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Natural Source Zone Depletion Rates from Subsurface Temperature Data: A Quantitative Analysis

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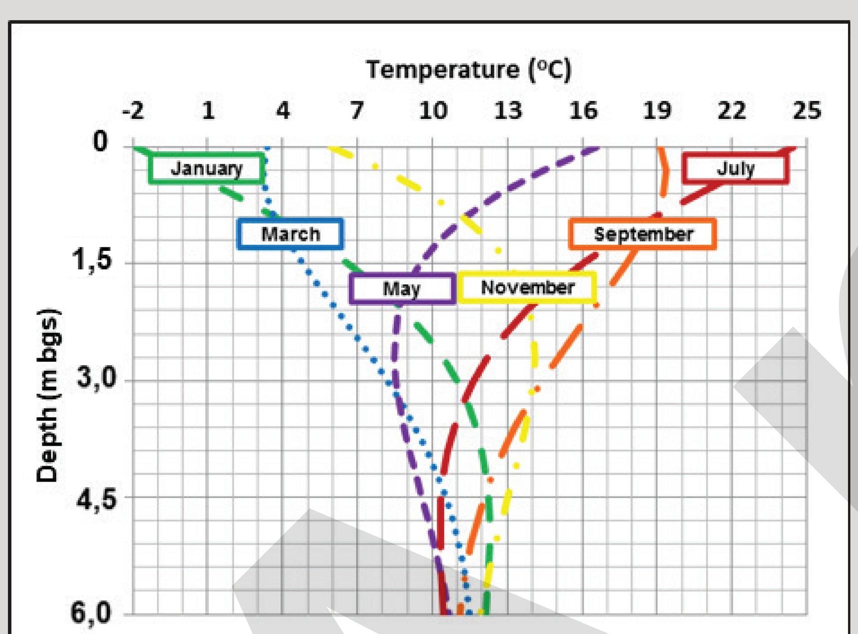
ABSTRACT

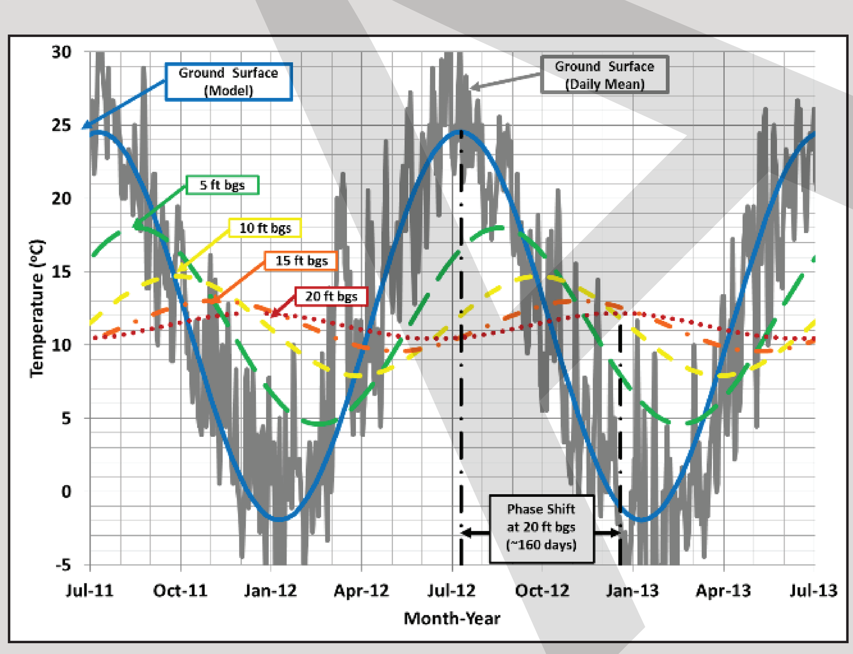
Common methods for quantifying NSZD rates are based on measurement of soil gas concentrations of oxygen and/or carbon dioxide with soil gas diffusivity, and/or carbon dioxide flux. These methods are viable, but can be challenging or costly to implement at sites where soil gas transport conditions are complex. This may include sites with impervious surface caps (e.g., gas stations), sites with low permeability strata in the subsurface that impede vertical gas transport, or sites where petroleum hydrocarbon impacts are at great depth.

The biologically mediated NSZD processes that destroy hydrocarbons and alter the composition of soil gas (e.g., consume oxygen and produce carbon dioxide) also release heat. The heat released to the surrounding subsurface materials creates temperature anomalies above the natural soil temperature profile. Recent research has focused on measuring temperature in and around LNAPL-affected areas and characterizing thermal anomalies (areas of warmer temperature) associated with exothermic NSZD processes.

Thermal anomalies can be measured in an existing monitoring well network through long-term deployment of dataloggers or instantaneous readings with a thermocouple. This relatively inexpensive method of data collection can identify where aerobic biodegradation is occurring. Although thermal anomalies are relatively easy to observe and document, correlations of the extent and magnitude of an anomaly to an NSZD rate are just now being developed.

A model was constructed to calculate heat flux associated with thermal anomalies identified in LNAPL source zones and, correspondingly, estimate the rate of hydrocarbon degradation generating the observed anomaly. Temperature signals from heat sources and sinks unrelated to NSZD processes, such as seasonal variability in radiant heating and cooling at ground surface, are filtered out of the analysis, and the model allows for input of thermal properties for subsurface materials.





Background Temperature Distribution

In the absence of a subsurface heat source, temperature distribution fluctuates around the mean annual atmospheric temperature. Seasonal variability from radiant heating at ground surface can extend to depths greater than 6 meters, while, diurnal variability is typically constrained to the upper few feet.

- Temperature fluctuation amplitude attenuates exponentially with depth
- Phase shift (time lag) with depth as temperature signal propagates from ground surface

Determining Background

- Background temperature profiles recorded in portions of site where LNAPL is not present
- Background profiles can also be modeled based on weather data and heat transfer properties of soil (Monteith 1973)
- Soil heat transfer properties are calibrated by matching predicted background temperature profile to measured profile

NSZD OVERVIEW

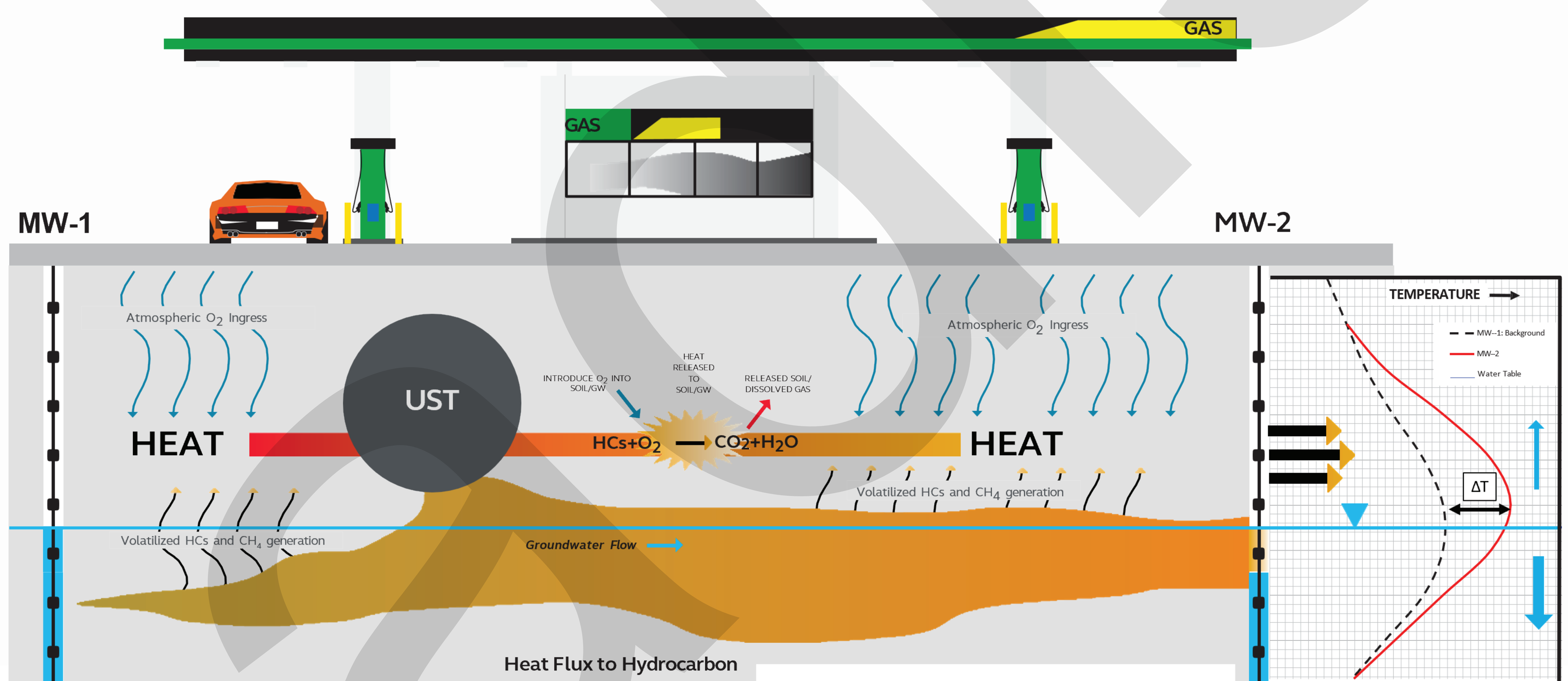
NSZD is the process of source zone mass loss due to the natural processes of volatilization, dissolution, and biodegradation.
As a remedial approach, NSZD can reduce lifecycle costs by:

- Satisfying regulatory source reduction policy to facilitate risk-based closure
- Demonstrating that an active LNAPL remediation system is providing negligible benefit compared to the natural mass loss of the LNAPL plume
- Providing a cost-effective, sustainable alternative to stakeholders

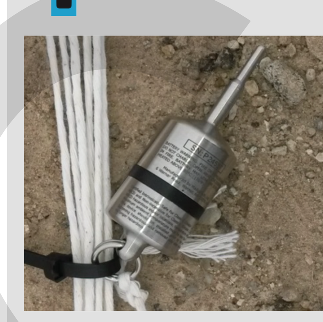
THERMAL ANOMALIES

Biodegradation of LNAPL produces heat and results in a measurable temperature change relative to background locations. An NSZD rate can be quantified through the temperature difference, which is a function of the hydrocarbon loss rate and thermal properties of the soil.

THERMAL ANOMALY CONCEPTUAL MODEL



Temperature vs depth plot shows an increase of temperature from heat generated during biodegradation. The **black** line represents the background temperature profile, and the **red** line represents the temperature profile in the LNAPL footprint.



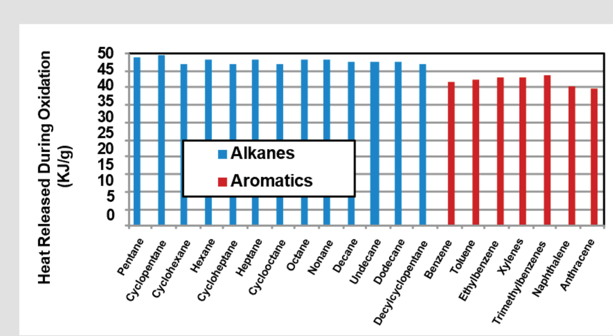
Temperature dataloggers can be placed in existing monitoring wells and provide vertical profiles of subsurface temperature over time. Background temperatures are measured at upgradient areas or modeled using weather data. "Snapshot" temperature profiles can also be collected manually using a thermocouple/ temperature probe lowered down monitoring wells.

Heat Flux to Hydrocarbon Loss Rates

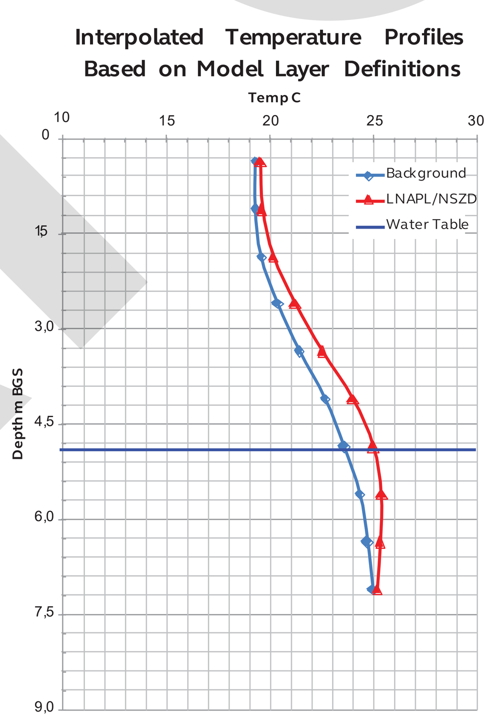
46.5 kilojoules of heat energy are released per gram of hydrocarbon depleted.

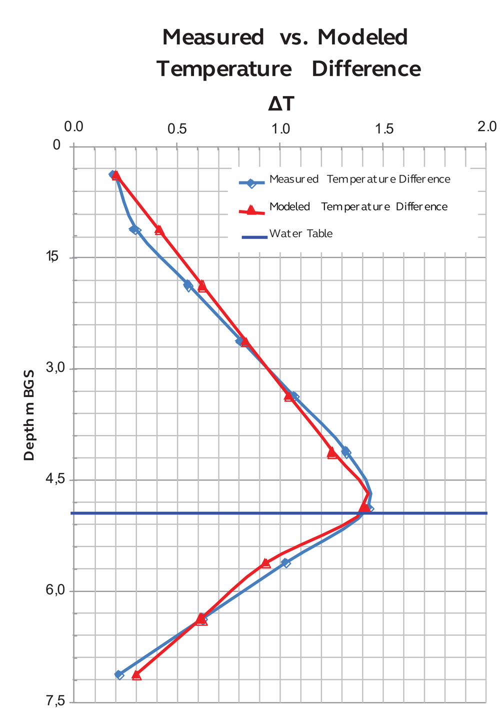
Per litre of LNAPL, approximately:

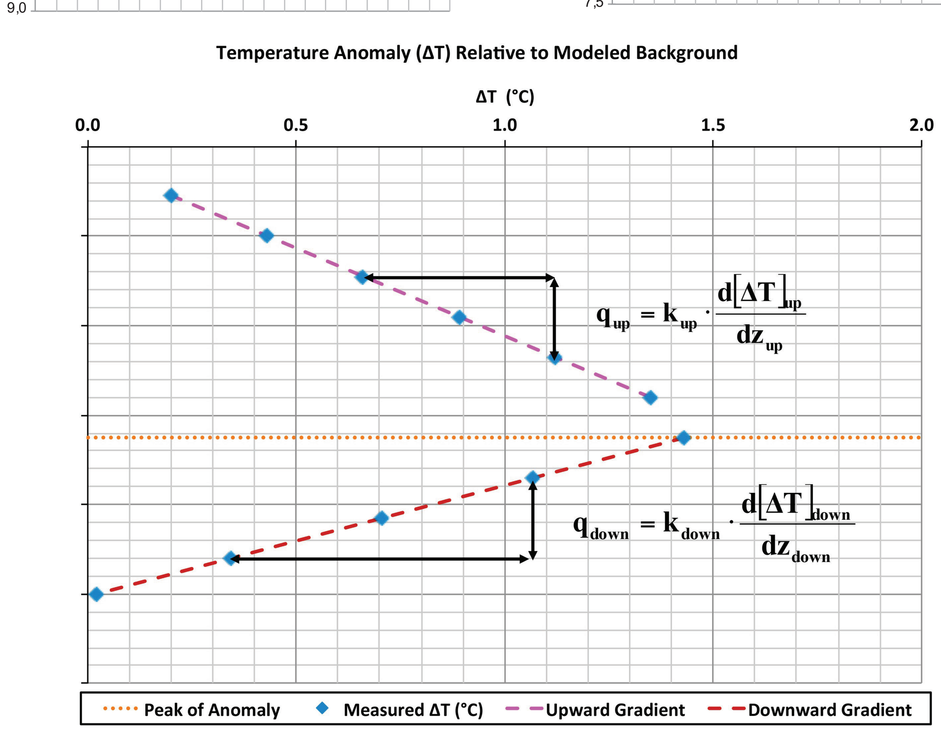
- 8,100 kcal. or;
- 30 SNICKERS , or;
- enough heat to warm 250 litres of water from ice-water to pool temperature



ESTIMATING NSZD RATES FROM SUBSURFACE TEMPERATURE DATA







Numerical Heat Transfer Model

- 1-D Numerical Energy Balance Model

  Ein = Eout + Estorage + Eloss

- Vertical profile divided into series of discrete layers with independently specified thermal properties
- Initial temperature values established using background temperature profile data
- Energy input rates adjusted for each layer to match observed temperature profile data within source zone
- Simulation is run through multiple iterations until a steady state is achieved
- LNAPL losses estimated based on stoichiometry and heat of reaction for aerobic oxidation of hydrocarbon compounds

Energy Input Rate (KJ/day/unit volume)	1.405
Estimated LNAPL Loss (litres/Ha/year)	2.264

Inverse Analytical Model

- Input Subsurface Temperature Profiles from Background and Source Zone to Generate ΔT Profile
- Estimate Thermal Gradients (Up and Down) from Peak of Thermal Anomaly
- Steady Heat Flux (Qup + Qdown) = Rate of Heat Production
- Convert to Equivalent LNAPL Loss Rate based on Stoichiometry and Heat of Reaction

Estimated LNAPL Loss (lites/Ha/year)	1.452
Percentage of Loss Due to Downward Heat Flux	16%
Percentage of Loss Due to Downward Heat Flux	84%

References

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- Monteith, J.L. (1973). Principles of Environmental Physics. Edward Arnold Publishers, Ltd., London, England.
- Ririe, T.G., R.E. Sweeney, and B. Tallant (2013). Use of Temperature to Determine Rate of Biodegradation in the Vadose Zone. Presentation at the Third International Symposium on Bioremediation and Sustainable Environmental Technologies in Jacksonville, FL, Battelle Memorial Institute, June 2013.

Summary

The use of temperature to evaluate NSZD rates has the potential to cost-effectively quantify natural LNAPL depletion at most sites and provides an alternative where soil gas gradient and soil gas flux methods are impractical.