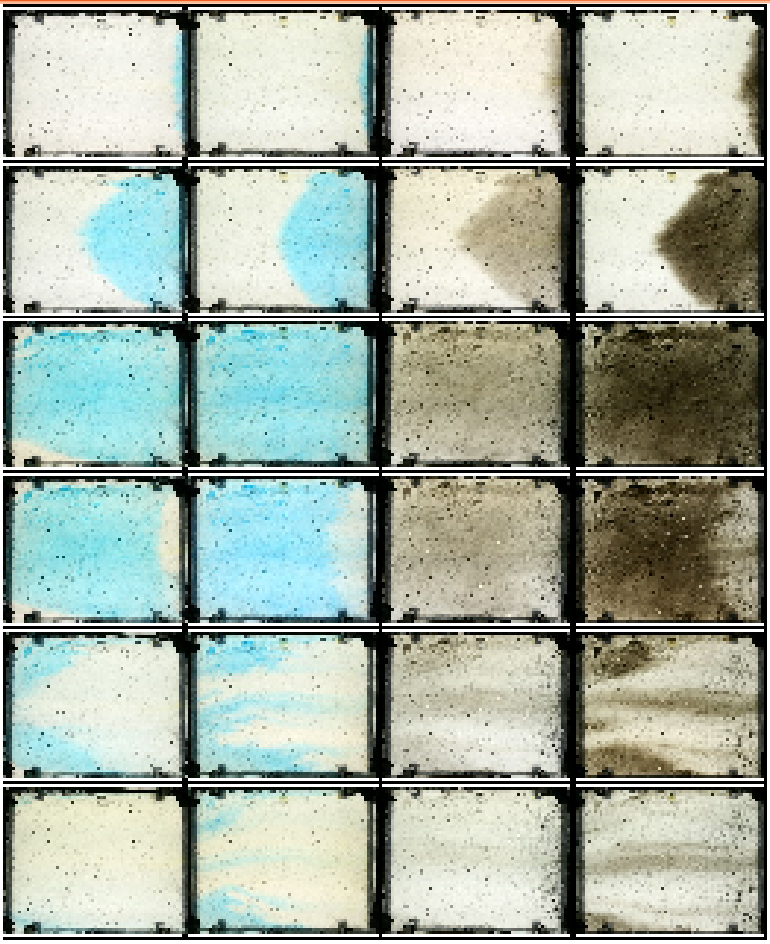


Photo Courtesy of Ziteng Cui. See explanation in textbox on Page 2.

# INTEGRATE Newsletter

March 2015

# Year 3 in Review

In this issue we review the main accomplishments of Year 3 of the INTEGRATE Project. This year's highlights include the creation of Savron Smouldering Solutions, a division of Geosyntec Consultants responsible for the commercialization of the STAR—Self-sustaining Treatment for Active Remediation—technology. Also, one of our students, Ziheng Wang, successfully defended his PhD. Mehrnoosh Ebrahimzadeh completed her MESc thesis, and PDF Magdalena Krol has finished her contract with INTEGRATE and is now an Assistant Professor at York University. And our Principal Investigators, together with Professors Clare Robinson (Western), Kent Novakowski (Queen's), and Neil Thomson (University of Waterloo) were awarded an NSERC-CREATE grant with Professor Brent Sleep as the lead principal investigator.

## Featured Students

This issue features Obai Mohammad, PhD candidate at Queen's working with Professor Kevin Mumford, and Ziteng Cui, visiting PhD student at UofT .

## nZVI Applications

***Bio-nZVI***

The potential for PCE biodegradation following injection of nZVI-CMC to contaminated sites is the research topic of Dr. Simone Larcher (Post-doctoral Fellow—PDF) in Professor Sleep's lab. Dr. Larcher wants to find out if indigenous microbes from a contaminated site (Dow Sarnia) are capable of growing using CMC as carbon and energy source for PCE biodegradation and its daughter products. During Year 3, Dr. Larcher focused on sampling, and on data analyses and interpretation of her microcosms, which she setup by adding soil (20 g) and groundwater (50 mL) into serum bottles under 6 different conditions:

*1: PCE in $NaBH_4$ solution*
*2: PCE (site conditions; no CMC or nZVI)*
*3: CMC only (no PCE or nZVI)*
*4: PCE with CMC and $NaBH_4$*
*5: PCE with nZVI-CMC (0.1, 0.5, 1 g/L)*
*6: PCE with CMC (no nZVI)*

## IN THIS ISSUE

So far, the lowest nZVI dose (0.1 g/L) showed PCE degradation (<LOQ) within 20 days in 3 of the 5 active microcosms being monitored. The other two doses tested (0.5 g/L and 1.0 g/L of nZVI) took 100 and 150 days for PCE disappearance, respectively. The main PCE breakdown products are TCE (with 0.1 g/L nZVI),VC (with 0.5 g/L nZVI), and ethene (with 1.0 g/l nZVI). Microcosms with PCE and CMC also showed PCE degradation to trans-1,2-DCE, cis-1,2-DCE, and VC but only at the highest CMC concentration. Dr. Larcher also observed that excess $NaBH_4$ alone does not drive PCE degradation (Condition 1), but when CMC is present (Condition 4) PCE concentration decreased and degradation products were formed (TCE, 1,1-DCE, trans-1,2-DCE, VC).

The observed PCE degradation trends in Dr. Larcher's microcosms, combined with the predominant formation of the less-commonly observed degradation-product trans-1,2-DCE (cis-1,2-DCE is typically the most common 1,2-DCE isomer observed during microbially mediated reductive dechlorination of PCE) demonstrate that there might be a unique pathway or microbial community at this location of the Dow Sarnia site. DNA extracted from microcosms, and application of qPCR and pyrotag sequencing will likely elucidate changes/differences in the microbial population that could help to explain the observed results.

### *nZVI Transport in Glass-Replica of a Slate Fracture*

Ziteng Cui, a visiting PhD student from Hohai University in China, is performing nZVI transport experiments in a glass-replica of a slate fracture in Professor Sleep's lab. Cui wants to understand the transport behavior of CMC-nZVI in a variable aperture fracture. The glass-replica fracture was prepared by creating molds with melted glass on two opposing sides of a fractured slate rock block. The fracture is 0.28 m long and 0.21 m wide. Lissamine green B (LGB) serves as a conservative tracer in the transport experiments. A dark box set-up with a light source and digital camera is being used to visualize the LGB and CMC-nZVI movement through the glass fracture (see photo on front page). Experiments are being performed to determine the effects of water specific discharge (20 and 30 m/d) and CMC concentration (0.4 and 0.8 % w/v) on the nZVI transport.

LGB and CMC recoveries have exceeded 90% in all experiments; however, LGB has shown higher peak normalized concentration (C/Co). Significant channeling has been observed in the fracture during CMC transport due to viscous effects (see cover photo). Lower recoveries have been observed for the nZVI compared to the LGB and CMC. In addition, CMC concentrations (0.4 and 0.8 %) have insignificant effects on the nZVI transport. Future steps include the creation of a NAPL pool in the fracture and treatment with CMC-nZVI.

### *Surfactants and nZVI*

Former PhD student, Ziheng Wang, and current students Silvia Zarate Munoz (PhD candidate) and Denis Hsu (MEng Student), supervised by Professor Edgar Acosta, have dedicated their research efforts to synthesize zero valent iron nanoparticles in different microemulsion environments. Their purpose is to produce microemulsified zero valent iron nanoparticles (MEnZVI) that are stable and reactive for a very long time, have high particle content, and match the salinity of groundwater.

Ziheng developed a method for synthesis of microemulsified nZVI (MEnZVI) (paper under preparation) with oil to water ratios of 5/5 and 1/9 that maintain at least 14 days stability. Silvia has been working on Ziheng's formulation and constructing ternary phase diagrams with and without nZVI to evaluate the effect of dilution on the formulations. Results so far demonstrate that under dilution, the microemulsions remain in one stable single phase. Additionally, reactivity tests using lipophilic and hydrophilic contaminants show that

Cover Photo

Observed LGB and CMC mixture, and CMC-nZVI distribution in glass fracture with time (flushed volumes). Each vertical sequence of 6 photos are for a different experiment, in which photos were taken when 0.7, 10.5, 39, 45.5, 91, and 220 mL volumes were injected and flushed.

*Columns:*
*1st: LGB pulse 100 mg/L (0.7 mL/min).*
*2nd: 100 mg/L LGB in 0.8% CMC (0.7 mL/min).*
*3rd: 0.4% CMC with 1 mg/L nZVI (0.7 mL/min).*
*4th: 0.8% CMC with 1 mg/L nZVI (0.7 mL/min).*

LGB - Lissamine Green B
CMC - Carboxymethyl cellulose
nZVI - Nanoscale zero-valent iron

Ziteng Cui- PhD Candidate

Ziteng Cui was a visiting international Ph.D student from Hohai University in China. His masters research focused on the estimation of fractural conductivity through slug tests and modeling approaches. Cui joined Professor Brent Sleep's research group in September 2013 and left in February 2015.

He conducted lab experiments and numerical simulations to investigate the transport behavior of CMC-nZVI in a variable aperture glass replica of a fractured slate. He also compared results from the glass fracture experiment to a variable aperture dolomite rock fracture. Cui wants to determine how water velocities and CMC concentration interfere with nZVI transport in fractures. He applied microscopy techniques and spectrophotometry to analyze the stability of CMC-nZVI mixtures.

A dark box set-up allowed Cui to take interesting photographs of the transport of LGB and CMC-nZVI through the glass fracture (photo on the cover).

MEnZVI is as reactive as bare nZVI. Mobility of Ziheng's MEnZVI formulation through porous media will be tested using a column study.

An important step towards commercialization of MEnZVI is underway in order to achieve low salt concentrations. This reformulated bicontinuous microemulsion contains 0.1 M total surfactants with 1 % NaCl in 5/5 oil to water ratio. The effect of dilution on this reformulated microemulsion is being evaluated through the construction of ternary phase diagrams. Once the reformulation containing the lowest o/w ratio is achieved, the synthesis of nZVI in this microemulsion environment will be performed, as well as the evaluation of its stability, reactivity, and mobility.

### *Secondary Impacts Associated with Gas Generation*

Obai Mohammed, PhD candidate with Professor Kevin Mumford, is investigating the effect that hydrogen gas ($H_2$) produced during nZVI injection has on porous media properties and on VOC mobilization. $H_2$ gas provides additional reducing equivalents to aid post-injection treatment, however, if it is trapped within the pores it may reduce aqueous phase permeability, hindering nZVI delivery. In addition, if substantial gas is produced, this may result in buoyant transport of $H_2$ gas outside of the injection zone, aiding post-injection treatment in regions above but also providing a pathway for accelerated VOC transport.

Obai has been trained by Dr. Pulin Mondal, PDF at UofT, on nZVI synthesis using the sodium borohydride ($NaBH_4$) technique, and is gathering equipment required to begin synthesizing it at Queen's. Literature and anecdotal reports suggest that excess $NaBH_4$ added to ferrous iron solution during nZVI synthesis may be injected during nZVI field applications.

Obai wants to investigate the effect this excess $NaBH_4$ has on the $H_2$ gas produced and on the sand permeability in a bench-scale experiment. The experiments will be monitored using light transmission equipment to quantify local, transient gas saturations. Experiments using only $NaBH_4$ injection will be performed prior to the planned nZVI injection experiments. This will provide a basis for comparison to the effect of gas produced by entrapment and gas produced during nZVI injection.

### *EK – nZVI and EK – ISCO in Low Permeability Soils, Bench Scale*

Ahmed Chowdhury, PhD candidate, is conducting his research on enhanced delivery of chemical oxidants (permanganate) and reductants (nZVI) in low permeability media (silts and clays) with EK.

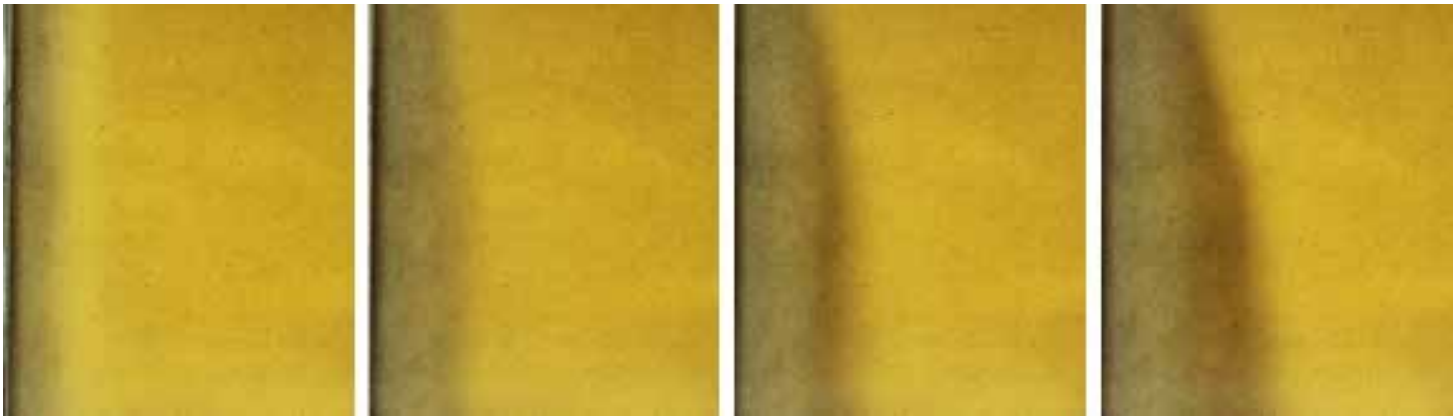
Experiments with EK-ISCO with permanganate as the oxidant are being performed on TCE contaminated silty soils (left photo at the top of page 4). After doing 80% of the EK-ISCO experiments, Ahmed's results show that EK does enhance permanganate delivery through low permeability porous media which otherwise is impractical, and EK application does impact TCE degradation. However, further work is still needed to clarify the degradation mechanism and how to enhance it with EK.

From the EK-nZVI experiments being performed in clayey soil, Ahmed has found that the development of osmotic pressure leads to swelling and subsequent collapse of the clay column (right photo at the top of page 4). He is investigating if clay packing has a role in clay collapse, and recently a packing method that shows promising results in preventing clay collapse has been developed. Ahmed is getting ready to test this new packing procedure.

### *Research on 1,2-DCA degradation by metallic formulations*

Remediation of 1,2-DCA with metallic formulations requires a metal with a reduction potential lower than -0.8 V, which is not provided by nZVI alone. This is the motivation for the research of three students, Ariel Garcia, Jorge Gabayet and Omneya Elsharnouby. Ariel (MESc student at Western), with support from Dr. Hardiljeet Boparai, is running batch experiments with bimetallic (Fe/Pd) nanoparticles, stabilized (CMC-nZVI) or non-stabilized (Bare-nZVI). Experiments so far have shown that Pd does not affect the reactivity of the nanometal towards 1,2-DCA. This has been confirmed by comparing pseudo-first order rate constants of monometallic and bimetallic nZVI, and by analysis of the degradation products. It has also been found that CMC-nZVI shows slower reactivity than bare-nZVI, possibly due to blocking of reactive sites on the nZVI surface. Iron nanoparticles 400 days old were characterized using XRD, XPS and SEM-EDX. Results indicate that zero valent iron is still present in the system, achieving unprecedented longevity for these iron nanoparticles.

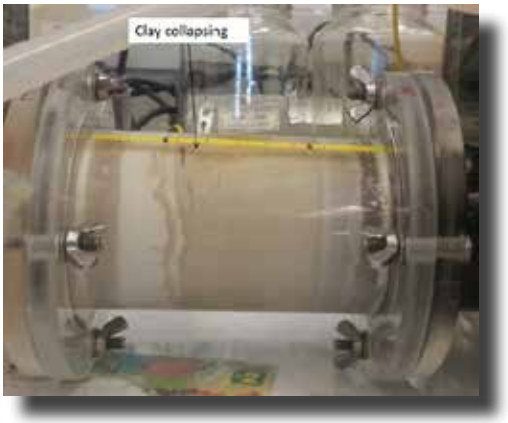
Omneya Elsharnouby, PhD candidate with Professors O'Carroll and Herrera, is developing a formulation to achieve liquid phase catalyzed reductive dechlorination of 1,2-DCA. Omneya wants to find an environmentally friendly reducing agent to substitute sodium borohy-



Production and advancement of a hydrogen gas front resulting from sodium borohydride injection on the left of a 2-D flow cell.
Photo courtesy of Obai Mohammed.

Obai Mohammed- PhD Candidate

Obai Mohammed received his BSc in Civil Engineering from the University of Khartoum (Sudan) in 2001, and MSc in Project Management from Boston University (U.S.) in 2008. He also obtained his MSc in Environmental Engineering from Lakehead University (Canada), and is now a PhD candidate under the supervision of Professor Mumford in the Department of Civil Engineering at Queen's University. His research is focused on the potential effects of hydrogen gas produced during nZVI applications. The objectives of Obai's research are to measure gas saturations during nZVI injection, as well as the resulting reductions in hydraulic conductivity caused by in situ gas generation, and investigate potential changes in the concentration of dissolved VOCs due to gas generation and transport. Obai's research activities will include experiments in clean sand as well as TCE-contaminated sand in small (~20 cm) and intermediate-scale (~1 m) flow cells. Recently, laboratory experiments were started to investigate hydrogen gas produced by the injection of sodium borohydride solution, to measure changes in hydraulic conductivity, assess gas transport mechanisms, and quantify gas saturations using light transmission.




Left: EK-ISCO with Permanganate in TCE contaminated silt. Note how permanganate travels across the whole silt column (turning pink) upon EK application.

Top-right: EK-nZVI in clay column showing the clay collapse upon EK application.

Courtesy Ahmed Chowdhury.

dride, a reducing agent used for nZVI synthesis and reduction of 1,2-DCA. Omneya would like to apply her formulation to aqueous phase contaminants representative of real field sites. Omneya has tested Pd as a metal catalyst for liquid phase reductive dechlorination of 1,2-DCA. With this novel technology, full 1,2-DCA degradation was achieved; however degradation rates depended on Pd loading and available surface area for reaction. Since Pd is an expensive metal, Omneya is testing combinations of Pd with other metals in order to make this an economically and environmentally friendly option.

### *Bio-nZVI Field Trial*

A second field trial was performed at the Dow Sarnia site. For this field trial, multilevel sampling wells were designed and built. The multilevel sampling wells were then installed with the help of a direct push rig from a hired well drilling company. After installation, the wells were developed, fines were removed, and hydraulic connectivity of the well screens were tested. 12 multi-level wells were installed in total, each with 7 levels. Two injection wells were installed with a two foot screened interval, one injection well for the nZVI and one for the CMC control zone. After well development, a tracer test was performed.

A special multi-port sampling set-up was constructed to make it possible to sample from 8 ports at once, and special holders were constructed to keep all the sampling containers in place. This set-up was then also used to collect background samples before injecting CMC-stabilized nZVI and CMC. Four batches of CMC-stabilized nZVI were injected, however in the CMC control zone less was injected because that injection well was located in a lower hydraulic conductive material. During the injection, samples were taken from a selection of ports; and directly after the injection, samples were taken from all sampling ports. These samples were later analyzed for the presence of nZVI.

Samples were taken post injection to determine contaminant concentrations. This was repeated two weeks later. During the next quarter other sampling rounds will follow to determine nZVI and CMC concentrations.

## STAR Updates

### *Process Sensitivity of STAR*

MESc student Laura Kinsman has completed her experiments investigating how key governing parameters—such as peak temperatures, velocities, and thicknesses of the smouldering front—scale from small to intermediate

and to large scale experiments.

Laura conducted 14 column experiments to investigate the fundamental differences in the way a smouldering reaction front propagates through a contaminated sand pack across various scales. A non-dimensionalized time scaling factor was developed in order to collapse the data and compare experiments across different scales on a single graph. Additionally, through the analysis of these experiments, it was found that short (10 cm) column tests display significantly different behaviour compared to the taller columns due to the strong influence of preheating on the entire contaminated sand pack. While 10 cm columns are useful for an initial assessment of the feasibility of a new fuel or soil type, taller contaminated sand packs should be used to fully assess the smouldering behaviour.

At larger scales, there was evidence of fuel mobility within the column. This fuel mobilization is dependent on both the airflow rate and the height of the contaminated zone, with greater mobilization evident in taller columns at lower airflow rates. While there is no impact on the overall remediation efficacy, significant fuel migration can lead to a concentration of fuel and energy resulting in elevated combustion temperatures. The possibility of these elevated peak combustion temperatures may be controlled through varying experimental conditions, or otherwise must be considered in the material design of reaction vessels.

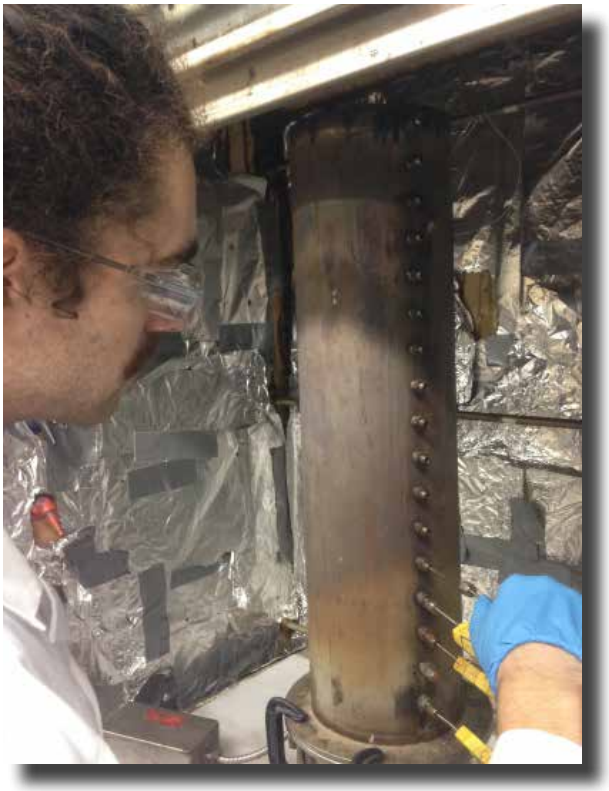
The recondensation of aerosols and condensable combustion products throughout the column experiments was also found to have a significant impact on the rate of mass loss of contaminants. This mass loss rate behaviour was further impacted both by the presence of a clean sand cap above the contaminated zone, as well as the presence of free water in the fuel mixture. A combination of these effects will impact the rate and composition of emissions over time and will ultimately affect the design of emission treatment systems.

### *New contaminants*

Tarek Rashwan, M.E.Sc. student, is exploring the potential of STAR to manage biosolids from wastewater treatment plants using a more sustainable approach than dewatering plus incineration (a low cost, low energy alternative). Tarek has conducted a suite of experiments to establish a moisture content and energy content envelope, which describe the parameters necessary for successful smouldering combustion.

Over the past year significant progress has been made in completing preliminary proof-of-concept experiments demonstrating that smouldering combustion is an effective method in managing high moisture content biosolids (75%-85%). The biosolids samples used in the laboratory experiments were obtained from Greenway Pollution Control Centre, in London ON. These experiments have been completed following established Self-sustaining Treatment for Active Remediation (STAR) experimental procedures using a 10 cm contaminant pack. A suite of experiments at the 40 cm scale are being completed, which altered the key properties of the system including energy, sand, and moisture contents. This will map out the parameter space where a self-sustaining smouldering reaction can be achieved. This research serves as the foundation for proposing STAR as a novel method for managing biosolids from a wastewater treatment plant (WWTP).

Tarek established a partnership with Savron via the Industrial Postgraduate Scholarship through the Natural Sciences and Engineering Research Council of Canada (NSERC-IPS). Through this partnership, Tarek expects to validate experiments with a greater variety of biosolids, conduct a financial analysis to evaluate savings from lower operational costs, and conduct larger scale experiments (3 m contaminant pack).



Tarek in the lab setting up his biosolids smouldering experiment. Tarek has achieved a self-sustaining smouldering reaction using biosolids with 74% moisture content at a concentration within a sand pack of 222g/kg. Photo courtesy of Tarek Rashwan.

### *STAR – Modelling*

The thesis project of MESc student, Rebecca Solinger (former STAR undergraduate thesis student), is to model the first ever in-situ field application of STAR at the New Jersey pilot test site using the developed In Situ Smouldering Model (ISSM, Tarek Hassan's MESc thesis). Rebecca's MESc is an evolution from her undergraduate thesis, as she would like to modify the ISSM model, which approximates the position of the smouldering front during bench top experiments, to an in-situ application. The model domain will be calibrated to reflect parameters applied during the New Jersey field test. The calibrated model will be used to determine the extent and propagation velocity of the smouldering front during the in-situ STAR applications. Preliminary work has identified the soil permeability, magnitude and mode of injected air, contaminant concentration, and depth of air injection screen as parameters of interest.

PhD student Marco Zanoni is another student that is making a lot of progress on STAR modelling. He is using COMSOL multiphys-

ics modelling platform to incorporate physics and chemical kinetics for a wide range of relevant thermodynamic processes and phases of STAR. Marco's model involves the transfer of mass, heat, and momentum in porous media, taking into account chemical reactions and heat transfer mechanisms. Marco's first step was estimating the kinetic parameters for coal tar pyrolysis and combustion. He successfully applied Genetic Algorithms to estimate the kinetic parameters related to the chemical reactions. In this way, a number of reaction frameworks are now available for the smouldering numerical model. Marco's second step involves improving our understanding of the relative importance of the heat transfer mechanisms—conduction, convection, and radiation—in smouldering involving an inert porous medium. A combined experimental-numerical strategy was developed to provide a new correlation for the volumetric heat transfer coefficient, representing the heat exchange at the interface between the solid and fluid phases. This step, still in progress, will provide a second key feature of the overall smouldering numerical model.

# Related Research

### *Biodegradation of Chlorobenzenes*

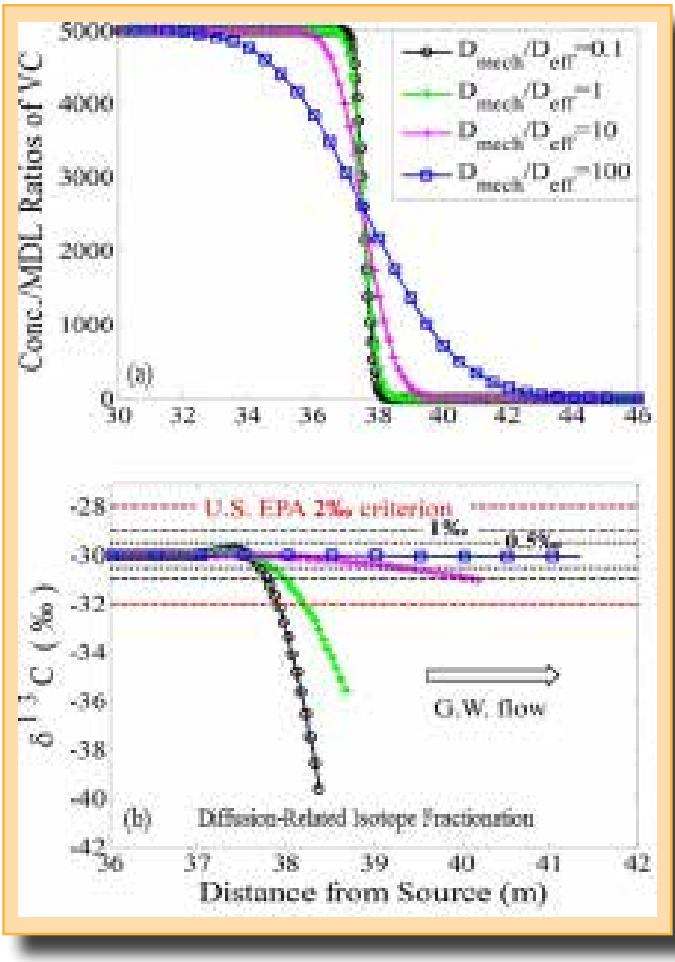
PhD student Luz Puentes, supervised by Professor Elizabeth Edwards, is investigating anaerobic biodegradation of chlorinated benzenes and lindane by organohalide-respiring bacterial consortia (OHRB). Chlorinated hydrophobic organic compounds such as the polychlorinated biphenyls (PCBs), chlorinated benzenes (CBs), and lindane, the γ isomer of hexachlorocyclohexane (γ-HCH), are widespread persistent environmental pollutants as well as highly toxic to higher organisms. The anaerobic biodegradation of lindane results in the production of toxic compounds monochlorobenzene (MCB) and benzene. Under anaerobic conditions, PCBs, CBs and lindane may be biodegraded via reductive dehalogenation by OHRB. Organohalide respiration is catalyzed by reductive dehalogenase (RDase) enzymes; these enzymes are found in consortia such as KB-1, which is capable of dechlorinating PCE to ethene. Therefore, one of Luz's objectives is to find out if PCBs and CBs can be anaerobically biodegraded by chloroethene-degrading consortia, such as KB-1 and identify any novel RDase(s) involved in the process.

Different bacterial consortia have evolved to dechlorinate a specific substrate or substrate group. OHRB consortia such as KB-1 and WBC-2, were established from field-site bioaugmentation cultures and contain around 30 and 61 rdh genes, respectively. From both an applied and scientific perspective, it is very important to understand if these cultures can dechlorinate substrates different from the ones used for their enrichment.

During the past year, Luz was able to demonstrate that the KB-1 culture can dechlorinate 1,2,4-trichlorobenzene (1,2,4-TCB) when TCE and 1,2,4-TCB are supplied simultaneously. This suggests that 1,2,4-TCB dechlorination is co-metabolic. Since TCB dechlorination occurred simultaneously with TCE dechlorination, one of the TCE-induced enzymes is likely responsible for the dechlorination of 1,2,4-TCB. However, recent microcosm data suggests that dechlorination may also occur in the absence of TCE. The cell dechlorination assays performed to date suggest that either the enzyme TceA or the Geobacter RDase enzyme are responsible for the dechlorination of 1,2,4-TCB. New assays that will be performed during the next quarter will elucidate this. On the other hand, KB-1 and WBC-2 were not able to dechlorinate a model PCB substrate (PCB 116) supplied individually or in combination with substrates used for culture enrichment. The latter suggests that TCE-induced enzymes do not dechlorinate PCB 116. Also, it indicates that PCB 116 alone may not trigger the necessary regulatory processes for the expression of other rdh genes that may have activity against this substrate. Regarding the biodegradation of Lindane, gamma-tetrachlorocyclohexene has been identified as an intermediate of Lindane degradation in the GT1 Lindane-degrading consortium. The latter has also been observed in previous Lindane-degradation studies. Lindane is quickly degraded to MCB and benzene at a rate of 1.7 mg/L*day. The GT1 consortium is being enriched by weekly addition of Lindane. The data collected during the last quarter will serve as the baseline for the mixed-consortium experiment that will evaluate the full bioconversion of Lindane.

### *Modelling non-Degradative Natural Attenuation Processes*

Stable isotope fractionation associated with non-degradative natural attenuation processes is the thesis topic of PhD Candidate




DRIF effects for different $D_{mech}/D_{eff}$ according to Bruce Xu's Study

Top: Ratios of VC concentration/MDL (method detection limit) during transport through porous media.

Bottom: Diffusion-related isotope fractionation (DRIF) corresponding to the different ratios of mechanical dispersion coefficient ($D_{mech}$) and effective diffusion coefficient ($D_{eff}$)

Different $D_{mech}/D_{eff}$ ratios represent different groundwater and soil conditions. The lowest ratio is typical of a clay aquitard. In this case, DRIF is most significant and corresponds to the smallest plume spreading (top figure).

Bruce Xu. Bruce wants to determine if isotopic changes in systems in which intrinsic biodegradation is occurring are significantly confounded by other less fractionating processes such as diffusion. Bruce is interested in determining diffusion-related isotope fractionation (DRIF) effects for common groundwater contaminants, whether DRIF would be observable in "typical" homogeneous and heterogeneous aquifer systems, and how mixing and blending during groundwater sampling affects the ability to detect DRIF. He has coupled CompSim and MT3DMS to model DRIF effects in a randomly generated heterogeneous permeability field (generated by MODFLOW), in which he used CompSim to calculate hydraulic heads and velocities, and MT3DMS to predict isotope concentrations during contaminant transport.

Bruce has completed a paper focusing not only on theoretical DRIF effects, but introducing the concept of "observable" DRIF effects for natural abundance isotope distributions. This paper investigates DRIF effects for 5 petroleum hydrocarbons and 5 chlorinated compounds. Bruce is now working on aquifer-aquitard systems and will introduce contaminant biodegradation using Monod kinetics and modifying RT3D (a multi-species reactive transport simulation software for groundwater systems).

# Latest Publications


1. Hasan, T. JI Gerhard, R. Hadden, G. Rein. 2015. Self-sustaining smouldering combustion of coal tar for the remediation of contaminated sand: Two-Dimensional Experiments and Computational Simulations. Fuel, 150: 288-297.

2. Salman, M., J.I. Gerhard, D. W. Major, P. Pironi, and RM. Hadden, 2015. Remediation of trichloroethylene-contaminated soils by STAR technology using vegetable oil smoldering. Journal of Hazardous Materials, 285: 346 – 355.

3. Gerhard, J.I., B.H. Kueper, and B.E. Sleep, (2014). Modelling Source Zone Remediation, pp. 113-140, in "Chlorinated Solvent Source Zone Remediation", Eds. B.H. Kueper, H.F. Stroo, and C.H. Ward. SERDP and ESTCP Series.

4. Jung, B., O'Carroll, D., Sleep, B. (2014) The influence of humic acid and clay content on the transport of polymer-coated iron nanoparticles through sand, Science of the Total Environment, 496:155 – 164.

5. Kokkinaki, A., Werth, C. J.; Sleep, B. E. (2014) Comparison of upscaled models for multistage mass discharge from DNAPL source zones, Water Resources Research, 50(4) 3187-3205.


# Announcements

Our third annual progress meeting, held on September 26, 2014, was attended by 65 people. Invited keynote addresses were delivered by Dr. Juliana Freitas from the Federal University of Sao Paulo, Brazil, and by Dr. Richelle Allen-King from the University at Buffalo, USA. Research results were presented by students and post-docs, followed by dinner at the UofT's Faculty Club. On September 27th 2014 UofT hosted the Symposium on New Re-

**Acknowledgements** to Ahmed Chowdhury, Omneya Elsharnouby, Ziteng Cui, Luz Puentes Jacome, Laura Kinsman, Simone Larcher, Obai Mohammed, Tarek Rashwan, Rebecca Solinger, Bruce Xu, Marco Zanoni, and Silvia Zarate Munoz for contributing to this issue.

## FAST FACTS

**30**
number of scientific publications

**91**
number of conference participations

**34**
number of HQP involved in the project

Partner Institutions

Private Sector Partners

Integrate Newsletter

Issue #5
March 2015

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This project is funded by the
Ontario Research Fund

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