Using Pilot-Scale Investigations to Estimate the Remaining Geosmin and MIB Removal Capacity of Full-Scale GAC-Capped Drinking Water Filters

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Pilot tests were conducted to investigate the removal of geosmin and 2-methylisoborneol (MIB) by new and semi-exhausted granular activated carbon (GAC) extracted from full-scale filters located in the City of Toronto’s drinking water treatment facilities. Four pilot filters containing core-sampled GAC and new sand were fed with settled water from a full-scale plant and operated under conditions similar to those employed at full-scale. None of the pilot filters appeared to be capable of reducing geosmin and MIB concentrations to below the commonly cited threshold odour limits of 4 ng/L for geosmin and 9 ng/L for MIB at the influent levels tested. When operated at a 5-min empty bed contact time (EBCT) with geosmin influent concentrations in the range of about 70 to 110 ng/L, removals ranged from 10 to 38% in filters with 25 to 30 cm of used GAC. In the filter with 25 cm of new GAC, removal was 83%. When operated with a 7.5-min EBCT, the filter containing 95 cm of used bituminous GAC removed 78% of the geosmin present in the influent. For both geosmin and MIB, the effluent concentration and the amount removed increased as influent concentration increased, as was expected. In general, geosmin was better removed than MIB.

Key words: geosmin, methylisoborneol, MIB, granular activated carbon, filtration, drinking water treatment

Introduction

Many drinking water treatment plants using Great Lakes water employ direct filtration followed by chlorination while others (such as some of those in the City of Toronto) utilize more conventional treatment trains which include coagulation, flocculation, sedimentation, filtration and chlorination (pre and/or post). None of these processes are particularly efficient with respect to the removal of the taste and odour compounds geosmin and 2-methylisoborneol (MIB). At reasonable chlorine residuals (3 mg/L) and contact times (2 h) the percentage removals for geosmin and MIB, respectively (Glaze et al. 1990). Even at high chlorine dosages (20 mg/L) and long contact times (16 h) removals of geosmin and MIB are only in the range of 35 and 25% (Lalezary et al. 1986). In addition, and aside from the issue of chlorinated disinfection by-product formation, prechlorination may exacerbate the problem by inducing physiological damage to cyanobacteria, thereby liberating cell-bound geosmin (Ashtiani et al. 1988; Brownlee et al. 1988; Peterson et al. 1995).

In response to seasonal taste and odour issues, many utilities have responded by applying powdered activated carbon (PAC) as needed, capping existing anthracite/sand filters with granular activated carbon (GAC), or adding GAC contactors. While PAC application is fairly efficient, the timing of application is important, stockpiles have to be maintained, and there are handling and respiratory issues. An advantage with PAC versus GAC from an adsorption point of view is that within the period PAC is exposed to water there is insufficient time for it to be preloaded by background organics (to the point of occupying adsorptive sites to the detriment of geosmin and MIB removal). This makes it easier to predict the true site-specific geosmin and MIB removal efficiency of a given product. GAC, on the other hand, is contained within a filter, reducing handling requirements and providing a residual benefit of removing potential organics of concern from a human health perspective and organic material which can be utilized by biofilms growing in the distribution system. However, specific contaminants to be removed by GAC must compete for adsorption sites with dissolved natural organic matter (NOM). Because NOM (at 1 to 2 mg/L) is present at much higher concentrations than geosmin (up to 125 ng/L) and MIB (up to 10 ng/L) at City of Toronto treatment plant intakes, and due to the lower adsorption kinetics of NOM in general (Li et al. 2003), NOM compounds move down GAC beds faster than many specific contaminants. As a result,
the GAC in the lower segment of GAC fixed beds can be preloaded with NOM before it is contacted by the contaminants of specific interest (Li et al. 2003). Research has shown that this preloading phenomenon can not only reduce adsorption capacity (Zimmer et al. 1997; Zimminger 1988) but also has a strong effect on adsorption kinetics (Li et al. 2003). The competitive effect of NOM on MIB adsorption is dependent on the size of the NOM compounds and the pore volume of the activated carbon (Newcombe et al. 1997).

Another issue that faces water utilities using activated carbon to remove contaminants is the presence of residual chlorine. It is typically reported that chlorine reacts with activated carbon, reducing the number of adsorption sites and the efficiency of adsorption of other compounds (e.g., Suidan et al. 1987, 1988). A recent full-scale study, however, showed a strong positive relationship between chlorine residual in the range of 0.1 to 0.6 mg Cl₂/L and filter efficiency with respect to the removal of geosmin and MIB (Ridal et al. 2001). As the chlorine residual decreased from 0.6 to 0.1 mg Cl₂/L, the removal of geosmin decreased from 90 to 31% and the removal of MIB dropped from 72% to essentially no removal. The authors speculated that chlorine may remove readily oxidized organic compounds that compete with geosmin and MIB, or alternatively that activated carbon catalyzes the reaction between chlorine and geosmin/MIB. Actual influent and effluent concentrations were not provided so it is not known if there was an effect of varying influent concentrations.

In selecting granular activated carbon for removing geosmin and MIB, isotherm tests and kinetic tests are often conducted as screening tools. Isotherm tests address the maximum adsorption capacity obtained using equilibrium conditions. Equilibrium times that vary from a few hours (3 h) to several days (7 d) have been reported (Suffet and Wable 1995). In practice the time chosen is such that a reasonable approximation to equilibrium is reached. An adsorption isotherm expresses the amount of substance adsorbed per gram of activated carbon (Q) at a given equilibrium concentration of that substance (Cₑ). In water treatment, the Freundlich model is the most common isotherm equation used (Suffet and Wable 1995) and is expressed as:

\[ Q = K_f C_e^{1/n} \]  

where \( K_f \) and \( 1/n \) are constants. The Freundlich model is represented by a straight line on a log-log plot.

Kinetic tests are conducted using contact times similar to those used in full scale; however, the short duration of these tests is not enough to show the preloading effect on the efficiency of the carbon to remove target contaminants. Field testing, using pilot filters designed and operated to simulate full-scale filters, conducted during a longer period of time will provide more information on the evolution of the GAC performance to remove the contaminants of interest as well as the preloading effect.

During the summer and the fall seasons most water utilities supplied by Lake Ontario experience earthy-musty taste and odour events caused by the presence of geosmin and MIB in the raw water. Following several severe seasonal taste and odour events with peak geosmin and MIB concentrations reaching 125 and 10 ng/L, respectively, the City of Toronto implemented activated carbon treatment in its water treatment plants in 2000. This research, undertaken approximately three years after the initiation of GAC filtration, was designed to investigate the removal of geosmin and MIB by new and “in-place” (i.e., semi-exhausted) GAC under experimental conditions similar to those employed in the full-scale filters of Toronto’s water treatment plants.

**Materials and Methods**

**Pilot Filter Description**

Figure 1 shows a schematic of the pilot filter setup. The pilot filters consisted of 4 columns constructed of 5-cm (2”) internal diameter clear PVC pipes. Larger columns were considered but ruled out due to the fact that the costs of the study would have been substantially increased due to the higher costs associated with increasing the amount of geosmin (~C$125/mL) and MIB (~C$200/mL) required. The pilot filters were equipped with Teflon tubing (Johnson Industrial Plastics, Toronto, Ontario) and Swagelok stainless steel fittings and valves (Niagara Valve & Fittings, Hamilton, Ontario). The columns were covered with black foam insulation material (Marks Supply Inc., Kitchener, Ontario) to prevent algal growth and to maintain consistent temperature. The four pilot filters were sized to simulate flow conditions and media composition of the full-scale filters of the City of Toronto water treatment plants.

Pilot Filters 1, 2 and 3 modelled the full-scale filters of the R.C. Harris Filtration Plant. Pilot Filter 1 and 2 contained 25 cm of used bituminous GAC (Picarb, Pica Carbon) core sampled from a full-scale filter and 25 cm of new bituminous GAC (Filtrasorb 820, Calgon Carbon), respectively. Pilot Filter 3 contained 30 cm of used lignite carbon (Hydrocarco 820, Norit Carbon) core sampled from a full-scale filter. Pilot Filter 4 modelled the design of the full-scale filters of the F.J. Horban Filtration Plant and contained 95 cm of used bituminous GAC (Filtrasorb 820, Calgon Carbon) core sampled from two full-scale filters at that plant. The core-sampled GAC had been in use for about 3 years. The sand and support gravel were not core sampled from the full-scale plant. New sand (effective size 0.5 mm, see Fig. 1 for depths) and gravel was installed at the time the core-sampled GAC was placed in the pilot filters. Three sizes of support gravel were used in...
each of the four filters (2 × 3.35 mm; 4.76 × 10 mm; and 12.7 × 19.05 mm). The depths of each in Filters 1 through 4 were, respectively, 15/13/30 cm, 18/12/28 cm, 16/12/28 cm and 13/7/10 cm.

The filtration rate through each column was controlled using a valve-equipped flow meter located in each effluent water line (filtration rates were based on EBCT and are discussed below). A constant water head above the filter media was maintained using an overflow port near the top of the filter column (specific to each filter, see Fig. 1). Each column was equipped with at least 4 sample ports. Sample Port 1, which was located 15 cm above the surface of the GAC, was used to sample the influent throughout the study. Sample Ports 2 and 3 were located halfway into the GAC layer and at the GAC-sand interface, respectively. Sample Port 4 was located following the sand layer. The total headloss was monitored using water level differentials.

Feed Water

The pilot filters were supplied with settled water from the R.C. Harris Filtration Plant (F.P.), one of a number of plants serving the City of Toronto. This plant treats Lake Ontario water using a conventional treatment train including coagulation with alum, flocculation, sedimentation and dual media GAC-sand filtration. Table 1 summarizes the quality of settled water at the time of sampling. Total organic carbon was not specifically analyzed for but raw water TOC samples taken at the R.C. Harris F.P. on September 9, October 6 and November 18, 2003, contained 2.92, 2.48 and 2.30 mg C/L, respectively. The raw water annual TOC average at this plant in 2003 was 2.55 mg/L (1/month, n = 12). This plant does not practice enhanced flocculation so little or no TOC removal would be expected through flocculation and sedimentation.

Pilot Filter Operation

During the study, Pilot Filters 1, 2 and 3 were operated either at 5-min EBCT (3.0 m/h for Filters 1 and 2, 3.6 m/h for Filter 3) or the EBCT corresponding to the design capacity of the particular full-scale filters being simulated (5.3 m/h for all three filters). Pilot Filter 4 was operated either at 7.5-min EBCT (7.6 m/h) or the EBCT corresponding to the peak day flow (3.8 min, 14.9 m/h). The operating conditions for each experiment are provided in the next section. These EBCTs relate only to the GAC layer of the filter media and not sand, gravel and freeboard.

The filters were run continuously for the period from August 29 to November 15, 2003. During the period when no experiments were being performed (i.e., spiking of geosmin and MIB) the filtered water flow rate was maintained at approximately 50 mL/min (1.5 m/h) to reduce backwashing frequency to once per week.

The filters were backwashed using their own effluent which had been collected and stored in 20-L carboys.
Pilot filter backwashing included air scour. The filters were backwashed the day before a sampling, after the sampling and once each week when no tests were being performed. To backwash the pilot filters, the influent water valve was closed, and the filter was drained until the water level was a few centimetres above the top of the media. Air and water were simultaneously pumped in the upflow mode such that air scour occurred in a process termed “collapse pulsing.” Water was pumped at 12 m/h and air was passed at 2 L/min (10 psi). The collapse pulsing was maintained for 3 min. After that, the air was shut off and the water flow rate increased to achieve a 30% bed expansion. This continued for 10 min to allow sufficient time for the turbid backwash water to be evacuated through the overflow at the top of the filter.

Geosmin and MIB Stock Solutions

For each pilot filter, a mixed geosmin and MIB solution was prepared and stored in a 2-L Teflon bottle (VWR International, Mississauga, Ontario) and pumped into the influent line using a valveless piston metering pump (FMI Fluid Metering Inc., Syosset, N.Y.) at a flow rate of 0.5 mL/min. The geosmin and MIB solutions (Sigma-Aldrich, Oakville, Ontario) were diluted in deionized water. The dilution volume was based on the manufacturer's estimation of concentration and the estimated concentration required based on flow calculations. Flow rate was then adjusted to achieve the target concentration at the influent port (#1), which was measured in all tests.

Description of Experiments Conducted

Prior to the placement of the media inside the columns, settled water was circulated through the pilot filters for approximately one week. The four sets of experiments described below and summarized in Table 2 were then performed.

**Experiment 1—geosmin and MIB system losses.** Experiment 1 was designed to investigate potential losses of geosmin and MIB due to adsorption on the surface of pilot filter column walls between the influent sample port just above the GAC layer (Port 1) and the effluent sample port. This also included the stainless steel media support screen, a stainless steel fitting/valve at the bottom of each pilot filter, and a short length of Teflon tubing.

Huck et al. (1995) reported geosmin system losses during a study which investigated the removal of odour compounds with biological treatment. A more recent study showed that tubing, plumbing and filter column surfaces may be important sources of geosmin and MIB losses (Elhadi et al. 2004). If these losses, which are specific to a small-scale apparatus with its high surface-to-volume ratio, are not properly accounted for, the

<table>
<thead>
<tr>
<th>Date (2003)</th>
<th>Experiment number</th>
<th>Influent temperature (°C)</th>
<th>Geosmin in influent (ng/L)</th>
<th>MIB in influent (ng/L)</th>
<th>Pilot filters’ EBCT (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 28 a</td>
<td>1</td>
<td>10.0</td>
<td>234–300</td>
<td>205–267</td>
<td>2.8</td>
</tr>
<tr>
<td>Aug. 29</td>
<td>1</td>
<td>NR b</td>
<td>215–328</td>
<td>184–282</td>
<td>2.8</td>
</tr>
<tr>
<td>Sept. 24</td>
<td>2</td>
<td>19.5</td>
<td>253–395</td>
<td>235–372</td>
<td>2.8 3.4</td>
</tr>
<tr>
<td>Sept. 25</td>
<td>2</td>
<td>14.0</td>
<td>216–541</td>
<td>211–519</td>
<td>2.8 3.4 3.8</td>
</tr>
<tr>
<td>Oct. 9</td>
<td>2</td>
<td>14.0</td>
<td>52–74</td>
<td>54–83</td>
<td>2.8 3.4 3.8</td>
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<tr>
<td>Oct. 29</td>
<td>3</td>
<td>11.0</td>
<td>— c</td>
<td>— c</td>
<td>2.8 3.4 3.8</td>
</tr>
<tr>
<td>Nov. 5</td>
<td>4</td>
<td>9.2</td>
<td>72–108</td>
<td>60–83</td>
<td>5.0 5.0 7.5</td>
</tr>
</tbody>
</table>

a Back to back runs in August and September are essentially replicates but raw water quality changes and geosmin and MIB concentrations vary slightly from day to day.

b NR; Not recorded, but raw water temperature on that date averaged 7.2°C so settled was probably close to that recorded on Aug. 28.

c Neither geosmin nor MIB was fed on this date (monitoring for desorption from the GAC).
removals obtainable by the carbon could be substantially overestimated, especially in short-term tests.

Experiment 1 was performed before the columns were filled with media and involved Pilot Filters 1 and 2 supplied with settled water spiked with geosmin and MIB. The EBCT (2.8 min) and hydraulic loading rate (5.3 m/h) used for this test corresponded to the design capacity of the full-scale filters at the R.C. Harris F.P.

The concentrations of the feed solutions of geosmin and MIB in the Teflon bottles were calculated to provide a target concentration of about 150 ng/L at Sample Port 1. This target value of 150 ng/L was corrected (increased) to account for estimated losses to surfaces with which the stock solution comes into contact that may occur in the feed bottle and between the point of injection and Sample Port 1. The assumed losses of geosmin and MIB were based on a previous study (Elhadi et al. 2004) and were 42 and 30%, respectively (based on a scenario consisting of a 2-L Teflon bottle, 3 m of Teflon tubing and a 60-cm glass column). In this scenario most of the losses were attributable to contact with the glass column. In the current study a clear PVC column was used instead of glass. Data for losses to clear PVC were not available. The test was performed twice, on consecutive days. For both filters, samples were collected at Sample Ports 1, 3, 4 and the effluent line following the flow meter, approximately 19 h after the start of the spiking. Although the filters were empty during these tests, the ports corresponded to the following locations when media was inserted: the influent just above the GAC, the GAC/sand interface, the sand grand interface and the filter effluent. Port 2 (midpoint in GAC layer) was not sampled.

**Experiment 2—removal of geosmin and MIB at design capacity.** The objective of this experiment was to assess the performance of the GAC filters when exposed to anticipated peak concentrations of geosmin and MIB in the feed water. Experimental conditions included two concentrations of geosmin and MIB at EBCT’s corresponding to the design capacity of the full-scale filters of R.C. Harris F.P. and the peak daily flow at F.J. Horgan F.P. Pilot Filters 1 and 2 were operated at 2.8-min EBCT. Pilot Filters 3 and 4 were operated at 3.4-min EBCT and 3.8-min EBCT, respectively.

**Experiment 3—desorption test.** The objective of this test was to investigate possible desorption of geosmin and MIB following the high concentration tests in Experiment 2 (influent geosmin and MIB concentrations ranged from 216 to 541 ng/L, and 211 to 519 ng/L, respectively). The filters were run at the same hydraulic loadings as in Experiment 2 with no geosmin or MIB being fed.

**Experiment 4—removal of geosmin and MIB at 5 and 7.5 minutes EBCT.** The removal of geosmin and MIB was investigated when the filters were run with hydraulic loadings corresponding to 5-min EBCT for Pilot Filters 1, 2, 3, and 7.5-min EBCT for Pilot Filter 4.

**Geosmin and MIB Analysis**

The samples were collected in 1-L amber glass bottles with Teflon-lined caps filled head space free following 19 to 23 h of routine operation after a filter backwashing (midpoint of typical operating cycle, pilot filters backwashed as per those in main plant). For the system losses experiment (Experiment 1), samples were collected at Ports 1 (influent just above GAC), 3 (GAC/sand interface), 4 (sand/gravel interface) and the effluent line. Recall, however, that filter and support media were not present in the columns for Experiment 1. For all other experiments, samples were collected at Ports 1 (influent just above GAC), 2 (halfway through GAC), 3 (GAC/sand interface) and the effluent line (Fig. 1). Sample point 4 (sand/gravel interface) was not sampled as any losses attributable to the sand and gravel could be inferred by subtracting the effluent concentrations from the Port 3 (GAC/sand interface concentrations).

The analysis of geosmin and MIB was carried out using a dichloromethane liquid/liquid extraction to concentrate the geosmin and MIB (Lin et al. 1997). Eight hundred millilitres of samples (including method blank) were used for liquid/liquid extraction with dichloromethane by tumbler. Geosmin-d3 (internal standard) and nitrosodimethylamine (NDMA)-d10 (surrogate standard) were spiked into each sample prior to extraction. The NDMA-d10 was used specifically to detect potential problems during the liquid/liquid extraction. The solvent extract was concentrated by N2 blowdown to ~0.5 mL using a Turbo VAP II concentrator (Caliper Life Sciences, Hopkinton, Mass., U.S.A.). One millilitre of final solvent extract was collected into an autosampler vial. The extracts were analyzed by selected ion monitoring (SIM) GC-MSD (HP GC 5890, MSD 5971A). The method detection limit (MDL) was 10 ng/L for both geosmin and MIB. The spiked recoveries of geosmin and MIB in the blank water were 96.0 and 96.5%, respectively. One extract sample was randomly chosen from each batch and the concentrations were found to be, in all cases, within 1% deviation. Further details on the method, MDL and recoveries are available in Lin et al. (1997).

**Results and Discussion**

All results reported here are from single analyses at each sample point. Although it would have been desirable to replicate each experiment, there were conditions which interfered with the ability to obtain “true” replicates. Each experiment is conducted over a period of about a day to allow for equilibration from when geosmin and MIB are initially spiked to the point when sampling is
initiated. Over this period, influent water characteristics change as do flow conditions as headloss increases, resulting in adjustment to valves to control settled water and geosmin spike solution flows (hence the ratio of spike solution to settled influent water volumes). Time was a factor in that the study had to be conducted during the traditional taste and odour season and the analytical capabilities with respect to throughput at the City of Toronto laboratories were challenged as routine geosmin and MIB sampling had to be conducted in parallel to this study. Due to the small size of the pilot filter columns and the need to collect 1 L of sample, the sample collection period varied from 16 to 35 min resulting in a composite over that time period.

System Losses

Table 3 shows the concentrations of geosmin and MIB at the different sample ports and the total losses calculated between the first sample port and the effluent. These tests were carried out on August 28 and duplicated on August 29. As stated previously, this test was conducted prior to the media being placed in the columns. The measured concentrations of geosmin and MIB (184 to 328 ng/L) at Sample Port 1 were higher than the target concentration of 150 ng/L. This was attributed to: (1) overestimation of losses prior to influent sample Port 1 resulting in the preparation of an overly concentrated stock geosmin/MIB solution and (2) difficulties in maintaining the total incoming flow at the target concentration throughout the experiment. The filters were designed to run in constant head, constant rate mode with filter effluent flow being manually controlled and excess influent water being diverted through an overflow valve located at the top of the pilot filter. In addition, (3) the actual concentration of the commercial solutions of geosmin and MIB were not precisely known, so nominal concentrations provided by the supplier were used to prepare the feed solutions.

The results in Table 3 show that the concentrations of geosmin and MIB decreased from the influent (Port 1) to the effluent, except for the sampling of Pilot Filter 2 on August 29 where the concentrations of both geosmin and MIB at Port 1 were lower than the concentrations at Port 3. No explanation has been found to account for this discrepancy. Concentrations of both compounds decreased between Port 3 and the effluent sample port in about the same proportion as was observed in all other runs. The total losses for geosmin and MIB were similar and ranged between 23 to 40% in new PVC columns containing no filter media. The losses seemed to be dependent on the concentrations of geosmin and MIB in the influent, with increasing losses when the initial concentration increased. These data also suggested that the losses may be negligible for low concentrations of geosmin and MIB in the influent.

Table 4 summarizes geosmin removals through the GAC layer and compares them to the whole filter removals (including the GAC layer) between the influent and effluent sample ports during actual experiments. It can be seen that the majority of the geosmin was removed in the GAC layer and that the filter column and support media contributed little to geosmin removal (similar results were obtained for MIB, data not shown). The losses in the actual experiments were lower than observed in empty new PVC columns (shown in Table 3). This is likely due to loading of potential adsorptive sites by geosmin, MIB and/or competitive background com-

<table>
<thead>
<tr>
<th>TABLE 3. Geosmin and MIB losses to filter column materials</th>
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<tr>
<td><strong>Concentration (ng/L)</strong></td>
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<tr>
<td><strong>Date (2003)</strong></td>
</tr>
<tr>
<td>Geosmin</td>
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<tr>
<td>MIB</td>
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*n = 1 at each point shown, Pilot Filters 1 and 2 appear to be replicates (neither filter contained media and both were fed with the same settled influent water). Geosmin and MIB, however, were fed from separate stock solutions using different pumps as flow splitting was not practical at the very small spike solution flows. Time to collect 1 L of sample for geosmin and MIB analysis varied from 16 to 35 min as water had to be slowly withdrawn to simulate sampling procedure followed with media in filters. Total losses are calculated using Port 1 and effluent data.
pounds in the month between the system loss experiment and the first experiment with media in the columns. Consequently, none of the following results were adjusted to reflect system losses (in this case adsorption to the PVC column material between the influent and effluent sample ports).

Geosmin and MIB Removals (Experiment 2 and 4)

The experimental conditions included “high” (216 to 541 ng/L) and “low” (52 to 86 ng/L) influent concentrations of geosmin and MIB concentrations combined with a 2.8-min EBCT for Pilot Filters 1 and 2, 3.4-min EBCT for Pilot Filter 3, and 3.8-min EBCT for Pilot Filter 4. For the September 24 and 25 runs, the high concentrations of geosmin and MIB were much higher than the target concentration of ~150 ng/L for each (theoretical peak geosmin concentration at the full-scale plant intake). As previously stated, this may have been due to the difficulties in controlling the incoming flow rates and knowing the “true” concentration of the commercial solutions. The spiking strategy was revised to achieve the lower concentrations specified for subsequent tests.

Experiment 4 investigated the removal of geosmin and MIB when the EBCTs were increased to 5 min in Pilot Filters 1, 2 and 3, and 7.5 min in Pilot Filter 4 (for the same filter media). The influent concentrations of geosmin and MIB were between 72 and 108 ng/L. Data for geosmin is shown in Table 4.

Figures 2 and 3 represent the filter effluent concentrations as a function of the filter influent concentration for geosmin and MIB, respectively. For both geosmin and MIB the effluent concentrations increased with an increase in the influent concentration, as would be expected. None of the pilot filters appeared to be capable of reducing the geosmin and MIB below the commonly cited threshold odour limits of 4 ng/L for geosmin and 9 ng/L for MIB under the conditions tested (even at the lower influent concentrations of 52 to 86 ng/L for geosmin and 54 to 83 ng/L for MIB). It should be noted that by the time these experiments were conducted the GAC had been exposed to preloading by NOM for several weeks. Based on work by Andrews et al. (1987) with trihalomethanes, it is reasonable to expect that even this relatively brief period could have had a measurable impact on reducing the GAC’s capacity from that of virgin carbon.

In Fig. 2 and 3, the amount removed in each filter at a given influent concentration is the difference between the line of equivalence (45°) and the plotted trend line showing the measured effluent concentration. Because the effluent concentration lines all have an overall slope less than 1, the amount removed increased with an increase in the influent, as would be expected.

Geosmin and MIB Desorption Investigation (Experiment 3)

Potential desorption of geosmin and MIB from the GAC was investigated following Experiment 2. In the settled water (influent to pilot filters), trace amounts of geosmin were observed (below 10 ng/L MDL) and no MIB was detected. Neither geosmin nor MIB was detected in any of

<table>
<thead>
<tr>
<th>Table 4: Summary of geosmin concentrationsa and removals (Experiments 2 and 4)</th>
</tr>
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<tbody>
<tr>
<td>Exp. Date EBCT GAC/sand Interface Effluent</td>
</tr>
<tr>
<td>no. (2003) (min) Influent GAC Whole GAC</td>
</tr>
<tr>
<td>Pilot Filter 1 (used bituminous GAC, Picacarb)</td>
</tr>
<tr>
<td>2 Sept. 24 2.8</td>
</tr>
<tr>
<td>2 Sept. 25 2.8</td>
</tr>
<tr>
<td>2 Oct. 9 2.8</td>
</tr>
<tr>
<td>4 Nov. 5 5</td>
</tr>
<tr>
<td>Pilot Filter 2 (new bituminous GAC, Filtrasorb 820)</td>
</tr>
<tr>
<td>2 Sept. 24 2.8</td>
</tr>
<tr>
<td>2 Sept. 25 2.8</td>
</tr>
<tr>
<td>2 Oct. 9 2.8</td>
</tr>
<tr>
<td>4 Nov. 5 5</td>
</tr>
<tr>
<td>Pilot Filter 3 (used lignite GAC, Hydrodarco 820) and 4 (used bituminous GAC, Filtrasorb 820)</td>
</tr>
<tr>
<td>2-PF3 Sept. 24 3.4</td>
</tr>
<tr>
<td>2-PF3 Sept. 25 3.4</td>
</tr>
<tr>
<td>2-PF4 Sept. 25 3.8</td>
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<tr>
<td>2-PF3 Oct. 9 3.4</td>
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<tr>
<td>2-PF4 Oct. 9 3.8</td>
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<tr>
<td>4-PF3 Nov. 5 5</td>
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<tr>
<td>4-PF4 Nov. 5 7.5</td>
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</tbody>
</table>

a = 1 at each point shown.
bWhole filter includes GAC, sand and gravel layers (Sample Port 1 concentration minus effluent concentration).

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the pilot filter effluents at concentrations above the analytical method detection limit. Desorption was, therefore, not occurring to any substantial degree approximately 3 weeks following the previous experiment (at least with respect to concentrations being employed in this study). Any desorption that may have occurred would have happened prior to this, even at the reduced hydraulic loading of 1.5 m/h that was maintained between experiments.

Effect of Empty Bed Contact Time on Filter Efficiency (Experiment 4)

For the lower concentrations of geosmin and MIB tested, the percentage removals were plotted against the EBCT (Fig. 4 and 5). The actual amounts removed follow the same pattern as the percentages; however, the latter are shown to facilitate comparison with other studies. For Pilot Filters 2 and 4, the percentage removals of geosmin and MIB increased with an increase in EBCT, as observed in other studies (Ridal et al. 2001; Kim et al. 1997). The geosmin percentage removals in Pilot Filter 2 increased from 69 to 83% as EBCT was increased from 2.8 to 5 min (new Filtrasorb 820 GAC). The geosmin percentage removals in Pilot Filter 4 increased from 38 to 78% when the EBCT was increased from 3.8 to 7.5 min (used Filtrasorb 820, deeper GAC bed, 95 cm versus 20–25 cm for other filters). The improvements observed in the removals of MIB for the same increase in the EBCTs were from 55 to 62% for Pilot Filter 2 and from 14 to 43% for Pilot Filter 4. Although experimental conditions differed among studies, the filter efficiencies reported herein are consistent with the work of Ridal et al. (2001) and Kim et al. (1997). Ridal et al. (2001) investigated the efficiencies of 2- and 12-month-old GAC to remove geosmin (6.4 ng/L) and MIB (17.8 ng/L). For the 2-month-old GAC, removals of geosmin and MIB were 75 and 52%, respectively. The removals observed for the 12-month-old GAC ranged from 71 to 84% for geosmin and from 55 to 78% for MIB. Kim et al. (1997) found that a GAC column operated at 10-min EBCT removed 59% of the influent geosmin (13.8 ng/L) and 46% of the influent MIB.
(65 ng/L), while for 15-min EBCT the removal efficiencies were 70% for geosmin and 60% for MIB.

An increase in Pilot Filter 1 EBCT (Fig. 4 and 5) produced no improvement in the removal of either geosmin or MIB with the percentage removals dropping slightly (in what was already a poorly performing filter). The amounts of geosmin and MIB removed were between 4 and 15 ng/L, which were less than or close to the method detection limits (10 ng/L). This coupled with the fact that the longer EBCT tests were conducted after the GAC had been in service for an additional month (i.e., increased background TOC loading), are likely explanations for the observed decrease in these low-concentration removals.

The percentage geosmin removals in Pilot Filter 3 increased from 29 to 38% following an increase in the EBCT from 3.4 to 5 min, while the percentage removals of MIB dropped from 15 to 6% with the amount removed (4 to 11 ng/L) again being close to or less than the analytical method detection limit (10 ng/L). The fact that the removal of MIB worsened while the removal of geosmin improved only slightly suggests that GAC exhaustion may be first indicated by the filter performance to remove MIB.

Normalization of Geosmin and MIB Removals

Up to this point, comparisons of the four pilot filters were based on simple graphic representations obtained under different experimental conditions (depth of the media, initial concentration, EBCT). In keeping with the general idea of an adsorption isotherm, an attempt has been made to represent the amount of geosmin and MIB removed per unit quantity of GAC as a function of the concentration in the effluent. To do this, the amount of geosmin and MIB removed was first divided by the depth of the media, which is proportional to the mass of the GAC. This procedure effectively calculates an average loading for the carbon in the column, because the amount adsorbed may vary somewhat throughout the depth of the column. Then, because the EBCTs differed between filters and experiments, the amount of compound removed per unit depth of GAC was subsequently divided by the EBCT. This roughly takes into account the rate or kinetics of adsorption. The final values were expressed in ng/L/cm/min and called normalized amount removed. They were plotted against the pilot filter effluent concentration on a log-log scale and linear regressions were performed as in Freundlich isotherm representations. This method provided a better comparison of the pilot filters by reducing the effects of the EBCT and GAC depth; however, the effect of the initial concentration still remains. The results can be used as an approximate estimate of the filters’ operating capacity.

Figures 6 and 7 show the normalized amount of geosmin and MIB removed by the whole pilot filter as function of pilot filter effluent concentrations. Although these figures provide useful insights, the subsequent discussion involves considerable extrapolation from the observed data. Numerical values for “treatable” influent concentrations should therefore be regarded as approximate. Figure 6 shows that the extrapolated line for Pilot Filters 1 and 3 intercepted the x-axis at values higher than 4 ng/L. Thus, extremely low normalized amounts removed (proportional to surface loadings) (below those shown on the logarithmic scale vertical axis) would be required for these carbons, if it were desired to reach the threshold limit. In practice, removals in these pilot filters are unlikely to be such that the threshold limit can be met. For Pilot Filters 2 (25 cm new bituminous GAC) and 4 (95 cm used bituminous GAC), the graph suggests that the effluent value of 4 ng/L could be achieved at more reasonable carbon loadings. Thus, there were influent levels of geosmin for which these two pilot filters may have been capable of reducing the concentrations to below the threshold limit. These influent levels of geosmin can be estimated using the equations shown.

![Fig. 6. Normalized amount of geosmin removed as a function of effluent concentration.](image1)

![Fig. 7. Normalized amount of MIB removed as a function of effluent concentration.](image2)
in the graph (Fig. 6). For example, for Pilot Filter 2 the normalized amount of geosmin removed by the whole filter \( y = 0.0374x^{1.0065} \) for an effluent concentration “x” of 4 ng/L is 0.15 ng/L/min/cm. For 5-min EBCT and a GAC depth of 25 cm, the calculated influent concentration is 23 ng/L. Thus Pilot Filter 2 may have been capable of reducing the geosmin concentration to below the threshold limit at influent geosmin levels of less than approximately 23 ng/L.

Figure 7 shows that none of the used GAC was able to reduce the MIB to lower than 9 ng/L at reasonable carbon loadings; however, there were influent levels of MIB for which Pilot Filter 2 may be able to reduce the concentration to below 9 ng/L. Calculations similar to those performed for geosmin show that Pilot Filter 2 may have been capable of reducing MIB concentrations to below the threshold limit for influent MIB levels of less than approximately 22 ng/L.

Data obtained using similar experimental methodologies were not found in the literature for comparison to the filters’ operating capacities estimated herein. However, efficiencies reported by other authors (Ridal et al. 2001; Kim et al. 1997) provided indications that the operating capacity of the filter containing the new bituminous GAC may have been even lower than the extrapolated values of approximately 22 and 22 ng/L for geosmin and MIB, respectively. Ridal et al. (2001) reported that 61 cm of GAC operated at 8.2-min EBCT reduced MIB from 17.8 to 8.6 ng/L. In the Kim et al. (1997) study, a GAC column operated at 10-min EBCT reduced the concentration of geosmin from 13.8 to 5.6 ng/L and the concentration of MIB from 65 to 35 ng/L.

Factors potentially contributing to observed filter performance include initial adsorption capacity of new GAC, low bed depth (insufficient EBCT), length of service of the GAC and background competition or pore blockage from other forms of organic carbon.

In practice, fresh GAC would normally be installed in treatment plants no later than the spring. Thus, for the Great Lakes, GAC-capped filters would have been in operation for probably 4 to 6 months by the time a taste and odour episode would typically occur. The time available for reduction of the GAC’s capacity by pre-loading would be greater than the approximately two months occurring in the current study.

Conclusions

On the basis of a pilot-scale assessment of new and exhausted core-sampled 3-year-old granular activated carbon media for geosmin and MIB from full-scale filters obtained from the City of Toronto’s drinking water treatment plants, the following can be concluded:

1. Under the experimental conditions investigated, none of the pilot filters were capable of reducing geosmin and MIB concentrations to below the commonly cited taste and odour threshold limits of 4 ng/L for geosmin and 9 ng/L for MIB. This included the filter containing fresh GAC, which had only been in operation for a few weeks when measurements were made. This might not be unexpected for the higher range of geosmin influent concentrations (200–400 ng/L) tested but even at low influent geosmin concentrations (50–100 ng/L) none of the filters could produce water below these threshold concentrations. Peak raw water geosmin and MIB concentrations at this treatment plant prior to this study were 125 and 10 ng/L for geosmin and MIB, respectively.

2. It is predicted that in the event of a raw water geosmin/MIB spike at the levels investigated, the full-scale filters containing exhausted GAC would not be able to reduce geosmin and MIB concentrations to less than threshold values.

3. This study also suggests that even new GAC of the type investigated may not be able to reduce geosmin and MIB spikes to below threshold concentrations for the EBCTs employed and the influent levels experienced in the full-scale plants; however, extrapolations of the experimental results show that at 5-min EBCT the new GAC may have been able to reduce the concentration of geosmin and MIB to below the threshold limits if the influent levels of geosmin and MIB were less than approximately 23 and 22 ng/L, respectively.

4. For both geosmin and 2-methylisoborneol (MIB), the effluent concentration and the amount removed increased with an increase in the influent concentration, as was expected.

5. As expected, geosmin was better removed than MIB. This is in agreement with previous studies (e.g., Lalezary et al. 1986).

6. An increase in the empty bed contact time (EBCT) from 2.8 to 3.4 min to 5.0 to 7.5 min increased the removal of both geosmin and MIB, as expected, when removals were good at the lower EBCTs to start with but not when removals were poor (≤ 20% at lower EBCTs). [Experiments at the lower EBCTs were run about 1 month prior to the higher EBCT experiments. Background organic carbon loading may have contributed to reduced capacity over that time.]

7. The pilot filter was tested for geosmin and MIB adsorption losses prior to loading the GAC to be tested. System losses are a potential issue at bench and pilot scale because of the high surface to volume ratio of the apparatus. Losses to pilot filter walls were initially substantial (20–40%), however, they decreased over time and were also less important at the lower influent concentrations fed later in the study. The results presented above have not been adjusted to reflect system losses; therefore, if some occurred on the filter column wall below the surface of the GAC the pilot scale performance reported herein may be
somewhat better than would be observed at full scale (i.e., not possible to quantify but more conservative).

Acknowledgements

Funding for this project was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) in the form of an Industrial Research Chair at the University of Waterloo. The current Chair partners include: American Water Canada Corp.; Brightwell Technologies Inc.; the cities of Brantford, Guelph, Hamilton, Ottawa and Toronto; Conestoga-Rovers & Associates Limited; EPCOR Water Services; the Ontario Clean Water Agency (OCWA); PICA USA Inc.; RAL Engineering Ltd.; the Region of Durham; the Regional Municipalities of Niagara and Waterloo; Stantec Consulting Ltd. and Zenon Environmental Inc.

We would like to acknowledge the assistance of analysts at the Trace Organic Laboratory of the City of Toronto for performing geosmin and MIB analyses. We would also like to thank Shawn Pillai for his logistical assistance and Doug Thompson and his team at the R.C. Harris Filtration Plant, for their considerable assistance in helping to set up the pilot filters and analysis of water quality parameters during testing.

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Received: June 30, 2005; accepted: April 10, 2006.