

**PILOT TESTS OF EVAPORATORS FOR CLEANUP OF
CONTAMINATED UMTRA PROJECT GROUND WATER**

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ABSTRACT

Ground water at the site of the former uranium-processing mill at Tuba City, Arizona, is contaminated with nitrates, sulfates, and uranium as a result of milling operations. The Uranium Mill Tailings Remedial Action Ground Water Project selected distillation as the remediation technology for this site. Two pilot units with different technological approaches were tested to establish a basis for final selection. One pilot unit used stainless-steel elements and a rotary compressor; the other unit used polymeric heat-transfer elements with a low-head fan. The pilot tests were conducted at the Tuba City site with ground water from on-site wells. Distillate quality from both units exceeded the remediation standards by up to 2 orders of magnitude, and the volume of contaminated water was reduced by as much as 97 percent. The unit containing stainless-steel elements exhibited slight fouling over the course of the test, while the other pilot unit showed no detectable fouling. Overall, the technology using polymeric heat-transfer elements offers technical superiority and lower total costs for the remediation project. Therefore, the vendor offering that technology was selected to supply the full-scale treatment unit for Tuba City. The treatment system will begin operation in the first quarter of 2000.

SITE DESCRIPTION

The Tuba City Uranium Mill Tailings Remedial Action (UMTRA) Project site is the first site selected for active remediation of contaminated ground water under Title I of the Uranium Mill Tailings Radiation Control Act. The Tuba City site is located just south of U.S. Highway 160 on the Navajo Reservation in Arizona, approximately 5 miles east of Tuba City. The uranium mill at the Tuba City site operated from 1956 until 1966, processing approximately 800,000 tons of ore using a sulfuric-acid leach process and, later, sodium carbonate in an alkaline process. All tailings from ore processing were placed as slurry in evaporation ponds at the site. Surface remedial action at the Tuba City site began in 1988 and ended in 1990, with a total of 1.4 million cubic yards of uranium mill tailings and associated materials being moved and stabilized in a 50-acre disposal cell within the 145-acre fenced site boundary. The U.S. Nuclear Regulatory Commission (NRC) licensed the Tuba City site in 1997, and ground-water cleanup was deferred to the UMTRA Ground Water Project, which is managed by the U.S. Department of Energy Grand Junction Office.

GROUNDWATER CHARACTERISTICS AND TREATMENT STANDARDS

The requirements for contaminant levels in the ground water at UMTRA sites are specified in 40 *Code of Federal Regulations* (CFR) 192.04, Table 1. The Navajo Nation has proposed secondary cleanup standards for the Tuba City site, based on the National Secondary Drinking Water standards in 40 CFR 143, for constituents not listed in 40 CFR 192. DOE has incorporated the Navajo Nation's suggested standards as nonbinding goals for aquifer restoration.

Concentrations of all constituents in the Tuba City ground water have been monitored since 1985. Samples from 21 of the 41 monitoring wells contain concentrations of at least one constituent in excess of either the aquifer restoration standards of 40 CFR 192.04, Table 1, or the secondary cleanup goals

recommended by the Navajo Nation. Table I presents a summary of the mean and maximum concentrations of all contaminants of concern in the contamination zone and the treatment levels for the aquifer for each contaminant. The treatment levels for molybdenum, nitrate, selenium, and uranium are treatment standards specified in 40 CFR 192; other treatment levels are project goals based on Navajo Nation recommendations. Total suspended solids and concentrations of organic contaminants are insignificant. All concentrations are given in milligrams per liter (mg/L) unless otherwise stated.

Table I. Contaminant and Treatment Levels

Contaminant	Mean	Maximum	Treatment Level
Chloride	91	440	250
Molybdenum	0.16	0.6	0.1
Nitrate	951	2,330	44
Selenium	0.096	0.469	0.01
Sodium	219	615	20
Sulfate	2,257	7,590	250
Total Dissolved Solids	4,548	15,600	500
Uranium	0.404	1.38	0.044
pH (S.U.)	6.67	6.32 - 8.28	6.5 - 8.5

Concentrations of all contaminants except nitrate, sulfate, and uranium exceed applicable standards only in the vicinity of the former tailings ponds. The most widespread contaminant is nitrate, which covers an area of about 240 acres. Assuming a porosity of 0.25 and an average thickness of 86 feet of contaminated aquifer, the estimated volume of contaminated water in the nitrate plume is 1.69 billion gallons.

OBJECTIVES OF PILOT TESTING

The selection of active treatment as the groundwater compliance strategy for UMTRA Ground Water Project sites followed the procedure specified in the *Final Programmatic Environmental Impact Statement for the Uranium Mill Tailings Remedial Action Ground Water Project* (Ref. 1). The results of the compliance strategy selection procedure, and a description of the process that resulted in the selection of distillation as the treatment technology for Tuba City, is provided in the *Final Site Observational Work Plan for the UMTRA Project Site near Tuba City, Arizona* (Ref. 2).

To demonstrate the applicability of the distillation process to the Tuba City site, DOE decided to perform a pilot-scale test of the distillation process at the site before purchasing the full-scale treatment unit. Proposals for the pilot test and the full-scale treatment system were solicited from leading manufacturers of distillation systems. Proposals were evaluated both for technical merit and for cost effectiveness.

The original intent of the pilot test program was to confirm the applicability of the process and equipment supplied by the company whose full-scale treatment system offered the best value to the government. Two of the four proposals received in response to the DOE's solicitation were judged to be technically superior and also offered attractive overall project costs. These proposals were submitted by the HPD Division of US Filter (Naperville, Illinois) and a firm that shall be referred to herein as Company X. DOE was unable to pick a preferred vendor based on the proposals and decided to invite both companies to perform pilot tests at the Tuba City site. The results of the pilot tests would be incorporated into the vendor selection process.

DESCRIPTIONS OF PILOT UNITS

Both pilot units use mechanical vapor recompression (MVR) to maximize energy efficiency. In the MVR process, a circulating concentrate solution flows across the outside surfaces of heat-transfer evaporation elements. A small amount of water vaporizes from the concentrate and is withdrawn as steam to the suction of a compressor. Compression increases the pressure and saturation temperature of the steam. The compressed steam enters the inside of the heat-transfer elements, providing the heat source for vaporization of the circulating concentrate. As the steam gives up its heat, it condenses to form clean water, or distillate, that is collected and discharged. A small amount of the circulating liquid is bled off as concentrated brine, which contains all the nonvolatile contaminants from the original feed.

The Company X pilot unit. The Company X pilot unit operates at atmospheric pressure. It uses six 12-by 48-inch plate-type, falling-film, heat-transfer elements and a rotary compressor with a variable-speed drive. The feed rate to the unit is about 24 gallons per hour, or 0.4 gallon per minute (gpm). A small packaged boiler provides heat for startup and replaces excessive heat lost during normal operation. Feed pretreatment consists of addition of sulfuric acid to decompose bicarbonate and an antifoam agent to suppress carryover of brine into the distillate.

The Company X pilot unit employs a technology called seeded-slurry evaporation. The seeded-slurry process minimizes formation of calcium sulfate (CaSO_4) scale by establishing and maintaining a slurry of CaSO_4 seed crystals in the circulating brine. The surface area of the seed crystals exceeds the surface area of the heat-transfer surfaces by several orders of magnitude, so CaSO_4 will precipitate preferentially on the crystal surfaces. A well-designed seeded-slurry system can concentrate wastewater to near saturation of sodium salts without scaling the heat-transfer surfaces.

The US Filter pilot unit. The US Filter pilot unit operates under vacuum with a nominal operating pressure of 160 millibars (mbar) or 2.32 pounds per square inch absolute (psia). It uses a low-lift fan that provides only about 10 to 15 mbar (0.15 to 0.22 psi) of pressure rise. The low pressure rise and low operating temperature allow the US Filter pilot unit to utilize flexible polymeric heat-transfer elements rather than metal elements. The flexible elements are more resistant to scaling than rigid metal elements, and the lower operating temperature that results from operation under vacuum minimizes precipitation of contaminants with inverse solubilities. The US Filter pilot unit produces about 2.2 gpm of distillate. An electric immersion heater provides heat for startup and replaces excessive heat lost during normal operation. Pretreatment for the US Filter test consists of the addition of sulfuric acid to decompose bicarbonate and a liquid acrylic polymer to minimize crystal growth and adherence of nuclei to heat-transfer surfaces.

Seeded-slurry technology has been in use for more than 20 years, and many seeded-slurry systems are operating successfully around the world. Company X intended its pilot test to confirm the applicability of its seeded-slurry process to the chemistry of the Tuba City ground water. The technology used by US Filter had never been applied to systems in which CaSO_4 precipitates were formed, so their more ambitious test program consisted of two possible phases. In the first phase, five-micron cartridge filters would be used to remove solid particles, relying on the polymer to suppress crystal growth so that supersaturation would be relieved on ultrafine circulating particles. If the first phase was unsuccessful, the filters would be discarded, and the second phase would allow the particles to grow until they were removed with the brine. This was essentially a seeded-slurry process, except that the system was allowed to seed itself by natural precipitation and crystal growth rather than having seed particles provided.

THE COMPANY X PILOT TEST

The first batch of contaminated ground water feed was added to the Company X pilot unit on September 8, 1998, followed by the addition of CaSO_4 solids that provided the seed for growth of CaSO_4 crystals within the evaporator body. Operation of the unit was erratic for several days because of a failure of the site water supply and a loss of brine concentration that was due to foaming. Steady-state operation was finally established on September 13. Except for a brief shutdown on September 21 to replenish the oil in the compressor, the Company X pilot unit operated continuously on ground water feed from the restart on September 13 until it was shut down for decontamination on September 25.

The feed mixture used in the unit through September 20 was chosen to simulate the mean concentration of the contaminant plume (see Table I). On September 21, the feed mixture was changed to simulate the higher concentrations expected during Phase I of full-scale treatment when ground water will be drawn from extraction wells in the more highly contaminated areas of the plume.

The unit was shut down for final cleanout and decontamination on September 25. When the sightglasses were removed for internal inspection, only a small amount of fouling was observed on the heat-transfer surfaces, so no chemical wash was performed. When the unit was inspected following its return to Company X's facility, several of the steam nozzles on the inside of the shell that attach the steam box to the plate assemblies were leaking. It was impossible to determine how much of the damage occurred during shipment to the site and how much occurred during return shipment.

THE US FILTER PILOT TEST

The US Filter pilot unit operated unattended on total recycle with clean water on October 3-4, 1998. Contaminated ground water feed began on October 5. The unit was unreliable for the next 2 days, with numerous trips caused primarily by high immersion heater temperature. The addition of more insulation improved reliability substantially. The brine rate was reduced in daily increments until the feed-to-brine ratio reached the desired value of 20:1. During the first 24 hours of the test, the cartridge filters were changed once every 4 hours. By October 10, the quantity of solids in the circulating solution had dropped dramatically and the filters were being changed less than once every 12 hours. Throughout this period, the feed rate dropped steadily from an initial rate of 450 liters per hour (Lph) to less than 320 Lph.

Ground water feed was stopped on October 11. Large amounts of solids were found on the surfaces of the heat-transfer elements and on the liquid distributors. Three buckets of solids were removed from the vapor body, and a chemical wash was then performed. The chemical wash procedure consisted of a soda ash solution to convert CaSO_4 (gypsum) to calcium carbonate and soluble sodium sulfate; a wash with a solution of citric acid to release carbon dioxide and dissolve calcium; a flush with water; a second citric acid wash; and a second water rinse. After completion of the chemical wash, the interior surfaces were clean, with only small patches of scale in stagnant areas. The heat-transfer elements were replaced on October 14.

Restart of the unit for the second phase of the US Filter test began on October 15, and brine withdrawal was initiated on October 17 when the desired concentration factor was reached. With the exception of several trips on October 25 because of a faulty fan vibration switch, the unit ran steadily throughout the second test. The unit was operated at 20:1 concentration for 3 days; at 25:1 for 3 days; at 27.5:1 for 1 day, at 30:1 for 2 days, and at 20:1 on the last day.

The US Filter pilot unit was shut down on October 28. After it was flushed with clean water, a visual inspection showed no buildup of solids on the surface of the heat-transfer surfaces and only a small amount of solid deposition on the inside surface of the evaporator. Chemical cleanout consisted of a soda

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ash wash, two citric acid washes, and a final flush with water. After chemical cleaning, the only visible solids were in dead areas of little or no circulation.

FEED COMPOSITION

To demonstrate the proposed distillation technology, the pilot units must operate for an extended period on feed that is reasonably representative of the expected average composition of the contaminated ground water. Because the full-scale extraction system was not in place at the time of the pilot tests, a representative feed composition had to be synthesized. Measured amounts of water from three existing extraction wells were combined with clean water in batch “recipes” to produce the desired feed composition.

After the Company X test had begun, analyses of the feed indicated that the feed recipe contained lower levels of the key contaminants nitrate and sulfate than desired. The recipe was adjusted several times to obtain a more nearly representative feed composition. Toward the end of the Company X test, the recipe was changed again to more closely simulate the composition during Phase I of remediation when the extraction will be concentrated in the more highly contaminated areas of the plume.

The Company X pilot unit consumed a 400-gallon feed batch in about 16 hours at its feed rate of about 0.4 gpm. The feed rate of the US Filter pilot unit was more than 2 gpm, so feed batches were required about every 3 hours during the US Filter test. The capacity of two of the on-site wells was limited, and the batch recipe used during the test of the Company X pilot unit required more water than those wells could supply in 3 hours, as needed for the US Filter test. So the feed recipe was recalculated for the US Filter test to produce a representative mixture that the wells could supply. Before beginning the second phase of the US Filter test, the recipe was recalculated once again using newly available analytical data. This recipe was used throughout the second phase of the US Filter test.

Table II shows feed compositions in mg/L for the pilot tests. The “Average Plume” composition, representative of the composition of the total plume, was the target feed composition for the pilot tests, and is also the design feed composition for the full-scale treatment units. The “Initial Feed” composition is representative of the expected feed composition at the beginning of remediation, when extraction wells will be concentrated in the more highly-contaminated areas of the plume. The Company X pilot unit was operated at approximately the average plume composition until September 21, when the feed was changed to simulate the initial feed composition. The US Filter pilot unit was not operated on an initial feed recipe because the wells could not supply the quantities of water required for a mixture of that composition in the time available. The effect of brine concentration was studied during the test of the US Filter pilot unit by operating at concentration factors higher than the design concentration factor of 20. This produces a brine composition similar to that produced with an initial feed composition at the design concentration factor. Since brine composition is the principal factor affecting the performance of an evaporator, this technique allows a reasonable simulation of evaporator performance under initial operating conditions.

All analyses presented in this report were performed by the DOE Grand Junction Office (GJO) Analytical Chemistry Laboratory.

Table II. Feed Compositions (mg/L)

Contaminant	Average Plume (Design)	Company X, Sept. 13	Company X, Sept. 20	US Filter, First Phase	US Filter, Second Phase	Initial Feed	Company X, Sept. 25
Calcium	548	N/A	659	466	491	523	646
Chloride	96	77.5	95.4	67.8	78	111	102
Magnesium	371	304	400	387	408	596	520
Nitrate	890	742	1,080	777	847	1,108	1,220
Sulfate	2,090	1,729	1,930	1,881	2,050	2,681	2,523

RESULTS: DISTILLATE QUALITY

During most of the Company X test, the distillate conductivity, as measured at the compressor suction, was about 40 to 50 microsiemens per centimeter ($\mu\text{S}/\text{cm}$). At about the time that the feed recipe was changed to simulate the Phase I feed mixture, the conductivity of the distillate increased to more than 100 $\mu\text{S}/\text{cm}$. This degradation in conductivity was not reflected in the chemical analyses of the distillate from Company X's pilot unit, which indicate that the quality of the distillate produced by the Company X pilot unit was remained remarkably good throughout the test. Table III presents the results of the distillate analyses, in mg/L, for all distillate samples taken during the test of the Company X pilot unit, as well as the aquifer restoration standard for each component. All samples are less than the aquifer restoration standard by at least a factor of 20.

Table III. Distillate Analyses for Company X Pilot Test (mg/L)

Constituent	Standard	Sept. 13	Sept. 20	Sept. 25
Calcium	n/a	n/r	0.13	0.088
Chloride	250	0.44	0.39	0.05
Magnesium	n/a	0.12	0.07	0.06
Nitrate	44	0.68	0.24	0.45
Sulfate	250	0.37	0.32	0.53
TDS	500	25	10	10

n/a = not applicable

n/r = not requested

Ammonia is not a contaminant of concern at Tuba City, and the average plume composition is low in ammonia. So the samples taken during the Company X test and submitted to the GJO Analytical Chemistry Laboratory were not analyzed for ammonia. However, the wells used to produce the feed for the pilot tests were located in a localized ammonia "hot spot," and it was suggested that the high conductivity might be due to ammonia carryover into the distillate. This seems to be confirmed by two samples analyzed by Company X in its laboratory. A distillate sample from September 20 showed 3.5 mg/L ammonia, while another sample taken on September 25 showed 35 mg/L ammonia.

Ammonia was added to the list of analytes for the US Filter test. Table IV gives the results of the distillate analyses, in mg/L, for all distillate samples from the US Filter test.

Table IV. Distillate Analyses for US Filter Pilot Test (mg/L)

Constituent	Standard	First Phase	Second Phase			
		Oct. 11	Oct. 20	Oct. 23	Oct. 26	Oct. 27
Ammonia	n/a	n/r	2.09	15.5	11.4	9.57
Calcium	n/a	0.475	n/r	0.194	<0.047	0.774
Chloride	250	0.31	<0.016	0.054	0.072	0.089
Magnesium	n/a	1.63	0.106	<0.103	<0.103	0.616
Nitrate	44	3.54	2.48	1.07	1.01	1.37
Sulfate	250	5.86	0.82	0.62	1.19	2.1
TDS	500	15	38	<20	<20	<20

Overall, the distillate quality for the US Filter test appears to have been markedly better during the second phase than during the first. As described above, the operation of the pilot unit was significantly better during the second phase, which may account for the higher distillate quality. However, the differences are minor; constituent concentrations are below standards by one or more orders of magnitude for all analyses in both phases of the pilot test.

The distillate conductivity averaged 29 $\mu\text{S}/\text{cm}$ during the first phase of the US Filter test. During the first five days of the second phase, the average conductivity was 11 $\mu\text{S}/\text{cm}$. After the sulfuric acid dosage to the feed batches was reduced to increase the evaporator pH, the average distillate conductivity increased to 35 $\mu\text{S}/\text{cm}$. The equilibrium between ammonium ion, NH_4^+ , and ammonia, NH_3 , is pH-sensitive, with NH_4^+ favored by lower pH. The brine pH averaged 4.4 before the acid dosage was reduced and 5.5 thereafter. The later samples showed lower TDS but higher conductivity, suggesting that the observed conductivity was largely due to dissolved ammonia. This was almost certainly true during the Company X test as well.

Table V shows the concentrations, in micrograms per liter, of metals in the distillate from both pilot tests. The elevated levels of metals in the distillate from the Company X pilot unit appear to be due to corrosive attack, probably by ammonia, of the Monel demister used in that unit. The US Filter pilot unit did not have a demister, and the polymer used in its distributor/heat transfer unit is not subject to corrosive attack.

Table V. Metals Concentrations in Distillate (micrograms per liter)

Species	Company X			US Filter				
				First Phase	Second Phase			
	Sept. 13	Sept. 20	Sept. 25	Oct. 11	Oct. 20	Oct. 23	Oct. 26	Oct. 27
Copper	836	917	1,500	12	3.2	5.2	<2.2	4.9
Iron	40.8	244	127	371	12.7	18.2	27.5	49.3
Nickel	292	235	344	8.1	5.5	3.3	5.3	5.9
Zinc	136	176	615	84.9	9.1	13.4	<6.7	9.9

The high levels of iron and zinc in the sample from the first phase of the US Filter test appear to originate from a galvanized iron fitting in the distillate piping that was replaced before the second phase. The iron level in the distillate rose throughout the second phase of the US Filter test, although the iron level in the feed varied randomly during that phase. The reason for the gradual increase in distillate iron level during

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the second phase of the US Filter test is unknown; it is not matched by an increase in zinc or any other metals.

CONCENTRATION FACTOR AND BRINE GENERATION

The brine will be dried in evaporation ponds constructed on site. A higher brine concentration factor (feed rate divided by brine rate) will permit a smaller evaporation pond. The capability of operating at higher concentration factors also allows flexibility in operation of the evaporation ponds during wet years and for uncertainties in evaporation rates that are due to brine composition variations.

The design concentration factor for the Tuba City remediation project is 20. Higher concentration factors result in increased boiling-point elevation (BPE), which reduces the driving force available for vaporization. To maintain the evaporation rate, the compressor output must be increased, increasing energy consumption. After the compressor reaches its maximum pressure differential, further increases in concentration will result in reduced vaporization.

The Company X pilot unit was operated at a concentration factor of about 30 during the Tuba City tests to assess the characteristics of the Company X pilot unit at the higher concentration factor. Observation of crystal behavior by the manufacturer's representatives indicated that the composition of the Tuba City ground water is well suited for seeded-slurry technology. The initial crystal shape was long and narrow. As the test progressed, the crystals became wider and more uniform in shape, and settling times improved, which may be due in part to the higher sulfate content of the feed in the later batches.

During the Company X test, the solids concentration in the brine dropped from around 10 percent (the initial seeding of 5 percent plus an additional 5 percent formed by CaSO_4 precipitation before brine withdrawal began) to about 7 percent. The steady-state solids concentration is between 6 and 7 percent, so the unit had approximately reached steady state by the end of the test.

During the first phase of the US Filter test, the concentration factor was increased gradually because of the initial poor reliability of the pilot unit, reaching a maximum of about 11 before the first test was aborted. At the beginning of the second phase of the US Filter test, the evaporator was brought up to the desired concentration factor of 20 as quickly as possible and was subsequently increased further.

In most cases the concentration factors based on analyses of magnesium, nitrate, and sodium, and the precipitation of calcium sulfate, closely matched those calculated from the mass balance, indicating that little or no precipitation of sodium, magnesium, or nitrate salts was occurring in the evaporator. This was confirmed by analyses of the solids from the US Filter pilot unit that did not show magnesium or silica. The mean particle size, as determined by US Filter's laboratory, was 46.2 microns on October 20, when the concentration factor was about 20, but decreased to 17.7 microns on August 26, when the concentration factor was increased to 30. The brine withdrawal rate was lower at the higher concentration factor, so the drop in particle size was not due to reduced residence time. The more likely cause was an increase in nucleation rate as more CaSO_4 was available.

Both units operated successfully at significantly higher concentrations than the target value for the remediation project. Therefore, either technology would be acceptable from this standpoint.

HEAT-TRANSFER PERFORMANCE

The standard measure of performance for evaporators and other types of heat-transfer equipment is the heat-transfer coefficient, which is defined by the formula

$$Q = U_o * A * \Delta T \quad (1)$$

where Q is the evaporator duty, U_o is the overall evaporator heat-transfer coefficient, A is the total surface area of the heat-transfer plates, and ΔT is the effective temperature difference. The units for heat-transfer coefficient in the English system are British thermal units per hour per square foot of surface area per degree of Fahrenheit temperature rise (BTU/hr-ft²-°F)

Both pilot units exhibited cyclic variations in evaporation rates between daytime and nighttime. The positive-displacement compressors used by both units had a constant volumetric vapor rate. The mass vapor rate, however, was a function of the evaporator pressure, which for both units would peak during the daytime, when ambient heat losses were minimized, and fall at night as the air cooled. The Company X pilot unit could compensate for this cycling to some extent by increasing the amount of steam added by the boiler, while the US Filter pilot unit could increase the output of the immersion heater. These actions dampened the ambient cycle but did not eliminate it. The vapor rate was significantly affected by this ambient cycling, but the temperature difference was affected only slightly because the difference between the steam and brine temperatures remained nearly constant. Therefore, the calculated heat-transfer coefficient exhibited the same cycling as the vapor rate.

Table VI presents daily average heat-transfer coefficients, brine concentration factors, and brine chloride concentrations for the Company X test for the dates on which samples were submitted to the GJO Analytical Chemistry Laboratory. The concentration factor was maintained as nearly constant as possible during the Company X test, but the feed concentration was increased to the Phase I mixture after September 20.

Table VI. Heat-Transfer Performance of Company X Pilot Unit

Date	Concentration Factor	Brine Chloride Concentration (mg/L)	U_o (BTU/hr-ft ² -°F)
Sept 13	32.6	2,530	414
Sept 20	27.9	2,660	408
Sept 25	30.2	3,080	389

These data indicate a slight tendency for the heat-transfer coefficient to decrease with time and with increasing brine concentration. A regression of more extensive data on brine chloride concentration (using daily analyses performed in the field) and heat-transfer coefficients indicates that operating for 64 days reduces the heat-transfer coefficient by about 25 percent, while doubling the brine concentration reduces it by less than 15 percent.

A gradual decline in heat-transfer coefficient over time suggests that the heat-transfer surfaces are fouling. After the pilot unit was shut down, a reddish-brown deposit was found on the heat-transfer plates. An analysis of this deposit by Company X's laboratory showed that it consisted of 25 percent calcium, 65 percent sulfate, 1 percent magnesium, and 3.3 percent silica. The deposit was easily cleaned with hot sulfamic acid, indicating the presence of an underlying carbonate scale. (The chemical analysis of the scale did not include carbonate.) In addition, a hard layer of scale about 1/8-inch thick was found on the steam coil in the feed tank. This scale consisted of 21 percent calcium, 68 percent sulfate, and 0.3 percent silica.

The heat-transfer coefficient could not be calculated for the US Filter pilot unit because the liquid temperature probe did not provide an accurate measurement. An alternative index of performance for the US Filter pilot unit was obtained by dividing the distillate rate by the fan pressure drop. This term, which

came to be known as the performance parameter, is simple to calculate, requiring only two terms that are readily obtained from reliable instrumentation, and exhibits little or no day-to-night cycling because the numerator and denominator are both affected by ambient changes to essentially the same degree.

Fouling will cause a decline in performance parameter over time, while increases in concentration will increase BPE, which should reduce performance parameter independent of time. The concentration factor during the first phase of the US Filter test did not exceed 11, but the heat-transfer surfaces became severely fouled with solid deposits as the run progressed. During the second phase, the concentration factor varied from 20 to 30, but solids buildup was minimal. Table VII shows some representative values for the performance parameter as a function of elapsed time and concentration factor during the first phase of the US Filter test and the early part of the second phase. The performance parameter is measured in liters of distillate produced per hour per millibar of fan pressure differential (Lph/mbar).

Numerical regressions of the complete sets of performance parameter data show that during the first phase of the US Filter pilot test, the performance parameter dropped by more than 3 Lph/mbar per day. Doubling the concentration factor from 5 to 10 reduced the performance parameter by only 0.5 Lph/mbar. During the second phase, the performance parameter actually increased slightly with run time, from 34.4 after 1.5 days to 37.9 after 4.5 days, but decreased by more than 0.5 Lph/mbar (as determined by the numerical regression) for each 1.0 increase in concentration factor.

Table VII. Performance Parameters, US Filter Pilot Test

Elapsed Run Time (days)	First Phase		Second Phase	
	Concentration Factor	Performance Parameter (Lph/mbar)	Concentration Factor	Performance Parameter (Lph/mbar)
1.5	5.0	33.8	20.8	34.4
2.5	3.9	28.8	19.8	37.2
3.5	5.2	27.6	20.0	37.2
4.5	6.5	24.2	19.6	37.9
5.5	9.8	21.0	24.1	34.7

Table VIII presents a comparison of average, minimum, and maximum values of the performance parameter for the first 20 hours of the second phase, when the concentration factor was 20:1, with the same parameters during the final 20 hours of the second phase, at the same concentration factor. The two data sets are virtually identical, indicating that no detectable performance degradation took place during the second phase of the US Filter pilot test. The correlation between performance parameter and time, which indicated that the performance parameter actually increased slightly with run time, suggests that the performance of the US Filter pilot unit would continue to gradually increase over time and the unit would never require cleaning to remove scale buildup. Of course, some fouling over time is inevitable and the unit would have to be cleaned eventually. But the rate of fouling of the US Filter pilot unit cannot be deduced from the pilot test data.

Table VIII. Performance Parameters at 20:1 Concentration

Function	October 17 (Initial 20 hours of test)	October 26-27 (Final 20 hours of test)
Average	35.1	35.4
Maximum	36.8	36.2
Minimum	33.7	34.4

TECHNICAL EVALUATION OF PROPOSALS FOR FULL-SCALE TREATMENT SYSTEMS

The pilot tests established that both processes were acceptable for the Tuba City remediation project. In accordance with DOE procurement procedures, the manufacturers of the two pilot units were invited to submit “best and final offers” (BAFOs) for the full-scale treatment units. The BAFOs include capital and installation costs and all anticipated operating and maintenance costs. Review of the BAFOs uncovered a number of items in both offers that were not consistent with the observations of the pilot tests, so the two vendors were requested to revise and resubmit their BAFOs. The selection of the treatment unit supplier was based on the revised BAFOs.

The technical evaluation ranked the two vendors according to three major and six minor criteria. Each proposal was assigned a rating of “Meets Requirements,” “Exceeds Requirements,” or “Substantially Exceeds Requirements” for each of these criteria, based on parameters that were determined before the evaluation began. The criteria used in this evaluation are given in Table IX.

Table IX. Technical Evaluation Criteria

Criterion Type	Criterion
Major	Design Feed Rate
Major	Number of Units in United States
Major	Delivery Schedule
Minor	Ease of Startup and Shutdown
Minor	Affect of Change in Feed Composition
Minor	Susceptibility to Foaming
Minor	Operating Temperature
Minor	Operating pH
Minor	External Seeding Required

The proposal from US Filter achieved higher overall rankings on the technical evaluation criteria and was rated technically superior. However, the evaluation stated that the differences were minor, and that both proposals were technically acceptable and would satisfy the requirements of the Tuba City remediation project.

COST EVALUATION OF PROPOSALS FOR FULL-SCALE TREATMENT SYSTEMS

DOE determined that the proposal which represented the best value to the government would be the one that offered the lowest estimated total project cost over the 20-year project lifetime. The total project cost was calculated by combining the capital and operating costs into a net present value, using a 7 percent discount rate as recommended by the U.S. Department of Management and Budget.

Capital costs as supplied by the vendors were adjusted for several factors, including different site infrastructure costs to accommodate the different physical sizes of the two full-scale units, additional costs to accelerate delivery schedules where necessary to match DOE’s requirements, and the requirement of the Buy American Act that a cost adjustment be added to foreign proposals for comparison with domestic proposals.

Operating costs included electricity, chemicals, and maintenance material. The cost of operating personnel was not included in the cost evaluations because both units were assumed to require the same number of operators. The operating cost calculations used the quantities and unit prices supplied by the

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vendors, and the pilot plant experience was used where possible to verify that the vendors' claims were reasonable.

When the capital and operating costs were combined into net present value, the total project cost of the Company X proposal was less than three percent higher than that of the US Filter proposal.

SELECTION OF TREATMENT SYSTEM VENDOR

The review evaluation committee summarized its findings as follows: "The distinctions between the two proposals are minor. The US Filter proposal has a slight cost edge ... (and) is also slightly superior from a technical standpoint... Therefore, we recommend beginning negotiations with US Filter to reach agreement on the final terms for a purchase award." The order for the Tuba City treatment system was placed with US Filter in February 1999, and the completed unit was delivered to the site in October 1999. Preliminary tests on clean water are scheduled for January 2000, with full-scale operation on site ground water to begin in February, 2000.

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FOOTNOTE

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