EMBRACING INNOVATION

By Sharon Aschaiek and Michael Mastromatteo

As innovation steadily assumes a more prominent role in the toolkit of today's engineering professional, here are the stories of some Ontario engineers who have taken to heart the innovation imperative.

The Canary System, shown in a marketing photo and in use, uses photothermal radiometry and modulated luminescence to detect dental decay at its earliest stages.

HARNESSING LIGHT AND HEAT FOR SOPHISTICATED DIAGNOSTICS

A chance encounter between two professionals led to the commercialization of an exciting new product that its developers say will lead to a "paradigm shift" in dental health care.

Andreas Mandelis, PhD, LEL, is a professor of mechanical and industrial engineering, and director of the Centre for Advanced Diffusion-Wave Technologies at the University of Toronto (U of T). His work focuses on light and heat properties, particularly in the areas of non-destructive testing and the use of laser-induced phenomena in electronic, optical and biomedical materials.

More than 10 years ago, Mandelis overheard his wife's dentist complaining about the lack of advanced methods for detecting dental decay. The dentist, Stephen Abrams of Toronto, bemoaned the lack of cavity detection and treatment options beyond the traditional "drill, fill and bill" method.

The two professionals put their heads together to consider a system that would make use of heat and light to gain more information about tooth enamel health and ward off dental decay at its earliest stages.

After more than 10 years of research and development, the Canary System (Quantum Dental Technologies) came into being. Named for the proverbial "canary in the mineshaft" or early warning system, the Canary System is described by its originators as a "new era" in dental care, through its innovative combination of photothermal radiometry (PTR) and modulated luminescence (LUM) to detect dental cavities.

The system's low-powered, laser-based device combines heat and light to examine the crystal structure of teeth and signal areas of tooth decay. In the Canary System, a hand-held instrument emits pulses of light at an optimal fixed frequency to the tooth surface. In response, the tooth glows and releases some heat at the same frequencies as delivered by the laser beam. The information is recorded by the Canary System to provide a fixed depth profile of the tooth. Two clinical trials have shown patients do not feel the heat and there is no harm to the tooth and surrounding gum tissue.

"There is a photothermal signal emission–mid-infrared–and a luminescence emission–near-infrared–both available for detection," Mandelis explains. "These are the two fields resulting from excitation of the tooth with laser light. No other dental instrument works on two responses. Also, no other instrument uses these two responses. Luminescence, or fluorescence, has been used before in detecting dental bacteria, but it was not used in a modulated fashion."

Mandelis says modulation not only adds greater accuracy to the recording, but eliminates "background signals" that would be there even without the laser source.

"The result of the two waves emitted from the system means there are four signals available–two amplitudes and two phases: PTR and LUM. This makes the signal a lot more dependable to assess the integrity of the enamel.

Also, the fact that sub-surface penetration is a function of modulation frequency is a definite plus, as one can 'see' deeper or shallower away from the surface. No other dental probing method has that ability."

The recorded LUM and PTR signals reflect the tooth's condition at and below the surface. The system is precise enough to detect lesions or mineral loss as small as 50 microns up to five millimetres below the tooth surface. It is said to detect cavities earlier and more accurately, and allow for re-mineralization treatments to prevent cavities from growing larger.

In fact, the Canary System gives greater information about de-mineralization, or loss of calcium and other minerals from tooth enamel, well before any discolouration or cavity is apparent to the naked eye.

The system affixes a number between one and 100 to each tooth scanned. Healthy teeth receive a lower number, and vulnerable or de-mineralized teeth receive a higher number. Canary System reports are displayed on an interactive monitor, enabling the dentist to discuss diagnosis with the patient. The patients are also given a printed report, which helps to engage them in their preventive care. As well, information is stored on the "Canary cloud," or database, which allows dentists and patients to monitor treatment options.

In a recent interview, Abrams said teaming up dentistry with engineering led to development of the "ideal solution" to the problem of detecting tooth decay, especially on biting surfaces of the back teeth. "Together we've looked at how to adapt the technology for use in humans and understand how PTR-LUM was able to detect and monitor tooth decay. We continue to work together on new and emerging methods for monitoring changes in oral tissues."

Mandelis and Abrams worked with Quebec's Institut Nationale d'Optique to develop the Canary System base unit. The system's software, user interface, back-end database and web portal were developed by ProLucid of Mississauga.

Health Canada approved the Canary System for sale in April 2011. Its developers believe the system has the potential to become standard equipment for up to 200,000 dentists in North America, and are enthusiastic about the system's advanced diagnostic capability and potential to prevent dental health issues rather than simply restore dental health.

During earthquakes, the steel fingers of the YBS yield in flexure so peak strains are lessened. The YBS absorbs seismic energy more effectively and for longer than current bracing systems.

RAISING THE BAR FOR EARTHQUAKE-RESISTANT BUILDING DESIGN

As policy-makers debate the most prudent course of infrastructure renewal, a team of researchers, educators, engineers and students from U of T might have something to contribute about wise investment in "life safety" buildings.

Constantin Christopoulos, PhD, P.Eng., professor of civil engineering, U of T, and a recipient of an Ontario Professional Engineers Award in the young engineer category, is a key player in commercializing a unique Yielding Brace System (YBS) designed to enable buildings in earthquake-prone regions to withstand greater seismic forces than they are able to currently.

Also known as the Scorpion high performance system, the YBS is shaped like a giant wrench resting diagonally across a structure's frame or foundation. The widened end of the wrench looks like a giant scorpion poised to do battle with any opposing forces.

"The YBS is engineered to achieve the optimal combination of stiffness, strength and ductility–the ability to deform in the plastic range and absorb energy without fracturing," Christopoulos told *Engineering Dimensions*. "Current bracing systems relying on the yielding of steel are made of standard shapes, such as plates, tubes or combinations of such shapes, and as such there is limited ability to achieve the optimum combination of stiffness, ductility and strength."

Christopoulos says currently available yielding systems rely on "axial yielding," which imposes a severe strain on yielding elements, while the YBS incorporates steel fingers that yield in flexure, so peak strains exerted during earthquakes are significantly lessened. Because of this design, the YBS absorbs seismic energy more effectively and for a longer duration, enabling the building to withstand the initial quake as well as aftershocks.

YBS designers point to their product's vital redundancy, noting if a YBS-constructed building experiences a large earthquake, the failure of a single yielding finger would not result in a complete loss of lateral strength.

"As a result of this, the YBS can resist two times the testing protocol that has been established for testing the current technologies," Christopoulos says. "Typically, the current technologies will be severely damaged after one such protocol and unlikely to survive a second one."

The YBS is also said to be more collapse-resistant due to its "post-yield behavior," which involves the YBS anticipating some deformation of a brace during seismic activity and incorporating a gradual stiffening factor to guard against collapse of any one element of the overall bracing system.

The Scorpion YBS is the result of a doctoral research project by U of T engineering student Michael Gray as a follow-up to an earlier project where graduate student Carlos de Oliveira, P.Eng., researched the use of castings to improve the connections of bracing members for enhanced seismic protection of steel structures. Christopoulos, along with U of T civil engineering colleague Jeffrey Packer, PhD, P.Eng., encouraged Gray and de Oliveira to continue their work and looked to the university's intellectual property patent group to protect the intellectual property and to develop and commercialize the technologies.

The result is Cast Connex Corporation, a U of T engineering start-up firm headed by de Oliveira, which is commercializing the YBS and other innovative products, such as universal pin connectors, high-strength connectors and custom cast steel components. Cast Connex holds a PEO Certificate of Authorization (C of A).

Cast Connex President and CEO De Oliveira highlighted many of the virtues of the Cast Connex "disruptive technology" in an article in *The Journal of Policy Engagement* (July 2009, p. 2).

"For me personally, it has been incredibly fulfilling to have had the opportunity to take my doctoral thesis research into the market, particularly given its potential to improve the performance and safety of earthquake resistant structures," de Oliveira told *Engineering Dimensions*. "What we have achieved with Cast Connex–technology transfer from a university setting into a start-up business that grows into a successful enterprise–doesn't happen very often, particularly in the construction industry, which is very conservative and slow to change."

Cast Connex captured the 2009 award for excellence in innovation in civil engineering from the Canadian Society for Civil Engineering (CSCE). The CSCE noted that the company's work would have "a significant and far-reaching beneficial impact on the prosperity and well-being of society."

But it's the yielding brace system that has really caught the attention of civil engineers and other building design professionals.

"The Scorpion has just gone through the final full-scale testing phases of its development, and Michael Gray is completing the final numerical analysis phase of this very large project," Christopoulos says. "Currently, it is being considered for a first project in Montreal and a number of engineers in North America have indicated their desire to use this technology in their upcoming projects. We expect a full line of products for different force ranges to be commercially available by the end of 2011."

For Christopoulos, the Scorpion YBS represents engineering design going beyond minimal standards or expectations of public safety. "Our current codes aim to provide life safety under one design level earthquake," he says. "There is currently no explicit consideration of any aftershock affect. The YBS offers a much higher performance alternative as it has the ability to undergo a second earthquake of the same magnitude."

This philosophy is summed up in a message on the educator's website: "My teaching and research philosophy is based on the belief that engineers must master the physical principles behind each engineering problem, acquire an understanding of the behaviour of structures, and possess sound and robust analytical capabilities. Codes, design equations and colourful software are not replacements for sound engineering principles."

HARD WORK AND PERSISTENCE PAY OFF FOR RYERSON DUO

Late nights and missed classes are often the result of the hard-partying university experience for many post-secondary school students–unless you're Thiago Caires, 23, and Michal Prywata, 20, in whose case they're what's necessary to come up with the next generation of artificial limb.

The two Ryerson University undergraduate biomedical engineering students–who have just completed their third and second years, respectively–are the innovators behind the Artificial Muscle-Operated (AMO) Arm, a prosthetic limb that's controlled by brain signals and uses compressed air as its main source of power.

Unlike traditional prosthetics that rely on intricate electrical and mechanical components, the AMO

Arm uses artificial muscles–simple pneumatic pumps and valves–to create movement. The first prosthetic using this kind of simulated muscle system, the device is more affordable and easier to use than its conventional counterparts and requires no invasive surgery before implementation.

"A lot of people doubted us and told us we wouldn't be able to do it. Even our friends were wondering why we were missing classes. They were saying, 'What are you doing with your life?' It was exciting when people saw what we were doing was real," Prywata says.

The digital device uses signals in the brain that keep firing even after a limb is amputated, and users wear a headset that senses a signal–for example, the thought "down"–and sends it wirelessly to a miniature computer in the arm. The computer then compares the signals to others in a database and makes a match. Once brain signals are interpreted by the computer, they're sent to a pneumatic system, which activates the arm to create the correct movement. Expanding and contracting like real muscles, the system uses compressed air from a small, refillable tank in the user's pocket.

Until now, most research and effort in this area have focused on analyzing the functions of specific brain signals for certain tasks, and then trying to use them to power prosthetics in similar ways. With the AMO Arm, Caires and Prywata have bypassed this time-consuming process of understanding and manipulating each signal, with the device using the entire collection of brain signals as a whole.

"We treat these signals as a black box–we don't care what the signals are, we just focus on how to filter and process them in a simple way. So it's like the arm is just recording and replaying signals," Prywata says.

The AMO Arm's pneumatic system features several advantages for amputees: its parts are far cheaper than the microelectronics and motors that are typically used in prosthetic arms, for example, reducing the cost of the arms to a quarter of the approximately $80,000 it costs for conventional prosthetic arms. The pneumatic system, which is non-invasive and can be mastered in minutes, also mean users can forego muscle reinnervation surgery–a complex procedure that costs about $300,000, is not available in Canada, and requires several months of recuperation and weeks of training.

Ryerson University engineering students Thiago Caires (right) and Michal Prywata have devoted great time and effort to develop their innovative prosthetic limb.

The AMO Arm utilizes simulated muscle movement to improve mobility for amputees.

The AMO Arm has won awards at the Canadian Engineering Competition and the Ontario Engineering Competition. Caires and Prywata are now attempting to commercialize their patented invention and attract investment through Bionik Laboratories Inc., their newly formed company.

"We're excited that we finally did it. With Michal's computer skills and my mechatronic and robotic skills, we worked together till 4 a.m. every day to make this happen," Caires says. "We have the idea and we know it works, but we now have to get the money, manufacturing facilities and connections to bring it to market."

PUTTING LIGHT TO BETTER USE IN IMAGE CAPTURE

It was only a matter of time and effort before nanotechnology specialist Ted Sargent, PhD, P.Eng., would begin to do more things with available light.

A professor of electrical and computer engineering at the University of Toronto, Canada research chair in nanotechnology, and author of the book *Dance of the Molecules: How Nanotechnology is Changing our Lives*, Sargent first came to wide attention for his cutting-edge research into quantum dots, solar cells and solution-processed semiconductors.

In 2006, Sargent founded InVisage Technologies Inc., a California-based company commercializing QuantumFilm technology, which improves the performance and light sensitivity of cellphone-based digital cameras.

While it might seem a luxury or even an extravagance to exploit such innovative technology to take better photos from a cellphone, there is a host of positive new applications for QuantumFilm.

In a June 3 interview with *Engineering Dimensions*, Sargent said QuantumFilm represents a significant advance in capturing light for digital cameras, in particular for cellphone units. The technology uses semiconductor quantum dots instead of the traditional silicon, enabling QuantumFilm image sensors to capture more than 90 per cent of available light. Silicon-based digital cameras capture only about 25 per cent of available light.

"Silicon is the basis of processors in our computers, and it's currently the basis for image sensors for mobile handsets," Sargent says. "But it was never really designed with light in mind. It was more designed or chosen with electronics in mind. That has led to a number of limitations on the efficiency or fidelity with which silicon is able to register images."

QuantumFilm, Sargent adds, is designed with material based on quantum dots. It has also been designed specifically to function as a light absorbing, light sensing layer.

He says the product is further enhanced through a post-process, in which the material is applied on top of a silicon integrated circuit.

"In a sense, what we've done is bring the light sensor closer to the light," he says. "At the moment in image sensors, the silicon is buried beneath a number of layers, and so getting the light onto the light detectors inside each pixel is a bit of a chore and involves a number of compromises. By overcoating the silicon with our QuantumFilm, we've brought it closer to the light, really breaking a number of the compromises inherent today."

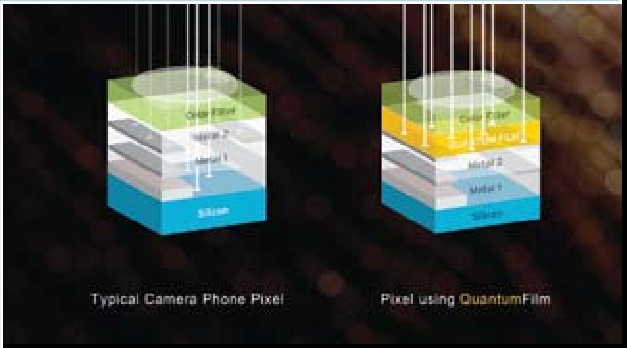
Sargent says that for all silicon's computer processing versatility, it remains a "light starved" element that is overcome by the addition of QuantumFilm.

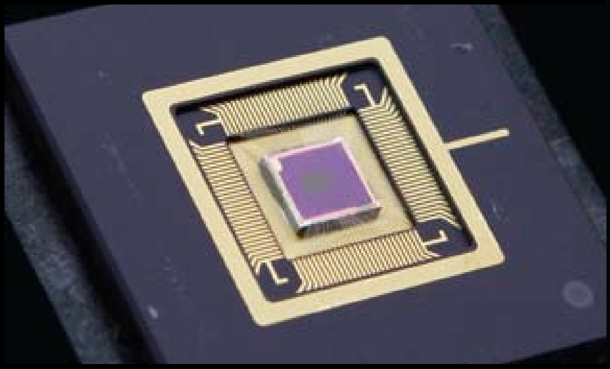
Sargent is equally enthusiastic about other applications for QuantumFilm, with security cameras, medical imaging and the ever-expanding field of night vision at the top of the future applications list.

"Just on the medical imaging side, our capacity to see in the ultraviolet and the X-ray regime gives us options for pursuing applications in medical imaging of various sorts," Sargent says. "So the strategy is to address a large existing market that has an urgent need where we solve that need. The longer-term roadmap is to explore all of the colours that silicon can't see, and to enable new applications in those broader spectral regimes."

Sargent says the engineering imperative to create and innovate was a key motivator in establishing InVisage. "What I've described in terms of the foundations of the company is really a fundamental scientific breakthrough," he adds. "The engineering is in our having brought together within InVisage a team of engineers from the world of silicon integrated circuits, circuit design engineers who were already world-class experts in their previous jobs, world-class experts in designing the circuits that allow you to make a very good image sensor circuit with all of the components, all of the properties, all of the features and functions you expect in a camera."

He says QuantumFilm is the end product of a team of material scientists and "device engineers," who came up with a way of putting nano-particles onto a chip, and linking it to a semiconductor wafer as a process that can be reduced to practice. "We brought together a team of people who spanned traditional electrical engineering, but also material science and engineering, and chemistry and physics. And we have built prototypes and we're now going towards building products that really combine materials, nanotechnology and integrated circuit engineering in a way that people simply haven't done before."





This graphic prepared by InVisage Technology shows the enhanced light capturing ability of QuantumFilm compared to traditional silicon-only digital imaging systems. The world's first image sensor using quantum dots will bring high-quality images to cellphones.

InVisage's QuantumFilm is spin-coated atop a silicon wafer so no metal wires obscure it. QuantumFilm is engineered to be highly light-absorbing–resulting in nearly 100 per cent conversion of photons to electrons.

Twenty-four lane-kilometres of Highway 401 were reconstructed with perpetual pavement, a heavy-duty pavement alternative designed to withstand heavier loads and resist structural failure for at least 50 years.

PAVEMENT BREAKTHROUGH BODES WELL FOR INFRASTRUCTURE INVESTMENT

A promising development in pavement technology may provide Ontario with tougher highways that will last longer, require less maintenance and ultimately cost less money.

Perpetual pavement is a heavy-duty pavement alternative with a flexible multi-layer asphalt structure that's designed to withstand heavier loads and resist structural failure for at least 50 years and require only periodic renewal. Traditional pavement lasts about 30 years and requires periodic reconstruction.

Over the last three years, 24 lane-kilometres of Highway 401 near Woodstock were reconstructed with perpetual pavement, and as the initiative wraps up this summer, testing will begin to determine its viability.

"The whole idea is to build pavement in layers that are really thick and strong so there's no cracking, and so the whole pavement structure lasts a long time and you only have to replace the surface layer every 10 to 15 years," says Nick Gilbert, P.Eng., head of the geotechnical section of the west region of the Ontario Ministry of Transportation (MTO) and designer of the perpetual pavement.

Like conventional pavement, perpetual pavement requires a 750-millimetre granular base. Where it differs is in the three distinct layers that sit atop it: a renewable surface layer; a strong, rut-resistant intermediate layer; and a flexible, fatigue-resistant bottom layer, which, when combined together, are 420-mm thick–40 per cent thicker than standard pavement. While conventional thin pavements exhibit distresses more readily under ongoing heavy traffic, thick-asphalt pavement deteriorates more slowly and pavement distress is localized to the top layer, which can be easily replaced.

Designed according to the principles of the American Association of State Highway and Transportation Officials' 1993 pavement design method, perpetual pavement is designed to withstand 400 million equivalent single-axle loads (ESAL)–an industry standard measure of wear and tear. This is far more than the ESAL rates for other highways in Ontario.

While the concept has been around for decades and is already in use in Europe, Australia and the US, perpetual pavement is relatively new to Ontario. In 2007, the approach was used to reconstruct a four lane-km test section of Highway 406 near Thorold.

This current initiative, costing $105 million, is the second largest single highway reconstruction project in MTO history and will determine to what extent perpetual pavement may be used on Ontario highways in the future.

From the outset, researchers from the Centre for Pavement and Transportation Technology, University of Waterloo, were involved in evaluating the potential structural and economic advantages of the approach. Before construction began, the materials were exposed to simulations of similar weight loads and temperature ranges to assess their durability. During construction, strain gauges were embedded into various parts of the pavement to provide real-time data on the structure's performance, which will be monitored over the next 10 years. MTO will use the resulting data to perform a 50-year life-cycle cost analysis of perpetual pavement, which costs 25 to 40 per cent more up front to build, but is likely cheaper in the long-run because of its significantly lower maintenance costs and fewer reconstruction-related user delays.

"In Ontario, our economy is so reliant on highway infrastructure through the transportation of goods and services. We also have harsh winters and lots of freeze and thaw cycles. All of this takes a toll on our highways," says Susan Tighe, PhD, P.Eng., director of the centre, Canada research chair in pavement and infrastructure management, and a recipient of an Ontario Professional Engineers Award. "If we can design long-lasting pavements that are more sustainable, require minimal maintenance and are more cost-effective, then that's a huge innovation."

SUBTERRANEAN PROJECT ONLY PARTIALLY HIDES ITS ACHIEVEMENT

The director of Ontario Power Generation's (OPG's) colossal $1.6-billion Niagara Tunnel Project (NTP) strikes an understated pose when asked to describe some of the unique technical challenges involved in the work.

Rick Everdell, P.Eng., a civil engineer who became project director of the Niagara tunnel operation in 2005, prefers to cite the experience and technical virtuosity of his international project team when accounting for the project's success and achievements to date.

In homage to Ontario Hydro founder Sir Adam Beck, the project involves the use of "Big Becky," the world's largest hard-rock tunnel boring machine (TBM) to excavate a 10.2-km-long tunnel between the Niagara River above the Horseshoe Falls and OPG's Sir Adam Beck hydro stations downstream at Queenston.

Built by the Robbins Company and assembled on site by the Austrian design-build contractor Strabag AG, Big Becky's 14.4-metre-diameter cutterhead surpasses her rivals by more than two metres. The completed tunnel will have a diameter of 12.7 m after the concrete liner is installed and will divert up to 500 cubic metres of water a second to increase the annual power generation at the Beck plants by 1.6 billion kilowatt-hours, a 14 per cent improvement over their existing output, and enough to supply the needs of 160,000 homes.

Everdell says he was not intimidated by the size and scope of the Big Becky operation. "We had a good grasp of the task, based on my knowledge of the project, my familiarity with the regulators and local stakeholders, and the experience of supporting OPG as the owner's rep and contractor staff assigned to the project," Everdell says.

A 36-year veteran of OPG and its predecessor, Ontario Hydro, Everdell was first licensed by PEO in 1978.

Although government approval for the project came in June 2004, feasibility studies to expand and upgrade the Niagara River hydroelectric facilities began as early as 1982, with "definition engineering" and environmental assessment beginning six years later and full environmental approval coming in 1998.

Big Becky hit a milestone in May with breakthrough to daylight at the intake site, marking the completion of the mining for the project. Remaining work includes completion of the concrete lining, installation of intake and outlet gates, removal of cofferdams and filling of the tunnel itself. Final completion is expected in 2013.

One of the primary constraints for the project's designers and managers was to reduce noise and surface disruption in the city of Niagara Falls as much as possible. In addition, worker safety and environmental protection have been top of mind for Everdell and the project team throughout the operation. The Niagara Tunnel is being heralded not only for its "green" renewable power, but also for its robustness and durability. OPG expects the tunnel will operate maintenance-free for at least 100 years.

Another constraint Everdell faced with the Niagara Tunnel was to avoid diverting too much water away from the falls themselves. There was also the duty to local residents not to turn the city into a noisy obstacle course during construction.

In fact, the tunnel descends down to 140 m below Niagara Falls' city streets, making it one of the deepest and least disruptive operations of its kind in North America.

Everdell suggests the project's greatest technical challenges involved modifications to the TBM to deal with significant overbreak in the tunnel crown, while safely excavating and supporting the over-stressed rock. Other challenges included acquiring and mobilizing the large purpose-built TBM and other equipment for lining the tunnel with a polyolefin waterproof membrane and 600 mm of cast-in-place, unreinforced concrete placement.

Surprises and setbacks during the excavation were few but challenging.

"In the Queenston shale formation, the combination of high in-situ horizontal stress and the relatively thin bedding of the rock led to significant overbreak in the tunnel crown before the initial rock support could be installed," Everdell says. "This resulted in slower than expected progress of the TBM, addition of an unprecedented overbreak infill operation, more concurrent tunnel construction activities, a change in the tunnel alignment, and increased project duration and cost."

As to the project's innovative qualities, Everdell remains plainspoken: "The tunnel boring machine was precedent-setting in that it's the largest hard-rock gripper in the world. Construction of the tunnel lining waterproof membrane and pre-stressing of the concrete lining to offset internal water pressure of up to 1.5 mega pascals (MPa) are the principal innovative elements of the NTP. Σ

The Big Becky tunnel boring machine prior to its excavation work under the city of Niagara Falls.

The mining side of the Niagara Tunnel Project came to an end with the May 13, 2011 breakthrough at the intake site.