

# **Condition Monitoring of Power Transformers using Dissolved Gas Analysis (DGA)**

Ahmad Shahsiah, Ph.D., P.E.  
Exponent Failure Analysis Associates

March 16, 2009

# Overview

- DGA - Why Do We Care?
- DGA Background
- Potential Source of Error
- Previous Works
- Theory
- Simulations and Results
- Experiments
- Summary and Conclusions

# DGA - Why Do We Care?

- Incipient faults could exist in power transformers
- Early detection of the faults could significantly reduce the cost of repair and loss of service
- Industry standards do not always give the right answer
- Understanding the dynamic nature of evolution and migration of characteristic gases improves our interpretation of DGA analysis

# DGA Background- History

- Breife History

- Late nineteenth century: Mineral oils have been used for electrical insulation and cooling purposes
- 1928: Attempts to diagnose the type of failure from gases evolved from oil-immersed power transformers started by Buchholtz
- 1970: Dorneneburg differentiated faults of thermal or electrical origin (Brown-Boveri Review publication)
- 1973: Halstead made a thermodynamic assessment the formation of gaseous hydrocarbons in Mineral Oil

# DGA Background- History

- Briefe History- continued
  - 1975: Rogers suggested the ratio method along with a coding system to recognize the type of the fault
  - 1977: Modified Rogers method also included in IEC document 10A 53
  - 1980's and early 1990's: attempts to incorporate expert systems in fault diagnosis based on DGA
  - 1999-03: IEC 60599 latest edition.

# DGA Background- Chemical Reactions

- Decomposition of Oil
  - Hydrogen, Methane, Ethane, Ethylene, Acetylene
  - Mechanism of formation:
    - Scission of C-H bonds: low energy faults such as partial discharge of cold plasma (Corona)
    - Scission of C-C, C=C and C≡C bonds and recombination: more and more energy or higher temperature needed.
  - Hydrogen can be generated as a result of variety of reactions
    - Large quantities of hydrogen have been reported in some transformers that had never been energized

# DGA Background- Chemical Reactions

- Decomposition of Cellulose Insulation
  - Mostly Carbon Monoxide and Carbon Dioxide
  - Minor amounts of hydrocarbons and Furanic compounds
  - Mechanism of formation:
    - C-O bonds in Cellulose polymer chains are thermally less stable than hydrocarbon bonds in oil
    - Scission of cellulose polymer chains higher than 105°C
    - Complete decomposition and carbonization above 300°C

# DGA Background- IEC 60599

- Electrical discharge - visually detectable faults defined by IEC 60599
  - Partial discharge (PD): Possible X-wax deposition, pin holes or carbonized perforation in paper
  - Discharge of low energy (D1): Large carbonized perforation through paper, carbonization of paper surface, or carbon particles in oil
  - Discharge of high energy (D2): Extensive destruction and carbonization of paper, metal fusion at the discharge location, extensive carbonization in oil, in some cases tripping of equipment

# DGA Background- IEC 60599

- Thermal faults - visually detectable faults defined by IEC 60599
  - Thermal faults, in oil or/and in paper, below 300°C if the paper has turned brownish (T1) and above 300°C if the paper has carbonized (T2)
  - Thermal faults of temperature above 700°C (T3) if there is strong evidence of carbonization of the oil, metal coloration(800°C) or metal fusion (>1000°C)
- Suggested ratios:
  - $C_2H_2/C_2H_4$ ,  $CH_4/H_2$ ,  $C_2H_4/C_2H_6$

# DGA Background- IEC 60599

Range of 90% typical concentration values observed in power transformers (all types) (ppm in volume)

TX type	H <sub>2</sub>	CO	CO <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>2</sub>
No LTC	60-150	540-900	5 100-13 000	40-110	50-90	60-280	3-50
Communicating LTC	75-150	400-850	5 300-12 000	35-130	50-70	110-250	80-270

Incremental ratios of CO<sub>2</sub>/CO less than 3 are generally considered as an indication of probable paper involvement in a fault

# Potential Source of Error

- Gases Fluctuate in Healthy Transformers.
- Gases Migrate Between the Oil and Paper.
- This Could Cause Problems when Interpreting DGA Results.
- No Published Information about the Phenomenon To Date.
- A Physical Model can Help with Interpretation of DGA Analysis Data Especially in the Case of CO<sub>2</sub> and CO.

# Review of Previous Works

- IEC 60599 and ANSI/IEEE C57.104.
- Detroit Edison Company Studied the Gas Migration in HPFF Cables.
- Khan and Miyamoto Studied the Migration of CO<sub>2</sub> and CO.

# Literature Data

- Diffusivity Data by Detroit Edison Co.
- ASTM D2779 - Gas Solubility in the Oil.
- CO<sub>2</sub> in Paper Pulp.
- Oommen's Method.

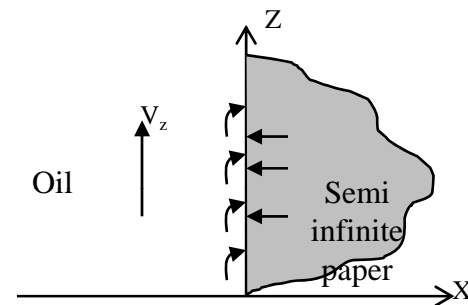
# Dynamic Model

Diffusion Equation:

$$\frac{\partial c}{\partial t} = D\nabla^2 c - \bar{v} \cdot \nabla c + \nabla(Dc\alpha\nabla \ln T)$$

Approximations:

- Soret Effect is Ignored.
- Diffusion in the  $x$  Direction.
- Velocity in the  $z$  Direction.

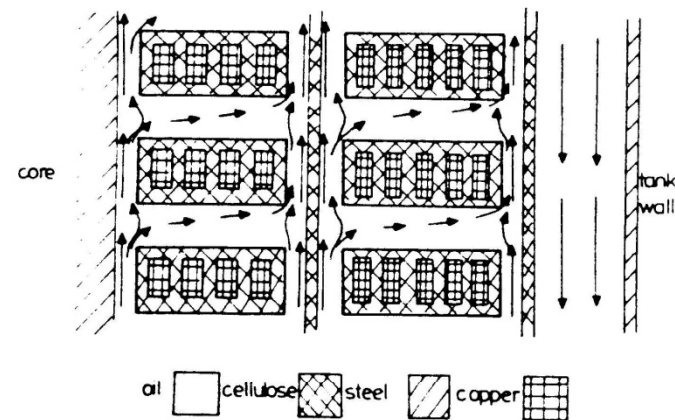


In a single Oil Duct:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - v_z \frac{\partial c}{\partial z}$$

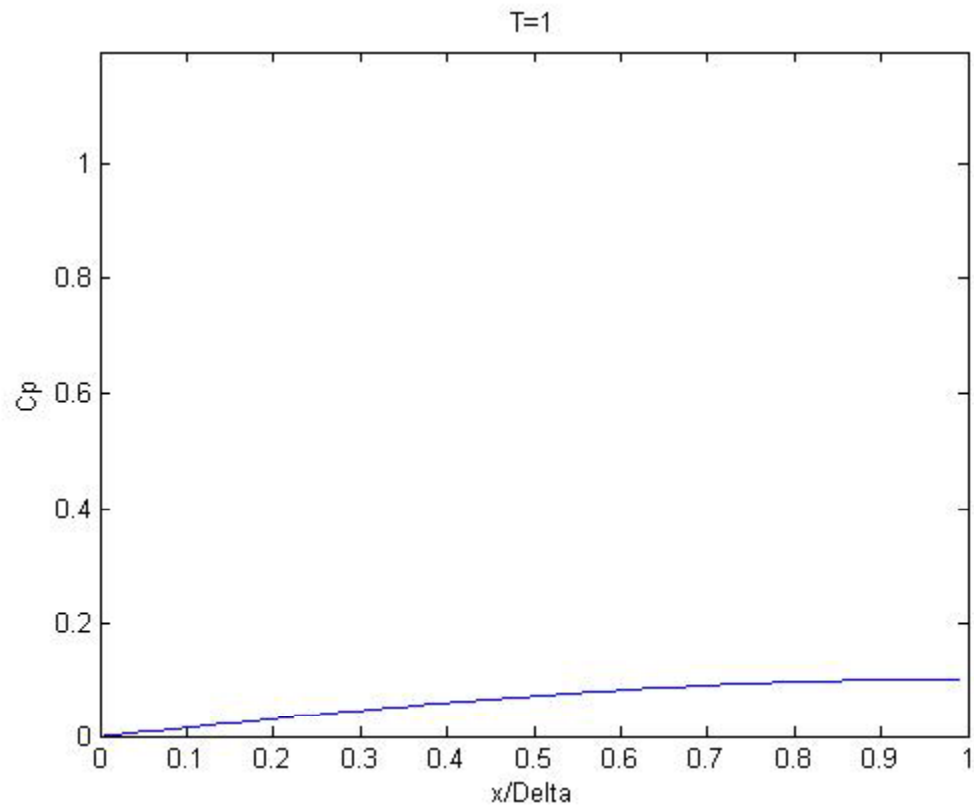
Transport in Oil is Faster than Diffusion:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}$$



# Simulation Results

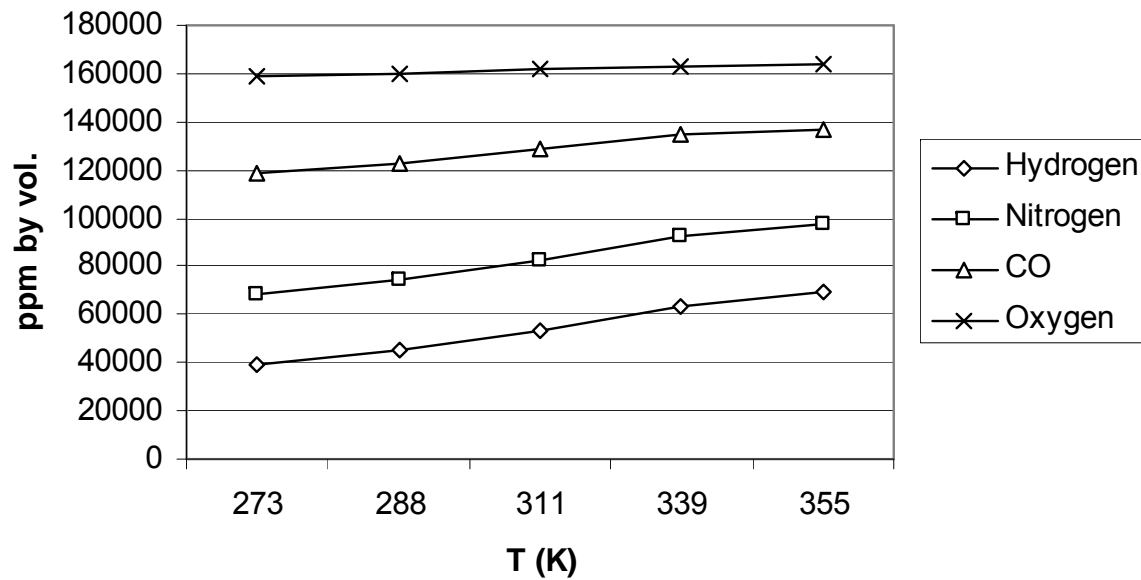
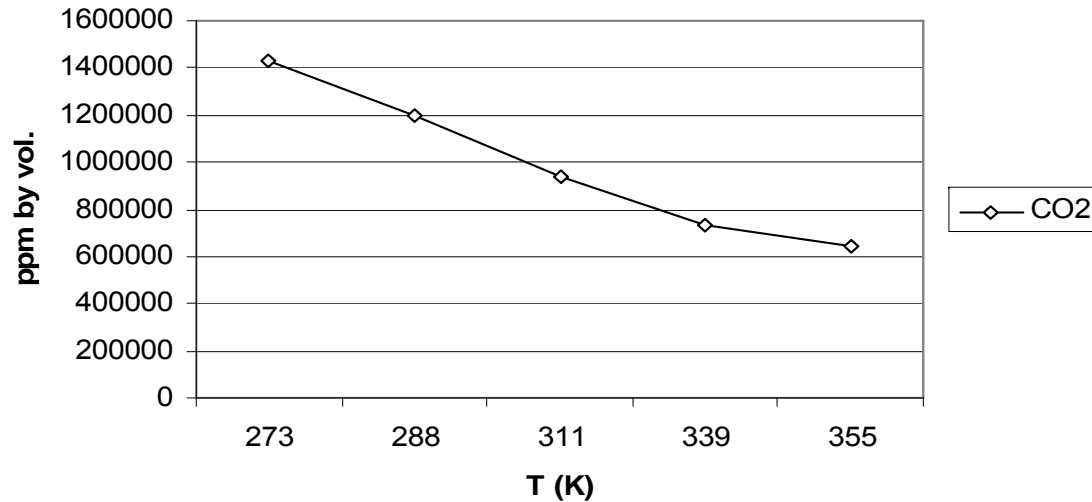
(animation)



## **CO<sub>2</sub> Equilibrium Curves**

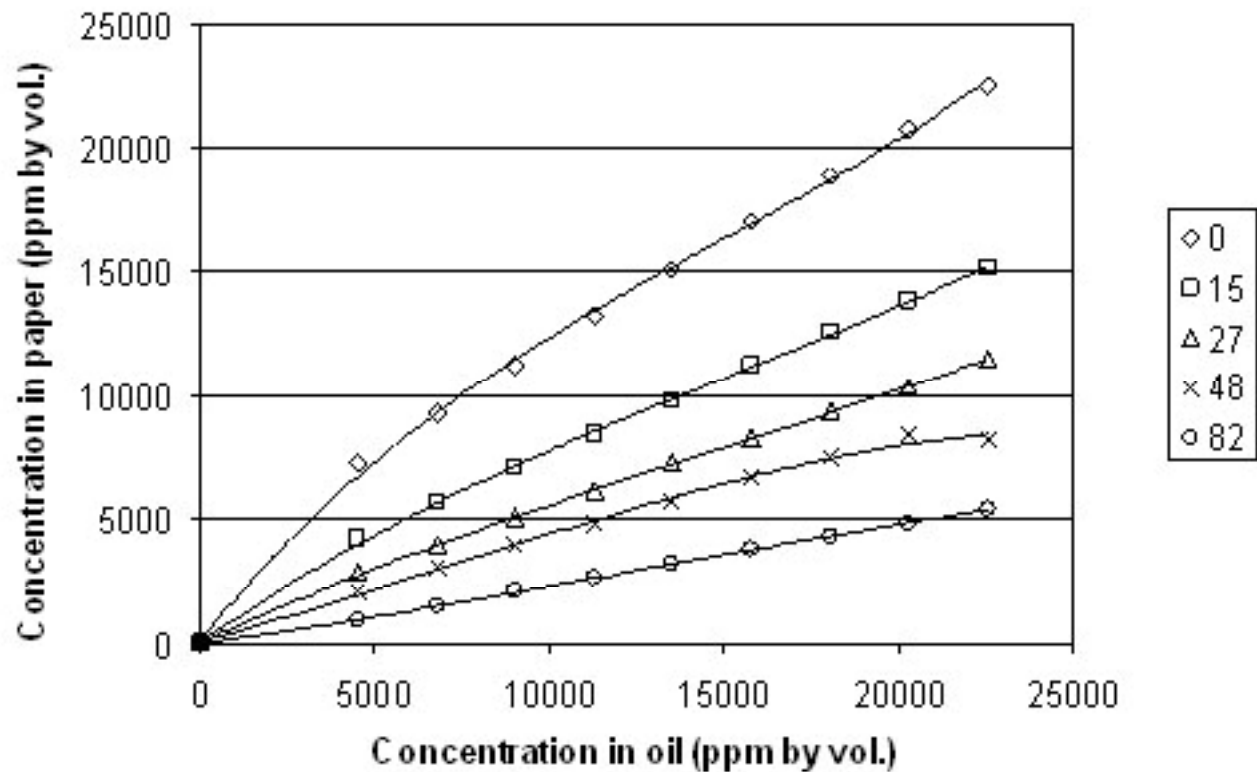
- ASTM D2779 - Gas Solubility in the Oil.
- CO<sub>2</sub> in Paper Pulp by D.J. Salley.
- Oommen's Method.

# ASTM D2779 – Solubility of Selected Gases in the Oil

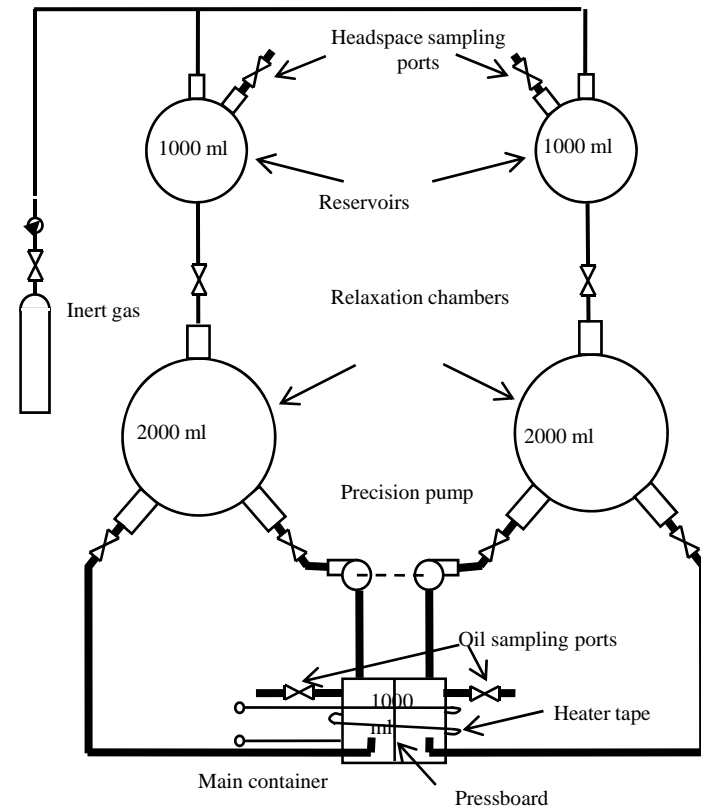




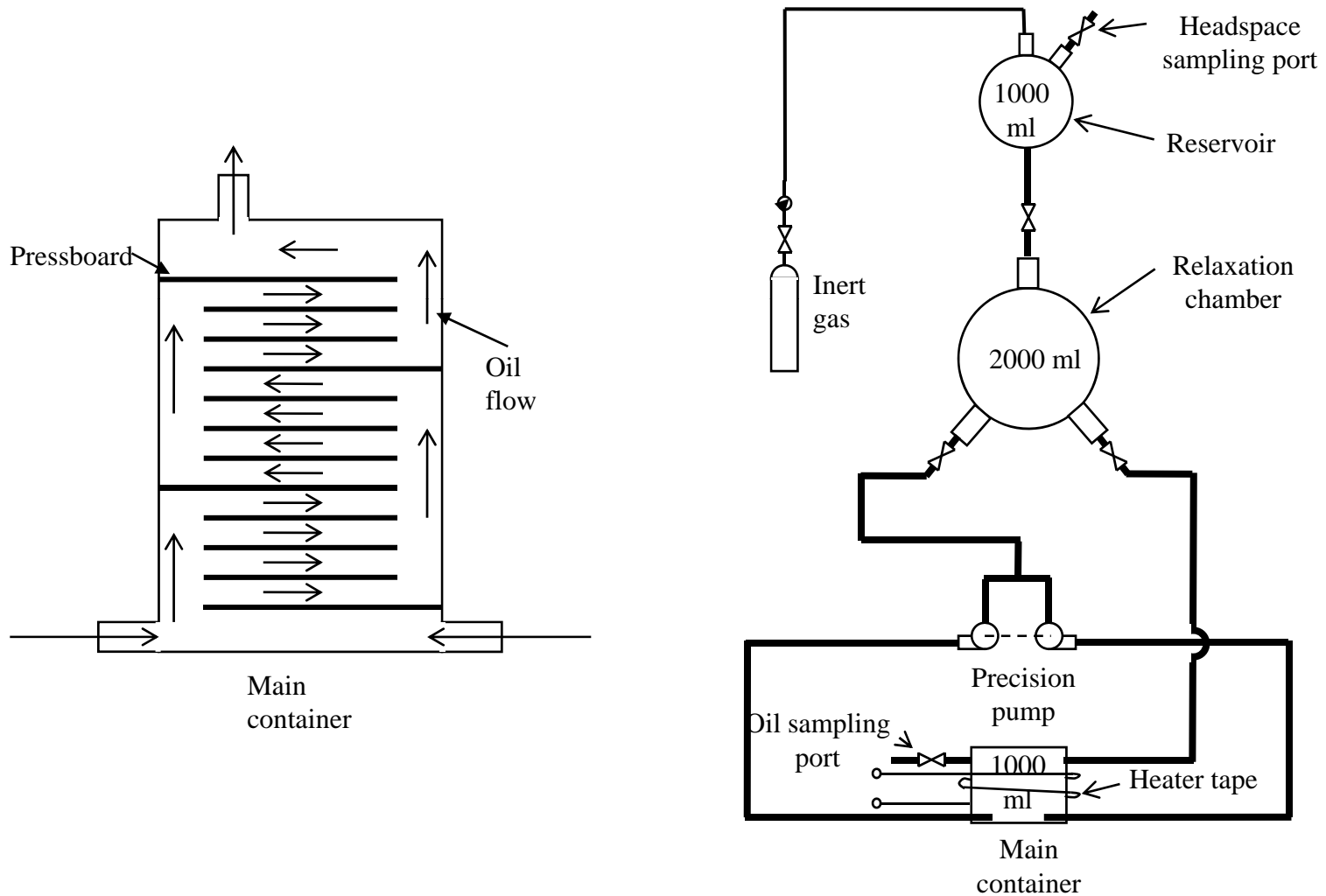
# CO<sub>2</sub> Equilibrium Curves at Lower Concentrations



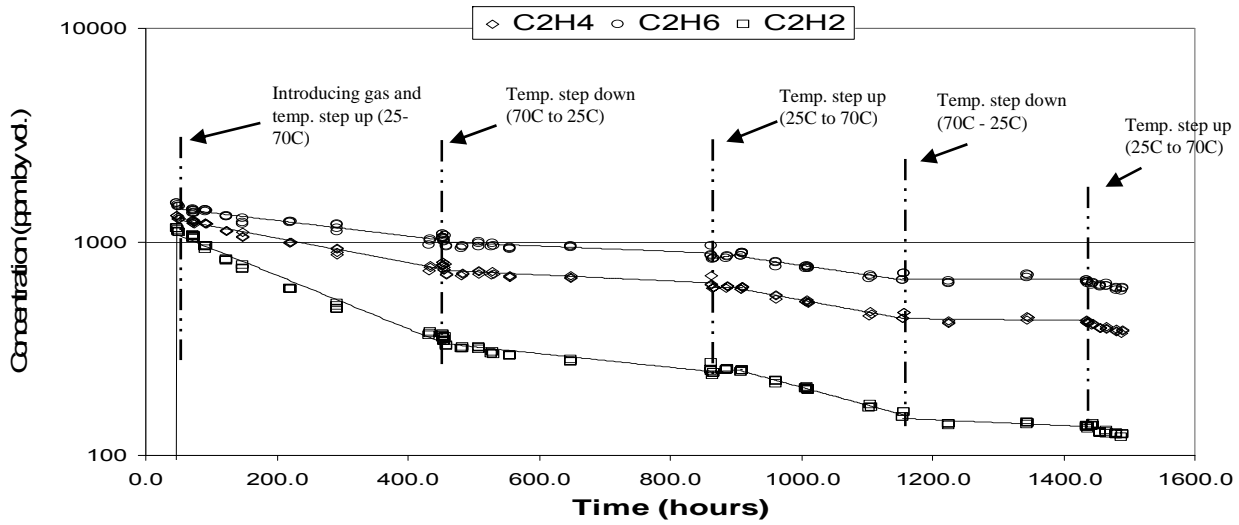
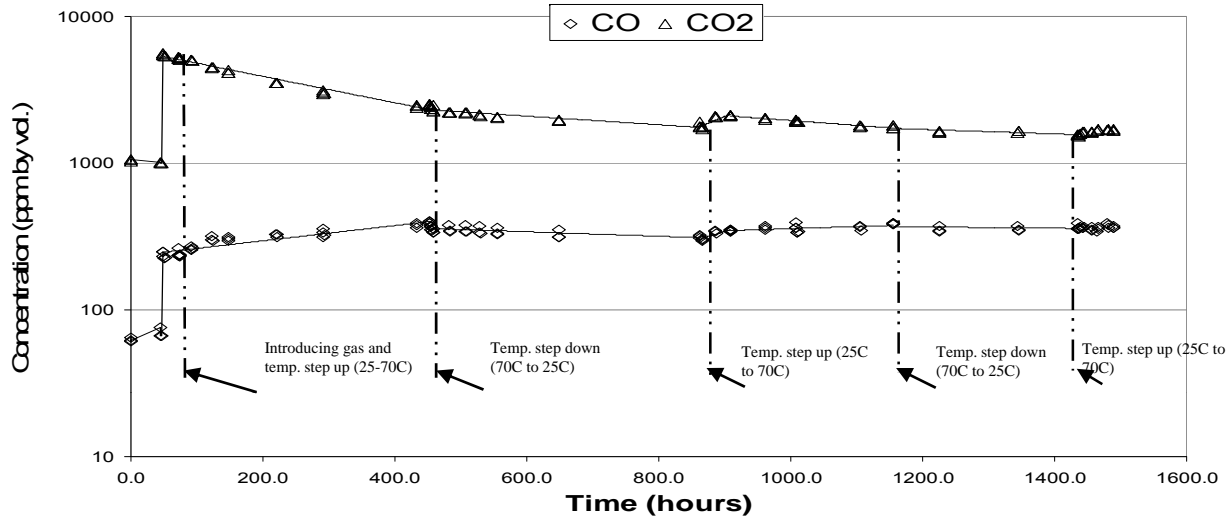
# Model Parameters



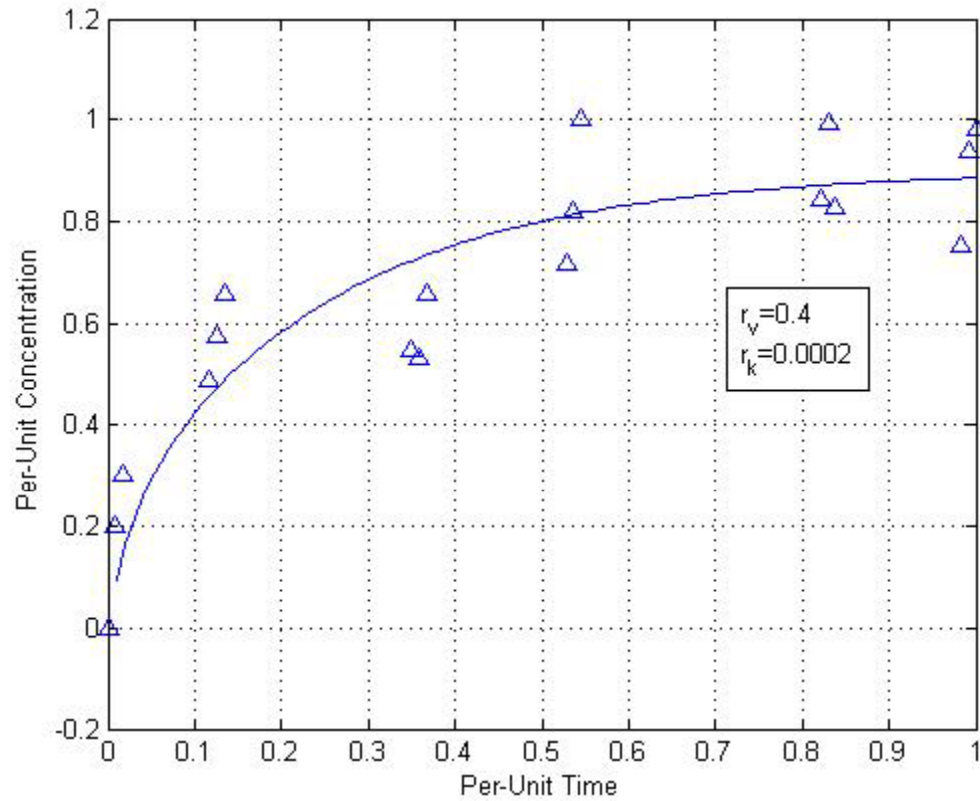
# Model Validation



# Experimental Data



# Experimental Comparison – CO<sub>2</sub>



# Summary and Conclusions

- Concentrations of CO<sub>2</sub> and CO in Transformer Oil can Change Considerably due to a Temperature Change Because of the Migration Process.
  - This can Lead to Significant Errors when Interpreting DGA Analysis Data
- Migration Phenomenon of Characteristic Gases can be Explained by Diffusion Process.
- Application of the Model Works Best in the Case of Carbon Dioxide and Carbon Monoxide.
- Diffusion Time Constant and Steady-State Ratio of Gases in an Oil-Paper System have been determined.
- Steady-state Ratio of CO<sub>2</sub> in Oil / Paper System was obtained using Oommen's Method Similar to the Case of Moisture.

- This Project Received the Endorsement of DEIS Liquids Technical Committee in 2004.
- This Project Received the DEIS Fellowship Award in 2005.
- Six Technical Papers, a Thesis and a Book have been Published based on the Methodology and Results of this Research

Questions?