ICR Treatment Study Summary Report

Evaluation of GAC Pilot Study for Compliance with the Information Collection Rule

CONDUCTED DURING THE PERIOD OF APRIL 14, 1998 THROUGH OCTOBER 30, 1998

JULY, 1999

CITY OF HOUSTON
TX1010013
2300 FEDERAL ROAD
HOUSTON, TX, 77015
PHONE #: (713) 330-2512
FAX #: (713) 451-1339

East Water Purification Plant III, ICR # 630
East Water Purification Plants I and II, ICR#631,
and Southeast Water Purification Plant, ICR#632

Attachments: 4 Diskettes Containing:
The *Data Collection Spreadsheets*
The *ICR Summary Report*
The *Summary Report Spreadsheets*
The pretreatment data

Montgomery Watson Americas, Inc.
Houston Regional Office
5100 Westheimer, Ste 580
Houston, TX 77056

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CONCLUSIONS AND RECOMMENDATIONS

A single treatment study was conducted jointly by the City of Houston and Montgomery Watson for multiple plants, to evaluate the removal or reduction of disinfection by-products (DBPs) precursors by granular activated carbon (GAC). As prescribed by the USEPA in the Information Collection Rule (ICR), a pilot-scale GAC test was utilized to simulate full-scale GAC performance. The ICR testing was conducted using the City of Houston's permanent research pilot facility located at the East Water Purification Plant (EWPP). The test was designed and conducted as required by the ICR Manual for Bench- and Pilot-Scale Treatment Studies. One operational run of approximately 4,600 hours was conducted to evaluate seasonal variability. During the run, two empty-bed contact times (EBCTs) (10 and 20 minutes) were evaluated. The run terminated when the TOC concentration in the 20-minute GAC effluent exceeded 70 percent of the running average TOC in the influent. Trinity River water was used as the raw water source for the pilot study. Full-scale processes used to remove DBP precursors were simulated at pilot-scale. Alum and anionic flocculation aid polymer were utilized in the pilot plant to pre-treat the raw water sample. Additionally, full-scale distribution system conditions were simulated during chlorination testing. All methods used to simulate distribution conditions and measure the formation of DBPs were in accordance with ICR prescribed methods.

GAC pretreatment consisted of alum coagulation along with a flocculation aid polymer, sedimentation, and dual media filtration. The pretreatment process produced a consistent GAC influent water quality with a relatively constant TOC (< 4.0 mg/L) and turbidity (< 0.2 ntu). This was achieved even when TOC levels in the raw water were increasing during tropical rainfall events. The study was conducted during both dry and rainy seasons.

The GAC contactors were monitored daily to determine when simulated distribution system disinfection by-products testing should be conducted. A minimum of 15 GAC influent and effluent contactor (10- and 20-minute EBCT) samples were collected as required by the ICR Guidance Manual. The results of the SDS testing can be summarized as follows:

- The 10-minute EBCT contactor exceeded 70% of the influent TOC after 1,862 hours (78 days).
- The 20-minute EBCT contactor exceeded 70% of the influent TOC after 4,230 hours (176 days).
- TOC removal by the contactors was gradual such that the pilot study exceeded 4,000 total hours.
- The 10-minute EBCT contactor exceeded the Stage 2 TTHM MCL and Stage 2 HAA5 MCL at 622 hours (26 days) and 1,990 hours (83 days), respectively.
- The 20-minute EBCT contactor exceeded the Stage 2 TTHM MCL and Stage 2 HAA5 MCL at 1,657 hours (69 days) and 2,119 hours (88 days), respectively.
- The TTHM MCL was exceeded before the HAA5 MCL.
- EBCT is an important parameter in GAC contactor design, using a 20-minute EBCT will result in the extension of the TOC removal run time.

GAC replacement and regeneration costs were calculated based on the carbon usage rates (CUR) to reach the design target of Stage 2 MCL for TTHM, since this MCL had the highest GAC cost/1000 gallons of treated water. The average annual GAC replacement costs to meet 80% of the Stage 2 TTHM MCL were estimated at $39,858,000 for a 10-minute EBCT and at $24,144,750 for a 20-minute EBCT. The most conservative CUR (to meet 80% Stage 2 TTHM MCL using a 10-minute EBCT) was utilized for estimating the surface area of a single reactivator for thermal regeneration. On-site thermal regeneration of the GAC was determined at $7,208,305 and $4,832,000 for annual reactivation costs for a 10-min and 20-minute EBCT, respectively. Cost analyses show that reactivation would be less expensive than carbon replacement after TOC exhaustion. To take a conservative measure, these costs were estimated using an average flowrate of 105 mgd for the EWPP III.

Total annual costs for a conventional concrete gravity adsorber (including GAC reactivation cost) were estimated at $8,561,100 for a 10-minute EBCT and $6,642,500 for a 20-minute EBCT. Without reactivation, the total annual costs were estimated at $1,351,100 and $1,810,500 for a 10-min and 20-minute EBCTs, respectively. Annual capital costs were estimated at $947,100 for a 10-minute EBCT and $1,406,500 for a 20-minute EBCT. These costs were estimated using an average flowrate of 105 mgd for the EWPP III capacity.

The reduction of DBP precursors with GAC would be an expensive treatment technology to implement for the City of Houston. Alternative technologies should be evaluated. These include: 1) enhanced coagulation to remove precursors to limit DBP formation, 2) alternative disinfectants (ozone and chlorine dioxide), and 3) GAC performance can be improved by enhanced coagulation to remove TOC. Blending GAC contactor effluents (contactors in parallel or in-series) would also result in the extension of column runs and the reduction of O&M costs, including GAC replacement or reactivation costs.

BACKGROUND INFORMATION

This section describes the project background pertinent to the set-up and completion of the ICR GAC pilot study. A main component of this section is a detailed description of the pilot plant set-up.

Full-Scale Treatment Facilities

The City of Houston's EWPP, located on the east side of Houston, is composed of three plants: EWPP I, II, and III. EWPP I and II are essentially one plant with dual treatment trains (Train ABC and Train DE). The City also is part owner of the Southeast Water Purification Plant (SEWPP). All of the plants are similar in nature, since each produces finished water using similar conventional treatment processes and chemical treatment scenarios. The total capacity of the four plants is 430 mgd. The capacity of EWPP III is 150 mgd, while EWPP I and II have a 200 mgd capacity. The capacity of the Southeast WPP is 80 mgd,. The raw water source for the three plants are the Trinity River/Lake Livingston and Lake Houston/San Jacinto River. The USEPA approved the study plan for this ICR program for the pilot facilities to treat Trinity River water. Hereafter, all references to full-scale processes will be designated EWPP.

Trinity River water supply is conveyed to the treatment plant via a long pipeline (approximately 12-13 miles) operated by the Coastal Water Authority (CWA). The water is pre-chloraminated to prevent the attachment of Asiatic clams and biogrowth. Permission was obtained from the USEPA to operate the pilot study with pre-chloraminated water since it was cost prohibitive to obtain water that was chloramine-free. The EWPP uses conventional treatment, and the same treatment scheme used at the full-scale level for removing DBP precursors was simulated on the pilot-scale. Pilot-scale treatment consistsof rapid mix, flocculation, sedimentation, granular media filtration, and a clearwell. Chemicals added at the full-scale include the following: chlorine, ammonia, alum, cationic coagulant aid polymer, anionic flocculant aid polymer, lime for pH control, caustic soda for final pH control, and fluoride. The pilot plant chemical additions were limited to alum and anionic polymer.

EWPP III Process Schematic

Figure 1 (Appendix A) illustrates a simplified schematic of the water treatment processes applied at the EWPP, and also shows the sample locations and analytes covered under the 18-month ICR monitoring. Chloraminated raw water is conveyed from Trinity River to the plant intake through the CWA pipeline. Chlorine is added at the low lift pumps and ammonia is added before rapid mix. Alum, polymers, PAC (when necessary), and lime are then added into the rapid mix. The water undergoes flocculation, sedimentation, dual media filtration, and a final disinfection (if required) with chlorine and ammonia before storage in a clearwell.

EWWP Design Information

Table 1 summarizes EWPP III general data. More complete design data tables were submitted to the USEPA for the ICR monitoring report.

TABLE 1
FULL-SCALE DESIGN DATA AT EWPP III

Treatment Process	Parameter		Value
Forebay	Surface Area (sq ft)		374,330
	Volume (gal)		29,375,000
Chlorine Dose	Dose Rate (mg/L)		6.0
Ammonia	Dose Rate (mg/L)		1.1
Rapid Mix	Type of Mixer		Mechanical
	Volume (gal)		130,000
	Mean Vel Gradient (s-1)		700.0
	Alum Dose Rate (mg/L)		68.0
Flocculation	Total Volume (gal)		2,872,520
	Stage 1	Vel Gradient (s-1)	65
		Volume (gal)	957,500
	Stage 2	Vel Gradient (s-1)	50
		Volume (gal)	957,500
	Stage 3	Vel Gradient (s-1)	35
		Volume (gal)	957,500
Sedimentation	Surface Area (sq ft)		206,000
	Volume (gal)		24,655,800
Filtration	Surface Area (sq ft)		21,632
	Volume (gal)		1,666,730
	Media Depth (in)		33
	Type		Dual
Transfer Well	Surface Area (sq ft)		14,800
	Volume (gal)		844,600
Clearwell	Surface Area (sq ft)		147,261
	Volume (gal)		37,500,000

Summary of Source/Finished Water Quality

The average, minimum, and maximum values are presented in Table 2 for selected water quality parameters for the influent to the EWPP using data collected monthly between July, 1997 and July, 1998 during the full-scale ICR 18-month Monitoring Program from EWPP III. Additional water quality data can also be found in the Treatment Study Summary Report Spreadsheet attached at the end of this document, see Appendix B.

TABLE 2
SUMMARY OF RAW SOURCE WATER QUALITY AT EWPP III
(JULY, 1997 THROUGH JULY, 1998)

Source Water Quality Parameter	Average Concentration	Standard Deviation	Maximum Value	Minimum Value
Temperature (°C)	21.0	7.2	30.0	8.9
PH	7.69	0.12	8.02	7.53
Turbidity (NTU)	29.2	18.0	56.0	11.1
Total Alkalinity (mg/L as $CaCO_3$)	99	11	112	80
Total Hardness (mg/L as $CaCO_3$)	119	10	136	98
TOC (mg/L)	5.3	1.1	7.0	4.0
UV-254 (cm^{-1})	0.236	0.132	0.483	0.121

Table 3 summarizes average finished water quality at the EWPP collected during the 18-month ICR Monitoring Program from Plant III.

TABLE 3
SUMMARY OF FINISHED WATER QUALITY AT THE EWPP
(JULY, 1997 TO JULY, 1998)

Finished Water Quality Parameter	Average Concentration	Standard Deviation	Maximum Value	Minimum Value
Temperature (°C)	22.6	6.1	30.0	14.4
pH	7.86	0.15	8.11	7.53
Turbidity (NTU)	0.07	0.01	0.09	0.05
TOC (mg/L)	4.2	0.4	4.9	3.5
UV_{254} (cm^{-1})	0.096	0.011	0.113	0.078
DS-TTHM (ug/L)*	36.2	11.5	45.0	19.3
DS-HAA5 (ug/L)*	57.9	13.9	73.1	39.3
DS-HAA6 (ug/L)*	69.2	16.8	86.8	47.3

* Based on four quarterly sampling periods (09/97; 12/97; 03/98; 06/98). Measured in the distribution system at the point of estimated average residence time.

MATERIALS AND METHODS

Water Quality of the Influent to the EWPP

According to the ICR guidelines, the feed water samples for the treatment study must be collected from a location in the treatment process prior to application of an oxidant that could form chlorinated by-products. Special consideration was made by the USEPA for the EWPP pilot study, since the raw water (Trinity River) is chloraminated to control Asiatic Clams and other biogrowth. The pilot study began on April 14, 1998 and concluded on October 30, 1998. Table 4 summarizes the variations that occurred in the raw water quality during the pilot testing period.

TABLE 4
SUMMARY OF PILOT PLANT RAW WATER QUALITY
(APRIL 15, 1998 THROUGH OCTOBER 30, 1998)

Parameter	Unit	Median	Minimum	Maximum	Count
pH	---	7.93	7.07	8.23	156
Temperature	°C	29	20	32	155
TOC	mg/L	4.73	3.98	11.13	150
Turbidity	NTU	17	8	51	154
Alkalinity	mg/L as $CaCO_3$	112	54	132	155
Total Hardness	mg/L as $CaCO_3$	130	88	156	155
Calcium Hardness	mg/L as $CaCO_3$	46	23	56	155
Filtered UV-254	cm^{-1}	0.135	0.092	0.522	153
Ammonia	mg N/L	0.4	0.3	0.5	146
Total Chlorine	mg/L	0.2	0.2	1.8	155

Pilot Plant Pre-Treatment Processes

Schematic of Pre-Treatment Processes

The City of Houston's research pilot facility (located at EWPP III) can be configured to examine several treatment scenarios. However, during the ICR pilot testing, it was configured specifically to meet the GAC pilot recommendations outlined in *The ICR Guidance Manual*. Figure 2 (Appendix A) illustrates the pilot-scale processes that were used to simulate the full-scale pretreatment processes.

The processes utilized during the ICR pilot test consisted of coagulation, flocculation, sedimentation, and granular media filtration followed by GAC adsorption. The chemical dosages and process loading rates in the pilot plant were set at values similar to those employed at the full-scale plant (only alum and flocculation aid polymer) to ensure that the GAC influent water quality at pilot-scale was comparable to the full-scale filtered water. A summary of the design criteria and operational variables for each unit of the pretreatment process is given in Table 5.

Alum was used as the primary coagulant and an anionic polymer was used as a flocculation aid to assist in clarification. Four stage-tapered flocculation was followed by sedimentation using a tube settler. A dual media filter having 18 inches of anthracite (ES = 0.9 mm, UC = 1.4, specific gravity = 1.66) on top of 18 inches of sand (ES = 0.5 mm, UC = 1.2, specific gravity = 2.65) was used for particle removal prior to GAC adsorption. The dual media filter upstream of the GAC contactor should ensure adequate media filtration and proper loading of the GAC particles by removing the fines and limiting the headloss across the GAC bed. Additionally, filtration prior to the GAC contactors minimized the need to backwash the contactors.

The *ICR Guidance Manual* states that chloramines shall not be added upstream of the GAC contactors. However, due to the nature of the biological agents (Asiatic Clams) present in the raw water source, low residuals of chloramines (<0.1 mg/L as Cl_2 in most cases) were present upstream of the pilot. However, as prescribed in the Guidance Manual, no further chloramine addition was made during the pretreatment process. Additionally, pH adjustment was not practiced during the course of the study.

TABLE 5
SUMMARY OF PILOT PLANT UNIT PRETREATMENT PROCESSES

Process	Units	Value
Coagulation		
Coagulant	-	Alum
Coagulant dose	mg/L	40 ± 20 as Alum Product
Coagulant aid	-	Not Used
Coagulant aid dose	mg/L	--
Flocculation		
Flow rate	gpm	15
Detention time	min	50
Number of stages	-	4
Velocity gradient	s^{-1}	
Stage 1		103
Stage 2		34
Stage 3		24
Stage 4		10
Flocculant aid	-	Anionic Polymer
Flocculant aid dose	mg/L	0.05 ± 0.02 Neat
Sedimentation		
Flow rate	gpm	<15
Operating goal	ntu	0.6 to 0.9
Granular media filtration		
Flow rate	gpm	0.44
Filtration rate	gpm/ft^2	5
Media design	-	18″ anthracite (ES=0.9 mm, UC=1.4) 18″ sand (ES=0.5 mm, UC=1.2)
Operating goal	ntu	Turbidity < 0.2
pH adjustment		None

Design Data for the GAC Adsorption Process

Design and Set-up of the GAC Columns

Two GAC contactors, 10- and 20-minute, were set up for the pilot testing. The GAC selected for the study was Calgon Filtrasorb 300 granular activated carbon, having an average diameter of approximately 1.0 mm. The inner GAC column diameter was approximately 100 times greater than the average particle diameter of the GAC, which means that short circuiting and channeling near the walls was not significant. Appendix C includes detailed instructions on the set-up and start-up of the GAC contactors.

The pilot plant was set-up so that filtered water is sent to an intermediate clearwell. Water from the clearwell is then pumped to the first GAC contactor (EBCT=10 minutes), with a second GAC contactor operated in series to provide an additional EBCT of 10 minutes. This is the preferred process flow set-up according to the *ICR Guidance Manual*. The arrangement is shown in Figure 2 (Appendix A). Samples for the 10-minute EBCT were collected at the effluent of the first contactor, whereas samples collected at the effluent of the second contactor corresponded to the 20-minute EBCT experiments. The surficial velocity (hydraulic loading rate) for the GAC contactors was set at 5 gpm/ft^2. In order to achieve a loading rate of approximately 5 gpm/ft^2, the 4-inch diameter columns were loaded at 0.44 gal/min. This translates into a bed depth of 80 inches to achieve a 10-minute EBCT and 160 inches bed depth to achieve a 20-minute EBCT. Table 6 summarizes the design of the GAC contactors.

TABLE 6
SUMMARY OF PILOT PLANT UNIT GAC PROCESS

Process	Units	Value
GAC adsorber - 10 minute		
Flow rate	Gpm	0.44
Hydraulic loading rate	gpm/ft^2	5
Media	-	Calgon Filtrasorb 300 (ES ≈ 1 mm)
EBCT	minute	10
Bed depth	inch	80
Column interior diameter	inch	4
Total column length	ft	13
Mass of GAC added	lb	19.9
GAC type and mesh size	-	Calgon Corp. F-300, 8×30
Average particle diameter (APD)	mm	1.0
GAC adsorber - 20 minute		
Flow rate	gpm	0.44
Hydraulic loading rate	gpm/ft^2	5
Media	-	Calgon Filtrasorb 300 (ES ≈ 1 mm)
EBCT	minute	20
Bed depth	inch	160 (total from 2 beds)
Column interior diameter	inch	4
Total column length	ft	13
Mass of GAC added	lbs	20.6
GAC type and mesh size	-	Calgon Corp. F-300, 8×30
Average particle diameter (APD)	mm	1.0

Pilot Column TOC Leaching Examination

The pilot-scale filter and GAC contactor columns were fabricated using clear PVC pipe. Concerns were raised that PVC might leach TOC during testing and skew the test results. To assure that leaching had not occurred, finished water from the full-scale plant was used to flush the contactor columns (without loading the GAC) for a period of over four weeks. Throughout the “blank run”, TOC samples were collected from the contactor columns influent and effluent waters. These results indicate that there was no statistical difference at the 95% confidence level in the TOC concentrations of the contactor columns influent and effluent water. The test results conclusively showed that no significant TOC leaching occurred due to the PVC material used in the construction of the contactors, piping, or wetted parts of the pumps. A technical memorandum was submitted and approved by the USEPA confirming these results. Table 7 summarizes the TOC leaching data submitted to the USEPA.

TABLE 7
SUMMARY OF THE BLANK RUN DEMONSTRATION RESULTS

Date	GAC-10 INF		GAC-10 EFF		GAC-20 INF		GAC-20 EFF	
	AVG	STDEV*	AVG	STDEV*	AVG	STDEV*	AVG	STDEV*
3/10/98	4.30	0.067	4.40	0.125	4.49	0.139	4.45	0.047
3/11/98	4.00	0.068	3.97	0.062	4.00	0.046	4.15	0.193
3/12/98	4.22	0.021	4.22	0.123	4.20	0.159	4.24	0.026
3/13/98	4.32	0.165	4.34	0.046	4.27	0.053	4.31	0.055
3/16/98	4.16	0.076	4.32	0.040	4.33	0.045	4.34	0.046
3/30/98	4.96	0.127	4.95	0.076	4.95	0.133	4.91	0.059
3/31/98	4.96	0.121	4.82	0.012	4.80	0.120	4.74	0.072
4/1/98	4.70	0.080	4.80	0.120	4.86	0.059	4.82	0.006
4/2/98	4.87	0.078	4.88	0.091	4.96	0.049	4.99	0.064
4/3/98	4.84	0.046	4.91	0.038	4.88	0.038	4.86	0.087
4/4/98	4.90	0.006	4.88	0.020	4.88	0.020	4.88	0.017

*STDEV: Standard Deviation

Experimental Design

This section describes the experimental design used for conducting the ICR GAC pilot study. This includes the simulated distribution system disinfection by-product (SDS DBP) test, as well as all sampling requirements.

Daily Pilot Plant Operation Summary

During the GAC study the pilot plant was operated in two stages. The first stage consisted of the pretreatment upstream from the GAC contactors, pretreatment processes include the following: raw water conveyance, coagulation, flocculation, and dual media filtration. The second stage consisted of the GAC adsorption. The GAC pretreatment processes were utlilized in order to maintain a relatively constant dual media filtered effluent, or GAC contactor influent. Alum dosage was varied to maintain a settled water turbidity of between 0.6 and 0.9 ntu. By maintaining the settled water turbidity in this narrow range, a relatively constant dual media filter effluent of between 0.1 and 0.2 ntu was achieved. With a filter effluent turbidity goal of 0.1 to 0.2 ntu, it was necessary to establish a backwash protocol. The granular media filters were backwashed when either of the two run termination criteria were triggered: effluent turbidity $\geq$ 0.2 NTU or run time $\geq$ 72 hours.

Daily Sampling and Analysis

Key water quality parameters were monitored at all points in the treatment process. See Table 8 for a list of the daily water quality parameters that were monitored.

In addition to the water quality parameters, a daily operational log for flow and chemical dosages was maintained. A spreadsheet of the daily pretreatment water quality parameters is included in Appendix B entitled: *Pretreatment Data.xls*.

TABLE 8
DAILY WATER QUALITY MONITORING REQUIREMENTS

Location	Analyses
Raw water	pH, Temperature, Turbidity, Alkalinity, Total and Calcium Hardness, TOC, UV_{254}
Settled water	pH, Turbidity, TOC, UV_{254}
Filtered water Effluent	Turbidity, Ammonia, Total and free Cl_2, TOC, UV_{254}
GAC-10 effluent	Turbidity, Ammonia, Total and free Cl_2, TOC, UV_{254}
GAC-20 effluent	Turbidity, Ammonia, Total and free Cl_2, TOC, UV_{254}

GAC Contactor Sampling and Analyses

Fifteen or more influent and effluent ICR compliance samples for both 10-minute and 20-minute EBCT contactors were collected to satisfy ICR regulatory requirements. Because the 10- and 20-minute EBCT runs were operated simultaneously, influent samples were collected at the same time as the 20-minute EBCT effluent samples.

The USEPA stipulated that after the first day, samples for ICR should be collected at 3% to 7% increments of the average influent TOC (defined as the running average of all influent TOC samples). Daily measurements of GAC influent and effluent TOC concentrations were made to determine exact sampling dates to ensure that the TOC breakthrough curve was well characterized. As required by the ICR, a minimum of 15 samples were collected for the analytes described in Table 9. Additionally, three duplicate samples (and three instantaneous samples) were collected from the influent and from the effluent of each column. These samples were analyzed for a variety of water quality parameters (Table 9).

TABLE 9
ICR ANALYTICAL REQUIREMENTS FOR THE GAC PILOT STUDY

Sampling point	Analyses
GAC influent	pH, alkalinity, turbidity, temperature, total hardness, calcium hardness, ammonia, bromide, TOC, UV_{254}, SDS testing for THM, HAA, TOX, and chlorine demand
GAC-10 effluent	pH, turbidity, temperature, ammonia, TOC, UV_{254}, SDS testing for THM, HAA, TOX, and chlorine demand
GAC-20 effluent	pH, turbidity, temperature, ammonia, TOC, UV_{254}, SDS testing for THM, HAA, TOX, and chlorine demand

Instantaneous DBP Sampling

Since the CWA practices pre-chloramination as a means of controlling Asiatic Clams, the USEPA stipulated that “instantaneous” THM, HAA, and TOX samples be collected to determine “background” concentrations for these DBPs. Three sets of samples were collected as illustrated in Table 10: one at the influent to the GAC contactors, another at the effluent of the first GAC contactor at 10 minutes EBCT, and the third at the effluent of the second GAC contactor at 20 minutes EBCT. These samples were collected at the same time as required ICR duplicate samples. Sample results are discussed herein.

TABLE 10
ICR REQUIREMENTS FOR "INSTANTANEOUS" DBPS

Sampling point	Analyses	Comments
GAC influent	THMs, HAAs, and TOX	Collect along with duplicate samples
GAC-10 effluent	THMs, HAAs, and TOX	Collect along with duplicate samples
GAC-20 effluent	THMs, HAAs, and TOX	Collect along with duplicate samples

Simulated Distribution System (SDS) Chlorination Testing

Strict SDS DBP formation testing protocol was followed during the pilot study. The SDS DBP test target conditions were obtained from USEPA publications and based on full-scale distribution conditions. Table 11 presents the target SDS conditions. The tolerances on the SDS target conditions were presented in the USEPA *ICR Treatment Study Fact Sheet* (November 1997). During these tests the sample water was placed in one liter amber bottles and dosed with chlorine to obtain a free chlorine residual in the range 0.5 – 1.0 mg/L at the conclusion of the incubation period. Following incubation, the chlorinated water samples were sampled for THMs, HAAs, and TOX.

TABLE 11
TARGET SDS CHLORINATION TESTING CONDITIONS

Season	Temperature (°C)	Incubation time (hour)	Incubation pH	Free Cl_2 residual (mg/L)
Rainy	25 ± 2.0	18 ± 1.0	8.0 ± 0.4	0.5 to 1.0 ± 0.4
Dry	25 ± 2.0	18 ± 1.0	8.0 ± 0.4	0.5 to 1.0 ± 0.4

Efforts were made to ensure that the incubation time, pH, and free chlorine residual remained relatively constant during the GAC run to facilitate comparison of DBP precursor removal. Variations in the distribution system temperature were incorporated in the incubation process, by storing the SDS bottles in a water bath prepared with running distribution system water in the City's Water Quality Laboratory.

One liter amber bottles with Teflon lined caps were used for SDS testing. The bottles were cleaned and made chlorine demand-free by soaking them in 100 mg/L chlorine solution for one day before rinsing them thoroughly with deionized water. Three to five bottles were dosed for each sample to cover a range of free chlorine concentrations for both GAC influent and effluent waters. The bottles were filled with the sample water, a pH buffer solution was added, then dosed with free chlorine to achieve the target residual, and placed in a water bath for 18 hours. The initial temperature, chlorine residual, chlorine dose, and pH were recorded. Following incubation, the bottles were sampled for chlorine residual, pH, temperature, THMs, HAAs, and TOX. It should be noted that the methodology for the SDS procedure prescribed by the ICR required free chlorine while the City practices chloramination. Using free chlorine was a worst case scenario for DBP formation and thus produced more conservative formation estimates than using chloramination.

Analytical Methods

The list of all the analytical methods used during the pilot testing and their corresponding Minimum Reporting Limits (MRLs) are presented in Table 12.

TABLE 12
LIST OF ANALYTICAL METHODS AND MRLS

Analyte	Method	Minimum Reporting Level (MRL)
Alkalinity	SM 2320 B	4 mg/L as $CaCO_3$
Ammonia	SM 4500-NH_3 D	0.025 mg/L as NH_3-N
Bromide	EPA 300.0	20 µg/L
Calcium Hardness	SM 3500	0.5 mg/L as $CaCO_3$
Total Hardness	SM 2340 B	4 mg/L as $CaCO_3$
Chlorine Residual/Dose	SM 4500-Cl D	0.1 mg/L as Cl_2
HAAs	SM 552.2	0.1 µg/L for all analytes
pH	SM 4500-H^+	Not Applicable
Turbidity	SM 2130 B	0.025 ntu
Temperature	SM 2550 B	Not Applicable
THMs	EPA 551	0.1 µg/L for all analytes
TOC	SM 5310 C	0.1 mg/L
TOX	SM 5320	25 µg/L
UV_{254}	SM 5910	0.009 cm^{-1}

Table 13 presents a listing of the laboratories involved in the analytical reporting and the period over which analyses were conducted by each laboratory. The City of Houston Water Quality Laboratory conducted the analyses of all parameters except the TOX. TOX samples were sent to Montgomery Watson Laboratories in Pasadena, California to complete the ICR test. Following Table 13 is additional information on the location and contact person at each individual laboratory. More information on these laboratories is included in Appendix B (ICR Summary Spreadsheet).

TABLE 13
LISTING OF LABORATORIES INVOLVED IN THE ANALYTICAL REPORTING

Laboratory	Dates of Service	Analyses Performed
City of Houston Water Quality Laboratory	04/15/98 through 10/30/98	Alkalinity, Turbidity, TOC, Hardness, Temperature, pH, UV_{254}, Chlorine residual, Ammonia, THMs , HAAs, Bromide, Ca-hardness
Montgomery Watson Labs	04/15/98 through 10/30/98	TOX (SM 5320)

City of Houston Water Quality Laboratory
Water Quality Laboratory
2300 Federal Road
Houston, TX 77015
Contact Person: Jim Reavis/Jim Greenlee
Phone #: (713) 330-2534
Fax #: (713) 451-1337

Montgomery Watson Laboratories
Montgomery Watson
555 East Walnut Street
P.O.Box 7009
Pasadena, CA 91101
Contact Person: Jim Hein
Phone #: (626) 568-6489
Fax #: (626) 568-6324

Study Termination Criteria

The ICR requires that both the 10- and 20-minute EBCT experiments be run continuously until:

- the effluent TOC concentration is 70% of the average influent TOC concentration on two consecutive sampling dates that are at least two weeks apart, or
- 50% TOC breakthrough occurs and a plateau is reached in which the effluent TOC concentration does not increase by more than 10% of the average influent value over a period of 1,440 hours.

This study was run continuously until condition number one was met, resulting in a total study run time of over 4,600 hours.

RESULTS AND DISCUSSION

Challenges Encountered (Study Observations)

GAC Column Backwashing Due to Excessive Headloss

During the course of the pilot operation, excessive headloss in the GAC contactors was encountered. According to the *ICR Guidance Manual*, excessive headloss is defined by an excess of greater than 10 psi above the clean bed value of 0.05 to 0.15 psi. In order to relieve the problems caused by excessive headloss, the bed was expanded by 25% for a period of 20 minutes to remove accumulated particles. The down-time resulting from the backwashing process was taken into account in the estimation of the GAC operation run time. The headloss buildup was attributed to two factors: biological growth and particle carryover from the filters. Algae or biogrowth, was noted midway through the study in the top layers of both GAC beds. This biological growth was due to the availability of sunlight and lack of a chloramine residual. After the GAC contactors were backwashed to remove the biological growth, the filter, GAC contactors, and clearwells were covered to minimize light penetration. It is also possible that headloss buildup was related in part to the carryover of particles from the dual media filter. Filter effluent turbidity did, on occasion, go above 0.2 ntu. Episodes of high filter effluent turbidity were typically due to loss of alum feed (chemical pump failure). Therefore, the GAC contactors did gradually buildup some particles, which compounded the biological growth problem, necessitating periodic backwashes.

Seasonal Water Quality Conditions

The GAC pilot study was originally set-up to be run as two studies which spanned both the dry and rainy seasons. The raw and finished waters produced by the City of Houston facilities do not historically show significant seasonal variability. The quality of the raw water is, however, strongly influenced by rainfall patterns. This study was conducted from May to October, and very unusual circumstances (El Nino effect) prevailed. During the first two-thirds of the study, the State of Texas experienced a severe drought. Since there was very little rainfall during this time, TOC levels in the Trinity River watershed declined until the TOC concentration stabilized at a level lower than would normally be expected. For the last one-third of the study, there were several rainstorms in the Texas region. The excessive rainfall from these storms “stirred-up” the watershed, resulting in a very large increase in raw water TOC. Thus, over the duration of the study, both wet and dry weather patterns were experienced. The water quality over the course of the study is shown in Figure 1.

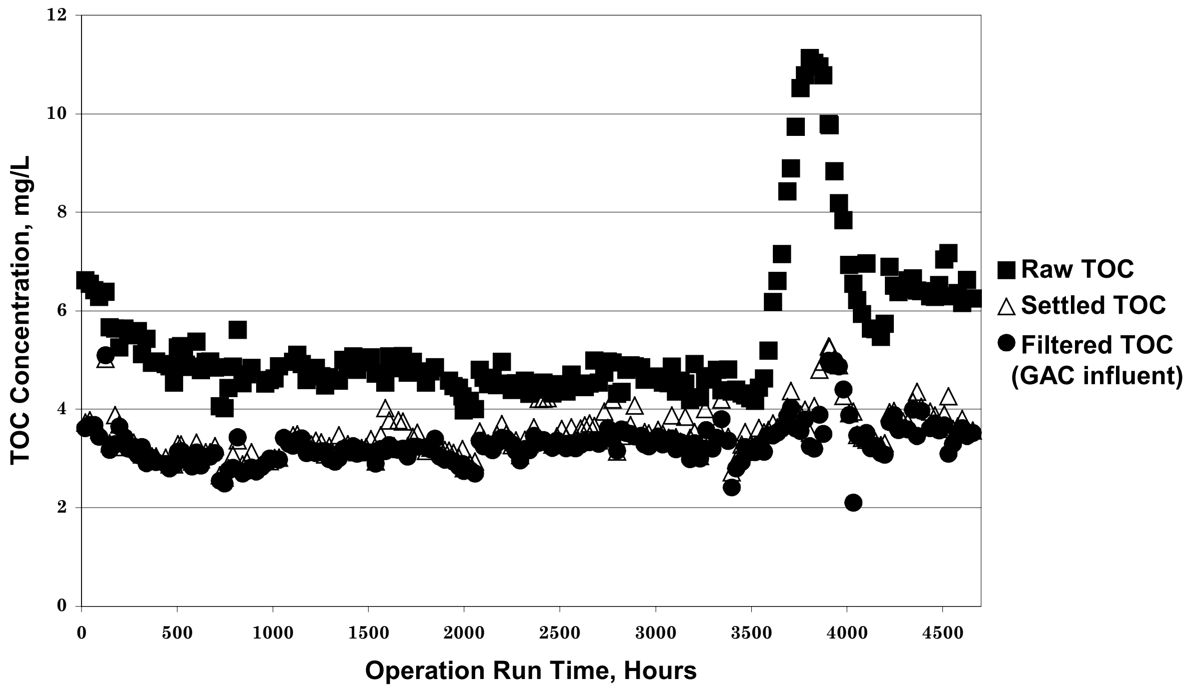

FIGURE 1. VARIATION OF TRINITY RIVER RAW WATER TOC CONCENTRATION OVER OPERATION RUN TIME

Episodes of High Chloramines in the Raw Water

The Coastal Water Authority, which operates the pipeline conveying Trinity River water, practices chloramination to control Asiatic clams. The raw water that reached the pilot plant had a minimal chloramine residual, <0.1 to 0.4 mg/L as Cl_2. The City of Houston was granted an exception to operate the pilot study with this amount of chloramines in the raw water supply. Typically, the chloramine concentration was kept low during the study, however, there was one occasion in which the chloramine level was raised for biological control. The chloramine level in the influent water was above 0.4 mg/L as Cl_2 from approximately 1,645 hours to approximately 2,155 hours. The peak was approximately 2.25 mg/L as Cl_2 at a run time of 1,818 hours. Thus, the background levels of disinfection by-products were expected to be higher during these times, and could cause a small spike in the overall DBP levels.

GAC Pre-Treatment Data

Water Quality of the Pretreated Influent to the GAC Columns

As described in Section 3, the GAC pre-treatment processes were monitored daily for multiple water quality parameters at all major process points. This data can be found in the spreadsheet attached in Appendix B entitled: *Pretreatment Data.xls*. Tables 14 and 15 illustrate the daily trends of the pre-treatment processes for the raw water and filtered water effluent. The filtered water effluent is the influent to the GAC contactors. Another summary of the detailed water quality for the influent water can be found in the ICR database sheets.

TABLE 14
SUMMARY OF PILOT PLANT RAW WATER QUALITY

Water Quality Parameter	Median
pH	7.93
Temperature (ºC)	29
TOC (mg/L)	4.73
Turbidity (ntu)	17
Alkalinity (mg/L as $CaCO_3$)	112
Total Hardness (mg/L as $CaCO_3$)	130
Calcium Hardness (mg/L as $CaCO_3$)	46
UV-254 (cm^{-1})	0.135
Ammonia (mg N/L)	0.4
Total Chlorine (mg/L)	0.2

TABLE 15
FILTERED EFFLUENT WATER QUALITY

Water Quality Parameter	Average	Standard Deviation
Temperature (°C)	26.6	3.6
PH	7.23	0.18
Turbidity (ntu)	0.12	0.07
Alkalinity (mg/L $CaCO_3$)	86	14
Calcium Hardness (mg/L $CaCO_3$)	113	11
Total Hardness (mg/L $CaCO_3$)	128	9
Bromide (µg/L)	121	13
Ammonia-N (mg/L)	0.10	0.04
TOC (mg/L)	3.28	0.21
UV-254 (cm^{-1})	0.060	0.010
SUVA (L/mg-cm)	1.94	0.25
SDS-THM4 (µg/L)	89	16
SDS-HAA5 (µg/L)	56	17
SDS-HAA6 (µg/L)	71	21
SDS-TOX (µg Cl^- /L)	262	39
SDS-Chlorine Demand (mg/L)	2.21	0.30
SDS-Chlorination Ttemperature (°C)	25.8	2.2

Note: * SDS chlorination temperature peaked at a high of 30.0 °C at run time 2,279 hours (lows at beginning and end of study were 21-23 °C)

Figures 2 and 3 illustrate the daily water quality trends of the raw water, settled effluent, and filtered effluent water for turbidity and UV-254. The variation of TOC concentration in the influent to the columns throughout the course of the column runs is plotted in Figure 4. The running TOC average is plotted on the same figure for comparison. The data plotted in Figure 4 is from the SDS DBP sampling data-set as opposed to the daily trends previously plotted in Figure 1. Also included with the SDS data are the duplicate samples for each set of SDS DBP samples.

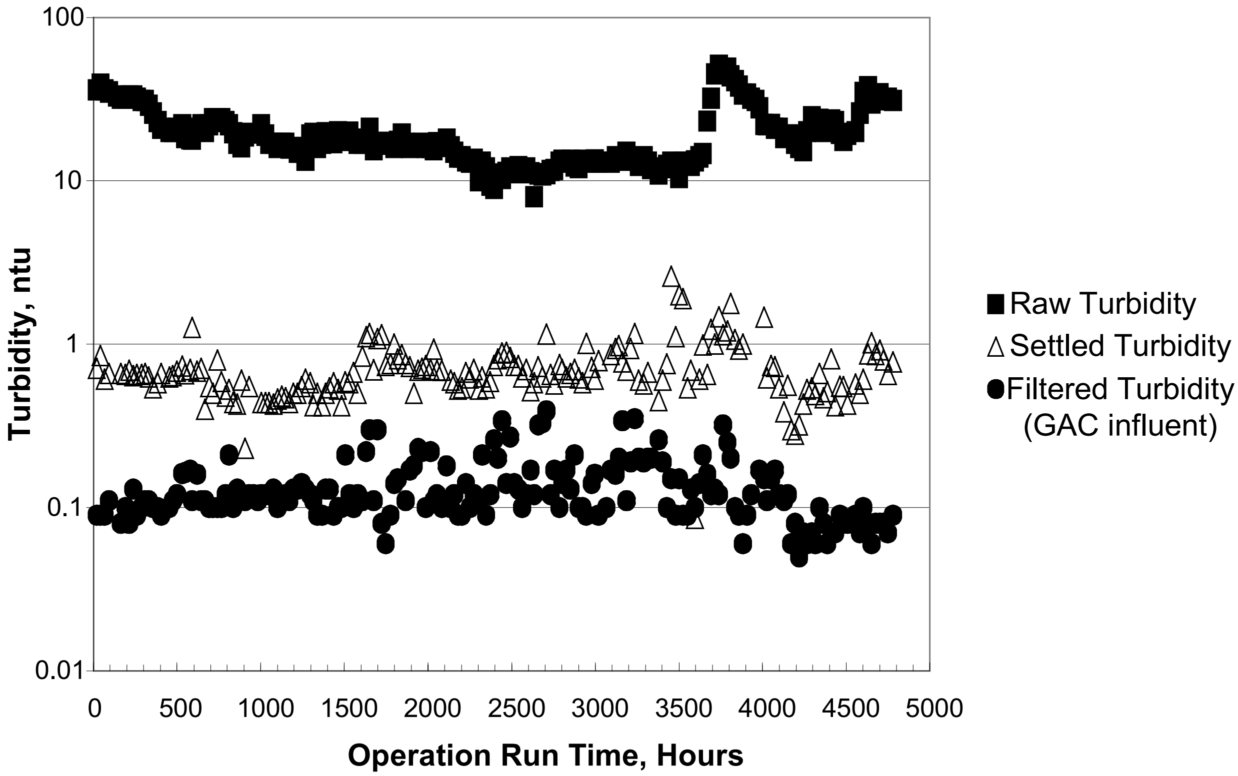

FIGURE 2. VARIATION OF PRETREATMENT TURBIDITY OVER OPERATION RUN TIME

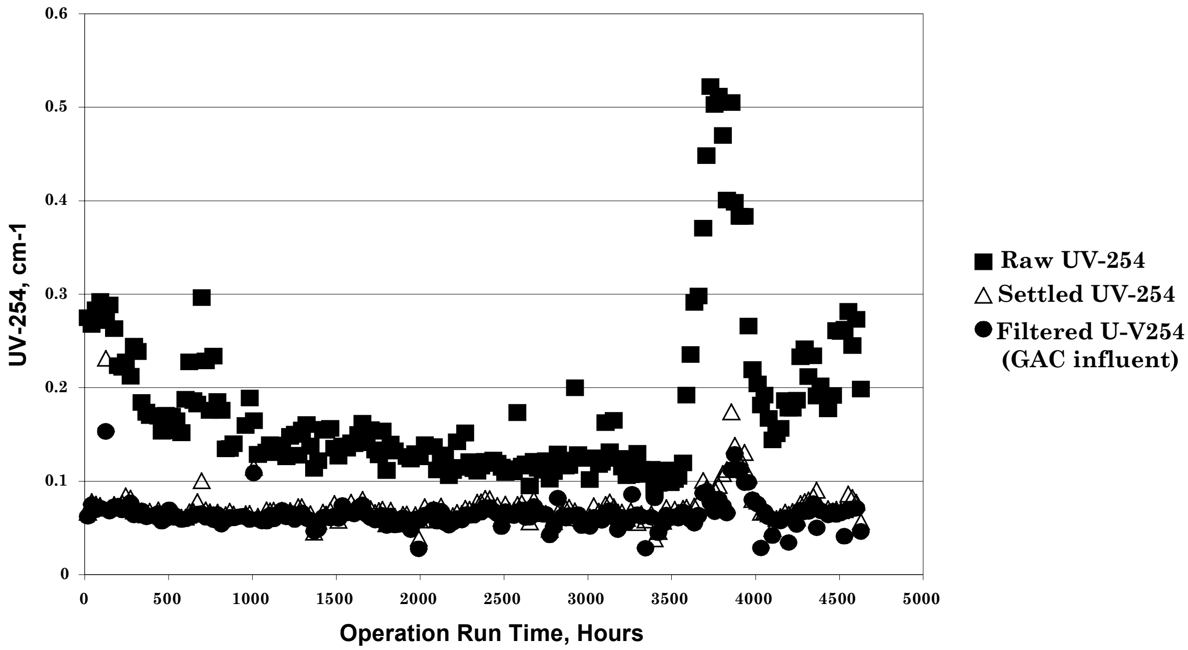

FIGURE 3. VARIATION OF PRETREATMENT UV254 OVER OPERATION RUN TIME

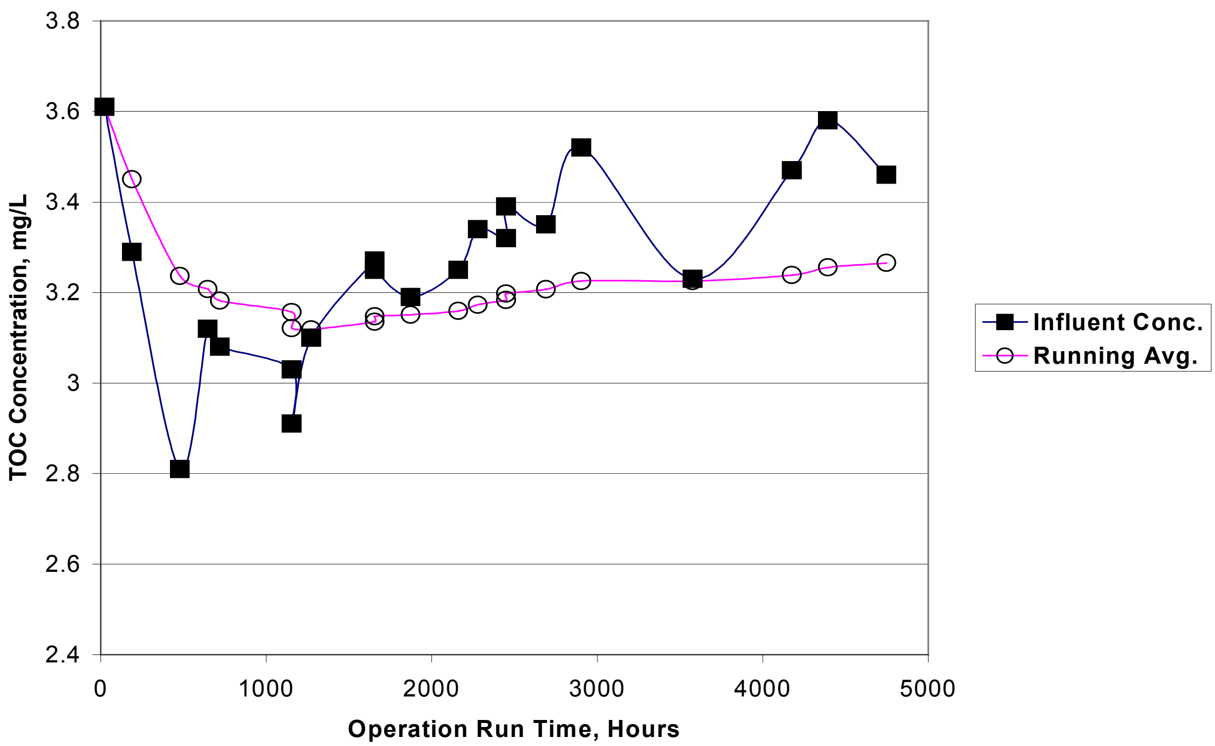

FIGURE 4. VARIATION OF INFLUENT TOC CONCENTRATION AND OF INFLUENT RUNNING AVERAGE OVER OPERATION RUN TIME

The following general conclusions can be drawn from the pre-treatment processes:

- The raw water quality was relatively constant through the first two-thirds of the pilot study, and then due to large rainfall events, there was a significant change in water quality. Both dray and rainy season conditions were evaluated during the course of this study.
- The alum coagulation process produced a high quality effluent averaging approximately 35% TOC removal and <1.0 ntu settled water turbidity. Although seasonal variations (dry and wet periods) occurred, the finished effluent produced was not significantly effected by the seasonal changes.
- Filter effluent was kept below 0.2 ntu throughout the study (only periodic episodes of turbidity above 0.2 ntu occurred primarily due to alum feed disruption).
- The variation in SDS-DBPs was substantial, as expressed by the standard deviation of approximately 16 µg/L for TTHMs and HAA5. Influent temperature did not appear to be a controlling factor in seasonal variability (temperature variation of 11°C, while the standard deviation was only 4°C). Natural organic matter (NOM) indicators in the pre-treated water, represented by TOC and UV-254 absorbance, did not change significantly during the course of the study. Incubation period and pH were kept close to the targets of 18 hours and 8.0, respectively. However, as indicated in Table 15, the chlorination temperature increased about 9°C to a high of 30°C at a run time of 2,279 hours. An increase in the incubation temperature will effect the DBP formation potential, resulting in higher amounts of DBPs formed as the temperature rises.

DBP Background Levels (Instantaneous DBP Sampling)

The background (or instantaneous) DBP levels were analyzed three times during the course of the study in the influent, and effluent of each GAC column. Instantaneous samples were collected to determine DBP background levels due to the presence of chloramines in the raw Trinity River water. Table 16 compares background DBP levels to the DBP levels formed upon SDS chlorination. The SDS levels are calculated from the average of duplicate samples and each of the three sampling times.

TABLE 16
COMPARISON OF DBP BACKGROUND AND SDS LEVELS
IN INFLUENT AND EFFLUENT WATER SAMPLES

Sample Location	TOX	TTHMs	HAA5
Filter Influent-background	19	3	BMRL
Filter Influent-SDS	258	97	52
Background % of SDS	*7*	*3*	--
GAC-10 background	11	2	2.5
GAC-10 SDS	114	56	24
Background % of SDS	*10*	*4*	*10*
GAC-20 background	BMRL	BMRL	4
GAC-20 SDS	50	37	20
Background % of SDS	--	--	*20*

BMRL: Below Minimum Reporting Level
Background % of SDS = 100 * (Background DBP/SDS DBP)

The TOX background levels in each of the three water samples were between 7 and 10 percent of the total SDS TOX concentration. The TTHM background concentrations were 3 to 4 percent of the total SDS TTHMs in each of the samples. Finally, the HAA5 background levels were between 10 and 20 percent of the total SDS HAA5 concentration. The background DBP levels are mainly due to the presence of chloramines in the influent water, which were typically less than 0.4 mg/L as Cl_2.

Impact of Operation Run Time on TOC and DBP Breakthroughs

Impact of Run Time on TOC Breakthrough

The increase in TOC breakthough throughout the total run time is plotted in Figure 7 for the 10- and 20-minute contactors, respectively. The three duplicates for each contactor effluent are also included with the plotted data. The percent breakthrough of TOC (normalized breakthrough) from the 10-min and 20-min GAC columns is plotted in Figure 5. To normalize the TOC, the effluent TOC concentration from each column is divided by the influent running average at that time. The TOC breakthrough from each contactor had a rate of approximately 0.048 percent per hour for the 10-minute EBCT contactor, and of 0.017 percent per hour for the 20-minute EBCT contactor. In the 10-minute EBCT contactor, the 70% TOC breakthrough criterion was exceeded after 1,862 hours (77.6 days), while the 70% criterion was exceeded after 4,230 hours (176.3 days) in the 20-minute EBCT contactor. Only one pilot run was required (according to the ICR requirements) since the run time to 70% TOC breakthrough in the 20-minute EBCT contactor exceeded 4,000 hours. During the course of the study, as discussed in Section 4.2.1, TOC concentration did not vary significantly in the influent (a value of 3.28 mg/L ± 0.21 mg/L). Seasonal variability and/or pretreatment were not observed to have a significant impact on TOC breakthrough.

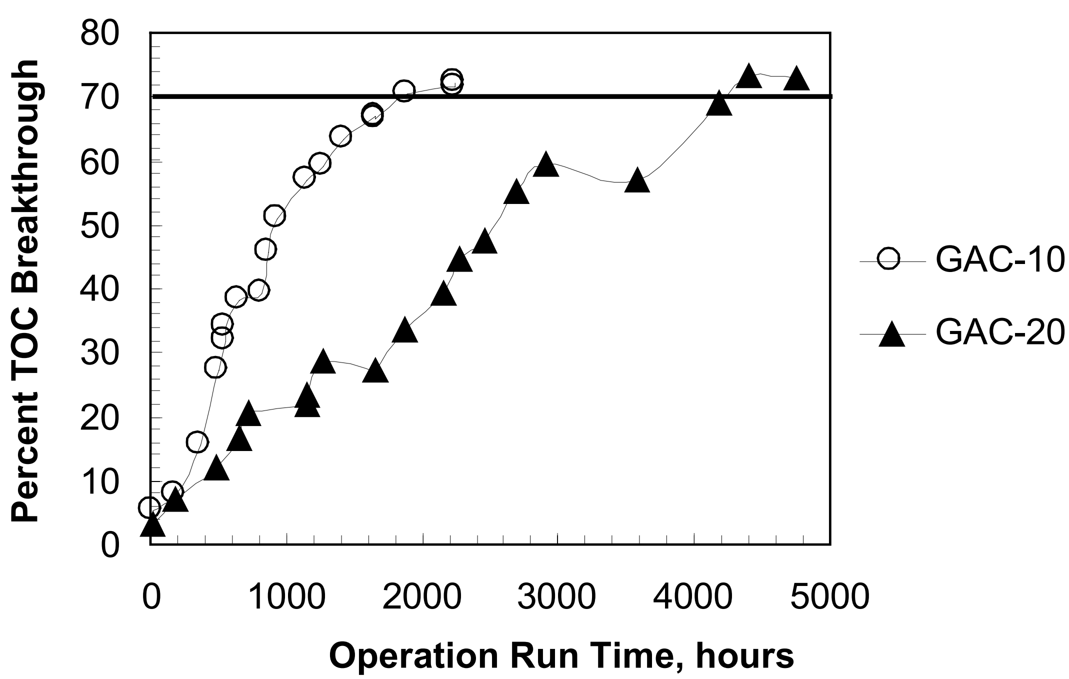

FIGURE 5. IMPACT OF OPERATION RUN TIME ON TOC BREAKTHROUGH

Impact of Operation Run Time on SDS-TTHM Breakthrough

Due to the variability in the SDS-TTHM concentration in the influent to the GAC columns, the SDS-TTHM breakthrough from each column was normalized in Figure 6. To normalize the SDS TTHM concentration, each effluent TTHM concentration was divided by the influent running average at that time. This value, the normalized TTHM percentage, represents a percentage breakthrough of the amount of DBPs that would have formed without GAC precursor removal. The influent SDS-TTHM concentration was also plotted as a reference.

According to the breakthrough data, the Stage 2 TTHM MCL of 40 µg/L was exceeded in the 10-minute EBCT column after approximately 622 hours (26 days). This corresponds to a 44% SDS-TTHM breakthrough. In the 20-minute EBCT column, the actual and the normalized SDS-TTHM breakthroughs were variable due to the deviation of SDS-TTHM concentration in the influent sample. The maximum SDS-TTHM concentration in the 20-min column effluent (56 µg/L) occurred at the same time as the high influent SDS-TTHM concentration was recorded (105 µg/L). Nevertheless, the Stage 2 TTHM MCL was exceeded after approximately 1,657 hours (69 days), corresponding to a 42% breakthrough. The 20-minute EBCT SDS-TTHM breakthrough curve reached a peak at approximately 2,000 hours, and decreased after 2,500 hours corresponding to the reduction in the influent SDS-TTHM concentration. Although the actual SDS-TTHM concentrations in the influent decreased during the later course of the run, the percent SDS-TTHM breakthrough decreased as well since it was normalized to the overall influent running average. The average 44% breakthrough line, representing the Stage 2 TTHM MCL, is plotted on Figure 6.

Variations in the SDS-TTHM formation of both the filtered influent and 20-minute EBCT samples are likely due to the SDS chlorination temperature increasing during the middle of the study. The chlorination temperature during incubation of the 10-minute EBCT samples rose steadily during the testing. These changes greatly impacted the variability of the DBP results. Further, it is likely that the chloramines present in the influent water impacted the variability of these results (a spike of up to 2.25 mg/L as Cl_2 occurred during the middle of the study). Background DBP concentrations were discussed earlier in this section.

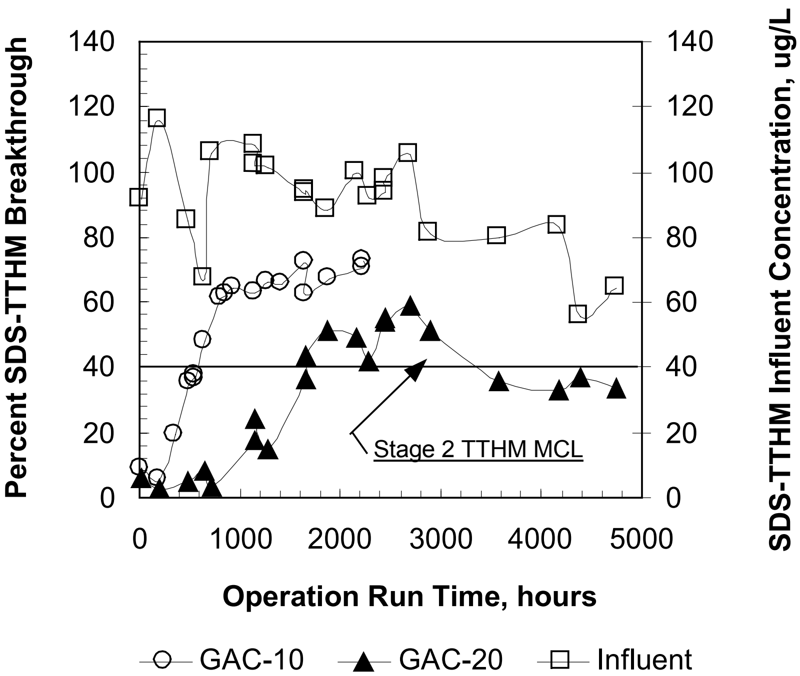

FIGURE 6. VARIATION OF SDS-TTHM CONCENTRATION IN THE INFLUENT AND EVOLUTION OF PERCENT SDS-TTHM BREAKTHROUGH FROM THE GAC COLUMNS WITH OPERATION RUN TIME

Impact of Operation Run Time of SDS-HAA5 Breakthrough

The normalized SDS-HAA5 breakthrough to the running SDS-HAA5 average from each GAC column was plotted on Figure 7, along with the SDS-HAA5 concentration in the influent to the columns. The normalized SDS-HAA5 breakthrough percentage was calculated by dividing the effluent SDS-HAA5 concentration by the running influent average SDS-HAA5 concentration at that time. Similar to the TTHM data, this normalized percentage represents the breakthrough of the total DBPs, which could have formed without removal of precursors with GAC.

According to the breakthrough data, the Stage 2 HAA5 MCL of 30 μg/L was exceeded in the 10-minute EBCT column after approximately 1,990 hours (83 days). This corresponds to a 65% SDS-HAA5 breakthrough. In the 20-minute EBCT column, the Stage 2 HAA5 MCL was exceeded after approximately 2,119 hours of operation (88 days). This corresponds to a 63% breakthrough. An average 64% breakthrough line, representing the Stage 2 HAA5 MCL, is plotted in Figure 9. The Stage 2 HAA5 MCL was exceeded in the 10-minute EBCT column at approximately the same time as in the 20-minute EBCT column. During the first 2,000 hours of operation, the rate of HAA5 breakthrough from the 10-minute EBCT column was as high as that from the 20-minute EBCT column, measured at approximately 0.03 percent breakthrough per hour. The variations of the SDS-HAA5 results are likely due to changes in the chlorination incubation temperature and a spike in the influent chloramine concentration, as discussed above for the TTHM results.

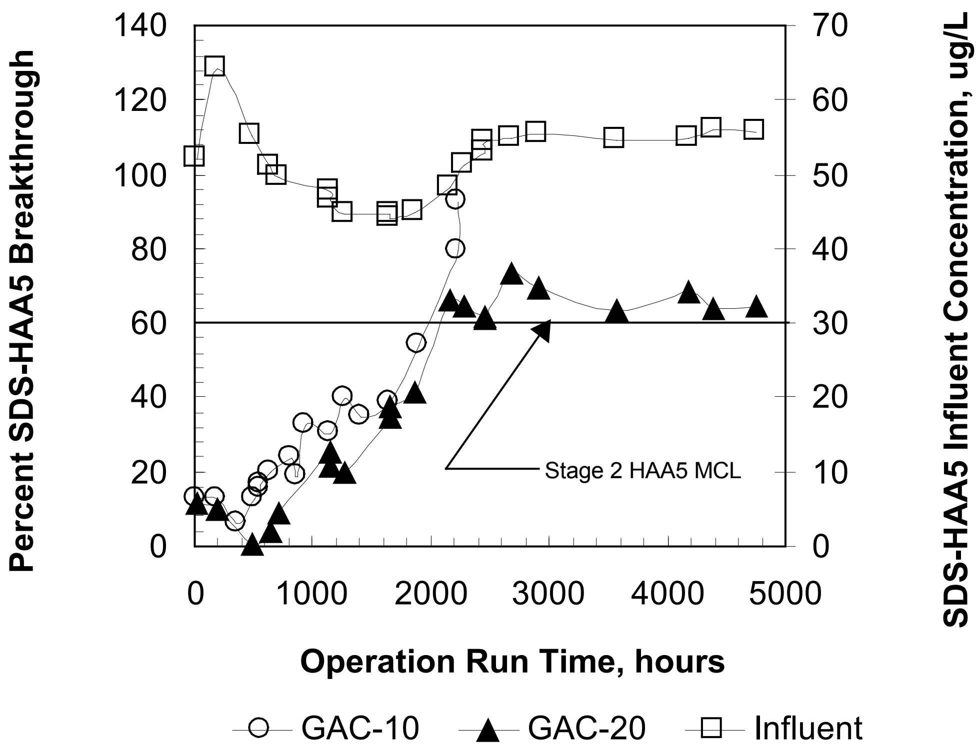

FIGURE 7. VARIATION OF SDS-HAA5 CONCENTRATION IN THE INFLUENT AND EVOLUTION OF PERCENT SDS-HAA5 BREAKTHROUGH FROM THE GAC COLUMNS WITH OPERATION RUN TIME

Impact of Empty Bed Contact Time

The impact of the EBCT on the removal of SDS-DBP precursors by GAC can be evaluated by plotting breakthrough curves versus bed volumes (BVs), instead of run time (hours). This will normalize the difference in the EBCT values between the two columns. Figures 8, 9, and 10 illustrate respectively the percent breakthrough (normalized over the influent running average) of TOC, SDS-TTHMs and SDS-HAA5 from the 10-min and 20-minute EBCT columns, versus throughput bed volumes.

In Figure 8, the slope of the curves for the 20-minute EBCT was equivalent to that of the 10-minute EBCT, indicating the same rate of breakthrough. However, a small benefit for removing DBP precursors was observed when using a 20-minute EBCT rather than a 10-minute EBCT. The SDS-TTHM breakthrough curves exhibited a different characteristic (Figure 9). Over the last 9,000 bed volumes of operation, a great benefit was observed for removing TTHM precursors when using a 20-minute EBCT over the 10-minute EBCT. In other words, using a 20-minute EBCT column should result in the extension of GAC runs between regeneration. It is important to note however that this observation may be misleading. The additional benefit observed in the 20-minute EBCT column during the last 7,000 BVs was probably due to a decrease in the TTHM concentration in the influent (a decrease from 105 µg/L to 64 µg/L over the last 6,000 BVs). The graph illustrates that the Stage 2 TTHM MCL corresponds to the 44% breakthrough level. This level occurs prior to the point at which the 20-min curve exhibits a negative slope. Figure 10 illustrates the behavior of the HAA5 breakthrough over the normalized bed volumes. It appears that during the first 12,000 bed volumes, the 10-minute EBCT was more beneficial than the 20-minute EBCT. This observation is, however, reversed during the last 2,000 BVs. The figure illustrates that the Stage 2 HAA5 MCL occurs at the 64% breakthrough level. This level occurs prior to the reverse of trend between the 10- and 20-minute EBCT curves.

A lower breakthrough curve translates into lower costs for replacing or regenerating the GAC when using either EBCT. It should be kept in mind that capital costs for a 20-minute EBCT GAC contactor are substantially higher than those for a 10-min contactor. Details on cost analyses are presented later.

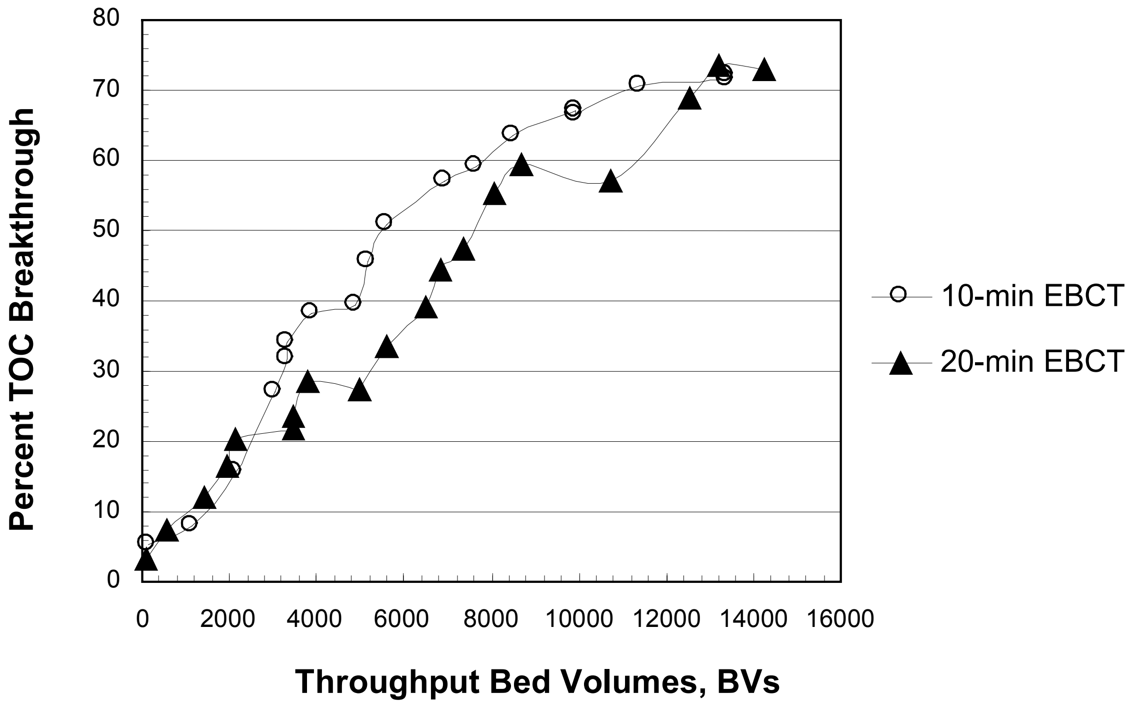

FIGURE 8. IMPACT OF EBCT ON PERCENT TOC BREAKTHROUGH

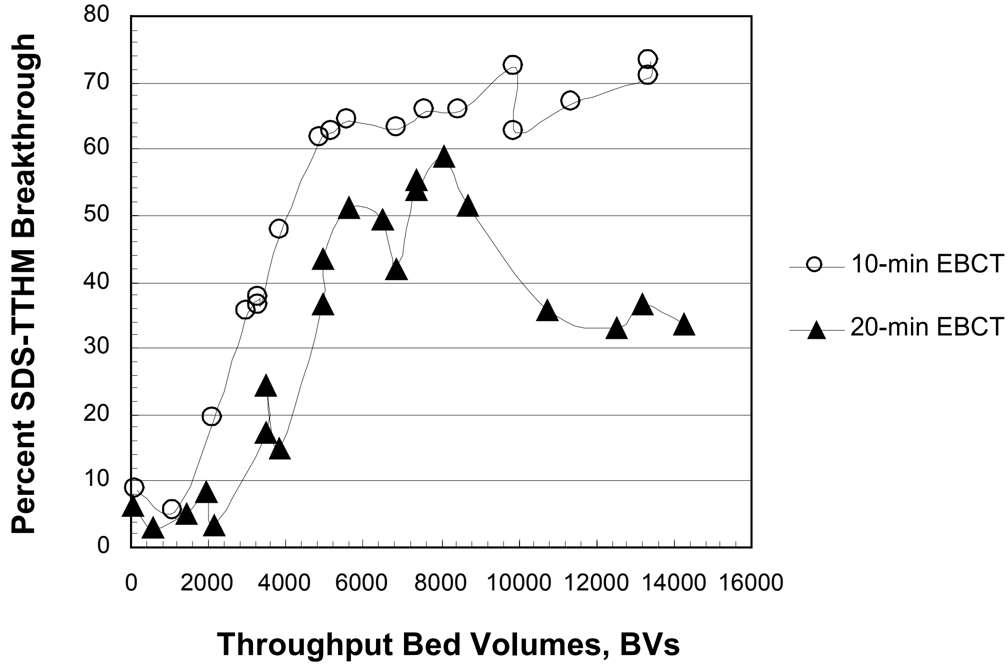

FIGURE 9. IMPACT OF EBCT ON PERCENT SDS-TTHM BREAKTHROUGH

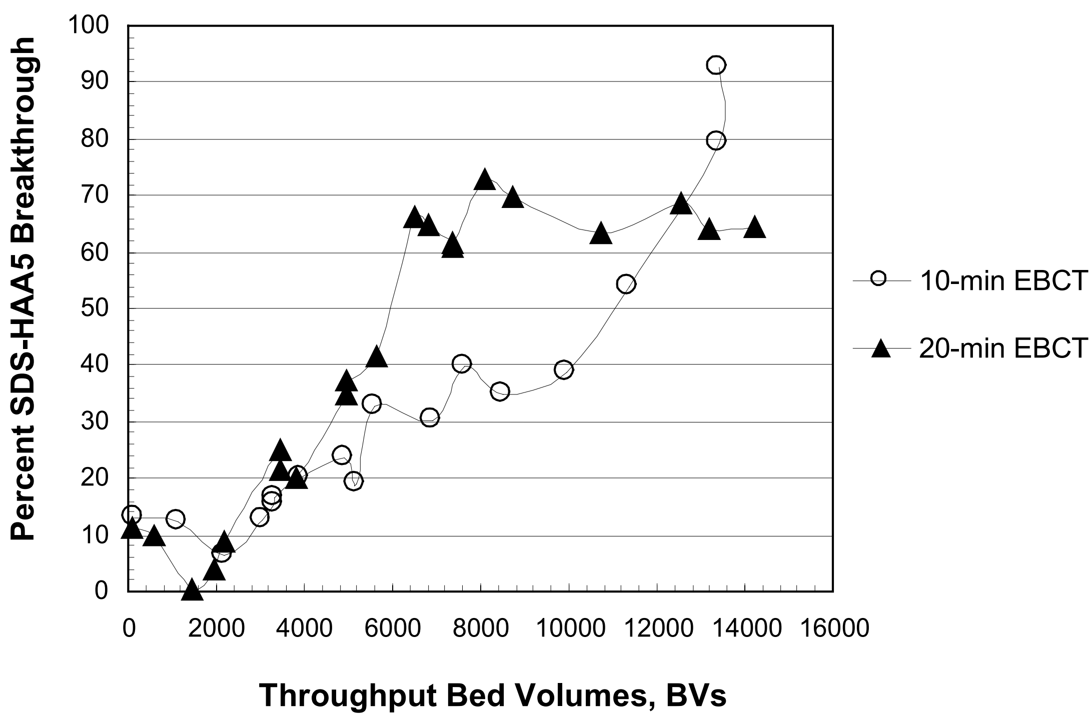

FIGURE 10. IMPACT OF EBCT ON PERCENT SDS-HAA5 BREAKTHROUGH

Indicators of DBP Formation

To evaluate the use of TOC concentration and UV-254 absorbance as indicators of SDS-DBP precursors, normalized breakthrough curves of TOC, UV-254, SDS-TTHM and SDS-HAA5, are plotted against the scaled operation run time, for both the 10-min and the 20-minute EBCT columns. Figure 11 and 12 illustrate, respectively, the breakthrough of the above parameters from the 10-min and 20-minute EBCT GAC contactors.

Based on the percent breakthrough curves from the 10-min and the 20-minute EBCT contactors, the following observations can be made: (1) TOC and UV-254 breakthrough curves correlate, relatively well with the TTHM and HAA5 breakthrough curves. The rate of breakthrough, represented by the slopes of the curves, is somewhat variable from one curve to the next; and therefore, (2) TOC concentration and UV-254 absorbance do not correlate well enough to be good indicators of SDS-DBP precursors breakthrough. However, they remain simple and cheap methods to quantify percent SDS-DBP breakthrough curves to give a relative indication of breakthrough. The percent breakthrough of SDS-HAA5 in Figure 11 is observed to be lower than that of the TOC concentration. However, it should be kept in mind that only five of the nine HAAs are reported in the data analyses (the Stages 1 and 2 MCL for HAAs are based on HAA5 concentration).

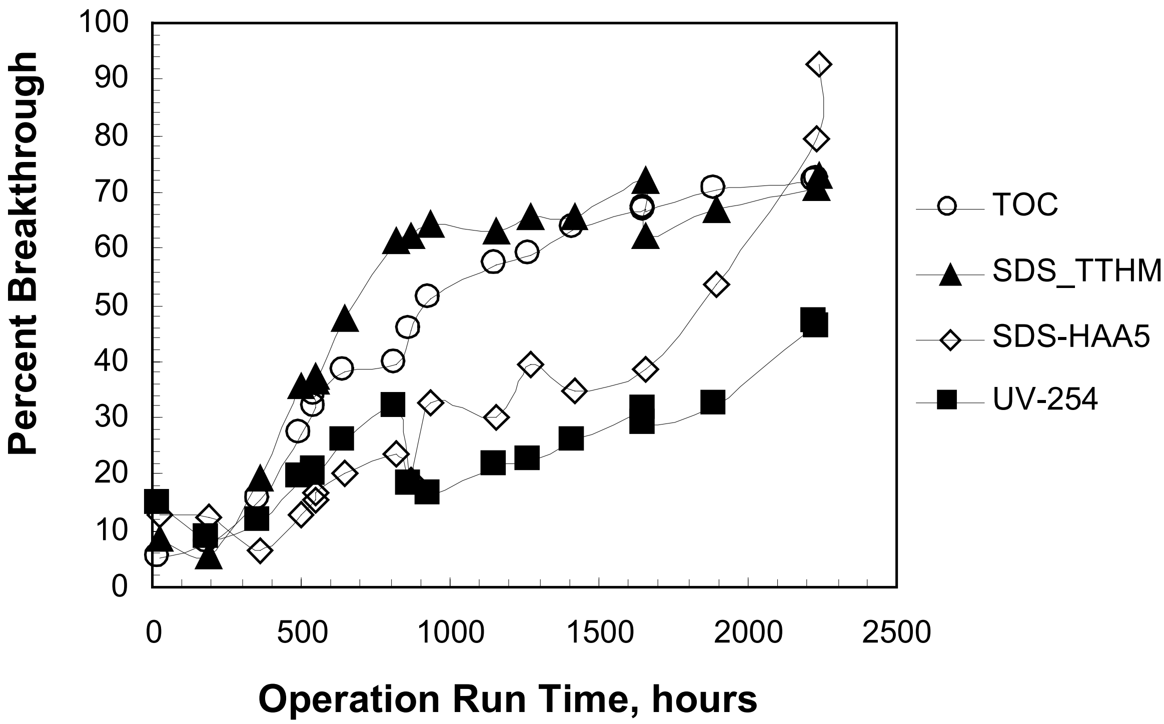

FIGURE 11. BREAKTHROUGH OF TOC, UV-254 AND SDS-DBPS FROM 10-MINUTE EBCT GAC COLUMN

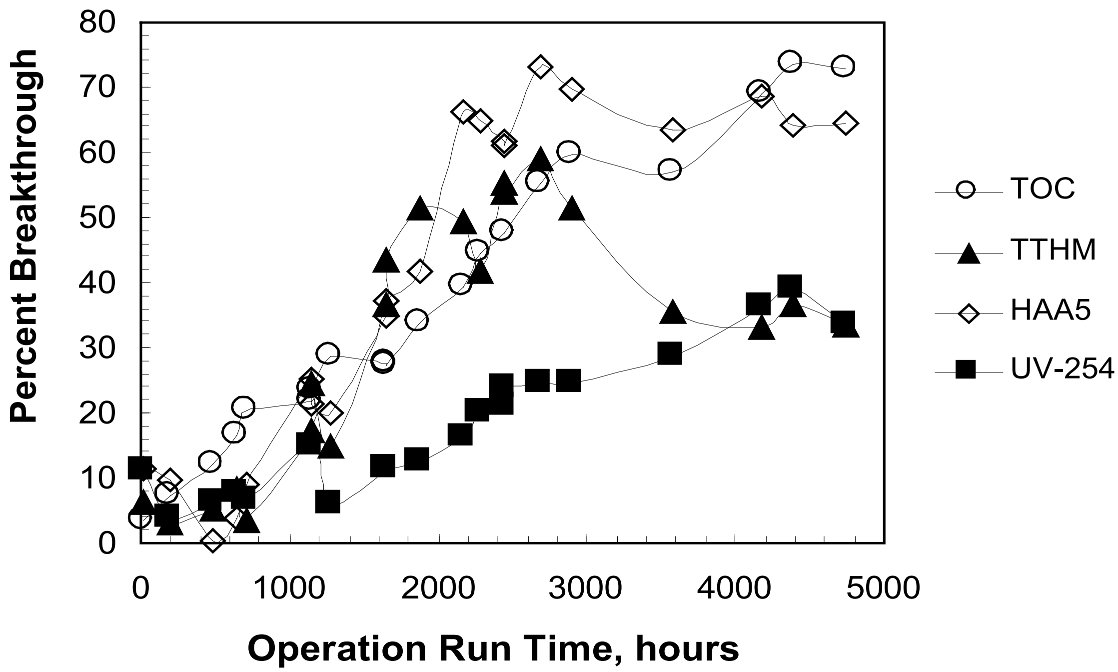

FIGURE 12. BREAKTHROUGH OF TOC, UV-254 AND SDS-DBPS FROM 20-MINUTE EBCT GAC COLUMN

Cost Analysis

GAC Replacement and Regeneration Costs

Carbon Usage Rates

The carbon usage rate (CUR), or the amount of GAC required to treat 1,000 gallons of water to Stage 1 or Stage 2 maximum contaminant limits of the Disinfection/Disinfection By-Products Rule (D/DBP Rule) was determined for the City of Houston. The calculated CUR is based on the pilot plant data, and is therefore based on data obtained using free chlorine and will be much more conservative than data obtained using chloramines. Table 17 summarizes the CURs for each of the 10- and 20-minute contactors for the target D/DBP Rule MCLs. The following methodology describes the calculation.

1. The total run time and quantity of bed volumes for the 10- and 20-minute EBCT contactors to reach and exceed the target Stage 1 and Stage 2 limits are determined from the pilot data (columns 4 and 5 in Table 17). The target limits set for these analyses were 80% of the MCLs set by the D/DBP Rule (column 2). This ensures that a conservative estimate for the carbon usage is obtained. The running average for the influent concentration at the time the MCL was exceeded is shown in column 1. Also, the percent breakthrough for the SDS-DBP at the time the MCL was exceeded in given in column 3. Note that during the pilot run of the 10-minute contactor, the target Stage 1 MCL for HAA5s was not exceeded. Thus, the total bed volumes are reported as greater than the total processed during this pilot study.

2. Once the bed volumes are known for each target MCL limit, the gallons of water required per pound of GAC used can be calculated. Using the bed volumes and a dry bed density of 4 lbs GAC/gallon water treated are shown in column 6.

3. The CUR, in lbs/1,000 gallons water treated, is now simply the inverse of column 8 times 1,000 gallons. This is shown in column 7.

4. Finally, the yearly CUR (column 8), in million pounds per year, is determined using an average design plant flowrate of 105 mgd. This flowrate is 70% of the rated capacity of 150 mgd, which provides for a more conservative estimate of the CUR as recommended by Adams and Clark (1988). Only the capacity of EWPP III was considered for this evaluation.

TABLE 17
CURS OVER PILOT RUN FOR THE 10-MINUTE EBCT DESIGN

Parameter	Running Average Influent Concentration	Target MCL* Concentration	Breakthrough Percent of Influent SDS	Total Run Time (hours)	Bed Volumes Processed	Gallons water/lb GAC	CUR lbs/ 1000 gal	CUR Million lbs/yr
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TTHM4 (ug/L)	96.8	64 (80% Stage 1)	66	1431	8588	2147	0.47	17.9
	97.4	32 (80% Stage 2)	33	481	2888	722	1.39	53.1
HAA5 (ug/L)	--	48 (80% Stage 1)	--	2234	>13404	>3351	<0.30	<11.4
	44.7	24 (80% Stage 2)	54	1897	11380	2845	0.35	13.5

* 80% of the Stage 1 and Stage 2 MCLs for each DBP

Table 18 summarizes the CURs determined for the 20-minute EBCT contactor. The same procedure described above are used in these calculations. Note that during the pilot run of the 20-minute contactor, the target MCLs of Stage 1 for both TTHM4 and HAA5 were not exceeded. Thus, the total bed volumes are reported as greater than the total processed during this pilot study.

TABLE 18
CURS OVER PILOT RUN FOR THE 20-MINUTE EBCT DESIGN

Para-meter	Running Average Influent Concentra-tion	Target MCL* Concentra-tion	Breakthrough Percent of Influent SDS	Total Run Time (hours)	Bed Volumes Pro-cessed	Gallons water/lb GAC	CUR lbs/ 1000 gal	CUR Million lbs/yr
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TTHM (ug/L)	--	64 (80% Stage 1)	--	>4748	>14243	>3561	<0.28	<10.8
	96.7	32 (80% Stage 2)	33	1596	4788	1197	0.84	32.0
HAA5 (ug/L)	--	48 (80% Stage 1)	--	>4748	>14243	>3561	<0.28	<10.8
	46.2	24 (80% Stage 2)	52	1995	5984	1496	0.67	25.6

* 80% of the Stage 1 and Stage 2 MCLs for each DBP

The CURs will be used in the following cost analyses sections to determine the total capital and operation and maintenance (O&M) costs of the GAC contactors applied full-scale at EWPP III. There are two methods for replacing GAC that has been exhausted after breakthrough of DBP precursors (or TOC): replacement with new GAC, or thermal regeneration of the existing GAC on-site. The cost of each method will be compared in the following sections.

GAC Replacement Costs

In the preceding section, the CUR was calculated. Based on these CURs, GAC replacement costs were estimated for a 10-minute EBCT and 20-minute EBCT designs. A unit cost of $0.75/lb GAC was used for the estimate. The costs of GAC in $/1,000 gal to meet target DBP MCL criteria are shown in Table 19. Based on the criteria to meet TTHMs MCLs, using a 20-minute EBCT resulted in a cost reduction in GAC replacement costs of approximately 39% as compared to the 10-minute EBCT.

TABLE 19
GAC REPLACEMENT COSTS FOR 10- AND 20-MINUTE EBCT CONTACTORS

	Target TTHM MCL		Target HAA5 MCL	
	Stage 1 (64 ug/L)	**Stage 2 (32 ug/L)**	**Stage 1 (48 ug/L)**	**Stage 2 (24 ug/L)**
10-Minute EBCT	$0.35/1,000 gal	$1.04/1,000 gal	< $0.22/1,000 gal	$0.26/1,000 gal
20-Minute EBCT	< $0.21/1,000 gal	$0.63/1,000 gal	< $0.21/1,000 gal	$0.50/1,000 gal

As this table illustrates, the highest costs are those based on meeting the Stage 2 TTHM design target. The average annual cost for each GAC contactor is determined based on this Stage 2 TTHM design target (higher cost estimate), for an average design flowrate of 105 mgd. On an annual basis, the average annual GAC replacement cost for a 10-minute EBCT contactor is estimated at $39,858,000. The average annual GAC replacement cost for a 20-minute EBCT is estimated at $24,144,750.

GAC Reactivation Costs

Thermal GAC reactivation costs are determined for the CUR values estimated above. The GAC reactivation design is based on the amount of GAC used (in million pounds/year) to reach the design target of 80% of the Stage 2 TTHM MCL (which was the highest replacement cost determined above). As in the preceding section, the GAC amounts were calculated using an average flowrate of 105 mgd.

The capital and O&M costs for thermal GAC reactivation are calculated using the equations by Adams and Clark (1988) in Appendix D. Table 20 summarizes the parameters used to calculate the reactivation cost. Capital and O&M costs for thermal reactivation, using a 10- and 20-minute EBCTs are presented in Table 21. Based on the 10-minute EBCT CUR of 53 million lbs/yr (6,050.2 lbs/hr) to reach 80% of the Stage 2 TTHM MCL, the total required effective hearth area is estimated at approximately 2,420 square feet. Based on the 20-minute EBCT average CUR of 32 millions lbs/yr (3,653 lbs/hr) to reach 80% of the Stage 2 TTHM MCL, the total required effective hearth area is estimated at approximately 1,461 square feet. The above surface areas fall out from the range of the developed existing cost equations shown in Appendix D; thus, for the purpose of these analyses, 5 reactivators will be assumed for the 10-minute EBCT design, and 4 reactivators for the 20-minute EBCT design. By using this number of reactors, the calculation result in an effective hearth area per reactivator at 484 square feet for the 10-minute EBCT and at 365.3 square feet for the 20-minute EBCT. The capital and O&M costs are estimated for one reactivator and multiplied thereafter by a factor of 5 for the 10-minute EBCT design, and by a factor of 4, for the 20-minute EBCT design (Table 21). Thus, the table shows a cost per reactor and a total cost for the complete system.

TABLE 20
ASSUMPTIONS USED TO ESTIMATE REACTIVATION CAPITAL AND O&M COSTS

Parameter	Assumption
Single reactivator area (10-minute EBCT), sq-ft	484
Total reactivator area, sq.-ft	2,420 or 1,461
Single reactivate area (20-minute EBCT), sq-ft	365
Total reactivator area, sq-ft	731
Capital amortization	*I* = 6 percent over *N* = 30 years
Capital recovery factor CRF	0.117
Labor and fringe rate	$25/hr
Electric rate	$ 0.05/kwh
Natural gas rate	$0.0055/scf
ENR Construction Cost Index (1983)	5,064
ENR Construction Cost Index (1998)	6,859
Producers Price Index (1983)	102
Producers Price Index (1998)	130.5

TABLE 21
CAPITAL AND O&M COSTS FOR GAC REACTIVATION USING MULTIHEARTH TECHNOLOGY

Parameter	10-minute EBCT	20-minute EBCT
DESIGN PARAMETERS		
lbs of GAC per hour (to meet 80% Stage 2 TTHM MCL) at 0.4 sq-ft required per lb/hr	6,050	3,653
Surface area per reactivator, sq-ft	484	365
Total numbers of reactivators	5	4
CAPITAL COSTS		
Construction Costs, 1998 $	$4,124,328	$3,672,651
Annual capital costs per reactivator, $/yr	**$299,600**	**$267,000**
O& M COSTS		
Process Energy Requirements, kwh/yr	1,034,359	904,264
Annual Process Energy costs, $/yr	**$51,718**	**$45,213**
Building Energy Requirements, kwh/yr	29,499	26,620
Annual Building Energy costs, $/yr	**$1,475**	**$1,331**
Maintenance Materials costs, 1998 $/yr	**$68,020**	**$60,763**
O&M Labor Requirements, workhours/yr	24,282	20,463
Annual O&M Labor costs, $/yr	**$607,049**	**$511,575**
Natural Gas Requirement, scft/yr	75,231,140	58,562,513
Annual NG cost, $/yr	**$414,000**	**$322,000**
Total O&M Annual Cost per reactivator, $/yr	**$1,142,000**	**$941,000**
TOTAL ANNUAL COST per reactivator, $/yr	**$1,442,000**	**$1,208,000**
TOTAL ANNUAL COST, $/YR	**$7,210,000**	**$4,832,000**

The total annual cost for thermal reactivation for the 10-minute EBCT and 20-minute EBCT contactors are $7,210,000 and $4,832,000, respectively. Overall, the costs for reactivation are much lower than that for replacing the carbon.

Annual Capital and O&M Costs (for Concrete Gravity Adsorbers)

This section presents the capital and O&M costs for a conventional concrete gravity adsorber based on an average flowrate and hydraulic loading rates. According to Adams and Clark (1988), in systems greater than 10 mgd, it is most cost effective to use concrete gravity adsorbers. These costs include the cost of GAC thermal reactivation costs, since it was shown to be more cost-effective than carbon replacement. The equations by Adams and Clark (1988) are used to estimate the costs, the equations are summarized in Appendix D. In this analysis, Table 22 lists the parameters assumed, and the costs are summarized in Table 23.

TABLE 22
ASSUMPSTION TO ESTIMATE COSTS OF CONCRETE GRAVITY ADSORBERS

Parameter	Assumption
GAC Contactor System Operation	70 percent of design capacity
Systems > 10 mgd	Use concrete gravity adsorbers
Capital amortization	I = 6 percent over N = 30 years
Capital recovery factor CRF	0.117
Labor and fringe rate	$25/hr
Electric rate	$ 0.05/kwh
ENR Construction Cost Index (1983)	5,064
ENR Construction Cost Index (1998)	6,859
Producers Price Index (1983)	102
Producers Price Index (1998)	130.5
Total Plant Capacity (Q'), Plant III	150 mgd
Design Capacity (70% Q' = Q)	105 mgd (9740.8 cu-ft/min)
Hydraulic Loading (Q/A)	5 gpm/sq ft (0.6685 cu-ft/min/sq ft)
105 mgd Pump Station Required for Each Option	$3,000,000

TABLE 23
CAPITAL AND O&M COSTS FOR A CONCRETE GRAVITY ADSORBER

Parameter	10-minute EBCT	20-minute EBCT
DESIGN PARAMETERS		
Bed volume per contactor, cu-ft	9,741	19,482
Total GAC effective volume, cu-ft	97,408	194,816
CAPITAL COSTS		
"z" Constant (Construction Cost equation)	1	1
Construction Cost, 1998 $	10,036,400	16,359,400
105 MDG Pump Station, $	$3,000,000	$3,000,000
Annual capital costs, $/yr	**$947,100**	**1,406,500**
O&M COSTS		
Process Energy Requirements, kwh/yr	174,900	174,900
Annual Process Energy costs, $/yr	**$8,700**	**$8,700**
Building Energy Requirements, kwh/yr	2,294,600	2,294,600
Annual Building Energy costs, $/yr	**$114,700**	**$114,700**
Maintenance Materials costs, 1983 $/yr	32,800	32,800
Maintenance Materials costs, 1998 $/yr	**$41,900**	**$41,900**
"z" Constant (in O&M Labor equation)	0	0
O&M Labor Requirements, workhours/yr	9,549	9,549
Annual O&M Labor costs, $/yr	**$238,700**	**$238,700**
Total O&M Annual Costs, $/yr	**$404,000**	**$404,000**
Annual GAC reactivation cost, $/yr	**$7,210,000**	**$4,832,000**
ANNUAL COSTS (excluding reactivation), $/yr	**$1,351,100**	**$1,810,500**
TOTAL ANNUAL COSTS, $/yr	**$8,561,100**	**$6,642,500**

According to Table 23, annual capital costs of a 20-minute EBCT contactor is estimated to be 38% higher than those for a 10-minute EBCT contactor. Annual O&M costs (excluding GAC reactivation costs) are the same for either a 10-minute EBCT or 20-minute EBCT contactor, since both of these costs are based on a 5 gpm/sq-ft hydraulic loading rate. Total annual costs (including GAC reactivation costs) for a 10-minute EBCT were observed to be approximately 22% higher than a 20-minute EBCT design.

Summary of Significant Results

The impact of seasonal variability and/or pretreatment was observed to be minimal on the water quality parameters in the influent to the GAC column. In the raw water, TOC concentration and UV-254 absorbance were observed to vary during the course of the pilot run. However, the impact of pretreatment resulted in an influent to the GAC column of a relatively constant NOM content.

Unlike the TOC and UV-254 parameters, the variation of the SDS-DBPs in the influent to the GAC columns was more substantial. This was illustrated in the breakthrough curves of precursors for TTHMs and HAA5 upon SDS chlorination. The curves exhibited variable slopes during the course of the pilot run. Based on the SDS-DBP data, the Stage 2 TTHM MCL was exceeded after 622 hours in the 10-minute EBCT column, and after 1,657 hours in the 20-minute EBCT column. The maximum SDS-TTHM concentration in the 20-min column effluent occurred at the same time as the high influent SDS-TTHM concentration. The Stage 2 TTHM MCL was exceeded before that of the HAA5, and the SDS-TTHM concentration in the GAC contactor effluent will therefore be the limiting factor in contactor design, regeneration scenario, and costing. The effluent DBP variation is due to changing influent concentrations and in part to a slight change in the SDS incubation temperature. However, even if the temperature was kept constant, there would be some variability since the SDS seems to have a low reliability. Additionally, free chlorine makes the DBP numbers much higher (more conservative) than would normally be expected for the full-scale.

When normalizing for EBCT, the SDS-TTHM and SDS-HAA5 breakthrough curves exhibited diverging behaviors. In the SDS-TTHM curve, a great benefit in carbon use was observed for SDS-THM control by using a 20-minute EBCT versus a 10-minute EBCT. In the SDS-HAA5 curve however, it appears that during the first 12,000 BVs, the 10-minute EBCT was more beneficial than the 20-minute EBCT. This observation is reversed in the last 2,000 BVs.

TOC breakthrough was observed to correlate well with those of SDS-TTHMs and SDS-HAA5. However, neither TOC concentration nor UV254 absorbance correlated well enough to be good indicators of SDS-DBP precursor breakthrough.

The GAC replacement costs were estimated for each EBCT. GAC replacement costs were limited by the SDS-TTHM concentration in the effluent of the columns. Based on the criteria to meet TTHM MCLS, using a 20-minute EBCT compared to a 10-minute EBCT resulted in a 39% cost reduction. The average annual GAC replacement costs to meet 80% of the Stage 2 TTHM MCL were estimated at $39,858,000 for a 10-minute EBCT and at $24,144,750 for a 20-minute EBCT. These costs are too high and GAC replacement would not be a feasible approach. Based on the carbon utilization rates, total annual costs incurred by on-site thermal regeneration of GAC were estimated at $7,210,000 for a 10-minute EBCT, and at $4,832,000, for a 20-minute EBCT. Although much lower than GAC replacement costs, reactivation costs remain high, and GAC reactivation may not be a practical and feasible approach.

The total annual cost (including reactivation cost) for a conventional concrete gravity GAC adsorber was increased by 22% when using a 10-minute EBCT design compared to a 20-minute EBCT design. Annual capital costs of a 10-minute EBCT contactor were estimated to be 38% of those for a 20-minute EBCT contactor.

Overall, the costs are very conservative for this analysis. They were determined from only one pilot study, free chlorine DBPs were considered instead of combined chlorine DBP formation, the MCL target was based on only 80% of the Stage 2 TTHM MCL, and the average capacity for the EWPP III was used. Thus, the costs would be expected to be much lower if the City of Houston was to implement GAC for DBP precursor removal.

Finally, adding GAC to the full-scale plant to reduce or remove DBP precursors would require a large capital investment and increase the annual operating costs by a significant amount. The City of Houston should explore other methods of reducing DBPs.

QA/QC SUMMARY

All analyses were performed according to QA/QC procedures described in the DBP/ICR Analytical Methods Manual. All field duplicates were collected at the rate specified. In addition, all methods used are found in the Standard Methods. TOX analyses were conducted by Montgomery Watson Laboratories. All other analyses were performed by the City of Houston's Water Laboratory located at the EWPP.

The *Summary Report Spreadsheets*, which include general QA/QC data for each laboratory involved in this study, are included in Appendix A. The QA/QC statistical analysis completed for the study is summarized in this spreadsheet. Please note that some of the DBP results were below the minimum reportable level (BMRL) and thus do not factor into the total QC duplicate count or statistical analysis. The minimum specified amount of QA/QC samples were collected according to the procedures outlined in the Analytical Methods Manual.

As a note, the MW Laboratory TOX analysis QA/QC Summary reported in the Summary Spreadsheets is a collective result of several analyses which were conducted for multiple clients, and therefore covers a period spanning September 1997 through May 1999.

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Appendix A: Full- and Pilot-Scale Treatment Schematics

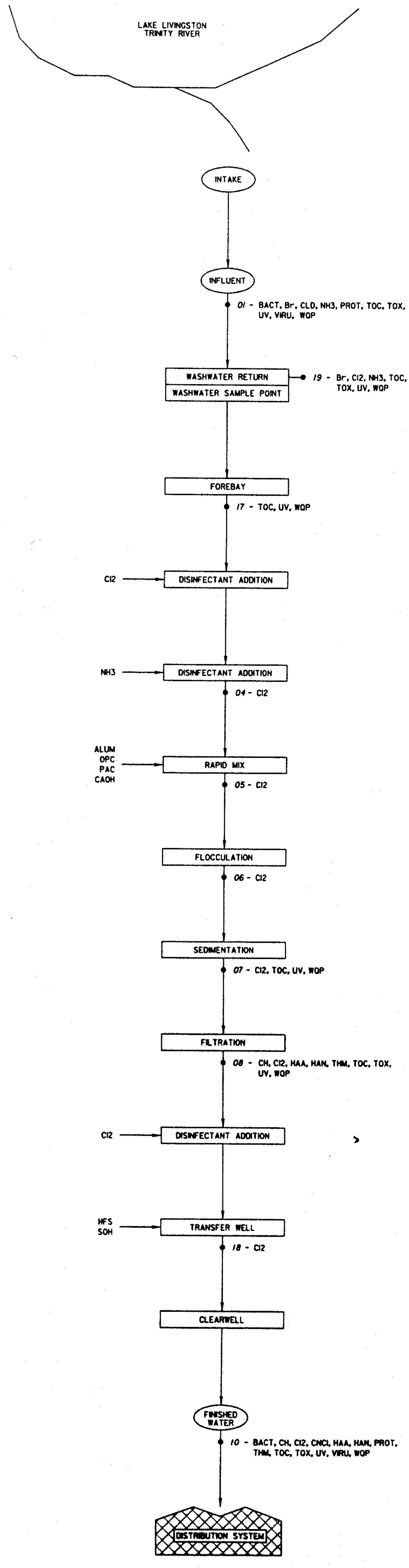

FIGURE 1: EWPP III FULL-SCALE SCHEMATIC
AND ICR MONITORING LOCATIONS

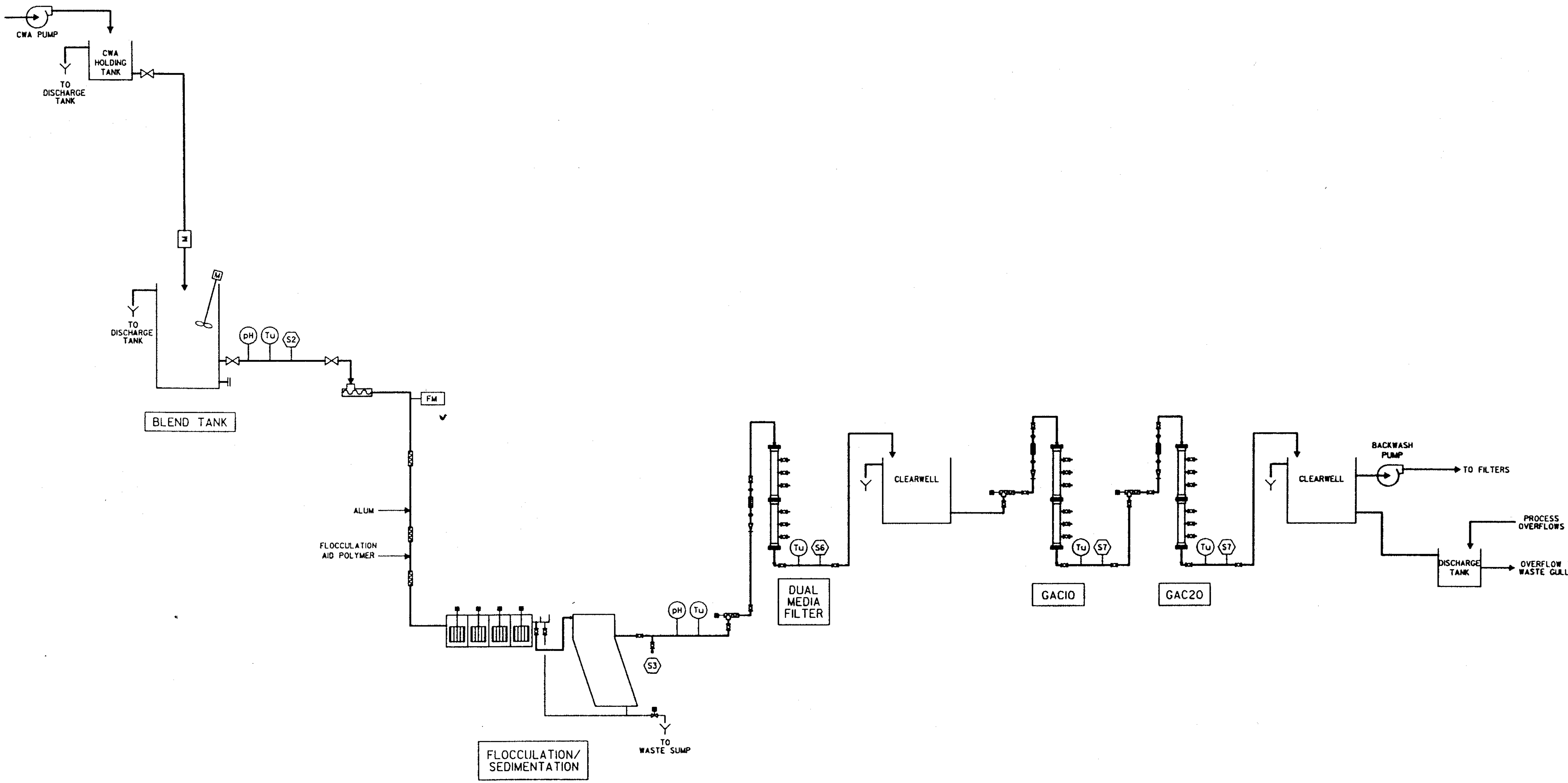

FIGURE 2: EWPP PILOT PLANT
ICR PROCESS FLOW DIAGRAM

Appendix B: Summary Report Sheets

Miscellaneous Information

PWSID	TX1010013
Plant ICR #	630-631-632

Full-Scale Plant Information

Item	Result
Primary Disinfectant	Chloramines
Residual Disinfectant	Chloramines
Source Type	River/Lake
Source Name	Trinity River/Lake Houston

Laboratory Information

Item	ICR ID or Abbrev	Lab Name	Lab Type	Lab City	Lab State
Lab #1		City of Houston Water Quality L	Utility	Houston	TX
Lab #2	MWL-CA013	Montgomery Watson Laboratori	Commercial	Pasadena	CA
Lab #3					
Lab #4					

Batch Sampling Dates for Quarterly Bench-Scale Testing

Item	Quarter 1	Quarter 2	Quarter 3	Quarter 4
Sample Collection Date	NA	NA	NA	NA

1998 Flow and Population Information

Source	Flow (mgd)	Population Served
Total Population Served		1327301
Surface Water	430	1,327,301
Ground Water	0	0
Purchased Finished Water	0	0
Total	430	

Full-Scale Water Quality Data

Full-Scale Influent Water Quality Data

Item	Units	Average	Std Dev	Min	Max	Count
Temperature	C	21.0	7.2	8.9	30	12
pH	Unit	7.69	0.12	7.53	8.02	12
Turbidity	ntu	29.2	18.0	11.1	56	12
Alkalinity	mg/L as $CaCO_3$	99	11	80	112	12
Total Hardness	mg/L as $CaCO_3$	119	10	98	136	12
Calcium Hardness	mg/L as $CaCO_3$	100	12	80	120	12
TOC	mg/L	5.3	1.1	4	7	12
UV_{254}	1/cm	0.236	0.132	0.121	0.483	12
Bromide	µg/L	121	37	78	190	12
TSUVA*	L/(mg*m)	4.2	1.6	2.6	6.9	12

*TSUVA = [UV_{254} (1/m)] / [TOC (mg/L)]. Summary information for TSUVA should only be calculated from TSUVA values with paired TOC and UV_{254} measurements

Full-Scale Finished Water Quality Data

Item	Units	Average	Std Dev	Min	Max	Count
Temperature	C	22.6	6.1	14.4	30	12
pH	unit	7.86	0.15	7.53	8.11	12
Turbidity	ntu	0.07	0.01	0.05	0.09	12
TOC	mg/L	4.2	0.4	3.5	4.9	12
UV_{254}	1/cm	0.096	0.011	0.078	0.113	12
DS-THM4	µg/L	36.2	11.5	19.3	45	4
DS-HAA5	µg/L	57.9	13.9	39.3	73.1	4
DS-HAA6	µg/L	69.2	16.8	47.3	86.8	4

QA/QC Data - Sheet 1

Analyte Identification	Units	Laboratory Identification	Start Service Date	End Service Date	Method	MRL		Count	Average	Std Dev	Percentiles 25th	50th	75th
pH	unit		4/15/98	10/28/98									
Temperature	C												
Alkalinity	mg/L as $CaCO_3$												
Ammonia	mg NH_3-N/L												
Calcium Hardness	mg/L as $CaCO_3$												
SDS-Cl_2 Residual	mg/L												
Total Hardness	mg/L as $CaCO_3$												
Turbidity	ntu												
Bromide	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
UV_{254}	1/cm						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
TOC	mg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-TOX	µg Cl-/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-$CHCl_3$	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-BDCM	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-DBCM	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						

QA/QC Data - Sheet 1

Analyte Identification	Units	Laboratory Identification	Start Service Date	End Service Date	Method	MRL		Count	Average	Std Dev	Percentiles 25th	50th	75th
pH	unit												
Temperature	C												
Alkalinity	mg/L as CaCO3												
Ammonia	mg NH3-N/L												
Calcium Hardness	mg/L as CaCO3												
SDS-Cl2 Residual	mg/L												
Total Hardness	mg/L as CaCO3												
Turbidity	ntu												
Bromide	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
UV254	1/cm						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
TOC	mg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-TOX	µg Cl-/L	ICR-CA013	9/1/97	5/1/99	SM5320B	25	RPE of Analytical Duplicates:	865	4%	4%	1%	3%	6%
							% Recovery for Lab Fortified Matrix:	883	100%	20%	92%	98%	105%
							% Recovery for PE Samples:	5	88%	8%	85%	86%	88%
SDS-CHCl3	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-BDCM	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-DBCM	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-CHBr3	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
THM4	µg/L						**Avg RPE of Indiv Anal Dupl:**						
							Avg % Recov for Indiv Lab Fort Matrix:						
							Avg % Recov for Indiv PE Samples:						
SDS-MCAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-DCAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-TCAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-MBAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-DBAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-BCAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-TBAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-CDBAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
SDS-DCBAA	µg/L						RPE of Analytical Duplicates:						
							% Recovery for Lab Fortified Matrix:						
							% Recovery for PE Samples:						
HAA5	µg/L						**Avg RPE of Indiv Anal Dupl:**						
							Avg % Recov for Indiv Lab Fort Matrix:						
							Avg % Recov for Indiv PE Samples:						
HAA6	µg/L						**Avg RPE of Indiv Anal Dupl:**						
							Avg % Recov for Indiv Lab Fort Matrix:						
HAA9	µg/L						**Avg RPE of Indiv Anal Dupl:**						
							Avg % Recov for Indiv Lab Fort Matrix:						

			% Recovery for PE Samples:	
SDS-$CHBr_3$	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
THM4	µg/L		**Avg** RPE of Indiv Anal Dupl:	
			Avg % Recov for Indiv Lab Fort Matrix:	
			Avg % Recov for Indiv PE Samples:	
SDS-MCAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-DCAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-TCAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-MBAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-DBAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-BCAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-TBAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-CDBAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
SDS-DCBAA	µg/L		RPE of Analytical Duplicates:	
			% Recovery for Lab Fortified Matrix:	
			% Recovery for PE Samples:	
HAA5	µg/L		**Avg** RPE of Indiv Anal Dupl:	
			Avg % Recov for Indiv Lab Fort Matrix:	
			Avg % Recov for Indiv PE Samples:	
HAA6	µg/L		**Avg** RPE of Indiv Anal Dupl:	
			Avg % Recov for Indiv Lab Fort Matrix:	
HAA9	µg/L		**Avg** RPE of Indiv Anal Dupl:	
			Avg % Recov for Indiv Lab Fort Matrix:	

Appendix C: GAC Procedures

OBTAINING A REPRESENTATIVE GAC SAMPLE

The recommended GAC loading procedure ("coning and quartering") is described next.

1. Place the total GAC volume from the original container in a cone shaped pile, scoop by scoop. Add each scoop to the center of the pile and allow even flow in all directions as shown in Figure A.

2. Flatten this pile evenly from above to form a shallow cylinder of uniform depth (Figure B).

3. Divide this cylinder into two halves, and then four quarters as depicted in Figures C and D, respectively.

4. Remove two opposite quarters and refill the original container (Figure E).

5. Weigh the two remaining pie shaped quarters.

6. Repeat steps 1 through 5 until the desired weight of carbon is obtained.

LOADING GAC CONTACTORS

1. Isolate the column to be loaded, and fill it with chloraminated, filtered water to a level of approximately 50% of the design GAC bed depth.

2. Add the previously weighed dry GAC powder so that a final depth of approximately 5% greater than the design bed depth is reached.

3. Allow the GAC in the bed to sit for approximately 24 hours for complete wetting.

4. Carefully backwash the bed to remove the fines. The bed should be expanded by approximately 10% for the entire duration when the fines are being washed out.

5. Over a 5-minute period, increase the backwashing rate to achieve a 40% bed expansion. Maintain this level of fluidization for 20 minutes.

6. Over a 30-second period, slowly turn off the backwash supply, allowing the GAC to settle.

7. At this time, the bed depth should be approximately 5% greater than the design depth. If not, add more GAC to attain this bed depth. Because the GAC bed will compact during operation, it is important to start out with a slightly higher bed depth compared to the design value.

8. Finally, allow the GAC to sit overnight before starting the run. This is expected to dissolve the air pockets in the pores of the GAC facilitating more complete wetting prior to conducting the experiments.

GAC COLUMN START-UP

1. Ensure that all pretreatment processes including filtration are performing satisfactorily.

2. Backwash the GAC to achieve a 40% bed expansion for 5 minutes.

3. Allow the bed to settle, and measure the bed depth.

4. Ensure that this is 5% greater than the design depth.

5. Weigh the mass of GAC remaining, and subtract this from the initial weight of GAC to determine the mass of GAC loaded on to the columns.

6. Start loading the GAC columns with filtered water.

7. After approximately 15 hours of operation, measure the bed depth again. Using this depth, adjust the loading rate to yield the appropriate EBCT (with 5% tolerance).

Appendix D: Cost Analysis Equations

GAC THERMAL REGENERATION COST EQUATIONS USED IN SECTION

According to Adams and Clark (1988), the following equations can be used to estimate construction costs (CC), cost estimates for electrical energy requirement (Process Energy (PE), and Building Energy (BE)), maintenance-materials MM costs, and O&M labor requirements (OL) costs for a multihearth reactivator.

$$CC = 144000 + 198300.4 * (\text{EFAREA})^{0.434}$$

where: CC = construction costs in 1983 dollars,

EFAREA = effective surface area in square feet of one reactivator,

CC in current dollars = CC* current CCI / 4,114.6, with CCI = construction cost index

Annual capital costs = CC *CRF

where CRF = capital recovery factor = $I(1+I)^N / [(1+I)^N - 1]$

where I = period lending interest rate and N = payback period.

$$PE = 354600 + 6387 * (\text{EFAREA})^{0.755}$$

where: PE = process energy requirement in kWh/year,

total filter area is in square feet.

PE* electric rate (in $/kWh) = annual PE costs

$$BE = 12250 + 312.1 * (\text{EFAREA})^{0.649}$$

where: BE = building energy requirements in kWh/year,

total filter area is in square feet.

BE* electric rate (in $/kWh) = annual BE costs

$$MM = 4456.6 * (\text{EFAREA})^{0.401}$$

where: MM = maintenance-materials costs in 1983 dollars per year,

total filter area is in square feet.

MM in current dollars = MM * current PPI / 287.1

Where PPI = producers price index for finished goods

$$OL = 2920 + 282 * (\text{EFAREA})^{0.7}$$

Where: OL = O&M labor requirements in workhours per year,

total filter area is in square feet,

OL* labor rate (in $/hr) = labor cost

$$NG = 648400 + 287714.9 * (\text{EFAREA})^{0.899}$$

Where: NG = natural gas requirement in standard cubic-feet per year,

NG* gas rate ($/standard cubic-feet) = annual gas cost

CAPITAL AND O&M COST EQUATIONS USED (INCLUDES THERMAL REGENERATION)

According to Adams & Clark (1991), concrete gravity adsorbers are assumed for GAC contactors greater than 10 mgd. Concrete gravity contactors will be assumed for the City of Houston. The following analysis will include GAC reactivation cost.

$$CC = 93700 + 1999.1 * (\text{CUFT})^{0.712} * (1.027)^{z}$$

where: CC = construction costs in 1983 dollars,

CUFT = total effective GAC bed volume in cubic feet of all contactors,

z = 1 if CUFT > 5,000 cubic feet and z=0 if CUFT ≤ 5,000 cubic feet.

CC in current dollars = CC* current CCI / 4,114.6, with CCI = construction cost index

Annual capital costs = CC *CRF

where CRF = capital recovery factor = $I\,(1+I)^{N} / [(1+I)^{N}-1]$

where I = period lending interest rate and N = payback period.

$$PE = 12 * (\text{total filter area})$$

where: PE = process energy requirement in kWh/year,

total filter area is in square feet.

PE* electric rate (in $/kWh) = annual PE costs

$$BE = 15150 + 350 * (\text{total filter area})^{0.916}$$

where: BE = building energy requirements in kWh/year,

total filter area is in square feet.

BE* electric rate (in $/kWh) = annual BE costs

$$MM = 540 + 23.6 * (\text{total filter area})^{0.753}$$

where: MM = maintenance-materials costs in 1983 dollars per year,

total filter area is in square feet.

MM in current dollars = MM * current PPI / 287.1

Where PPI = producers price index for finished goods

$$OL = 1160 + 0.3 * (\text{total filter area})^{1.068} * 1.152^{z}$$

Where: OL = O&M labor requirements in workhours per year,

total filter area is in square feet,

z = 1 if total filter area < 7,000 square feet and z = 0 if area ≥7,000 square feet.

OL* labor rate (in $/hr) = labor costs