DEVELOPING AND TESTING THE DECONTAMINATION EFFLUENT TREATMENT SYSTEM

污染消除廢水處理系統的開發與測試

By Dr. Victor F. Medina[1], Mr. Scott A. Waisner[2], Dr. Edith Martinez-Guerra[3], and Mr. Jared L. Johnson[4]

作者：Victor F. Medina 博士、Scott A. Waisner 先生、Edith Martinez-Guerra 博士與 Jared L. Johnson 先生

From: Army Chemical Review (ACR), Summer 2018

出處：美國陸軍化學兵半年刊，2018 夏季號

譯者莊孝感先生，畢業於國立清華大學化學系(學士) 61 年班、化學研究所(碩士) 63 年班，曾任國家中山科學研究院化學研究所化學戰-防護計畫主持人。

Introduction 緒言

Decontamination operations of personnel, vehicles, and the affected area following a chemical, biological, radiological, and nuclear (CBRN) attack require large volumes of water. The resulting wash water from these

---

1.Dr. Medina is a research engineer for the Engineer Research and Development Center. He holds a bachelor’s degree in geology from the University of California, Los Angeles; a master’s degree in civil engineering from the University of Southern California, Los Angeles; and a PhD in civil engineering from the University of Southern California. Medina 博士是“工程研究與發展中心”的研究工程師。他擁有加州大學洛杉磯分校的地質學學士學位；洛杉磯南加州大學土木工程碩士學位；並獲得南加州大學土木工程博士學位。

2.Mr. Waisner is a research engineer for the Engineer Research and Development Center. He holds a bachelor’s degree in civil engineering from the University of Missouri, Columbia. Waisner 先生是“工程研究與發展中心”的研究工程師。他擁有哥倫比亞密蘇里大學土木工程學士學位。

3.Dr. Martinez-Guerra is a research environmental engineer for the Engineer Research and Development Center. She holds a bachelor’s degree in civil engineering from Arkansas State University, Jonesboro; a master’s degree in civil and environmental engineering from Mississippi State University, Starkville; and a PhD in civil and environmental engineering from Mississippi State University. Martinez-Guerra 博士是“工程研究與發展中心”的研究環境工程師。她擁有瓊斯伯勒阿肯色州立大學土木工程學士學位；密西西比州立大學斯塔克維爾分校土木與環境工程碩士學位；並獲得密西西比州立大學土木與環境工程博士學位。

4. Mr. Johnson is a research environmental engineer for the Engineer Research and Development Center. He holds a bachelor’s degree in chemical engineering from the University of Missouri, Columbia, and a master’s degree in civil and environmental engineering from Mississippi State University. 約翰遜先生是“工程研究與發展中心”的研究環境工程師。他擁有哥倫比亞密蘇里大學化學工程學士學位和密西西比州立大學土木與環境工程碩士學位。

operations will likely contain an unpredictable mixture of toxic and hazardous contaminants alongside sediments, surfactants, soaps, and disinfecting agents such as bleach that threaten human health and the environment. The Army currently has no capability to treat or recycle the effluent from its aqueous-based CBRN decontamination operations. This effluent is very hazardous, and is a major handling and logistical problem and, potentially, a political burden. To address this, the Deployable Treatment of Decontamination Effluent Project was initiated to develop and evaluate technologies and approaches to achieve effective treatment of contaminated wash water. An alpha version of a pilot-scale treatment system, which is called the Decontamination Effluent Treatment System (DETS), was developed for the project.

在化生放核(CBRN)攻擊之後，人員、車輛和受影響區域的污染消除作業需要大量的水。由這些作業產生的洗滌水可能含有不可預測的有毒與有害污染混合物，連同沉澱劑、表面活性劑、肥皂和消毒劑等，例如漂白劑，都會威脅人類健康和環境安全。陸軍目前沒有能力處理或回收其水基化生放核(CBRN)污染消除作業的污水。這種污水十分危險，是一個重要的處置和後勤問題，並且可能是一種政治負擔。為了解決這個問題，"可部署的污染消除污水處理計畫"啟動了，供開發和評估各種技術與方法，以達成有效處理污染的洗滌水。本計畫開發了一個 alpha 版本的先導規模處理系統，命名為"污染消除污水處理系統(Decontamination Effluent Treatment System, DETS)"。

This study evaluated field treatment of decontamination wash water at a pilot scale. Holistic evaluation of the DETS proceeded along three axes. The first goal was evaluating the feasibility of integrating the DETS into CBRN decontamination operations. The second goal was establishing viable performance metrics for a scaled-up system. The third goal was identifying shortcomings of the system with the idea that any such shortcomings could be addressed in a beta version of DETS.

本研究評估了先導規模的污染消除作業洗滌水的野戰處理。污染消除污水處理系統(DETS)的整體評估已三個主軸進行。第一個目標是評估將污染消除污水處理系統(DETS)整合到化生放核(CBRN)污染消除作業的可行性。第二個目標是為擴大規模系統建立可用的性能指標。第三個目標是確定系統的缺點，並認為任何此類缺點都可以在污染消除污水處理系統(DETS)的 beta 版本中得到解決。

System Size 系統大小

The system was sized to address a chemical release event involving people and vehicles. For this study, the DETS was designed to render-safe wash water from the decontamination of approximately 200 people and 10 large military vehicles (representative of a battalion size event). Water use factors were calculated from Army G-3/5/7 decontamination planning factors.

Combining the estimated water generated over a 12-hour treatment period resulted in an approximate rate of 10 gallons (38 liters) per minute.

該系統的大小適用於包含人員和車輛的化學品釋放事件。對於這項研究，污染消除污水處理系統(DETS)設計用於從大約 200 人和 10 個大型軍用車輛(代表營級大小事件)的污染消除作業中提供安全的洗滌水。用水因子是根據陸軍 G-3/5/7 污染消除作業規劃因子計算的。結合 12 小時處理期間，估計產生水的速率為每分鐘大約 10 加侖(38 公升)。

Treatment Strategy 處理策略

The objective of DETS is to have the capacity to treat any chemical, metallic, radioactive, or biological contaminant to a sufficient level so that the effluent can be safely discharged with no limitation. To achieve this goal, an agnostic treatment approach is needed, meaning that the treatment approach is effective for all contaminants. Membrane treatment is an effective, agnostic treatment that can be readily adapted for this approach. However, membrane treatments can be compromised by constituents that foul, clog, or degrade the membrane; pretreatments were added to protect the reverse-osmosis system. The constituents that are expected in decontamination effluent and the treatment process that targets those constituents are identified below:

污染消除污水處理系統(DETS)的目標是有能力將任何化學、金屬、放射性或生物污染物處理到足夠的水準，以便可以沒有限制、安全地排放流出物。為了實現這一目標，需要一種實證的處理方法，這意味著處理方法對所有污染物都有效。薄膜透析處理是一種有效的、實證的處理方法，可以易於適用的方法。然而，薄膜透析處理可能受到污染、堵塞或降解薄膜組成的影響；需增加前置處理以保護逆滲透系統。在污染消除流出物中預期的成分和針對這些成分的處理過程如下所示：

- Sediment. Sediment could cause clogging in the reverse-osmosis system. A settling process (tank or blivet) and filtration in the sand filter are used to remove particulates.
  沉積物：沉積物可能導致逆滲透系統堵塞。在砂濾器中的沉砂過程和過濾是用於去除顆粒。
- Hardness. Some forms of bleach (particularly supertropical bleach) can greatly increase water hardness (the combined concentration of calcium and magnesium ions). Excessive hardness could result in scaling that would compromise the granular activated carbon column and the reverse osmosis. An ion exchange resin media filter removes calcium and magnesium ions before the granular activated carbon treatment.
  硬度：某些形式的漂白劑(特別是超級漂白粉)可以大幅增加水的硬度(鈣和鎂離子的組合濃度)。過高的硬度可能導致結垢，這會損害顆粒活性炭管柱和逆滲透系統。離子交換樹脂介質過濾器在顆粒活性炭處理前去除鈣和鎂離子。

- Surfactant. Surfactants (the active components of soaps) can foul reverse-osmosis systems. Granular activated carbon is an effective pretreatment.
  介面活性劑：介面活性劑(肥皂的活性成分)會污染逆滲透系統。粒狀活性炭是有效的前置處理。
- Bleach. Granular activated carbon is an effective pretreatment.
  漂白劑： 粒狀活性炭是有效的前置處理。
- Oils, greases, and miscellaneous organic compounds. These were washed off people or vehicles during decontamination. Two processes target these compounds: granular activated carbon and reverse osmosis.
  油、油脂和其他有機化合物：這些是在污染消除過程中由人或車輛洗刷下來。顆粒活性炭和逆滲透兩種方法針對這些化合物。
- Chemical warfare agents. Chemical warfare agents are effectively removed by granular activated carbon. In addition, reverse osmosis provides complete removal for any agents that might pass the granular activated carbon process.
  化學戰劑：經由粒狀活性炭可有效地除去化學戰劑。此外，逆滲透可以完全去除任何可能通過顆粒活性炭處理的化學戰劑。
- Radioisotopes. Most radioisotopes are in the form of particulates, so they should be effectively removed by the same processes that target the particulates - settling and sand filtration. However, some radioisotopes (such as ionic cesium) could be in ionic form. For these forms, the most effective removal method is reverse osmosis.
  放射性同位素：大多數放射性同位素都是顆粒狀的，所以它們應該可經由針對顆粒的沉降和砂濾相同過程有效地去除。然而，一些放射性同位素(例如銫離子)可以是離子形態。對於這些形態，最有效的去除方法是逆滲透。

In addition, removal can occur during the treatment of another contaminant. For example, chemical weapon residue could be adsorbed on sediments and particulates and removed during settling or sand filtration.

此外，在處理另一種污染物時可同時去除，例如，吸附在沉積物和顆粒上的化學武器殘留物，在沉降或砂濾過程中被除去。

System Costs 系統成本

Table 1 summarizes the costs of system elements. Equipment costs were $60,000 (including the trailer). If a DETS unit were needed in a highly contaminated environment, it might be more economical to surplus the unit. Keeping costs low allows for a unit to be disposed of in its entirety if it gets highly contaminated during treatment.

表 1 概述系統諸元的成本。設備成本為 60,000 美元(包括拖車)。如果在高度污染的環境中需要污染消除污水處理系統(DETS)的單元，過剩的單元可能更

為經濟。為保持低成本，如果單元在處理期間受到高度污染，允許將其整體廢棄。

Field Evaluation 野戰評估

The field evaluation was conducted at the Waterways Experiment Station, operated by the U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. The evaluation focused on vehicle decontamination. Vehicles were moved to a wash area where they were pressure-washed using a firehose, scrubbed with soapy water, and then washed again with a firehose. Water was collected using the storm drainage system present at the site. Influent water was spiked with supertropical bleach, Malathion (a simulant for organophosphate chemical warfare agents), and cesium (Cs-133). DETS was then used to treat the water in the 250-gallon influent tank. The concentrate was collected in another 250-gallon tank. The treated effluent was allowed to flow into an open storm drain downstream of the test area.

野戰評估在密西西比州維克斯堡的美國陸軍工程師研發中心運作的水路試驗場進行。評估重點在於車輛污染消除。將車輛移至洗滌區域，在其中使用消防水帶對其進行壓力洗滌，用肥皂水擦洗，然後再用消防水帶洗滌。使用現場的雨水排水系統收集水。進水中加入超級漂白粉、馬拉松(Malathion)(有機磷化學戰劑的模擬劑)和銫(Cs-133)。然後用污染消除污水處理系統(DETS)處理 250 加侖進水筒中的水。將濃縮物收集在另一個 250 加侖的筒中。處理過的流出物流入測試區域下游的開放式雨水排水系統。

The field evaluation test took approximately 6 hours. However, the actual DETS operational time was 2 hours, during which time approximately 1,200 gallons (4,500 liters) of contaminated water were treated.

野戰評估測試大約需要 6 個小時。然而，實際的污染消除污水處理系統(DETS)操作時間為 2 小時，在此期間處理了大約 1,200 加侖(4,500 公升)的污染水。

Operation 作業

The system performance was evaluated as very successful. The system showed no signs of performance degradation. One minor leak occurred after 1 hour of use; however, it was quickly repaired, and the operation continued. At approximately the 2-hour mark, the system pressure of the reverse-osmosis unit climbed by about 20 pounds per square inch, resulting from sediment buildup in the 5-micrometer prefilter cartridge at the entry point of the reverse-osmosis system. The system was stopped for a few minutes, and the cartridge was immediately replaced.

系統性能評估相當成功。該系統沒有顯示出性能下降的跡象。使用 1 小時後發生輕微洩漏；然而，它很快被修復，並繼續運作。在大約 2 小時的標記處，逆滲透裝置的系統壓力上升約 20 磅/平方吋，這是由於在逆滲透系統入口處的 5

微米前置過濾器濾筒中沉積物積聚造成的。系統停止了幾分鐘，前置過濾器濾筒立即更換。

Treatment Results 處理結果

Figure 1 shows a comparison of samples collected from the system influent and effluent. The influent on the left was brown and opaque, and the effluent on the right was very clear, which demonstrates the effective performance of the system for turbidity and suspended solids removal. A colorimetric measurement method was used to detect total chlorine (as a measurement for bleach). The influent sample had a strong color response to the reagent, indicating a high chlorine concentration, and the effluent sample was clear, indicating that bleach was effectively removed.

圖 1 顯示從系統進水和出水中收集的樣品的比較。左邊的進水是棕色和不透明的，右邊的出水非常清澈，這證明了該系統對濁度和懸浮固體去除的有效性能。比色測量方法用於檢測總活性氯(作為漂白劑的量度)。進水樣品對試劑具有強烈的顏色回應，表明活性氯濃度高，出水樣品清澈，表明漂白劑被有效去除。

Samples were collected during operation and analyzed. The constituents, analytical method, average concentrations, and percentage removal are given in Table 2. Turbidity, hardness, total chlorine, and Cs-133 were 100 percent removed. Surfactants and total organic carbon were 98.7 and 98.0 percent removed, respectively. Malathion was measured using two methods. With the first method, a phosphorus balance method, Malathion was 98.7 percent removed. With the second method, U.S. Environmental Protection Agency Method 8141A, Organophosphorus Pesticides-GC Capillary Column (gas chromatograph with electron capture detector), essentially 100 percent of the Malathion was removed.1 All measurements indicate that DETS is highly effective when treating constituents found in decontamination wash water.

在操作期間收集樣品並進行分析。表 2 中列出了成分、分析方法、平均濃度和去除百分比。濁度、硬度、總活性氯和 Cs-133 被 100%除去。介面活性劑和總有機碳分別去除 98.7%和 98.0%。使用兩種方法測量馬拉松(Malathion)。採用第一種方法磷平衡法，馬拉松(Malathion)去除率為 98.7%。採用第二種方法，美國環境保護局方法 8141A，有機磷農藥-氣相層析儀(GC)毛細管柱(具電子捕獲檢測器的氣相層析儀)，基本上 100%的馬拉松(Malathion)被去除。1 所有分析量測結果表明，污染消除污水處理系統(DETS)在處理污染消除洗滌水成分時非常有效。

Aqueous Wash Water Treatment 水洗滌處理

Water is a very effective solution for decontamination. Most CBRN agents are at least partially soluble in water, and washing with water can be very effective. Water can also be readily used with additives (such as bleach, surfactants, adsorbents, and enzymes) to further improve decontamination. For continental United States events, water-based decontamination is the primary approach and is expected to continue to be so into the future.

水是一種非常有效的污染消除作業解決方案。大多數化生放核(CBRN)毒劑或多或少部分溶於水，用水洗滌可能非常有效。水也可以很容易地與添加劑(如漂白劑、介面活性劑、吸附劑和酵素)一起使用，以進一步改善污染消除效果。對於美國大陸事件，水基污染消除是主要方法，預計未來將繼續如此。

Due to transportation logistics and the lack of water availability, the Army is aggressively studying methods for nonaqueous decontamination for overseas operations. Such methods include the use of wipes that remove and sequester the constituents for people and equipment as well as the use of fixatives, which can be applied as a patch to isolate the agents on vehicles and equipment, allowing them to complete the missions.2, 3 Efforts to reduce the role of water in decontamination are expected to continue, but nonaqueous methods are currently applicable primarily to small-scale applications. It may still be several years before water-based decontamination is supplanted, even for overseas operations.

由於後勤運輸和可用水源的缺乏，陸軍正在積極研究海外作戰的非水污染消除方法。這些方法包括使用擦拭粉撲提供人和設備去除和隔離毒劑的元素，如同固定劑的使用，固定劑可用作貼劑以隔離車輛和設備上的毒劑，使他們能夠完成任務。2, 3 預計將繼續努力減少水在污染消除作業中的作用，但非水方法目前主要適用於小規模應用。即使對於海外作戰，取代水基污染消除可能還需要幾年時間。

Recycling 回收

William Horne describes the need to conserve water during decontamination in his article entitled “The Need to Conserve Water During CBRN Decontamination.”4 Operating environments are frequently located in areas with limited water, and decontamination operations can use a substantial amount of water. This may stress local water resources and adversely affect friendly or neutral populations. The DETS system can address this issue because it has shown that high contaminant removal produces treated water that is suitable for reuse.

William Horne 在他的“在化生放核(CBRN)污染消除作業中需要節約用水”文章中敘述了在污染消除作業中節約用水的必要性。[4] 作戰環境通常位於水源有限的區域，污染消除作業可能會使用大量的水。這可能會對當地水資源造成壓力，並對友好或中立群眾產生不利影響，污染消除污水處理系統(DETS)可以解決這個問題，因為它已經顯現高污染物去除，並產生處理過適合再利用的水。

Figure 2 (page 45) demonstrates the advantage of water reuse based on a scenario of 85 percent water recovery (which was achieved by DETS) and an initial water volume of 600 gallons. The scenario assumes that 100 percent of the wash water is captured. The solid lines represent the scenario in which the treated water is reused for decontamination and the concentrate is simply collected. In this scenario, 600 gallons can be used instead of 4,000 gallons for decontamination (see solid blue line). The total collected concentrate would be 600 gallons (solid grey line).

圖 2 顯示了基於 85％水回收(由污染消除污水處理系統(DETS)達成)和初始水量為 600 加侖的情景下，水再利用的優勢。該方案假設捕獲了 100％的洗滌水。實線表示處理過的水被重新用於污染消除作業，且只有收集濃縮物的情況。在這種情況下，可以使用 600 加侖水而不是 4,000 加侖水進行污染消除作業(參見實心藍線)。收集的總濃縮物為 600 加侖(實線灰色)。

In addition, the concentrate could be treated and reused as well (see dashed blue line). If the original 600 gallons can be reused, this would produce a total volume of more than 7,000 gallons of recycled water. The total collected concentrate (dashed grey line) would be more than 550 gallons. In either case, reuse of treated wash water can greatly extend water resources.

此外，濃縮物也可以進行處理和重複使用(參見藍色虛線)。如果原來的 600 加侖可以重複使用，那麼這將產生超過 7,000 加侖的再循環水。收集的總濃縮物(灰色虛線)將超過 550 加侖。在任何一種情況下，經過處理的洗滌水的再利用，可以大大擴充水資源。

Conclusions 結論

Based on this study, several conclusions can be derived. DETS is a low-cost treatment system—the first of its kind to treat and recycle decontamination effluent. DETS as an effective means of capturing wash water from vehicle decontamination was clearly shown, and the process was effective at 98 percent or higher removal of all constituents tested. The system was easy to use and performed reliably.

基於這項研究，可以得出幾個結論。污染消除污水處理系統(DETS)是一種低成本的處理系統–這是第一個處理和回收污染消除污水的系統。污染消除污水處理系統(DETS)作為從車輛污染消除作業中捕獲洗滌水的有效手段，被清楚地顯示出來，且該程序有效的對所有測試成分具有 98％或更高的去除率。該系統易於使用且具可靠的功能。

Endnotes 頁尾註釋

1. U.S. Environmental Protection Agency Method 8141A, Organophosphorus Pesticides - GC Capillary Column, 1 September 1994.
2. Mark Disbrow, et al., “Hazard Mitigation, Material, and Equipment Restoration (HAMMER),” Advanced Technology Demonstration, Joint Military Utility Assessment, Edgewood Chemical Biological Center, ECBC-TR-1211, 2013.

3. Joint Requirements Office for Chemical, Biological, Radiological, and Nuclear Defense, "Capability Development Document–Joint Service Equipment Wipe (JSEW)," 2013.
4. William H. Horne, "The Need to Conserve Water During CBRN Decontamination," Army Chemical Review, Summer 2015, pp. 27–30.
5. Jonathan A. Brame et al., Composition of CBRN Decontamination Effluent and Development of Surrogate Mixtures for Testing Effluent Treatment Technologies, U.S. Army Corps of Engineers, Engineer Research and Development Center, ERDC/EL SR-16-2, July 2016.

Table 1. Cost of System Elements

表 1. 系統諸元的成本

Unit 單元	Cost 成本	Comments 說明
Reverse osmosis unit with pump and prefilter 具泵和前置過濾器的逆滲透過濾裝置 Cleaning units for scale and organics 用於水垢和有機物的清潔裝置 Sand filter media unit 細砂過濾介質單元 Carbon filter media unit 活性碳過濾介質單元 Water softener media unit 水軟化劑介質單元 Ultraviolet sterilization unit (not used in these studios) 紫外線殺菌裝置(未在此工作平台中使用)	$13,621.44	Price is for all of the units listed 價格包含所有列出的單元
Generator 發電機	$9,922.45	
Breaded pumps with mounting equipment and hoses 具安裝設備和軟管的帶襯套的泵	$13,283.09	Two were purchased for this study, but only one was used. Cost is for one unit. 本研究購買了兩套，但只使用了一套。成本是單套價格。
Flanges 法蘭	$1,066.00	
Hose reels 軟管捲軸	$8,939.92	
Trailer 拖車 Trailer upgrades 拖車升級	$5,000.00 $1,500.00	We determined that upgrades were needed after the field evaluation. 我們確定在野戰評估後需進行升級

Control units with associated software 具相關軟件的控制單元	$1,800.00	
Instrumentation and wiring 儀表和佈線	$5,045.00	
Total 合計	$60,177.00	

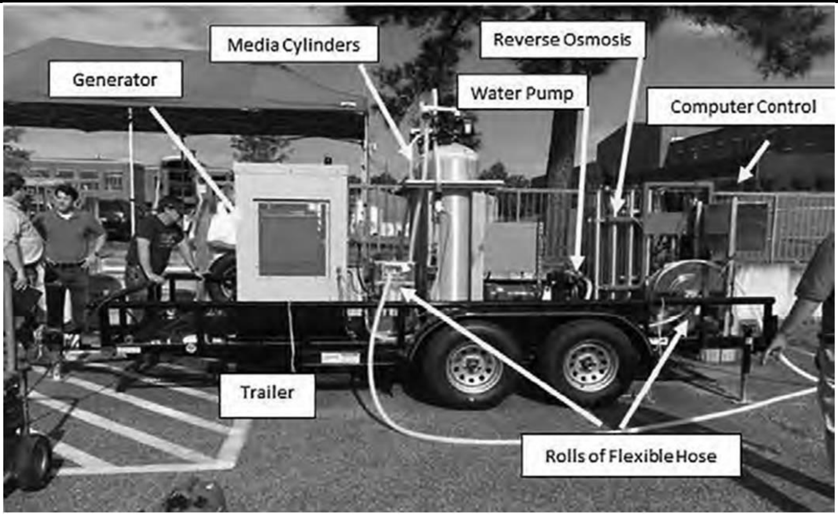
Table 2. Summary of Treatment of Key Constituents by DETS Field Evaluation 表 2. DET 野戰評估關鍵成分的處理結果綜整

Constituent 關鍵成分	Analytical Method 分析方法	Influent Concentration 進水濃度	Effluent Concentration 出水濃度	% Removal 移除率
Turbidity 濁度	USEPA Method 180.1[1]	>4200 NTU	1.825 ± 1.145 mg/L	100.0
Hardness 硬度	Summation of Ca^{2+} and Mg^{2+} concentrations as measured by ion chromatography	82.36 ± 40.79 mg/L	0 mg/L	100.0
Total Chlorine 總活性氯	Standard Method 4500-Cl G[2]	0.26 ± 0.07 mg/L	0 mg/L	100.0
Surfactants 介面活性劑	Spectrophotometric method[3]	1.422 ± 0.359 mg/L	0.019 ± 0.017 mg/L	98.7
Total Organic Carbon 總有機碳	USEPA 9060[4]	58.23 ± 29.7 mg/L	1.18 ± 0.84 mg/L	98.0
Malathion (馬拉松)	Phosphorus balance	26.71 ± 12.16 mg/L	0.08 ± 0.05 mg/L	98.7
Malathion (馬拉松)	USEPA 8141A[5]	24.7 mg/L	0.000097 mg/L	100.0
Cesium (銫)	USEPA 6020A[6]	2.97 ± 4.21 mg/L	0 mg/L	100.0

Legend:
USEPA—U.S. Environmental Protection Agency
Ca^{2+}—calcium ion
Mg^{2+}—magnesium ion
mg/L—milligram per liter
NTU—Nephelometric Turbidity Unit
Cl—classifier

Endnotes:
1. USEPA Method 180.1, Determination of Turbidity by Nephelometry, August 1993.
2. Standard Method 4500-Cl G, DPD Colorimetric Method, 2011.
3. Ralf Kloos, "Measuring 'LAS' Based Surfactants with Hach Barcode Cuvette Testing TNTPlus 874," Application Note, Hach Company, Loveland, Colorado, 2015.
4. U.S. Environmental Protection Agency Method 9060, Total Organic Carbon, November 2004.
5. USEPA Method 180.1. Determination of Turbidity by Nephelometry, August 1993.

6. USEPA Environmental Protection Agency Method 6020A, Inductively Coupled Plasma/MS, 1 January 1998.



A pilot-scale DETS

Figure 1. System Samples

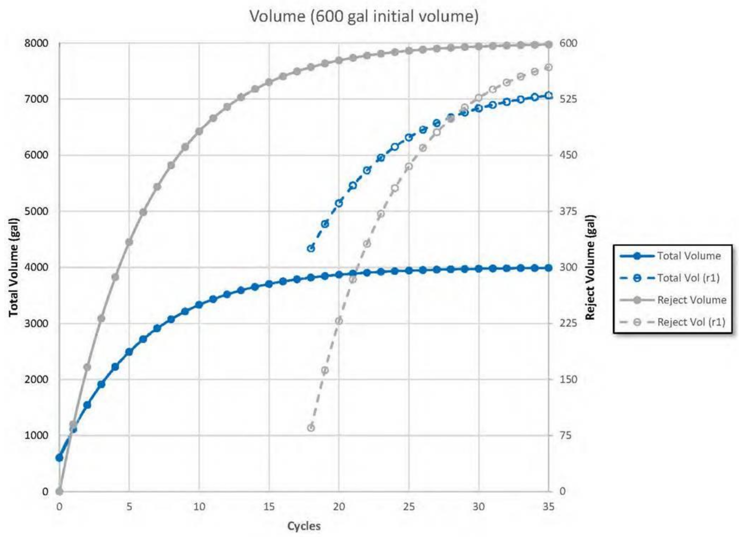


Figure 2. Water Reuse With DETS