In-Situ MVA of CO_2 Sequestration Using Smart Field Technology

FE - 0001163

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Petroleum Engineering & Analytics Research Lab (PEARL)

West Virginia University

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS

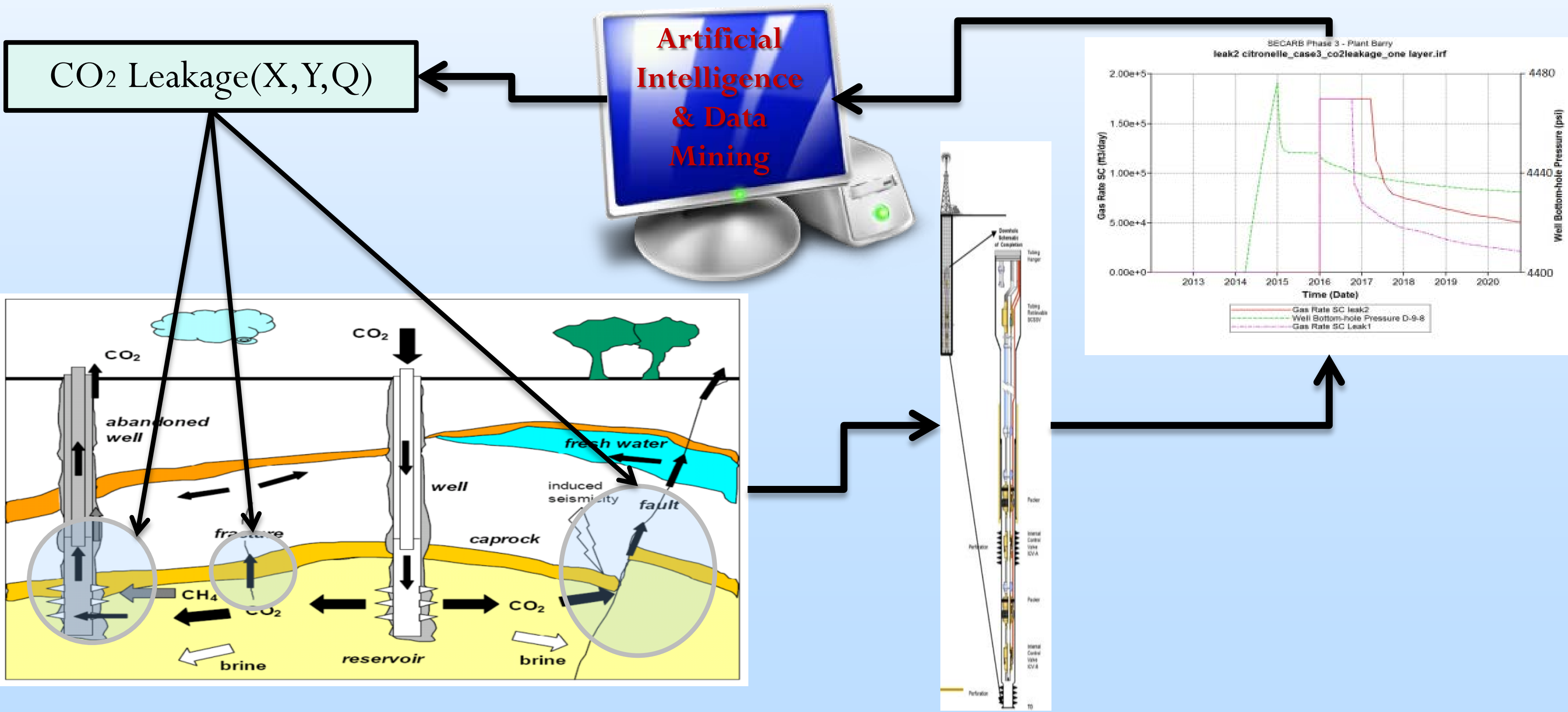
August 20-22, 2013

Presentation Outline

- Introduction
- Reservoir Simulation Model
- Intelligent Leakage Detection System (ILDS)
- Accomplishments
- Summary

Objective

- Develop an in-situ CO_2 leak detection technology based on the concept of Smart Fields.
  - Using real-time pressure data from permanent downhole gauges to estimate the location and the rate of CO_2 leakage.



Industrial Advisory Committee (IAC)

- Project goes through continuous peer-review by an Industrial Review Committee.

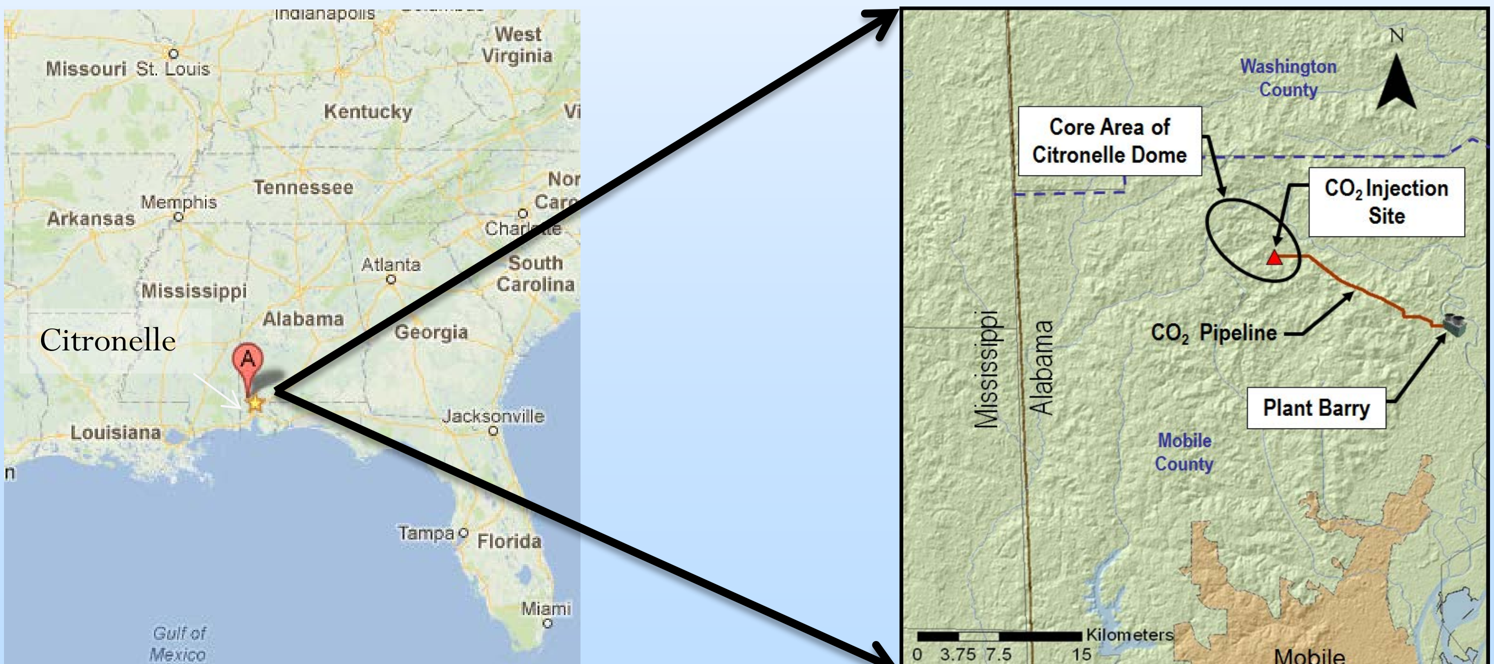
Name	Affiliation
Neeraj Gupta	Battelle
Dwight Peters	Schlumberger
George Koperna	ARI
Grant Bromhal	DOE-NETL
Richard Winschel	CONSOL

- Meetings:
  - November 6th 2009 :
    - Conference call
    - Site selection criteria
  - November 17th 2009:
    - A meeting during the Regional Carbon Sequestration Partnership Meeting in Pittsburgh
    - Selection of a suitable CO_2 sequestration site
  - November 18th 2011:
    - Reporting the modeling process to IAC
  - February 16th 2012:
    - Reporting the modeling process to NETL/DOE
  - April 18th 2013:
    - Reporting project's progress to NETL/DOE

Background

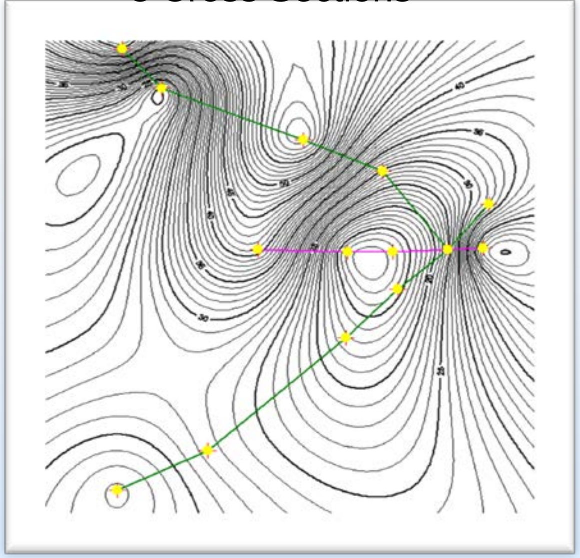
Injected Fluid: ***Carbone Dioxide***
Depth of Injection Well: ***11,800ft***
Depths & Geological Name of Interval:
9,400-10500 ft (Paluxy Formation)

Injection Volumes: ***500 ton/day(9.48 Bcf/day)***
Injection Duration: ***3 Years(2012-2015)***

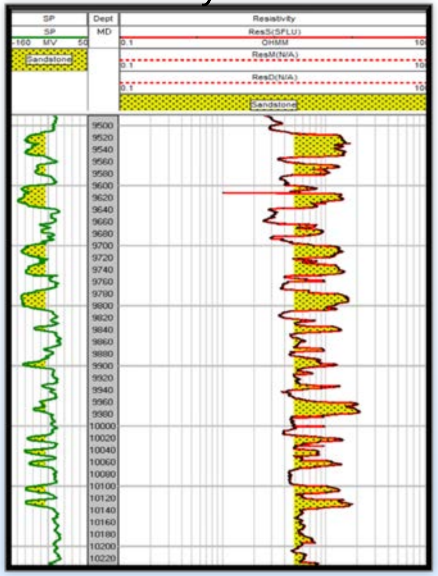


Geological Model

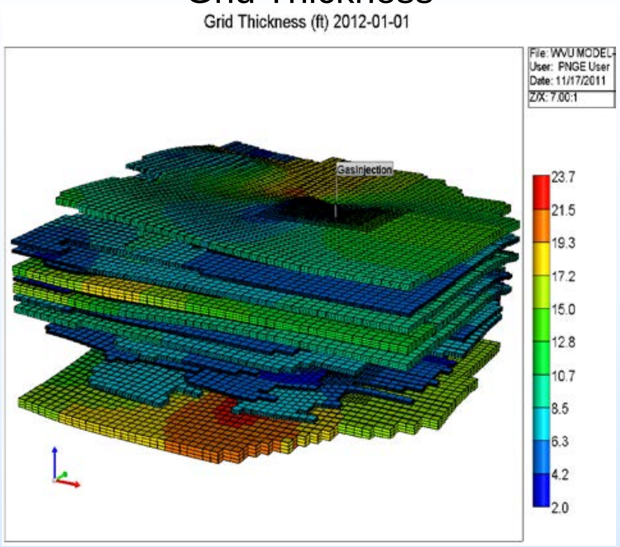
3 Cross Sections



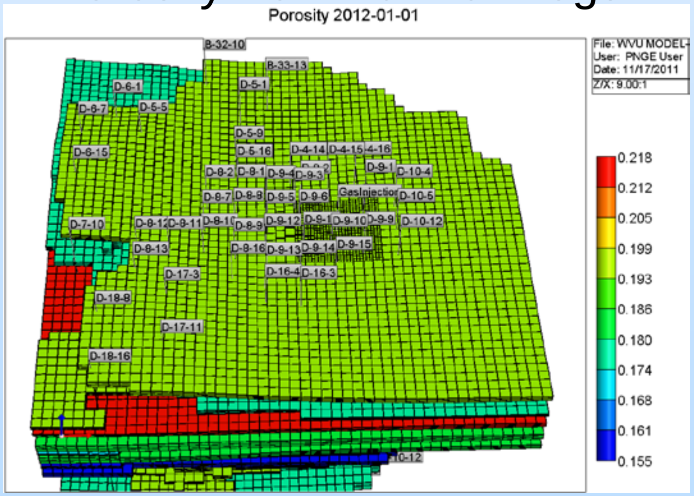
Sand Layers-D-9-7



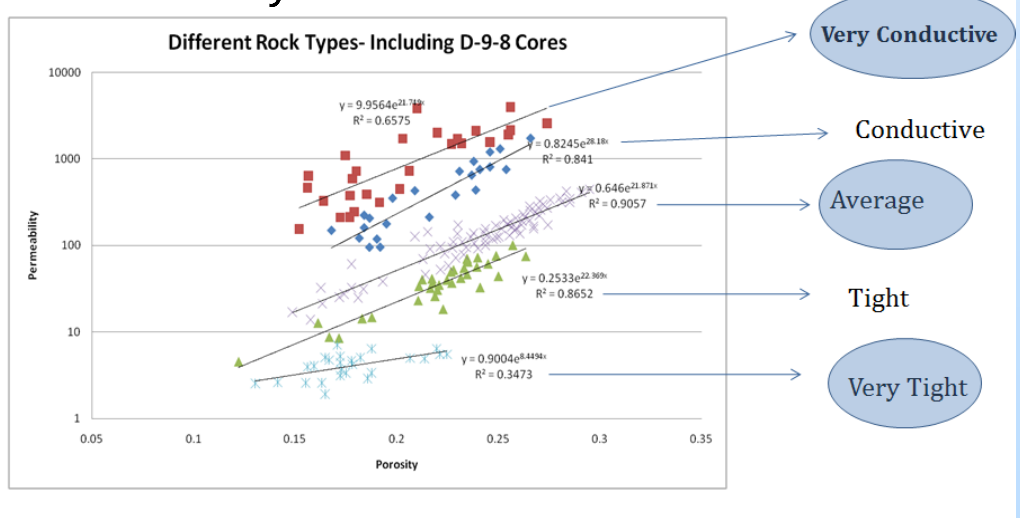
Grid Thickness



Porosity from 40 Well Logs

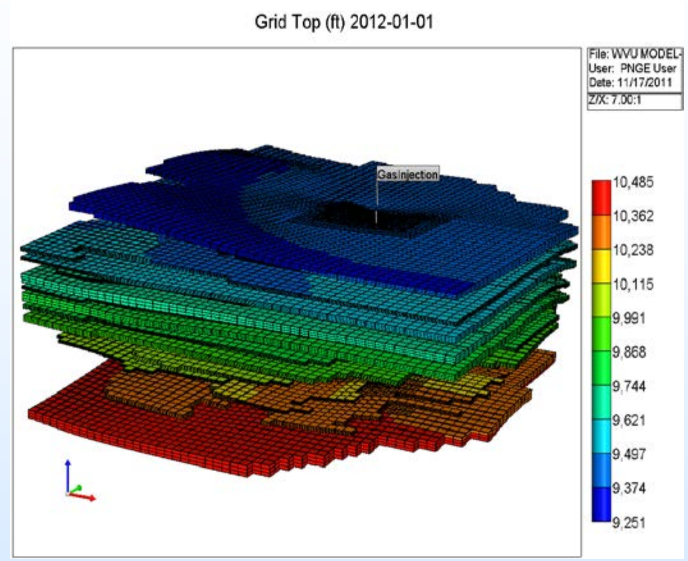


Permeability Realizations

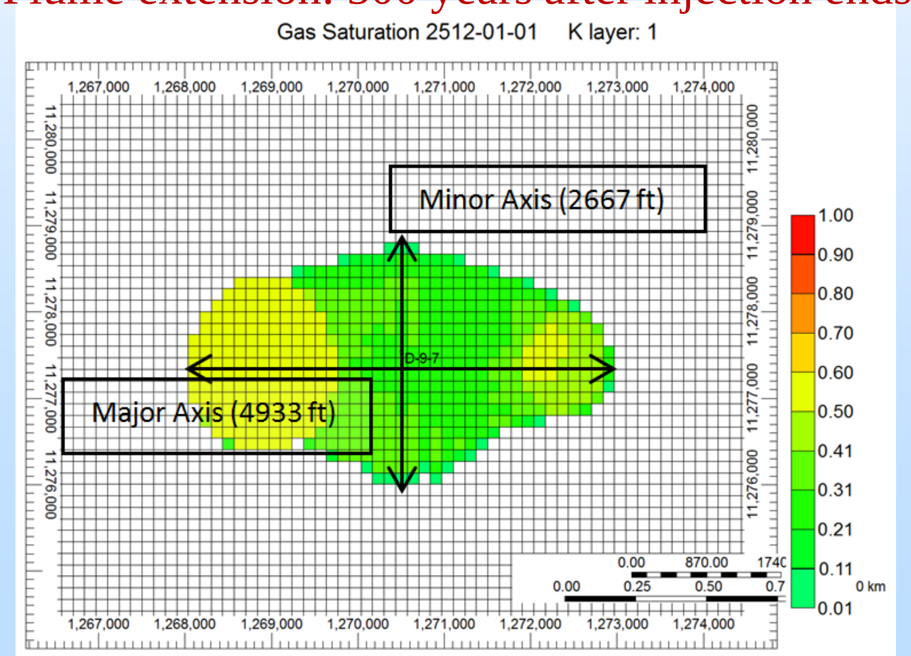


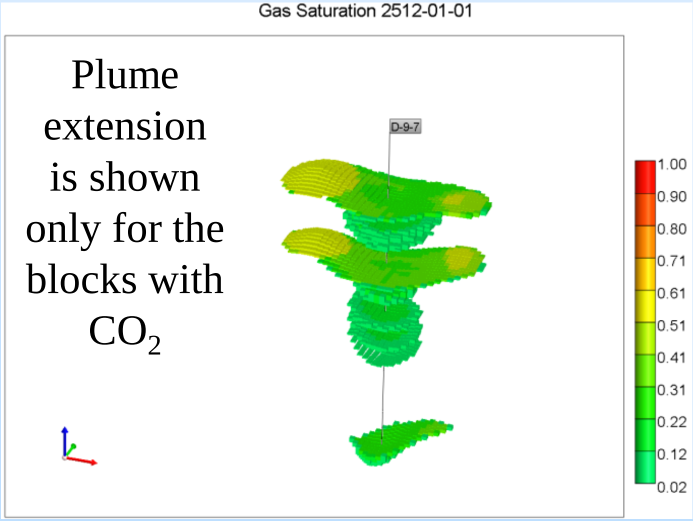
Reservoir Simulation Model

17 Layers(10 Injection Layers)
51 Simulation Layers
Porosity Distribution from 40 Well Logs
Permeability Distribution: Conductive
1,147,500 Grid Blocks

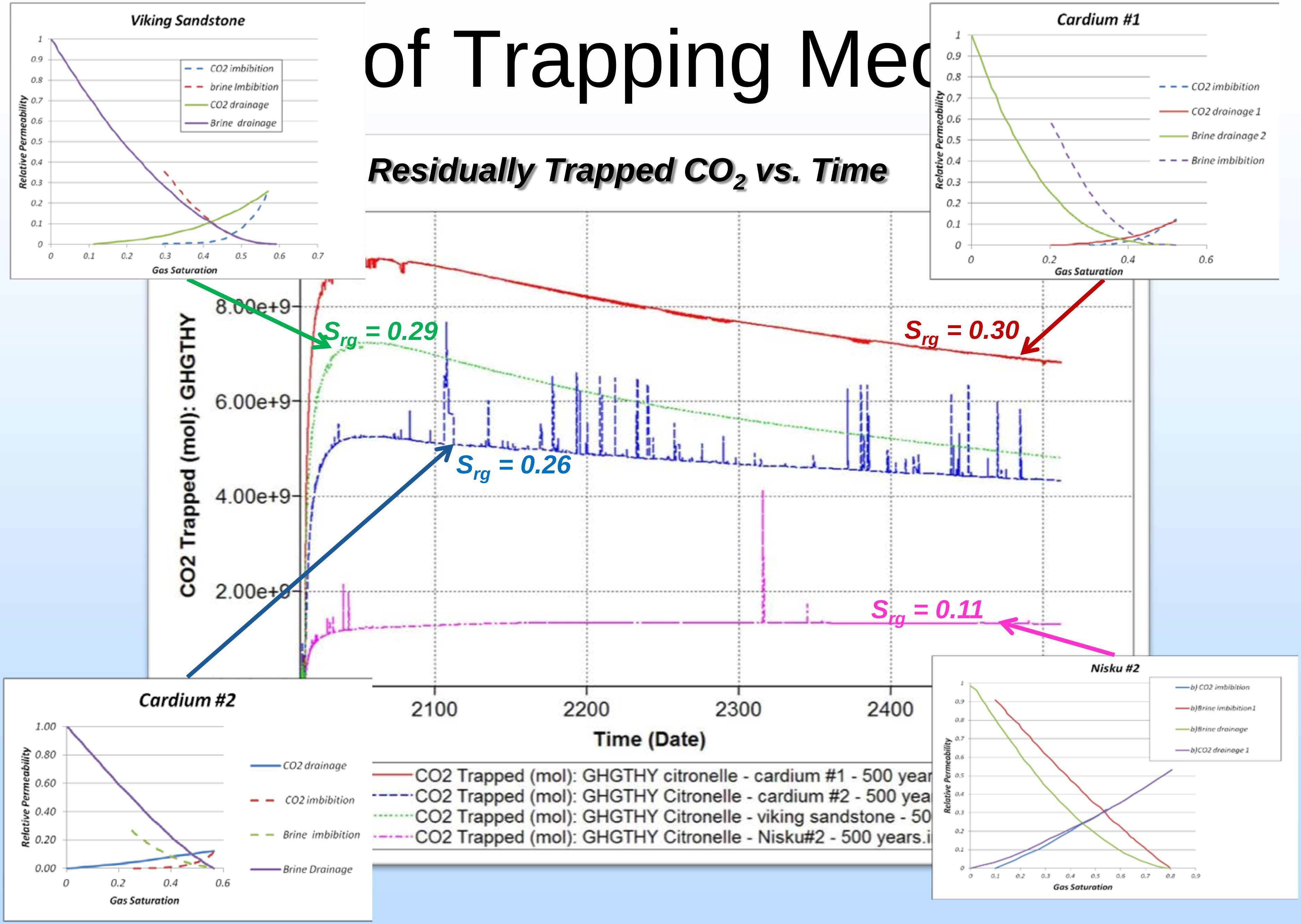


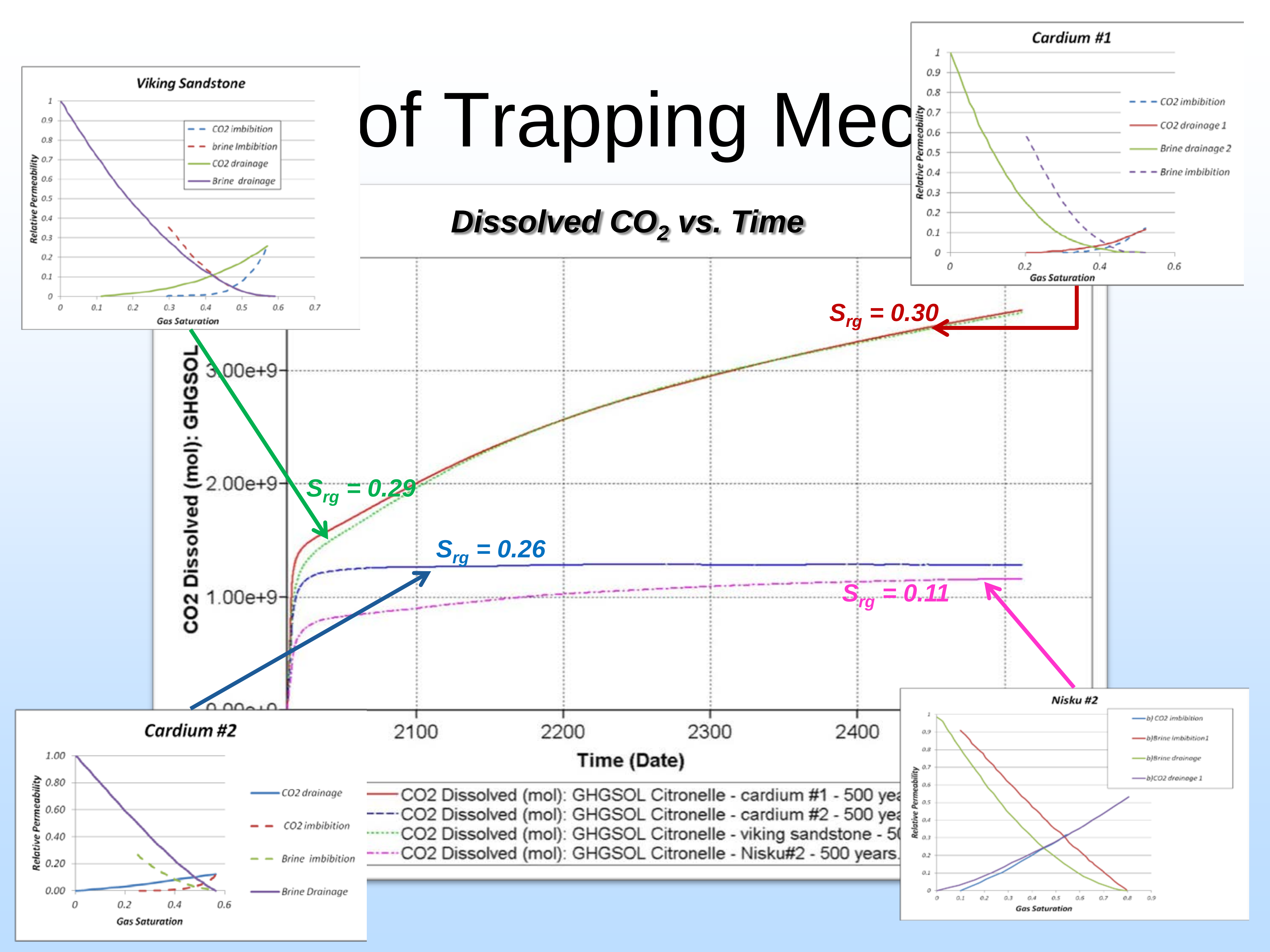
Plume extension: 500 years after injection ends.





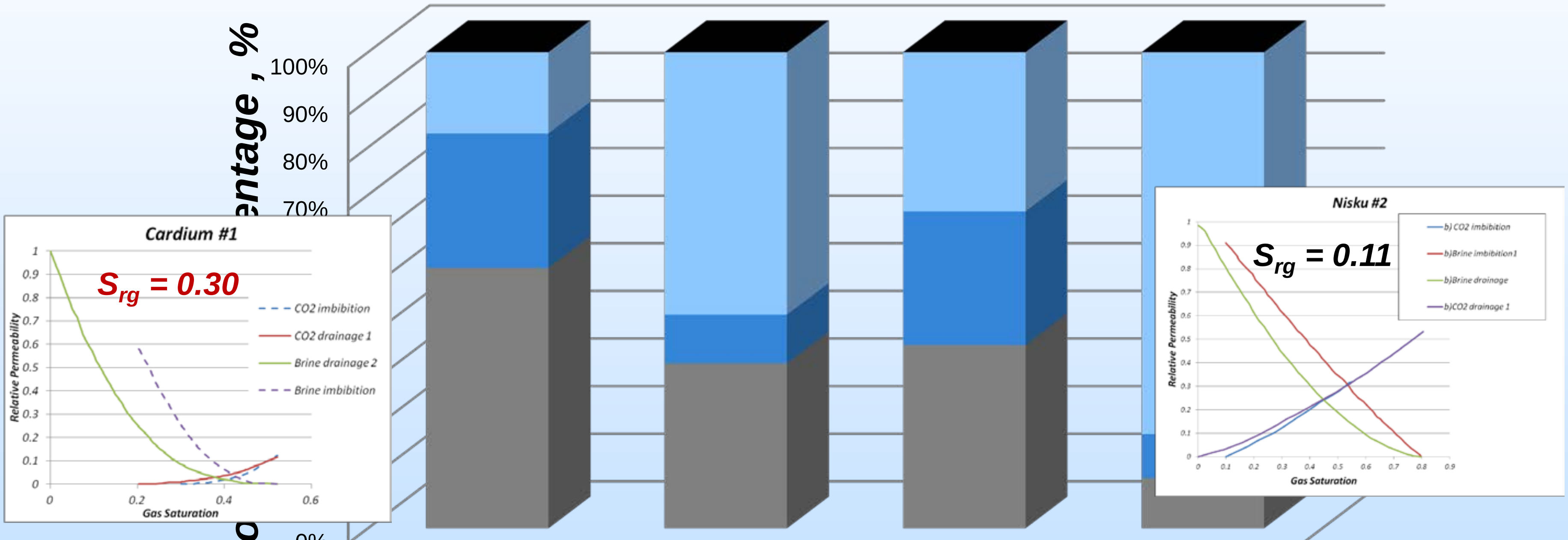
# of Trapping Mec




of Trapping Mec
Dissolved CO2 vs. Time
CO2 Dissolved (mol): GHGSOL
3.00e+9
2.00e+9
1.00e+9
2100
2200
2300
2400
Time (Date)
CO2 Dissolved (mol): GHGSOL Citronelle - cardium #1 - 500 yea
CO2 Dissolved (mol): GHGSOL Citronelle - cardium #2 - 500 yea
CO2 Dissolved (mol): GHGSOL Citronelle - viking sandstone - 50
CO2 Dissolved (mol): GHGSOL Citronelle - Nisku#2 - 500 years.
Srg = 0.30
Srg = 0.29
Srg = 0.26
Srg = 0.11
Viking Sandstone
Relative Permeability
Gas Saturation
CO2 imbibition
brine Imbibition
CO2 drainage
Brine drainage
Cardium #1
Relative Permeability
Gas Saturation
CO2 imbibition
CO2 drainage 1
Brine drainage 2
Brine imbibition
Cardium #2
Relative Permeability
Gas Saturation
CO2 drainage
CO2 imbibition
Brine imbibition
Brine Drainage
Nisku #2
Relative Permeability
Gas Saturation

Impact of Trapping Mechanism

Trapping Mechanism Contribution to the Storage Process (After 500 years)



	Cardium #1	Cardium #2	Viking Sandstone	Nisku #2
Mineral Trapping	*0.000%*	*0.000%*	*0.000%*	*0.000%*
Structural Trapping	*17.101%*	*55.176%*	*33.482%*	*80.237%*
Solubility trapping	*28.250%*	*10.238%*	*28.064%*	*9.254%*
Resiudual traping	*54.649%*	*34.586%*	*38.455%*	*10.510%*

Total CO_2 Injected (MMCF) ***15,045***

Total CO_2 Injected (TONS) ***550,596***

Seal Quality

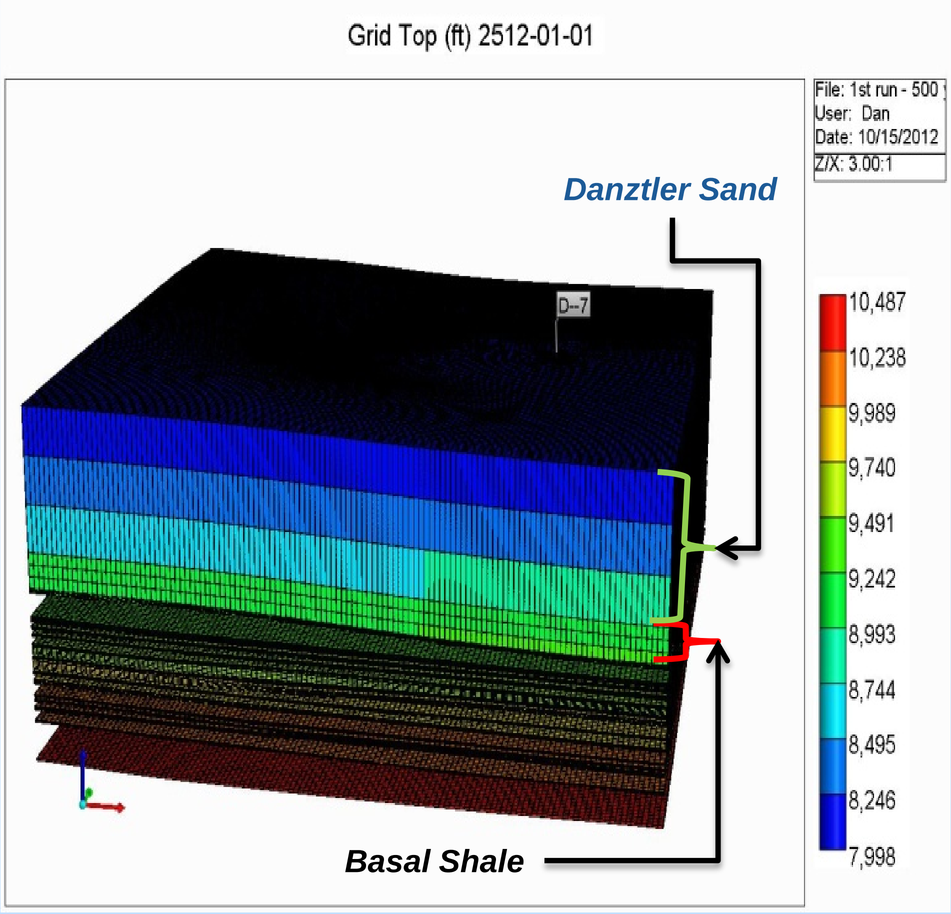
Two additional geological layers where included in the model corresponding to the Washita-Fredericksburg interval (on top of the Paluxy formation):

- *Basal Shale (Seal)*
- *Danztler Sand (Aquifer)*

Realization	Thickness (ft)	Permeability (Darcy)
1	150	10^-3
2	150	10^-5
3	150	10^-7
4	200	10^-3
5	200	10^-5
6	200	10^-7
7	250	10^-3
8	250	10^-5
9	250	10^-7

150 ft < h < 250 ft

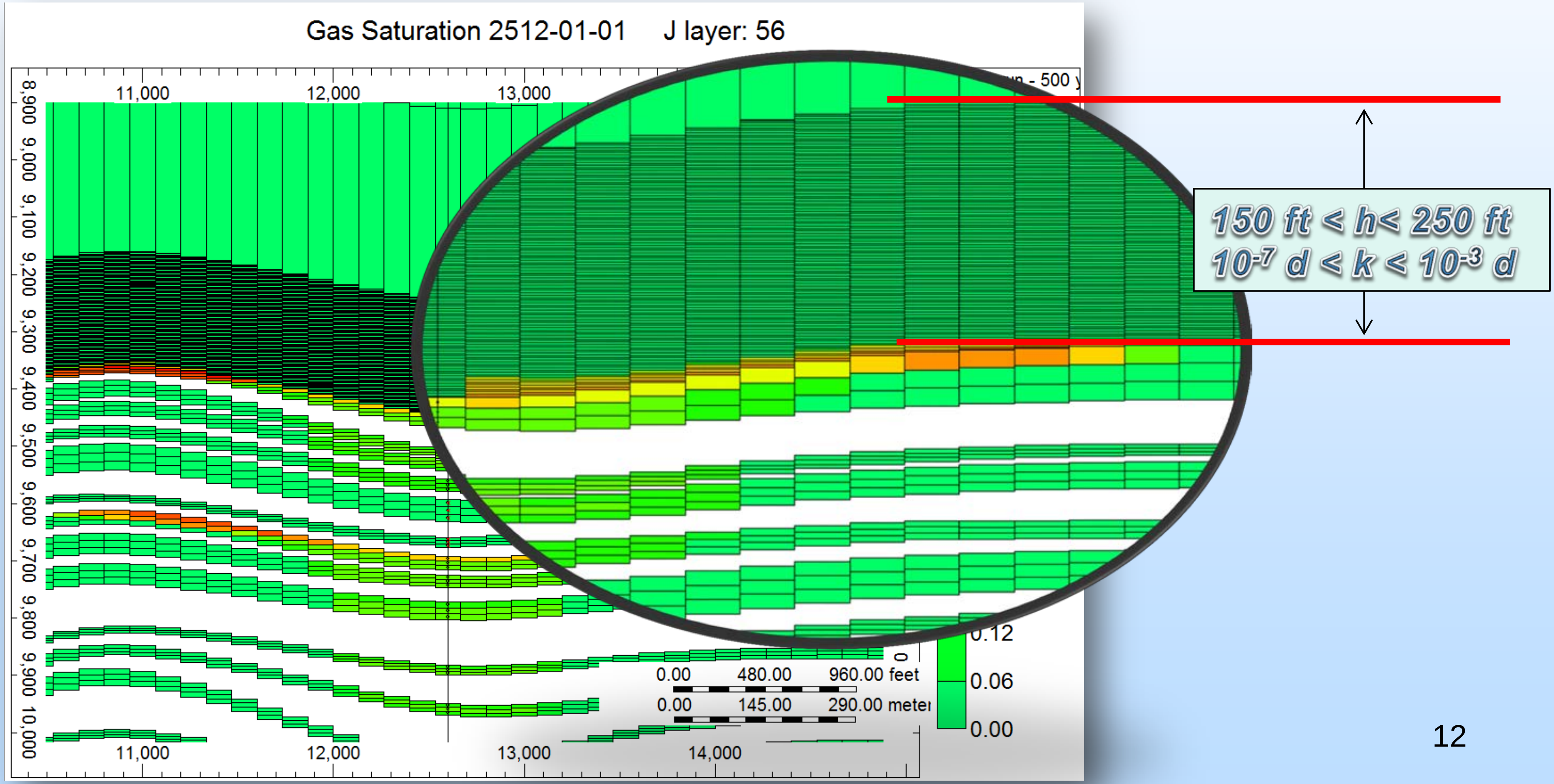
10^{-3} darcy < k < 10^{-7} darcy



Seal Quality

Grid refinement of the basal shale simulation layers:

Grid was refined vertically into 75 to 125 simulation layers to generate grid-blocks with thickness of 2 ft.



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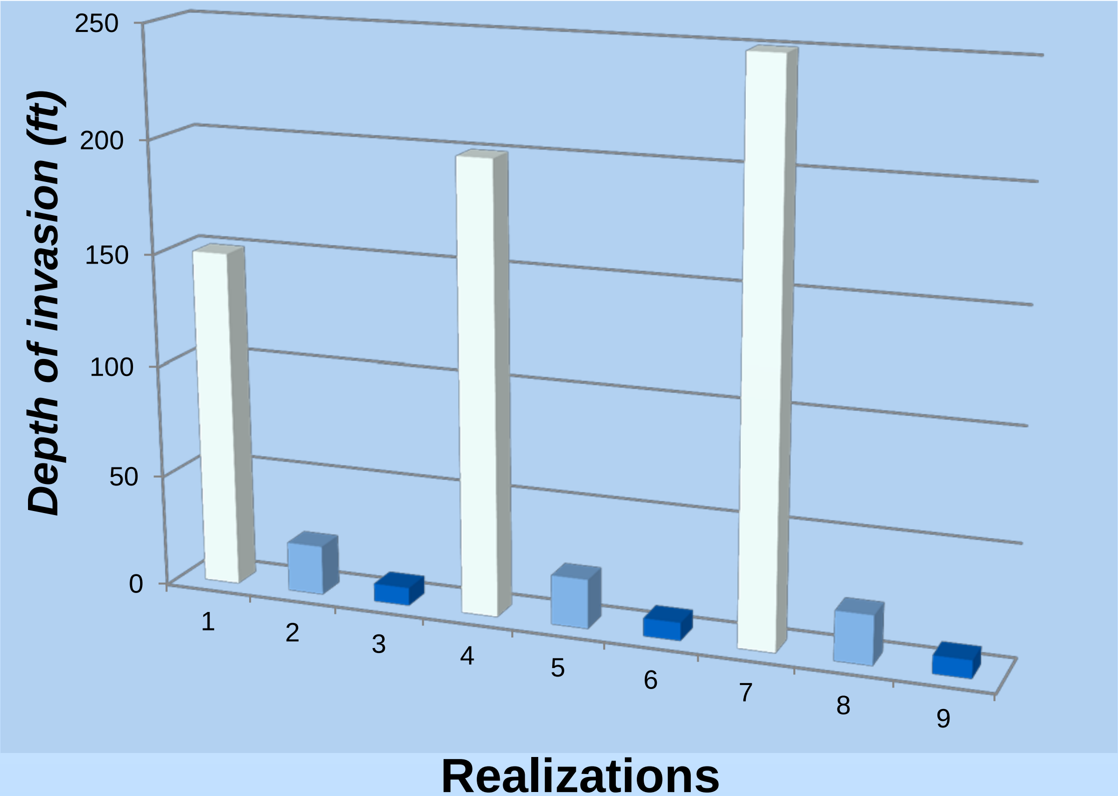
9	250	10^-7

150 ft < h < 250 ft

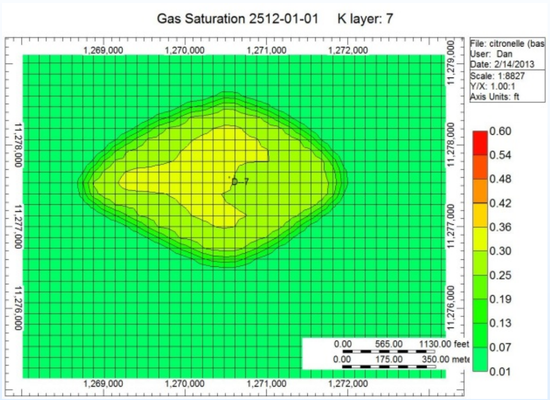
10^{-3} darcy < k < 10^{-7} darcy

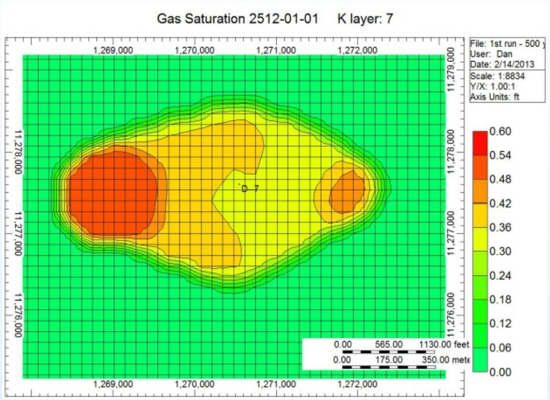
Depth of invasion of CO_2 within the Basal Shale (all realizations)

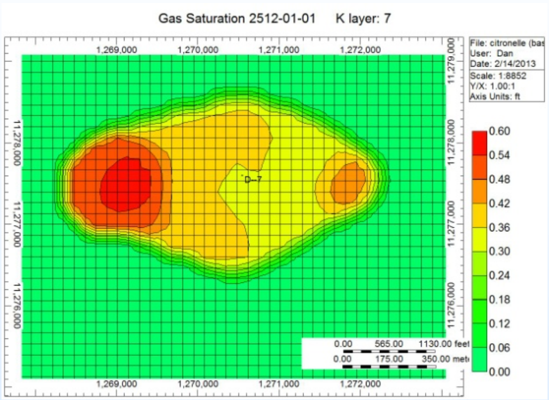


Seal Quality

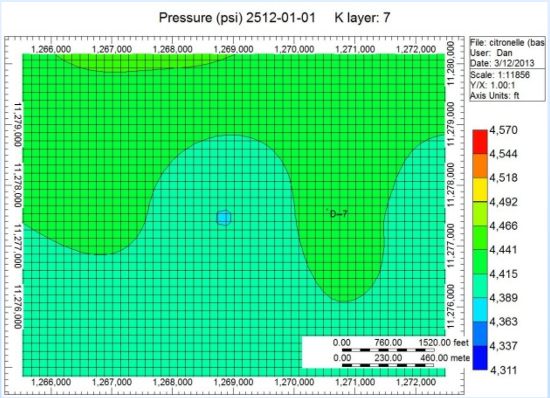
Saturation

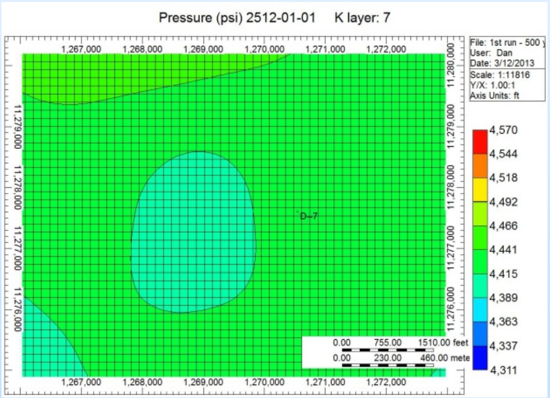


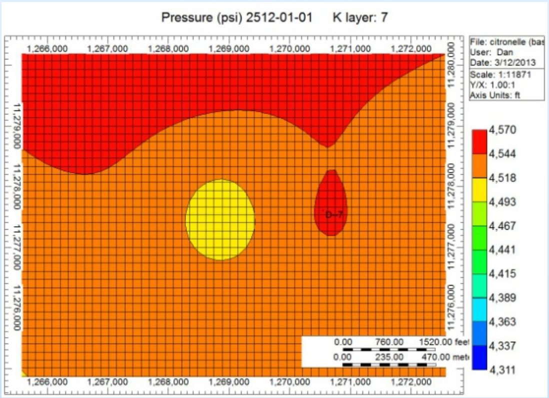




Pressure







Conductive Seal
*150 md-ft< k*h< 250 md-ft*

Tight Seal
*1.5 md-ft< k*h< 2.5 md-ft*

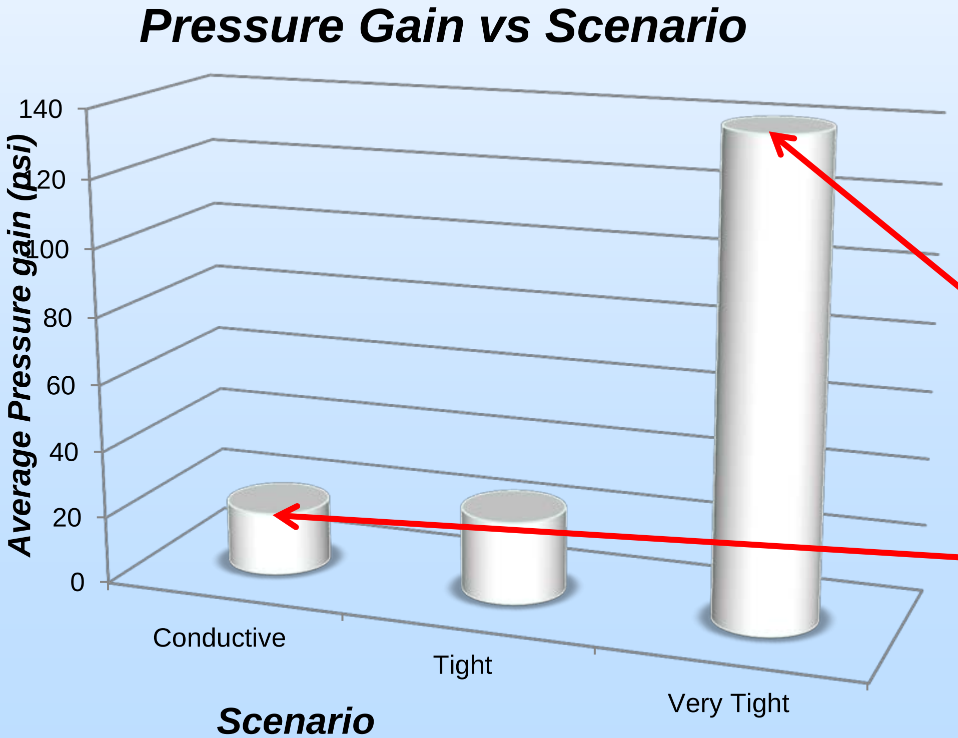
Very Tight Seal
*0.015 md-ft< k*h< 0.025 md-ft*

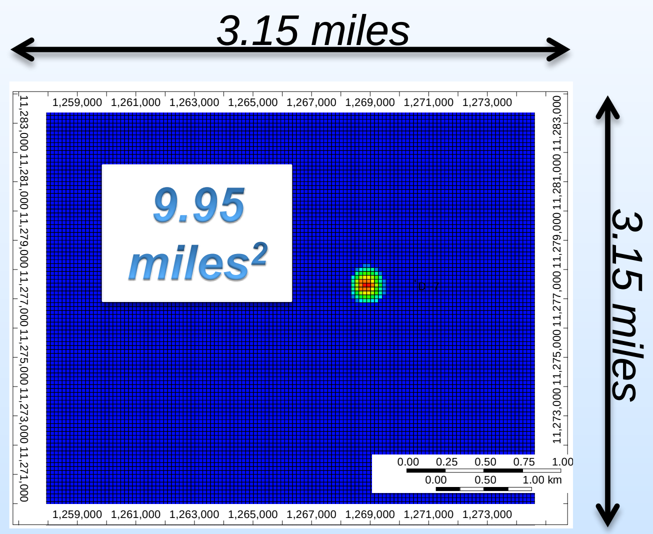
Seal Quality

Pressure Gain = Avg. P @ 500 years – Initial Avg. P

Pressure gain – all scenarios

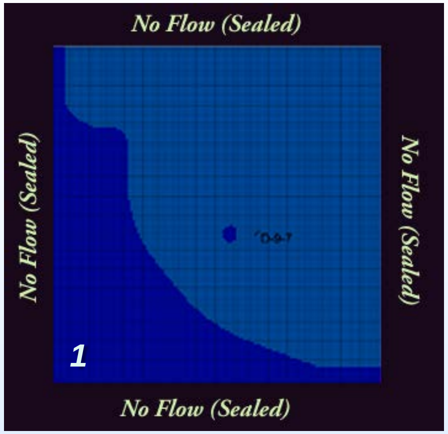
Seal Conductivity Scenario	*Permeability of the Confining Unit (md)*	*K*h range of the confining unit (md-ft)*	
Conductive	*1*	*150*	*250*
Tight	*0.01*	*1.5*	*2.5*
Very Tight	*0.0001*	*0.015*	*0.025*

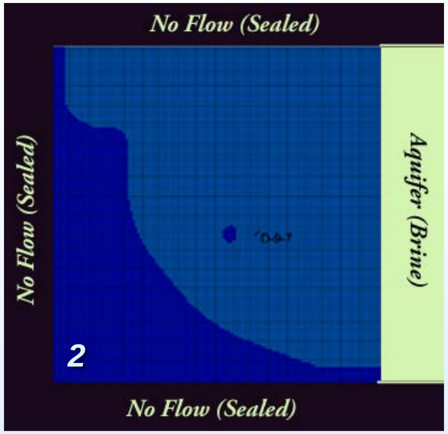


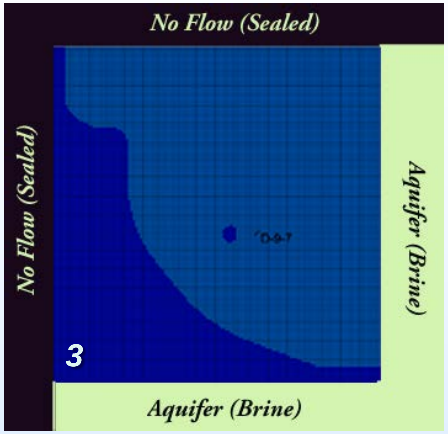


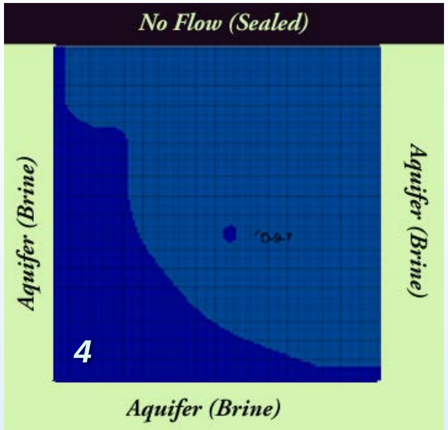
0.43 % and 3.18% of the initial average reservoir pressure

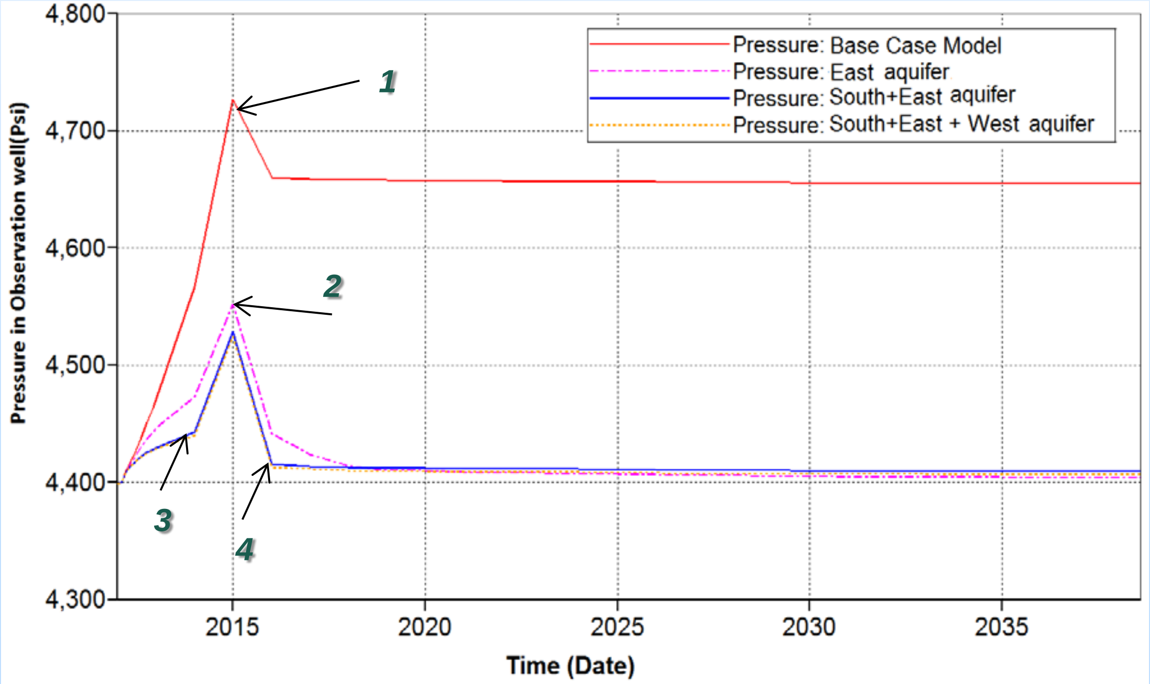
Impact of Boundary Conditions





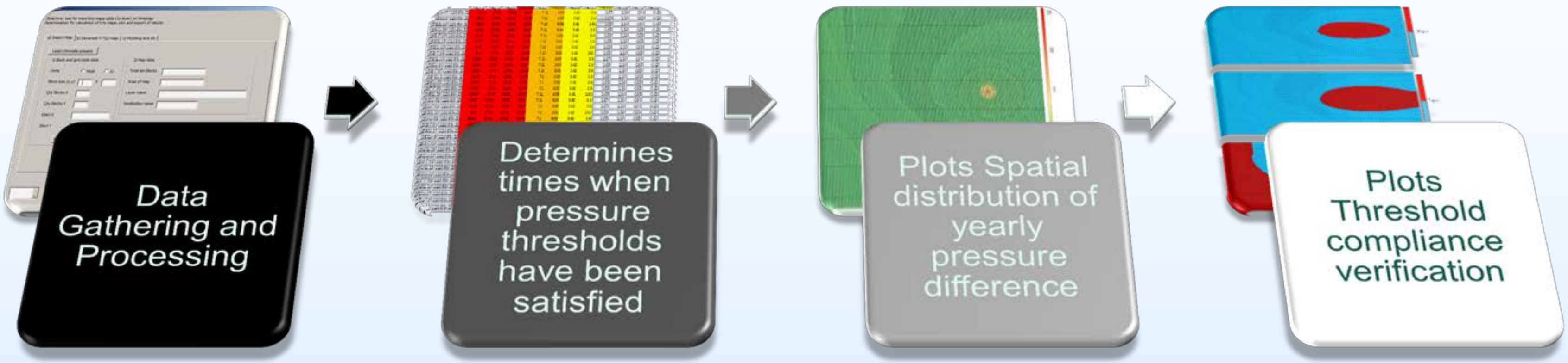






Pressure Behavior in Observation Well(D-9-8)

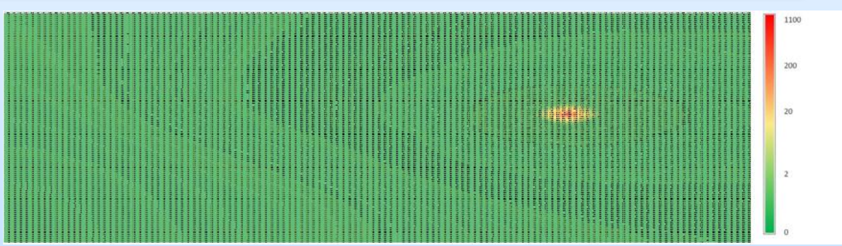
Post Injection Site Care (PISC)



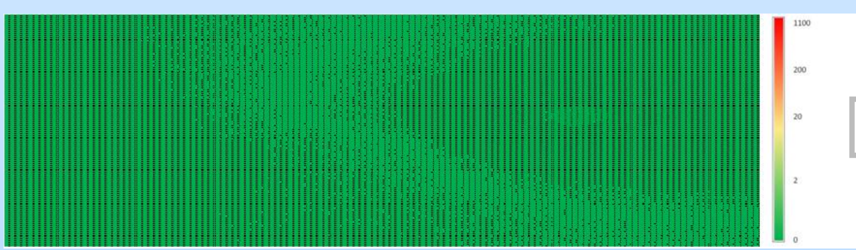
Yearly Pressure Difference distribution

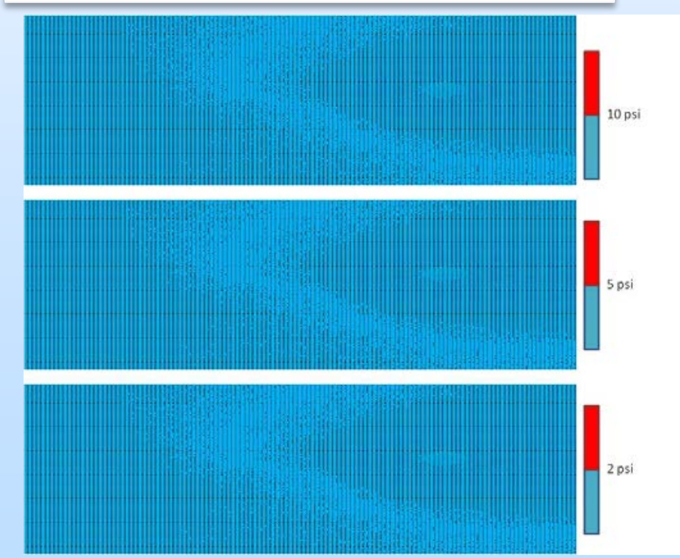
Threshold Verification

1 year post-injection



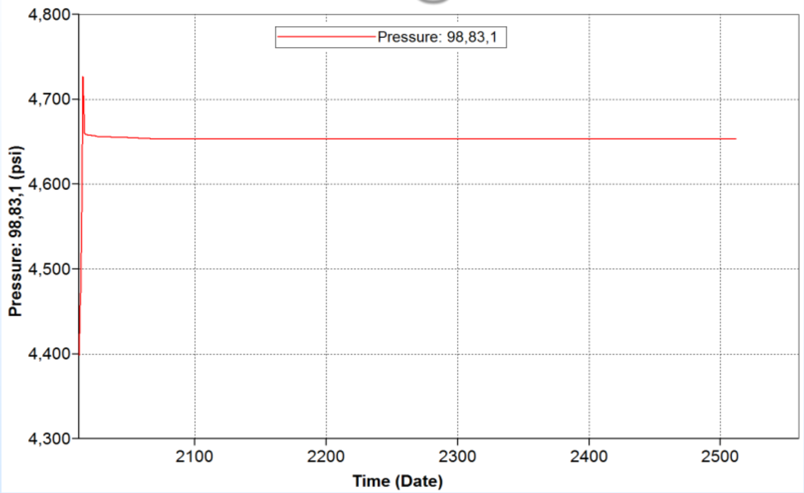
2 year post-injection



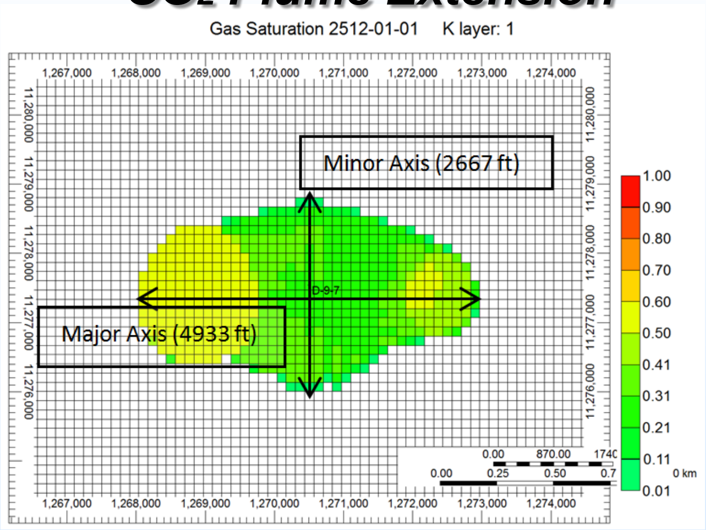


Sensitivity Analysis

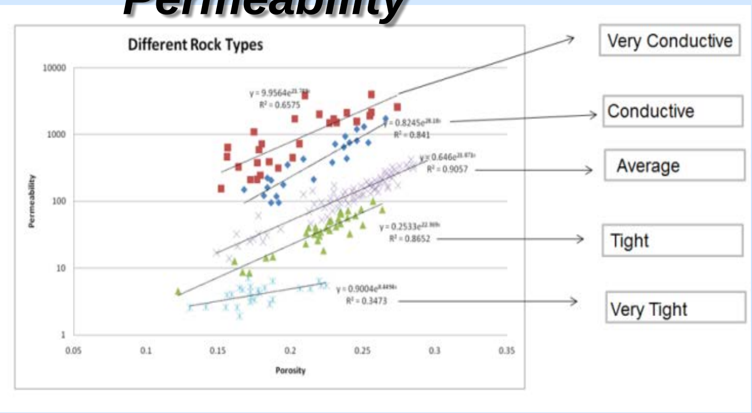
Reservoir Pressure @ Observation Well



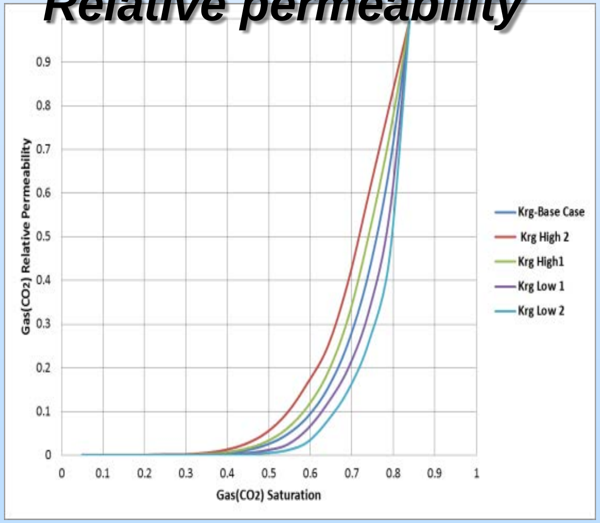
CO_2 Plume Extension



Permeability



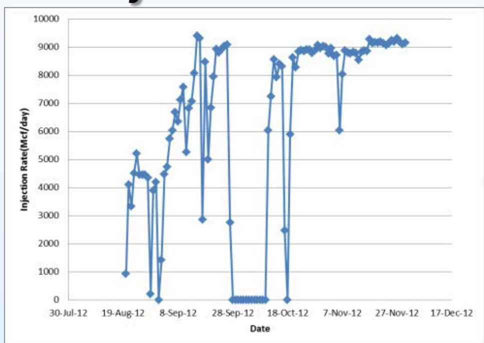
Relative permeability

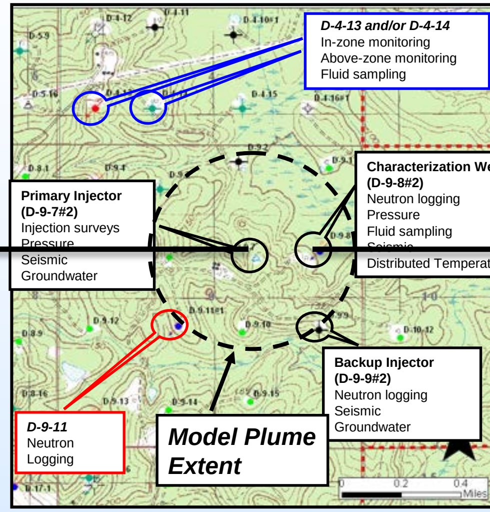


- ***Kv/Kh***
- ***Maximum Residual Gas Saturation***
- ***Brine Density***
- ***Brine Compressibility***
- ***Boundary Condition***

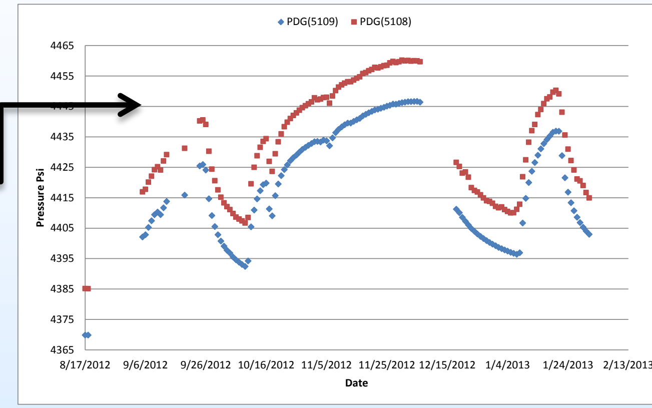
History Matching

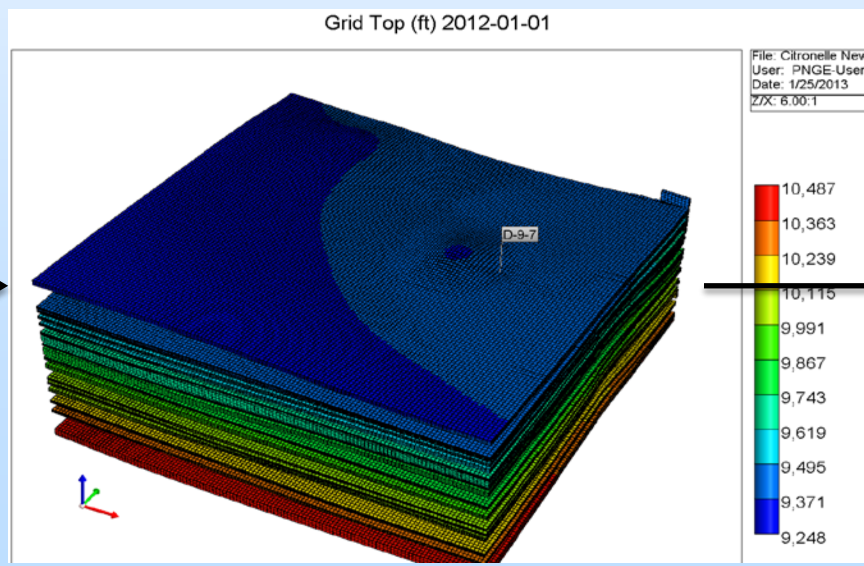
Injection Data

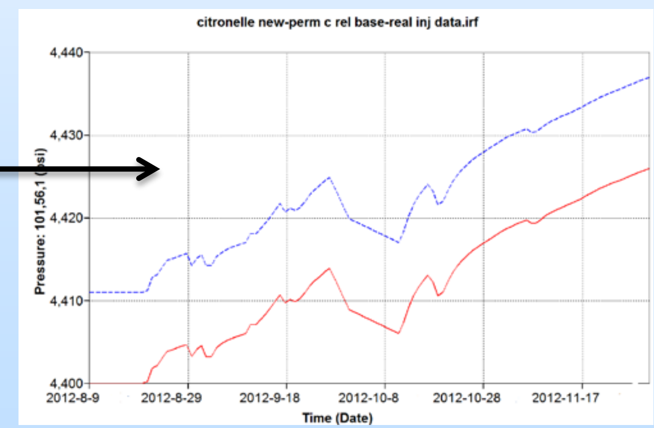




PDG Data



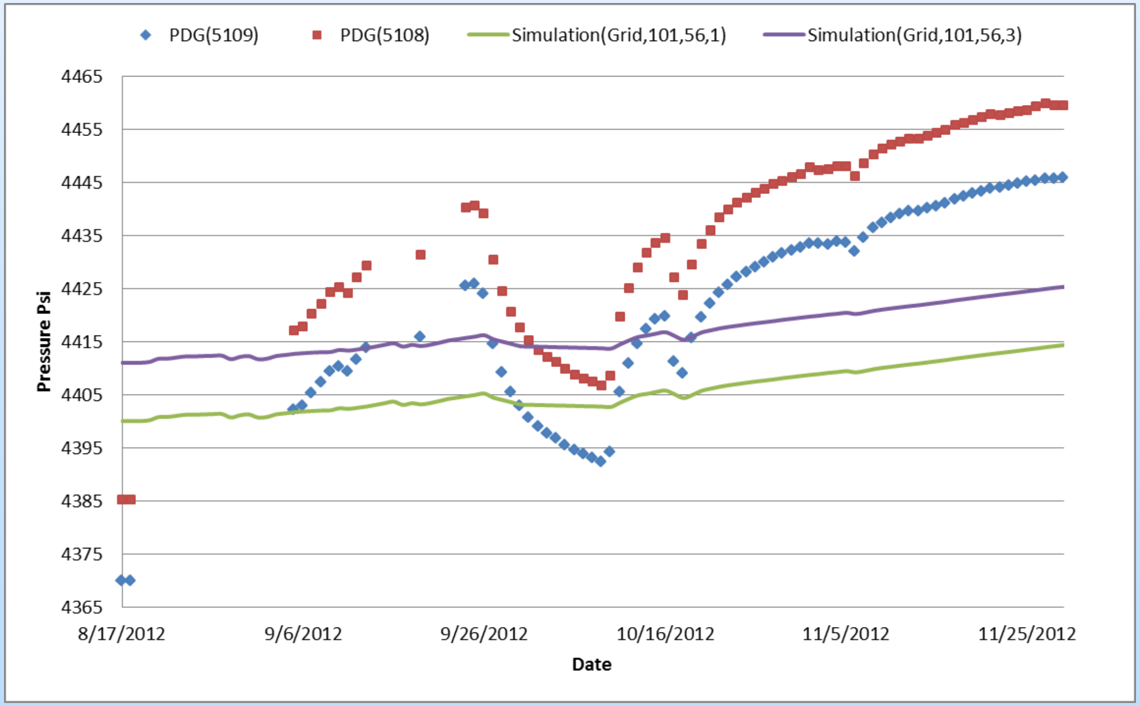




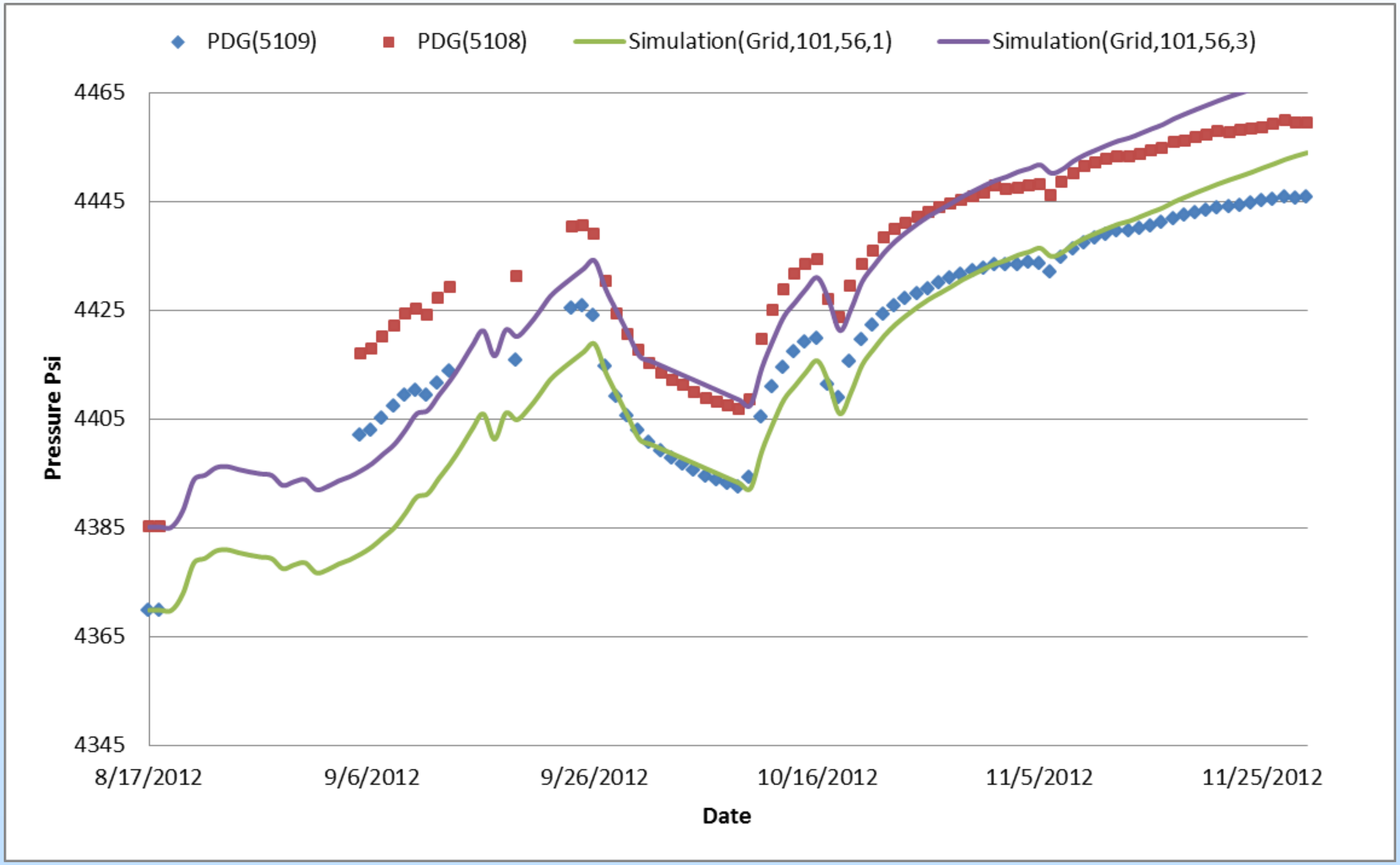
History Matching

17 Layers(10 Injection Layers)
51 Simulation Layers
Porosity Distribution from 40 Well Logs
Permeability: 460md
125*125*51 (800000)
Grid Blocks ($\Delta x = \Delta y = 133.3$ ft)
Relative Perm: Mississippi Test site (sg=7.5%)

Operational Constraints
(actual rate +Max 6300 psi)
P_{brine} = 62 lb/ft3
C_{brine} = $3x10^{-6}$ (1/psi) at 14.7 psi
$P_{reference}$ = 4393psi at 4015 ft.
Kv = 0.1Kh

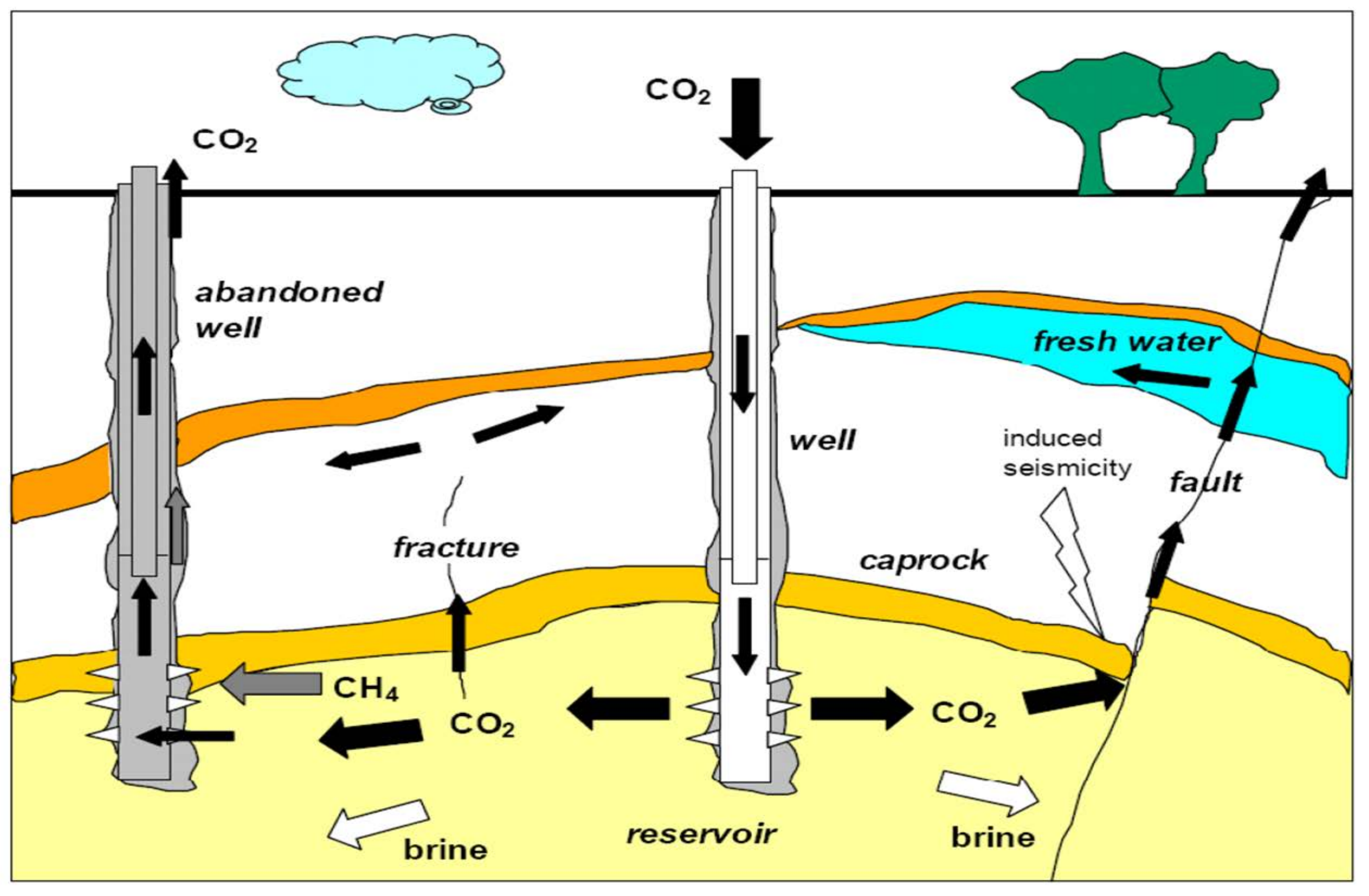


History Matching

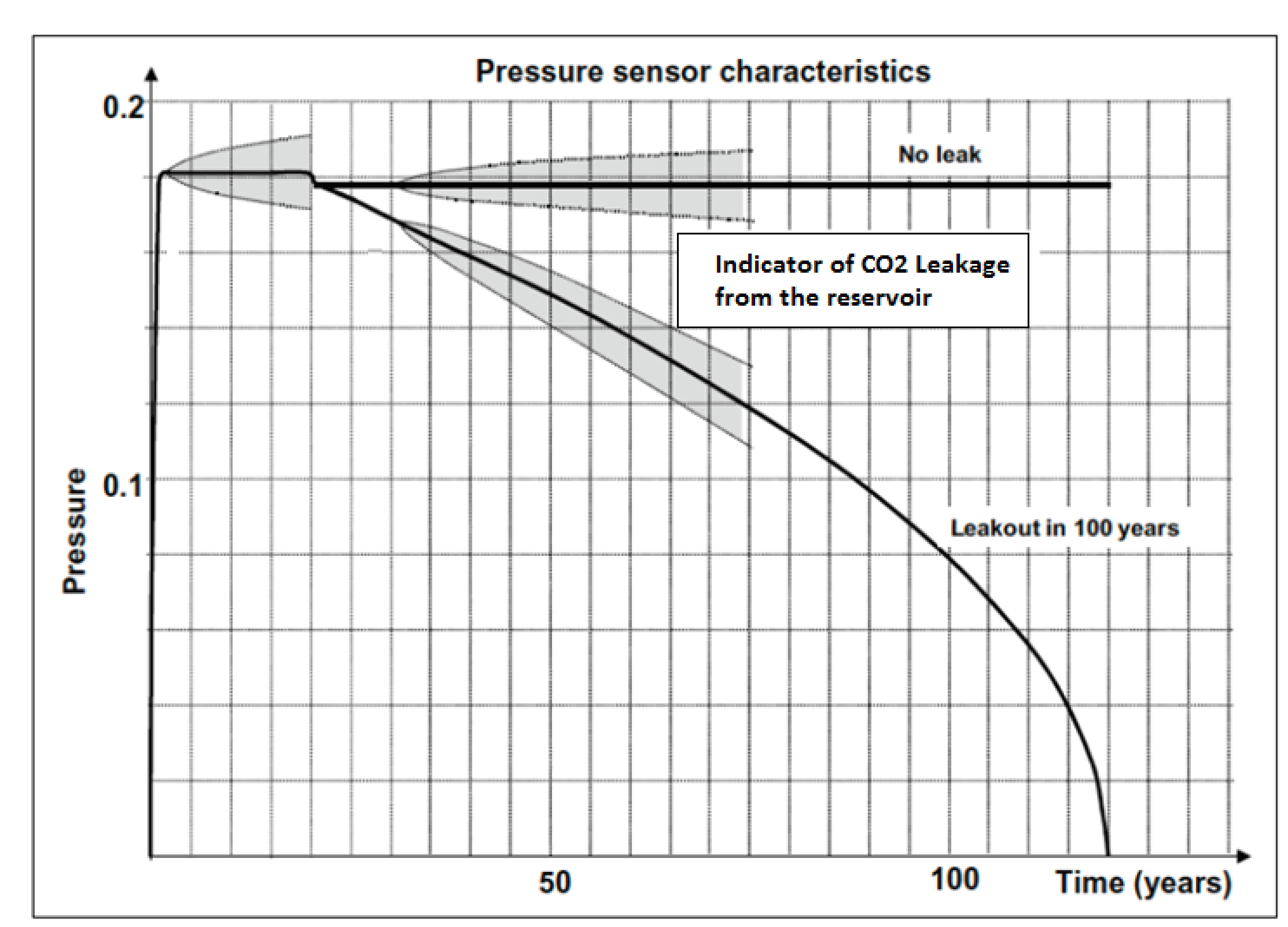


Matching Parameter
Absolute Permeability
Brine Density
Reference Pressure
Transmissibility Multiplier
Reservoir Boundary
Relative Permeability

CO_2 Leakage Modeling

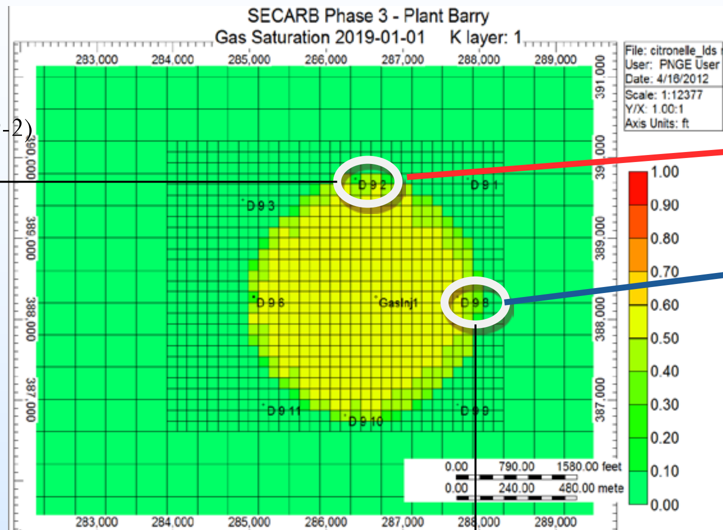


CO_2 Leakage Modeling

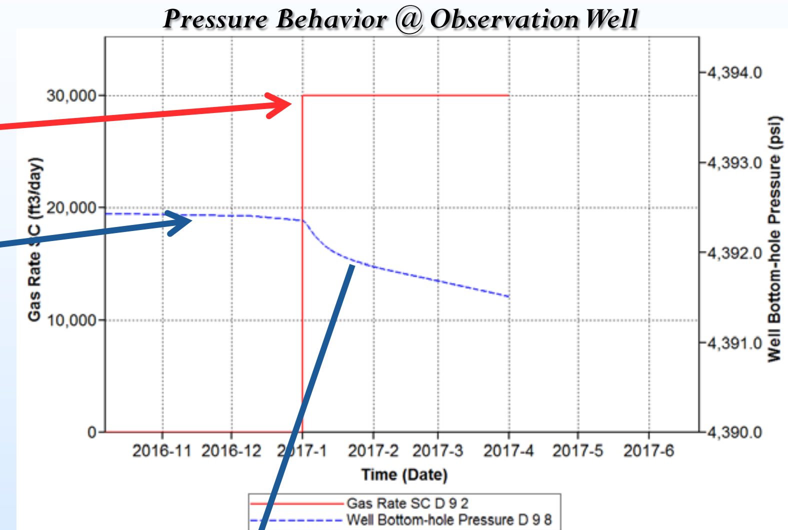


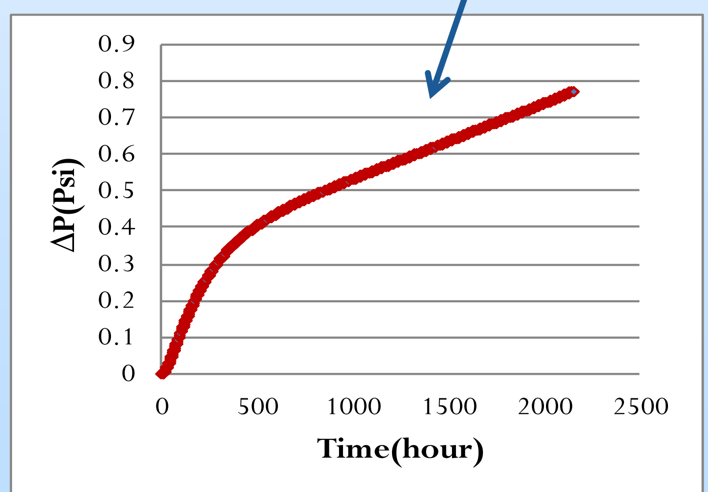
CO_2 Leakage Modeling

Leaking Well(D-9-2)
Leakage rate = 30MSC/day

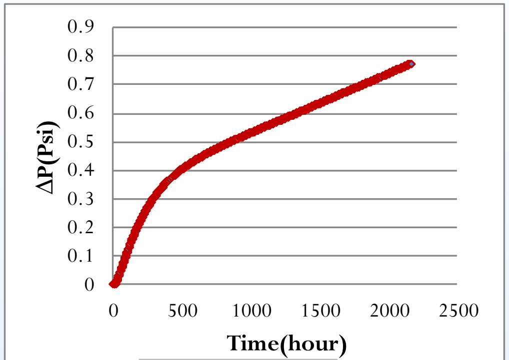


Observation Well





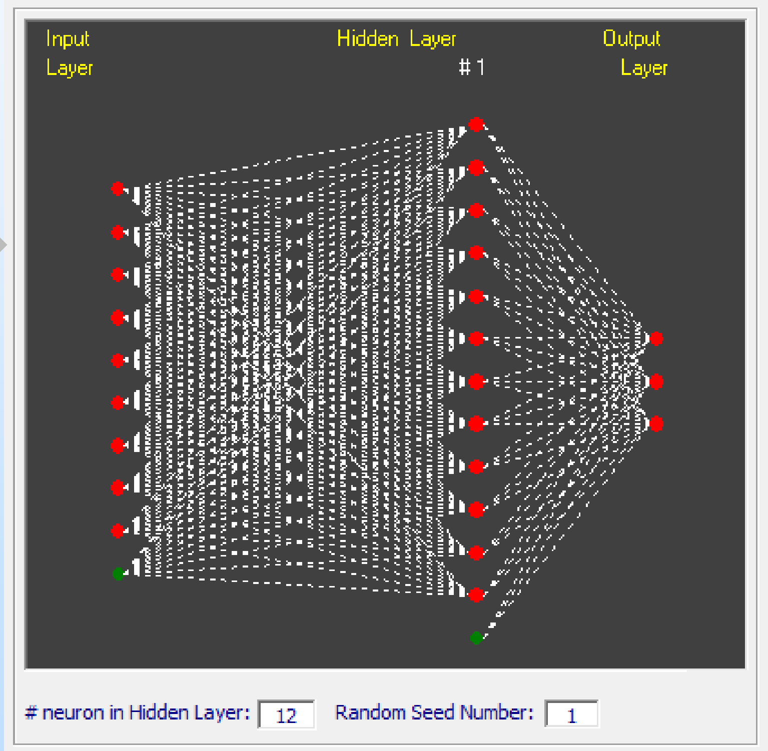
AI Model Development



Data Summarization

Descriptive Statistics

Mean	0.091
Standard Error	0.0047
Median	0.092
Mode	0
Standard Deviation	0.062
Sample Variance	0.0038
Kurtosis	-1.31
Skewness	0.029
Range	0.195
Minimum	0
Maximum	0.195
Sum	15.38
Count	168



-Leakage Rate

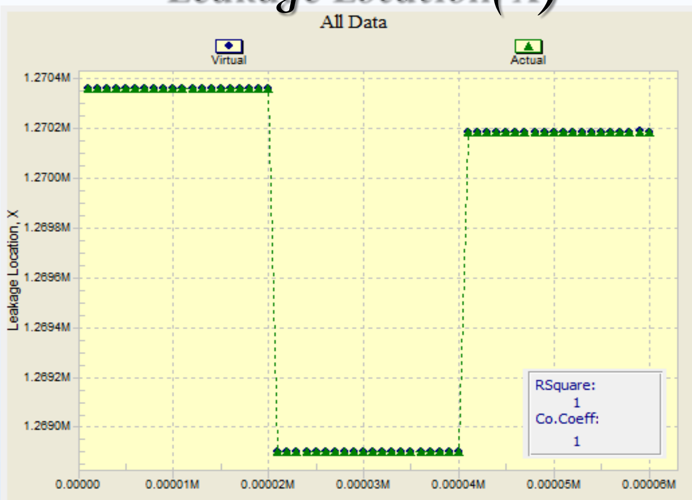
-Leakage Location(X,Y)

AI Model Development

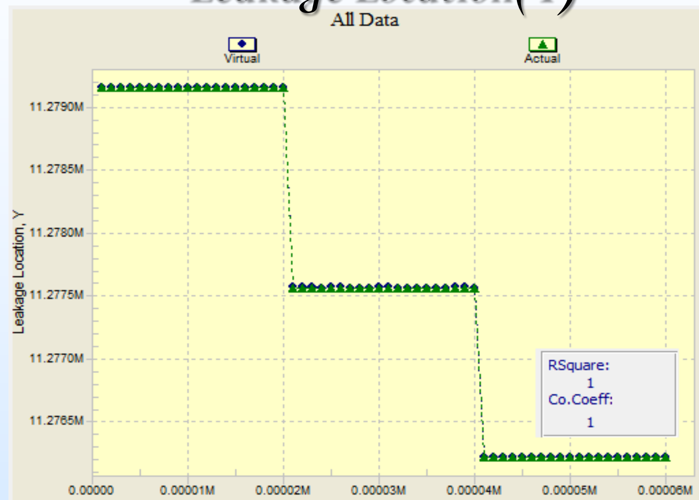
Input

Hourly Pressure
one week after Leakage (168 data points
for each leakage rate)

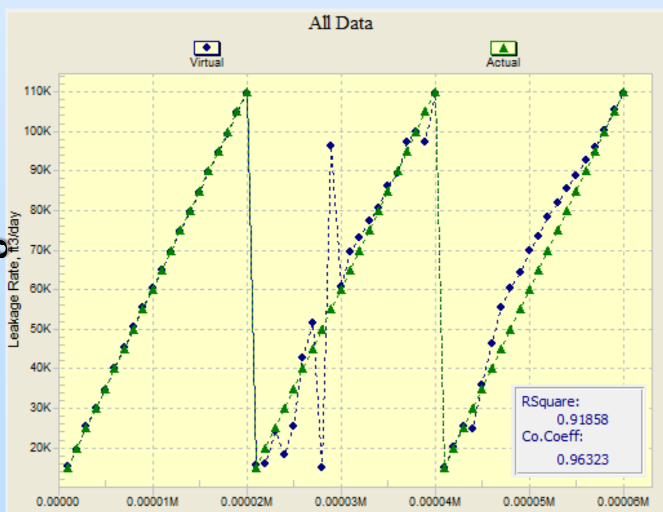
Leakage Location(X)



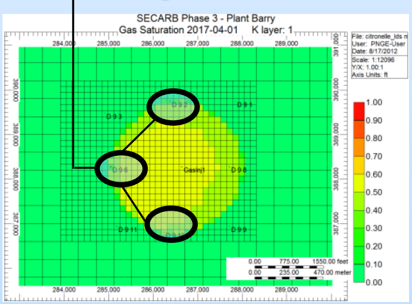
Leakage Location(Y)



Leakage Rate



Leakage Locations



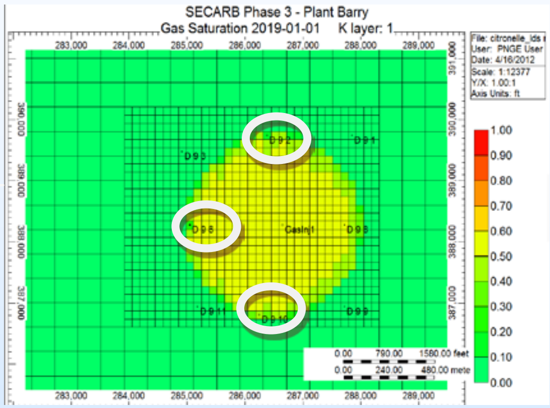
Output

Leakage Rate Mcf/day
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110

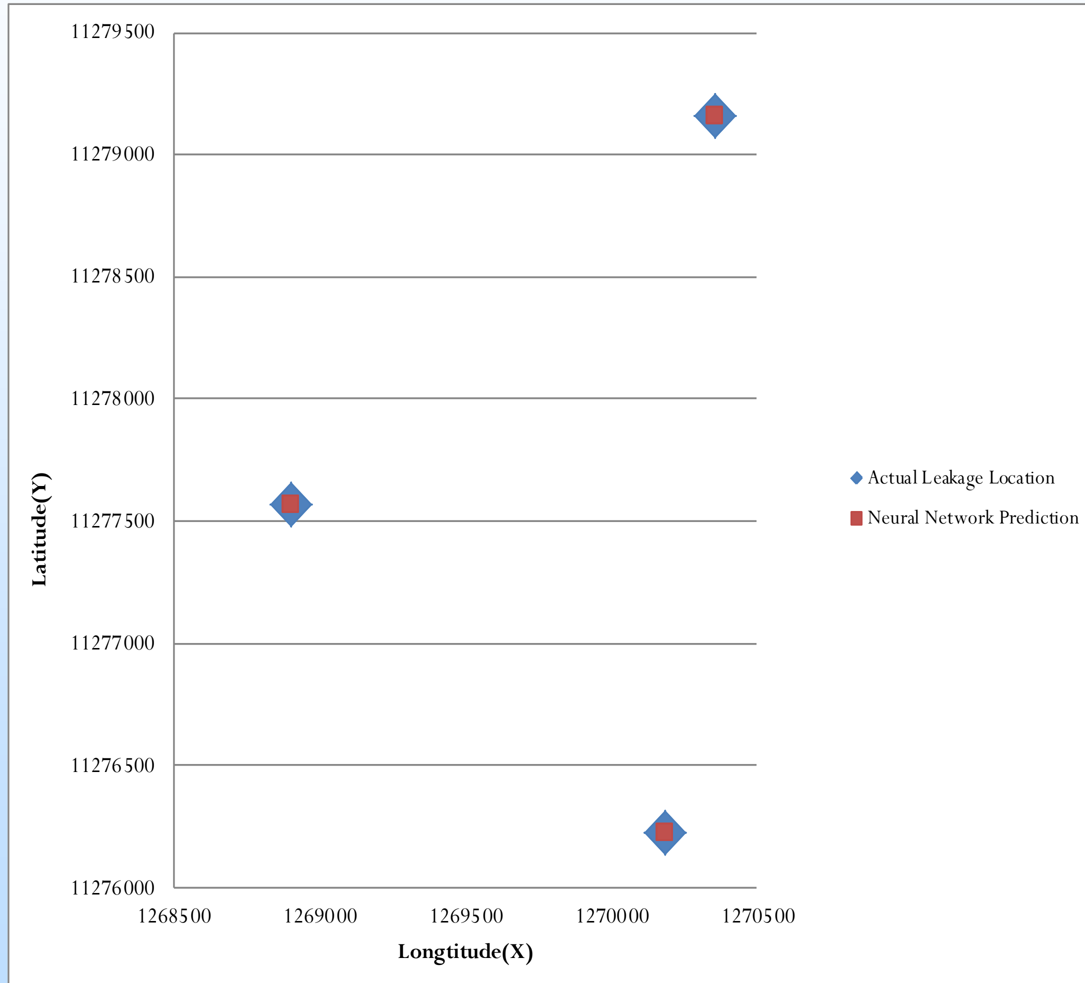
Validation – Blind Runs

Nine new leakage Scenarios

Leakage Rate Mcf/day
26
52
88

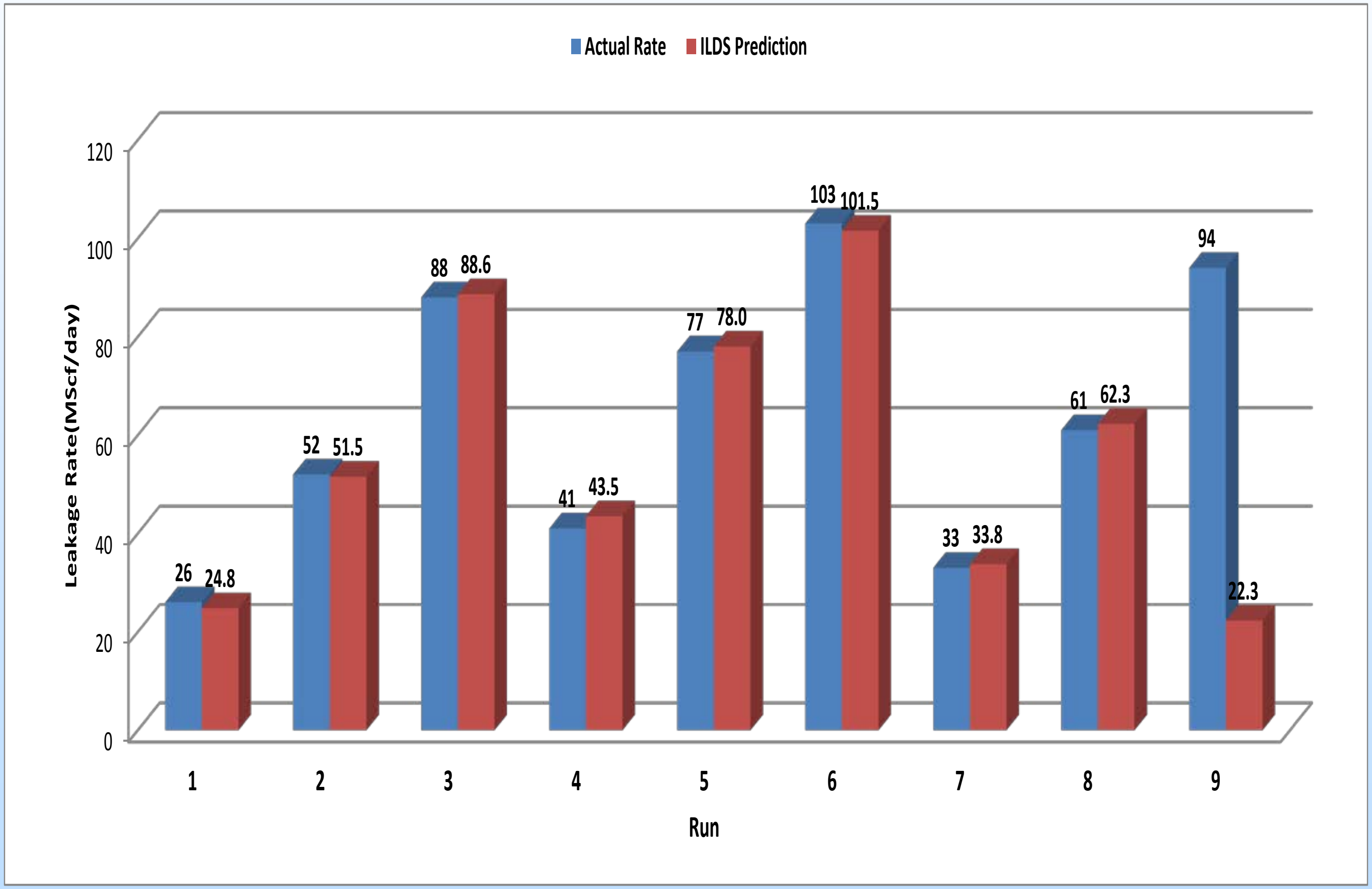


Run	Leakage Location(X) Actual	Leakage Location(X) N.N	Leakage Location(Y) Actual	Leakage Location(X) N.N
1	1268902.53	1268903.05	11277566.74	11277569.97
2	1268902.53	1268902.78	11277566.74	11277565.13
3	1268902.53	1268902.55	11277566.74	11277567.57
4	1270359.37	1270359.03	11279158.24	11279157.46
5	1270359.37	1270359.11	11279158.24	11279157.51
6	1270359.37	1270359.17	11279158.24	11279157.44
7	1270184.29	1270184.53	11276221.98	11276223.47
8	1270184.29	1270185.16	11276221.98	11276224.14
9	1270184.29	1270183.81	11276221.98	11276222.66

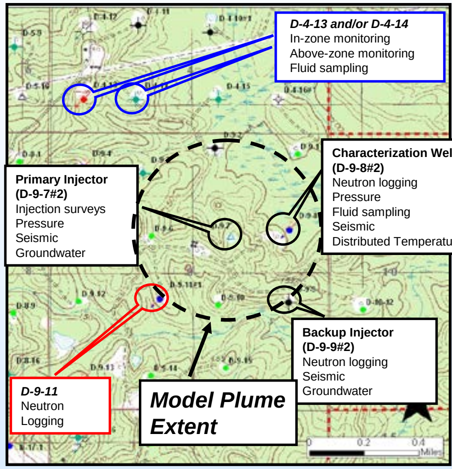


Validation – Blind Runs

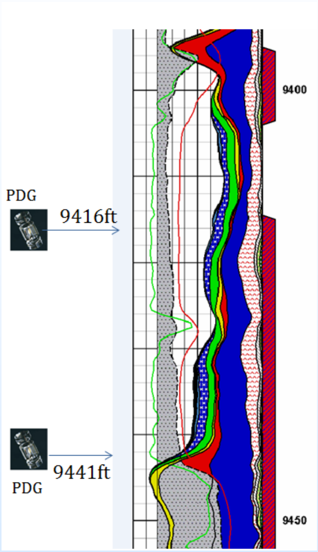
ILDS Leakage Rate Prediction

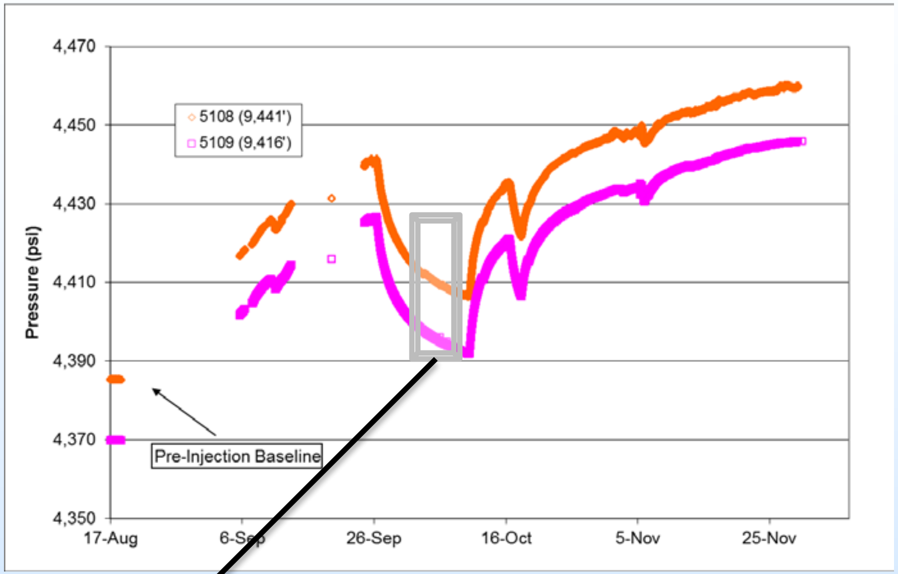


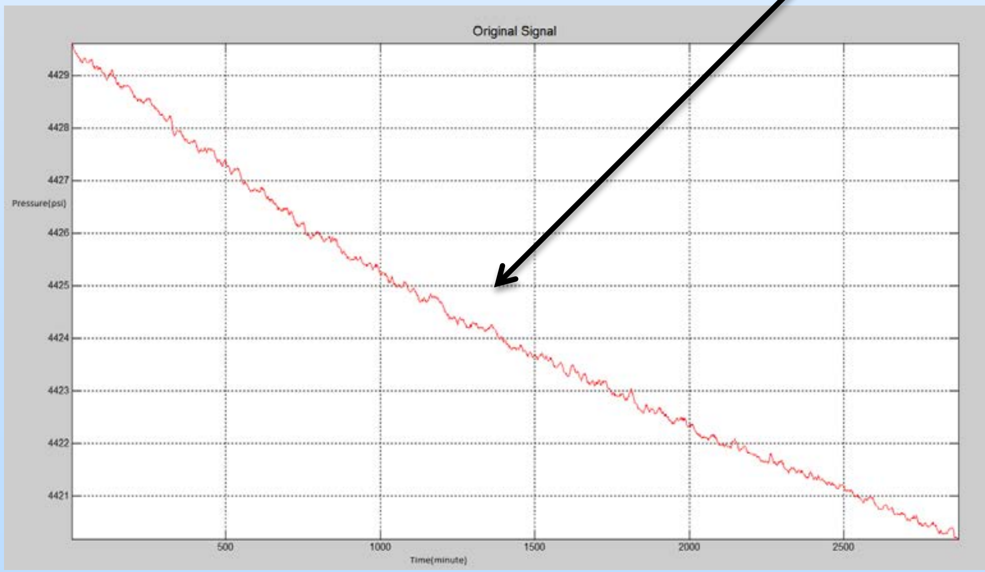
PDGs at Citronelle Site



Ref: ARI



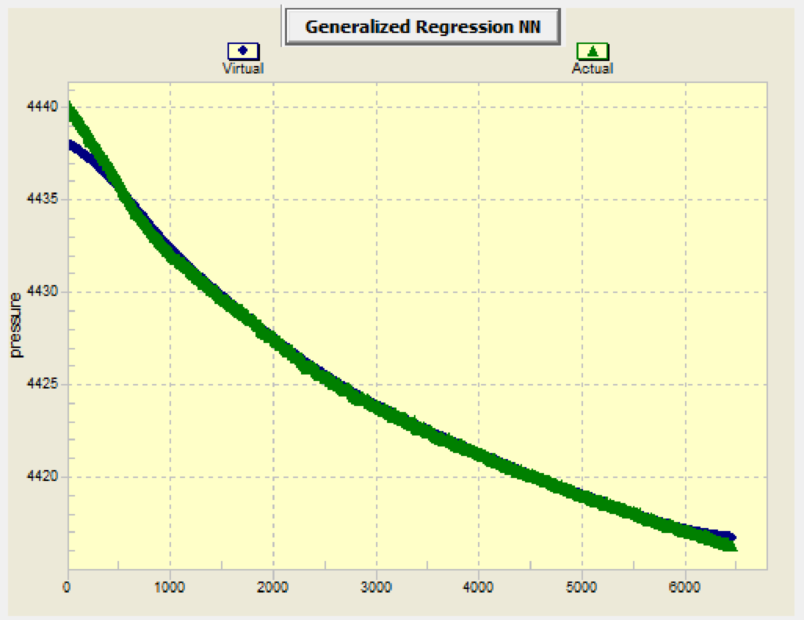




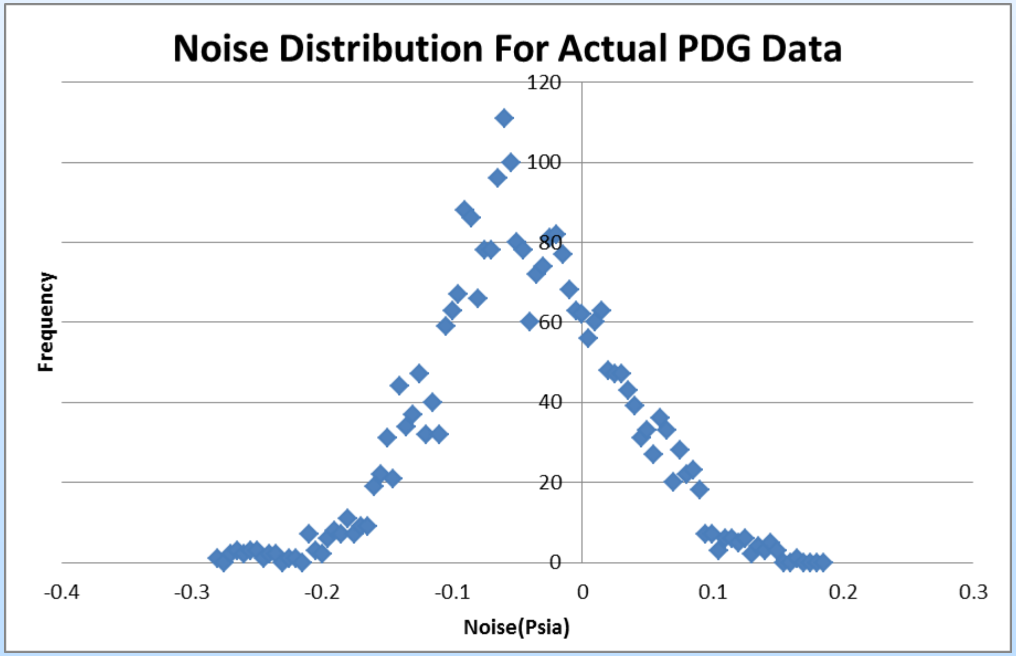
Noise Analysis - PDGs

$$Ni = P_{actual} - P_{fitted} \rightarrow Noise\ Level = \left(\frac{1}{n-1}\sum_{i=1}^{n} N_i^2\right)^{1/2}$$

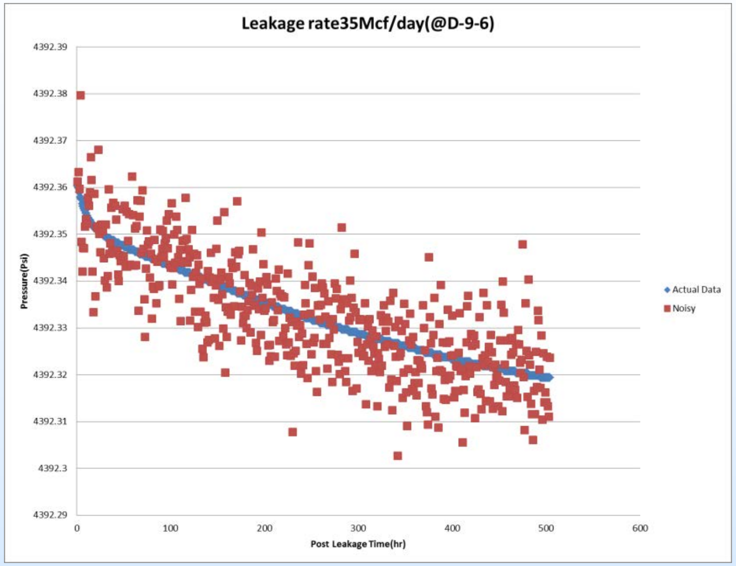
Noise Level = 0.08 Psi

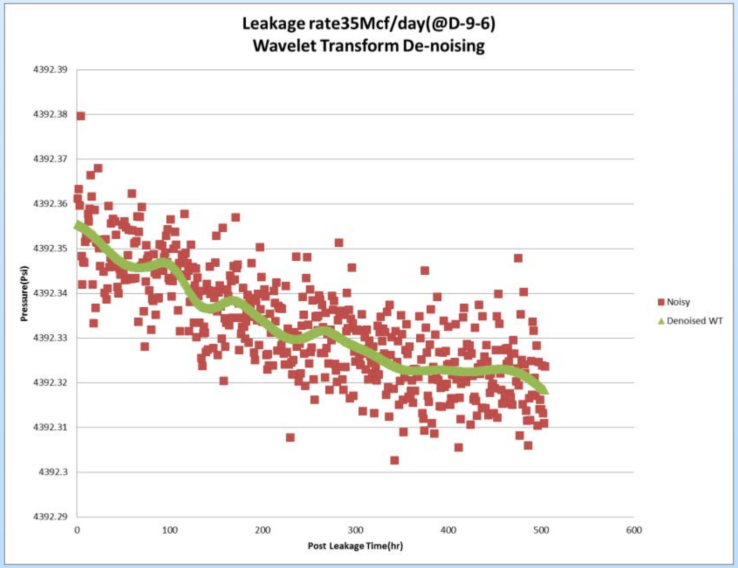


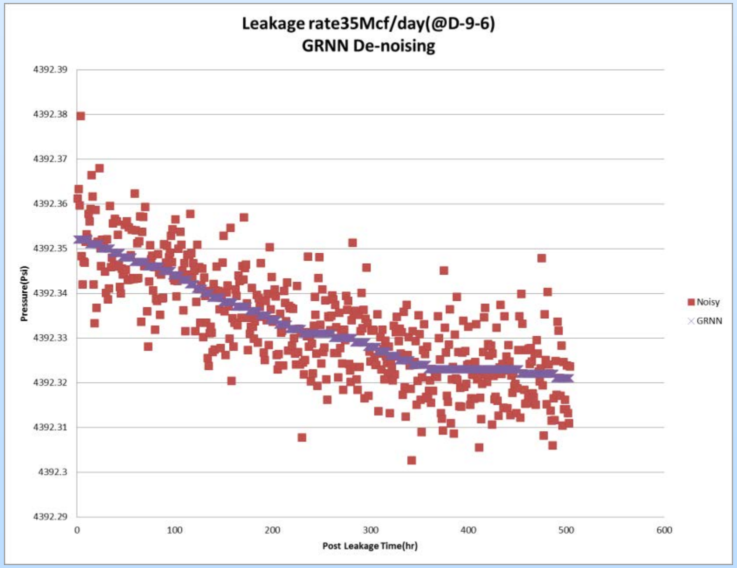
Distribution = Normal (Gaussian)



De-noising Process

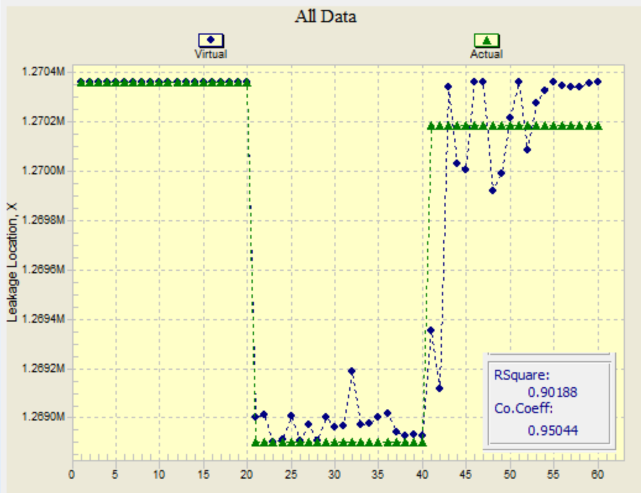




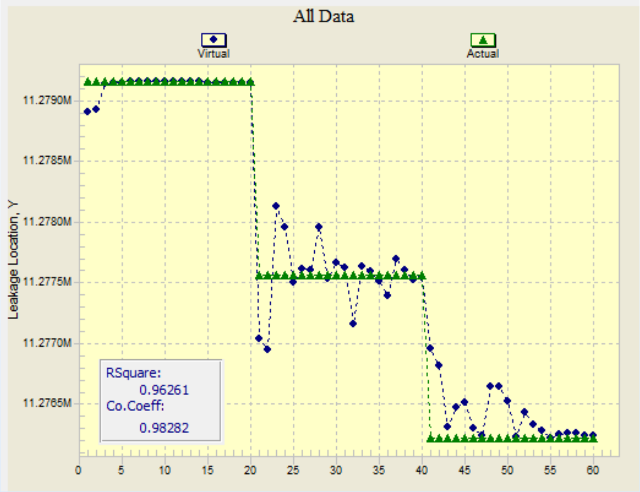


Training with De-Noised Data

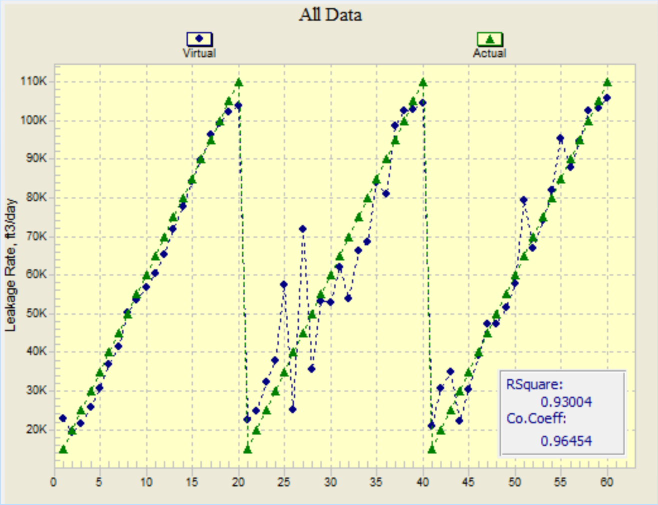
Leakage Location(X)

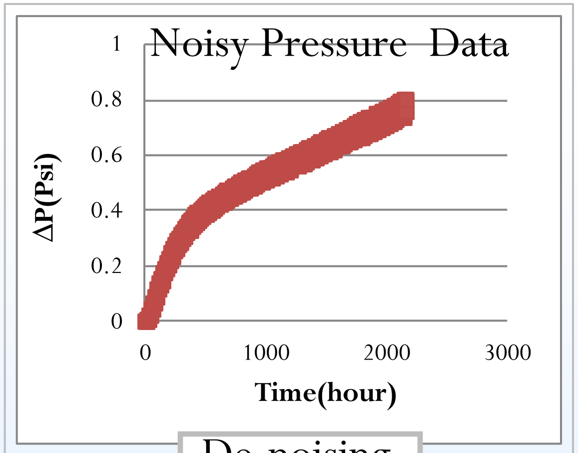


Leakage Location(Y)

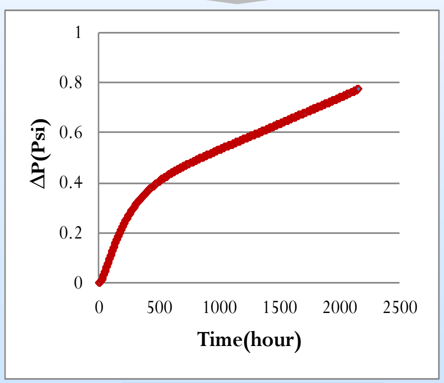


Leakage Rate





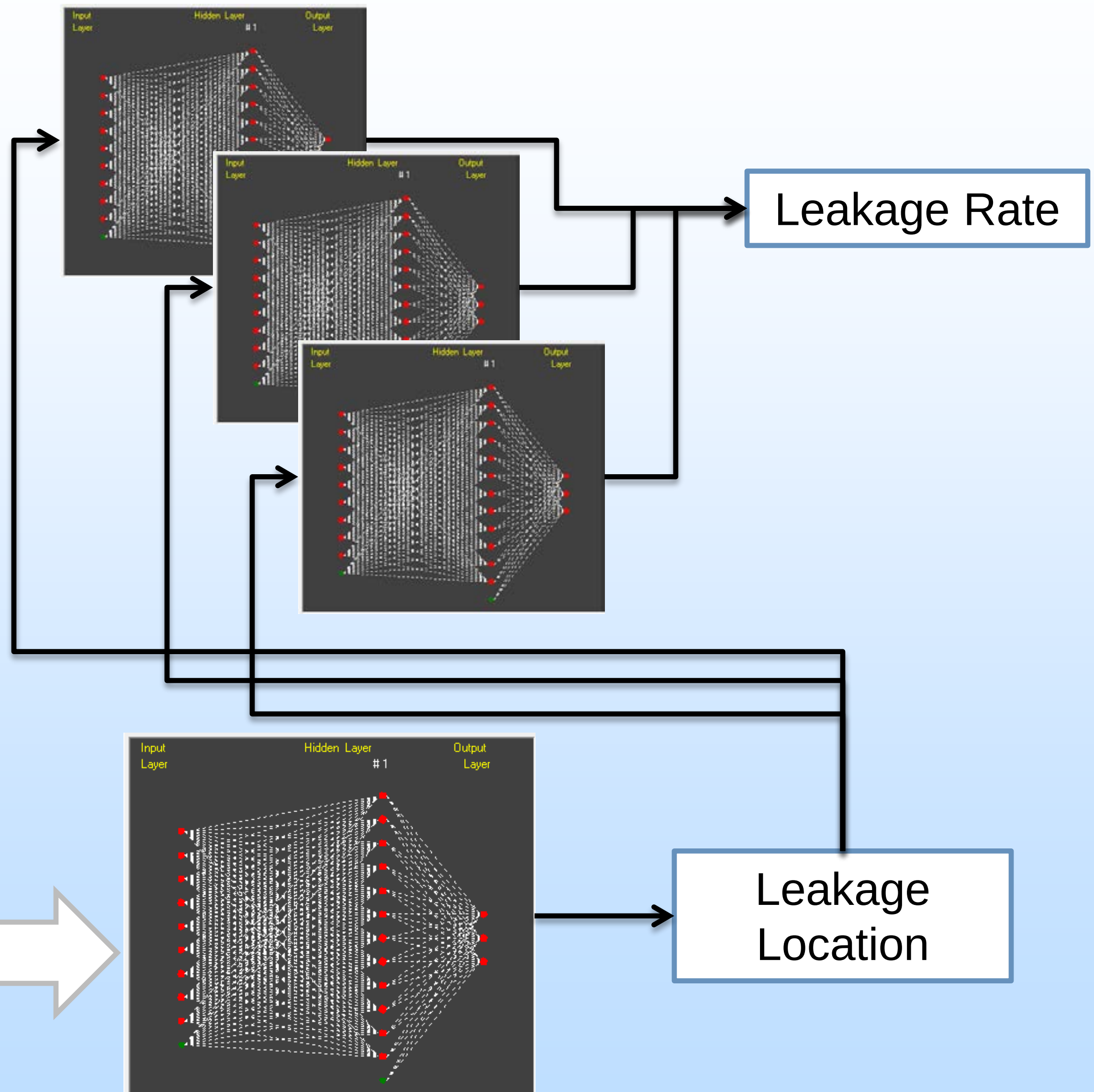
De-noising



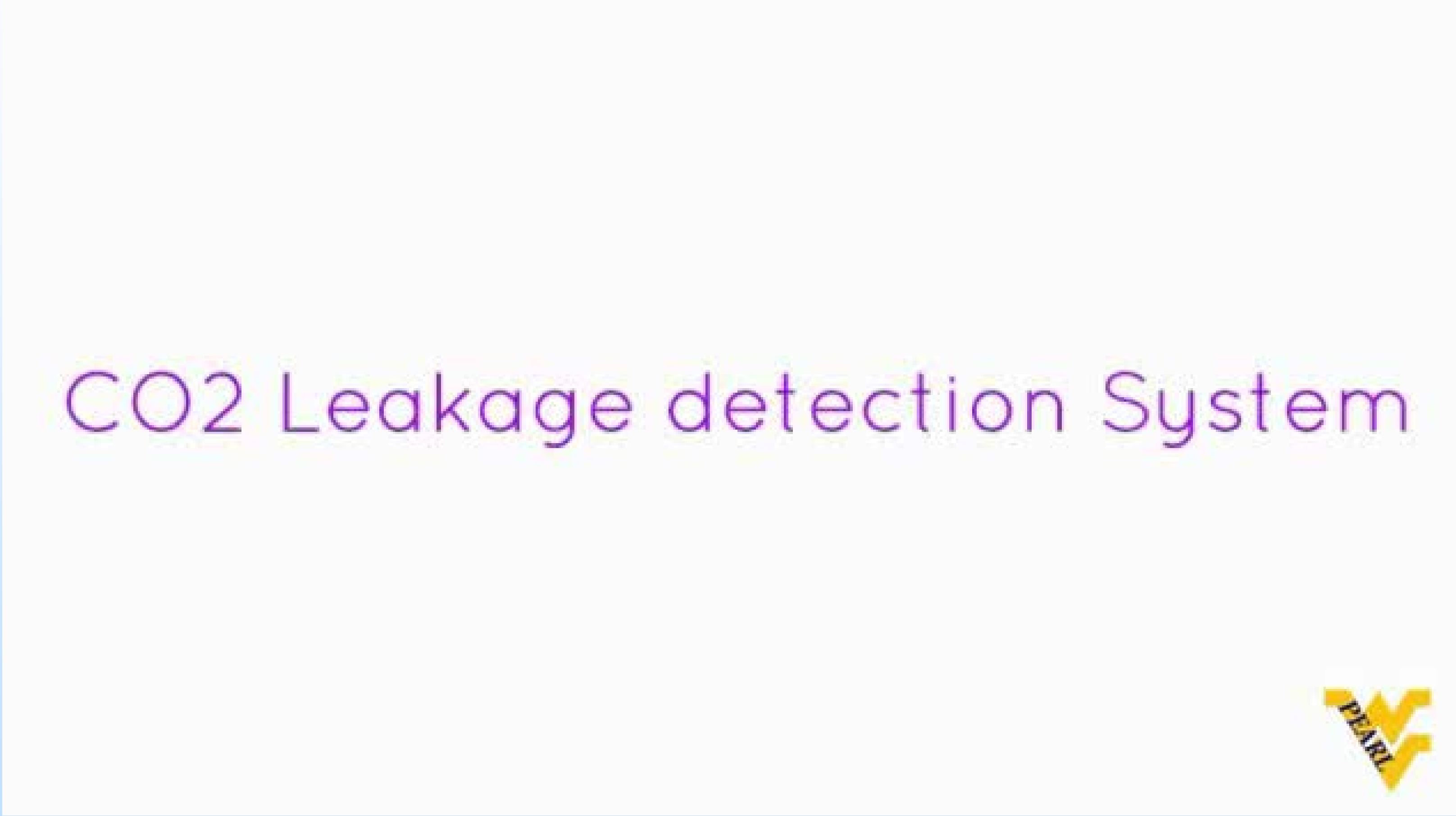
Summarization

Descriptive Statistics

Mean	0.091532	Kurtosis	-1.31344
Standard Error	0.004755	Skewness	0.029047
Median	0.091797	Range	0.194824
Mode	0	Minimum	0
Standard Deviation	0.061636	Maximum	0.194824
Sample Variance	0.003799	Sum	15.37744



The Interface Development



Accomplishments to Date

- Geological model was developed.
- Reservoir Simulation Model was developed.
- Impact of Relative Perms of Trapping Mechanism was determined
- Seal Quality and Integrity was studied
- Sensitivity analysis was performed
- Reservoir Simulation Model was history matched
- Intelligent Leakage Detection System (ILDS) was designed and developed.
  - Initial Design
  - Validated for Simple Reservoir System
  - Validated for Simple Leakage System
- High Frequency data was cleansed and summarized
- ILDS interface was developed

Summary

- **Key Findings:**

  - Location and amount of CO_2 leakage can be detected and quantified, rather quickly, using continuous monitoring of the reservoir pressure.
  - Pattern recognition capabilities of Artificial Intelligence and Data Mining may be used as a powerful deconvolution tool.

Lessons Learned(proof of concept):

- Development of an Intelligent Leakage Detection System (ILDS) is initiated for detection and quantification of CO_2 leakage.

Future Plans:

- Increase the robustness of ILDS by:
  + Using history matched model
  + Examining impact of different boundary conditions,
  + Including more sources of leakage(like Cap rock Leakage)
  + Examining detection of simultaneous multiple leakages.

Bibliography

List peer reviewed publications generated from project per the format of the examples below

- Journal, one author:
  - Gaus, I., 2010, Role and impact of CO2-rock interactions during CO2 storage in sedimentary rocks: International Journal of Greenhouse Gas Control, v. 4, p. 73-89, available at: XXXXXXX.com.
- Journal, multiple authors:
  - MacQuarrie, K., and Mayer, K.U., 2005, Reactive transport modeling in fractured rock: A state-of-the-science review. Earth Science Reviews, v. 72, p. 189-227, available at: XXXXXXX.com.
- Publication:
  - Bethke, C.M., 1996, Geochemical reaction modeling, concepts and applications: New York, Oxford University Press, 397 p.

Appendix
Benefit to the Program

- Program goals :
  - Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones.

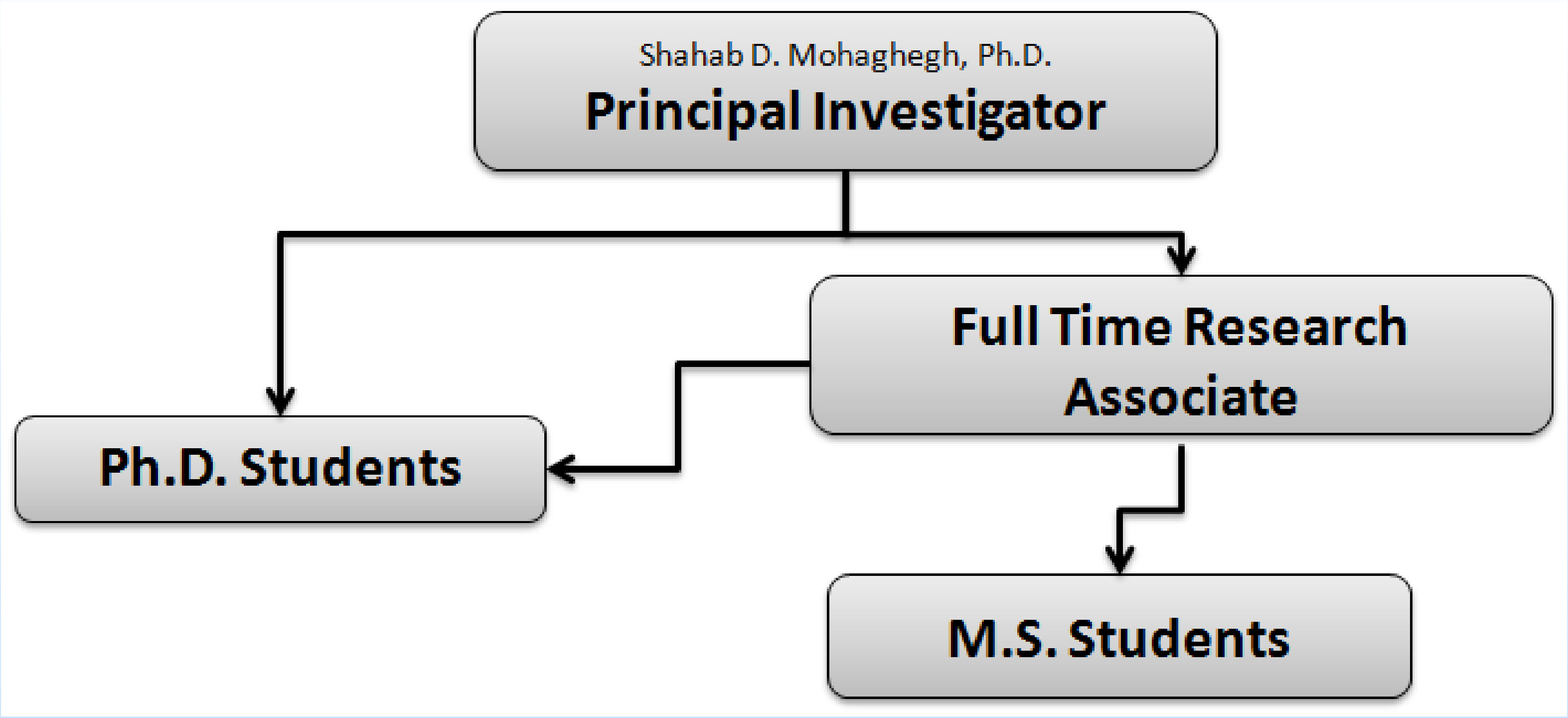
- Benefits statement:
  - This project is developing the next generation of intelligent software that takes maximum advantage of the data collected using “Smart Fields” technology to continuously and autonomously monitor and verify CO_2 sequestration in geologic formations. This technology will accommodate in-situ detection and quantification of CO_2 leakage in the reservoir.

Appendix
Project Overview:
Goals and Objectives

- Goals and objectives in the Statement of Project:
  - This project proposes developing an in-situ CO_2 Monitoring and Verification technology based on the concept of “Smart Fields”. This technology will identify the approximate location and amount of the CO_2 leakage in the reservoir in a timely manner so action can be taken and ensure that 99 percent of the injected CO_2 remains in the injection zone.

- Success Criteria and Decision Points:
  - There are a total of 10 milestones (and 4 sub-Milestone) in this project.
  - Decision points come at the end of quarters 4 (Milestone 2.2) and 15 (Milestone 6). At the decision points a “go” or “no go” decision on the continuation of the project is made based on the accomplishments of the project up to that point.

Appendix
Organization Chart

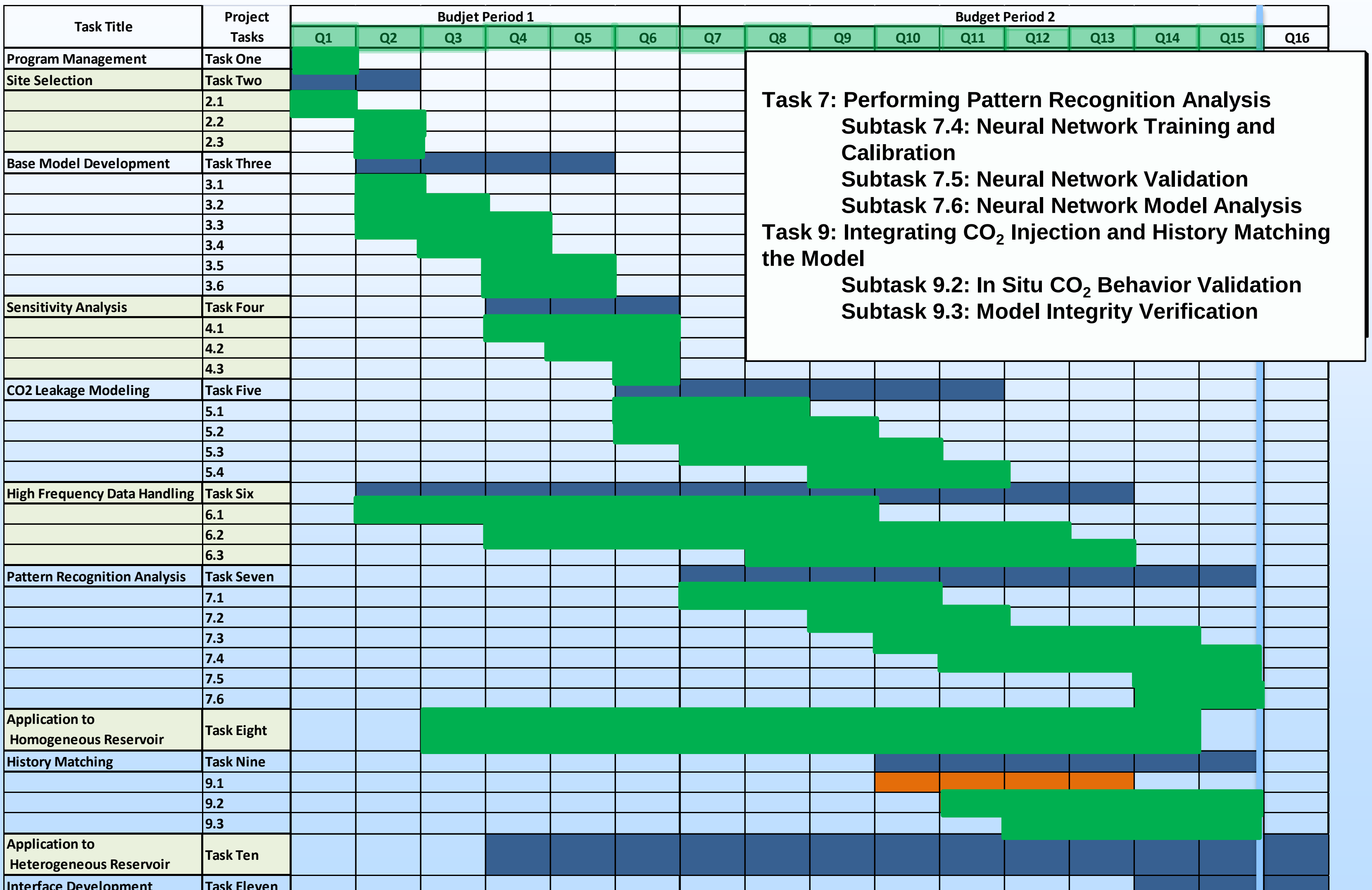


Main Contributors (Research & Development): Alireza Haghighat, Alireza Shahkarami, Daniel Moreno, Najmeh Borzoui, and Yasaman Khazaeni.

Full Time Research Associate: Vida Gholami,

Appendix
Gantt Chart

August 22, 2013



Milestone Timelines

Milestone log				
	Title	Description	Related task or subtask	Completion Date
Budget Period 1				
Milestone 1.1	Advisory Board Meeting	Advisory board should get together for a meeting (or conference call) to select a site for the project.	Subtask 2.1	End of First Quarter
Milestone 1.2	Site Selection	A site must be selected for the project.	Subtask 2.2, 2.3	End of Second Quarter
Milestone 2.1	Data collection	Completion of geologic and production data collection	Subtask 3.2	End of Third Quarter
Milestone 2.2	Completion of geological model	Completion of geologic/geo-cellular model	Subtask 3.3	End of Fourth Quarter
Milestone 2.3	Completion of the base model	Completion and testing the base flow model	Subtask 3.6	End of Fifth Quarter
Milestone 3	Sensitivity Analysis	Completion of the sensitivity analysis on the reservoir model	Subtask 4.3	End of Sixth Quarter
Budget Period 2				
Milestone 4.1	CO2 Leakage Modeling	Model realistic CO2 leakage from the formation	Subtask 5.1	End of Eighth Quarter
Milestone 4.2	Downhole pressure modeling	Model realistic real-time downhole pressure measurements.	Subtask 5.2, 5.3, 5.4	End of Eleventh Quarter
Milestone 5	Handling High Frequency Data	Developing techniques for handling high frequency data	Subtask 6.1, 6.2, 6.3	End of Thirteenth Quarter
Milestone 6	Pattern recognition	Completing pattern recognition analysis	Subtask 7.1, 7.2, 7.3, 7.4, 7.5, 7.6	End of Fifteenth Quarter
Milestone 7	Application to Homogeneous system	Completing of analysis and application to Homogeneous system	Task 8	End of Fifteenth Quarter
Milestone 8	CO2 Injection Modeling	Completion of modeling the CO2 injection.	Subtask 9.3	End of Fifteenth Quarter
Milestone 9	Application to Heterogeneous system	Completing of analysis and application to Heterogeneous system	Task 10	End of Sixteenth Quarter
Milestone 10	Build Program Interface	Completion of Software Package	Task 11	End of Sixteenth Quarter