Final Report

The Regional Municipality of Wood Buffalo &

SALT Canada Inc.

C.C.E.M.C. Project ID # C110131

Project Title: Fort McMurray Landfill Aerobic Bioreactor

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Executive Summary

The partnership of SALT Canada Inc. and The Regional Municipality of Wood Buffalo, coupled with support from Climate Change & Emissions Management Corporation (now Emission Reduction Alberta) produced an extraordinary result. A result hailed by National & International respected and knowledgeable industry sources as the most important innovation in carbon reduction and landfill management in the last 100 years.

During the design and construction phases of the project, there were inefficiencies in standard practices at landfill sites that were identified. The project teams consulted experts in the field of landfill technology and those from other geophysical fields to attempt to bring new technologies for use at landfills to help fix these inefficiencies. Some of the testing yielded quick results and will now be used at future landfill sites to make construction projects more efficient. Other attempts to use technologies from other fields were not successful at the landfill site; while these tests were considered failures, they did open the doors to different technologies that will be tested at future sites.

The requirements for optimizing the control of all components of the aerobic landfill bioreactor also led to the development of new valves, through partnerships between SALT Canada Inc. personnel and environmental technology providers. This new valve design has become a cornerstone valve in the supplier's catalogue of equipment for landfill gas extraction systems.

Due to a series of unexpected delays in initiating the aerobic landfill bioreactor, the system was scheduled to begin operation in June 2016 to manifest the long anticipated result of generating 1.2 to 1.8 million tonnes of carbon equivalent reductions over a three year period. Unfortunately, on May 3rd, 2016, the Fort McMurray wild fire raced over the site and inflicted fatal damage to the construction rendering the site unable to fulfill its mandate.

While there was widespread frustration among the partners due to the inability to consummate the project and obtain the results anticipated, there was also both pride and a sense of accomplishment. The project spawned new construction techniques, led to the development of new commercial products and demonstrated for a wide variety of experts an entirely innovative approach to monitoring and controlling landfill biological processes. The consensus is that this project has developed world-class technologies that could influence the social strategies of waste disposal for mankind, while simultaneously providing a major source of GHG relief affecting climate change. Moreover, the adoption of this technology will have a positive financial impact for communities in addition to solving major environmental concerns that affect all landfill locations. It creates a **Sustainable Landfill.**

Project Description

Introduction:

The Regional Municipality of Wood Buffalo (RMWB) is a progressive and environmentally conscious municipality that desires to become the first carbon neutral city in Canada. This environmental goal was shared by the oil producing region and the entire Province of Alberta as a method of altering the widely held perception of Alberta as a carbon-generating region.

Simultaneously, SALT Canada Inc. (SALT) was seeking a large-scale landfill project in order to demonstrate the advantages of the aerobic landfill bioreactor in eliminating methane generation within conventional landfill sites.

The goals of the RMWB and SALT were both satisfied with the "partnership" that allowed SALT's aerobic landfill bioreactor technology to be employed on a publically owned 1.3 Million tonne closed landfill site in Fort McMurray.

The Province of Alberta assisted this development through the acceptance of a carbon reduction protocol that allowed aerobic landfill bioreactor projects to quantify and monetize the amount of methane avoided (as carbon dioxide equivalents). Furthermore, Alberta Environment and Parks provided all necessary approvals for the development and operation of an aerobic landfill bioreactor.

Climate Change & Emissions Management Corporation assessed the project for technical capability and concluded that the technology was appropriate for financial support, consequently awarding a sum of $ 500,000 toward the project costs.

Technology Description:

Conventional landfills are large volume waste storage devices. Waste that is stored in the landfill is slowly biodegraded by anaerobic microorganisms to produce a landfill gas that is mostly made up of methane and carbon dioxide. Throughout the degradation process, there are many types of microorganisms that are involved in the creation of secondary by-products, such as hydrogen sulphide and ammonia (leading to odours at the site and in the surrounding areas) and a leachate containing metals, nutrients, humic and fulvic acids, inorganic salts and xenobiotic compounds which must be treated to protect the receiving environment.

The premise of SALT's aerobic landfill bioreactor technology is to create conditions in the stored waste mass that will inhibit anaerobic microorganism growth and activity while maintaining aerobic degradation of the waste. This is achieved through the controlled injection of low-pressure compressed air into the landfill cell and controlling the flow of air within the landfill through the controlled extraction of landfill gas (Figure 1). The anaerobic microorganisms responsible for the production of methane are obligate anaerobes (they cannot survive in an aerobic environment); therefore oxygen introduction will kill the microorganisms and allow for new growth of aerobic microorganisms. This will cease the production of anaerobic landfill gas (mostly comprised of methane and carbon dioxide) and start the production of aerobic landfill gas (mostly comprised of carbon dioxide, nitrogen, and water vapour). Under aerobic respiration, all organic carbon is converted to biogenic carbon dioxide (anthropogenic methane is avoided), organic nitrogen is nitrified to nitrate (no associated ammonia odours) and all sulphur is oxidized to sulphate (hydrogen sulphide is avoided). There are also limited secondary reactions occurring during aerobic respiration; there is no production of volatile fatty acids that allow metals to become mobile in the leachate and therefore the conversion to aerobic conditions will also limit the toxicity of any leachate generated. Furthermore, the temperatures produced in the landfill, paired with the high flow-through rate of injected air and extracted landfill gas will remove the majority of the moisture from the landfill, effectively stopping leachate production.

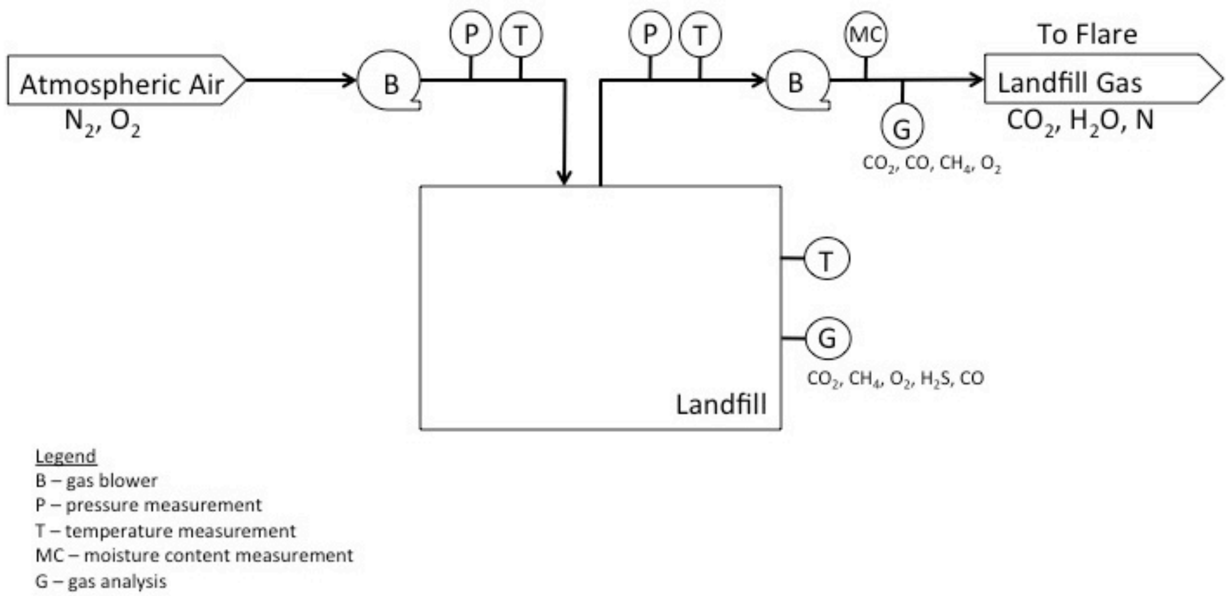

Figure 1 Aerobic landfill bioreactor process flow diagram

In addition to the environmental advantages of the aerobic landfill bioreactor, substrate utilization rates (a measure of how quickly the microorganisms will degrade the organic material in the waste) of aerobic microorganisms are higher than those of anaerobic microorganisms. This increased substrate utilization rate leads to faster waste stabilization rates. A conventional anaerobic landfill site will require over 100 years to stabilize (degrade all of the stored organic material), while an aerobic landfill bioreactor will require only 4 years to stabilize. After waste stabilization, the site can be considered safe for mining and site recovery (no gas production, no odours, and no leachate production). The recovered site can be mined for recyclable and reusable materials, at which point the site can be restarted as a landfill or returned to virgin conditions and reused by the municipality. Either of these options represents an increased revenue stream for the municipality through new tipping fees at the landfill or as a tax income generating site.

The aerobic landfill bioreactor technology will achieve major decreases in greenhouse gas emissions (through methane avoidance) in a short period of time. The use of this technology in Alberta can also generate carbon offset credits, which more than offset the costs of system design, construction and operation. Converting the landfill to aerobic conditions will eliminate odours at the site and halt leachate generation. These are two major environmental and aesthetic concerns associated with landfills. After the site becomes stabilized, the landfill can be mined and returns to virgin conditions, which removes the potential liability and insurance requirements after 4 years post closure, as compared to a minimum of 25 years as provincially mandated for conventional landfills.

Project Goals:

The major project goal for both the RMWB and SALT were the construction and operation of a large-scale aerobic landfill bioreactor at the closed RMWB site. Accomplishing this goal required many smaller tasks, many of which led to experimentation and innovative solutions:

1. Testing and development of an engineered grid plan for the drilling of wells into the surface of the landfill.
2. Selection and testing of an unconventional method of well drilling on a landfill site.
3. Engineering and selection of sophisticated technologies to enable on-site and remote control of the aerobic process. Including measurement of moisture and gases as well as temperatures throughout the site.
4. The development and implementation of a data reporting system that met all the requirements of Alberta Environment and Parks and interested international organizations.
5. Engineering and construction of mechanical devices to enable delivery of air and moisture, as well as extraction of moisture and gases, all within a system that could be delivered as a functioning mobile unit.
6. The experience of integrating all the various technologies and disciplines required for construction of such a project.
7. The development of a cadre of individuals that understood the principals of the aerobic process, gained experience in the construction of a major system, and were capable of operating the system.
8. Development of construction costs of a large scale aerobic landfill bioreactor, in a Northern Alberta location.

A second goal of the aerobic landfill bioreactor project was the achievement of large-scale reductions in methane generation and translating the methane reductions into carbon equivalents and carbon offset credits.

A final goal of the project was to demonstrate the system to national and international engineering organizations that would recognize the importance of the technology and adopt its use.

Work Scope Overview:

Many of the sub tasks within the major goal of this project are focussed on learning lessons through the large-scale construction process as well as training knowledgeable personnel in the operation of the aerobic landfill bioreactor and developing realistic costs associated with such a project. These are tasks that focussed more on lessons learned through the process than actual work within the project. These tasks and goals were achieved through constant evaluation of the processes and creating logs of best practices and lessons learned.

The engineering and construction of mechanical devices to enable delivery of air and moisture, as well as extraction of moisture and gases, all within a system that could be delivered as a functioning mobile unit required communication between SALT personnel (system designers), Integrated Sustainability Consultants Ltd. (Canadian engineers) and Product Recovery Management (fabrication). This was a typical process of engineering and design; as with many major projects it requires constant approval and verification of design changes and system design review. As with the aforementioned sub tasks, this was focussed on lessons leaned on all levels to create a more streamlined process for future construction projects.

Other subtasks within the major project goals resulted in new studies and experimentation on site, either to increase construction efficiencies, create a more efficient operational process or as requirements for regulatory reporting. These processes all fit into the sub tasks listed in the project goals.

Characterization of the site was required for sub tasks 1 and 4 of the project goals, and involved the following projects:

1. **Determining the physical properties of the stored waste in the landfill**. This project was required to determine the proper well spacing within the landfill to optimize the air injection process and the gas extraction process. If wells were placed too far apart, the pressures required to pass air through the waste would be too great, taxing the flow systems and creating inefficient use of electrical and mechanical power in the system. If the wells were too close together the designed flow pressures would cause air to pass

through the waste too quickly to be efficiently used by the microorganisms causing more air to be used to achieve the environmental goals of the project.

2. **Determining the Biological Methane Potential (BMP) of the stored waste**. The BMP of a landfill is an indirect measure of the amount of organic material stored in the waste and, therefore used as both an indication of the potential greenhouse gas emissions from the site, and as an indication of the amount of oxygen required to degrade the organic matter. Furthermore the reduction of BMP over the life of a project was a major part of the application for carbon offset credits and therefore the data reporting to regulatory bodies.
3. **Determining the bottom profile of the landfill**. Knowledge of the bottom profile of the landfill is critical in the design, installation and operation of these types of systems. If the bottom profile of the landfill were not known during the well drilling phase of the operation there is a risk of passing a well through the bottom of the landfill and allowing leachate to seep into the receiving environment. The bottom profile of the landfill is also critical in determining the overall volume of stored waste in the landfill. The total volume of stored waste, combined with the BMP (Project 2), determines air requirements (system design parameter) as well as total methane avoidance (for regulatory purposes).

Once the well placement study was completed, the well layout design was started. At this landfill it was determined that there are approximately 4 wells every 100 m^2 of landfill area for gas extraction and 4 well clusters of wells (designed to allow depth variation in air injection) in every 100m^2 of landfill area. This means that over 1800 wells would need to be installed in the landfill, which brought on a new optimization project that was a part of sub task 2:

4. **Determining efficient method of well drilling**. The heterogeneity of the waste stored in a landfill makes drilling into the waste problematic. Conventional auger drilling need to be maintained at a low speed, even in loose material, due to the risk of hitting unexpected dense pockets of waste or large piece of metal (appliances and automotive parts) that can damage the auger if it is moving too quickly. The augers are typically not capable of passing through large pieces of metal or construction waste and therefore some of the wells need to be abandoned and refilled if they cannot be completed, and a new well needs to be drilled. Conventional augers also bring waste to the surface of the landfill as the holes are drilled, leading to a need to dispose of and handle the drill waste. Traditional auger drilling at a landfill is therefore a very inefficient project and a new method of drilling needed to be employed if the over 1800 wells were to be installed quickly and efficiently.

After all of the construction and design projects were completed, the system required commissioning, testing at which point it can be used to verify the validity of design calculations, these projects would fulfil requirements of sub tasks 3, 4, and 5:

5. **Create lineal flow vales**. The efficient operation of the aerobic landfill bioreactor requires control over air movement through the stored waste in the landfill. This requires a controlled injection and/or extraction rate at each well in the landfill. Centralized blowers at the system enclosure control the air injection and gas extraction systems and therefore the only way to control flow at individual wells is through the use of valves. Conventional valves were not able to provide a linear relationship between valve positions and flow rate; the use of available valves would create inefficiency in flow control. Therefore a new valve needed to be designed.
6. **Testing System Operation**. After the system was built and delivered to the site it was connected to all of the wells and all components of the system were tested to ensure proper functioning of all system. This was a long process for all of the components since in many cases the errors in the system could not be manually triggered. Any flaws in the design and programming that could be identified through manual triggering were found quickly, while the flaws that required environmental triggers (extreme cold or windy conditions) took longer to identify.
7. **Testing Flue gas composition**. A computer model was used to estimate the production rate of methane in the landfill. This model required multiple inputs of values that are assumed based on the knowledge of the modeller, since the exact values are not known. There is a risk that the model will either under, or over estimate methane production. Monitoring the actual landfill gas production at the site will help to identify if the values input during modelling were correct or if there is a need to revisit the modelling. This data also supports the regulatory reporting requirements.

Outcomes & Learnings

Literature Review

Landfill disposal is currently the most employed method of waste management worldwide. Conventional landfilling involves storing a large volume of heterogeneous waste and allowing the waste to degrade, with limited input from the operators. This leads to anaerobic conditions mediating the organic waste decomposition. Landfills become uncontrolled anaerobic digesters and therefore follow the conventional dynamics (4 phases) of these processes[1].

[1] Farquhar, G.J. and Rovers, F.A. 1973. Gas production during refuse decomposition. Water Air and Soil Pollution. 2(4): 483-495.

Phase I is the aerobic phase of waste degradation. In this phase oxygen present during waste filling is used, through aerobic respiration, to convert organic matter to carbon dioxide and water; nitrogen is hydrolysed to ammonia and nitrified to nitrite and nitrate and sulphur is oxidized to sulphate (Figure 2).

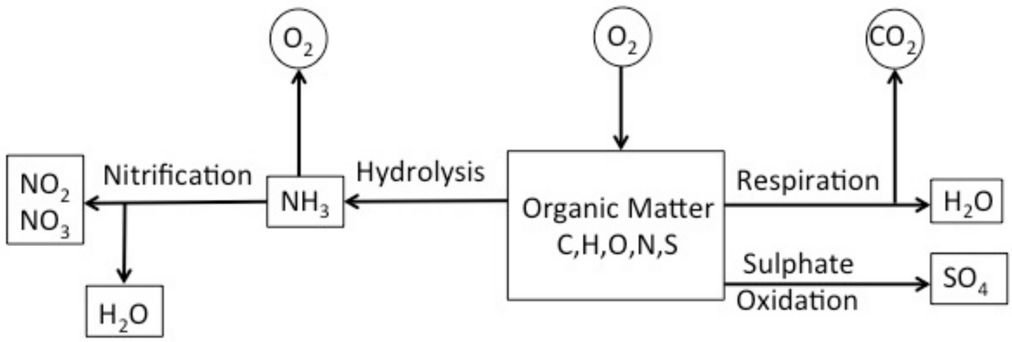

Figure 2 Phase I (aerobic) of waste degradation

Once all of the available oxygen is utilized, Phase II, acid production (Figure 3), commences. In this phase organic material is fermented to carbohydrates, amino acids, and long chain fatty acids, which are further fermented to volatile fatty acids. Organic nitrogen is hydrolysed to ammonia and sulphur is reduced to hydrogen sulphide. There is also evidence of hydrogen gas formation. This phase will decrease pH, due to the production of organic acids. This low pH environment paired with the low oxidation-reduction potential leads to metals becoming mobilized into the leachate that is formed.

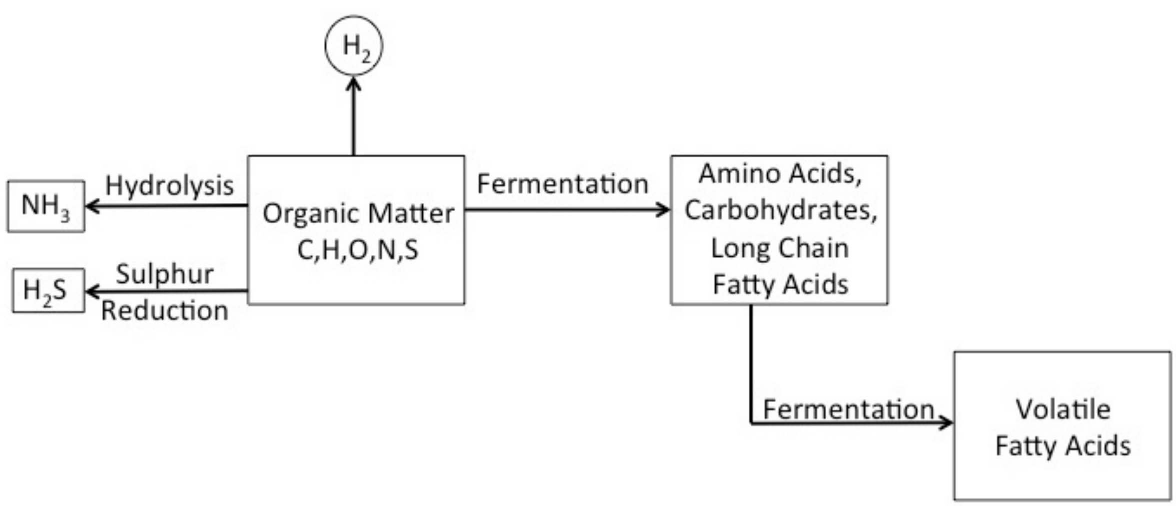

Figure 3 Phase II (acid production) of waste degradation

Phases III and IV are both methanogenic phases (Figure 4) characterized by the biologically mediated conversion of the volatile fatty acids and hydrogen produced in Phase II. Phase III (unsteady methanogenesis) is characterized by the growth of methanogenic microorganisms, which leads to an unsteady production rate of methane. Phase IV is achieved once the growth rate of microorganisms is constant and therefore the production of methane is steady.

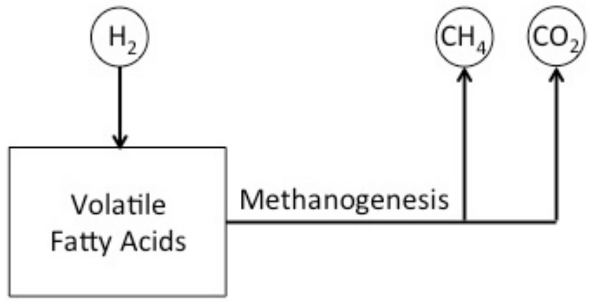

Figure 4 Phase III and IV (methanogenesis) of waste decomposition

The aerobic landfill bioreactor design is based on a controlled injection of air (containing approximately 21% oxygen) into the stored waste within the landfill. This will rapidly return the waste in the landfill to phase I of the waste degradation process, since methanogenic microorganisms are obligate anaerobes (they die in the presence of oxygen), and aerobic microorganisms will outcompete the anoxic fermenting microorganisms (Phase II) for organic matter under aerobic conditions. In one study, the original landfill gas methane content of 60% decreased to fewer than 15% within a week of aerobic system operation[2]. The increased oxygen in the system has also been shown to decrease the overall volatile fatty acid concentrations in the landfill, thereby reversing the affects of Phase II waste degradation on the pH; a study has demonstrated that with aeration and leachate recirculation volatile fatty acid concentrations in the leachate decreased from between 38000 and 30000 ppm to as little as 500 to 800 ppm in 120 days with aeration[3].

Waste stabilization rates in landfills are the main factor that defines the overall length of the environmental impact at landfill sites. Waste stabilization rates depend on many factors including, but not limited to: moisture content, pH, types of waste stored, temperature, and compaction of the waste. Waste stabilization rates also depend on the microbial communities present within the waste. Without knowing the specific microorganisms that are active in a landfill it is difficult to estimate the variations in growth rates between aerobic and anaerobic treatment, however it is generally accepted that the rates of substrate utilization in aerobic systems are greater than those in anaerobic systems[4]. This does not translate directly to a

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[2] Leikan, k., Heyer, K.U. and Stegmann, R. 1999. Aerobic in situ stabilization of completed landfills and old sites. Waste Management and Research. 17(6): 555-562
[3] Bilgili, M.S., Demir, A. and Varank, G. 2012. Effect of leachate recirculation and aeration on volatile fatty acid concentrations in aerobic and anaerobic landfill leachate. Waste Management and Research. 30(2): 161-170
[4] Hendrics, D. 2016. Fundamentals of water treatment unit processes. CRC Press.

difference in times to reach waste stabilization; there are other factors that need to be addressed, such as the passive nature of conventional landfilling, and the active and controlled distribution of oxygen through an aerobic landfill bioreactor. In test plots researchers have noted a volume decrease in aerobic landfill bioreactor cells of 37% within 375 days, while a similar conventional anaerobic cell experienced a volume decrease of only 6% in 630 days[5]. This rate of volume loss is directly proportional to the amount of organic material that is degraded in the waste and can be extrapolated out to indicate that a landfill that will take over 100 years to stabilize under anaerobic conditions can be stabilized in approximately 4 years under aerobic conditions.

A further environmental advantage of aerobic landfill bioreactors is the effect that these systems have on the quality of leachate within the landfill as well as the quantity of leachate that is produced during waste degradation. In the initial stages of the conversion from anaerobic conditions to aerobic conditions, the existing leachate is, in essence, being treated aerobically as a secondary effect of aeration[6]. Leachate concentrations of ammonia were seen in one case to decease by two orders of magnitude[7]. The high flow rate of air and gas extraction in aerobic landfill bioreactors as well as the high temperatures generated by the biological activity in the stored waste has even been noted to stop leachate production altogether if controlled correctly[8].

Aerobic degradation of solid waste is clearly a more efficient method of waste stabilization; the waste is stabilized in approximately 4 years (as compared with over 100 years anaerobically), the landfill gas emissions are lower in green house gases (methane is avoided) as well as hazardous and malodourous gasses (ammonia and hydrogen sulphide are eliminated), and leachate is eliminated. Even converting a closed landfill that has been experiencing anaerobic degradation to an aerobic landfill bioreactor will have large advantages; the leachate that was being produced anaerobically will be internally treated to eliminate any potentially hazardous impacts to the receiving environment.

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[5] Erses, A.S., Onay, T.T. and Yenigun, O. 2008. Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. Bioresource Technology. 99(13): 5418-5426.

[6] Vitello, C. 2001. Aerobic degradation: increasing landfill efficiency. Solid Waste and Recycling. 6(1): 25-27.

[7] Borglin, S.E., Hazen, T.C., Oldenburg, C.M., and Zawislanski, P.T. 2012. Comparison of aerobic and anaerobic biotreatment of municipal solid waste. Journal of Air and Waste Management Association. 54(7): 815-822.

[8] Bilgili, M.S., Demir, A. and Ozkaya, B. 2007. Influence of recirculation on aerobic and anaerobic decomposition of solid wastes. Journal of Hazardous Materials. 143(1-2): 177-183.

Project 1: Determining the physical properties of the stored waste in the landfill

Determining the physical properties of the stored waste in the landfill was critical for determining both the well spacing as well as the air injection and gas extraction rates and pressures.

Experimental Procedures

The physical properties of the stored waste were estimated by taking 40 core samples at evenly distributed and random sampling locations throughout the landfill cells. Each core sample was then visually inspected to identify the variations in types of waste, moisture content of the waste and waste density. Variations in waste type, density and moisture content are used to determine the overall heterogeneity of the site as well as indicating depths that require the most aeration to achieve waste stabilization. Moisture content is also used to determine the ability of the air to pass through the stored waste mass; if leachate remains perched in areas, it indicates that the underlying waste may be too densely packed to allow air flow.

The University of Saskatchewan was asked to conduct soil permeability test between test wells on the site. This measure allows for the determination of optimal flow rates. The results also lead to the determination of the optimal well spacing in the landfill.

Results of Experimentation

Analysis of the core samples indicated the expected heterogeneity of the stored waste, as well as large variation in the degree of degradation of the various locations in the landfill. This result indicated that the landfill was operating in the expected manner with older waste being more degraded than the newer waste regions.

The core samples also indicated perched leachate zones (areas where there was standing water on top of stored waste layers). This was an indication of either uneven compaction in the landfill cells, or areas where the stored waste had consolidated, due to organic degradation, to a high density and low porosity waste mass (a common occurrence in landfills). These high density sections could impede the flow of air through the system, however core samples did not identify many of these areas and it was assumed that these would not be a problem.

The permeability test results from the University of Saskatchewan (Appendix A) showed a large amount of variability throughout the landfill both aerially and with depth. It was concluded that the permeability would be acceptable for air flow but there was a risk of permeability changes and the organic material is degraded.

Project Outcomes

Once the results from the core samples were extrapolated over the total landfill area it was expected that the high-density locations in the stored waste were minimal and the overall flow of air through the stored waste mass was achievable. The specific locations and depths of the high density lenses were also used to determine the depths of air injection within the landfill. Based on their locations it was determined that air injection depths of 5, 10 and 15 m could be used to avoid flow impedance from the high-density areas.

The landfill area also showed large variations in stored waste density throughout the total surface area of the landfill. The heterogeneity would allow for different optimal well spacing in many different areas of the landfill. The design team evaluated to the option of creating different zones with varied well spacing against the option of maintaining a consistent well spacing over the entire landfill area. The final decision was to maintain a constant well spacing using the most conservative flow path estimate of 14 m from injection to extraction wells. This would create inefficiencies in some of the lower density regions, but would lead to more efficient installation and operation of the site.

During gas production rate flow testing (Project 7) SALT operators were working on the landfill cell, setting gas extraction rates at the wells. This work involved disconnecting the gas extraction line at individual wells, installing a flow meter, and then reinstalling the gas extraction line. Each well is done individually while the gas extraction system is operating at the other wells in the area. SALT operators indicated that as gas extraction wells were disconnected, there was suction drawing air into the landfill cell. This suction was a result of the gas extraction system operating at the other wells. This inadvertent observation indicated that the estimations of sufficient porosity for air flow through the cells was correct at an even greater distance than expected between wells (20 m as opposed to the designed 14 m).

Project 2: Determining the Biological Methane Potential (BMP) of the stored waste.

The BMP is the maximum amount of methane that will be produced by the landfill. This value is an indirect measurement of the amount of organic waste stored in the landfill, which is used to determine the overall oxygen requirements of the site. This value is also used as the baseline for carbon offset generation in the province of Alberta. System design and operation can occur without the exact value, as the oxygen requirements and flow rates can be determined through experimental testing during system operation.

Experimental Procedures

Samples were taken from the core samples used for Project 1. These samples were sent to the University of Winnipeg to determine the BMP using standard analytical methods. The BMP test involves analysing the organic carbon content of the samples as well as the chemical oxygen demand (a test to determine the amount of oxygen required to oxidize all of the material in the sample), as well as moisture content and solid makeup (mass ratio of organic material to inorganic material). The sample is then placed in an anaerobic environment with seed bacteria (to increase the content of methanogens and decrease test times) and monitored daily to determine the amount of gas produced and the methane content of the produced gas. The test continues until the volume of gas produced decrease to a level that indicates at least 95 percent of the organic material is degraded (typically 60 to 100 days after the start of the test).

Results of Experimentation

Unfortunately due to material storage and handling concerns the samples were deemed non-viable for BMP analysis, so no analysis was completed and the experimental BMP value of the site remains unknown.

New sampling was planned, however the forest fire and resulting destruction of the equipment on site has further delayed this schedule.

Lessons learned

The analysis of samples for BMP is a long process requiring planning and specialized equipment. Many analytical facilities only have the infrastructure for a small number of samples at a time. The analytical equipment is regularly turned over for more analysis, however the timeline for each test is long and not necessarily constant. This, paired with the requirement to create a biological seed, means that there are many constraints on the analytical start time. Most labs require a lead time of approximately two months. This lead time and pre-scheduling with the labs needs to be taken into account to ensure sample viability.

SALT has learned that for the next BMP analysis, the labs need to be contacted and they will in turn contact SALT when the sampling process can commence. At that point, the samples will be taken and sent for analysis. This has added an extra step to the logistics of sampling and analysis that was not foreseen.

Project 3: Determining the bottom profile of the landfill.

Determining the actual bottom profile of old landfills is difficult since there is neither historical data from when the landfills were established, nor was there any excavation to create a smooth, flat bottom. Old landfills were typically constructed in existing landscape depressions using the existing surface soil profile.

The conventional method of determining the bottom profile of the landfill consists of drilling a series of wells through the waste at various locations within the cell. This method can be environmentally hazardous since the wells represent preferential flow pathways for leachate; the leachate can follow any well penetrations to the bottom of the landfill and escape the cells causing potential environmental impacts to the surrounding soil or the groundwater table.

This method is also inaccurate and costly due to the potentially variations in the bottom profile. Depending on well locations and numbers, large variations in the bottom profile may be missed and assumed to be flat. These errors can result in erroneous estimates of landfill profiles and therefore large over, or under, estimations of total landfill volume. Increasing the number of wells can refine the bottom profile, making it more accurate and more costly.

Seismic Profiling technology has been used successfully for years to determine subsurface profiles in many industries. This technology is based on the monitoring of seismic wave velocity profiles in the subsurface. Each homogenous layer of subsurface will result in a different velocity profile. The potential issue with using this technology in landfills is that the waste stored within a landfill is non-homogenous and there are concerns that the large heterogeneity of the landfilled waste may confound the results of the seismic wave velocity profiles.

Experimental Procedures

To determine the efficacy of the seismic bottom profiling process, conventional bottom profiling techniques were used to validate the results. For the conventional bottom profiling process, forty wells were drilled into the subsurface material below the stored waste.

The seismic reflection and refraction system included a high-resolution seismograph, high frequency geophones, an accelerated weight drop system, as well as surface and down well geophone strings.

Researchers at the University of Saskatchewan conducted this work.

Results of Experimentation

Results from the seismic reflection and refraction tests could best be described as disappointing. The heterogeneity of the stored waste resulted in erratic seismic wave velocity profiles. In typical application of this process, the seismic waves are expected to maintain a relatively constant velocity profile as the wave progress deeper into a homogenous layer of subsurface material. The large variations in materials within the landfill cause variations in the wave velocity profiles that the analytical algorithms cannot account for.

In the upper 13 m of the landfill the velocity profiles increased in a manner as expected (albeit with a very large degree of variability) with this type of analysis. This was attributed to the lower and more consistent density of the newer landfilled waste. The large variability was due to the heterogeneity of the waste. The velocity profiles below 13 m, were highly variable in terms of rate of increase, with some velocity profiles decreasing. These large changes in profiles were attributed to the large variations of density caused by organic material degradation, leachate ponding and the heterogeneity of the waste. Because of these variable (and sometimes decreasing) seismic velocity profiles in the waste, the processed model results could not be taken as accurate. The data could be curve fit, to match the determined depths of the conventional bottom profiling method, but no confidence could be found in the results.

Project Outcomes

After considerable analysis of the data from the landfill, which included discrete modeling and comparison with the results from the conventional bottom profiling methods, an inferred bottom profile was produced. Due to the heterogeneity of the waste, a large portion of the bottom profile determination was through curve fitting to the results of the conventional bottom profiling methods. Therefore the use of seismic reflection and refraction techniques for bottom profiling of landfills is not a cost saving option, nor does it simplify the process. Based on the above results it was evident that the seismic process could potentially help refine the bottom profile when using conventional methods without increasing the number of wells drilled. However, It is likely that the cost of the seismic process would be greater than the cost associated with drilling more wells. The bottom profile as estimated by the model was also not reliable and could not be stated with any great confidence.

A report of the finding as outlined by the University of Saskatchewan is located in Appendix A.

Project 4: Determining efficient method of well drilling.

Drilling in landfills in a long and costly process. This is mostly due to the conventional auger drilling technologies used at these sites. The augers present many disadvantages at a landfill site:

1. The heterogeneous material density in the landfill means that the augers must be set with a rotational velocity and downward force that is able to pass through the most dense material at all times. This protects the equipment from damage due to striking unexpected materials in the landfill. This also prolongs the drilling process through the low-density material resulting in major time losses.
2. There are large solids materials in landfills (especially older closed landfills) that the auger is not capable of boring through (metals, and construction debris). If the auger strikes one of these materials there is a risk of damaging the equipment. If a solid is found in the landfill the well must be abandoned and a new well needs to be drilled. This not only prolongs the drilling process, it also leaves and opening in the landfill that needs to be re-filled and properly capped to minimize fugitive gas emissions.
3. The auger transports drilling waste from within the landfill to the surface and leaves a pile of material that requires disposal.

The site required over 1800 wells to be drilled in a cost and time effective manner and therefore there was a need to find a more efficient method of well drilling.

SALT found a contractor in Alberta that utilizes a sonic drilling rig to drill into geological formations more rapidly than conventional auger drilling. This technology had never been employed at landfill sites; however the contractor was confident that there would be no issues.

Sonic drilling uses pressure, water injection and a drilling tip that vibrates at ultra-sonic frequencies to penetrate the drilling tip through small pores in the material through which it is boring. This pushed material away from the drill tip rather than bringing the material to the surface to be dealt with.

Experimental Procedures

Sonic drilling uses water injection, hydraulic pressure and a drilling tip that vibrates at ultra-sonic frequencies to penetrate the drilling tip through small pores in the material through which it is boring. Variations in vibration frequency and pressure change the ability for the equipment to bore through different materials.

The drilling contractor was charged with all experimentation, which included test wells with different pressures and vibration frequencies to determine an efficient setting for the entire site.

Results of Experimentation

It only took the contractor a few wells to determine the optimal working pressures and frequencies and any variation due to density changes or solids in the waste were dealt with quickly at any required locations.

No wells were abandoned due to contact with solids in the waste and there was no down time to fix the equipment due to striking solid materials. There was evidence that solid materials were contacted (during one coring event the drill tip was shown to pass through an engine block - there was a cross section of a piston located in the core). This would have caused a conventional auger rig to abandon the well, the sonic drilling rig slowed down as it contacted the metal, but operators quickly changed the frequency and pressure and the drill continued through the metal.

Project Outcomes

The sonic drill rig was shown to more efficiently drill for core samples and well as well installations at a landfill site. Where the auger drill would take more than an hour at each location, and wells might require abandoning if the drill strikes something solid; the sonic drill averaged 30 minutes for a 15m well, including movement and setup and never found a material it could not bore through.

Technology Development

The use of a sonic drilling process on the Fort McMurray landfill was a first in Canada and proved to have advantages over conventional processes. SALT and the drilling contractor were able to prove that the technology is viable for landfill sites and far superior to conventional auger drilling techniques.

Project 5: Create lineal flow vales.

Proper control of the injection rate of air and the extraction rate of landfill gas is critical to the optimal performance of the aerobic landfill bioreactor. The ability to rapidly and precisely change the flow rate will also increase the efficiency of operational staff. There are many commercially available valves that can be used to control flow rates based on the degree of valve opening (Figure 5). None of these valves have a truly linear relationship between flow rate and valve opening, even the PR ball valve has regions in the opening of the valve that don't meet ideal requirements.

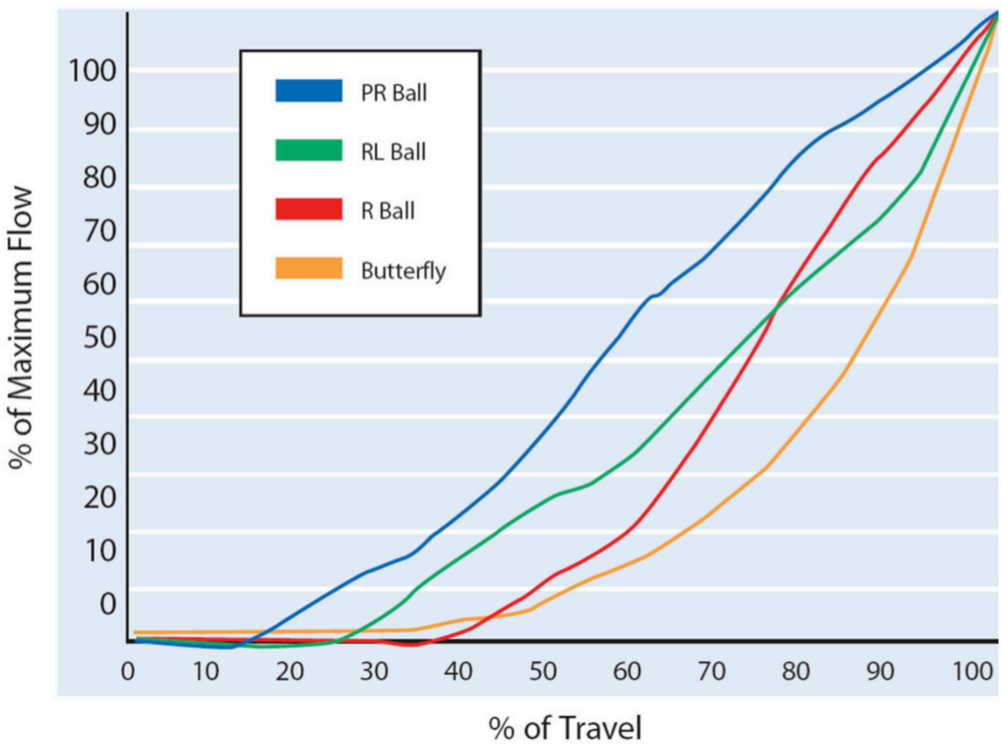


Figure 5 Flow rates as compared to valve opening from various valve types[9]

Experimental Procedures

SALT approached two separate landfill product suppliers to attempt to create a valve that was capable of maintaining a linear relationship between the valve opening and the flow rate through the valve. Both providers designed and created valves that they said would meet the needs of the site.

SALT personnel received prototypes of the valves and were involved in the testing to ensure that the valves maintained a linear flow relationship under all required flow conditions.

[9] Image courtesy of Teejet Technologies, Denmark

SALT personnel constructed a testing apparatus consisting of a pressure controlled flow valve attached to an air compressor and a flow meter. This valves were required to be capable of maintaining a linear flow rate at two different pressure to simulate both air injection and gas extraction. Both valves were tested in both a pressurized setup (injection flow) and backwards in a vacuum setup (extraction flow).

Results of Experimentation

Both valves were capable of achieving a linear relationship between valve opening and flow rate under pressurized conditions at both injection and extraction pressures.

The major difference in the valves came under vacuum conditions. One supplier's valves were incapable of maintaining the required linear relationship, while the others did.

The two differences between the pressure and vacuum setup are the pressures and the direction of flow. Both suppliers provided a variation on a standard needle valve, a valve setup with a needle that seats into a conical receiver when closed. The opening is therefore smaller than the diameter of the pipe and depending on the layout of the back of the valve there can be friction losses due to turbulence as the flow expands from the small needle opening to the complete pipe volume. The design flaw in this plan is that when the valve are used in reverse there can be more friction as the flow is rapidly reduced from the total volume of the pipe to the small needle opening. It was apparent that the supplier whose valve worked in both layouts had done something different to minimize the friction loss, thereby relying on the valve body to control the flow without the additional friction losses.

Project Outcomes

This project resulted in the development of a new type of valve that is able to maintain a linear relationship between extent of valve opening and flow rate under both air injection and gas extraction pressures and flow directions. This new valve will greatly increase the efficiency of changing flow rates at individual wells since an operator can merely adjust the valve to the desired flow rate based on the extent of valve opening. There is no need to install a flow meter each time the valves are being adjusted.

Technology Development

SALT tested and assisted in the development of well valves to enable lineal adjustments. These valves enabled the precise adjustment of air injection to control the oxygen environment within each 20 metre grid sections, thereby creating precise control over each 20 metre landfill section. This is important, as landfills are not homogeneous and therefore comprised of different constituent elements requiring various levels of oxygen to propagate the aerobic process safely.

This valve has since become a cornerstone of the landfill providers landfill gas extraction catalogue.

Project 6: Testing System Operation.

The process and control equipment was a designed to allow control of the air injection system, gas extraction system and landfill gas flare from a single console that can be connected to a remote device for monitoring and control. The system also had to be built with all of the proper controls for safety and compliance with all applicable Canadian codes. There was a large volume of sensors, equipment and controls that were not directly responsible for the operation of the aerobic landfill bioreactor but were necessary to meet code requirements. After the system and enclosure were delivered and installed on site, all components of the system needed to be tested. The system was fully installed and commissioned in May of 2014, but the testing continued through the winter of 2015. The long testing time was due to the large number of environmental controls that needed external environmental stresses (low temperatures, high winds) to identify proper function or issues.

Experimental Procedures

The first step of the process was commissioning all components. This involved starting each component individually and manually causing faults to ensure that all safeguards were in place.

The second step was to test the effects of the auxiliary equipment (flare, compressor, safety equipment) failing. Each piece of auxiliary equipment was manually stopped to ensure that this would result in system shutdown, properly and safely.

Third, all of the analytical equipment was calibrated and verified using external manual analyzers.

Results of Experimentation

The experimentation and commissioning demonstrated many minor issues with the control system logic (typical of new equipment builds). All of these minor issues were easily and quickly corrected resulting in a complete system that operated within the design parameters and exceeded all safety code requirements.

The gas extraction system was capable of drawing the required flow rates of landfill gas from the landfill and delivering it to the flare.

The air injection system is capable of producing the required volume of air at the required pressures.

The flare system is working within specification and with all the required safety features.

Project 7: Testing Flue gas composition.

The final testing project was the production rate and composition of the landfill gas. All design work for the system was based on the original LANDGEM modelling of the landfill site. BMP testing (Project 2) was to be used to verify some component of the computer model, but as noted above this was unable to be conducted. The gas extraction system can be used to determine the actual landfill gas generation rates to verify the model results.

Experimental Procedures

There has been active methane production in the stored waste since the landfill was capped and therefore there was landfill gas built up and stored within the pores paces of the landfill. Prior to testing, this gas needed to be removed. This was accomplished by using the landfill gas collection system and no flow control system to draw as much landfill gas from the site as possible. This process started by providing over 1000 CFM of landfill gas containing approximately 50% methane. This flow and concentrations decreased over 30 days.

After the pore spaces were cleared of methane the system was consistently removing approximately 800 CFM of gas from the landfill with approximately 20% methane. This corresponded well with the model estimation of the landfill gas production rates. Which demonstrated that the expected methane production from the model was a good design basis.

Results of Experimentation

Based on the results of the flue gas composition test, the model results were assumed to be valid and the system should be able to produce the expect reduction in methane emissions and therefore the expected amount of carbon offset credits.

Other project Goals

The remaining project goals required no experimentation as they were designed as learning through the construction and design process, as well as the education of operators. As such, this section will focus on outcomes from the design process and lessons learned throughout the construction process.

Technology development

SALT installed over 3000 sensors and connections and tested these to record and ensure an accurate measurement of carbon dioxide, methane, oxygen, and hydrogen sulphide along with moisture and temperature within the waste mass. This is a world's first on that scale of operation and designed to control the reaction of the anaerobic and aerobic processes.

SALT installed 12 surface data collection towers that continuously monitored temperature on specific areas of the landfill and the data was transferred wirelessly to the central computer device and uploaded to third party recording software to enable visual and numeric analysis of landfill conditions, along with remote access to real time data.

Project outcomes

Overall, the development of the construction process was entirely beneficial. The process routines were established and refined. Specific techniques and equipment development appropriate to the installation of the aerobic system were successfully tested and approved.

The construction timeframe took much too long due to unforeseen factors. Weather conditions in Fort McMurray were considerably worse than anticipated and caused long breaks in the construction process. The well drilling utilized moisture and could not continue during cold weather. Frozen surfaces and snow cover impeded installation of large HDPE headers. Temperatures that often reached minus 40 C and below made installation of valves extremely difficult.

Certain factors were entirely unforeseen. Two examples would be the delivery of electrical power to the site and certification of specific devices. The electrical power source originated on the east side of highway 63, while the landfill is on the west side. In order to secure power the electrical utility was required to drill and place a conduit under highway 63. To obtain a permit, the utility was required make a request to the province. Permission took several months and after permission was obtained, the utility was overwhelmed with other work orders and took additional time to complete the work. Similarly, some aspects of the installation required inspection and certification by qualified industry personnel. These personnel often times required months of advance notice before completing the inspections. Last but not least, one of the financial considerations by Fort McMurray was the generation of carbon offsets through an Alberta Environment protocol. Although the project had a protocol at the onset of construction, it expired in 2013 and it took the province 3 ½ years to renew the protocol.

The training and development of personnel to construct and operate an aerobic landfill bioreactor was partially successful. We engaged and developed 8 individuals that gained the experience of aerobic theory, construction experience and specific elements of the unique nature of aerobic processes. It was considered as completely successful until May of 2016 when the site burned to the ground and we were forced into laying off some of the staff due to no available work. We fear that some of those laid off may not be available again on a re-start of the construction.

Costs of the far northern construction were considerably higher than anticipated. Costs amounted to $ 12,000,000 for a 1,300,000 tonne site. This translates to about $ 9.25 per tonne. These costs were impacted by many elements:

1. High costs of living in Fort McMurray, resulting in very high wages.

2. Remoteness and the cost of transport to Fort McMurray.
3. High cost of oil at the time of purchase of HDPE pipe, resulting in high cost of plastic elements.
4. Delays in construction due to weather conditions.

Lessons learned

Because of the experience obtained, we have identified specific suppliers that are also now experienced at the construction process and are more efficient. We have experienced personnel that can operate effectively. We expect and can accommodate the inclement weather factors.

We now are familiar with the various regulatory agencies and the issues that can affect performance timing and account for these potential delays in the build cycle.

Green House Gas & Non GHG Impacts

Based on the initial LANDGEM model results, it was expected that converting the landfill to an aerobic landfill bioreactor would result in avoiding 65 000-72 000 tonnes of methane release to the atmosphere. Methane is a more potent greenhouse gas than carbon dioxide (25 times); this would amount to 1.6-1.8 $MTCO_2eq$ (million tonnes of carbon dioxide equivalence).

It is expected that the degradation of organic matter will maintain a pseudo-steady state with a constant degradation rate and therefore a constant rate of methane avoidance. This project was expected to avoid 500 000 TCO_2eq annually. This is difficult to compare directly to the emissions from a conventional landfill due to the variation in degradation rates leading to a longer process life in convention landfill system. The avoided methane in the four-year process at the aerobic landfill bioreactor will actually be stopping low volumes of methane seeping from the landfill for over 100 years (It is generally accepted that methane production at closed landfill decreases by 50% every 15 years).

Other major advantages of aerobic landfill bioreactors are the eliminations of odours from the landfill site. Ammonia and hydrogen sulphide are the main culprits in landfill gas odours and the aerobic landfill bioreactor has been show to not produce these by-products, and furthermore will eliminate any of these by-products that are stored in the landfill prior to conversion to aerobic conditions.

The leachate generated at conventional landfills in another major liability. As long as the leachate is contained there is no concerns, but the release of leachate can have detrimental effects on the receiving environment. Many sites decide to pump the leachate out of the landfill to allow for treatment to ensure there is no concern, but this comes with an added operational cost. It has been shown that the aerobic landfill bioreactor can be operated in such a manner that there is no leachate formation, thereby eliminating the associated risks. The aerobic processes in the aerobic landfill bioreactor can also treat any leachate that has been produced; further minimizing the risk that leachate poses to the receiving environment.

After application of the aerobic landfill bioreactor the waste will have consolidated due to aerobic degradation of the organic material, there will be no odour, a stabilized waste mass and no leachate. This site can then be re-opened to receive more waste if it is required by the landfill operator. A better option would be to mine the landfill to recover any material that was disposed of that could be recycled. The landfill could then be recovered as useable land (eliminating the post-closure monitoring requirements and insurance costs) or re-designed as a new landfill. Both of these reuse options represent potential additional tax revenue for the municipality.

Overall Conclusions

The expected conclusion that the aerobic landfill bioreactor was capable of degrading the organic material in a landfill in approximately 4 years, avoiding methane, not producing leachate and producing carbon offset credits in Alberta was unfortunately not able to be tested. The May 2016 Wildfire in Fort McMurray destroyed the site prior to the system starting to turn the landfill to aerobic conditions (expected to start June 2016).

There were many findings over the course of the project and lessons learned that would go a long way towards facilitating future designs and construction of aerobic landfill bioreactors.

The work that was done on the site demonstrated that ultra sonic drilling is not only feasible on a landfill, it is far more efficient (in terms of time and ease) than conventional auger drilling.

The project led to the development of a new style of flow control valve that provides a linear relationship between extent of valve opening and flow rate.

Other testing was conducted on the landfill site to determine if new and more efficient techniques could be applied to determine the bottom profile of the landfill. It was determined that seismic reflection and refraction was not a viable technique in landfills. There is still opportunity for the testing of resistivity sounding, but this will require a fresh site.

Scientific Achievements

While there have been no patents issued as a consequence of the aerobic landfill bioreactor project, there are a number of areas that are under consideration by SALT for potential patent development. These include a patent that might eliminate the need for injection blowers, another for a device that can properly measure moisture content within a landfill, and a change to the precision valves that can control the air flow.

SALT Canada Inc. participated in many workshops and well attended venues throughout Canada, with a booth and making many presentations. These included national conferences of Canadian Municipalities on several occasions from PEI to Ontario. Many separate SWANA meetings throughout Canada and the USA, including British Columbia, Alberta, Saskatchewan, Manitoba Ontario, New Brunswick, PEI, and such states as Pennsylvania, Florida, South Carolina, Alabama, Utah, Tennessee, Kentucky, California, North Carolina, New Jersey.

SALT Canada engaged the University of Saskatchewan on two separate occasions to conduct studies on behalf of SALT / Wood Buffalo. The result was that Ian Fleming PhD PEng produced reports on the aerobic approach and recommended certain changes in the landfill assessment process.

SALT Canada also engaged with the University of Western Ontario to do several studies for RMWB and SALT. The staff included professors Ernest Yanful, Amarjeet Bassi, and Sohrab Rahani. Added to this were seven post-graduate students that participated in the various program elements. These included unique approaches to leachate treatment including the transfer to development of algae for additional purpose, development of a functional landfill simulator to conduct tests of hypothesis, and development of computer models. To date one paper has been published, one paper had been submitted for publication, one paper is in progress, and more are expected:

1. Omar, H., and Ronahi, S. (2015). Treatment of Landfill Waste, Leachate and Landfill Gas: A Review. Frontiers of Chemical Science and Engineering. 9(1): 15-32
2. Omar, H., Alizadeh, A., Salman, M., A. Paintsil, A., Yanful, E., Rohani, S. (in progress). Start-up of a large scale aerobic landfill bioreactor: The Regional Municipality of Wood Buffalo aerobic landfill project.
3. Omar H., and Rohani, S. (Submitted). The mathematical model of the conversion of a landfill operation from anaerobic to aerobic. Applied Mathematical Modelling.

At the University of Western Ontario, SALT interfaced with the head of micro-biology, Irena Creed. Irena is head of the Great Lakes Water Commission, participates as the Canadian representative on ocean pollution, is the National Research Council head of Groundwater matters, and is president of the Africa Commission. Irena is convinced that the aerobic approach is the key to solving groundwater contamination created by landfill sites. This would be particularly true in places like Africa where surface water is drying up and groundwater resources are being contaminated by indiscriminate landfill practices.

SALT was at the stage of engaging Irena to conduct micro-biological studies on the effects of cold weather on the propagation of aerobic bacteria when the wild fire eliminated the possibility.

Effects of the Fort McMurray Wild Fire

On May 3rd 2016, wild fire raced through Fort McMurray causing the evacuation of the entire community of over 100,000 individuals. Through the valiant efforts of the Fire Department of Fort McMurray, supplemented by heroic efforts of dedicated resources of the Province of Alberta and other Canadian volunteers, complete disaster was averted.

Some neighbourhoods, particularly in the south west, were destroyed by the intensity of the fire. Many of the key infrastructure elements of Fort McMurray were saved including water and wastewater treatment, airport, McDonald Island, downtown Fort McMurray, the operational landfill and new landfill office. Unfortunately, the fire raced toward the aerobic landfill site fuelled by the forest surrounding the site and finally set the plastic (HDPE) header pipes on fire as temperatures are estimated to be as high as 1,000 degrees F. The fire simply swept towards the major equipment enclosures and consumed everything within the structures. This included all construction and operations manuals, computer monitoring devices, mainframe computer, communications devices, generators, four 250 HP air injection blowers, two landfill gas extraction blowers, moisture injection devices, gas analyzing equipment, moisture condensers in addition to a variety of pumps, electrical, and mechanical devices, too numerous to list. In addition, the gas flare system designed to ignite and destroy any methane detected upon landfill gas extraction was fatally damaged. On the surface, the main header system was materially damaged and large parts destroyed along with the leader lines to the wells and the precision valves designed to control air flow. In addition, some 250 wells were totally destroyed and others severely damaged.

The site has three landfill cells with the largest and most recently used being in the north west section. This cell was the most damaged and some of the fill material within the landfill caught fire. SALT personnel were dispatched in an emergency role to seal the open wells leaking methane into the atmosphere and Municipal staff assisted in extinguishing the fire on the landfill cell.

We estimate that the damage to the site to be in excess of $ 10 Million, and including operation and final closure, to be approaching $ 12 Million. Indeed it was a very unfortunate and sad experience for a project that had the potential to alter methane and carbon equivalent values for Alberta by substantial amounts.

Photos of the site prior to and after the Wildfire are available in Appendix B.

Next Steps

Because of the destruction of the initial aerobic site by the wild fire, it is the goal of SALT and RMWB to reconstruct that project and deliver the elimination of 48,000 tonnes of methane or 1.2 $MTCO_2eq$.

A silver lining to SALT from the wild fire destruction relates to the reality of the current operating landfill site filling much faster than originally anticipated. Current expectations indicate that the site will fill in late 2017 or early 2018. Wood Buffalo has indicated a desire to transform the current operating site to an aerobic landfill bioreactor. Making Fort McMurray both the first and second large scale operational locations. The second location is larger (1.8 Million tonnes) and has fresh material generating much more methane. This location is estimated to generate some 148,000 tonnes of methane or 3.7 $MTCO_2eq$.

As indicated above, SALT has visited many locations throughout Alberta and other places in Canada and elsewhere. The consensus is that a majority of the Alberta locations will adopt an aerobic approach as soon as the Fort McMurray location is able to publish results consistent with the expectations expressed by RMWB and SALT.

Elsewhere throughout Canada and internationally, the reaction to efforts to expand the technology use has been the same. Provide positive results that are evidenced by competent third party experts and the municipalities and regions will subscribe to a successful technology that offers up so many positive aspects.

In Canada, Conestoga Rovers and Associates have indicated that the largest financial benefit associated with the SALT approach is the ability to rapidly stabilize a landfill and subsequently excavate the site thereby eliminating post closure costs and insurance liabilities, and providing valuable land resources to generate municipal taxes.

Conestoga Rovers and Associates has identified several sites that they feel are obvious targets for the technology, as soon as the results are verified and made public.

Communication Plan

The RMWB had hosted several open houses prior to the May 3rd fire. This included public tours of the site, and several tours by interested Alberta Environment and Parks officials seeking education (not required inspections). In addition, inspections and tours were conducted for national and international engineering agencies from as far away as Australia, Indonesia, India, and various places in the United States. Within Canada, Conestoga Rovers and Associates, the largest environmental firm within Canada, indicated strong desire to adopt the aerobic technique and indicating that the process represents the single largest change in landfill practices within the last 100 years.

The Regional Municipality of Wood Buffalo also prepared and distributed a pamphlet describing the technology and advocating the advantages of it's adoption within the landfill community (Appendix C).

Within Alberta, SALT Canada travelled to Edmonton, Red Deer, Calgary, Leduc, Lethbridge, Ryley, Morinville, Wetaskiwin, Drumheller, Medicine Hat, Pincher Creek, Canmore, High River, and Stettler to name some. In all of these cases, SALT personnel distributed pamphlets, toured landfill sites, made presentations to community groups and landfill personnel, promoting the adoption of an aerobic approach.

Leon Green, of SALT, travelled extensively throughout Europe and the middle east promoting the aerobic approach and creating a carbon credit protocol for the United Nations. John Baxter, President of SALT, travelled to Mexico and South America making presentations.

In 2014, Business Elite Canada Magazine published an article outlining the project and the prospect of the RMWB becoming carbon neutral (Appendix C).

Appendix A. University of Saskatchewan Report

UNIVERSITY OF SASKATCHEWAN

July 17, 2013

MR John Baxter
SALT Inc.
58 Milan Place
London, Ont. N5Z 5A2

Status Report: NRC IRAP Project 796991 for SALT Canada and the Regional Municipality of Wood Buffalo – Aerobic Bioreactor Landfill Project

This brief report is intended to summarize the progress and status of this project as of today's date. A Final Report will be issued by August 15, 2013

Task 1. Geophysics to profile the bottom of the landfill

Objective: elevation contour of contact between waste and native ground.

Benefit: Confirm the depth of waste and volume of waste fill.

Method: seismic reflection / refraction and resistivity soundings to determine the best method for profiling the waste/native sand interface at this particular site.

Completed:

- high resolution seismic profiling with various sources and instrumentation
- extensive analysis and modelling of data

Pending:

- Resistivity soundings were originally scheduled for May, however the very late spring, followed by flooding and wet weather during June has repeatedly forced rescheduling. This work will be completed as soon as practically possible.

Results to date:
Seismic efforts at the site has yielded results that are disappointing in terms of reliably profiling the landfill base. In part, this appears to reflect the greater than expected heterogeneity of the material. Based on the data, after considerable analysis, it has been possible to generate an inferred profile of the base of the waste, however this profile is not provided with any significant degree of confidence. Figure 1 presents velocities inferred from the raw data which were used to generate the profile.

Department of Civil & Geological Engineering, University of Saskatchewan
57Campus Drive, Saskatoon SK S7N 5A9 Canada Telephone: (306) 966-5341 Facsimile: (306) 966-5427

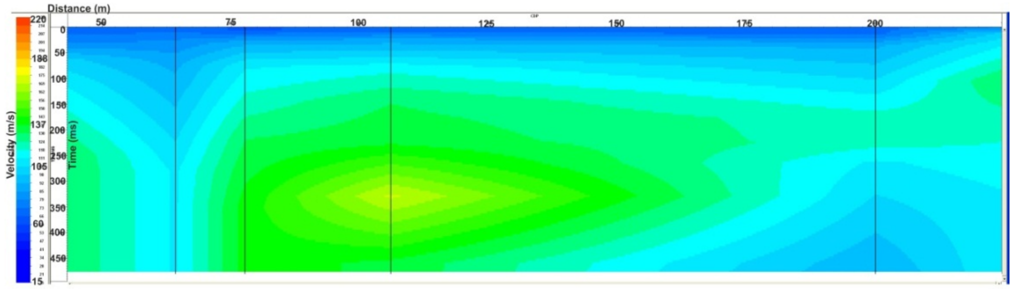


Figure 1: Stacking velocity model for the seismic reflection line.

By using this velocity model, the image presented as Figure 22 can be understood as a cross-section of the subsurface, with amplitudes (red peaks and troughs) representing the relative strengths of reflectors. We used three check wells (MW17, MW15 and MW03) to identify the bottom of the landfill. Based on this image, the landfill bottom varies from 11.5 m to 20 m within the area of study.

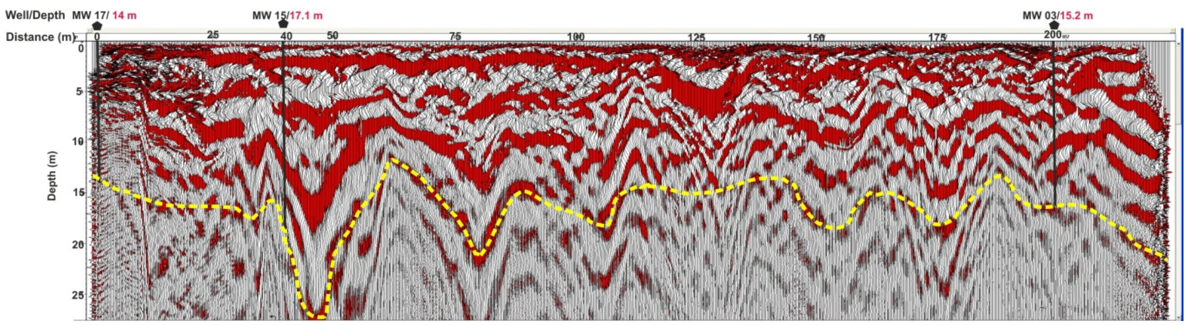


Figure 2: Interpreted depth image along the profile. Check wells are shown by black and the bottom of landfill shown in dashed yellow lines. Red labels indicate the depths to the base of waste from well data.

There are a number of conditions that have contributed to this finding. In particular, it appears that a zone of relative low velocities may be present in the lower part of the landfill along the midpoint of the profile. The following two figures summarize in 2 dimensions the variability of seismic wave velocity within the subsurface. It is evident that the significant variability, (along with the presence of randomly-located reflectors of scale similar to the geophone spacing) has yielded an inferred profile that is not likely to be reliable

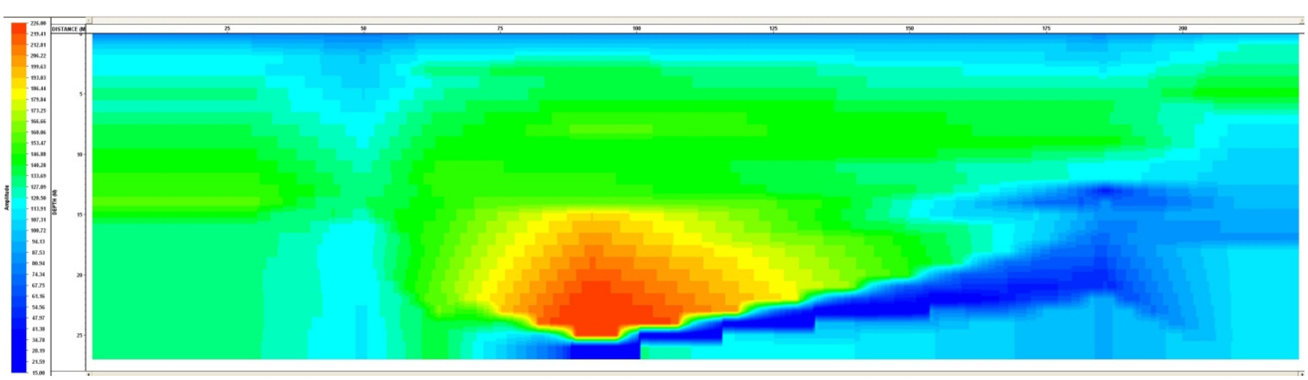


Figure 3: Interpreted seismic velocity of subsurface materials

These findings can be shown by plotting the vertical distribution of seismic velocity at various locations as shown in Figure 4. It is evident that the upper 13 metres exhibit a consistent (although somewhat variable) pattern of velocity increase with depth, as expected based on our work and that of other researchers at various other landfill sites. It is equally evident that the material response below about 13 metres is extremely variable and that accordingly, the processed model profile of Figure 2 is not considered to be particularly accurate.

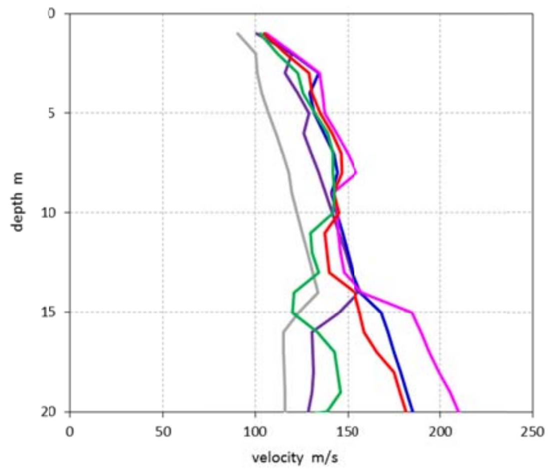


Figure 4: Velocity profiles with depth at various locations

Future work:

- Resistivity holds promise as an alternative technique, however it requires both unfrozen ground and cooperative weather conditions, which have not been yet coincided with availability of personnel.

Task 2. Measurements and monitoring during drilling and installation of air injection wells

Objective: Variation of air permeability at the site, spatially and with depth.

Benefit: Optimize the layout and spacing of air-injection wells.

Method: permeability characteristics of waste were determined insitu through pumping and injection tests in screened gas / air-injection wells post completion.

Completed:

- flow-response tests of wellhead pressure and gas flow rate at various flows and for various well clusters
- analysis of results to yield air permeability for 10 different locations within the waste fill
- analysis and modelling of data for comparison with other similar data

Results to date:

Well response tests were carried out to determine the variability of the waste fill both spatially and with depth. Figure 5 presents wellhead pressure vs flow data for a number of tests. It is evident that for a particular flow rate, the required wellhead vacuum is significantly higher for the deeper wells. This has significant practical implications for operation of the aerobic bioreactor.

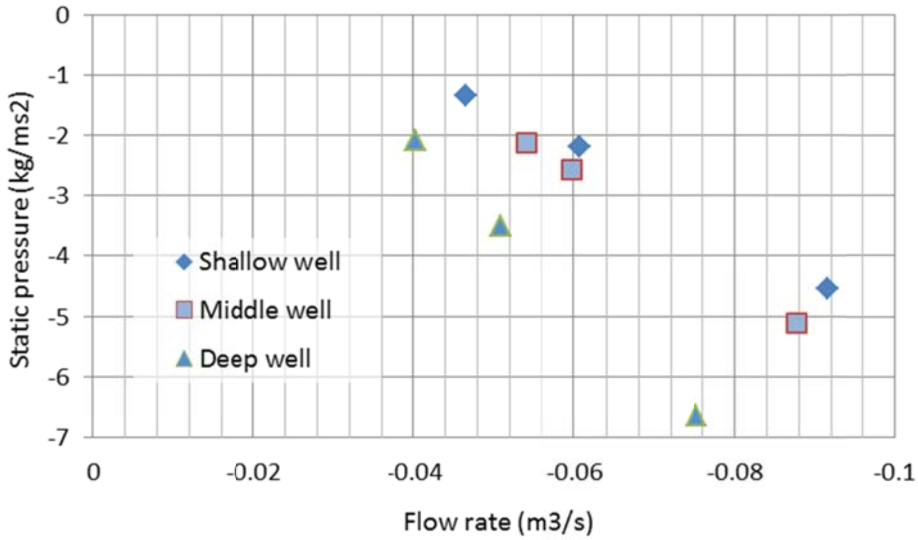


Figure 5: Flow rates and wellhead pressures during testing

The test results were analyzed to determine the air permeability, assuming anisotropy $k_X/k_Z \leq 10$. It is evident that the permeability of the waste fill at the Wood Buffalo site does vary with depth, and the variation is consistently approximately half an order of magnitude between the uppermost and lowermost well screens. Significantly, there is as much, or more spatial variation in the measured permeability – this implies that significant efforts in monitoring and control will be required during operation of the air injection system at full scale.

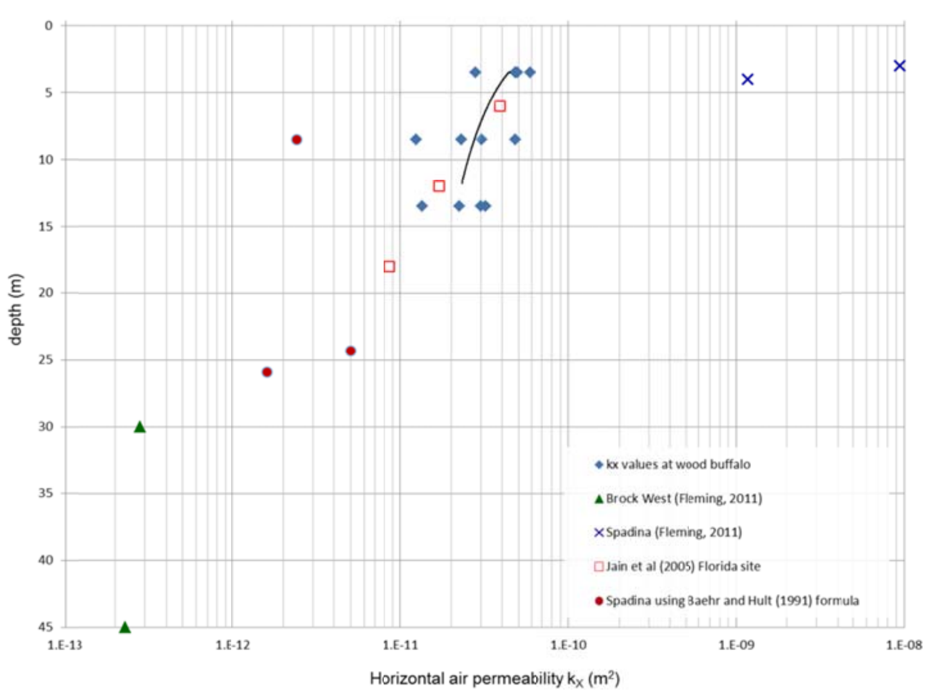


Figure 6: Air permeability measured at the Wood Buffalo site, compared with measured permeability from other landfills from published and unpublished data.

These results are generally encouraging, insofar as they clearly show that the waste fill at the Wood Buffalo site exhibits properties that are not dissimilar to those measured at other sites and should thus respond similarly. It must be emphasized, however, that the Wood Buffalo site does appear to exhibit significant heterogeneity in terms of both its seismic response and its permeability. During operation of the aerobic bioreactor, degradation-induced settlement will likely result in significant permeability changes over time, and the importance of a rigorous and thorough monitoring programme cannot therefore be overemphasized.

I.R. Fleming, Ph.D., P.Eng.

Appendix B. Site photos before and after the wildfire

Site Photos - Prior to Wild Fire

Equipment Enclosures that contain all Air Injection / Gas Extraction Equipment and Flare System

Header Piping – Air Injection and Gas Extraction Headers

Well Cluster – three of the 1800 gas extraction and air injection wells

After Wild Fire

Equipment Enclosure Fire Damage

Internal Equipment Enclosure Fire Damage

Header Fire Damage

Wells Destroyed by Fire

Well Destroyed by Fire

Appendix C. Communication information

Pamphlet

Regional Municipality of Wood Buffalo

The region's landfill gas management project

— leading the way throughout North America

When the Regional Municipality of Wood Buffalo's old landfill closed in 2012, the Municipality saw an opportunity to underline its environmental leadership and commitment by reducing its carbon footprint.

Without any regulatory or environmental obligation, the Municipality chose a state-of-the-art aerobic bioreactor landfill gas system to stabilize the old landfill. This decomposes organic material to make the site sufficiently stable so it can be redeveloped for other uses.

This advanced technology allows the Municipality to lead the way in landfill carbon reduction in North America and showcase 'best practice' landfill gas management throughout North America's solid waste management industry.

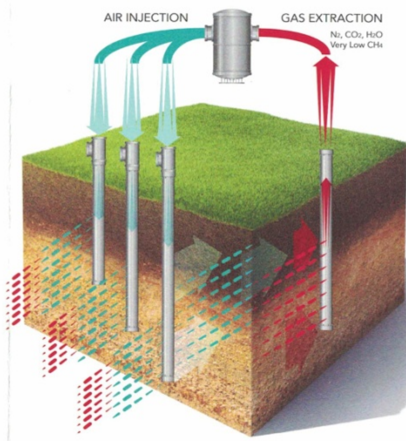
The Wood Buffalo project is the first full-scale aerobic bioreactor project in North America.

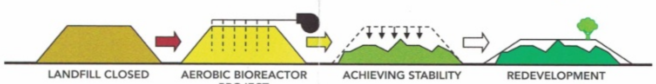
The Wood Buffalo project is one of the largest landfill gas management and carbon reduction projects in the world.

The project is expected to reduce emissions by as much as 1.8 million tonnes of carbon equivalence in about five years.

The AEROBIC BIOREACTOR PROJECT — supporting Wood Buffalo's vision

The Regional Municipality of Wood Buffalo's aerobic bioreactor landfill gas project is part of the Municipality's greenhouse gas reduction program, in place to significantly offset the amount of carbon produced through municipal operations. These include snow removal, park maintenance, building heating, electricity consumption, water production and landfill operations. Through this initiative the municipality is striving to become a national leader in carbon reduction and environmental stewardship.





Reducing landfill gas with 21st century technology

The Regional Municipality of Wood Buffalo's new, state-of-the-art regional landfill officially began operation in 2012. The RMWB followed several steps to officially close the old site and introduce the aerobic bioreactor landfill gas project.

1: **(2012 – 2014)** After a closure plan was developed and the waste operations were transferred to the new regional landfill, the old landfill was graded and the side slopes capped to prevent the release of gas from the landfill and promote surface water drainage. The aerobic bioreactor was constructed on the surface of the landfill.

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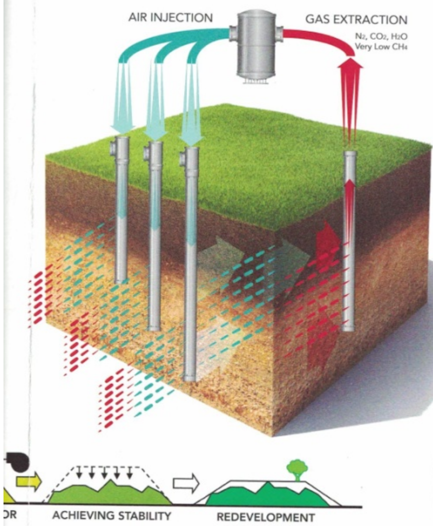

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2: **(2014 – 2018)** The landfill gas system began operation to collect existing landfill gas and eliminate the production of further methane. The gas management system:

- will eliminate about 90% of methane (CH_4), a major greenhouse gas contributor to global warming. Each tonne of methane is the equivalent of 25 tonnes of carbon dioxide (CO_2), this eliminates the equivalent of up to 1.8 million tonnes of CO_2,
- is designed to capture and destroy any existing methane,
- will significantly lessen methane formation and will treat the existing leachate, and
- rapidly degrades all organic waste materials.

3: **(2018 – 2020)** Once the landfill gas project is complete, the old landfill will either be immediately "mined," a process to remove all recyclable material and screen the organic material before the site can be redeveloped, or the top of the site will be capped so landfill mining can take place later.

4: **(2018)** The landfill gas system will be moved to the regional landfill to treat an additional 700,000 to one million tonnes of waste. The aerobic bioreactor is designed to allow most of the hardware to be moved, reducing project cost.

This second phase of the aerobic bioreactor project will offset an additional one to two million tonnes of CO_2 equivalent.

Understanding the science behind methane gas reduction

In a nutshell, aerobic landfill technology speeds up the process of composting organic waste by controlled injection of air and managing the existing moisture content in the landfill. The addition of oxygen significantly reduces the formation of methane gas.

To enable the injection of compressed air into the landfill, about 900 wells have been installed in three closed sections of the landfill. Injection of air promotes the growth of aerobic bacteria, needed to break down the organic material.

An additional 900 wells in the same sections of the landfill will collect the gases (nitrogen, carbon dioxide and methane) formed when the organic material is decomposing and send them to a flare stack.

Maintaining optimal composting conditions by managing the balance between organic material, moisture and leachate levels will greatly speed up the breakdown of the organic component of the landfill.

Moving from anaerobic to aerobic landfill management

The closed landfill is currently in an anaerobic state, reflecting technology available at the time it was developed. Anaerobic landfills produce methane gas when organic material is decomposing.

The oxygen injected into the landfill as part of the aerobic bioreactor landfill gas project kills the anaerobic bacteria. Aerobic bacteria quickly and naturally take the place of the anaerobic bacteria and produce no methane while transforming the organic material into a compost-like material.

The aerobic bioreactor stage is expected to stabilize the old landfill within five years. Traditional landfill stabilization requires 60 to 100 years.

Aerobic bioreactor technology — protecting our environment

The Municipality has worked closely with the Alberta government and other regulatory bodies to ensure closing the old landfill and establishing the aerobic bioreactor landfill gas project meets or exceeds all environmental requirements.

As part of this work, the Municipality has put in place a number of monitoring systems and procedures to offer ongoing environmental safeguards. These include:

- installation of an extensive groundwater monitoring well network and monitoring program,
- installation of the most advanced landfill gas monitoring system available,
- regular monitoring of leachate levels,
- temperature monitoring of the landfill gas extraction wells,
- annual sampling of the landfill waste, and
- annual waste analysis to monitor the effectiveness of the aerobic process.

Interestingly, Wood Buffalo's northern climate makes the efficient application of this 21st century aerobic bioreactor technology possible. In warmer regions, aerobic bioreactor projects need cooling equipment to manage the core temperature of the landfill cells. In Wood Buffalo, the relatively cold climate allows the outdoor air to be used for system cooling — saving the electricity needed for cooling equipment and further reducing the environmental footprint.

REGIONAL MUNICIPALITY OF WOOD BUFFALO'S

AEROBIC BIOREACTOR

LANDFILL GAS MANAGEMENT PROJECT

Protecting our environment through vision, leadership and cutting-edge technology.

The initiative will:

- CONTRIBUTE SIGNIFICANTLY IN MAKING THE MUNICIPALITY CARBON NEUTRAL,
- RAPIDLY DEGRADE ORGANIC WASTE TO PREVENT METHANE GAS FROM FORMING,
- REDUCE THE RISK OF LONG-TERM NEGATIVE ENVIRONMENTAL IMPACT ON GROUNDWATER,
- STABILIZE THE LANDFILL WITHIN FIVE YEARS COMPARED WITH THE TRADITIONAL PERIOD OF UP TO 100 YEARS,
- ACHIEVE SIGNIFICANT LONG-TERM COST SAVINGS FOR WOOD BUFFALO RESIDENTS, AND
- ASSIST IN ESTABLISHING THE MUNICIPALITY AS THE FIRST CARBON NEUTRAL MUNICIPALITY IN CANADA AND A GLOBAL LEADER IN CARBON REDUCTION.

woodbuffalo.ab.ca

Regional Municipality of Wood Buffalo

Article from Business Elite Magazine, October 2014

SALT Inc: Helping the Regional Municipality of Wood Buffalo (RMWB) become a Carbon-Neutral Municipality

By Cheryl Long

A landfill site is often considered a necessary evil, particularly to residents who live within breathing distance of the odour-emitting facility. Now imagine an alternative that gives off little to no odours, emits no greenhouse gases into the environment, prevents groundwater contamination and can transform a landfill into reusable resource within a short period of time. It's an alternative that's poised to change the way the world deals with waste disposal.

Sustainable Aerobic Landfill Technologies (SALT) Inc. is based in London, Ontario and uses what seems like simple technology to tackle a worldwide problem – growing populations that produce more waste than the globe will eventually be able to handle. Traditional landfills are anaerobic, or oxygen-deprived, and pose environmental risks through greenhouse gas emissions, odour production and leachate – a resulting landfill liquid that can contaminate groundwater. The mountainous sites can take centuries to decompose their organic materials. SALT uses compressed air and moisture to remediate and recover landfill space by transforming the site from an anaerobic to aerobic state, creating a healthy environment where bacteria rapidly break down the waste organics.

"Aerobic bacteria produce zero methane and degrade organic material 30 to 35 times faster than under anaerobic conditions," said SALT President and CEO John Baxter. "That means a landfill site that would normally take over 100 years to fully degrade, can be done in three to four. There are significant advantages."

SALT began developing their landfill technology about 15 years ago, motivated by the realization that current municipal waste disposal methods were ineffective and harmful to the environment. Canada is home to the company's first full-scale endeavour. In 2008, the Regional Municipality of Wood Buffalo selected SALT Inc.'s aerobic bioreactor technology as the long-term landfill gas management plan for the Fort McMurray Landfill. The Regional

Municipality of Wood Buffalo was seeking a viable technology to significantly reduce the environmental footprint of that facility while reducing the quantity of methane emitted annually. SALT Inc.'s technology will help achieve the goal of the municipality and will assist with establishing the Regional Municipality of Wood Buffalo as a national and global leader in carbon reduction action.

"In the case of Fort McMurray, we are going to reduce carbon emissions by 1.2 to 1.8 million tonnes" Baxter explained. "That by itself will be the largest single carbon reduction project on a landfill in the world." Climate Change Emissions Management Corporation of Alberta (CCEMC) has recognised the importance of this technology and has made a significant investment in the project.

The company's process, which can be used for both active and closed landfills, involves drilling wells to various depths in the site and then injecting air and moisture into the wells. The change in environment quickly kills the anaerobic bacteria, which are replaced by aerobic bacteria that begin to rapidly decompose the organic material. Methane production and odours from anaerobic decomposition ceases within two to three weeks and the quality of the leachate improves. Heat generated by the process turns the leachate into water vapour. SALT condenses the water vapour and then either releases it into the environment in the form of non-polluting water or adds it back into the site when additional moisture is required.

After three to four years, the site becomes inert and as a result of compaction, up to 30 percent of the original airspace is recaptured. The site can then be excavated using mature open pit mining techniques where composted materials are removed and products such as plastic, rubber and glass can be recovered. Hazardous materials such as batteries, propane cylinders and chemical drums are disposed of safely.

"Costs and liability issues are mitigated after the first phase," Baxter said. "We then add companion technologies." These technologies, developed by SALT with assistance from the National Research Council of Canada, can transform the site's non-organic materials into durable products. Co-mingled plastics, glass, rubber and carpet can be manufactured into items such as utility poles, railway ties, marine wharves and landscaping products that are cost-effective, non-toxic and resistant to erosion. At the end of the process, municipalities have not only reduced expenses associated with landfill operation but can also recover costs.

"Space in a landfill is extremely valuable," Baxter explained. "We can recover that space and turn it back into a performing municipal asset that produces revenue for the community."

Alberta Environment requires major carbon emitters to reduce their footprint by 15%. However, the Regional Municipality of Wood Buffalo project is a voluntary and self-promoted initiative to reduce the environmental impact of its regional operations and not subject to the above requirements. The Regional Municipality of Wood Buffalo made this investment to reduce its carbon footprint, reduce the environmental impacts of its closed landfill and to showcase "best practice" in waste management methane reduction. The goal was to establish the region as a global leader in environmental stewardship and these principles are further supported within the region's sustainable development plans. Carbon neutrality was also a significant factor in the decision. As well, the size of the landfill, age of the waste and newly established Alberta Carbon offset program, made this project an ideal fit for the first large scale application of this technology.

"The Aerobic Bioreactor project is a significant milestone for the region and will vastly reduce the annual carbon emissions of the Municipality" Says Jarrod Peckford, Supervisor of Environmental and Public Services with the Regional Municipality of Wood Buffalo. "Not only will the project reduce the methane generation within our region, but it will showcase a technology that can be utilized globally to reduce the greenhouse gases emitted from landfill operations. Annually landfill operations contribute 4-5% of the global carbon emissions which could be reduced through the aerobic bioreactor process.

There is a wealth of talent and knowledge supporting SALT's technology. The company is working closely on the Fort McMurray project with a team of three tenured engineering professors, two post-doctorate fellows and three graduate students from Western University in London, Ontario. The group is studying the site's aerobic reactions, leachate conditions and also conducting emissions analysis. Another associate, Dr. Irena Creed, of Western's Biology Department is Canada Research Chair in Watershed Sciences and a director of the Africa Institute. Dr. Creed believes that the aerobic technology is the key to preserving groundwater particularly in areas where it is the only source of water and can be easily polluted by landfill runoff.

SALT is also working with Conestoga Rovers & Associates, the largest environmental engineering firm in Canada. Located in Waterloo, Ontario, the firm is responsible for a significant number of landfills in Canada as well as sites in the U.S., Mexico and South America, Baxter said. One of their engineers, Dr. Tej Gidda, is an expert in anaerobic and aerobic reactions and is very interested in SALT's technologies. He said that the SALT approach is "the single greatest modification and change to the landfill business that has occurred in the last 100 years," Baxter recalled. Dr. Gidda visited the Fort McMurray site, and said that "there is absolutely nothing like this in the entire world" and that the process has "the opportunity of changing the environmental, financial and social consequences of most organizations in countries around the world," Baxter said.

Upon completion of this project the Regional Municipality of Wood Buffalo will deploy the technology within the Regional landfill as phase 2 to degrade the waste in that facility after it has been filled and closed in 2018. SALT intends to build its' client base in other regions. "We believe our growth will be very rapid and that our services will be in great demand both domestically and internationally."