Assessment of alternate characterization tests for prediction of taste and odour control by granular activated carbon

Kyla Smith, Xiaodan Zhang and Ron Hofmann

ABSTRACT

The acetoxime number test was recently identified by the American Society for Testing and Materials as a method to characterize activated carbon. This adsorption isotherm gives information about the number of high energy adsorption sites on the surface of an activated carbon. A similar test uses tetrafluoromethane for the same purpose. In contrast, the more common iodine number and Brunauer, Emmet and Teller (BET) surface area parameters are a measure of the total number of adsorption sites. 2-Methylisoborneol (MIB) is reported to require high energy sites for removal, so it was hypothesized that data from acetoxime and tetrafluoromethane isotherm tests for different activated carbons would be better correlated to MIB removal than iodine numbers or BET surface areas. MIB breakthrough was monitored in rapid small-scale column tests (RSSCTs) using four natural waters and five activated carbons. Results showed no correlation between acetoxime or tetrafluoromethane isotherms and MIB breakthrough.

Key words | geosmin, granular activated carbon, 2-methylisoborneol, taste and odour, trace capacity number

INTRODUCTION

In drinking water treatment, there are many types of granular activated carbons (GAC) available for taste and odour control. To select a GAC, utilities may employ relatively sophisticated techniques to estimate predicted performance and service life, including pilot testing and rapid small-scale column tests (RSSCTs) (Crittenden et al. 1994). These tests can be designed to account for most of the kinetic and thermodynamic factors affecting adsorption, but while pilot testing and/or RSSCTs are useful, the cost, time and complexity of such tests are beyond the reach of many utilities.

In practice, utilities often select GAC with the help of non-site-specific carbon specifications provided by suppliers, which typically include the iodine number and the Brunauer, Emmet and Teller (BET) surface area (ANSI/AWWA 2006). These are thermodynamic (isotherm) parameters designed to represent the total surface area available per unit mass of carbon for adsorption, and are measured in otherwise pure solution and given enough time for the adsorbate to reach equilibrium. It is generally believed and reported that the iodine number and BET surface area may not accurately reflect the ability of a specific GAC to remove taste and odour-causing compounds under actual operating conditions, where not only thermodynamics, but kinetics, are important, and where there are competing adsorbates such as natural organic matter (NOM). Both Chen et al. (1997) and Yu et al. (2007) reported a lack of correlation between iodine numbers/BET surface areas and geosmin/MIB isotherms when pooling isotherm data from activated carbons made from a variety of base materials (bituminous coal, lignite coal, wood and coconut). Freese et al. (2000) reported a similar lack of correlation based on geosmin isotherm tests performed on 42 different powdered activated carbons over a number of years by a utility in South Africa.

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Furthermore, while the iodine and BET parameters characterize the total surface area available on an activated carbon, taste and odour-causing compounds – and in particular geosmin and 2-methylisoborneol (MIB) – are reportedly relatively poorly-adsorbed (Nowack et al. 2004). Polanyi adsorption theory models the surface of GAC as containing adsorption sites with a range of adsorption potential energies (Greenbank & Manes 2004). The high energy sites are associated with the smallest pores in the activated carbon (there is a direct relationship that can be calculated between pore size and adsorption potential energy, and the two concepts can be considered to be interchangeable (Halsey 1948)). Only the high energy sites (or small pores) may adsorb weakly-adsorbing compounds such as geosmin and MIB when those compounds are at low concentrations in solution. As such, the total number of adsorption sites indicated by iodine numbers or BET surface areas may not be relevant: instead, a measure of only the high energy sites might be a better indication of the ability of a GAC to remove geosmin and MIB.

Recently, a new thermodynamic test has become available through the American Society for Testing and Materials (ASTM). The acetoxime number (ANSI/AWWA 2006), also called the trace capacity number (TCN) in this paper, is an isotherm test that is similar to iodine number or BET surface area tests, but instead uses a weakly-adsorbing compound, acetoxime, to measure only the high energy adsorption sites on the surface of the GAC. The standard suggests that the TCN may be used ‘as an index of activated carbon’s ability to remove some low molecular weight compounds’. This test may therefore provide some information about the ability of an activated carbon to adsorb a weakly-adsorbing compound such as MIB or geosmin. A similar but operationally simpler method for measuring only the high energy adsorption sites is the trace capacity number gas-phase (TCNG) test, developed by Calgon Carbon Corporation, which is an adsorption isotherm test using tetrafluoromethane (CCC 2005).

The purpose of this study was to test the hypothesis that the TCN and TCNG parameters are better predictors, when compared to iodine number or BET surface area, of GAC effectiveness in removing taste and odour-causing compounds in natural waters. Such information would be useful, for example, to a utility that could use TCN or TCNG specifications as part of a ‘paper study’ to identify candidate GACs for pilot or RSSCT testing.

**EXPERIMENTAL**

The general approach of this work was to test GAC performance for taste and odour-compound adsorption using RSSCTs as surrogates for full-scale GAC contactors when using different natural waters. The GAC performance was then correlated to the various thermodynamic (isotherm) parameters reported or measured for the different GACs.

**Materials**

**Sample water**

RSSCTs were run using four different water samples from two sources (referred to as Lake Simcoe 1, 2 and 3 and Lake Ontario 1). The water from Lake Simcoe (Ontario, Canada) was sampled three times over the course of a year, and came from the Georgina drinking water treatment plant which employs prechlorination, membrane filtration and GAC contactors. The samples were collected immediately pre-GAC contactors. Water from Lake Ontario was collected at the Ajax drinking water treatment plant, a direct filtration plant with GAC filter caps for taste and odour control. The sample was taken following prechlorination and alum coagulation/flocculation. Relevant water quality parameters for the samples are shown in Table 1. All water samples were filtered through a 1 μm fibrous polypropylene string-wound cartridge (EW-01508-77, Cole-Parmer, Anjou, Canada) followed by a 0.5 μm pleated cartridge filter (RK-01512–86, Cole-Parmer, Anjou, Canada).

<table>
<thead>
<tr>
<th>Lake Simcoe 1</th>
<th>Lake Simcoe 2</th>
<th>Lake Simcoe 3</th>
<th>Lake Ontario</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC (mg/L)</td>
<td>4.05</td>
<td>3.84</td>
<td>4.15</td>
</tr>
<tr>
<td>pH</td>
<td>8.24</td>
<td>8.40</td>
<td>8.33</td>
</tr>
</tbody>
</table>

**Table 1 | TOC and pH for natural waters tested**
Canada) to remove particulate matter. Water was stored at 2–4 °C.

**Adsorbents**

Five different types of GAC from major suppliers to the drinking water industry were used, and are described in Table 2. Bituminous coal and lignite coal carbons were selected, and all carbons were steam activated. The carbons are referred to as Carbons A to E. Initially, only three carbons were tested, but partway through the study the RSSCT apparatus was expanded to allow for six carbons (six parallel RSSCT columns) to be run simultaneously.

**Adsorbate**

MIB was used to represent taste and odour compounds, since it is commonly reported to be the most difficult taste and odour compound to remove by GAC. The MIB was obtained in solid form from Wako Chemicals USA Inc., and prepared as a 1 mg/L spiking solution in Milli-Q® water. The solution was found to be stable when kept refrigerated for 5 months.

**Methods**

**Analytical methods**

Total organic carbon (TOC) samples were analysed using an Aurora 1030 TOC Analyser (O. I. Analytical) according to Standard Method 5310 D (Standard Methods 2005). MIB was extracted by headspace solid-phase microextraction (SPME) and quantified using gas chromatography-mass spectrometry (Varian® 3800 gas chromatograph with a Varian® ion-trap mass spectrometer detector, using electron impact ionization) following methods described by Boutou & Chatonnet (2007). The quantification of MIB was based on a de5-geosmin internal standard.

**Thermodynamic tests**

Iodine numbers for all five carbons were measured following Standard Method D4607 (Standard Methods 2005). The MIB equilibrium adsorption capacity (MIB isotherm)

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**Table 2** Properties of five activated carbons used in this study, and bed volumes treated to breakthrough

| Carbon Raw material | Iodine number (mg/g) | TCN (mg/mL) | TCNG (g/100 cm³) | BET surface area (m²/g) | Adsorption isotherm MIB q₁₀ (ng/mg) | Bed volumes to MIB breakthrough (20% of C₀) in parentheses
<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A Bituminous coal</td>
<td>869</td>
<td>10.96</td>
<td>5.4</td>
<td>625</td>
<td>230</td>
<td>12,564 (3)</td>
</tr>
<tr>
<td>B Bituminous coal</td>
<td>961</td>
<td>11.9</td>
<td>6.4</td>
<td>683</td>
<td>302</td>
<td>42,145 (1)</td>
</tr>
<tr>
<td>C Bituminous coal</td>
<td>813</td>
<td>15.7</td>
<td>7.7</td>
<td>584</td>
<td>159</td>
<td>7,612 (3)</td>
</tr>
<tr>
<td>D Lignite coal</td>
<td>633</td>
<td>4.6</td>
<td>3.5</td>
<td>539</td>
<td>83</td>
<td>13,339 (2)</td>
</tr>
<tr>
<td>E Bituminous/ Subbituminous coal</td>
<td>1,001</td>
<td>8.3</td>
<td>8.3</td>
<td>797</td>
<td>51</td>
<td>34,752 (1)</td>
</tr>
</tbody>
</table>

- Single-solute bottle point adsorption (Freundlich) isotherm parameters, q₁₀ = adsorption capacity of carbon at solution concentration of 10 ng/mL.
- Prior to RSSCT set up expansion (Lake Simcoe waters), only three carbons were tested simultaneously.
- Note: Rank 1 = highest number of bed volumes or throughput at breakthrough value.

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of the carbon samples is defined as the MIB loading on activated carbon (ng MIB per mg activated carbon) at equilibrium with a 10 ng/L MIB solution, measured using batch isotherm experiments according to methods given by Randtke & Snoeyink (1985) and modified based on the micro-isotherm technique described in ASTM D5919 (ASTM 2011). BET surface areas were not measured directly, but were instead taken from the activated carbon specifications provided by the manufacturers. The TCN (TCN, also called the acetoxime number) was determined according to ANSI/AWWA B604-05 (ANSI/AWWA 2006), and is defined as the acetoxime loading on the activated carbon (mg/mL) at 50 mg/L residual acetoxime in solution at equilibrium. The TCNG of the carbon sample was determined using the tetrafluoromethane adsorption method TM-85 developed by Calgon Carbon Corporation (CCC 2005). TCNG is defined as the ratio (g/100 mL) of the mass of tetrafluoromethane (CF₄) adsorbed by a volume of activated carbon sample when the carbon is saturated with tetrafluoromethane vapour under specific test method conditions. The TCNG method is modified from the butane number method described in ASTM D5742-95 (ASTM 2010).

Rapid small-scale column tests

RSSCTs were performed according to Crittenden et al. (1991). The GAC columns in the laboratory were arbitrarily designed to simulate a full-scale GAC contactor with an empty-bed contact time (EBCT) of 7.5 min, a length of 1.5 m, and a surface loading rate of 10 m/hr. The scaling factor used in the RSSCT design (Crittenden et al. 1991) was selected as 1.1, following discussions with personnel at Calgon Carbon Corporation (Pennsylvania, USA) who observe that this factor is appropriate for taste and odour compound adsorption in natural waters. Others have used a scaling factor of 2.0 (i.e. so-called ‘constant diffusivity’) when using RSSCTs to simulate full-scale adsorption of small organic compounds in otherwise pure water, but a value of 1.0 (i.e. proportional diffusivity) is often used when modeling breakthrough of NOM (Crittenden et al. 1991). The selection of the appropriate scaling factor is critical when trying to ensure accurate simulation of a full-scale adsorber. In this research, however, simulation of a specific full-scale adsorber is not important, since the goal is solely to compare the performance of different activated carbons under similar RSSCT conditions. Nevertheless, the assumption that a constant scaling factor exists for all activated carbons tested may not be correct. In theory, the scaling factor is a function of the combination of activated carbon type, adsorbent and water matrix. As such, the scaling factor should be determined experimentally for every unique set of conditions. This was beyond the scope of the present work, and indeed, the authors are aware of only one previous study where such adjustments have been made (Corwin 2010).

The activated carbon was packed into 0.46 cm (inside diameter) stainless steel columns with a 2 cm support base of glass wool. A glass wool pre-filter was installed prior to the carbon filter to remove particulate matter in the influent water. Fifty-litre stainless steel reservoirs held the sample water and contained Teflon®-lined (3 mm) polystyrene foam floating lids to minimize the loss of MIB to the atmosphere.

Two RSSCTs run under identical conditions two months apart (same activated carbons and same stored water sample) showed the results to be reproducible, implying that no significant change in the water matrix occurred during storage and that results between RSSCTs could be compared ($P = 0.0025$).

RESULTS AND DISCUSSION

Thermodynamic tests

The thermodynamic parameters for each of the five activated carbons are shown in Table 2, and their correlations are reported in Table 3. The TCN and TCNG values were strongly correlated to each other, as might be expected since under the conditions of the tests, the adsorption of the acetoxime and tetrafluoromethane, respectively, required very similar adsorption potential energies as shown in Table 4 (calculated using Polanyi theory according to methods described by Greenbank (1981)). Similarly, the iodine numbers and BET surface areas for the five activated carbons were also strongly correlated to each other; again, as would be predicted given the similar adsorption potential energies in Table 4. It was hypothesized that MIB, being a
weakly-adsorbing species, would require high energy sites similar to acetoxime or tetrafluoromethane for adsorption, and therefore that the MIB isotherm parameter would be well correlated to the TCN or TCNG parameters. Instead, Table 3 indicates a very poor correlation of the MIB parameter to TCN and TCNG but, surprisingly, a good correlation to iodine and BET parameters.

The poor correlation between the MIB parameter and the TCN and TCNG parameters may be partially explained by inspection of the adsorption potential energies in Table 4. Under the isotherm test conditions, while each of MIB, acetoxime and tetrafluoromethane all required high adsorption energies (or analogously, required very small pores sizes for adsorption), the MIB still required four to eight times the energy of the other two compounds (i.e. 141,042 J/mol vs. 28,853–17,869 J/mol). These data suggest that there may be considerable differences in the proportion of adsorption sites between the 17,869 to 141,042 J/mol ranges among the five activated carbons – i.e. a carbon with more 17,869 J/mol sites (adequate for tetrafluoromethane adsorption) than another carbon may not necessarily have more 141,042 J/mol sites needed for MIB adsorption. A second possible factor that may have led to a lack of correlation between MIB and TCN/TCNG parameters was the presence of background organic matter in the Milli-Q water used for the isotherm tests. Milli-Q water contains as much as 0.1 mg/L of organic carbon, which is several orders of magnitude greater than the trace solutes being tested. The potential confounding role of this organic matter in terms of competitive adsorption during the isotherm tests is unknown. Other similar research was surveyed and this issue has not been widely addressed, with authors generally stating the amount of dissolved organic content (DOC) present in the lab-grade water but not suggesting any resulting competition for adsorption sites with target compounds. It is recommended that future research explore the role of this background organic matter in typical adsorption isotherm tests of trace compounds.

The good correlation between MIB adsorption and iodine number/BET surface area cannot be explained using the information available. The data reveal that the activated carbons with the greater density of high energy adsorption sites (i.e. greatest number of very small pores) also had the greatest density of total adsorption sites (i.e. total pores), but this need not always be the case. A more thorough exploration of this phenomenon was outside of the scope of the study.

### RSSCT breakthrough results

RSSCTs were performed on four water samples that were collected over the course of a year from treatment plants drawing water from Lake Simcoe and Lake Ontario. Due to enhancements in laboratory capacity during this time, a different number of activated carbons were evaluated for each water sample. This, coupled with differences in water quality among the four samples, leads to the treatment of the data as four separate experiments rather than pooling the data.

**Table 3** Examination of correlation between characterization tests (least-squares linear regression)

<table>
<thead>
<tr>
<th>Method</th>
<th>TCN $R^2$</th>
<th>$P$ Value</th>
<th>TCNG $R^2$</th>
<th>$P$ Value</th>
<th>BET surface area $R^2$</th>
<th>$P$ Value</th>
<th>MIB $q_{10}$ $R^2$</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iodine</td>
<td>0.1489</td>
<td>0.5212</td>
<td>0.1833</td>
<td>0.472</td>
<td>0.8097</td>
<td>0.0575</td>
<td>0.9129</td>
<td>0.0112</td>
</tr>
<tr>
<td>TCN</td>
<td></td>
<td></td>
<td>0.9686</td>
<td>0.0024</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCNG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BET</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MIB $q_{10}$</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Table 4** Adsorption potential energies for the thermodynamic tests

<table>
<thead>
<tr>
<th>Potential energy (J/mol)</th>
<th>MIB</th>
<th>TCN</th>
<th>TCNG</th>
<th>Iodine</th>
<th>BET</th>
</tr>
</thead>
<tbody>
<tr>
<td>141,042</td>
<td>28,853</td>
<td>17,869</td>
<td>493</td>
<td>1,327</td>
<td></td>
</tr>
</tbody>
</table>

Breakthrough of MIB was monitored as a function of bed volumes of water treated. To deal with variability in the MIB measurements, an asymmetrical sigmoid curve (Gompertz function) was fit to the breakthrough data (Clark 1987). A typical example of the data is shown in Figure 1. Breakthrough was arbitrarily defined as 20% of the influent concentration, although the evaluation of the results would not be affected by the selection of a different breakthrough value.

The number of bed volumes of water treated before breakthrough for each activated carbon and for each of the four water samples is shown in Table 2. The bed volume data were then correlated to the thermodynamic parameters using linear regression to test the hypothesis that the thermodynamic parameters – and in particular the TCN and TCNG – could be predictors of GAC service life. These results are given in Table 5, and indicate that the TCN and TCNG parameters consistently showed the weakest correlations to breakthrough of all the thermodynamic parameters, with $R^2 < 0.5$ for all waters tested. Iodine number and BET surface area showed moderate correlations ($R^2 > 0.5$, and occasionally $>0.8$) with breakthrough in two of the four water samples tested. No single thermodynamic test, applicable to all types of carbons, was consistent in terms of a quantitative prediction of adsorption performance for taste and odour control.

On closer examination of the correlations associated with the Lake Ontario dataset in Table 5 (the most comprehensive), it is apparent that when Carbon D is removed, the correlations between all thermodynamic parameters and bed volumes of water treated to breakthrough improve significantly, with iodine number, BET surface area and MIB isotherm parameters all showing correlation coefficients greater than 0.90. TCN and TCNG remain very poorly correlated to breakthrough, however. Activated carbon D is made from lignite coal, while the other activated carbons are made from bituminous coal. In terms of the thermodynamic parameters shown in Table 2, Carbon D is the lowest performing activated carbon of the five evaluated. In the RSSCT runs, however, it performed much better than some of the other activated carbons. A possible explanation may be that Carbon D, as a lignite carbon, has a more macroporous structure than the other four bituminous coal carbons. The reported adsorption and transport pore volumes of the five activated carbons tested are shown in Table 6. The adsorption pore volumes of all the carbons are relatively similar, but activated carbon D has a distinctively higher transport pore volume. It is plausible that this greater transport volume allows more rapid movement of MIB to adsorption sites within the carbon particle, allowing more MIB to be removed than would be predicted based solely on its thermodynamic properties. This hypothesis is supported by findings from Newcombe et al. (2002) who also found that carbons with a higher volume of transport pores showed greater adsorption.

![Figure 1](image_url) | MIB breakthrough curve for Carbon B with Gompertz curve fit, Lake Simcoe. (C/C₀ is the RSSCT effluent MIB concentration over influent MIB concentration.)

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Comparison of MIB breakthrough (20% of C₀) to characterization results ($R^2$ values, +/− indicates positive or negative slope in linear regression analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lake Simcoe 1</td>
</tr>
<tr>
<td>Iodine number</td>
<td>0.55 (+)</td>
</tr>
<tr>
<td>TCN</td>
<td>0.001 (+)</td>
</tr>
<tr>
<td>TCNG</td>
<td>0.004 (+)</td>
</tr>
<tr>
<td>MIB isotherm</td>
<td>0.77 (+)</td>
</tr>
<tr>
<td>BET surface area</td>
<td>0.80 (+)</td>
</tr>
</tbody>
</table>
of low molecular weight compounds (<200 g/mol) than the microporous carbons.

The RSSCT data, with Carbon D omitted, were then interpreted more simplistically by correlating the rankings of the activated carbons in terms of bed volumes of water treated to breakthrough, to the thermodynamic parameters. For all four water samples, the iodine numbers, BET surface areas and MIB isotherms, when ranked from ‘best’ to ‘worst’, correlated perfectly with best-to-worst MIB breakthrough characteristics. In contrast, there was no successful correlation between the TCN/TCNG rankings and ranked breakthrough performance.

These good correlations between MIB breakthrough and iodine numbers, BET surface area and MIB isotherms should be viewed with caution. From a thermodynamic perspective, the theory does not support a causal link between these parameters. It is possible that the observed correlations, while very strong, were entirely coincidental. If there is a true mechanistic link between MIB breakthrough and the iodine/BET/MIB breakthrough characteristics, it is due to a complex relationship of factors whose explanation would require a more detailed study than performed here. Nevertheless, the correlation is intriguing. As indicated earlier, others have noted a lack of correlation between MIB breakthrough and iodine/BET parameters, but these previous studies explored activated carbons from different parent materials. The good correlation (in terms of rankings) observed in this study was observed when censoring the data to include only bituminous-based activated carbons.

**RSSCT loading results**

While a utility would be most interested in using thermodynamic properties of GAC to predict service life in terms of breakthrough, out of interest, we explored whether the thermodynamic properties might relate to the total MIB loading (ng MIB per g activated carbon) that could be achieved during the service life of the different GACs. Cumulative MIB loading was plotted from data using Lake Ontario water (Figure 2). Ideally, loading would be determined at a state of saturation, as shown by a levelling-off of the curves in Figure 2. In this experiment, however, saturation was not reached, so an arbitrary run time of 50,000 bed volumes of treated water was chosen to compare loading results. This is equivalent to approximately 9 months of run time in the full-scale treatment plant. The rationale behind exploring loading capacity from RSSCT results is that as a mostly thermodynamic phenomenon it, in theory, would better correlate to isotherm tests (such as the iodine number and TCN). Corwin (2010) showed, however, that equilibrium reached in RSSCTs will be an apparent capacity due to the presence of dissolved organic matter causing fouling of the activated carbon. This is also clearly shown in this study’s results where the loading capacity of MIB is 1.5–3 times higher in carbons tested with Lake Ontario water (TOC = 2.30 mg/L) versus carbons tested with the organically-rich Lake Simcoe water (TOC = 4.02 mg/L) (Figure 3).

Correlations between the thermodynamic parameters (iodine, TCN, TCNG, BET surface area, MIB isotherms) and the MIB loading at 50,000 bed volumes are shown in Table 7. No strong correlations were observed ($R^2 < 0.6$). In particular, the poor correlation between the MIB isotherm parameter obtained from experiments in otherwise pure water and the MIB loading observed in natural water demonstrates the confounding effect of NOM on the ability to predict GAC performance in natural waters.

### Table 6 Adsorption and transport pore volumes for five carbons (CCC 2009)

<table>
<thead>
<tr>
<th>Adsorption pore volume (mL/g)</th>
<th>Transport pore volume (mL/g)</th>
<th>Transport:Adsorption pore ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon A 0.331</td>
<td>0.295</td>
<td>0.88</td>
</tr>
<tr>
<td>Carbon B 0.384</td>
<td>0.218</td>
<td>0.57</td>
</tr>
<tr>
<td>Carbon C 0.308</td>
<td>0.147</td>
<td>0.48</td>
</tr>
<tr>
<td><strong>Carbon D 0.348</strong></td>
<td><strong>0.795</strong></td>
<td><strong>2.28</strong></td>
</tr>
<tr>
<td>Carbon E 0.458</td>
<td>0.399</td>
<td>0.87</td>
</tr>
</tbody>
</table>

![Figure 2 | MIB loading, Lake Ontario.](https://iwaponline.com/ws/article-pdf/12/4/531/416910/531.pdf)
SUMMARY AND CONCLUSIONS

Our initial hypothesis was that thermodynamic characterization parameters specifically designed to quantify the high energy adsorption sites on activated carbon (i.e. TCN, TCNG parameters) would be better correlated to MIB removal performance when measured using RSSCTs than the traditional iodine numbers and BET surface areas. Our experiments showed the opposite: there was no predictive ability observed for the TCN or TCNG parameters while, interestingly, there was a weak to moderate correlation observed for iodine, BET and MIB adsorption isotherms. When the lignite coal carbon was omitted from the data and the analysis was restricted to the remaining four bituminous coal carbons, an even stronger correlation between GAC service life and these isotherm parameters was observed. In particular, the relative rankings of bituminous coal GACs in terms of iodine, BET and MIB isotherms perfectly matched the rankings in bed volumes treated prior to MIB breakthrough, under the limited conditions explored.

The poor correlation between TCN/TCNG parameters and MIB removal (both adsorption isotherms and breakthrough under dynamic conditions) may be, in part, related to an incorrect assumption that the high energy adsorption sites identified by the TCN/TCNG parameters are very similar to those responsible for MIB removal. In fact, the calculated adsorption energies under isotherm test conditions were different by a factor of more than four. Another hypothesis involves a possible confounding impact of competitive adsorption by trace organic matter in the Milli-Q water during the isotherm tests.

The good correlation observed between MIB removal and iodine/BET parameters was unexpected and is not supported by thermodynamic theory. MIB removal requires far higher adsorption energies than the adsorption of iodine or nitrogen under the test conditions. The observed correlation may be coincidence, or there may be a more complex phenomenon at work that involves the role of competitive adsorption of background organic matter, or other factors. The study was not designed to explore this phenomenon but the strong correlation suggests that some future work might be valuable.

The main conclusion of this study is that the TCN and TCNG parameters did not appear to provide information that could add to a utility’s ability to predict GAC performance for MIB control, under the conditions explored.

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