{eq} - C_{out})$$

BUILDUP/STEADY STATE TEST



Concentration Decay Test

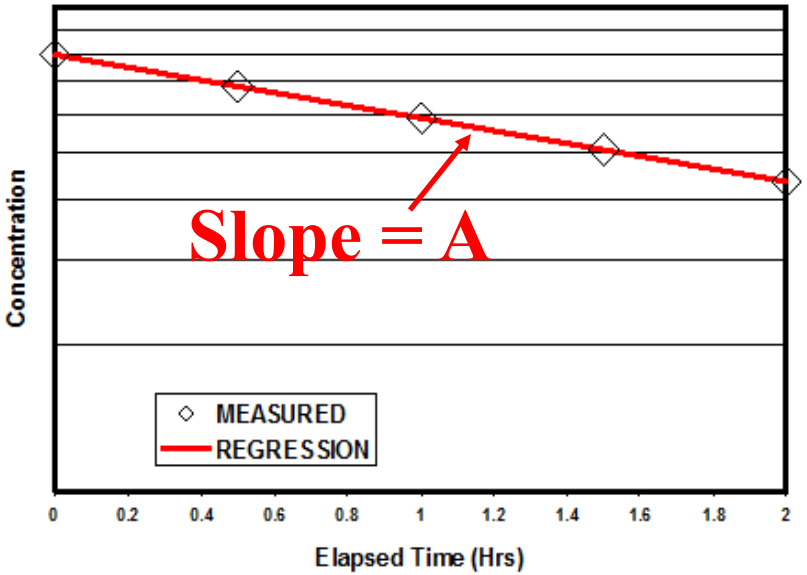
1) Inject tracer and thoroughly mix in the volume



2) Measure mean concentration as function of time

Time (Hrs)	Mean Concentration
0.0	C0
0.5	C1
1.0	C2
1.5	C3
2.0	C4

3) Plot concentration vs time and calculate slope by regression.



4) Multiply slope (A) by volume to determine Total Inflow

$$Q_{tot} = A \cdot V$$

Pressurization Air Flow Measurement (Q_{mu})

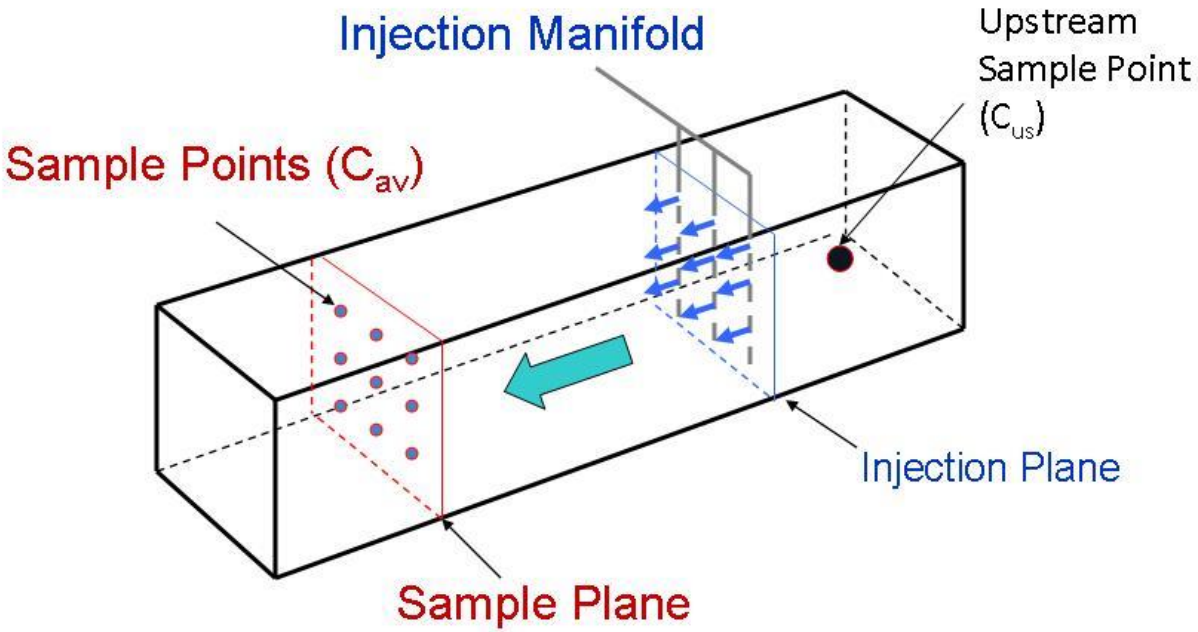
- Flow traverse
  - Pitot tube
  - Thermo-anemometer
    - Accuracy is in 5% to 10 % range (per ASHRAE Std 111)

- Tracer Gas dilution measurement
  - Continuous injection of tracer into duct at known flow rate
  - Described in ASTM Standard E2029
    - Can achieve accuracy of +/-3%

Tracer Gas Flow Rate Measurement

(ASTM Standard E2029)

$$Q_{mu} = S/(C_{av} - C_{us})$$



Major Inaccuracies

- CRE Concentration Uniformity
  - Must be approx 2% or better for low inleakage P-mode tests
  - Require minimum of 10-20 sample points
- Calibration gas concentration uncertainty
  - Laboratory Analysis uncertainty 2%
- CRE Volume Uncertainty for Decay Tests
  - Typically 5% - 10 %. Not suitable for low inleakage P-mode tests
- CRE Concentration uncertainty consists of
  - Calibration uncertainty, analyzer repeatability, uncertainty in calibration curve, and degree of non-uniformity

Additional Uncertainties

- Tracer injection gas concentration uncertainty
  - approx 1% for mixtures, 0.01 % for pure gas
- Tracer gas injection flow rate uncertainty
  - approx 1% for mass flow controller, 5% for rotameter
- Tracer re-entrainment concentrations.
- Measured CRE concentration MUST be in analyzer calibration range

Re-entrainment and MER Background

- Re-entrainment of tracer gas must be measured and taken into account.
- Many plants have MERs that are external to the CRE.
  - Outleakage of tracer from HVAC housings and duct work in MER causes increased concentration and will impact test results.
  - This leakage MUST be corrected for.
- KFTL/LAT has the knowledge and experience to understand these subtle details.

Sulfur Hexafluoride, SF6, is used for Inleakage testing

- Non toxic, inert, colorless, odorless.
- Not a normal constituent of plant atmosphere.
  - Possible background from switchyard
- Not adsorbed by nuclear carbon filter systems.
- Detectable at very low concentrations (parts per billion to parts per trillion).

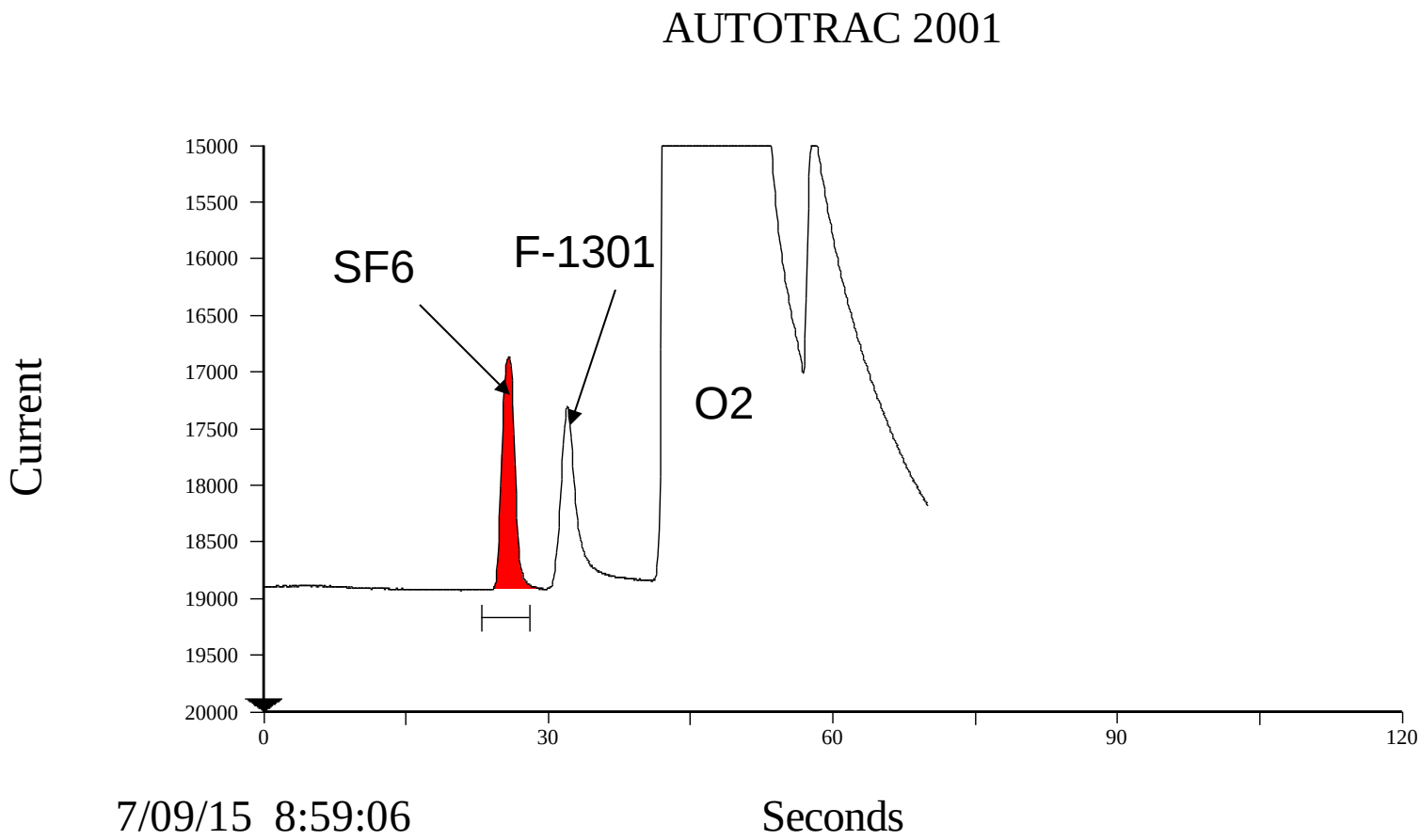
SF6 is potent greenhouse gas

- 100 year Global Warming Potential is 22,300.
- Thus 1 kg of SF6 absorbs 22,300 times as much thermal energy as 1 kg of CO2!
- To minimize environmental impact, use as little SF6 as possible in a particular test to achieve a desired result.
  - Use a very sensitive gas analyzer

Gas Analyzers for Inleakage Testing

- Continuous Photoacoustic Detector (PAD)
  - SF6 Measurable Limit >20 parts per billion.
  - Atmospheric moisture induced Baseline Drift.
  - Moisture must be corrected for Calibration stability.
  - No visual output to check interferent response
- Gas Chromatograph
  - Accepted method for precision gas analysis
  - Electron Capture Detector (ECD)
    - Lower Detection Limit of 1 to 100 parts per trillion
    - Specific response-very few interferences
    - Uses small radioactive source for ionization of gas stream

Chromatogram plot showing different gaseous constituents



Gas Chromatograph

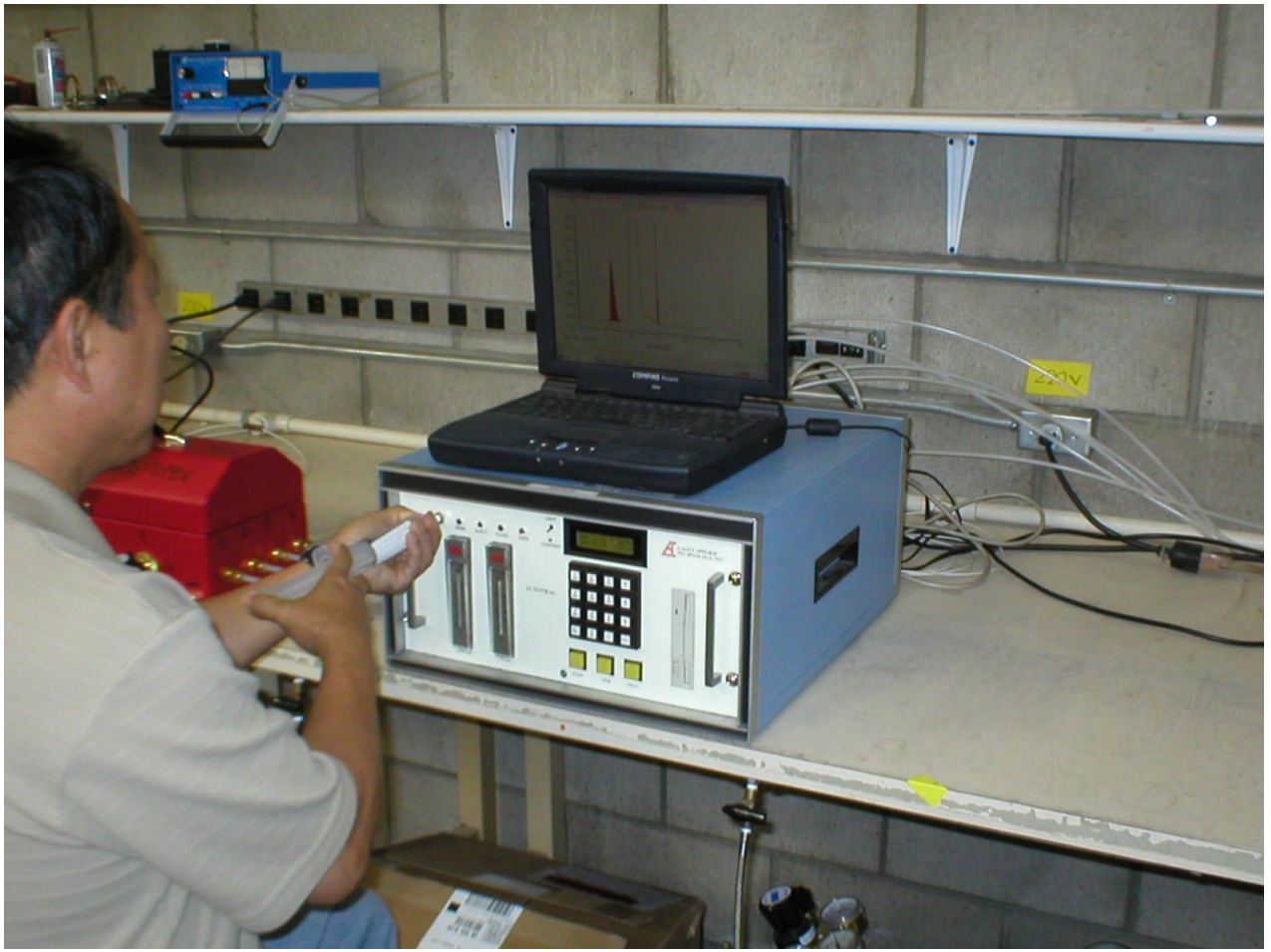
- Reliable, precise and accurate
- Operating principles of various types of detectors are well known and documented
- Calibration and operation protocols are well understood
- Sensitivity (detection limits) and stability (response & drift characteristics) are well known
  - Chromatograph response doesn't exhibit significant drift
  - Onboard cal gas cylinder corrects for drift

AUTOTRAC Chromatograph

ITEM		UNCERTAINTY
AUTOTRAC Chromatograph		
	Repeatability	1-3% of value
	Drift	< 2% of value
Calibration Gas		
	> 1ppm	1% of value
	1 ppm – 0.1 ppb	2% of value
Automatic Calibration		Check
Sample using gas tight syringes		

Syringe Sampling

Syringe Analysis



Syringe Sampling

- Sample syringes are inexpensive.
- Syringes are never re-used, thereby eliminating any issues of cross contamination of samples.
- Syringes are easily used in conjunction with AUTOTRAC Analyzer.
- Simple to collect large number of samples.

Photo-acoustic Detector (PAD)

- Operates as a continuous gas analyzer.
- Detector uses pulsed IR source.
- Measures small changes in detector temperature depending on IR absorption of particular gas.
- Uses different optical filters to detect different gases.

Photo-acoustic Detector (PAD)

ITEM		UNCERTAINTY
PAD		
	Repeatability	1 % of value*
	Drift	2.5% of value/3 months
	Calibration Gas	
	Not Specified	
	Calibration	**Required 4X per year**
Grab Samples using inert sample bags		* Above 50 ppb

Bag Analysis

Bag Sampling

- Sample bags are more expensive than syringes
- Sample bags require a pump to fill bag with an individual sample.
- Sample bags must be evacuated and tested for contamination before re-use.
  - With PAD can't measure less than 20 ppb
  - This is a time consuming process
- Because of the above three points, often fewer samples are obtained.
  - E741 *requires* sufficient samples to demonstrate gas mixing in CRE (section 12.4)

PAD vs. AUTOTRAC

- ASTM E741 suggests daily field calibration check.
- ASTM E2029 *requires* field calibration check.
- AUTOTRAC does this automatically.
- AUTOTRAC measurable limit for SF6 is 0.1 ppb
  - (when configured for CRE inleakage testing)
- PAD does not provide automatic calibration check capability.
- PAD measurable limit for SF6
  - Lies between 20 and 50 ppb.

Analyzer Summary

- PAD measurable limit is >20pbb. Chemical analysis practice recommends measurements at 10X.
  - E 741 suggests 20X.
  - Minimum operating concentration is 200 ppb.
  - Operating at 400 ppb to 500 ppb is preferable.
- PAD is useless for inleakage testing below about 50 ppb.
- AUTOTRAC uses a 15 ppb cal point.
  - Typically operate near 20 ppb.
  - Can configure to analyze over a lower range.
- AUTOTRAC requires 10-20 times less SF6 for inleakage test with a corresponding lower environmental impact.

KFTL/LAT Joint Testing

- KFTL/LAT sample all zones in CRE to verify Uniformity of Concentration criteria. ONLY adequate number sample points will satisfy this requirement.
  - A recent test at a new plant showed low tracer concentrations in computer room
    - Inadequate supply air to the computer room.
    - Cause was damper failure to open--retest was required.
- In prior testing of 7 Korean plants KFTL/LAT obtained between 85 up to 145 CRE samples
  - Demonstrate Uniform Concentration

Summary

- KFTL/LAT is the *only* test team that has been trained by the developers of the test techniques that are mandated by the US NRC for use in CRE Inleakage Testing.

- KFTL/LAT have jointly undertaken inleakage testing at 7 Korean nuclear power plants.

- KFTL/LAT developed extensive set of copyrighted test procedures that ensure technically superior and defensible inleakage data.

- KFTL/LAT use tracer gas analyzers specifically designed for use in tracer gas ventilation testing.