MVA – Near Surface

Carbon Dioxide Storage Program R&D Needs Workshop

Pittsburgh Oct. 2011

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Monitoring Zones

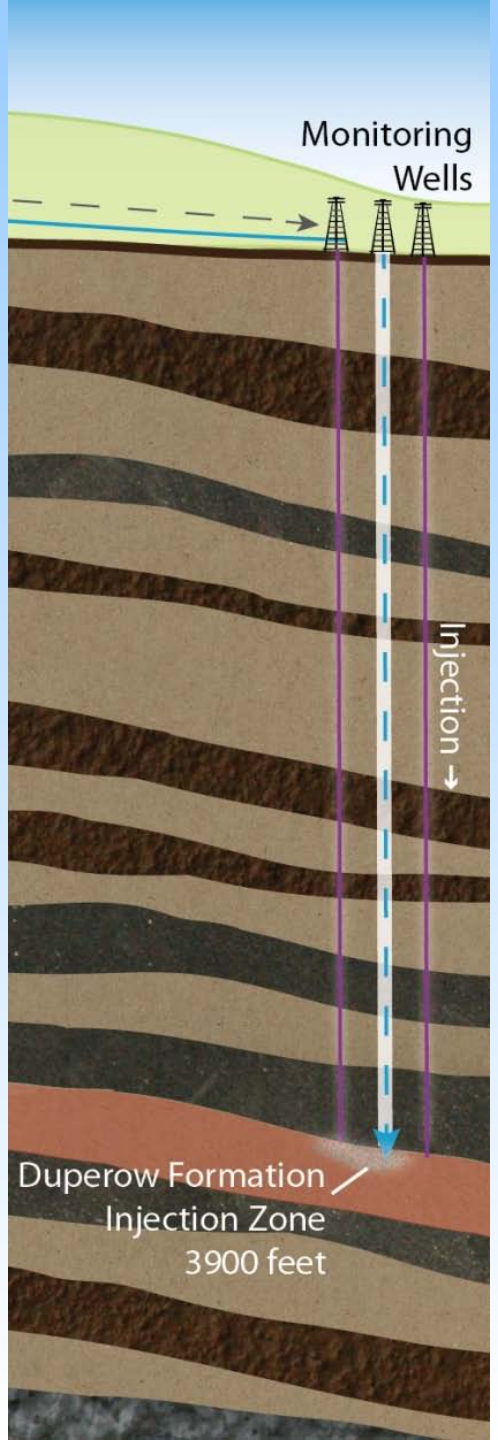
Atmosphere

Biosphere

Soil
(Vadose & Shallow
Saturated Zones

Caprock &
Deep Overburden

Injection Zone



- **Atmosphere**
  - Ultimate Integrator
  - Dynamic
  - Monitoring & Modeling
- **Biosphere**
  - dynamic
  - requires protection
  - opportunity for wide area monitoring but indirect methods
- **Soil**
  - Integrates
  - dynamic
- **Aquifers**
  - Integrates
  - Requires protection

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NETL CARBON SEQUESTRATION TECHNOLOGY PROGRAM PLAN CORE R&D GOALS

Table 3-6: MVA Technologies

MVA Objective	Description	Research Focus
Atmospheric Monitoring Technologies	Testing at the surface and in the atmosphere to identify and quantify possible releases from storage projects is critical to the success of future CCS projects. It is unlikely that CO_2 will reach the atmosphere, but in the event it does, technologies will be necessary to monitor and quantify releases of CO_2 from wellbores, faults, and diffuse soil releases.	• Research the development and application of novel chemical and isotopic tracers which may be precursors to CO_2 release at the surface. • Develop systems to monitor flux from soils to determine changes from baselines to identify release and quantify releases. • Research open path systems and CO_2 detectors to identify releases from injected CO_2.
Remote Sensing and Near-Surface Monitoring Technologies	Detecting near-surface releases in the vadose zone and groundwater sources are important to protecting USDW. It is also important to be able to detect pooling of high concentrations of CO_2 in low lying areas and in structures. The benefits of monitoring in this zone are that natural variations of CO_2 in the soil are typically minimal since biological activity typically occurs closer to the surface.	• Utilize remote sensing platforms to detect gas concentrations, land surface deformations, and biological impacts as indicators of CO_2 release and fate of CO_2 in the subsurface. • Advance water quality and soil gas analysis for isotopes, tracers, and organic and inorganic carbon as advanced warning signs of release. • Advance geophysical methods needed to image CO_2 or sense changes in geochemistry in the vadose zone.

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What Is the Monitoring Purpose?

- Climate change mitigation?
  - 1% over 1000 yrs – climate models?
- Retention in the reservoir?
  - Subsurface techniques typically do not measure properties directly proportional to concentration / quantity
- Overall storage security?
- HSE, Resource protection (USDW)?
  - Measure to ensure levels are below impact levels
- Public assurance?
- Verification and accounting?
  - Mass flow meters only accurate to ~1%

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How We Have Learned

Natural Analogs

- Mammoth Mountain
- Laacher See
- Latera
- Soda Springs, ID
- Crystal Geyser, UT

How analogous is the analog?

Flow through significant overburden

Fluxes may be much higher than leaky engineered system

Controlled Releases

- ASGARD (Nottingham)
- ZERT (Montana State)
- Australia
- Norway

Source term known

Ability to establish detection limits

Relatively little overburden

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Methods

- Soil Gas Monitoring
- In-situ soil gas probes
- Soil Flux chambers
- Open path FTIR, Differential Absorption LIDAR
- Cavity ring-down, other isotopic measurements
- Water chemistry
- Tracers
- Hyperspectral / mutispectral imaging
- Many more

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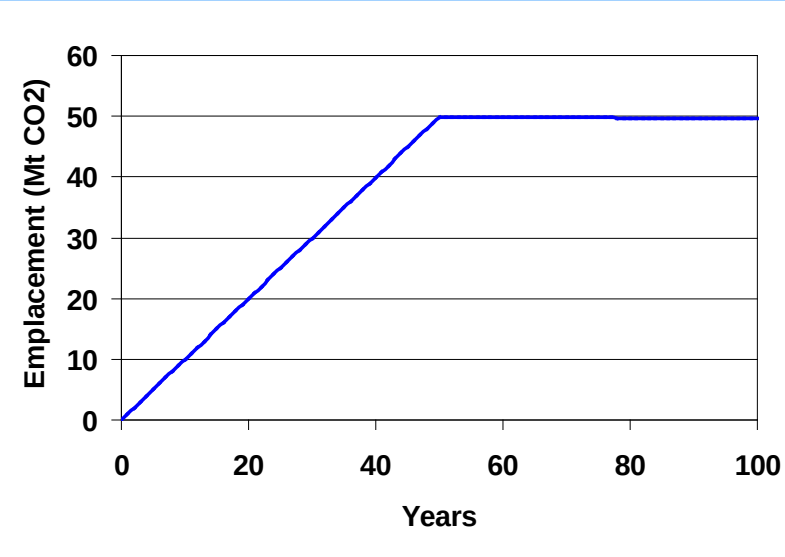
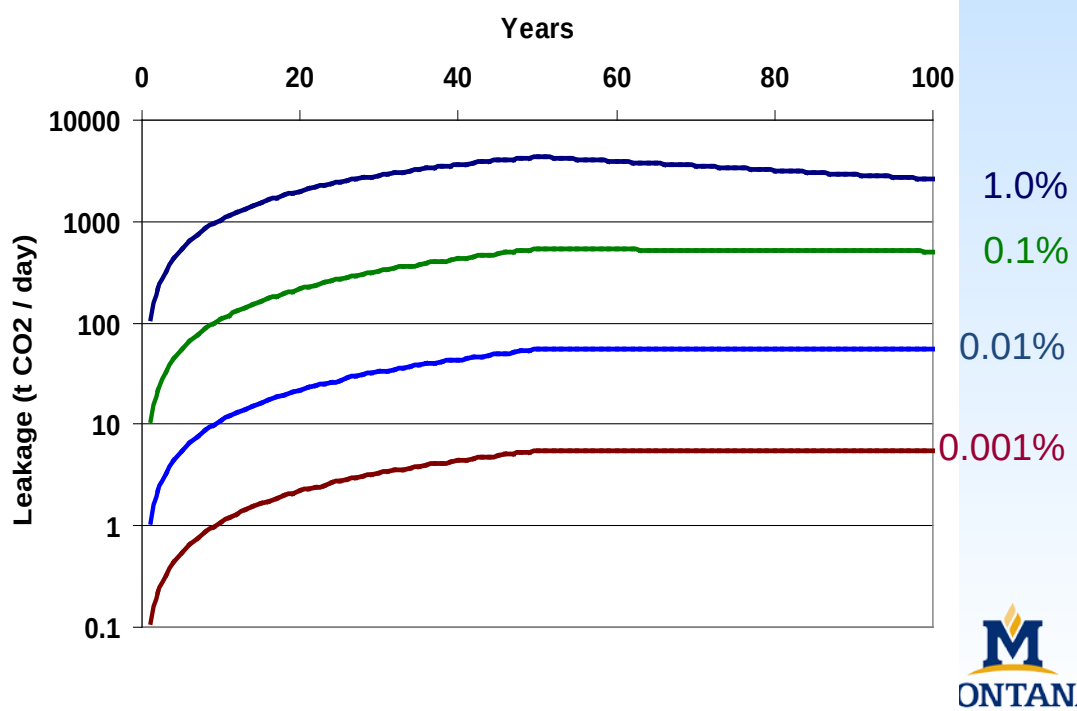
What Are Relevant Release Rates?

- 4 Mt/year injection from 500 MW power plant
- 50 years injection
- Four Leakage rates
  - 1% / year
  - 0.1% / year
  - 0.01% / year
  - 0.001% / year



- 1% over 1000 yrs = 0.001% / yr = 0.00001
- Daily leakage = 5.5 Tonnes / day
- Equivalent to ~92 idling cars



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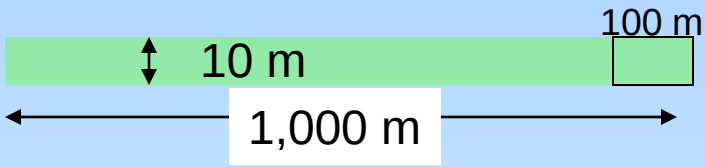
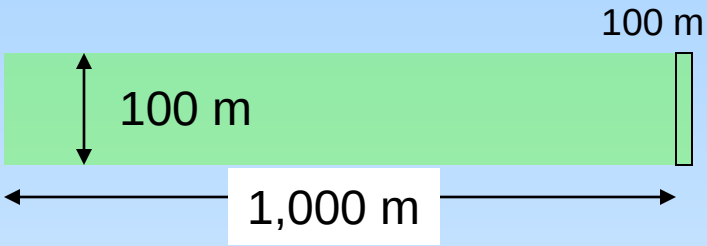
Injection Rate

Sally Benson





Scale to 1000 m leak
1,000 kg/day: 1 tonne/day

Lee Spangler

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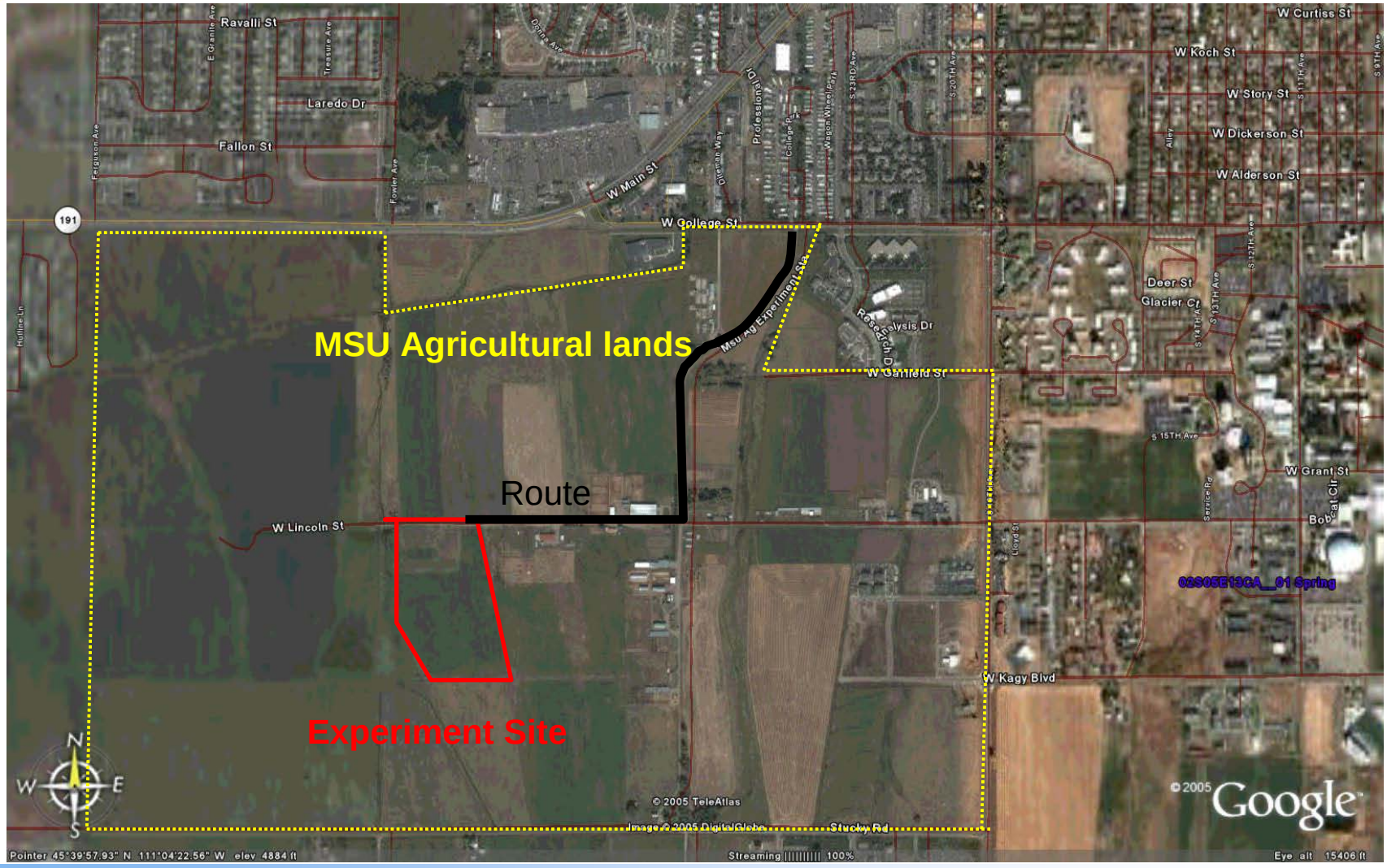
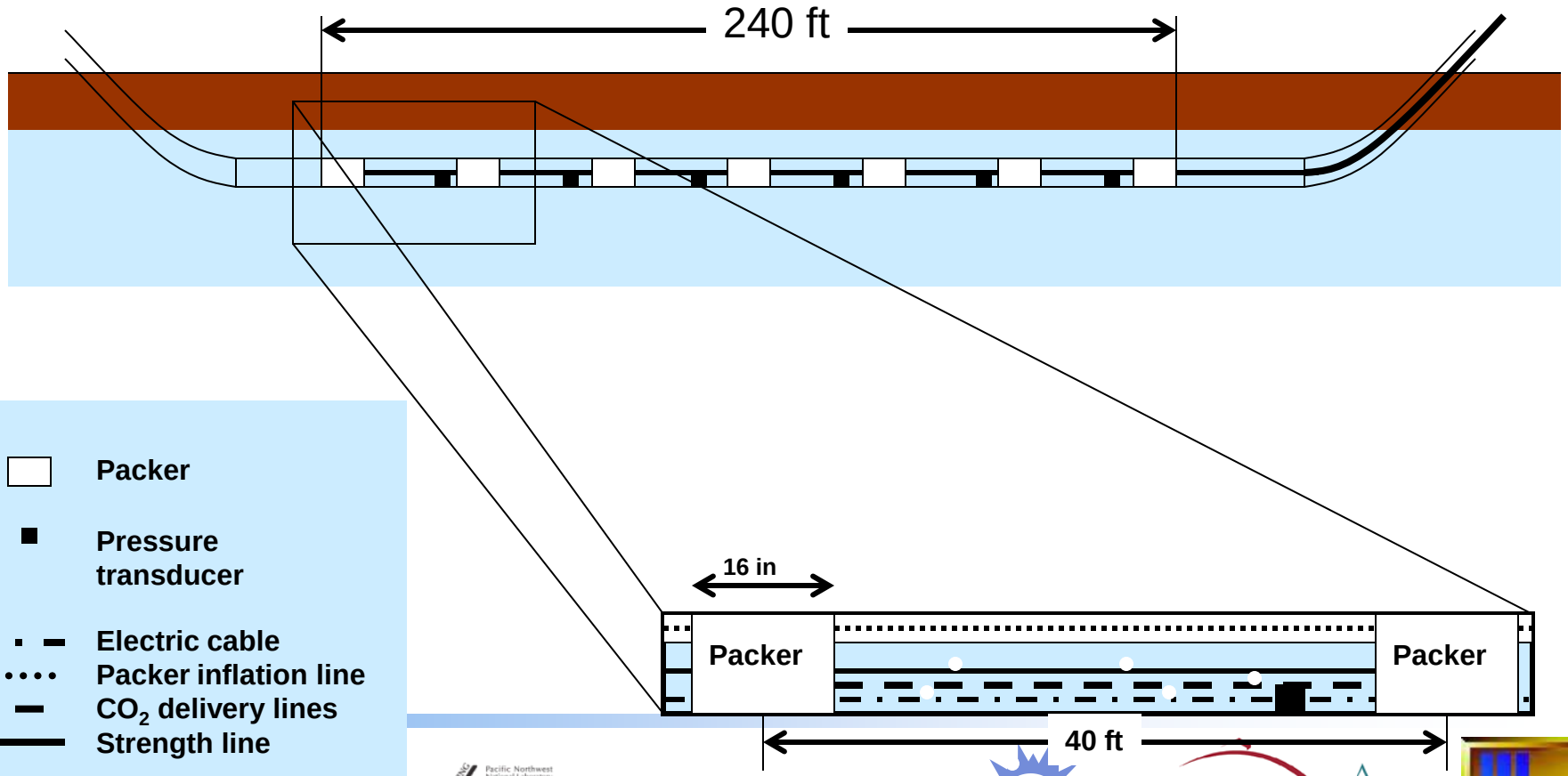
Field Test Facility



Horizontal Well Installation

Ray Solbau, Sally Benson



Large Number of Participants / Methods

47 investigators
31 instruments / sensor arrays
5 univ. 6 DOE labs, 4 companies

Investigator	Institution	Monitoring Technology	Number of Sensors
Arthur Wells Rod Diehl Brian Strasizar	National Energy Technology Laboratory	Atmospheric tracer plume measurements	1 tower (4m) Blimp (Apogee Scientific) with 3 tether line samplers
		Bee hive monitoring for tracer with sorption tube and pollen trap	2 hives
		Automated Soil CO_2 flux system	4 chambers
William Pickles Eli Silver Erin Male	University of California- Santa Cruz	Hand held hyperspectral measurements (plant health)	1 instrument
Yousif Kharaka James ThordsenGil AmbatsSarah Beers	United States Geological Survey*	Ground water monitoring	1 EC and temperature probe, Dissolved oxygen probe, lab analysis of water samples
Henry Rauch	West Virginia University	Water monitoring well headspace gas sampling	1 sensor
Lucian Wielopolski Sudeep Mitra	Brookhaven National Laboratory*	Ineleastic neutron scattering (total soil carbon)	1 instrument
Martha Apple Xiaobing Zhou Venkata Lakkaraju Bablu Sharma +2 students	Montana Tech*	Soil moisture, temp. Chlorophyll Content Meter , Fluorescence Meter , LI-COR 2000 to measure leaf area index Leaf Porometer to measure stomatal conductance	5 sensors
		Infrared radiometry (plant health)	2 instruments
		Atmospheric humidity and temperature, accumulated rainfall	1 sensor each
		Plant root imaging	1 camera
		Soil conductivity	1 sensor
		Handheld hyperspectral measurements (plant health)	1 instrument
William Holben Sergio Morales	University of Montana*	Microbial studies	Lab analysis

ZERT Zero Emissions Research and Technology

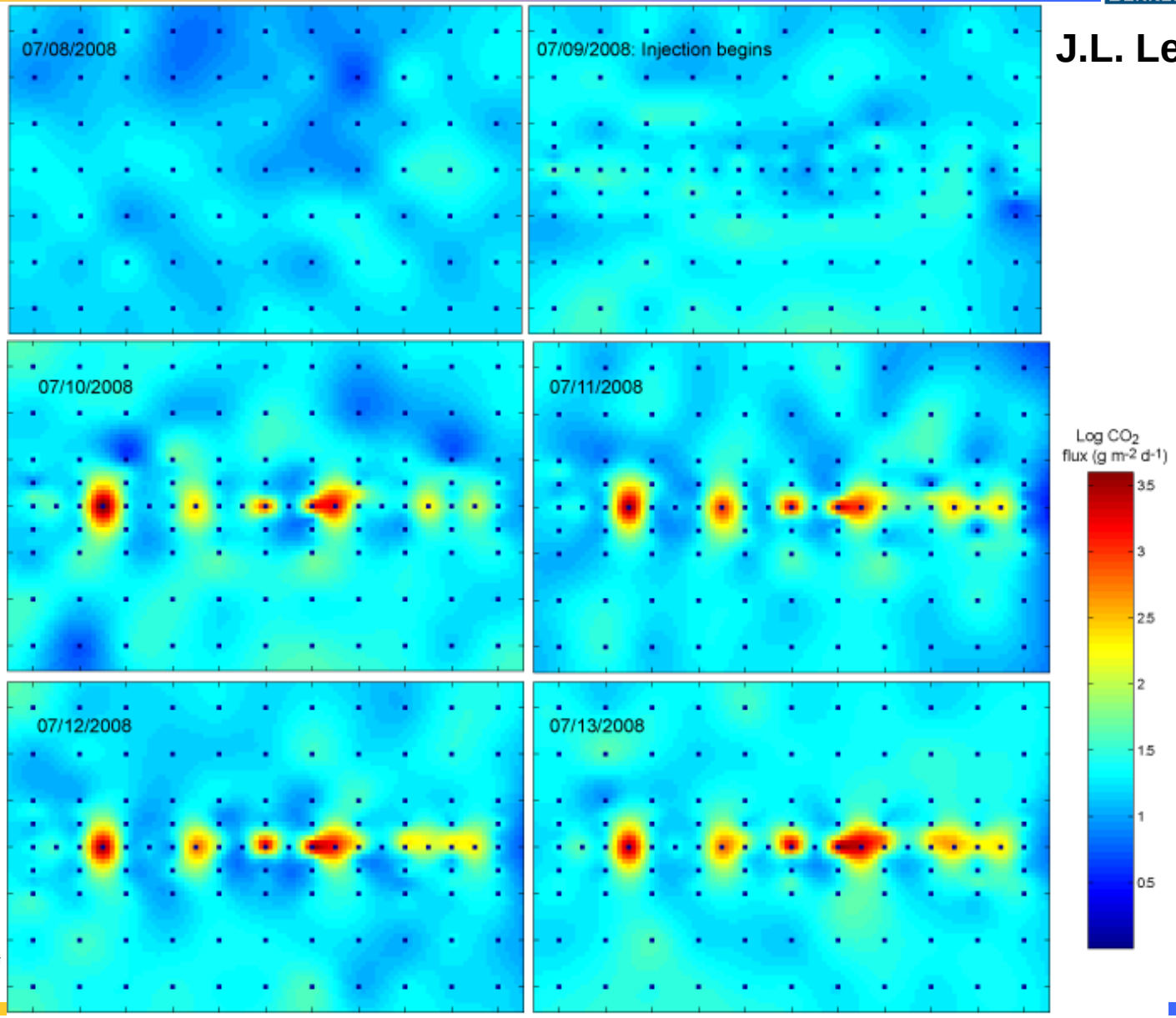
Large Number of Participants / Methods

Investigator	Institution	Monitoring Technology	Number of Sensors
Lee Spangler Laura Dobeck Kadie Gullickson	Montana State University	Water content reflectometers (soil moisture)	15 sensors
		Automated soil CO_2 flux system	5 long term chambers, 1 portable survey chamber
		CO_2 soil gas concentration	6 sensors
Kevin Repasky (PI) Jamie Barr	Montana State University	Underground fiber sensor array (CO_2 soil gas concentration)	4 sensors
Rand Swanson	Resonon*	Flight based hyperspectral imaging system	1instrument
Joseph Shaw (PI) Justin Hogan Nathan Kaufman	Montana State University	Multi-spectral imaging system (plant health)	1instrument
		Meteorological measurements	1 tower
Julianna Fessenden +3 students	Los Alamos National Laboratory	In situ (closed path) stable carbon isotope detection system	1 instrument
		Flask sampling for in situ isotope detection	Lab analysis
Sam Clegg Seth Humphries	Los Alamos National Laboratory	Frequency-modulated spectroscopy (FMS) open-air path	1 instrument
Thom Rahn	Los Alamos National Laboratory	Eddy covariance	1 tower
James Amonette Jon Barr	Pacific Northwest National Laboratory	Soil CO_2 flux (steady-state)	27 chambers
Sally Benson (PI) Sam Krevor Jean-Christophe Perin Ariel Esposito Chris Rella (Picarro)	Stanford University* / Picarro Instruments*	Commercial cavity ringdown real-time measurements of $\delta^{13}C$ and CO_2 in air	1 instrument
Greg Rau Ian McAlexander (LGR)	Lawrence Livermore National Laboratory /Los Gatos Research*	Commercial cavity ringdown real-time measurements of $\delta^{13}C$ and CO_2 in air	1 instrument
Jennifer Lewicki	Lawrence Berkeley National Laboratory	CO_2 soil gas concentration	8 sensors
		CO_2 atmospheric concentration	2 sensors
		Chamber soil CO_2 flux measurements	1 instrument
		Meteorological	1 tower

ZERT Zero Emissions Research and Technology

Flux Chamber

J.L. Lewicki

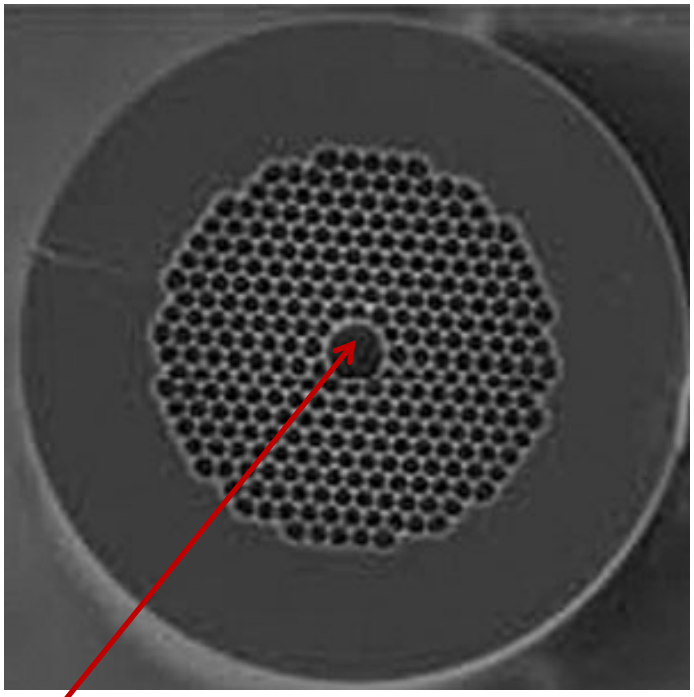


J.L. Lewicki, LBNL

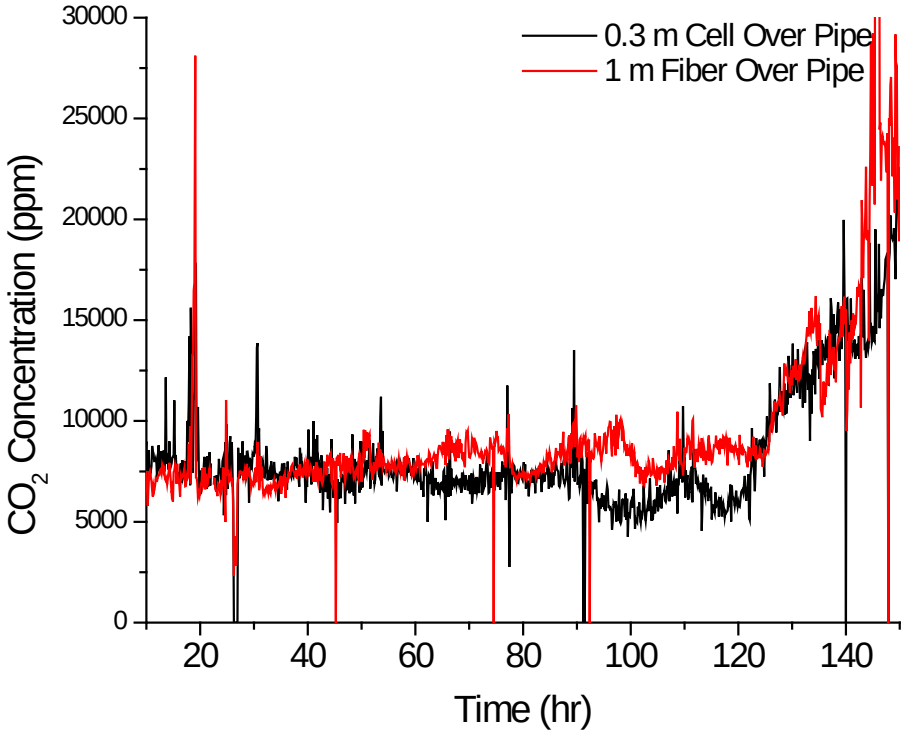
0 50 m

Underground Fiber Sensor

Jamie Barr
Kevin Repasky

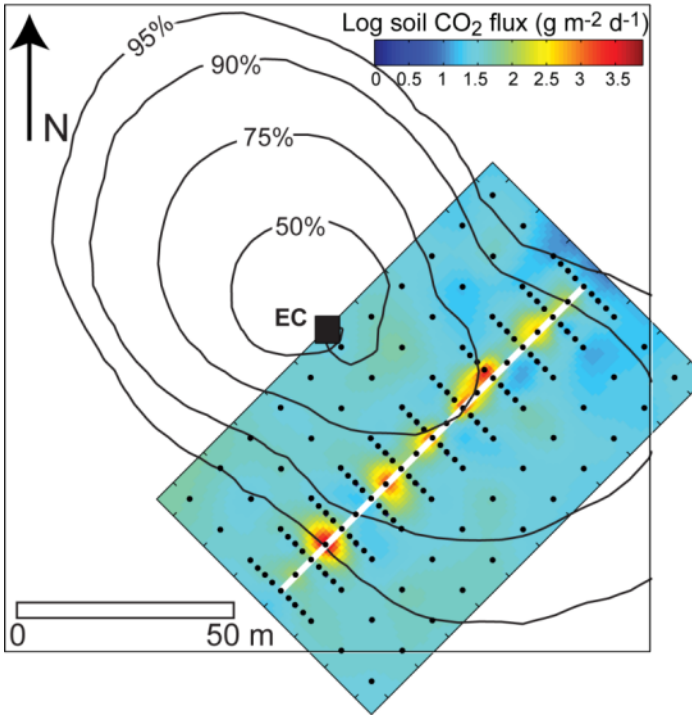


Hollow core where the light interacts with the carbon dioxide

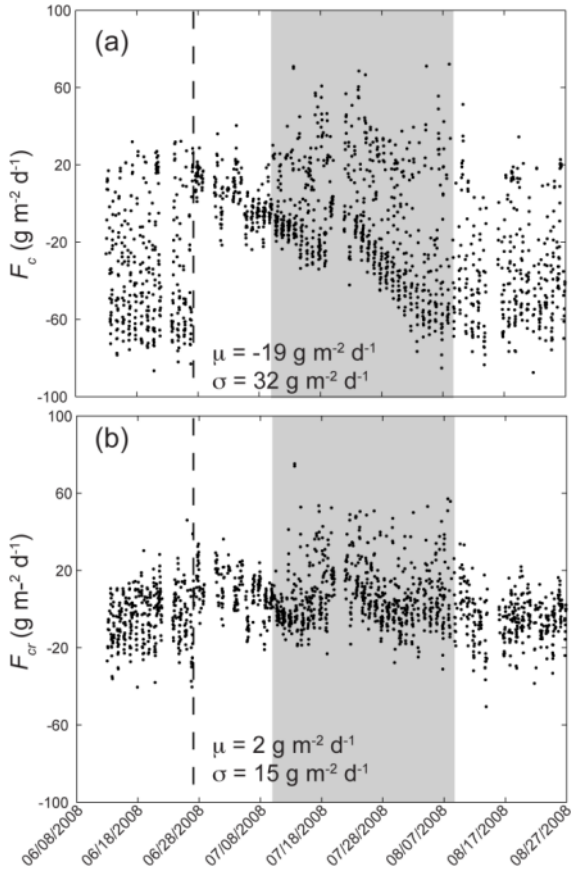


Eddy covariance net CO_2 flux monitoring

An eddy covariance (EC) station was deployed ~30 m NW of the release well in 2006, 2007, and 2008.

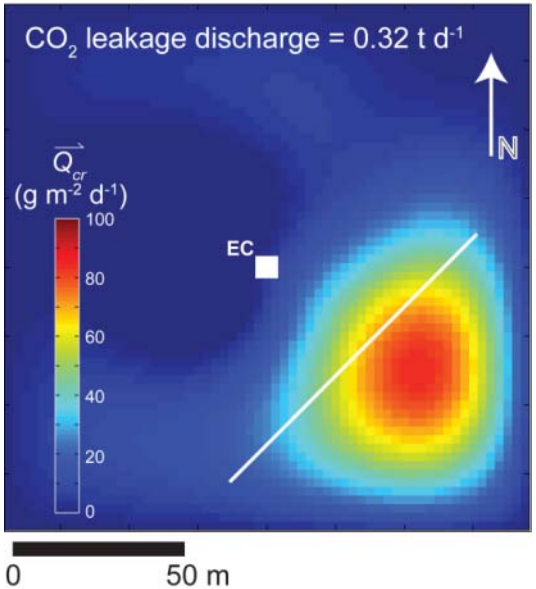


In 2008 (0.3 t CO_2 d^{-1} for 1 month) leakage signal was detected in raw EC CO_2 flux (F_c) data. Ecosystem CO_2 fluxes were modeled and removed from F_c to improve signal detection in residual flux (F_{cr}) data.

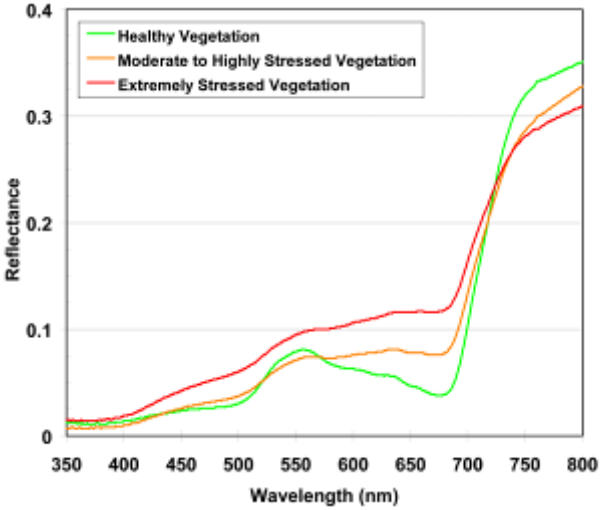


J. Lewicki (LBNL)

A least-squares inversion of measured residual CO_2 fluxes and corresponding modeled footprint functions during the 2008 release modeled the distribution of surface CO_2 fluxes, allowing us to locate and quantify (to within 7%) the leakage signal.

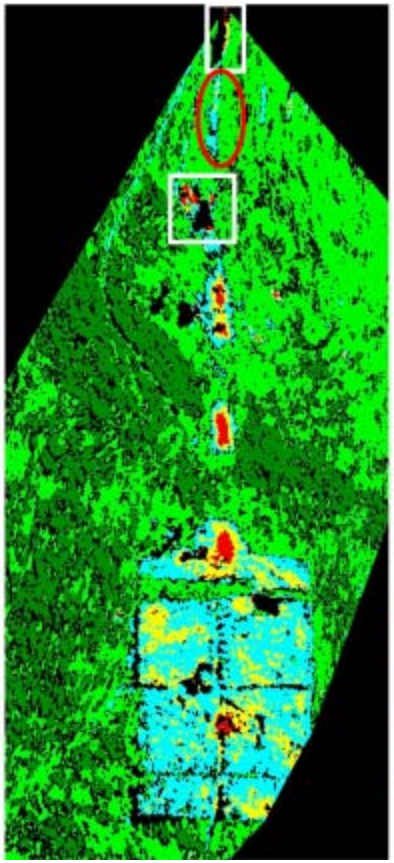


Hyperspectral Imaging



Kevin Repasky

True Color **Analyzed Image**



High Stress

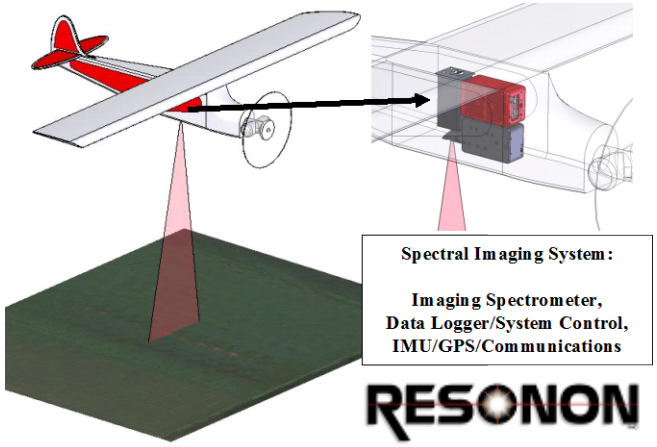
Moderate Stress

Low or Seasonal Stress

Healthy Vegetation (Grasses)

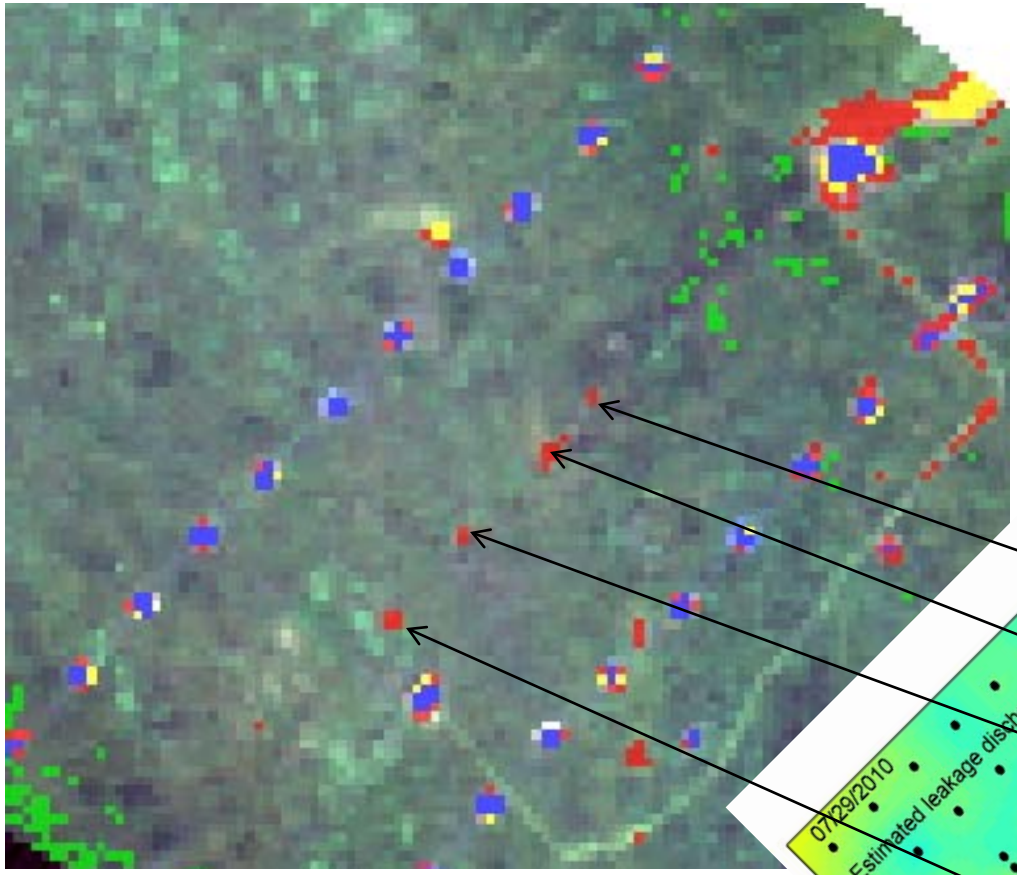
Healthy Vegetation (Herbaceous Legumes)

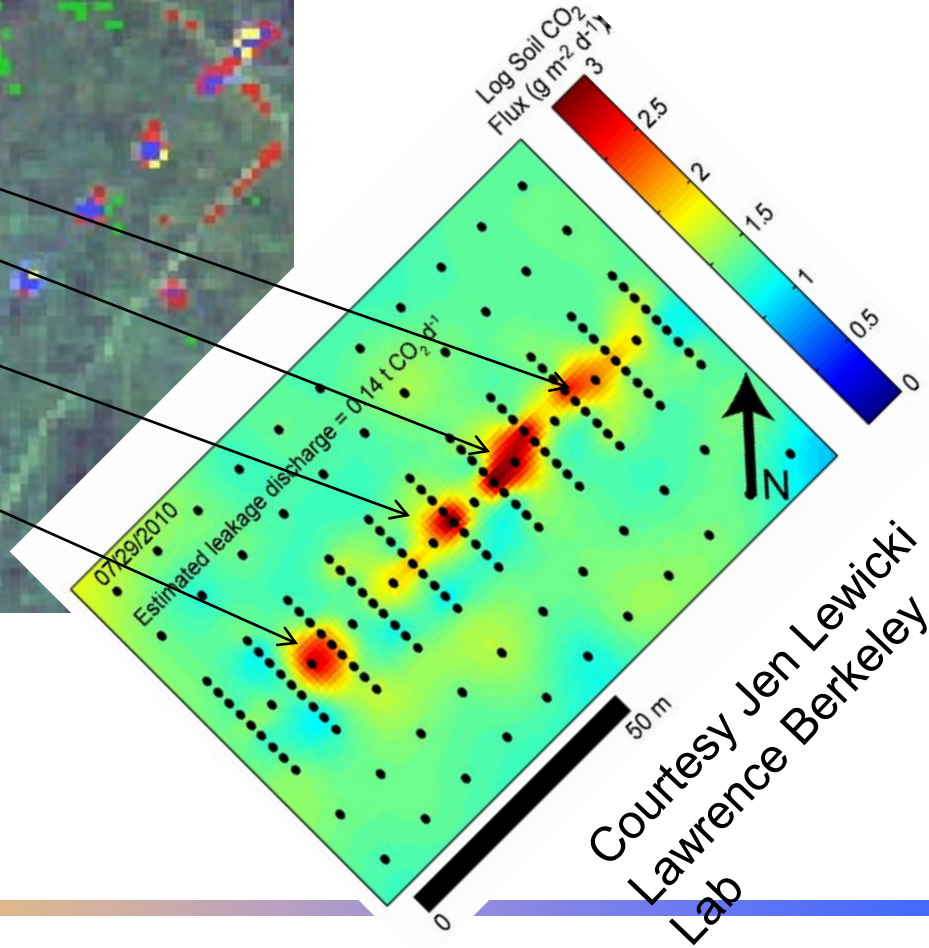
Unclassified



Hyperspectral Imaging Unsupervised Classification

Kevin Repasky



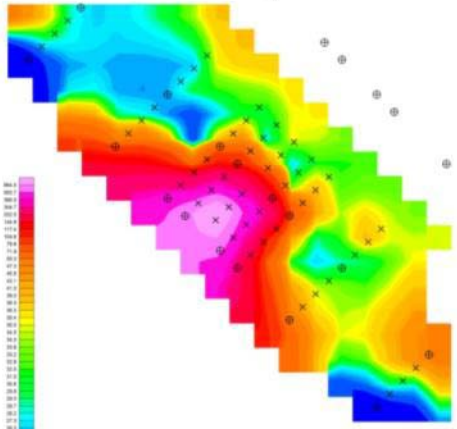


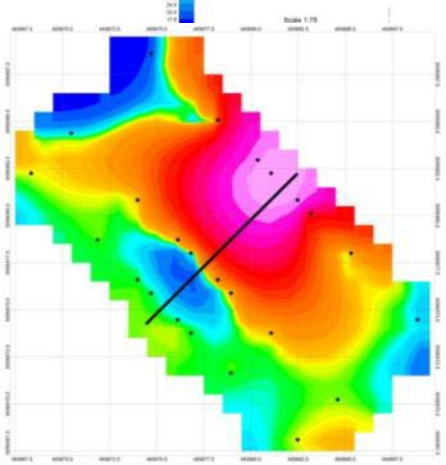
Courtesy Jen Lewicki
Lawrence Berkeley
Lab

Near-surface monitoring technologies were tested at the MSU field site.

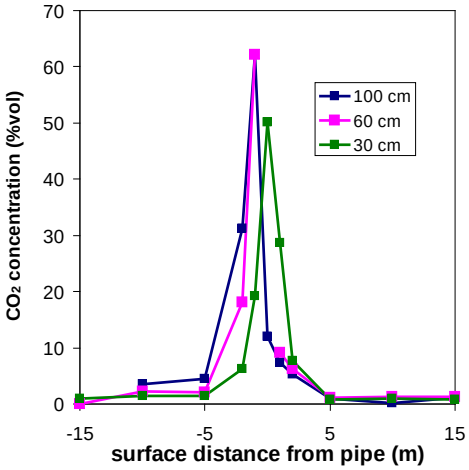
- Surface flux monitoring, soil gas sampling, and perfluorocarbon tracers were tested at the MSU site
- All methods were able to detect plumes at both wells out to 5m
- PFC tracers were most sensitive for detection

Surface flux measurements





PFC tracer measurements



Soil gas measurements

What We Have Learned

- Many near surface methods are quantitative <u>but</u>
  - Diurnal, seasonal, annual variations in ecosystem background flux affect detection limits
  - Appropriate area integrated, mass balance is a challenge
- Nearly all methods could detect 0.15 tonnes / day release at ZERT site.
- Scaling, 6 tonnes per day would be detectable over an area 40 times as large
- Surface expression was "patchy" – 6 areas of ~5m radius
- Natural analogs also seem to have "patchy" surface expression
- Will engineered systems that leak have similar properties?
- **What are the relevant fluxes?**

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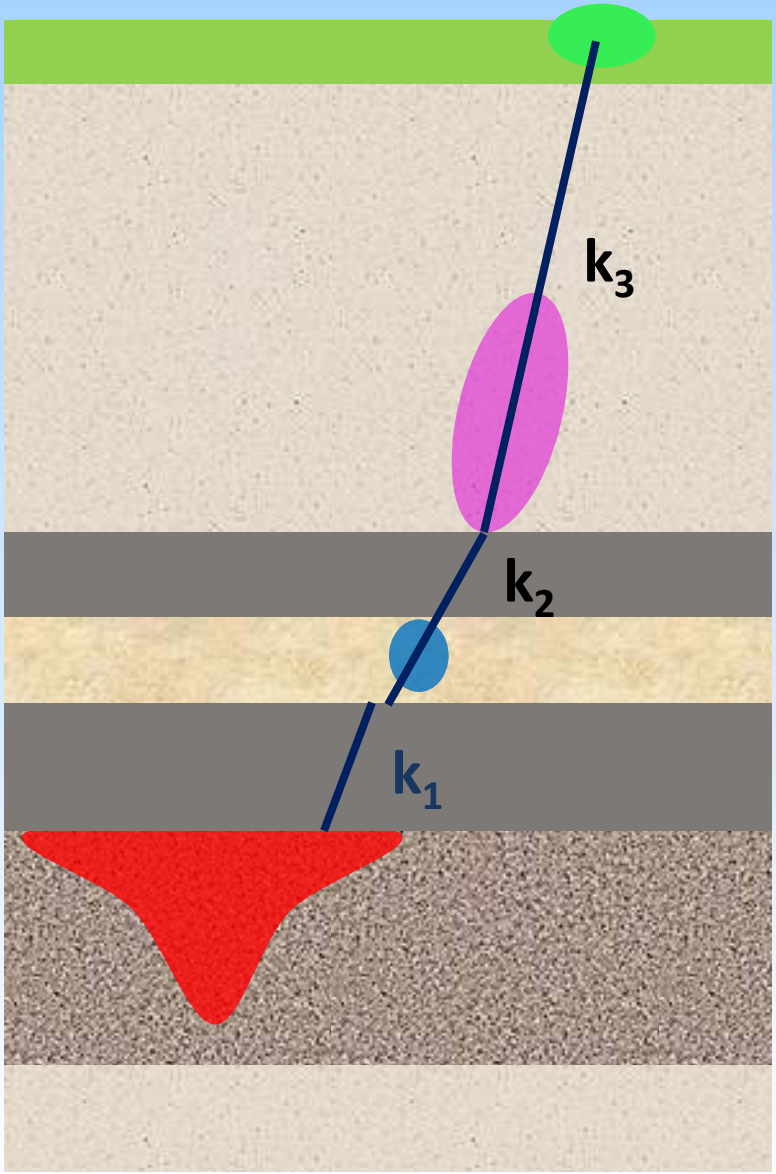
What Are Relevant Fluxes?



Mechanisms, their transport rates and <u>relative</u> rates will affect:

- Residence times and quantities
- Induction periods
- Flux (both area and rate)

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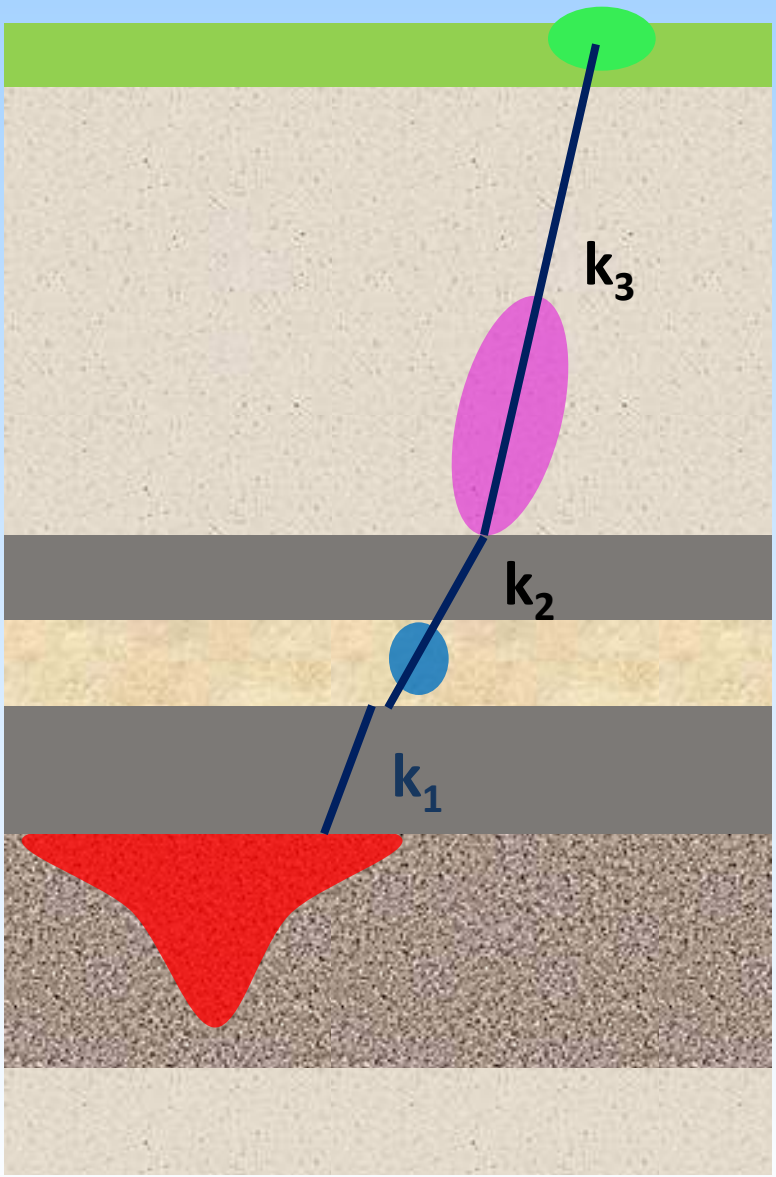
What Are Relevant Fluxes?



- Simple model assumes 1st order rates (exp functional form) and solves three coupled differential equations.
- GHG mitigation relevant rates are used so effective time constant is very large (rates small)
- Under these conditions, most functional forms should be quasi-linear and qualitative results would be similar
- Allows support for "thought experiments" concerning induction periods, secondary accumulation, etc.

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Test Case One Excellent Seal

1% over 1000 yrs

Fast subsequent processes

200 Megatonnes in place

```
(* A → B → C → D *)
k1 = 0.00001; k2 = 1.0002; k3 = 1.01;
sol = NDSolve[{a'[t] == -(k1) a[t], b'[t] == (k1) a[t] - (k2) b[t], c'[t] == (k2) b[t] - (k3) c[t], d'[
   a[0] == 200000000, b[0] == 0, c[0] == 0, d[0] == 0}, {a[t], b[t], c[t], d[t]}, {t, 0.0, 10000}
$TextStyle = {FontFamily → "Ariel", FontWeight → "Bold", FontSize → 14};
Plot[Evaluate[{a[t], b[t], c[t], d[t]} /. sol], {t, 0.00, 1000}, PlotRange -> {0, 200000000}, Backgr
  PlotStyle -> {{RGBColor[1, 0, 0], AbsoluteThickness[3]}, {RGBColor[0, 0, 1], AbsoluteThickness[3]},
    {RGBColor[1, 0, 1], AbsoluteThickness[3]}, {RGBColor[0, .9, .1], AbsoluteThickness[3]}}];
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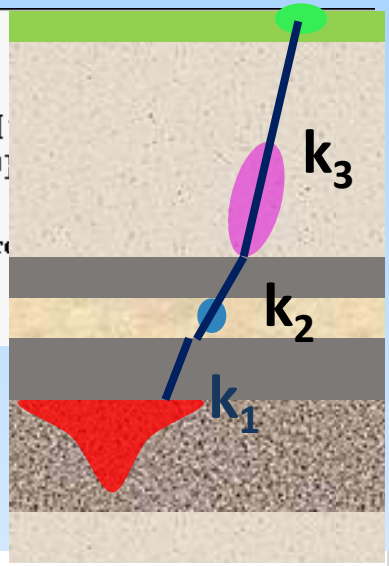

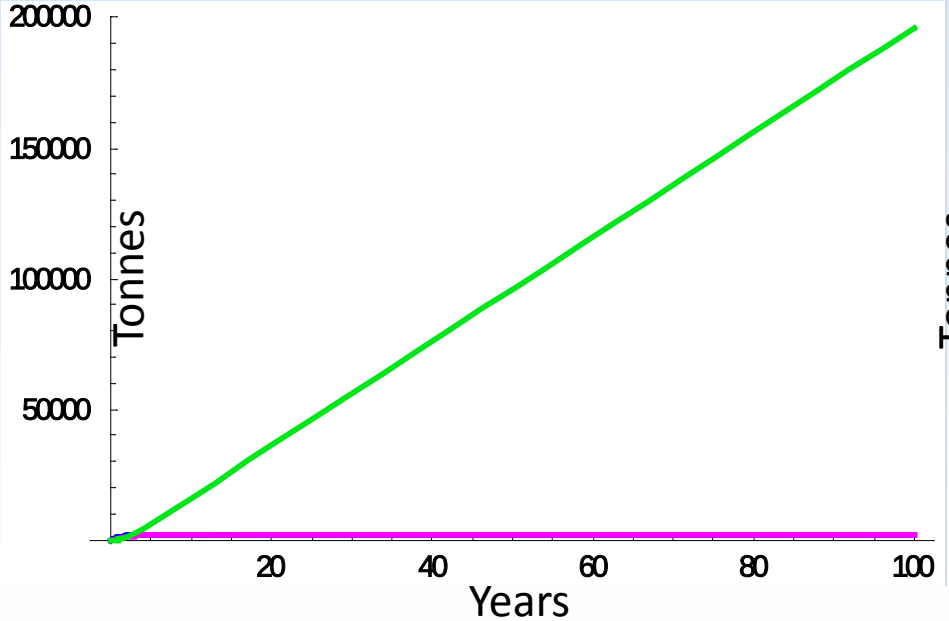

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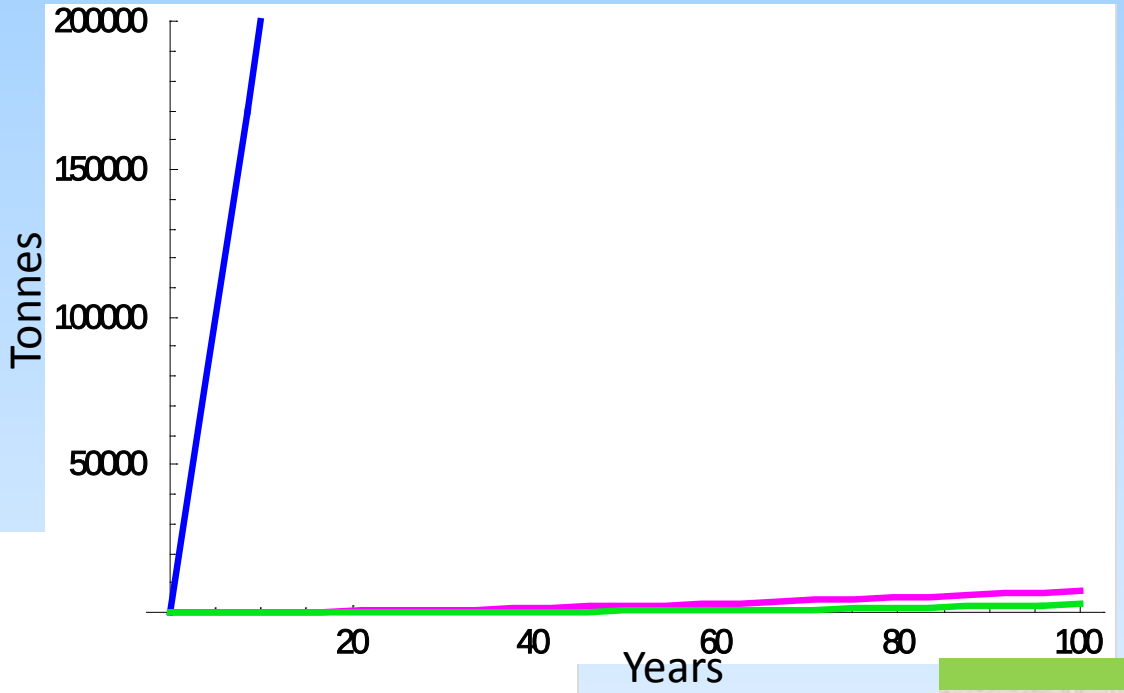
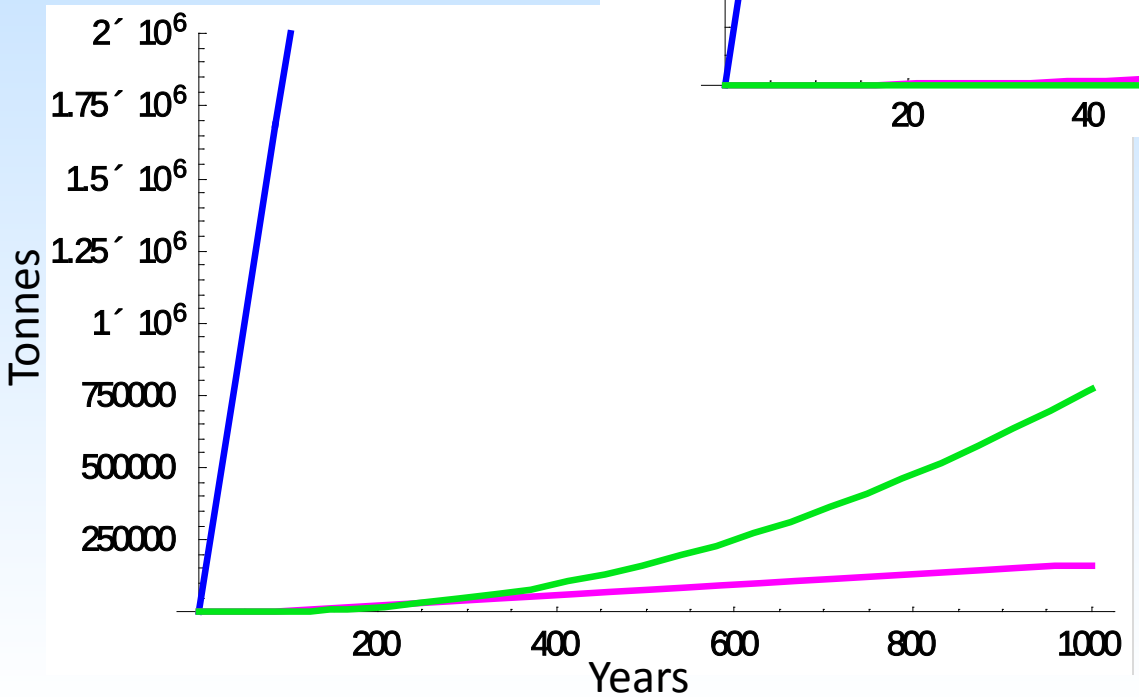
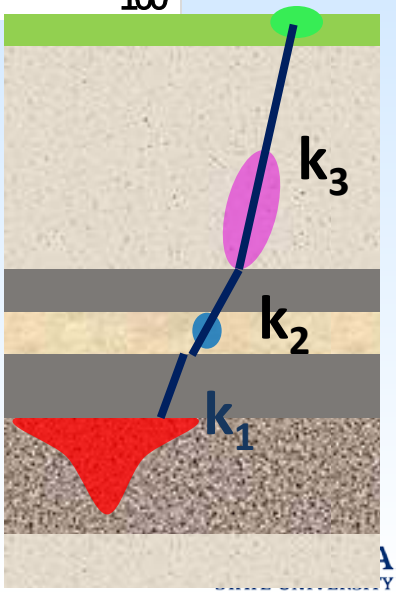
Two Good Seals

$k_1 = 0.0001$ (10 x faster than default of 1% per 1000 yrs)
$k_2 = 0.0001$ (10 x faster)
$k_3 = 0.01$

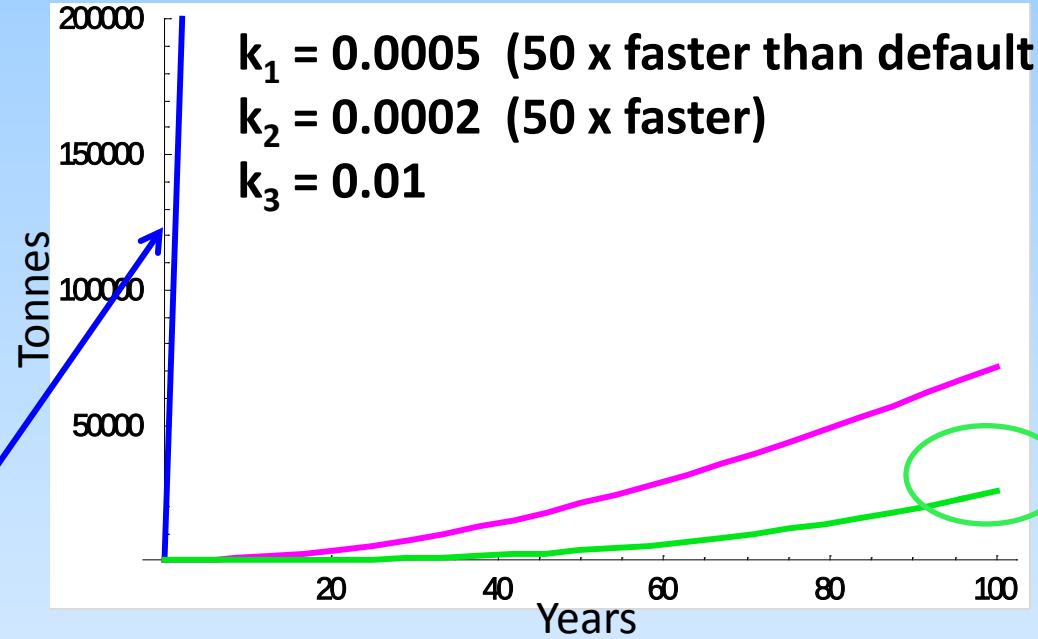




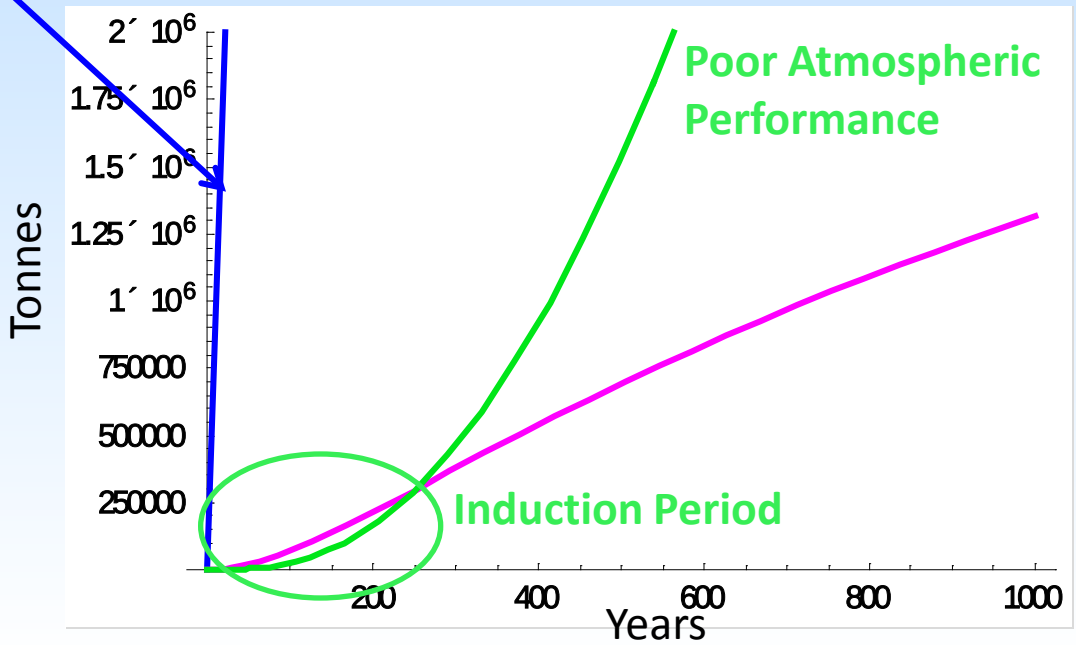


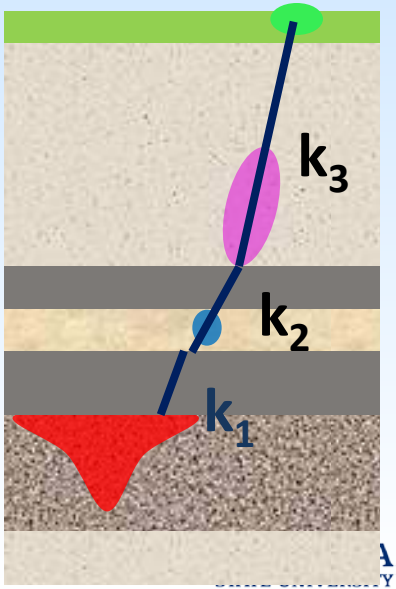
Induction Period

But there is a large and rapid accumulation under secondary seal that should be detectable



Near Surface Monitoring seems to Indicate Good Performance





Class VI Regulations

§ 146.90 Testing and monitoring requirements.

(h) **The Director may require surface air monitoring and/or soil gas monitoring to detect movement of carbon dioxide that could endanger a USDW.**

- (1) Design of Class VI surface air and/ or soil gas monitoring must be **based on potential risks to USDWs within the area of review**;
- (2) The **monitoring frequency and spatial distribution** of surface air monitoring and/or soil gas monitoring must be **decided using baseline data**, and the monitoring plan must describe how the proposed monitoring will yield useful information on the area of review delineation and/or compliance with standards under § 144.12 of this chapter;
- (3) **If an owner or operator demonstrates that monitoring employed under §§ 98.440 to 98.449 of this chapter (Clean Air Act, 42 U.S.C. 7401 *et seq.*) accomplishes the goals** of paragraphs (h)(1) and (2) of this section, and meets the requirements pursuant to § 146.91(c)(5), a **Director that requires surface air/soil gas monitoring must approve** the use of monitoring employed under §§ 98.440 to 98.449 of this chapter. Compliance with §§ 98.440 to 98.449 of this chapter pursuant to this provision is considered a condition of the Class VI permit;

(i) Any additional monitoring, as required by the Director, necessary to support, upgrade, and improve computational modeling of the area of review evaluation

Class VI Regulations

(j) **The owner or operator shall periodically review the testing and monitoring plan** to incorporate monitoring data collected under this subpart, operational data collected under § 146.88, and the most recent area of review reevaluation performed under § 146.84(e). In no case shall the owner or operator review the testing and monitoring plan less often than **once every five years.** Based on this review, the **owner or operator shall submit an amended testing and monitoring plan or demonstrate to the Director that no amendment to the testing and monitoring plan is needed.** Any amendments to the testing and monitoring plan must be approved by the Director, must be incorporated into the permit, and are subject to the permit modification requirements at §§ 144.39 or 144.41 of this chapter, as appropriate. **Amended plans or demonstrations shall be submitted to the Director as follows:**

- (1) **Within one year of an area of review reevaluation**;
- (2) **Following any significant changes to the facility, such as addition of monitoring wells or newly permitted injection wells within the area of review, on a schedule determined by the Director; or**
- (3) **When required by the Director**.

(k) **A quality assurance and surveillance plan for all testing and monitoring requirements**.

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Subpart RR – Reporting Requirements for Geologic Sequestration

- No threshold
- Research & Development exemption (must apply)
- Report (quarterly)
  - Mass received
  - Type of source
  - Mass produced
  - Mass leaked by equipment at surface
  - Mass emitted by surface leakage

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RR – Measurement, Reporting & Verification

Contents of MRV plan

- Delineation of the maximum monitoring area and the active monitoring areas.
- **Identification of potential surface leakage pathways for CO2 in the maximum monitoring area and the likelihood, magnitude, and timing, of surface leakage of CO2 through these pathways.**
- **A strategy for detecting and quantifying any surface leakage of CO2.**
- A strategy for establishing the expected baselines for monitoring CO2 surface leakage.
- MRV plan revisions required if material changes made to monitoring or operational parameters (large changes in volume injected, addition of injection wells, unpredicted plume development, etc.)

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MVA Discussion Questions

- Is current monitoring technology sufficient to meet EPA MVA requirements for Class VI and GHG reporting?
- Is technology sufficient to monitor pressure and plume migration?
- Is technology sufficient to monitor for leaks? In wells? In the subsurface? At the surface?
- Is technology sufficient to monitor for induced seismicity?
- Is technology sufficient for all depositional environments, including those containing oil and gas?
- Is technology sufficient to establish baselines? In the subsurface? At the surface?
- Are additional small and/or large scale field tests needed to validate MVA technologies?
- Is technology sufficient for post-injection monitoring?
- Is current technology sufficiently cost-effective? Are there opportunities for significant cost reductions?
- Are there opportunities for MVA advances which would enable improved storage performance?

What Is the Monitoring Purpose?

- **Climate change mitigation?**
  - 1% over 1000 yrs – climate models?
- Retention in the reservoir?
  - Subsurface techniques typically do not measure properties directly proportional to concentration / quantity
- Overall storage security?
- **HSE, Resource protection (USDW)?**
  - Measure to ensure levels are below impact levels
- Public assurance?
- Verification and accounting?
  - Mass flow meters only accurate to ~1%

If we had a better understanding of realistic leakage mechanisms, rates, and fluxes we could develop better monitoring strategies.

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