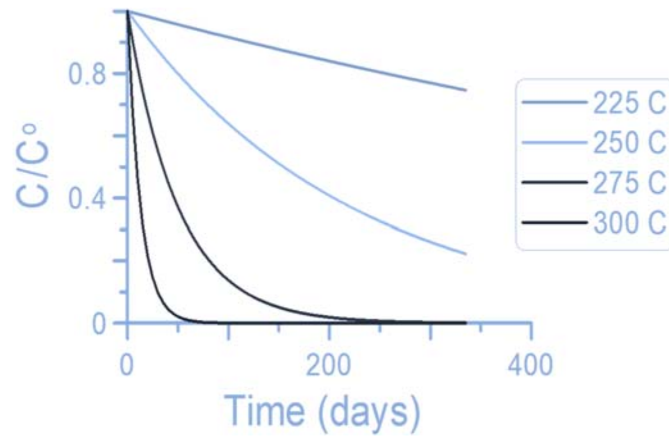
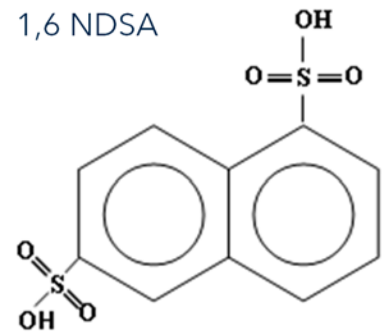
Tracer Chemicals

An IWTT involves injection of a unique tracer into each injection well(s), with sample collection and analysis from production wells to determine produced tracer concentrations vs. time. The liquid tracers injected must be *conservative* - they cannot partition significantly to the vapor phase, adsorb onto rock, clays or sands, decay chemically or thermally while in the reservoir for up to several months. The tracers must also be very detectable at ultra-low concentrations (sub-ppb) without interference from high concentrations of dissolved minerals in the produced water.



Thermochem uses proven tracers such as naphthalene sulfonates (NSA) and perfluorocarbons (PFC) for this purpose. The candidate tracers are bench- tested in the lab with brine from the field to confirm compatibility, chemical and thermal stability, lack of partitioning and analytical interferences. There are more than 12 tracers to choose from for multi-injection well tests, with many stable to > 300 °C. Thermally-reactive tracers are also available.

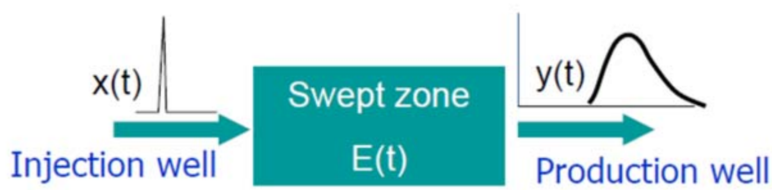
1,6 NDSA



Tracer Sampling

Representative sample collection of the separated water phase without cross-contamination between wells or injected tracer is critical to the success of the tracer test. Thermochem has 30 years' experience in multi-phase sampling and has written ASTM standard practices on the subject (E-1675). Multi-phase separators, sample coolers and collection flasks can be provided by Thermochem, as well as all on-site sampling activities. Thermochem can also train the local operators in proper sampling techniques and provide QA/QC oversight and audits.

Tracer Injection



$$y(t) = x(t-u)*E(t)$$

E(t): Residence Time Distribution

If $x(t) = \delta(t)$ – dirac pulse, then $y(t) = E(t)$

In order to maximize the delectability of tracers in the production wells, the tracers must be injected at the highest concentration possible in the injection water to each well, within the limit of solubility for each tracer compound. Regardless of the mass of tracer injection, it is the initial "pulse" of tracer concentration that is critical. A weak initial pulse of tracer, for example 100 ppm, are less detectable than an initial pulse of 10,000 ppm. Thermochem uses specialized injection equipment to deliver a controlled pulse of tracer at high flow, even under very high injection pressures (500 psig or more).

The tracers are injected using the Thermochem Rapid-Injection Pulse System (RIPS, Figures 1 and 2) for maximum input concentration (Dirac pulse). This will help ensure that the tracer is ultimately detected in the production wells. The concentrated tracer solutions are injected at a high rate in order to maximize the initial tracer pulse concentration, up to a concentration of about 10,000 ppm in the injection water.

The RIPS tracer skid is used on all Thermochem tracer projects and is capable of injecting at up to 500 psi and up to 12 LPM with the high-flow pump. Higher injection rates are possible at lower pressures. Low injection rates of tracer may result in non-detection of tracers from the production wells given low initial concentration and broad injection peak (non-Dirac pulse).

The injection rate for each well are calculated in advance based on the injection wellhead pressure, the injection water flowrate, the injection water temperature and the tracer solubility in the injection water. A detailed, proprietary SOP for tracer injection is finalized based on this information prior to mobilization to the site.

Figure 1: Thermochem Rapid-Pulse Tracer Injection Skid (RIPS)

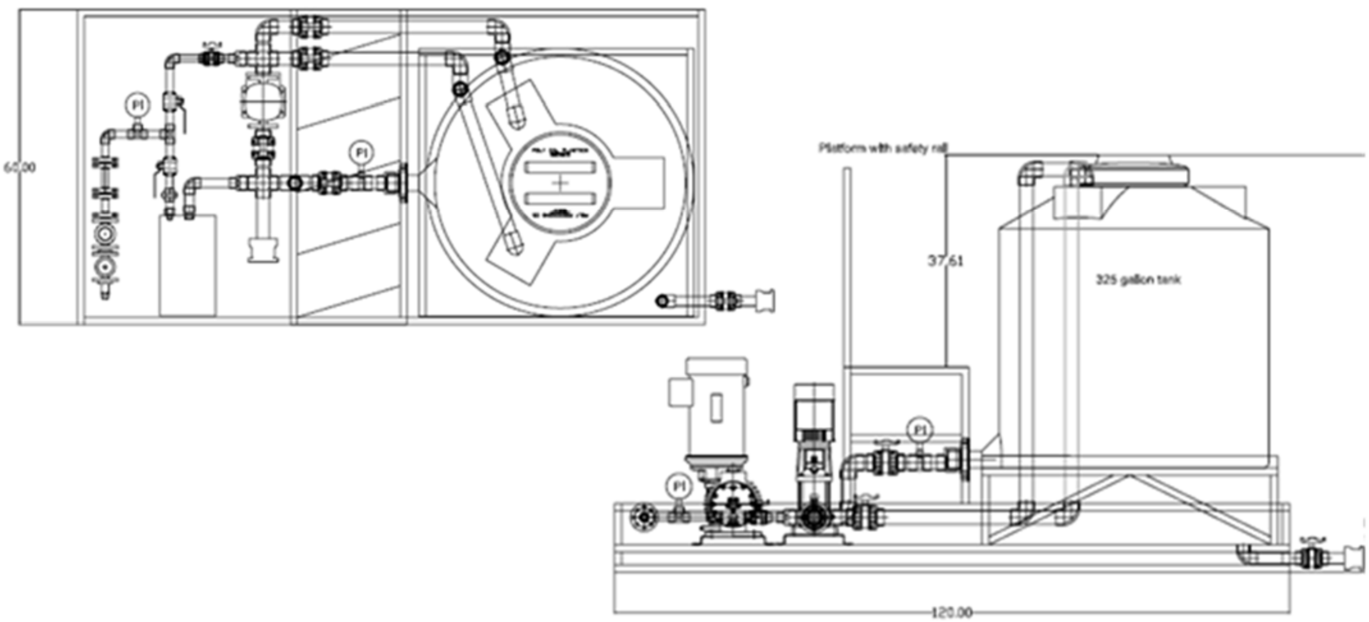


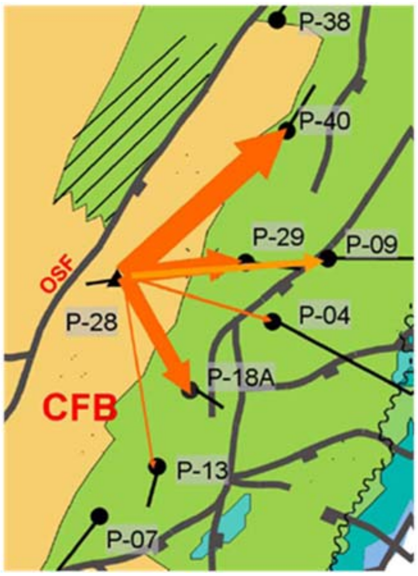
Figure 2: Thermochem Rapid-Injection Pulse Skid (RIPS), view from top (top left image) and view from side (bottom right image)

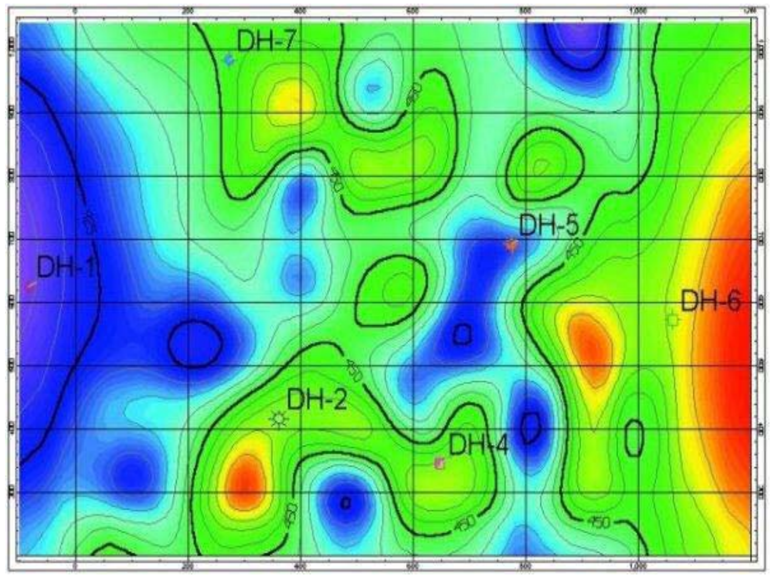
Tracer Analysis

Tracers must be detected to obtain useful information from an IWTT. Given the huge swept volumes in a typical IWTT, the injected tracers are diluted immensely. Even when present at ppb or ppm levels, the dissolved minerals cause severe interferences with most analytical techniques. Thermochem has developed and perfected the analytical methods needed for ultra-trace level detection of the non-toxic and non-radioactive tracers, NSA class (NDSA, NSA, NTSA) of tracer compounds, and others.

Reservoir Simulation

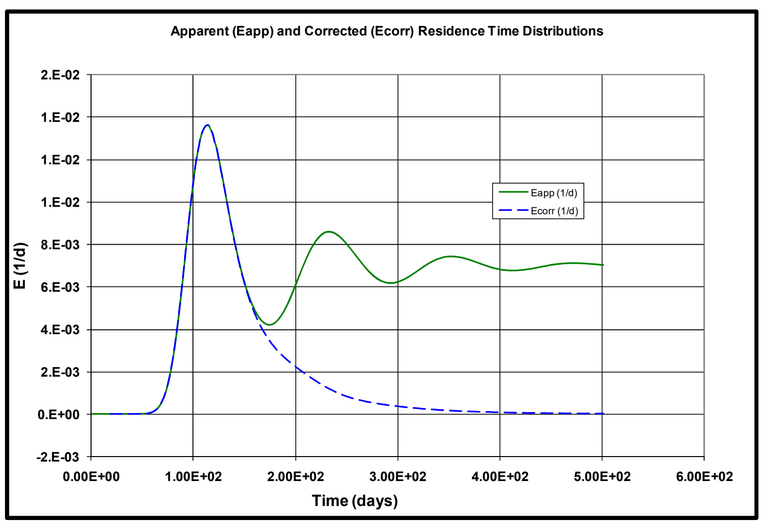
Tracer tests are expensive and must be deigned carefully to ensure success. Roughly estimating tracer quantities and breakthrough times based on simplistic calculations of pore volume between wells may not be sufficient. Thermochem always recommends that a reservoir simulation model is used to determine the optimum tracer injection quantity and to provide a realistic constraint on possible breakthrough times. If the quantity of tracer needed and/or the breakthrough time is excessive, proceeding with a tracer test may not be cost effective or useful for current operational needs. Thermochem can provide these reservoir engineering simulation services as needed for optimum and effective test design.





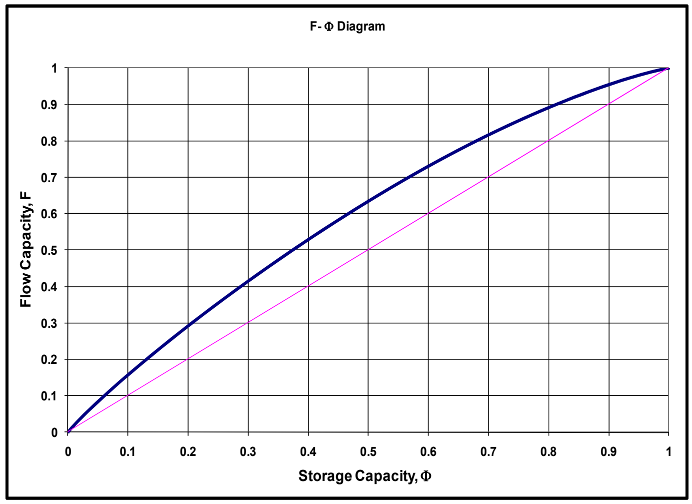
Interpretation of IWTT Data

Often IWTT data is only used qualitatively, to identify a connection between injector and producers and to determine tracer breakthrough time (relative tracer flow). IWTT data contains a wealth of information if the test is conducted and interpreted properly. It is possible to extract more useful, quantitative information from tracer testing, based on temporal behavior of tracers. These methods were originally developed for closed reactor vessels and have more recently been applied to general open boundary conditions, characterization of porous and fractured media, and estimates of flow geometry.



The interpretation methods have a rigorous mathematical basis and offer additional information about the subsurface. The data can also be used to constrain and calibrate numerical models by defining Injection Well volume and flow geometry. These interpretation methods and applications are all based on analysis of tracer Residence Time Distributions (RTD). The mean residence time, or first temporal moment, is the most useful single property derived from a tracer test, although other properties have been used as well. Total pore volume swept by a tracer can be determined from its mean residence time. Certain restrictions are inherent in the calculation; for example, steady state conditions and conservative tracer behavior, as mentioned above. Nevertheless, the methods have a rigorous mathematical basis and have been extensively validated analytically and experimentally for numerous IWTT worldwide.

By integrating tracer recovery data at production wells, the effective fluid velocity (related to streamline permeability and length) and reservoir storage (pore volume) can be estimated. The method is a generalized description of flow capacity and storage capacity. The tracer-derived flow-capacity storage-capacity diagrams are called F-ϕ plots in the literature. The F-ϕ diagrams were originally developed for Injection Well tracer testing.



In summary, the information that can be obtained from an IWTT:

- Communication between injector and producer
- Tracer Breakthrough Time
- Tracer Recovery
- Mean Residence Time
- Swept Volume
- Sweep Efficiency
- Moment Analysis
- Flow and Pore Volume Geometries
- Estimates of "Dynamic Heterogeneity"
- Number of Fractures/Layer between Wells
- Average Permeability
- Properties of each Fracture/Layer
- Reservoir Simulation Model Input for Matching and Calibration

Tracer Sampling – QA/QC

Thermochem samples the injection water downstream of the tracer injection point, during tracer injection, to verify the injected tracer and concentration is correct. This provides another level of QA/QC to the tracer injection task- the measured concentration in the injection water can be confirmed against the tracer injection plan and field report.

The production well sampling locations are inspected by Thermochem in advance to determine if they are sufficient for the test.

Thermochem can perform all the sampling for an IWTT or train the local field personnel in proper sampling techniques. Sampling separators designed by Thermochem and meeting ASTM E-1675 standards are used to separate brine from steam. Samples coolers are used that also meet ASTM standards in order to cool the brine before collection. Only new, high-quality polypropylene or polyethylene bottles are used for sample collection.

Fluids from the production wells may have variable concentrations of tracers, depending on the return profile of each well. Rigorous sample hygiene must be practiced in order to prevent cross-contamination of samples between wells and between individual sampling events for the same wells. Prior to collection of samples at a given location, each member of the sampling crew should thoroughly wash hands with soap, and rinse with large amounts of water. Disposable rubber gloves must be worn during the sampling process, and care must be taken to prevent any fluids that contact the gloves from entering the sample bottles. Each sample jug and bottle must be rinsed at least 3 times with water before filling. Rubber gloves should be discarded after sampling, and new gloves must be worn at the next well to prevent carrying tracer from well to well.

The potential for contamination is greatest during and soon after tracer is injected, and production / monitoring well samples are impacted the most by any contamination given the very low levels of tracer expected in these samples. Extra care must be exercised during this period. Cross-contamination between wells has a greater potential later when tracer return concentrations increase (this could be weeks or months). Extra care must be exercised to prevent cross-contamination between samples and equipment from different wells.

Thermochem uses a detailed, proprietary SOP's for tracer sampling, as well as the sample bottles and labels. All samples collected are labeled with a unique Sample Descriptor as described below and logged into a Thermochem Chain of Custody form. Every sample collected are labeled with a waterproof, solvent resistant label. Use only the pre-printed labels supplied for this project.

Laboratory and Field Equipment Inventory

Thermochem maintains the flowing specialized equipment for tracer testing. Items listed in bold are particularly relevant for IWTT.

Laboratory Liquid-Phase Tracer Analysis Instrumentation

UPLC:

- Acquity Sample manager
- Acquity Binary solvent manager
- Acquity Column heater
- Acquity FLR detector
- Acuity TUV detector
- Waters 1525 Binary HPLC pump with column heater
- Waters 717plus Autosampler
- Waters 2475 Multi wavelength fluorescence detector
- Waters 2487 Dual wavelength absorbance detector

LC/MS:

- Agilent 6460 Triple Quad Mass Spec detector
- Agilent 1260 Infinity Binary Pump
- Agilent 1260 Standard Autosampler
- Agilent 1260 Infinity Column Compartment

LC/IC:

- Alcott 718 HPLC Autosampler
- Dionex 4500; HPLC with Gradient Pump Module (2)
- Dionex Variable Wavelength UV/Vis Detector, series 4500i
- Dionex ASM-3 Autosampler (3)
- Dionex AI-450 Chromatography Data Stations (3)
- Hitachi F-2000 Spectrofluorometer 1 cm discrete sample cell, flow analysis cell
- Oasis HLB 6CC LP extraction station with cartridges
- Dionex Omni Pac PAX-100 ion-exchange column for FBA analysis
- Waters BetaBasic C-18 HPLC column, BetaBasic C-18 guard column for NSA analysis

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Laboratory Gas-Phase Tracer Analysis Instrumentation

- Hewlett Packard 5890 and 7890 Gas Chromatographs (7)
- Agilent GCMS 7890/ 5975
- Entech 7150-LN2 Headspace Gas Concentrator
- Flame Ionization Detectors (2)
- Thermal Conductivity Detectors (2)
- Hewlett Packard Electron Capture Detector (2)
- O-I 4420 Electrolytic Conductivity Detector
- HNU PI-52 Photoionization Detector
- Tekmar 3100 Purge and Trap Concentrator

Field Tracer Analysis Instrumentation

- Turner PicoFluor Handheld Fluorometers (3)
- Turner OptiTrace on-line Fluorometers (2)
- Portable Field GC with Electron Capture Detector (2)

Field Tracer Injection and Sampling Equipment

- MicroMod MFC Gas Mass Flow Controller (4)
- MicroMod LDS Liquid Tracer Delivery System (4)
- Rapid-Injection Pulse System (RIPS) Skid, 1200-liter tank, 500 and 2500 psi pumps
- High-Pressure Gas Tracer Delivery Units, Liquefied-gas pumps, 120 bar (2)
- Two-Phase Sampling Separators ASTM, water /steam (6)
- Sample Coolers, High-pressure Sample Hose (20)
- 250 ml Poly Bottles, Sample Storage (1500)

Reservoir Simulation Software for Tracer Tests

- Tetrad
- Tough2
- ToughReact