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LIST OF ABBREVIATIONS

FPM	Flavor Profile Method
CFU	colony forming units
cm	centimeter
°C	degrees Celsius
GAC	granular activated carbon
g	gram
g/L	grams-per-liter
GC/MS	gas chromatograph/mass spectrometer
Lb/gal	pounds-per-gallon
L	liter
MIB	2-methylisoborneol
mg	milligrams
mg/L	milligrams-per-liter
mg/mL	milligrams-per-milliliter
m/h	meters per hour
min	minutes
mL	milliliter
mm	millimeter
MTZ	mass transfer zone
ng/L	nanograms-per-liter
NOM	Natural Organic Matter
OWASA	Orange Water and Sewer Authority
oz	ounce
PAC	powdered activated carbon
PCA	Principal Component Analysis
ppt	parts-per-trillion
RO	reverse osmosis
rpm	rotations per minute
RSSCT	Rapid Small Scale Column Test
TOC	Total Organic Carbon
TON	Threshold Odor Number
UPW	Ultra Pure Water

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ABSTRACT

The Orange Water and Sewer Authority (OWASA), which services the towns of Chapel Hill and Carrboro, has experienced taste and odor causing algal blooms in the two reservoirs from which it draws water – University Lake and Cane Creek Reservoir. These algal blooms generate earthy-musty odors by the production of the secondary metabolites geosmin and methylisoborneol (MIB). Although taste and odor are of secondary concern in water treatment consumers will frequently judge the quality of their tap water by its aesthetic appeal. Since geosmin and MIB are highly resistant to oxidation by conventional treatment methods, this study investigated adsorption by powdered activated carbon (PAC) added at the coagulation step and granular activated carbon (GAC) as a replacement for existing filter media (a filter cap). The Flavor Profile Method (FPM) and an "electronic nose", the Aromascan, were employed as analytical tools to evaluate the extent of odor removal in treated samples of OWASA raw and settled water. Bench-scale studies showed that the effectiveness of PAC was variable over summer sampling and was also dependent on the type of PAC (Westvaco Aquanuchar vs. Hydrodarco B). GAC as a filter cap offered more positive control than PAC, but competition with natural organic matter lessened its effectiveness.

CHAPTER 1. INTRODUCTION

Although taste and odor are of secondary concern in water treatment, consumers will frequently judge the quality of their tap water by its aesthetic appeal. Thus, while taste and odor are not necessarily major health concerns, utilities must address taste and odor problems if they wish to maintain consumer confidence in the finished product.

The Orange Water and Sewer Authority (OWASA), which services the towns of Chapel Hill and Carrboro, draws its raw water from two reservoirs – Cane Creek Reservoir and University Lake, both of which are relatively high in natural organic matter (NOM) and have experienced algal blooms during the summer months. One of the major problems caused by algal blooms is the associated earthy-musty odors. These odors stem from secondary metabolites produced by actinomycetes and blue-green algae in both reservoirs and the distribution system. The two major earthy odor metabolites – geosmin and methylisoborneol (MIB) – are cyclic tertiary alcohols that are highly resistant to oxidation by conventional water treatment methods (Cross 1981, Izaguirre et al. 1982). The most common approach to remove these compounds is the addition of powdered activated carbon (PAC) although the dosing strategy is more art than science.

The difficulties with odor control have prompted OWASA's interest in exploring the effectiveness of PAC treatment in more detail and to also examine the potential for treatment by granular activated carbon (GAC). PAC presents the advantages of low capital costs and ease of operation, but selection of the correct dosage to control a given odor event in the raw water is difficult. The dosage of PAC must be sufficient to adsorb enough of the odor-causing compounds to reach a target control level. In contrast, GAC

is charged into the existing filter boxes, usually to replace the upper layer of anthracite and thus to produce a "filter cap." GAC is more expensive than PAC but it provides a more positive way to remove odor-causing compounds because a fixed-bed of adsorbent material can remove nearly all of the adsorbable compounds so long as adsorption capacity remains. Unlike PAC, where dosage must be adjusted depending on the intensity of the odor problem, compounds will be adsorbed by GAC despite variations in the feed concentration of odor-causing compounds. Depending on the frequency of events, GAC may be cost competitive with PAC, particularly in cases where high doses of PAC are required for a sustained period of time.

Because of the subjective nature of odor in water, the selection of a technique to measure odor and its removal by treatment is as critical as the treatment method itself. The traditional odor measurement used at the OWASA water treatment plant (WTP) has been the Threshold Odor Number (TON) wherein one OWASA employee serves as the judge of odor in the water. The TON is the number of dilutions of the water needed until no odor is perceived. TON can be unreliable for the identification of earthy musty odors, since it only gives overall intensity rather than intensities for individual odor components (Krasner et al. 1985). In addition, odor is judged by a single OWASA employee who may be not as sensitive as an OWASA customer. As an alternative to TON, OWASA is currently using an "electronic nose" called the Aromascan in hopes of achieving a more quantitative measure of odor. The Aromascan employs a series of 32 polymer sensors over which a volatilized water sample passes. The response of the sensors produces a unique pattern that identifies the odor. As a new instrument, the Aromascan's ability to

detect odors in drinking water, which are generally present in low concentrations (geosmin and MIB create problems at the parts per trillion level), is relatively unknown.

Over the last 15 years, the Flavor Profile Method (FPM) has emerged as an alternative to the TON. Instead of a single panel member, multiple panelists are used in the FPM. They must reach a consensus on the quantification of the odors and this makes the results consistent and reliable. In addition, the panelists are trained by exposing them to different sources of odors so that both odor intensity and class of odor can be reported. The FPM has been used successfully in the drinking water industry, most notably in the Philadelphia Suburban Water District and the Metropolitan Water District of Southern California, as an indicator of odor events and effectiveness of treatment. Both utilities found FPM to be a more effective tool than the TON, and the FPM has become a well-established method for sensory detection in the last 15 years.

The objectives of this research were four-fold: (1) determine if Aromascan has been useful to OWASA in control of PAC dosing to remove earthy-musty odors; (2) assess the effectiveness of two brands of PAC for control of earthy-musty odors in jar test experiments that simulated coagulation conditions at OWASA; (3) compare the FPM to Aromascan as a way of measuring the effectiveness of PAC treatment in jar test experiments; and (4) assess the effectiveness of GAC for removal of geosmin and MIB spiked into OWASA water in laboratory-scale column tests that simulated a full-scale filter cap.

CHAPTER 2. LITERATURE REVIEW

2A. Generation of Earthy-Musty Odors

Earthy-musty odors in municipal water supplies are most frequently attributed to the presence of two compounds – geosmin and 2-methylisoborneol (MIB). Geosmin was isolated by Gerber and LeChevalier (1964) while MIB was identified by Medsker et al. (1969) and separately by Rosen et al. (Izaguirre 1982). Both are known metabolites of cyanobacteria (blue-green algae) and actinomycetes (Safferman 1967, Dougherty et al. 1966).

Romano and Safferman (1963) identify soil, particularly the exposed banks of streams and reservoirs, as the primary site of development of actinomycetes. Actinomycete counts in bank mud can reach upwards of 1 million CFU/g (Goodfellow and Williams 1983). The plant and animal debris in bank mud provide more nutrients than does reservoir water. This results in high concentrations of geosmin and MIB that enter the reservoir either through runoff or seepage into the water. Cyanobacteria are widely distributed in nature and can thrive in both soil and water. As photolithotrophs, they prosper in the summertime when intense sunlight enables them to outcompete many microbial species.

No direct relationship has yet been established between microbial counts and earthy-musty odors. This is evidently due to the fact that geosmin and MIB are secondary metabolites of the microbial species (Cross 1981). Secondary metabolites are produced near or during the stationary phase of growth and their formation is highly dependent on

growth conditions. Unlike primary metabolites, it is often possible to get overproduction of secondary metabolites, particularly when nutrients are abundant (Brock 1997).

2B. Characterization of OWASA Source Waters

Natural organic matter in the waters of University Lake and Cane Creek Reservoir was characterized by Dr. Gary Amy's research group at the University of Colorado, Boulder (OWASA 1998). Both source waters have low alkalinity (35 mg/L as $CaCO_3$ in University Lake and 23 mg/L as $CaCO_3$ in Cane Creek Reservoir) and relatively high organic content (dissolved organic carbon levels of 5.58 mg/L in University Lake and 6.36 mg/L in Cane Creek Reservoir). The two sources also demonstrated similar molecular weight distribution of the organic matter, with a large fraction of moderate to high molecular weight – around 850 Daltons. From a treatment perspective, this is beneficial since coagulation tends to interact more effectively with the larger molecular weight fraction. The organic matter in the water of Cane Creek Reservoir is also of a more hydrophobic nature than University Lake and may thus be more easily coagulated.

A series of studies were performed by Ecological Consultants in order to characterize the microbial nature of Cane Creek Reservoir and University Lake. Many species of blue-green algae had been identified previously in Cane Creek Reservoir (OWASA 1997) and *Lyngbya contorta*, a planktonic alga, was identified in the waters of University Lake. The two reservoirs tend to experience planktonic algal blooms in the period between April and early September (OWASA 1996) and positive identification of taste and odor causing phytoplankton was performed in these analyses.

In research done at the University of North Carolina, Chapel Hill, William M'Coy (1986) characterized the odor in the OWASA source water using the Flavor Profile Method. Musty odor was present throughout the oxygenated layer of University Lake and in the raw water intake to the Jones Ferry Plant. OWASA raw water from the late summer was sent to the Metropolitan Water District of Southern California for analysis and was found to contain 2 ng/L of MIB and 4 ng/L of geosmin. It was postulated that the concentrations of these odorants is higher in mid-summer, since the odor intensities reported for that time period were correspondingly higher. The research also demonstrated that a large portion of the odor was removed after coagulation (with PAC) and settling. After chlorine addition, the panel was no longer able to detect the musty odor; it was either masked or oxidized by the chlorine.

2C. Detection of Earthy-Musty Odors

General

In order for a substance to be detected by the human nose, it must be volatile and able to reach the olfactory nerves. The olfactory nerves in the nose are extremely sensitive; a sensitive individual can detect geosmin at concentrations as low as 4 ng/L and MIB at 9 ng/L (AWWARF 1991). The two most common methods for odor detection in municipal water supplies are the Threshold Odor Number (TON) and the Flavor Profile Method (FPM).

Threshold Odor Number (TON)

The TON test is the traditional method for quantifying odor intensity in drinking water (AWWARF 1991). In this test, several aliquots of the sample to be evaluated are

diluted to varying degrees with odor-free water, warmed and then the odor is evaluated by one or more individuals. The highest dilution in which an odor can be perceived is considered to be an indirect expression of that sample's threshold odor concentration, and this dilution is reported as the "threshold odor number."

TON analysis can be unreliable since individual odor sensitivity varies and may not even be consistent on a day to day basis. In addition, the TON method merely gives an overall odor perception; individual odor descriptors cannot be tracked by this method.

Flavor Profile Method (FPM)

The FPM presents significant advantages over TON in identifying earthy-musty odors. The FPM employs a panel of sensitive individuals who have been trained to detect a set of odors commonly present in drinking water. The point at which panelists begin to detect objectionable odors is known as the threshold odor concentration

Selection and training of panel members for FPM is critical if the method is to generate reproducible results. Bartels et al. (1985) identify three important characteristics for selecting panel members. These are a panelist's willingness to participate, an ability to express one's findings and assertiveness about findings even if they are in the minority. Panelists are trained in hour-long sessions during which they are exposed to odor standards at different concentrations. Some examples of chemical standards for basic odors present in drinking water appear in Table 1. Training with standard chemicals over time will allow the generation of a sensory response curve.

Table 1. Typical odors found in drinking water and the suggested standards for use in the FPM

Odor Description	Standard
Earthy-Musty	Geosmin, 2-Methylisoborneol, 2, 4, 6 – Trichloroanisole
Bitter	Quinine
Geranium-like	2-Ethoxyhexa-3,5-diene
Fishy	Trimethylamine
Chlorinous	Sodium Hypochlorite
Grassy	Coumarin

FPM presents significant advantages over TON, particularly for the purposes of this investigation. Since TON only gives an overall intensity, the individual intensity of the earthy-musty odor is not necessarily discernible (Bartels et al. 1985, Krasner et al 1985). Objectionable odor may be due to an integrated response to the mixture of chemicals, not all of which are in the same concentration (AWWARF 1991); the value given by TON in such cases is not very descriptive. With respect to individual rankings, the FPM panelists are able to monitor each other's performance; oversensitive individuals will scale their rankings down and undersensitive individuals must scale their rankings upwards. Additionally, the pre-selection of sensitive individuals ensures that the panel will detect odor problems before the customers. The utility can then use the panel to determine when problems are just beginning so that they can be dealt with before reports of complaints escalate (Bartels, Burlingame and Suffet 1986).

Aromascan

The Aromascan represents part of a continuing effort to establish an instrumental method for odor detection that matches the ability of human sensory perception. The

Aromascan employs an array of 32 polymer sensors, each of which changes in resistance when exposed to volatile chemical species (Byun et al. 1997). The response of the polymer array should produce a unique pattern for any given chemical species, which through Aromascan support software is modeled in a linear fashion. The data processing program for Aromascan then transforms these data into a two dimensional Principal Component Analysis (PCA) map. This map, of which examples appear in Appendix I, gives the analyst a visual representation of how different odorants are related to each other.

The Gulf Coast Water Authority utilized the Aromascan to detect MIB and geosmin in water samples (Thompson et al. 1998). Analysts at the water authority "trained" the Aromascan to recognize concentrations of MIB and geosmin as low as 5 ppt. Data from the Aromascan were compared against GC/MS analysis for the same samples and the results were comparable; for example, a sample identified as having 9.3 ppt of geosmin in the GC/MS was identified by the Aromascan as having between 5-9.99 ppt of geosmin.

Treatment of Earthy-Musty Odors

Geosmin and MIB are both members of the earthy-musty odor group, reflecting a similar chemical composition. As such, it is assumed that treatment schemes for odors in the same group should be similarly effective. In a finished water, earthy-musty odors can be masked by the stronger odor of chlorine but can be detected as chlorine is consumed by demand within the distribution system (AWWARF 1991).

Geosmin and MIB are very difficult to oxidize (Amoore 1985). Two recent studies have evaluated biodegradation as a tool for eliminating geosmin and MIB

(Tanaka et al. 1996, Saito et al. 1999). Bacteria of the genera *Pseudomonas* and *Enterobacter* are capable of MIB degradation and were employed in a study by Tanaka et al (1996). The researchers identified several biodegradation products from the cultured bacteria, some of which were odorous. Camphor, for example, was among the products present in the culture solution. A study of geosmin by Saito et al. (1999) found that it was much more difficult to biodegrade than MIB – after several months of culture, no products of biodegradation were found in the culture solution. The addition of ethanol yielded four previously unidentified biodegradation products. Addition of a high energy yielding primary substrate in both studies greatly increased the yield of geosmin and MIB biodegradation products, but this would not be useful in the practice of water treatment.

Within the last two decades, it has been established that MIB and geosmin are effectively removed by adsorption (AWWA 1999). PAC is the treatment most commonly selected for taste and odor treatment (AWWARF 1987). PAC has the advantages of being cheaper and requiring a minimal capital expenditure for feeding and contacting equipment. PAC can be applied only as needed for utilities experiencing only episodic taste and odor problems.

During odor-producing episodes, the negative effects of disinfectants and natural organic matter on PAC removal of geosmin and MIB can be of particular significance (Najm et al. 1981). Lalezary et al (1988) found that MIB and geosmin removal by PAC are significantly decreased at chlorine dosages as low as 2 mg as Cl_2/L, with the effect being greater on MIB removal. It has been shown that the carbon surface can be deactivated by chlorine through production of surface oxides, thus lessening adsorption of organic compounds. It was later reported by Gillogly and Snoeyink (1998) that the

amount of chlorine reacted, not the initial concentration of chlorine, determines the extent of surface oxide production and hence the magnitude of the negative effect on adsorption. In their study of MIB adsorption, they found that chlorine oxidized the activation sites for MIB, and reduced adsorption by 33 percent. By minimizing the time for interaction between the PAC and the chlorine, the adsorption of MIB can be maximized and PAC performance can be optimized.

The presence of background organics can also have a negative effect on PAC performance (Lalezary et al. 1988). The organics can block active sites on the carbon, thereby decreasing the number of absorptive sites available for MIB and geosmin removal. As with chlorine, the negative effects are greater for MIB than for geosmin. Lalezary et al. found that by increasing the carbon dose, the negative effects of background organics could be eliminated.

GAC is highly effective at removing taste and odor causing compounds (AWWA 1999). The adsorption mechanism in a GAC bed is best explained by the concept of the mass transfer zone (MTZ). The MTZ defines an adsorption front behind which the GAC particles are saturated with adsorbate. Ahead of the adsorption front, the GAC particles have not yet been exposed to the contaminant. The degree of saturation within the column can therefore range from 100 percent (behind the adsorption front) to zero (ahead of the adsorption front). If operation is stopped before the adsorption front arrives, the concentration of the adsorbate in the filtrate will be very close to zero. This is in contrast to PAC, where the concentration of adsorbate in the water will decrease with increased PAC contact time, but the concentration of adsorbate in both the water and the PAC will

eventually reach some non-zero equilibrium value. It is therefore impossible to achieve the same low contaminant concentrations with PAC as with GAC (AWWA 1999).

Studies by Chen et al. (1997) demonstrated that the high adsorption capacity of GAC for MIB can reduce effluent MIB levels to less than 10 ng/L. As with PAC, the type of carbon used and presence of dissolved NOM can greatly affect performance. Chen et al. (1997) found bituminous carbon to have the highest adsorption capacity for MIB, followed by peat, lignite, and wood carbons. In general, when GAC is used for taste and odor removal, changeout is required only every 2-5 years (Oxenford and Lykens 1991) depending on the frequency and severity of the taste and odor events.

Although many studies have shown that fresh GAC is effective for the removal of MIB and geosmin, only recent work by Gillogly et al. (1999) has focused on more practical concerns about loss of adsorptive capacity due to adsorption of NOM. Given that taste and odor problems are often sporadic, it is important to determine if GAC filters that are in service for a long period of time prior to a taste and odor event will continue to provide effective removal. The concern centers upon pre-saturation of adsorption sites and/or blockage of adsorption sites by NOM.

Gillogly et al (1999) devised a new laboratory GAC column test to measure the reduction in adsorption efficiency of MIB of GAC filters that had been in service for various lengths of time before a simulated occurrence of high levels of MIB. These researchers used a very short column (1 cm. in length) filled with GAC taken from full-scale operating filters in Chicago, IL. The GAC media was not crushed to smaller particle diameter as is required by the Rapid Small Scale Column test (RSSCT). For fresh GAC, this is acceptable practice because grinding does not alter its adsorption

capacity (AWWA 1999). Gillogly et al. claim that crushing partially exhausted GAC (with respect to NOM adsorption) would open pores that had previously been blocked, thus providing more adsorption capacity for MIB than would exist on the uncrushed GAC. In other words, previous studies using the RSSCT to simulate performance of GAC partially saturated with NOM would overestimate the residual adsorption efficiency for micropollutants as well as naturally occurring compounds such as MIB and geosmin. The laboratory-scale GAC columns used by Gillogly et al (1999) provided an Empty Bed Contact Time (EBCT) of 3.3 minutes, identical to that used in the pilot-scale GAC filters to which they were being compared. The results showed that the percent removal of MIB (with a feed concentration of 50 ng/L) decreased from 80 % to 40 % as service time increased from startup (0 years) to 2 years.

In addition, the experimental method of Gillogly et al. (1999) minimizes the volume of feed water required thereby simplifying sample collection and storage. The volumetric flowrate (Q) is given by:

$$Q = \frac{V_b}{EBCT} = \frac{\left(\pi D^2/4\right)L}{EBCT} \qquad (1)$$

where V_b is the volume of the GAC bed, D is the GAC column diameter and L is the GAC bed length. Gillogly et al. (1999) used a very short bed depth (L = 1 cm) and small column diameter (D = 10 mm). The choice of L and EBCT determines the approach velocity (v) which is also referred to as the application rate of water:

$$v = \frac{L}{EBCT} \qquad (2)$$

For L = 1 cm and EBCT = 3.3 min, as used by Gillogly et al., the approach velocity was 0.18 m/h. This is considerably lower than in the design of filters ($v \sim 10$ m/h is typical). If mass transfer of adsorbate to the GAC surface is controlled by the external-film transport step, the approach velocity could affect the shape of the breakthrough curve. However, Gillogly et al. explored other GAC column designs that included higher approach velocities and showed that the breakthrough pattern of MIB was unaffected, implying that external mass transfer was not rate controlling. Thus, the experimental design was adequate to simulate pilot and, possibly, full-scale performance of GAC in removing MIB.

CHAPTER 3: METHODS AND MATERIALS

2A. Panel Training for the Flavor Profile Method (FPM)

Preparation for Panel Sessions

The glassware used for sample mixing and storage consisted of 250 mL French-square bottles with Teflon-lined screw caps. These bottles were cleaned by washing in warm tap water and detergent, rinsing five times with warm tap water, and then placed into an acid bath consisting of 15% nitric acid by volume where they remained for 24 hours. Following this treatment, the bottles were rinsed with taste- and -odor-free water and placed in a drying oven (Stability-Therm, Blue M Electric company). The taste-and-odor-free water used for the cleaning of glassware was local tap water that was treated by GAC filter in series with an ion-exchanger, provided by Dracor Water Systems (Durham, NC). The product water was thus deionized and nearly free of organic carbon. In this report, this water will be referred to as ultra-pure water (UPW).

In order for the panel leader to identify the samples during panel sessions, the glass sample bottles were labeled using labeling tape, marked with a china marker. Prior to testing, the bottles were placed in 30° C water baths for 30 minutes to equilibrate the temperature of all the samples.

For the panel training sessions, UPW was spiked with different concentrations of MIB and geosmin. The MIB and geosmin were obtained from the Waco Chemical Co.(Richmond, VA). These chemicals were dissolved in methanol at a concentration of 0.1 mg/mL. Using a micropipette, a stock solution (heretofore referred to as Stock Solution 1) of each was made by pipetting 0.25 mL of the Waco solution into a 250 mL

French-square bottle. The remainder of the volume was filled with UPW and agitated. This gave a stock solution of MIB/geosmin of $1x10^6$ ng/L that was kept refrigerated. Prior to each training session 0.25 mL of Stock Solution 1 was pipetted into a 250 mL French bottle and filled with UPW, yielding a new stock solution (referred to as Stock Solution 2) with a MIB/geosmin concentration of 100 ng/L. Stock Solution 2 was further diluted to 250 mL with UPW as shown in Table 2 to create solutions for the panel training sessions.

Table 2. Preparation of MIB and Geosmin Concentrations for FPM Panel Training

mL of Stock Solution 2 Diluted to 250 mL with UPW	Final Concentration of MIB/Geosmin (ng/L)
12.5	5
25	10
37.5	15
62.5	25
87.5	35

The MIB and geosmin solutions were placed in 9 oz. Solo plastic cups from which panelists were asked to respond to odor. Solo cups are considered the only brand that do not impart odor to the sample (M'Coy 1986). These cups were color coded red for geosmin samples and blue for MIB samples and coded with a letter/number code. Once water samples were transferred from the sample bottles to the plastic cups, the plastic cups were covered with a watch glass to prevent the volatile odorants from escaping.

Panelists were required not to eat or drink for up to one hour before sessions. In addition, panelists were not permitted to wear perfume, cologne, or aftershave on the day of the session. Just prior to testing, panelists washed their hands with Ivory soap. In

addition, panelists were given a cup of taste and odor free spring water (Harmony Brook) and salt free crackers (Carrs Water Thins) to cleanse the palate before sensory testing began.

Panel training and testing was performed in Room 107, a conference room, in Rosenau Hall, at UNC-Chapel Hill. This room was located away from any laboratory areas in the building and had the advantage of a large conference table around which the panel could convene as well as a large blackboard to record the consensus results.

Selection of Panel Members

Prospective panelists were recruited through an e-mail sent to the School of Public Health listserve. Panelists were given $10 per hour for participation. Six graduate students in the Department of Environmental Sciences and Engineering at the University of North Carolina –Chapel Hill responded and they were invited to a one-hour screening session from which five individuals (four to convene regularly and one for backup) would be selected for the panel. All of the panelists were relatively new to the Chapel hill area and thus had not been consuming OWASA water for more than three years.

The panel screening session consisted of a brief explanation of the project objectives and an explanation of the FPM followed by exposure to different water samples. These samples consisted of UPW spiked with different concentrations of MIB and geosmin (see Table 2) as well as raw, settled and finished water samples taken from the OWASA water treatment plant.

Panel Training

The first session was used to assess the volunteers' sensory ability. The volunteers entered the room and were asked to cleanse their palates with a water cracker. They were then presented with the taste-and-odor-free water (which would be considered to have a FPM intensity of zero) and a cup of UPW spiked with 35 ng/L of geosmin that they might be made aware of the full range of odor strength to which they were to be exposed. The panelists were then presented with cups of water spiked with 5, 10, 15, 25 and 35 ng/L of geosmin and asked to rank the odor intensity on a scale of 1-10. In between each sample, they cleansed their palates with a water cracker and smelled the taste-and-odor-free water. The volunteers were then given a 5-minute break and exposed to samples of water spiked with MIB concentrations of 5, 10, 15, 25 and 35 ng/L. The results of this session were analyzed and five volunteers were selected for further training based upon their ability to detect changes in earthy-musty odor intensity. Since the purpose of this research was to assess the removal of earthy-musty odors, the panelists were not trained to recognize chlorine, another common source of customer complaints.

The subsequent three training sessions were similar to the first, but also enabled panelists to gain familiarity with the FPM. The scale used for evaluation was that of the FPM, ranging from 0 to 3 as described in Table 3.

The panelists were first exposed to geosmin at concentrations of 5, 15, 25 and 35 ng/L following the same procedure as in the first session. A sample evaluation sheet is in Appendix I. After giving an initial rank to the samples, the panel discussed the results and reached a consensus rank for each, which was recorded on a blackboard in the front of the room. The panelists then ate a cracker and were presented with samples of water

Table 3. Description of FPM intensities used during panel training sessions. Scale increases in 0.5 increments from 0 to 3.

FPM Intensity	Description
0	No odor
0.5	Threshold odor
1	Slight odor
2	Moderate odor, would call utility
3	Strong odor

spiked with MIB at concentrations of 5, 15, 25 and 35 ng/L. As before, once the initial rankings were recorded, the panel reached a consensus on the rankings for each, which was recorded on the blackboard. Each training session lasted no more than an hour, to avoid sensory fatigue.

2B. OWASA Raw Water: Alum Coagulation/PAC Jar Tests

The jar tests described here were designed to simulate the chemical coagulation and settling conditions existing at the OWASA Water Treatment Plant (WTP). Liquid alum is added as the primary coagulant with Semifloc 1340 cationic polymer (Southeastern labs, Goldsboro,NC) as a coagulant aid. THM-R (Dabco Chemical, Inc., York, PA) is added to increase the removal of NOM and thus to reduce the formation of disinfection byproducts (DBPs) upon later chlorination. THM-R is a proprietary chemical that oxidizes NOM to render it less able to form DBPs. The dosages of each chemical used are listed in Table 4. The concentrations listed were selected after consultation with the OWASA laboratory staff.

For all tests, raw water was taken from the OWASA Jones Ferry Road plant and treated with alum and PAC. Samples were taken on: 6/1/99, 6/22/99, 7/7/99, 7/13/99,

7/19/99, 7/26/99, 8/3/99, and 8/11/99. On each of these dates, the raw water supply (Cane Creek Reservoir, University Lake or a combination of each) varied depending on demand.

Table 4. Chemical dosages for the jar tests

Chemical	Dosage (mg/L)
Alum	30
THM-R	9.2
Polymer	0.3

Liquid alum was provided in a concentration of 5.34 lb/gal. A stock solution was prepared by diluting the original solution by a factor of ten with UPW in a glass beaker on a magnetic stirring plate. The resulting alum concentration as $Al_2(SO_4)_3$ was 6,400 mg/L. For a 2 L jar, 9.4 mL was then needed for the desired alum concentration. The polymer was provided in dry, granular form. A stock solution of polymer was prepared by adding 2.032 g of the polymer crystals to 1 L of UPW in an Erlenmeyer flask and mixing on a magnetic stirring plate for one hour to completely dissolve the crystals. A volume of 0.3 mL was pipetted into the jar-test containers to yield a final concentration of 0.3 mg/L.

THM-R was provided at a concentration of 170.5 g/L. A stock solution was prepared by pipetting 25 mL of this solution into a beaker and filling to 250 mL with UPW. The volume of stock solution needed to achieve the desired THM-R concentration (9.2 mg/L) for the jar test was 1.1 mL.

The effectiveness of Westvaco Aqua-Nuchar and Hydrodarco B PAC in removal of odors was evaluated in the jar tests. Hydrodarco B is the PAC currently in use at the

OWASA WTP. Westvaco Aqua-Nuchar PAC was selected by the OWASA laboratory manager for testing. A 1 g/L slurry of each PAC was prepared by adding 500 mg of PAC into a 500-mL Erlenmeyer flask filled to the mark with UPW: the slurry was mixed on a magnetic stirring plate for one hour to ensure uniform concentration. A pipette with a wide tip was used to deliver aliquots of PAC slurry to each jar test container in order to achieve the desired PAC dosage.

The two PACs are made from different materials that can potentially affect their performance with regard to adsorption of both NOM and odor-causing compounds. The Westvaco Aqua-Nuchar PAC is derived from wood and the Hydrodarco B PAC is made of lignite; the properties of both are listed in Table 5. The Iodine Number relates the adsorbability of iodine and is thus a surrogate for small molecules. The Molasses Decolorizing Index relates the adsorbability of molasses and thus serves as a surrogate for large molecules (AWWA 2000). Considering these two parameters, the Westvaco Aqua-Nuchar would be rated as better than the Hydrodarco B PAC for adsorption of both small and large molecules. The literature, however, suggests better adsorption of the chemicals of concern – MIB and geosmin – onto lignite carbon (Lalezary et al. 1988 Chen et al. 1997, and Gillogly et al. 1998).

Table 5. Properties of the two brands of PAC used in the jar test experiments (Najm et al. 1991)

	Westvaco Aqua-Nuchar	Hydrodarco B
Source Material	Wood	Lignite
Iodine Number (mg/g)	800	550
Molasses Decolorizing Index	9	4
Apparent Density (g/cm^3)	0.64	0.5

Jar Test and PAC Dosing

A Phipps and Bird 2-L jar test apparatus was used to simulate the coagulation and settling conditions at the OWASA WTP. The apparatus provided for six jar tests to be conducted in parallel. The same dosage of alum, polymer and THM-R was added to 2 L of raw OWASA water as given in Table 4. The PAC dosages used in each experiment were: 6, 12, 20, 30 and 40 mg/L. The remaining jar served as a control containing alum, polymer and THM-R but no PAC.

To simulate rapid mix, each jar was placed on a stirring plate for 30 seconds for mixing. The water was then flocculated on the Phipps and Bird jar test apparatus for 39 minutes at 35 rpm. The paddles were then removed from the jars, and the samples allowed to settle for 59 minutes. These times were provided by OWASA staff as representative of plant conditions. Following settling, the water samples were filtered through a Whatman No. 40 filter to simulate the filtration process. Samples were then placed in acid-washed bottles and stored in the refrigerator overnight. Samples were placed in a 30^0 C water bath for one hour prior to subjecting them to the panel.

2C. PAC Treatment of OWASA Raw Water Spiked with MIB and Geosmin

The jar test experiments with OWASA raw water, as described above, were useful to determine the effectiveness of PAC in odor removal but the source of these odors was unknown. The next series of jar test experiments was designed to more specifically measure the effectiveness of PAC in removal of MIB and geosmin from OWASA raw water in the presence of background NOM.

Raw water was taken from taps at the OWASA WTP on 12/6/99 and placed in glass carboys. The water was stored in a walk-in refrigerator set to a temperature of 25°C. Just prior to executing the jar test, the settled water was spiked in the laboratory with 25 ng/L each of MIB and geosmin to simulate a worst-case scenario for the OWASA water supply. The jar test was otherwise performed as described in the previous section. The resulting water samples were placed in both 1-L amber glass bottles and 250-mL French -square bottles. The amber bottles were sent to the Philadelphia Suburban Water Authority for an analysis of MIB and geosmin concentrations. The French-square bottles were used to transport the samples to Room 107, Rosenau Hall for FPM analysis.

2D. GAC Treatment of OWASA Settled Water Spiked with MIB and Geosmin

GAC is an alternative to PAC treatment for control of odor-causing compounds in drinking water. To incorporate GAC into the treatment scheme, the anthracite layer above the sand layer in the dual media filters at the OWASA WTP could be replaced by GAC. The depth of the filter box, however, restricts the EBCT of such "GAC filter caps." Based on current application rates of water to the filters (about 10 m/h) the

practical limit of EBCT would be about 3 minutes, assuming that a sand layer of 12 inches must be maintained below the GAC.

The design basis for the laboratory study of a GAC filter cap was adopted from the work of Gillogly et al. (1999) as described in the Literature Review. The overall goal was to compare the effectiveness of GAC in removal of geosmin and MIB of a fresh and partially exhausted GAC bed. The measure of exhaustion of GAC is the adsorption of Total Organic Carbon (TOC), the usual surrogate for background NOM.

The two important features of the GAC column design that were taken from Gillogly et al. (1999) were the column length and GAC particle size. Column length (L) determines the application rate of water (i.e. approach velocity) for a specified EBCT:

$$v = \frac{L}{EBCT} \qquad (2)$$

With L = 1 cm and EBCT = 3 min, the application rate (v) is 0.56 m/h. This bed velocity is considerably less than the application rate of 10 m/h used in the practical design of filters. However, if mass transfer of adsorbate to the GAC surface is not controlled by the external transport step, then the breakthrough curve will not be affected by the choice of v.

The diameter of the column was 1.5 cm and thus the flow rate to achieve an EBCT of 3 min is determined by:

$$Q = \frac{\left(\pi D^2 / 4\right) L}{EBCT} \qquad (1)$$

This yields a design flow rate of 0.85 L/day. The small flow rate minimized the volume of settled water from the OWASA WTP that was collected and stored in a laboratory refrigerator.

Calgon F 400 GAC was used to test the efficiency of GAC adsorption of geosmin and MIB. As noted in the Literature Review, the GAC is not crushed in the Gillogly et al. (1999) design of the laboratory experiment. The GAC particles diameter for Calgon F400 is stated as 12 x 40 U.S. Standard Mesh, which translates to a geometric mean particle diameter of 1.05 mm. The weight of GAC that occupies the volume of the column defined by Equation 3 is 1 g.

The concentration of geosmin and MIB chosen for spiking the OWASA WTP settled water was 25 ng/L, the same as that used in the PAC experiment described in Section III. The background NOM as measured by TOC was 3.4 mg/L. For the test in which the fresh GAC was loaded into the column, the spiked OWASA water was continuously fed into the column for three days, simulating a taste and odor event of moderate length. For the test in which partially saturated GAC was loaded into the column, the spiked OWASA water served as the column influent for five days, a likely worst case scenario for the OWASA WTP.

A rough estimate was made of the volume of water that could be treated to exhaust the adsorption capacity of geosmin and MIB in the presence of NOM for the stated flowrate and this EBCT in the laboratory column. Chen et al. (1997) provided an adsorption isotherm for MIB on Calgon F400 (Figure 4 of this reference). The equilibrium adsorptive capacity corresponding to an aqueous-phase concentration of 25

ng/L was estimated as 100 ng/g (the adsorptive capacity for geosmin and MIB are of the same order of magnitude). Ignoring competitive adsorptive effects between geosmin and MIB and the mass transfer limitations in the adsorption process, the mass balance is:

$$C_f V = q_e W \tag{3}$$

where C_f is the feed concentration of either odor-causing chemical, V is the volume of feed before breakthrough, q_e is the adsorptive capacity and W is the weight of GAC in the laboratory column. The estimated volume of feed is:

$$V = \frac{q_e W}{C_f} = \frac{(100\,ng/mg)(1\,g)(1000\,mg/g)}{25\,ng/L} = 4000\ L \tag{3}$$

The corresponding time of operation of the GAC bed is:

$$t = V/Q = 4000\,L / 0.85\,L/day = 4718\ days \tag{4}$$

This estimated service time would be reduced by competition between geosmin and MIB for adsorption sites and by mass transfer limitations that cause both adsorbates to appear earlier. The service time is very long because of the low feed concentrations, but it illustrates the potential effectiveness of GAC, at least in theoretical terms.

Experimental Setup

A flow diagram for the GAC column experiment is given in Figure 1. A 5 L glass carboy was used to supply the feed water to the GAC column. A Milton Roy Mini-Pump was used to deliver a flow rate of 0.59 mL/min to the GAC column to provide an EBCT of 3 min.. The pump was adapted for use in this experiment. It was originally part of a high-pressure liquid chromotography set-up.

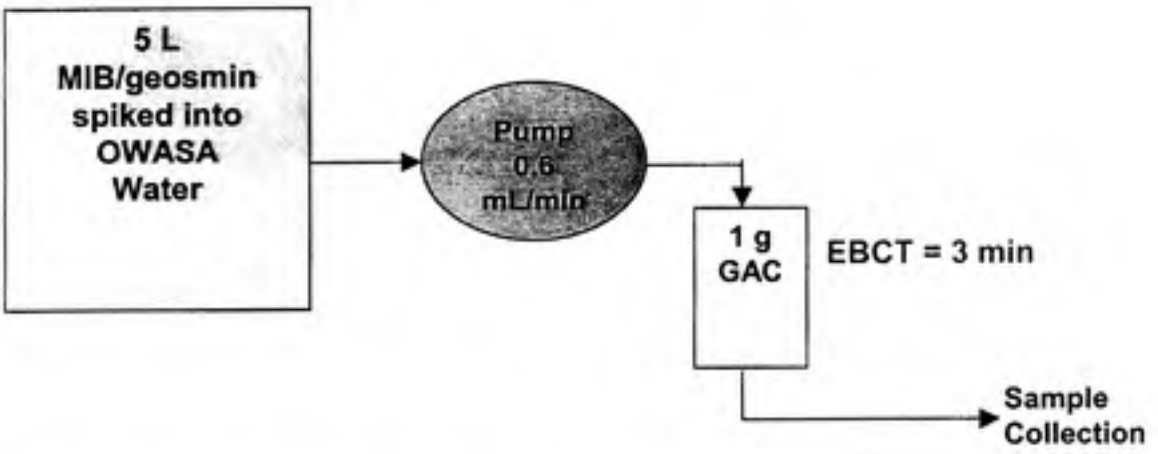

Figure 1. Bench-Scale Laboratory Setup for GAC Column Experiment

Fresh GAC Column Test

Fresh Calgon F400 GAC (1.5 g) was soaked in a beaker of UPW for one hour to allow for the release of oxygen bubbles. The water was then decanted off and the GAC was funneled into the column so that it occupied a 1-cm length of the column (This corresponds to 1 g of GAC). Settled water was taken from the OWASA WTP on 9/23/99 and stored in the laboratory walk-in refrigerator. The experiment was begun on 9/30/99 and run for nearly four days with effluent being collected every eight hours (the approximate length of time to fill a 250 mL French-square bottle).

Exhausted GAC Column Test

A technique was devised to preload the GAC with NOM in order to simulate a GAC filter cap after long exposure to background NOM. Based upon the rough estimate of service time for this GAC column, which was on the order of several thousands of days, it was expected that all of the geosmin and MIB would continue to be completely adsorbed over the course of the experiment if there was no interference from NOM. Two alternatives are possible to preload the GAC with NOM before charging it to the column

and feeding the spiked water: 1) feed settled water continuously to the GAC laboratory column for a time long enough to reach complete exhaustion of adsorptive capacity (i.e., to reach complete breakthrough of TOC, the surrogate for NOM), or 2) contact the GAC with a batch of settled water that has an NOM concentration much higher than in the expected feed water to drive the adsorption process toward a position approximating the equilibrium with the feed TOC concentration. As a rough estimate, if the feed TOC is 2 mg/L, the adsorption capacity for TOC is about 50 mg/g and the weight of GAC is 1 g, the first method would require feeding at least 25 L of water. At a flow rate of 0.59 mL/min (or 0.85 L/day), several weeks would be needed to preload the GAC. The second method was selected to reduce the time and make the experiment more convenient.

NOM in a 16-L batch sample of settled water from the OWASA WTP from 10/23/99 was preconcentrated by a laboratory reverse osmosis (RO) unit in the set-up shown in Figure 2. The permeate of the RO unit, which should contain a negligible TOC concentration, was discarded and the concentrate was returned to the feed tank. In this way, the volume of the feed solution decreased over time and the NOM concentration (as measured by TOC) increased. With the RO pumping rate of this laboratory unit, only 30 minutes were needed to reduce the feed volume from 16 L to 1.5 L. The TOC increased from 4.0 mg/L to 45 mg/L. A mass balance check on TOC gives 16 L x 4.0 mg/L or 65 mg that should be conserved. The final solution contained 1.5L x 45 mg/L or 69 mg. This discrepancy can be explained by possible instrumental and dilution error: since 45 mg/L is exceeds the TOC concentration for which the TOC analyzer is calibrated, the solution was diluted by ten times. A small instrumental error multiplied by ten could

have an effect on the mass balance. Likewise, a small dilution error may register a slight change in the TOC reading which is then exacerbated by the dilution factor.

The preconcentrated NOM solution was then contacted with the GAC that would later be charged into the laboratory column. The GAC charge of 1 g was divided into four approximately equal fractions and these were added to four, 250-mL French-square bottles. Each bottle was filled with 250 mL of the preconcentrated NOM solution. The bottles were capped and placed on a shaker table and agitated at a speed of 180 rpm for six days. At the end of the six days, water samples were taken from each of the bottles for TOC analysis. The results are shown in Table 6.

Figure 2. Diagram of Reverse Osmosis (RO) unit used to preconcentrate NOM in OWASA settled water for use in saturating GAC

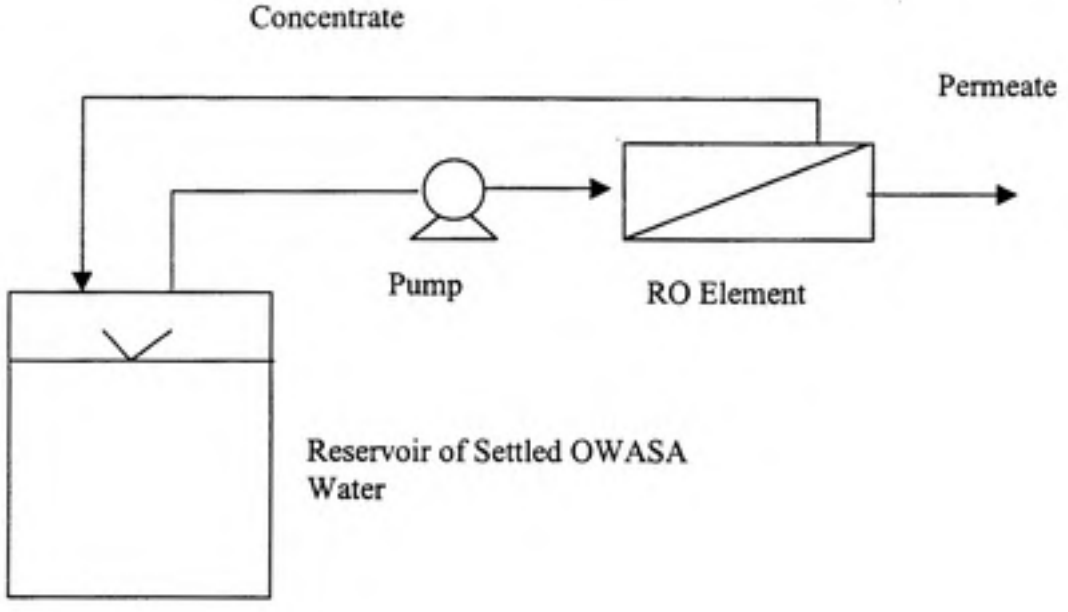

Table 6. TOC data for NOM preconcentration step; the NOM Concentrate represents the OWASA settled water that was concentrated through the RO device. The shaker flasks represent the water after 6 days of agitation with GAC in 250 mL French bottles

Sample ID	TOC (mg/L)
NOM Concentrated Water	45.0
Shaker Flask 1	10.5
Shaker Flask 2	10.8
Shaker Flask 3	8.6
Shaker Flask 4	6.9
Mean Value for all four shaker flasks	9.2

In order to approximate the actual service time represented by the NOM saturation of the GAC in the second experiment, the TOC measurements given in Table 6 were used in the following mass balance calculation:

$$q = \frac{(C_i - C_t)V}{W} \qquad (5)$$

where q is the amount of contaminant adsorbed per unit weight of GAC, C_i is the initial contaminant concentration, C_t is the contaminant concentration remaining after six days of agitating, V is the batch volume of water and W is the weight of GAC in the batch volume. Using the mean final concentration, as listed in Table 6 as the value of C_t in equation 5, this yields 36.1 mg of NOM adsorbed per gram of GAC. A mass balance on

TOC in the laboratory scale GAC column yields:

$$QC_o t = qW \tag{6}$$

where t is the time of operation, C_o is the estimated feed TOC concentration (3 mg/L based on OWASA records) and W is the weight of the GAC (1 g) in the column. The estimated service time for the loading of GAC before the introduction of MIB and geosmin is thus:

$$q = \frac{QC_o t}{W} = 36\,mg/g \tag{6}$$

$$t = \frac{36}{QC_o} = \frac{36\,mg/g}{(0.85\,L/day)(3\,mg/L)} = 14\ days \tag{7}$$

Once the GAC had been preloaded with NOM, the GAC column test was run as before, from 11/4/99-11/10/99. Samples were taken every 8 hours for six days and then sent to Philadelphia Suburban Water Authority for MIB and geosmin analyses. Samples were also analyzed for odor using FPM. The purpose of this test was to determine whether the adsorption of geosmin and MIB would decrease due to interference from NOM already on the surface.

CHAPTER 4: RESULTS AND DISCUSSION

4A. Odor Perception During the Panel Training Sessions

Subsequent to the pre-selection of the six individuals for use in the panel, three further panel-training sessions were executed. For each of three training sessions, the FPM responses of each panel member to geosmin are presented in Figure 3; those for MIB are in Figure 4. These figures demonstrate: 1) a fair amount of reproducibility from session to session for each panelist (odor impressions do not generally differ by more than 0.5) and 2) any differences in individual sensitivity that are revealed in the initial odor impressions from the training sessions. The relationship between odor intensity, as measured by FPM, and the concentration of MIB is shown in Figure 5. A similar relationship for geosmin in the water is shown in Figure 6. As described in the Literature Review, odor intensity is a linear function of the logarithm of the odorant concentration per the Weber-Fechner Law. The relationship was linear in each case, with about the same slope, indicative of a similar panel response to increasing concentration. The data for Figures 5 and 6 are consensus data from the training sessions; more training and a wider range of concentrations should improve this calibration. Figure 7 demonstrates directly that the panel was less sensitive to geosmin than MIB. A review of the literature indicates that humans are generally more sensitive to geosmin than MIB (AWWARF 1987); whereas these results showed the opposite. It should also be noted that concentrations of geosmin at or above 35 ng/L and concentrations of MIB at or above 25 ng/L are considered objectionable and readily detectable by the panel.

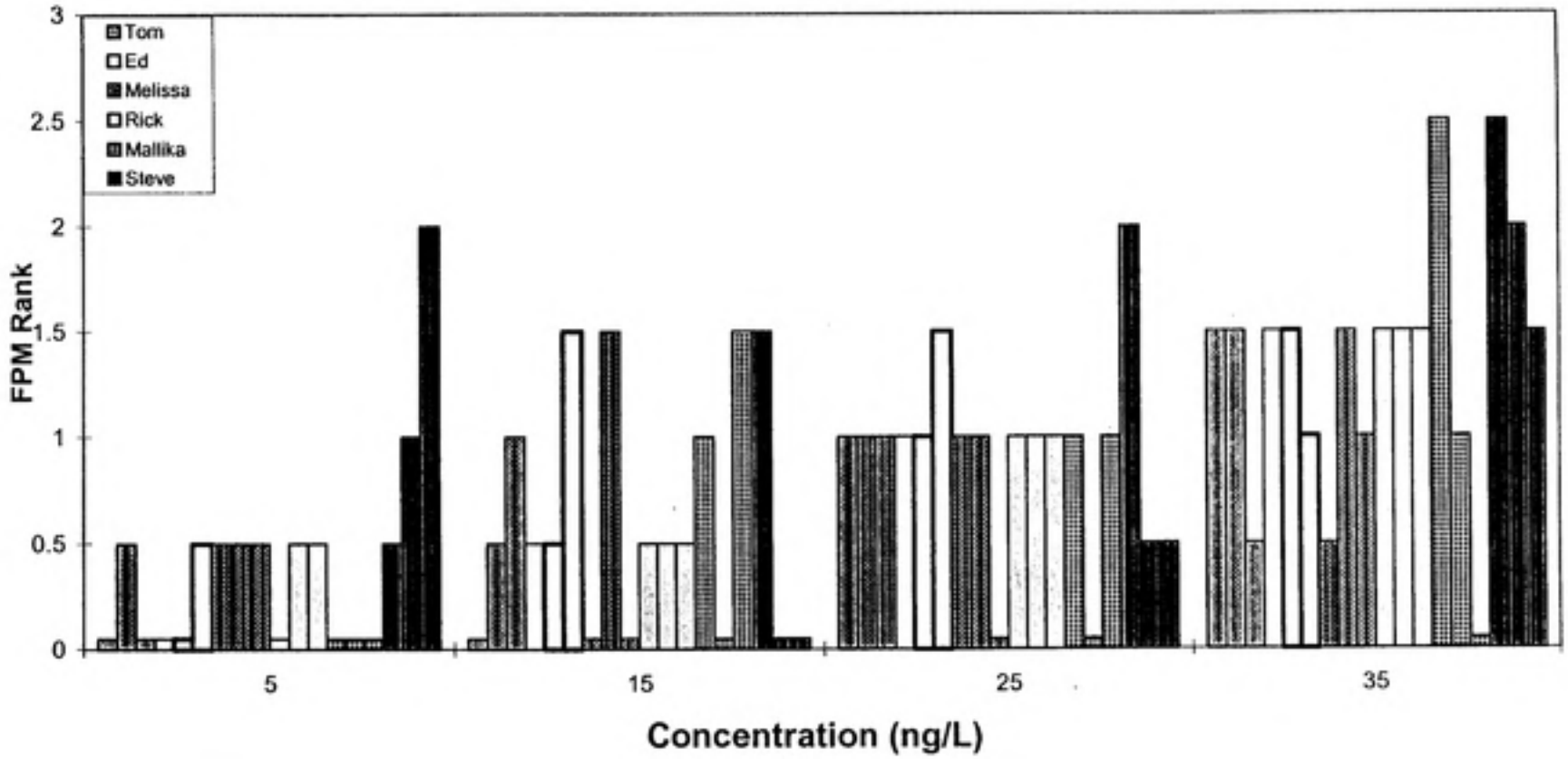

Figure 3. Individual Results for Exposure to Geosmin During Panel Training Sessions

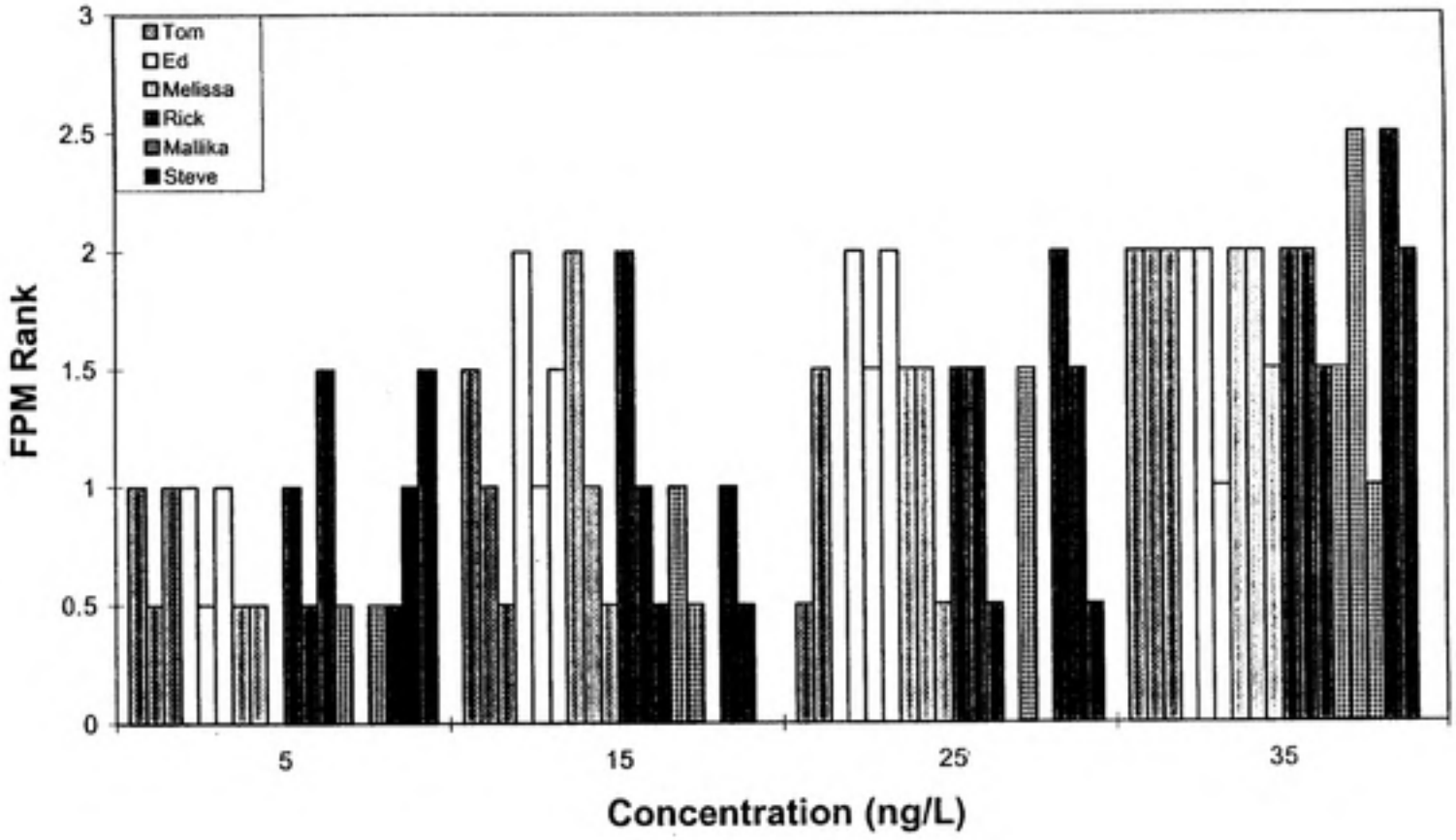

Figure 4. Individual Results for Exposure to MIB during Panel Training

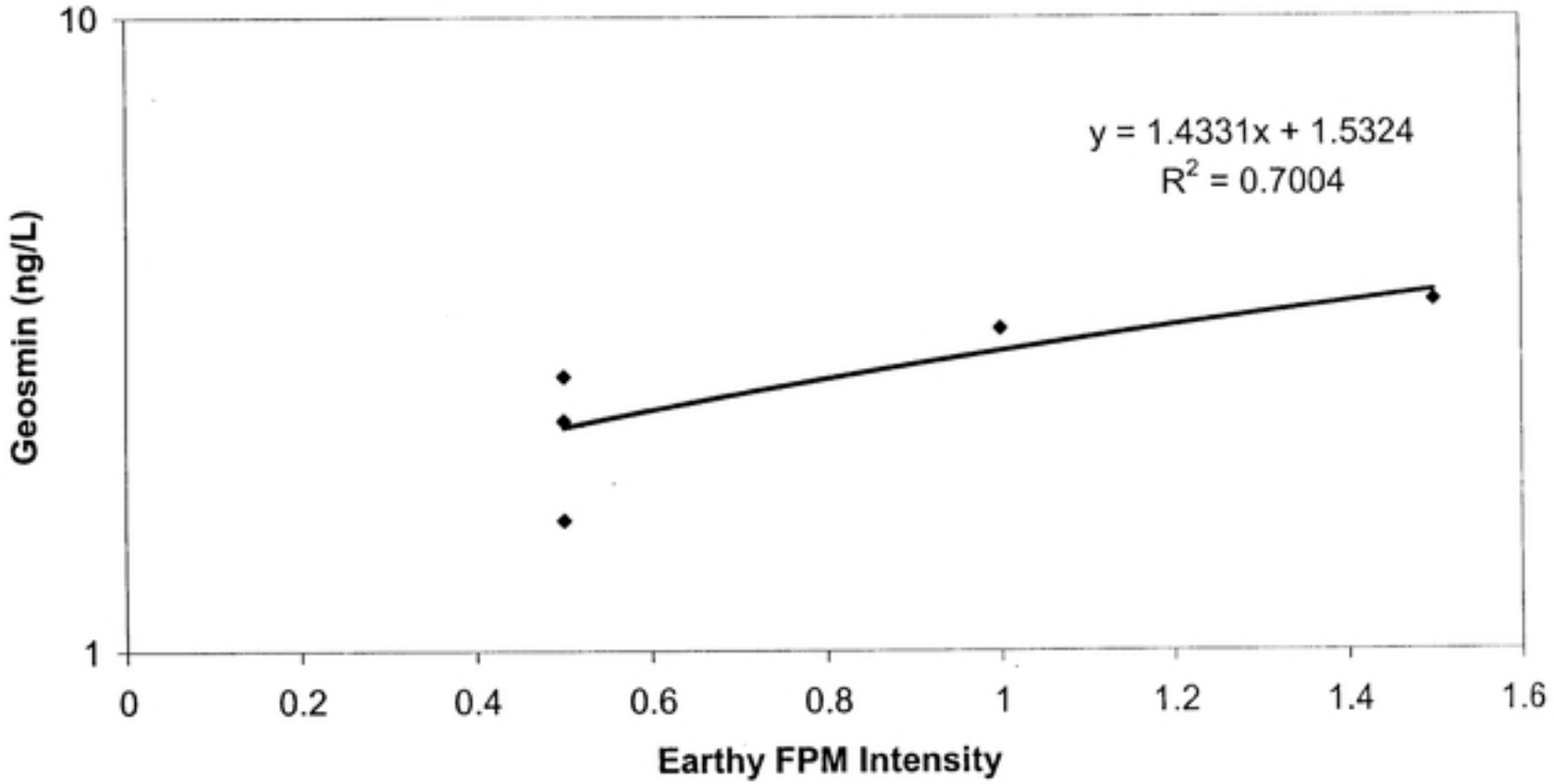

Figure 5. Correlation of earthy flavor intensities with geosmin concentration. Geosmin is plotted on a logarithmic scale as per the relationship between concentration and intensity predicted by the Weber-Fechner Law.

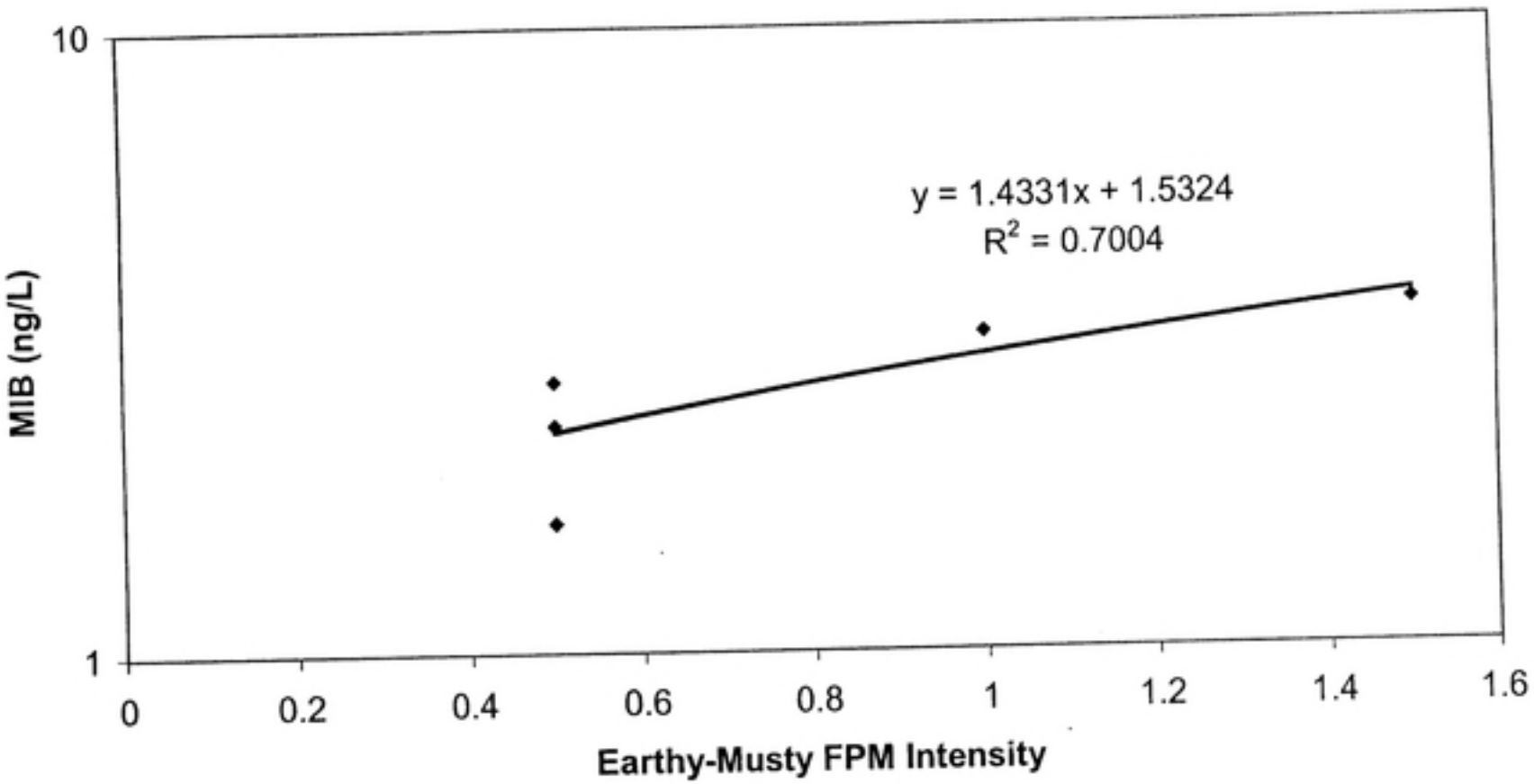

Figure 6. Correlation of earthy flavor intensities with MIB concentration. MIB is plotted on a logarithmic scale as per the relationship between concentration and intensity predicted by the Weber-Fechner Law

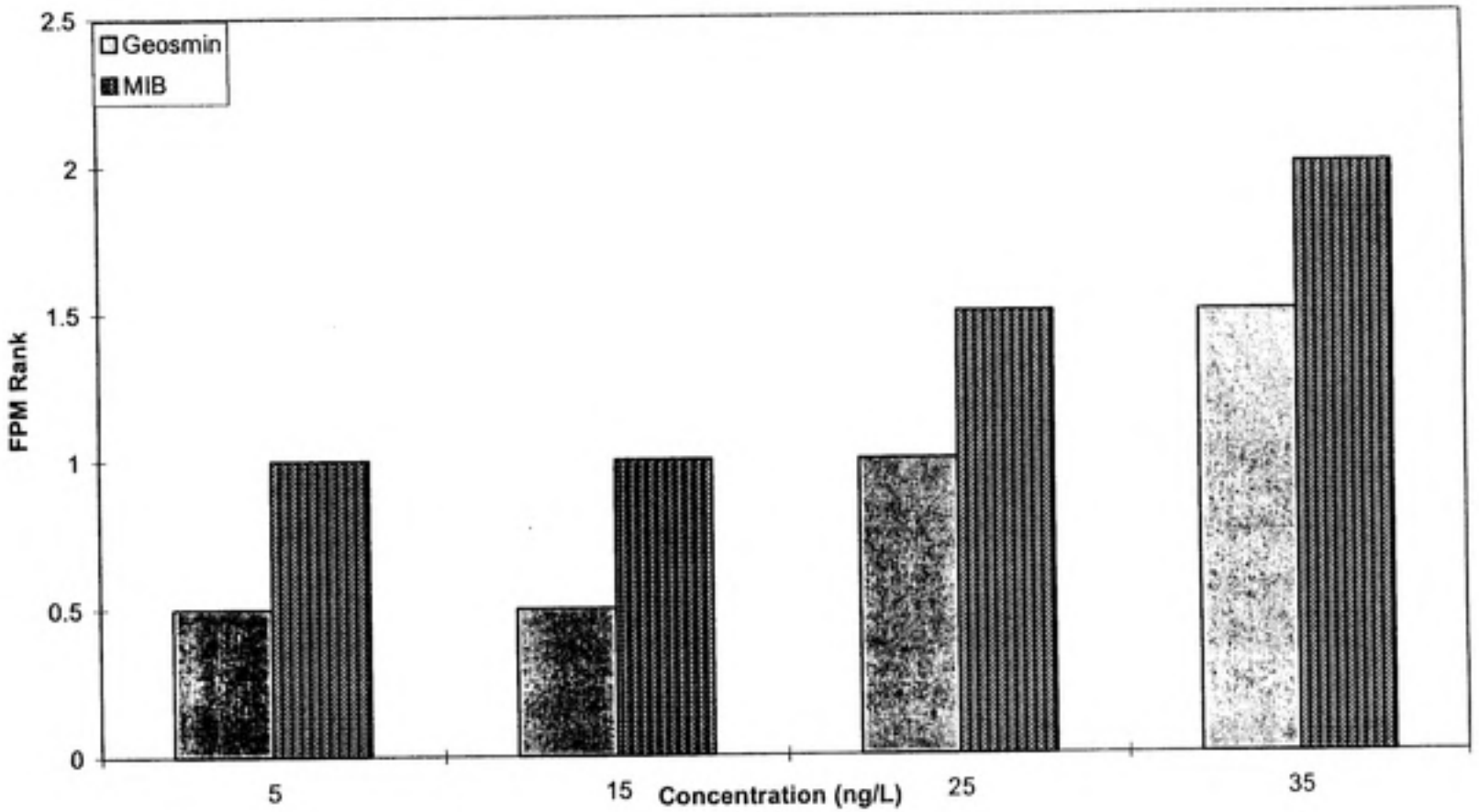

Figure 7. Comparison of Consensus Panel Response for MIB and Geosmin

4B. Aromascan As An Analytical Method

The results of several trials in which Aromascan was used to detect geosmin and MIB are given in Figures 8 and 9, respectively. In Figure 8, the same concentration of geosmin (15 ng/L) was analyzed by Aromascan on four different dates. The results show that Aromascan was not able to provide reproducibility in response.

As demonstrated in Figure 9, the quality factor did not increase with an increase in geosmin concentration from 5 ng/L to 35 ng/L. During a personal communication with the customer service department (Wayne Gagne 9/99) at Aromascan, it was confirmed that the instrument is unable to detect geosmin and MIB accurately at concentrations below 100 ng/L. It is quite possible that Aromascan was also detecting methanol (MeOH), the solvent in which MIB and geosmin were dissolved as supplied in the stock solution. Given that 0.1 mg of MIB or geosmin was dissolved per mL of MeOH and that the density of MeOH is about 0.8 g/mL, the ratio of MeOH to MIB or geosmin is 8000 to 1. Regardless of the dilution of the solution, this ratio remains fixed. The MeOH concentrations in each standard solution of MIB and geosmin used to test the response of the Aromascan are given in Table 7. If the Aromascan was sensitive to MeOH, the response to MIB or geosmin would be clearly overwhelmed. Unfortunately, control solutions containing only MeOH were not tested for response to Aromascan. Thus it is not possible to conclude that lack of sensitivity to MIB or geosmin was due to the MeOH response. Measurements with Aromascan were continued throughout the testing program

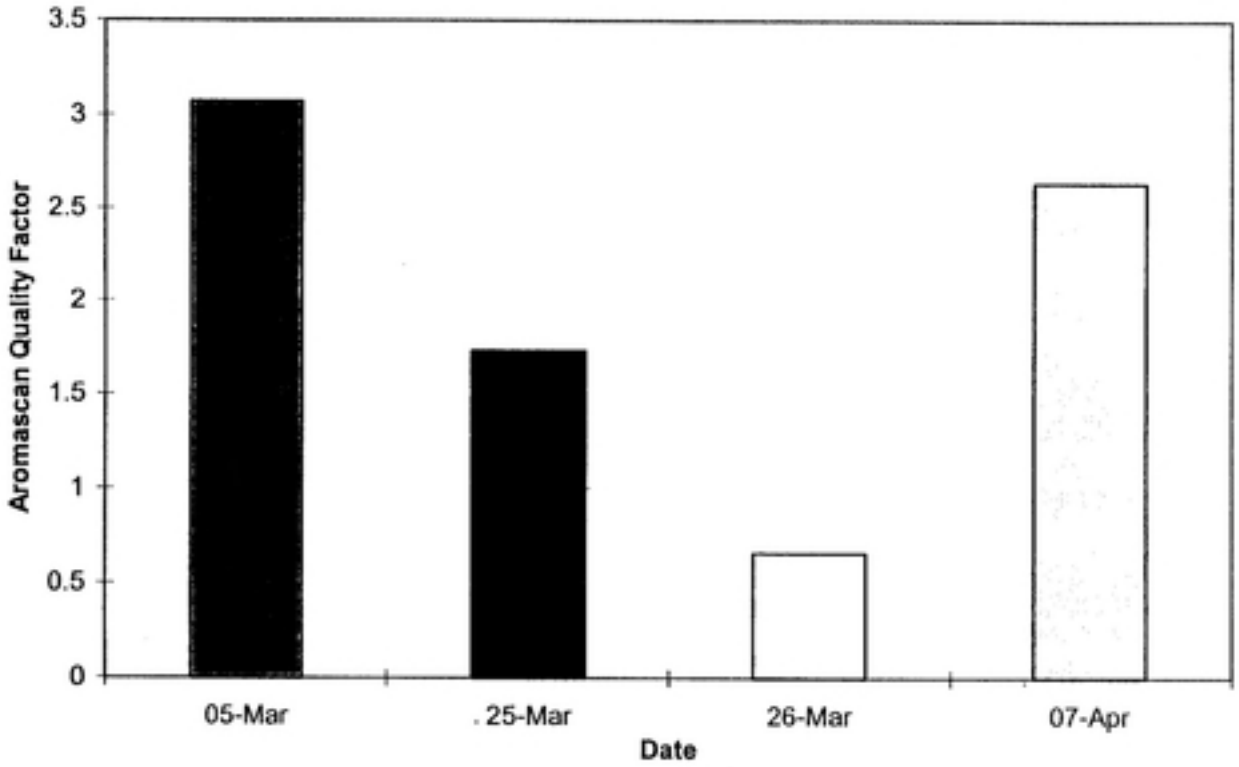

Figure 8. Comparison of Aromascan Quality Factors for a sample of geosmin at the known concentration of 15 ng/L on different trials

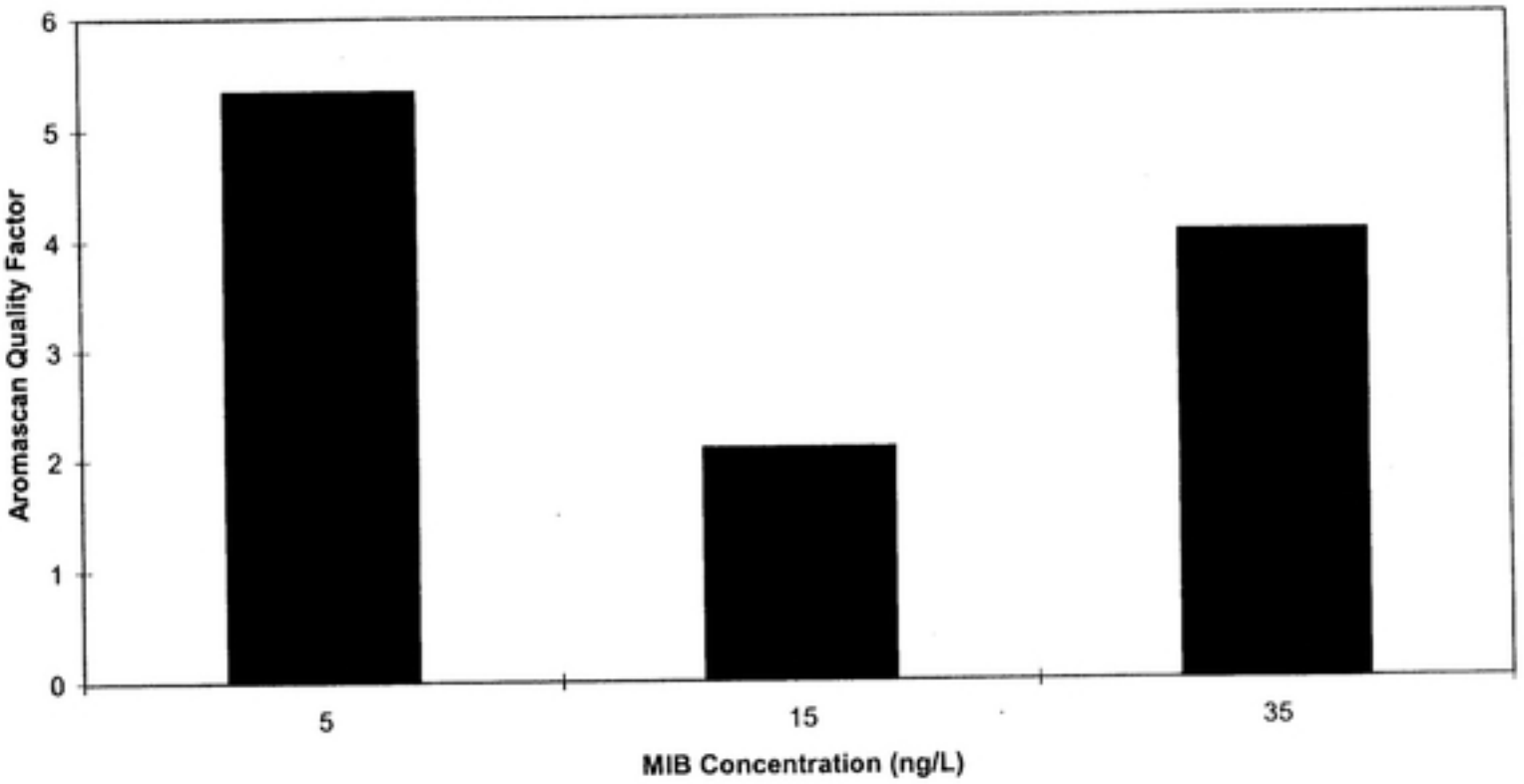

Figure 9. Aromascan quality factor for exposure to different concentrations of MIB

Table 7. Methanol (MeOH) concentration in standard solutions used to test the response of the Aromascan for MIB and geosmin (stock solutions as received from supplier contained 0.1 mg of MIB or geosmin per mL of MeOH; density of MeOH assumed as 0.8 g/mL for these calculations).

Reference Standard Concentration of MIB/geosmin (ng/L)	Methanol Concentration in Solution (ng/L) x 10^{-4}
5	40
10	80
15	120
25	200
35	280

for odor reduction with PAC in this research (see Section 4C) in order to have a point of comparison with the FPM.

4C. Treatment Strategies and Aromascan Data from the OWASA WTP

For the period of time under investigation, operational data from the OWASA WTP was obtained and analyzed with respect to PAC dosage, raw and finished quality factors from the Aromascan and algal counts for the two reservoirs. Unfortunately, the microscope used for the enumeration of algae needed repair in July; thus algal count data were unavailable again until late August.

Figure 10 shows that the total algal counts varied temporally in both University Lake and Cane Creek Reservoir from between the months of June and September of 1999. This can be expected due to the dynamics of algal blooms that often defy prediction from the typical measures of water quality (e.g. nutrient concentration). There was clear evidence of a bloom in University Lake in June. In six days (6/4/99 to 6/10/99), the algal count increased by a factor of nearly 50. The aftermath of such a

bloom is also apparent in the Cane Creek Reservoir in late June; algal counts decreased by a factor of 36 from 6/25/99 to 7/11/99.

Figure 11 represents the raw water quality factor (as measured by Aromascan) as a function of the weighted total algal count for the two reservoirs. The weighted total algal count was obtained by multiplying the fraction of the total inflow that the intake from the reservoir represented by the algal count for that reservoir. The weighted counts for each reservoir were then summed to obtain the total, as plotted in Figure 11.

Figure 11 shows no discernible increase in Aromascan response to raw water with an increase in algal count. There are even some outlier points for both low counts and high odor and high counts and low odor. These results call into question the ability of the Aromascan to quantify odor adequately in a raw drinking water sample. It may also be true that algal counts by themselves are not indicative of the odors produced by secondary metabolites such as geosmin and MIB.

The reliability of the Aromascan data is further in doubt upon examination of Figure 12, which shows the PAC dosage and the raw water quality factor. The maximum PAC dosage was 13 mg/L on 9/4/99 and the minimum PAC dosage was 5 mg/L on 8/1/99. The raw water quality factor also varied, but there appears to be little correspondence to PAC dosage; the dosage does not necessarily increase with an increase in the raw water quality factor. The operating rule that was supposed to be in effect was that PAC dosing would be used whenever the Aromascan Quality Factor was greater than 2. Some of the highest PAC dosages were used when the Quality Factor was far less than 2.

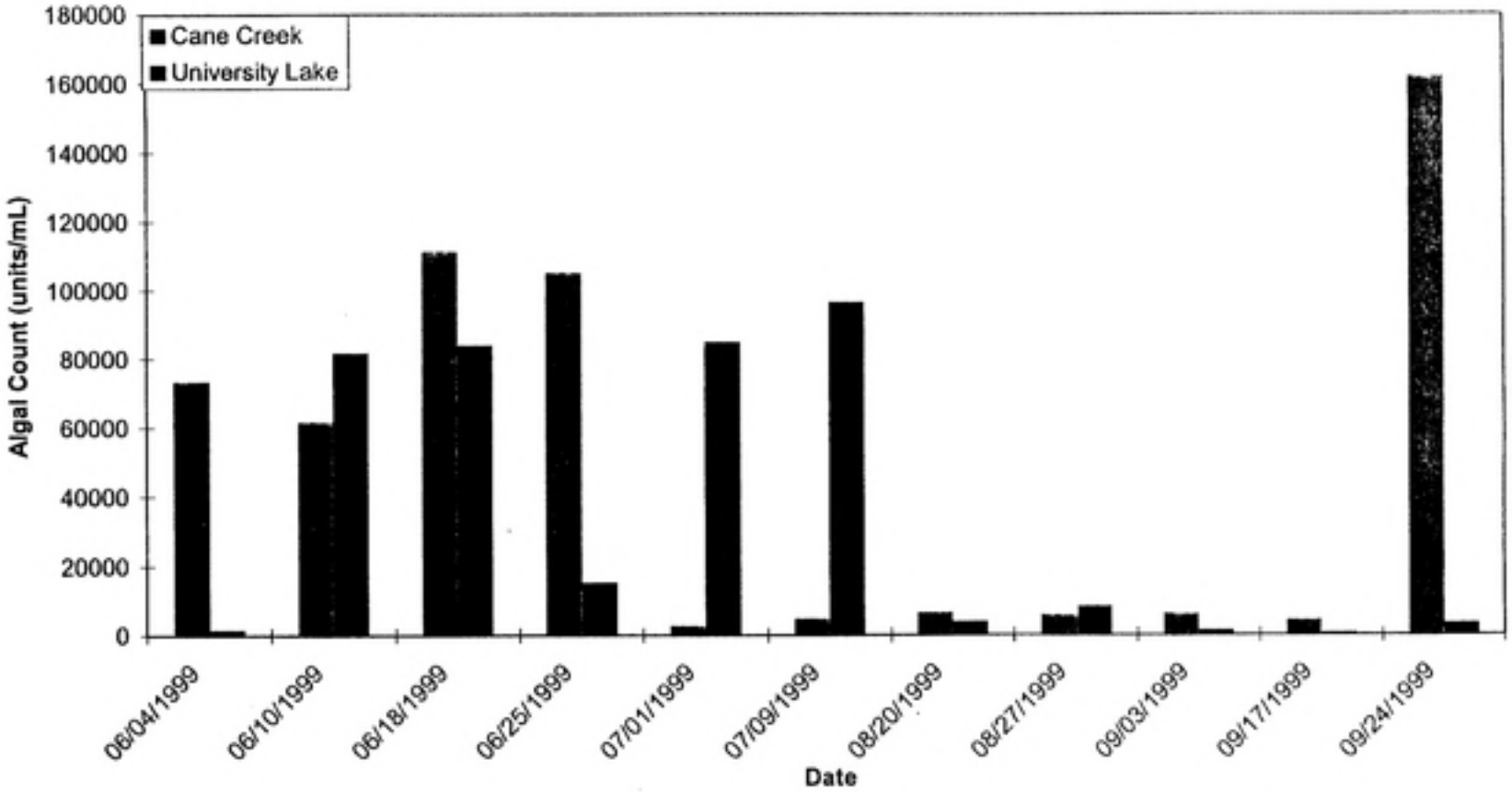

Figure 10. Algal Counts (units/ml) for the Cane Creek and University Lake Reservoirs for the Summer Months

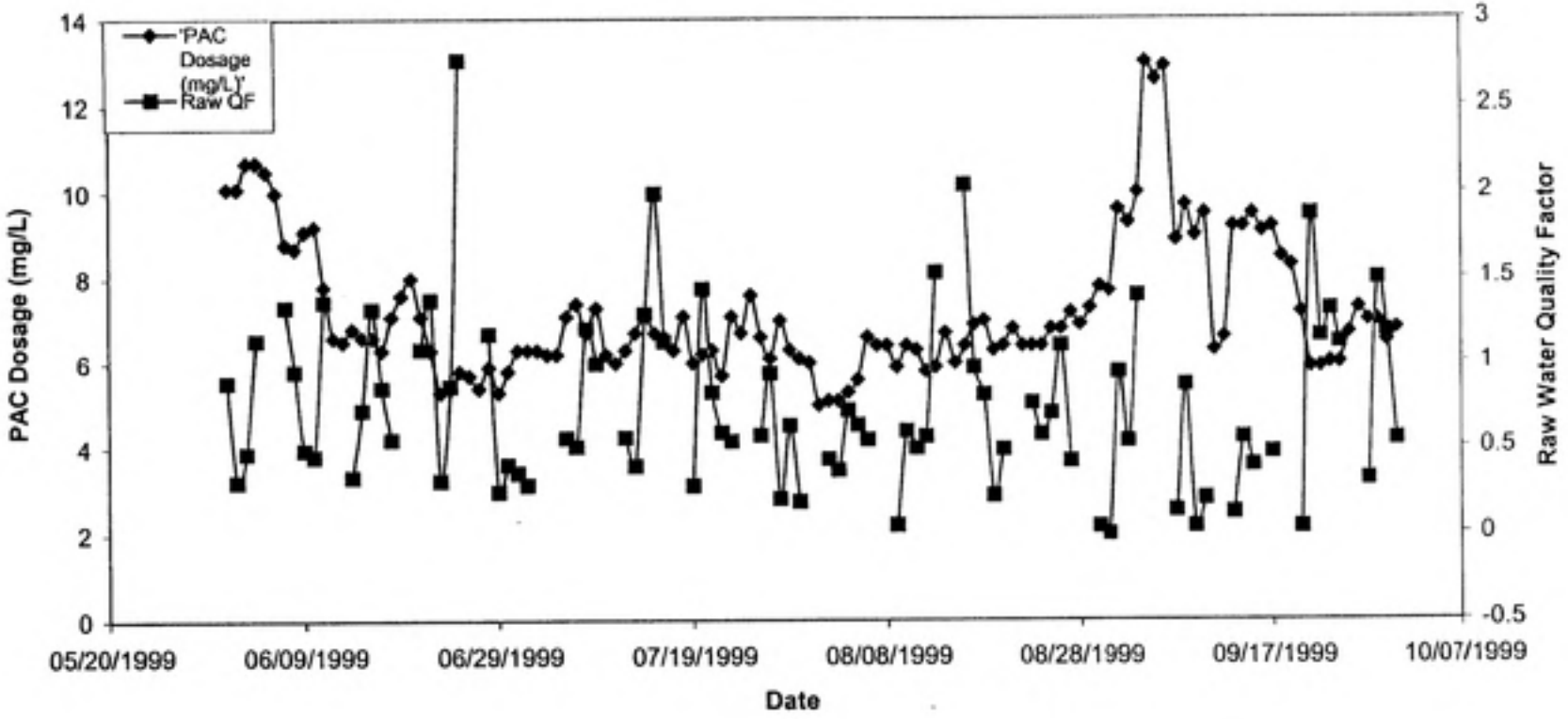

Figure 11. Variability in Hydrodarco PAC dosage and Aromascan Quality Factor of Raw Water at the OWASA WTP

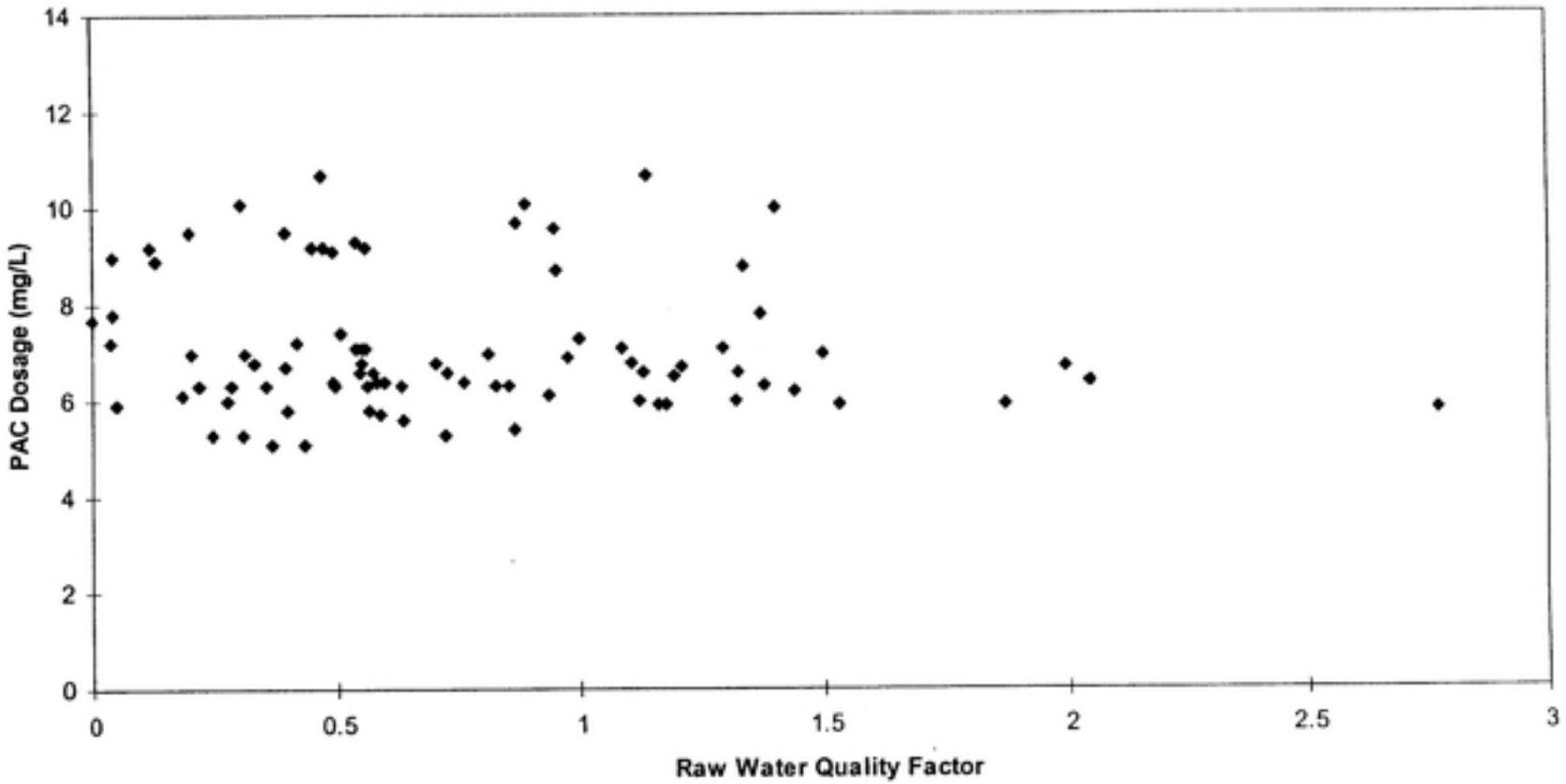

Figure 12: Relationship of Aromascan Raw Water Quality Factor to the PAC Dosage at the OWASA WTP

Figure 13 allows a more direct determination of whether or not the Aromascan Raw Water Quality Factor was used to set the PAC dosage by plotting the raw water Quality Factor as a function of PAC dosage. The PAC dosage should be proportional to the Aromascan Raw Water Quality Factor. The data in Figure 13 indicate, however, that the PAC dosage was not being paced with the Aromascan response. This implies that the operators at the OWASA WTP are perhaps relying more upon prior experience than the data being generated by Aromascan.

The ratio of finished water-to-raw water quality factor as measured by Aromascan is shown in Figure 14 for each of the sampling dates. The finished water quality factor does not include the effect of chlorine because the chlorine was chemically reduced before measurement by Aromascan. A ratio greater than 1.0 indicates that the odor-causing chemicals in the finished water were more significant than in the raw water. Given that PAC was used to remove odor-causing compounds, it is difficult to explain why Aromascan gave values that suggest production rather than removal of odor- causing chemicals on 30 out of the 84 sampling dates. High values in finished water cannot be attributed to chlorine because of the quenching reaction prior to Aromascan analysis. The most logical conclusion is that Aromascan did not provide a reliable measure of odor-causing compounds in either finished of raw water.

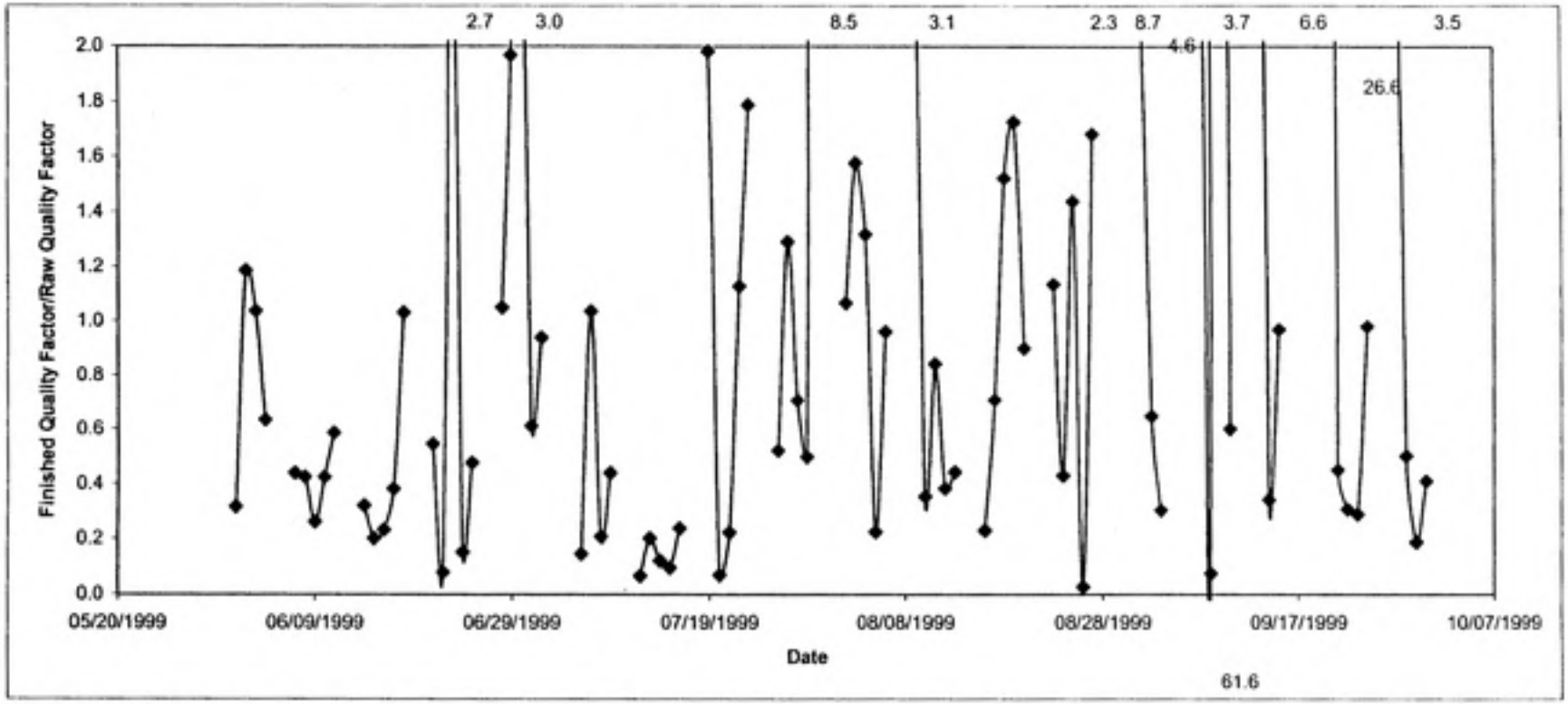

Figure 13. Ratio of Finished-to-Raw Water Quality Factor determined by Aromascan or all sampling water over time; a ratio value greater than 1 indicates that Aromascan has measured an increase in odor through the course of the treatment process

4D. Earthy-Musty Odor Removal in Alum/PAC jar tests on OWASA Samples

The objectives of coagulation-PAC jar testing on samples of raw water taken from University Lake and Cane Creek Reservoir water were:

- To assess the ability of PAC to remove earthy-musty odors in OWASA raw water
- To compare the performance of Hydrodarco and Westvaco PAC
- To compare the utility of FPM and Aromascan as analytical methods for the detection of earthy-musty odors in drinking water and for the evaluation of treatment effectiveness

The effectiveness of coagulation jar tests with and without PAC addition in removal of earthy-musty odor-causing compounds is illustrated for two different sampling dates in Figure 15. In this plot, the FPM Intensity is used to evaluate removal of odor-causing compounds. On both dates, the FPM Intensity of the raw water was the same. However, the effectiveness of PAC was very different. On 7/12/99, a PAC dosage of 12 mg/L reduced the FPM Intensity significantly. On 8/12/99, a PAC dosage of 40 mg/L was still insufficient to give the same removal as on 7/12/99. These results are presented to show the range of observations in jar testing for eight sampling dates. The remainder of the complete sets of data is given in Appendix III.

To simplify the analysis of PAC effectiveness, the results of FPM intensity vs. PAC dosage for each sampling date will not be presented here. Instead, Table 8 provides the PAC dosage for each sampling date that was needed to reach the FPM Threshold

Intensity, which is defined as the point at which odor is barely perceptible and is given a value of 0.5.

The results in Table 8 indicate that neither brand of PAC at dosages as high as 30 mg/L was effective in reducing the earthy odors to the threshold value in four of the eight grab samples taken over the summer months of 1999. A dosage of 12 mg/L was needed for two of the samples for which PAC was considered successful; based on current practice, this dosage would be considered very high. With the exception of one day (7/19/99) the PAC dosage that was able to reduce odor to the FPM threshold value (0.5) was considerably higher than that in use at the OWASA WTP. The fact that a PAC dosage of only 6.0 mg/L was used at the OWASA WTP on 7/19/99 was probably because the FPM intensity in the raw water was very low on that day. The panel results suggested that coagulation without PAC was sufficient to reach the threshold value, thus rendering the need of PAC questionable.

Table 8 also shows that the Hydrodarco PAC was effective in reducing the odor to threshold value at a dose of 12 mg/L for grab samples taken on 7/7/99 and 7/13/99. In these cases, a FPM Intensity of 1.5 in the raw water indicated a moderate level of odor. The FPM Intensity was then reduced to a value of 1 by coagulation. Odor was then further reduced to the FPM Threshold Intensity by a Hydrodarco PAC dosage of 12 mg/L. This dosage was significantly higher than the PAC dosages of 6.7 and 7.4 mg/L that were added to the raw water at the OWASA WTP. Of the eight dates on which jar tests were conducted, the Hydrodarco PAC was unable to reduce the FPM Intensity for the earthy-

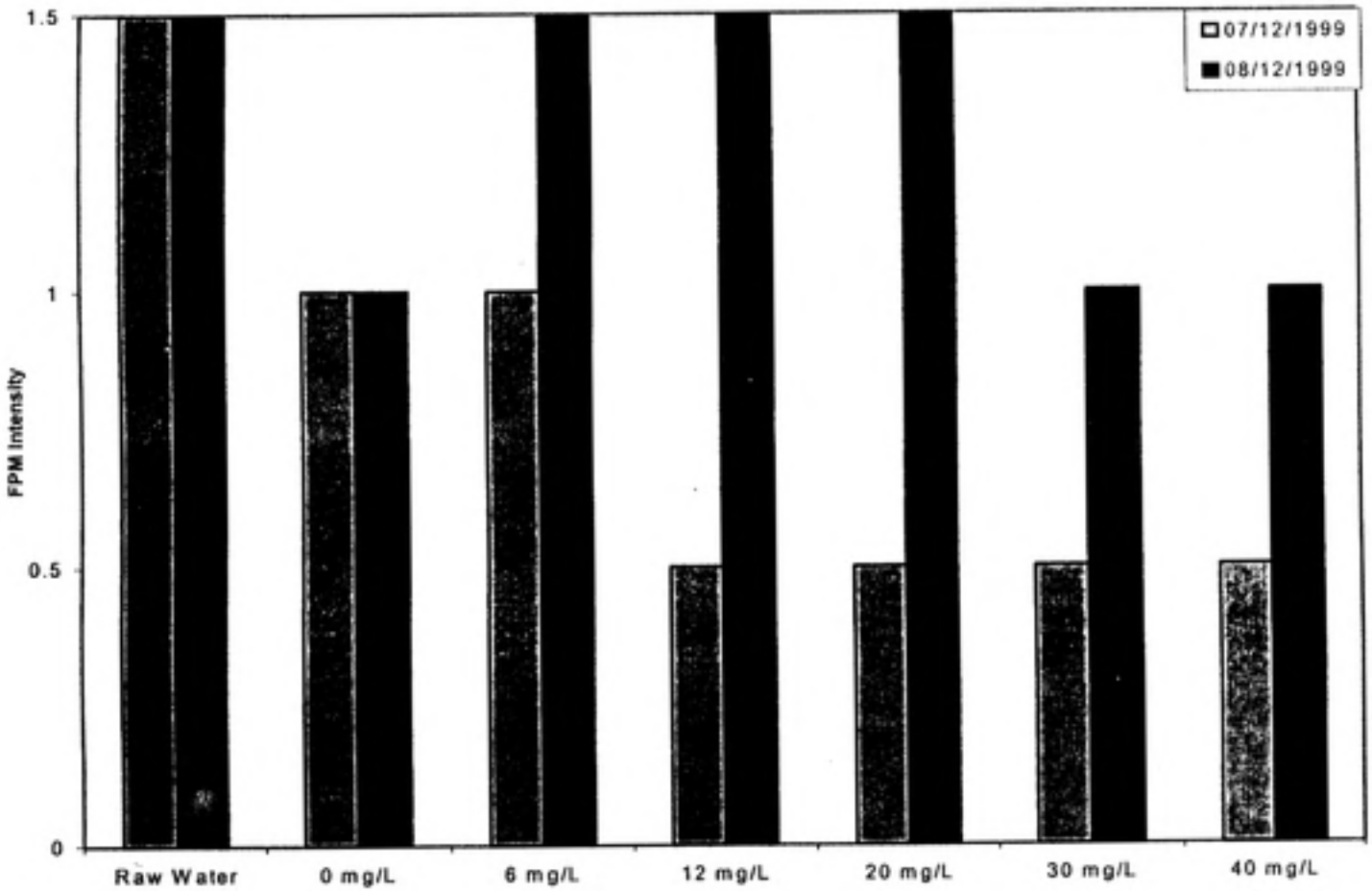

Figure 14. FPM Data for two OWASA grab samples. Though both have the same initial FPM Intensity, the sample from 8/12/99 has a persistent earthy-musty odor

Table 8. Effectiveness of Coagulation-PAC to Reduce Odor to Threshold Odor Intensity as Defined by FPM in Grab Samples o f Raw Water Taken from Cane Creek and University Lake. CCR denotes Cane Creek Reservoir as the source water; UL denotes University Lake as the source water. FPM Intensity w/Coagulation Alone refers to samples for which no PAC was added to the jar.

Sample Date	Raw Water Source	Panel Test Date	Raw Water FPM Intensity	FPM Intensity w/ Coagulation Alone	PAC Dosage to Reach Threshold Intensity in Jar Tests (mg/L)		PAC Dosage at OWASA WTP
					Hydrodarco	Westvaco	
6/1/99	CCR + UL (3:1)	6/4/99			30	Never attained	10.1
6/22/99	CC	6/24/99	1.25	1.5	Never attained	12	6.3
7/7/99	CC + UL (6:4)	7/12/99	1.5	1	12	12	7.4
7/13/99	CC	7/14/99	3	1.25	12	Never attained	6.7
7/19/99	CC + UL (15:85)	7/21/99	1	0.5	6	6	6.0
7/26/99	CC + UL (64:36)	7/29/99	2.5	0.75	Never attained	Never attained	6.6
8/3/99	CC + UL (33:67)	8/4/99	2.5	1.5	Never attained	Never attained	5.1
8/11/99	CC + UL (67:33)	8/12/99	1.5	1.25	Never attained	Never attained	6.3

musty odor on four (6/22/99, 7/26/99, 8/3/99, 8/11/99). Somewhat better results were obtained with Westvaco PAC: earthy-musty odor was reduced to FPM Threshold Intensity in four out of eight samples.

The results of the jar tests for the samples taken on 7/7/99 and 7/14/99 in Table 8 are worth special note. The Westvaco PAC dosage needed to reduce odor to the FPM Threshold Intensity was 12 mg/L on 7/7/99 and 30 mg/L on 7/13/99. Increasing the PAC dosage above these values, however, did not reduce the FPM Intensity as expected but instead increases it to a value of 1. The evidence from the panel calibration with geosmin and MIB as earthy-musty odor causing chemicals supports the FPM Intensity of 1 as being discernable from an FPM Intensity of 0.5 (see Figure 8). Accepting this

observation, the sole explanation for an increase in FPM Intensity with a higher PAC dosage is that the PAC may have removed only certain odor-causing chemicals that were readily adsorbable. These adsorbable chemicals may have been masking the odor from other chemicals that were not adsorbable.

Alum coagulation without PAC addition was somewhat effective in removing odors on 7/13/99 and 8/3/99 (see Column 5 of Table 8). The FPM Intensity on each of these dates was very high (3 and 2.5, respectively). Alum coagulation without PAC addition reduced the odor to a FPM Intensity of 1.25 on 7/13/99 and to a 1.5 on 8/3/99. A dosage of 12 mg/L of Westvaco PAC further reduced the odor to the threshold value on 7/13/99. The Hydrodarco PAC was far less effective on this particular date. A dosage of 30 mg/L only reduced the odor to a FPM Intensity value of 1 and a dosage of 40 mg/L (over six times the dosage being used at the OWASA WTP on that day) produced no further reduction in odor.

Equally interesting was the change in effectiveness of the two PACs on 7/13/99 and 8/3/99 as highlighted in Table 9. Although the Westvaco PAC was able to attain the FPM Threshold Intensity on 7/13/99, it performed far worse on 8/3/99. Even at a dosage of 30 mg/L, the FPM Intensity was only reduced to a 1.5. In contrast, the Hydrodarco PAC was more effective on 8/4/99 than on 7/14/99 but on neither date was the odor intensity reduced below a value of 1. The Hydrodarco PAC dosage to achieve a FPM Intensity of 1 was only 12 mg/L on 8/3/99 in contrast to 30 mg/L on 7/14/99.

Table 9. Comparison of the efficacy of Westvaco and Hydrodarco PACs for two sample dates. "Lowest FPM Intensity" represents the highest level of odor removal for that date; the lowest PAC dosage needed to achieve that Intensity is also listed in the table.

Date	Westvaco PAC		Hydrodarco PAC	
	Lowest FPM Intensity	PAC Dosage (mg/L)	Lowest FPM Intensity	PAC Dosage (mg/L)
7/13/99	0.5	12	1	40
8/3/99	1.5	6	1	12

All of the results shown in Tables 8 and 9 point to the changing nature of the chemicals responsible for odors in the raw water and to the difficulty of selecting a PAC and a dosage that will be effective in all cases. Effective control of odors, therefore, would require much more sophisticated information about the source of odors and more specifically, about the chemistry of algal metabolites for protected watersheds such as those in the OWASA system.

The TOC removals on each sampling date are provided in Table 10. Without the addition of PAC, alum coagulation removed over 60% of the TOC on all but one sampling date where the removal was only 45%. The addition of PAC only increased the TOC removal by 10 to 15% regardless of dosage. The ineffectiveness of PAC in TOC removal is not surprising given that NOM is well known to be poorly adsorbed (Lalezary et al. 1988, AWWA 1999).

The fact that PAC removes even a small percentage of TOC may still reduce the removal of odor-causing compounds such as geosmin and MIB. TOC represents NOM, which is of relatively high molecular weight (1000 – 10,000 Daltons or more). NOM can

Table 10: Summary of TOC removals in percent for the Hydrodarco and Westvaco PACs

Date	PAC Dose (mg/L)	Type of PAC	
		Hydrodarco	Westvaco
6/24/99	0	61	65
	12	68	71
	30	71	77
7/7/99	0	65	63
	12	72	68
	30	79	74
7/14/99	0	45	48
	12	52	58
	30	60	68
7/21/99	0	65	63
	12	72	68
	30	79	74
8/4/99	0	65	63
	12	72	68
	30	79	74
8/12/99	0	65	63
	12	72	68
	30	79	74

either block pores within the PAC or compete directly with MIB or geosmin for adsorption sites. In either case, there is good evidence in the literature (Lalezary et al.

1988, Gillogly et al. 1998) for reduced efficiency in removal of these odor-causing chemicals in the presence of NOM.

The differences in performance of the PACs may be attributed to their standard properties, as reported by the manufacturers. As noted in the Materials and Methods section (see Table 4), Westvaco PAC has a higher Iodine Number and Molasses Decolorizing Index. If only these two parameters were used to judge PAC effectiveness, the Westvaco PAC would be expected to remove odor-causing compounds and NOM more effectively than PAC. The fact that the effectiveness of these two PACs was not always as expected from these properties simply suggests the limitations in using such performance guides

FPM and Aromascan provide two alternative measurements of odors in raw water and for the assessment of their removal through treatment. Of the sampling dates on which jar test experiments were conducted, FPM and Aromascan results were available on 6/22, 7/7, 7/13, 7/19 and 8/4. The availability of both measurements allowed a direct comparison of their usefulness. Because both measurements are subjective, it was not fruitful to compare all values. Instead, a comparison was made of FPM and Aromascan values that are generally accepted to represent the presence of non-objectionable odor: FPM Intensity <1 and an Aromascan Quality Factor <2. The results are summarized in Table 11.

The results in Table 11 show little correspondence between the Aromascan Quality Factor and the FPM. On some sampling dates (e.g., 7/19 for Hydrodarco PAC), the Aromascan Quality Factor increases with PAC dosage, whereas the FPM Intensity was at the threshold value. On other days, both Aromascan Quality Factor and the FPM Intensity decrease, but not in the same proportion. For example, on 7/13/99, the panel detected a significant decrease in odor from the coagulation without PAC addition (0 mg/L) to a PAC dosage of 12 mg/L. The Aromascan Quality Factor only decreased from 44 to 41, a very small change given the decrease in FPM Intensity from 1.5 to 0.5. When the PAC dosage increased from 12 mg/L to 30 mg/L, the panel detected an increase in the FPM Intensity from a 0.5 to 1. The Aromascan Quality Factor, however, decreased by nearly 20. Thus an increase in PAC dosage form 12 to 30 mg/L produced a much larger decrease in Quality Factor than adding 12 mg/L of PAC to coagulated water.

Table 11: Comparison of the Aromascan and FPM Data for the jar test treatment with alum coagulation and Westvaco/Hydrodarco PAC

Date	Type of PAC	Dosage (mg/L)	Aromascan Quality Factor	FPM Intensity
6/22/99	Westvaco	0	0.7	1.5
		12	0.8	1
		30	0.3	1
7/7/99	Westvaco	0	1.2	1
		12	0.8	0.5
		30	1.7	1
	Hydrodarco	0	2.7	1
		12	2.1	0.5
		30	2.2	0.5
7/13/99	Westvaco	0	43.8	1.5
		12	40.8	0.5
		30	29.6	1
	Hydrodarco	0	28.7	1
		12	17.5	1.5
		30	15.9	1.2
7/19/99	Westvaco	0	0.8	0.5
		12	0.9	0
		30	0.7	0
	Hydrodarco	0	0.8	0.5
		12	3.4	0.5
		30	1.7	1
8/4/99	Westvaco	0	2.5	1.5
		12	1.9	1.5
		30	2.2	1.5
	Hydrodarco	0	1.4	1.5
		12	1.8	1
		30	3.2	2

Table 12. Results of analyses performed on spiked raw OWASA water treated with Hydrodarco PAC. FPM analysis was performed for sensory analysis of the earthy-musty odor while the same samples were sent to the Philadelphia Suburban Water Authority for MIB/Geosmin analysis. The split in Column 2, Row 4 indicates that half the panel members ranked the sample one way, while half the panel ranked it another way (number of panelists assigning a rank is given in parenthesis)

Sample Description	FPM Intensity	Odorant Concentrations (ng/L)	
		MIB	Geosmin
Raw, spiked water	2	21	23
Coagulated, settled water	1	7.5	11
12 mg/L Hydrodarco PAC	1(2)/1.5(2)	7.6	8.2
30 mg/L Hydrodarco PAC	0.5	5.7	4.4

4E. Removal by PAC of Geosmin and MIB Spiked into Raw OWASA Water

Table 12 contains the MIB and geosmin concentrations as determined by the Philadelphia Suburban Water Authority along with the results of the FPM. Coagulation alone removed over 50 percent of the MIB and geosmin present in the samples. This removal was confirmed by a corresponding reduction in odor; i.e. the FPM Intensity was reduced from 2 to 1. The addition of 12 mg/L of Hydrodarco PAC caused far less reduction in MIB or geosmin concentrations than coagulation alone.

The panel could not reach consensus as to whether odor had increased or decreased for the sample treated with 12 mg/L PAC; the split in Column 2, Row 4. A dosage of 30 mg/L of Hydrodarco PAC reduced the FPM Intensity to the Threshold value. Correspondingly as expected, both the MIB and geosmin concentrations were below 10 ng/L.

The fact that coagulation removed about 50 percent of the geosmin and MIB was unexpected. During the PAC jar tests with unspiked water as described in Section 4C, it

was noted that coagulation removed a significant amount of odor as measured by the FPM Intensity value. MIB and geosmin, which are dissolved, small molecular weight chemicals, cannot be removed by coagulation. However, if these chemicals were bound to NOM it may be possible for coagulation to remove them.

Adsorption studies have demonstrated that geosmin is more strongly adsorbed than MIB as measured by the Freundlich adsorption constant, ***K*** (Lalezary et al. 1987; Huang, van Bencshoten and Jensen 1996). The results of this PAC study (see Table 12) confirmed this difference in adsorbability for the 30 mg/L PAC dosage.

The analytical measurements of MIB and geosmin concentrations along with FPM allowed for another point of comparison. The FPM panel data provided a correlation of geosmin and MIB concentrations with FPM Intensity, as shown earlier in Figures 5 and 6. Based upon the intensity vs. response curves generated in panel sessions, there appears to be an additivity effect present in the perception of the earthy odors. These correlations were used to determine the predicted FPM Intensity from the known measurements of MIB and geosmin concentrations listed in Table 12. For example, the MIB concentration of 21 ng/L in the raw water corresponds to a FPM intensity of approximately 1. Likewise, a geosmin concentration of 23 ng/L corresponds to a FPM intensity of 1. If the odors were additive, then the FPM Intensity should be 2 for the raw water. In fact, the panel gave an FPM Intensity of 2 to the raw water. Thus, these data suggest additivity of odors where panels are used. The additivity concept is common in animal toxicology, where the term "narcosis" is used. In other words, two compounds that are below their

toxic concentrations can cause a toxic effect if the sum of their concentrations is at the toxic level (Storm 1987).

4F. Removal of MIB and Geosmin Using a GAC Filter Cap

The removal of MIB and geosmin in a GAC filter cap was measured in two different experiments. The first experiment involved the use of fresh GAC while the second involved a column that had been filled with partially exhausted GAC by pre-adsorption of NOM. In both experiments, the feed water to the columns was settled water form the OWASA WTP to which MIB and geosmin were added to reach concentrations of 23 ng/L each. Both analytical measurements of MIB and geosmin concentrations and the FPM were used to measure the effectiveness of earthy-musty odor removal by GAC.

During the first column test, an air bubble entered the pump feed line overnight, causing flow interruption after three days of operation. The results of the experiment, however, were sufficient to measure MIB and geosmin removed in a fresh GAC filter cap. The pump was re-primed and oiled in preparation for the second experiment using partially exhausted GAC instead of fresh GAC. This experiment was run for 5 days.

Table 13 shows the concentrations of MIB and geosmin along with the FPM Intensities for both experiments. The results were similar to those reported by Gillogly et al. (1999) using a similar design for the laboratory column test. They used Calgon F300 GAC which is almost the same as the F400 Calgon GAC used here. Moreover, the influent MIB concentration was 28 ng/L and the EBCT was 4.4 min, both being very similar to conditions in this research. With fresh GAC in the column, they found that the

Table 13. Comparison of the effectiveness of fresh and partially exhausted Calgon F400 GAC (EBCT = 3 min) in removal of MIB and geosmin spiked into OWASA settled water. "After x hours" indicates the number of hours of column operation. A "w(x)/y(z)" in Column 2 indicates that the panel did not come to consensus on the sample. The number in parenthesis is the number of panel members assigning a sample a particular intensity.

Sample Description	FPM Intensity	MIB (ng/L)	Geosmin (ng/L)
Settled, spiked water	2	23	23
Effluent --Fresh GAC after 27.1 hours	0 (2)/0.5(2)	<1.7	<1.6
Effluent --Fresh GAC after 85.6 hours	0	<1.7	<1.6
Effluent --Partially Saturated GAC after 35 hours	0	5.0	2.9
Effluent --Partially Saturated GAC after 108 hours	0 (3)/0.5(1)	6.7	3.7

MIB was reduced to the threshold odor concentration (about 5 ng/L of MIB). A shorter EBCT of 2.6 min. still removed MIB to a large extent (< 13 ng/L), but this concentration would cause customer complaints. By comparison, Table 13 shows that both MIB and geosmin were removed to below 1.7 ng/L for an EBCT of 3 min and fresh GAC. There was no detectable increase in these concentrations from 27.1 to 65.6 hours of operation. It can thus be concluded that the GAC filter cap contained sufficient adsorptive capacity.

Gillogly et al. (1999) found that an EBCT of 10 minutes would be required to achieve reduction of MIB to <5 ng/L for a filter bed that had been in service for one year. They showed, therefore, that NOM adsorption greatly decreased the removal of MIB.

The decrease in removal of MIB and geosmin was also apparent in this research as seen by a several –fold increase in effluent concentration (see Table 13).

Figure 10 of Gillogly et al. (1999) shows percent breakthrough of MIB as a function of service time and thus loading of NOM on GAC. This relationship was generated by comparison of the initial breakthrough of MIB in the laboratory-scale columns for fresh GAC and GAC that had been preloaded with NOM for varying service times. They also found that percentage breakthrough is constant regardless of feed concentration. Accepting this conclusion, their data can be used to predict effluent concentration of MIB in this study as well. From Figure 10 of Gillogly et al. (1999), the expected breakthrough concentration at start up for fresh GAC would be 20%, or 5 ng/L, for the feed of 25 ng/L used in this research. By contrast, the MIB concentration at start-up in this research was below detection (<1.7 ng/L). The fact that Gillogly et al. found as much as 20% breakthrough for fresh GAC was difficult to explain because nearly complete removal is generally expected. However, it is possible that direct competition with adsorption of NOM in the feed water was very strong. It may suggest less competitive adsorption with NOM in this study than observed by Gillogly et al. For a service time of 1 month, which corresponds roughly with that simulated in this research (see Equation 7), Gillogly et al. showed an increase in breakthrough to 30%. Using the same MIB concentration of 25 ng/L, the initial breakthrough concentration predicted by Gillogly et al. would be 7 ng/L. The results of this study (Table 13) show MIB concentrations of 5.0 and 6.7 ng/L, which are very close to those of Gillogly et al.

The major conclusion from the GAC filter cap experiment is the superiority of this process over PAC for removal of MIB and geosmin. Figure 16 compares the efficiency of fresh GAC and partially exhausted GAC in removal of MIB and geosmin. Although there is a marked decrease in the removal of partially exhausted GAC over the fresh GAC, the effluent concentrations were still well below 10 ng/L. By contrast, a PAC dosage of 30 mg/L (see Table 12) was not enough to reach this concentration. The fact that the feed of MIB and geosmin was sustained at 25 ng/L each for a period of five days and breakthrough remained below 10 ng/L each even when GAC was partially exhausted is good evidence of an effective process. To achieve the same removal with PAC would require dosages well in excess of current practice.

Finally, the effectiveness of the GAC filter cap can be assessed using the FPM instead of the concentration of MIB and geosmin. In fact, the FPM is a better way of judging GAC effectiveness than measuring MIB and geosmin concentrations because it simulates the customer response to odors in the tap water. The FPM results for fresh and partially exhausted GAC is presented in Figure 17. All of the effluent measurements were below the FPM Threshold Intensity of 0.5. This agrees qualitatively with the low concentration of MIB and geosmin found in these samples. Again it should be stressed that the feed concentrations of MIB and geosmin used in this GAC filter cap test were much higher than in typical events at the OWASA WTP and thus the FPM Intensity of the feed water was 2. Customer satisfaction, for which the FPM results serve as a surrogate, could be greatly increased during taste and odor events through the use of a GAC filter cap.

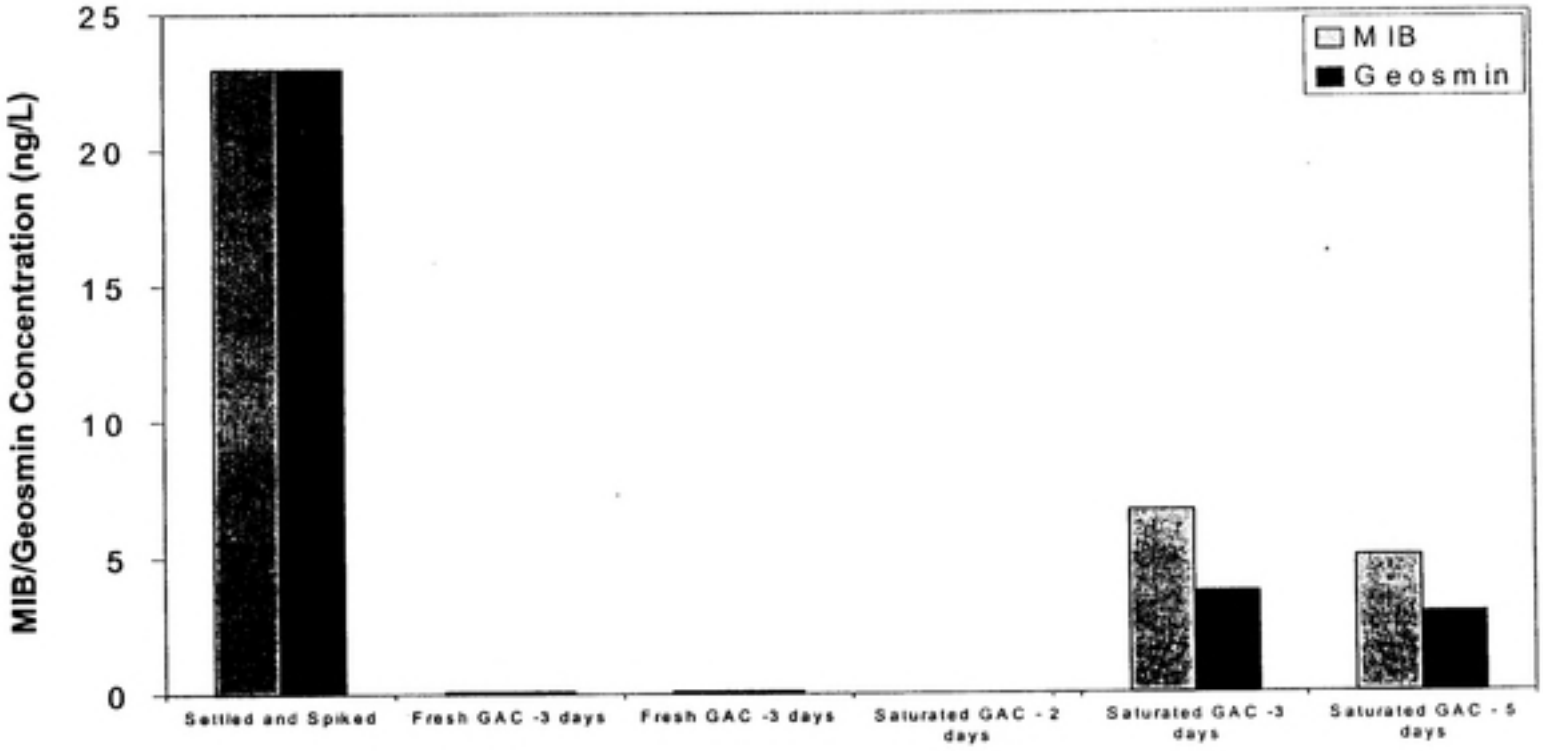

Figure 15. Results of MIB/geosmin analysis by Philadelphia Suburban. Fresh GAC effluent had MIB/geosmin levels below detection limit

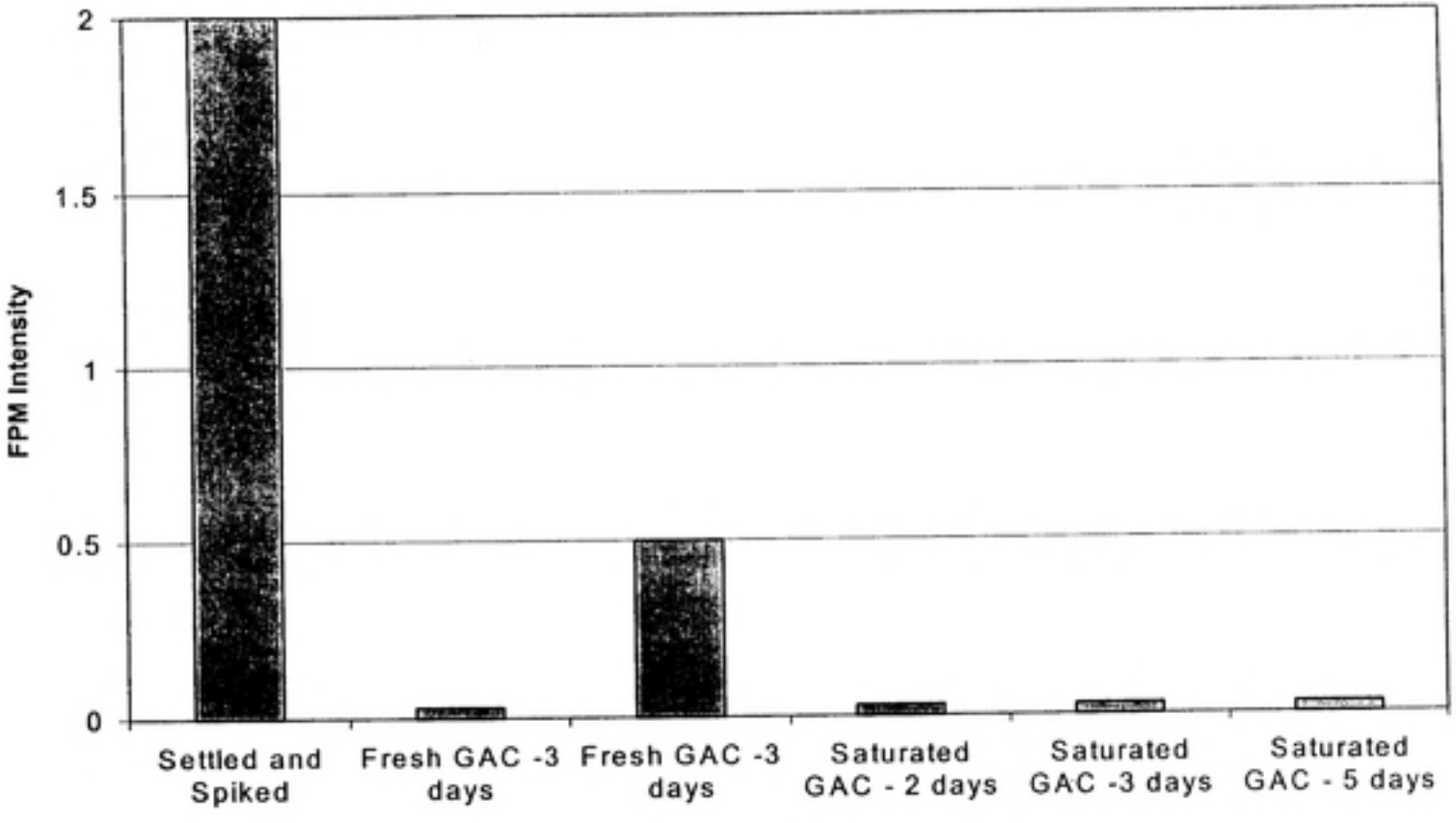

Figure 16. FPM Intensity data for GAC column effluent

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5A. Conclusions

The FPM was successfully used to evaluate the presence of geosmin and MIB in the OWASA drinking water supply. After training, the sensory panel was able to detect MIB and geosmin in concentrations as low as 5 ng/L.

The FPM showed the effectiveness in treating OWASA samples with PAC and GAC. PAC did not produce high removals of odor on a consistent basis when added during coagulation of raw water. Westvaco Aqua-Nuchar PAC was sometimes more, and at other times, less effective than Hydrodarco B. Thus, seasonal variations in odor causing compounds may shift the effectiveness of one PAC over another. Spiking the OWASA raw water with MIB and geosmin at high concentrations (25 ng/L each) further demonstrated the ineffectiveness of PAC. In this case, 30 mg/L of Hydrodarco B was needed to reach the FPM Threshold Intensity of 0.5. This concentration is in considerable excess of the current average dosage of 6 mg/L.

The laboratory simulation of a GAC filter cap produced very high removals of MIB and geosmin from spiked OWASA settled water. Fresh GAC gave effluent MIB and geosmin concentrations that were below detection levels (<1.7 ng/L). GAC that had been partially saturated with NOM also gave low effluent concentrations (<10 ng/L). Excellent removals continued after 4.5 days of continuous feed of 25 ng/L each of MIB and geosmin. These effluent concentrations of MIB and geosmin (6.7 ng/L of MIB and

3.7 ng/L of geosmin) were below those which most consumers are capable of detecting. All the GAC filter cap results showed superior performance to PAC dosing in coagulation.

Aromascan gave responses to odor-causing compounds that were inconsistent with the FPM. This instrument, while purchased by OWASA to control PAC dosing, did not appear to be useful to the OWASA operational staff. That is, the analysis of daily Aromascan Quality Factor values in the raw water during the summer of 1999 did not correlate with the PAC dosages in use by OWASA. Moreover, the results of the jar tests involving coagulation and PAC addition in this research were more logically interpreted with the FPM. The validity of the FPM was confirmed by measurements of MIB and geosmin during spiked jar tests and filter cap tests. All the results from this research suggest, therefore, that the Aromascan is not a reliable substitute for human analysis by either FPM or TON.

5B. Recommendations

Further study of the odor removal by different brands of PAC should be performed throughout the year. PAC may be a more cost-effective solution for the utility if indeed odor problems are sporadic. The data presented in this research suggest that a higher dosage of PAC is needed than that currently in use at OWASA. However, an increase in the PAC dosage will increase OWASA's cost to treat the water. Thus, if odor problems persist with the current PAC dosing strategy, OWASA should consider replacement of the anthracite in the existing filters with GAC. Long-term pilot plant studies may be useful to confirm the ability of GAC to remove odor-causing compound even after NOM adsorption capacity has been exhausted. In this regard, it should be

noted that the simulated extent of exhaustion with respect to NOM adsorption in this research was quite substantial. Equally important, the simulated odor event (by spiking MIB and geosmin) was probably far more severe than would be experienced at OWASA.

If OWASA continues to use PAC as a treatment strategy, odor-causing compounds should be identified in both University Lake and Cane Creek Reservoir. The variations in PAC effectiveness noted in this research may be due to the presence of odor-causing chemicals other than MIB and geosmin, which were evaluated here. A commercial laboratory could, for example, perform gas chromatography (GC) on raw water samples to provide a profile of potential chemicals of concern. Recognizing that such analyses are expensive ($350 per sample), this recommendation should be implemented with attention to specific odor events in the raw water. The identification of odor-causing chemicals, combined with data for PAC dosage, algal counts, customer complaints, and FPM Intensity values would enable OWASA to better understand the dynamics of the system. The ultimate goal would be to develop a predictive tool, perhaps even an expert-knowledge based approach, to pace PAC dosage more effectively. Alternatively, a GAC filter cap may greatly simplify the control strategy.

The FPM may well be the best predictive method for OWASA to control odors. One OWASA employee would be required to lead and train the panel but the panel itself should be composed of volunteers from the community. Such volunteers would potentially serve as a better gauge of odor problems than an OWASA employee who is exposed to the same water on a daily basis. The results from this research showed that FPM was a reliable measure of the effectiveness of either PAC or GAC treatment. This was most evident from the correspondence with MIB and geosmin concentrations.

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APPENDIX I.

SAMPLE AROMASCAN PCA MAP

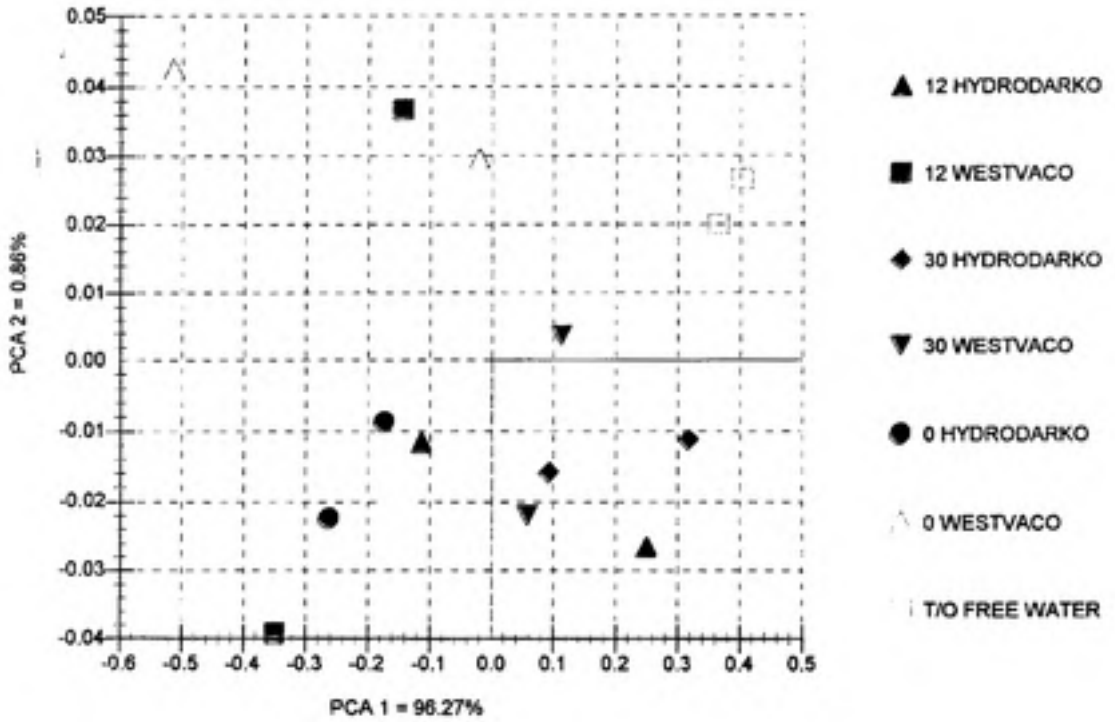


Figure AI-1. Sample Aromascan PCA Map

This map is the product of the Aromascan Data Processing program. The response from the 32 polymer sensors forms a multi-dimensional response array which the software maps to give the operator a visual representation of the manner in which the odor of the samples are related to one another. Quality factors are given based upon the spacing between the points on the map. For our purposes, all quality factors reported are relative to taste and odor free water.

APPENDIX II.

SAMPLE FPM PANELIST DATA SHEET

Note: Panelists are asked to note earthy odor first. The additional columns allow panelists to note any additional odors

NAME:_____.

Date: 07/14/1999

FLAVOR PROFILE ANALYSIS

TREATMENT OF OWASA RAW WATER W/ PAC

I. OWASA RAW WATER

Please rank the raw water on the FPA scale of 0-3, 0 being no odor, 3 being overwhelming

	Odor Description		
	Earthy		
Rank			

II. Treatment w/ Hydrodarco PAC

Please rank the raw water on the FPA scale of 0-3, 0 being no odor, 3 being overwhelming

	Odor Description		
	Earthy		
A1			
A2			
A3			
A4			
A5			
A6			

II. Treatment w/ Westvaco PAC

Please rank the raw water on the FPA scale of 0-3, 0 being no odor, 3 being overwhelming

	Odor Description		
	Earthy		
B1			
B2			
B3			
B4			
B5			
B6			

APPENDIX III.

RESULTS FROM REGULAR PANEL SESSIONS

Figure AIII.1: FPM Intensity data for 6/24/99

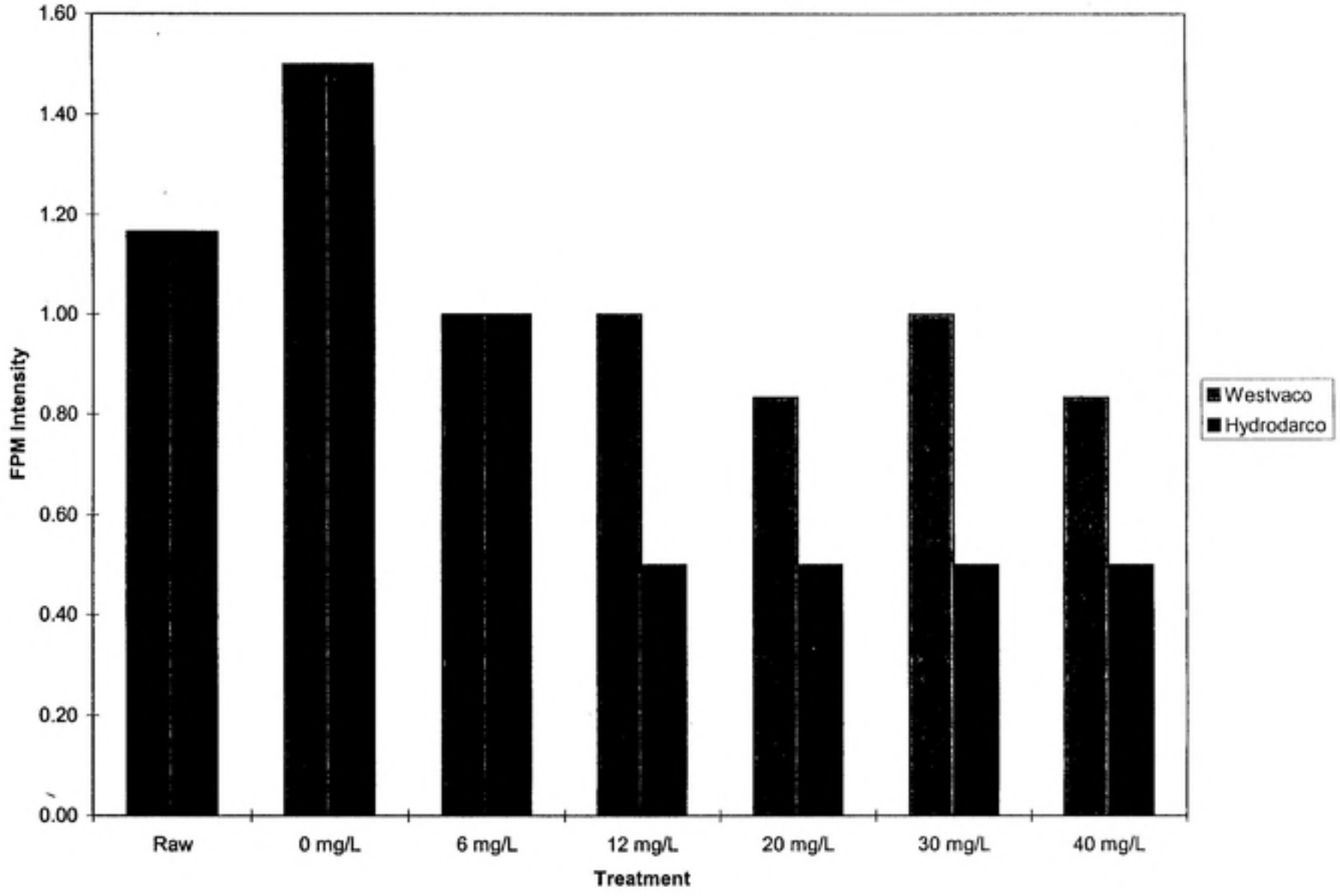


Figure AIII.2. FPM Intensity data for 7/12/99

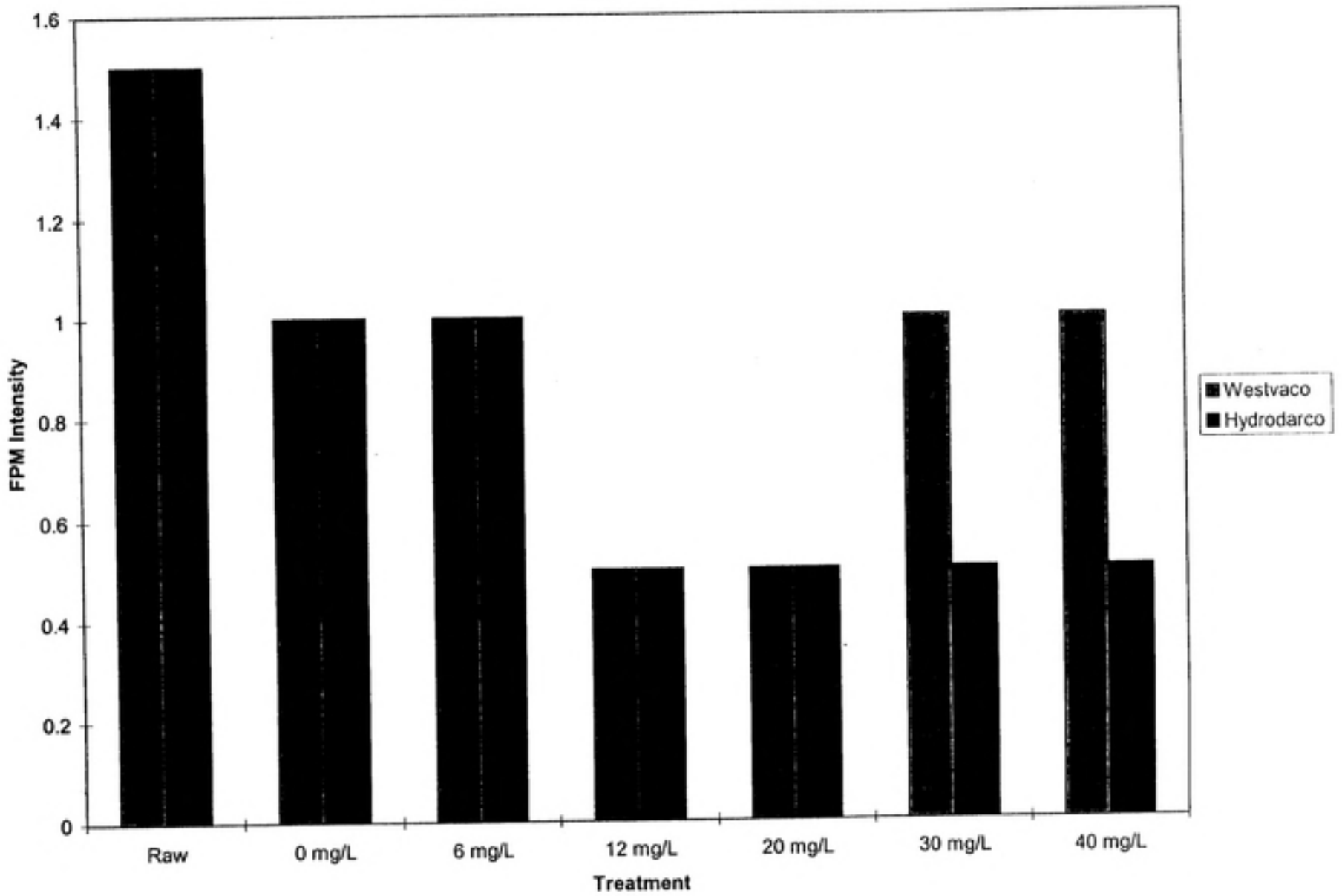
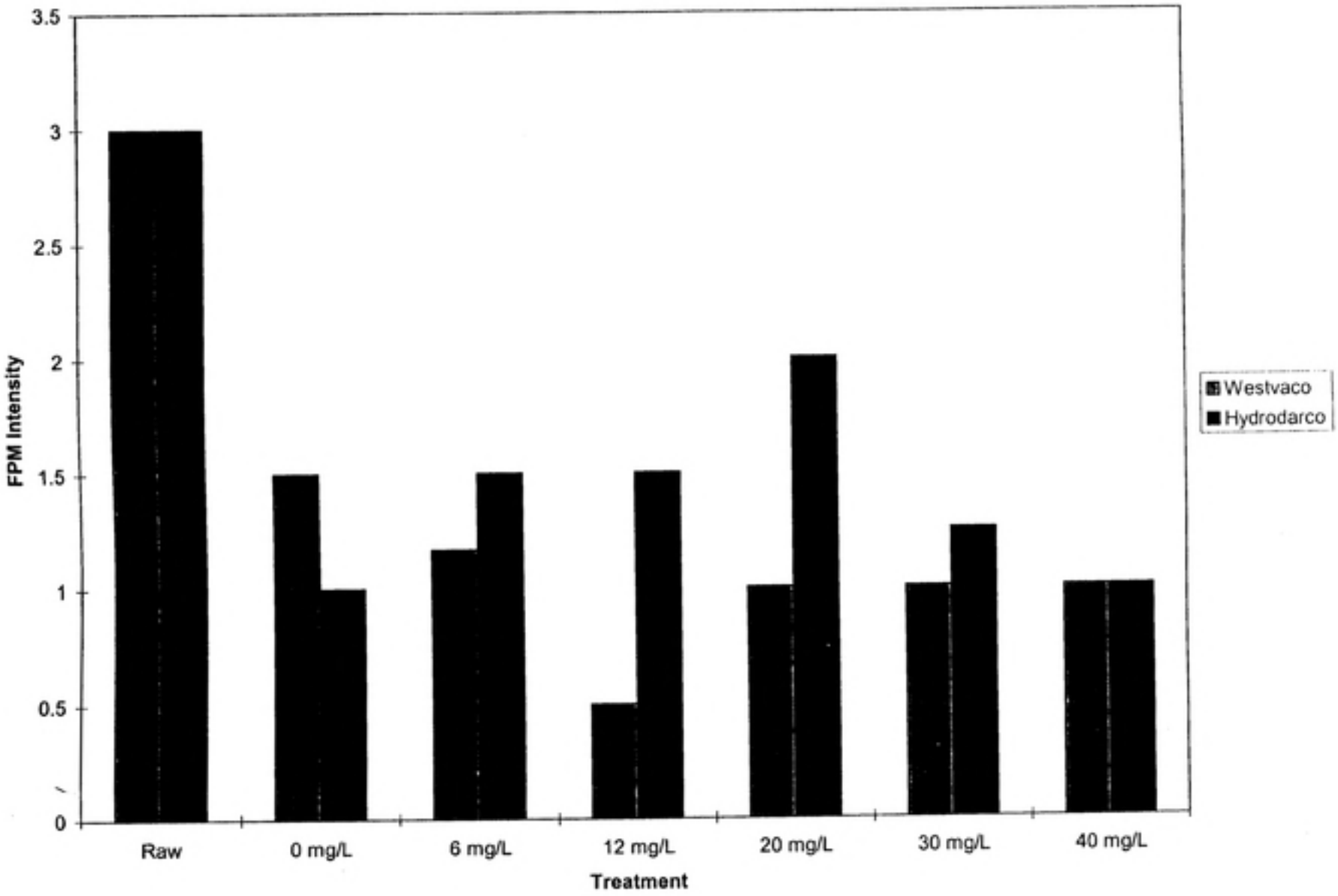


Figure AIII.3. FPM Intensity data for 7/14/99



Att.4. FPM Intensity data for 7/21/99

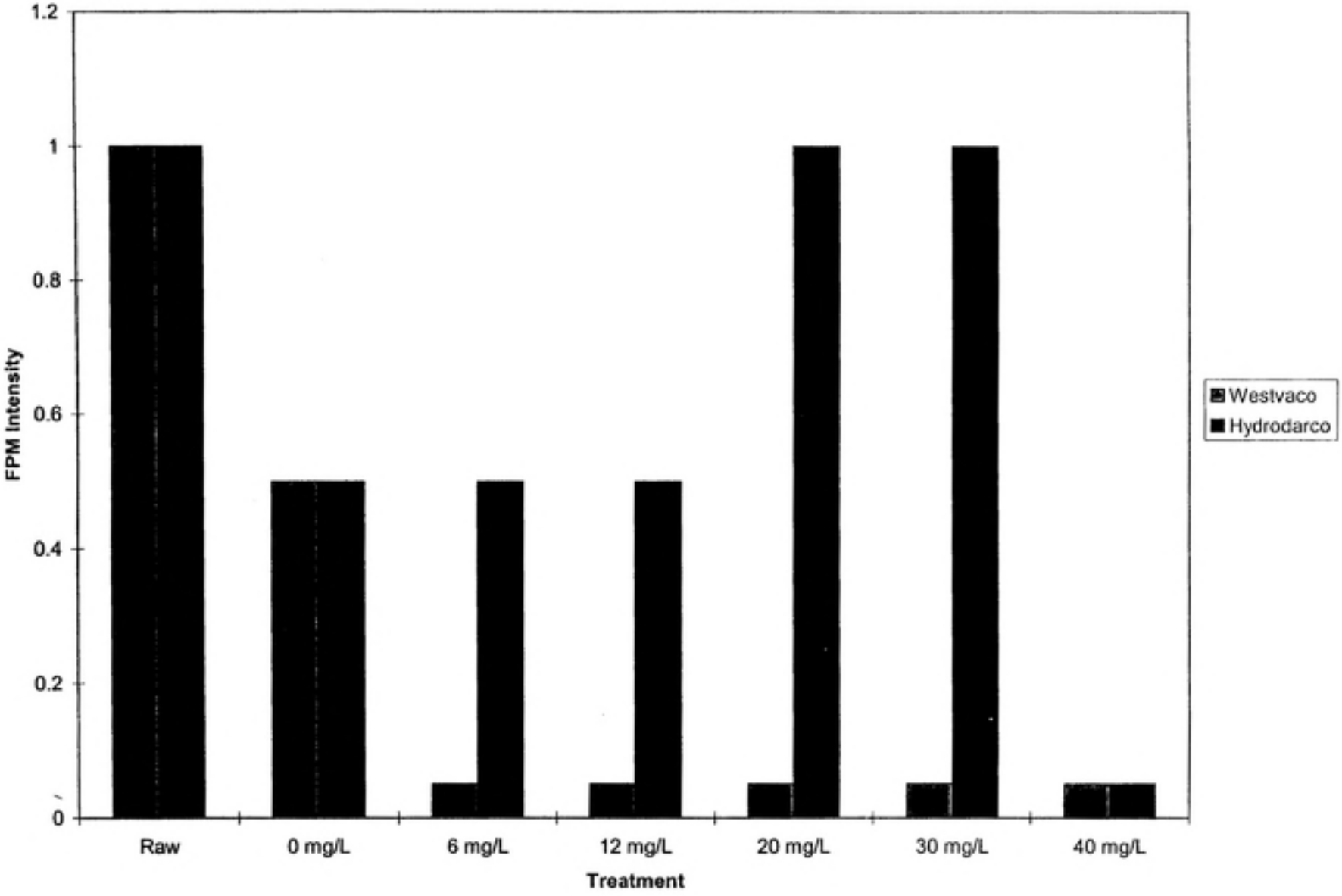


Figure AIII.5. FPM Intensity data for 7/29/99

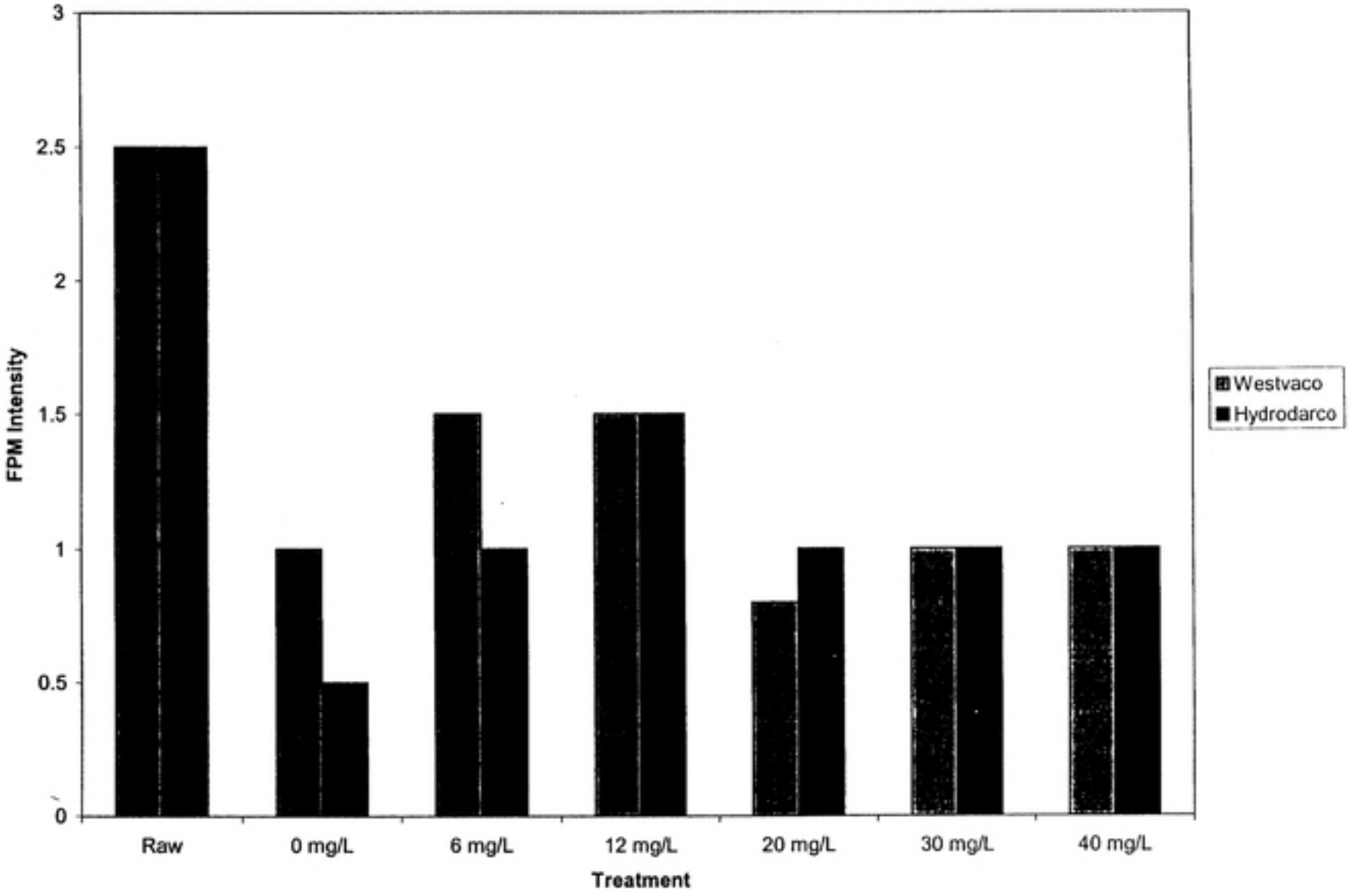


Figure AIII.6. FPM Intensity data for 8/4/99

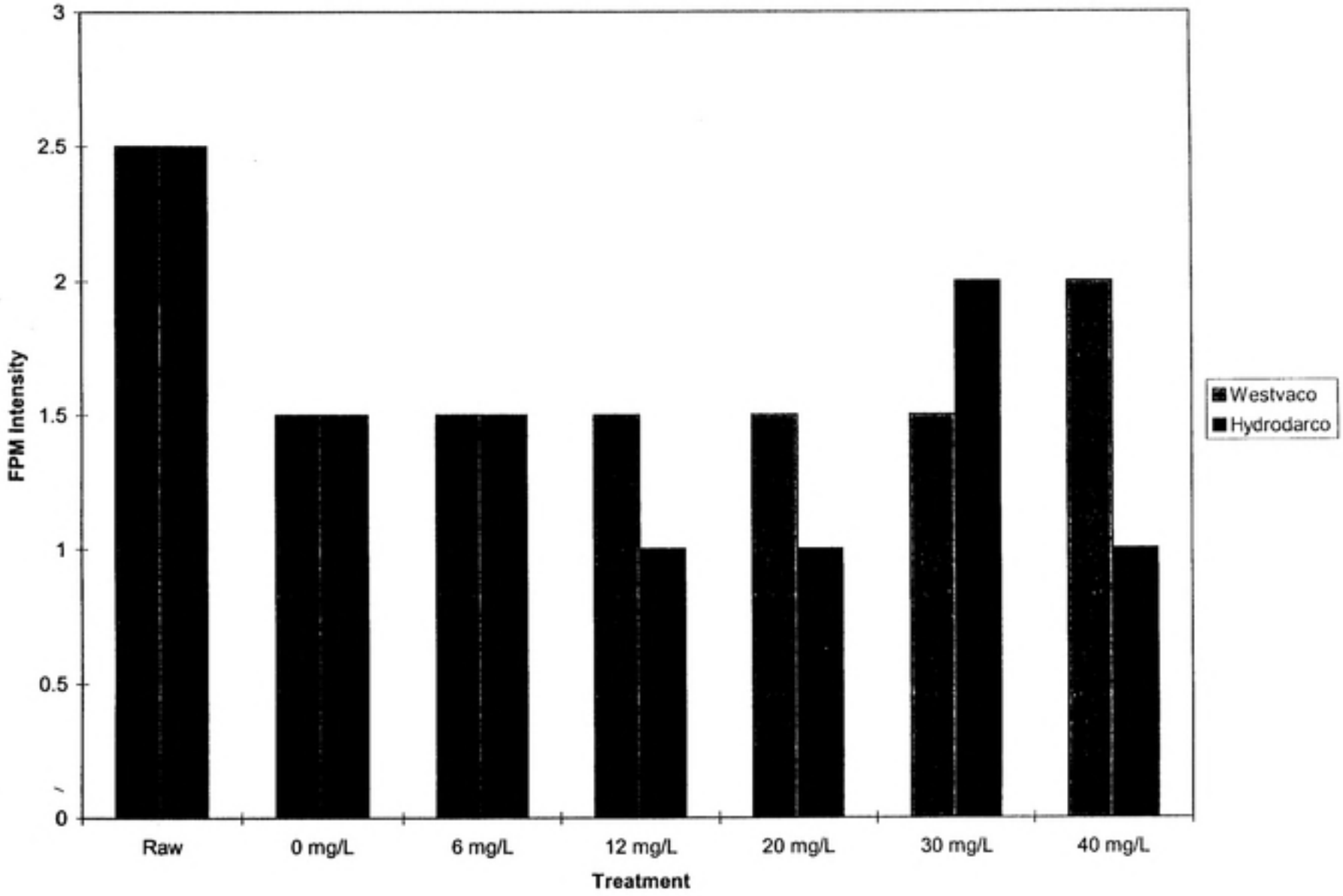


Figure AIII.7. FPM Intensity data for 8/12/99