

Capacitive Deionization TechnologyTM: An alternative desalination solution

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Received 27 January 2005; accepted 21 February 2005

Abstract

This paper reports on research conducted on Capacitive Deionization Technology (CDT) as an alternative to the more conventional membrane desalination technologies like reverse osmosis and electrodialysis. The main objective of the research was to develop an industrial type module and to evaluate the performance of the module for brackish water desalination. The term “industrially re-producible” refers to the fact that the module manufacturing process must be scaleable, practical and cost effective. Once a successful industrial prototype was developed, a secondary research objective was to test such a module in order to determine if CDTTM could compete as a potential alternative to membrane processes. The following criteria were used to compare the results from the “industrial type” CDTTM bench-scale unit to other membrane processes:

- Feed and product water quality requirements
- Energy consumption per volume water treated
- Pre and post treatment requirements
- Ion storage capacity of electrodes/overall desalination reaction kinetics
- Automatic Control or Operation/Maintenance Requirements
- Fouling and scaling tendencies.

Desalination by CDTTM occurs when a saline solution flows through an unrestricted capacitor type module consisting of numerous pairs of high-surface area (carbon aerogel) electrodes. Carbon aerogel contains a very high specific surface area (400–1100 m²/g BET), and a very low electrical resistivity (<40 mΩ·cm). Anions and cations in solution are electrosorbed by the electric field upon polarization of each electrode pair by a direct current (DC) power source. By using the laboratory scale unit as a model, an industrial type bench scale test unit was developed and tested as part of this research. Earlier laboratory test work indicated that the intrinsic energy required by CDTTM to reduce the TDS of brackish water from 1000 mg/l to 10 mg/l is 0.1 kWh/m³. These estimates assumed that 50–70 % energy recovery could be obtained via the electrical discharge

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*Presented at the Conference on Desalination and the Environment, Santa Margherita, Italy, 22–26 May 2005.
European Desalination Society.*

regeneration phase. Research conducted on the industrial type bench scale unit concluded that it would require 0.594 kWh/m^3 of brackish water (1000 mg/l). By including energy recovery and the optimization of internal electrical connections, future industrial scale units could approach the laboratory scale energy consumptions. It is concluded from test results and an associated cost evaluation that CDTTM could be an alternative desalination technology in the near future for brackish and sea water sources.

Keywords: Capacitive deionization; Desalination; Electrochemical

1. Introduction

Capacitive Deionization TechnologyTM (CDTTM) is a low-pressure non-membrane desalination process, with the potential to be a “power tool” in the desalination toolbox of the future [7]. However at the time when this research was started in 1998, the technology was only at the laboratory scale level. The research objective was to move from laboratory scale to industrial scale by developing and evaluating the first industrial CDTTM prototype.

The motivation for this research came from the continuous global need to improve on existing desalination technologies to facilitate a major step-change in the overall cost of desalinated water to make it viable not only for potable use, but also for industrial and agricultural uses as well [18]. It is important to view the research conducted for this dissertation, against the existing world water crises, which is briefly summarized in the rest of this section.

1.1. *The problem, solution and tools*

The existing global water crises is covered in detail by various authors [11,12,14,15,16,17], where they discuss several aspects of the growing need for water over the next century.

Solutions require both national and international measures be taken, including resolution of water disputes and increased funding for desalination research and alternative technologies. One of the key tools to resolve future international water crises is the

continued research into methods that will provide low-cost desalination. Thereby creating greater economic and political stability in many regions of the world, where scarcity of water could lead to warfare in the same way that oil has lead to wars in the past [15].

Already in 1992, more than 7500 desalination plants operated worldwide, turning 4.8 billion cubic meters of salt water into fresh water annually. Nevertheless, this accounts for only one percent of the world's water use. The reason for desalination's small contribution to the water supply is its cost [14]. Most existing technologies like reverse osmosis and distillation require a great deal of energy. Even nuclear power has proven too expensive for desalination, and is the most expensive water supply option.

Existing advances in membrane technology is gradually reducing the required cost to produce potable water for human consumption. However, membrane technologies are not yet economically viable for the mass desalination of industrial and agricultural markets. These markets utilize $\pm 85\%$ of all water used by humanity [15]. Existing energy consumption levels, as for membrane processes, would need to be dropped drastically before desalination becomes a source for industrial and agricultural water supply [18].

Most of the existing industrial scale desalination facilities get their energy from the combustion of fossil fuels, and thus in effect exchange potable water for CO_2 , which causes global warming and eventually contributes to the demise of fresh water [15]. As a

result, Global warming increases the need even more for additional desalination. Therefore, it is imperative to find more energy efficient methods to desalinate water. Electrochemical desalination tools like Capacitive Deionization Technology™, as the first new desalination technology in over 50 years [7], have the potential to be such an energy efficient desalination method.

2. Objective of research

CDT™ has been identified as a potential mass desalination alternative in laboratory conditions by Lawrence Livermore National Laboratories (Berkeley, USA). The overall objective for this research was to convert a laboratory scale CDT™ system into an industrial system to be used in the “real world”.

Previous laboratory scale test work has been conducted successfully [3,], but in order for the technology to be evaluated as a potential competitor for existing technologies, a more industrialized prototype test unit was needed.

The research objective was to develop and evaluate an “industrially re-producible” CDT™ module by using the initial laboratory scale test work as a starting point.

“Industrially re-producible” in this contents meaning a small-scale model of a future industrial manufacturing process.

3. Scope of research

Due to the relatively young (less than 10 years) nature of this technology, most of the research had to be conducted in the USA, more specifically Tucson, Arizona and San Diego, California (both areas are considered water poor, with ample brackish water). It must further be noted that although various international patents currently exist for the electrochemical desalination of brackish and seawater, the research conducted for this

dissertation focused on Capacitive Deionization Technology™ specifically.

It was further decided to limit the scope for the research, to brackish water applications. The main reasons for this scope selection was that 70% of the world’s available ground water is brackish [15].

4. Theoretical aspects to CDT™

In order to fully explain Capacitive Deionization, it is necessary to review some basic electrochemical principles. The basic electrochemical cell consists of a pair of electrodes, connected externally and immersed in an electrically conducting liquid or paste. The liquid is usually referred to as the electrolyte.

The anode and cathode can be made out of any material, not necessarily only metals. In the case of capacitive deionization, the material is an inert carbon based solid (aerogel or other nanostructure). When two dissimilar metals with different electrochemical potentials are used as the anode and cathode, a current will flow in the external connection, without the need for a power supply (battery or voltaic cell).

4.1. Electrode surface chemistry

When an object is electrically charged in an electrolyte (voltaic or electrolytic cell), an environment is created around the object, which has unique physical features. Such an object can be a solid-state electrode or a colloidal particle. There are interactions between the dissolved ions and the charged surface, the ions and the bulk liquid, and between the bulk liquid and the solid surface. Water is a polar molecule, and is thus also electrochemically involved.

The electrodes in capacitive deionization and other electrodes generally follow the electric double layer theory. This theory states that if an electrode is negatively charged and

immersed in an electrolyte, then positively charged ions and solvent molecules (water in the case of this research) are adsorbed onto the surface, thus forming a layer of positive charge on the surface.

A second negative layer is formed by negative ions attracted to the positive charge, thus the double layer. The second layer contains less charge (negative) as compared to the total charge (positive) of the first layer.

This is due to the effect of distance and shielding by solvent (water) molecules. Water molecules also undergo Brownian movement between the layers [13].

CDTTM utilizes all of the above-mentioned basic electrochemical principles to remove dissolved ions from an electrolyte (water) stream. Fig. 1 illustrates the basic operating principle.

An electrolyte stream flows between two electrodes. The electrodes typically have a potential difference of 1.2 – 1.5 Volts (Direct Current). The various cations (positive charge) and anions (negative charge) in solution are attracted to opposite charged electrodes. The ions are adsorbed on the electrode surface and held in electric double layers (Stern Double Layer Theory). The normal operational cycle continues until the electrode surfaces are saturated with adsorbed ions.

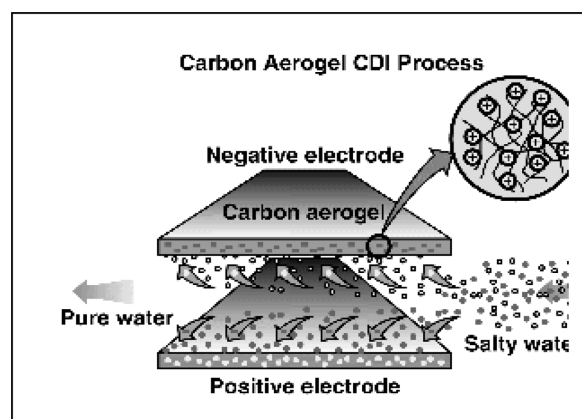


Fig. 1. CDTTM Operating principle.

During the regeneration cycle, the two electrodes are shorted, or to recover stored energy the capacitor can be discharged under controlled conditions. The ions are released into a rinse stream, which can have a much higher TDS level, as compared to the feed stream.

CDTTM does not require high-pressure pumps, which contributes to the overall low energy requirements.

4.2. Carbon aerogel electrodes

Carbon Aerogel is an ideal electrode material because of its low electrical resistivity ($<40 \text{ m}\Omega \text{ cm}$), high specific surface area ($400\text{--}1100 \text{ m}^2/\text{g}$), and controllable pore size distribution ($<50 \text{ nm}$). CDT Systems, Inc are also looking into the use of other nanopore materials as electrodes for selective removal of ions [2].

5. Industrial prototype development process

The main objective of the research was to take Capacitive Deionization TechnologyTM from laboratory scale to a “real world” industrial type bench/pilot scale scenario. The research conducted with regards to the design, manufacturing, and testing of an industrial bench scale prototype, will form the foundation of future industrial scale manufacturing, as well as the design and operational basis for larger pilot and industrial size treatment plants.

The main components of the technology, as identified by the original laboratory research conducted at Lawrence Livermore National Laboratories (Berkeley, California) were used as the basis for the design of the bench scale unit’s manufacturing and operational/control system. The optimized industrial prototype bench scale unit was then used in test runs to compare its performance against membrane processes.

To assist with future design/construction of industrial plants, and to ensure that a single treatment module is of a practical size, the design team decided that the basis for the design of an industrial size unit is to be 1 000 ft² (929 m²) of aerogel/electrode surface area.

Earlier laboratory test work indicated that on average, such an electrode surface area should be able to reduce the TDS of a feed stream by 1000 mg/l at a flow rate of 1000 gallons per day (37,854 liters per day). This basis of design would make future scale-up formulations also more linear. The bench scale unit was designed to be 1/40th (per aerogel surface area) the size of a full-scale industrial unit. Original laboratory experiments were conducted by utilizing extremely thin carbon aerogel films in titanium housings. Fig. 2 illustrates the first laboratory scale capacitive deionization module developed by Lawrence Livermore National Laboratory.

Although these experiments were very successful [3,4,5,6,7,8,9,10], the technology still

needed to be taken to the next level to prove cost effective industrial scale manufacturing and operation in a “real world” environment.

The development of the overall industrial test module consisted of 3 phases:

5.1. Phase 1: electrode development

During this phase, the aerogel electrode pilot manufacturing process was established.

A resorcinol/formaldehyde aerogel manufacturing process was developed.

Electrode quality control: After the manufacturing of the aerogel electrodes, a quality control test was conducted to ensure that the electrodes to be used in the prototype test unit conformed to certain minimum standards. Due to the fact that each cell acts as a capacitor, the total energy stored and discharged from a cell is measurable. The energy storage capacity of an electrode is directly proportional to its ion storage capacity.

A small quality control test unit was constructed whereby each batch of carbon aerogel produced could be quality controlled by using two 25 mm × 25 mm pieces at a fixed distance from each other in a saline solution. Energy to (capacitor charge cycle) and from (capacitor discharge cycle) could be determined by measuring the current (I) to the capacitor and potential difference (V) across the capacitor at fixed time intervals. For the regeneration cycle, the capacitor was discharged through a resistor, and the associated energy calculated by means of the resistor size as well as the measured discharged current. The equations used to determine the energy for the charge and discharge cycles were as follows:

$$E = V \times I = I^2 \times R$$

The aerogel density was also checked as a quality assurance procedure. The average density was 0.78 g/cm³. The aerogel sheets

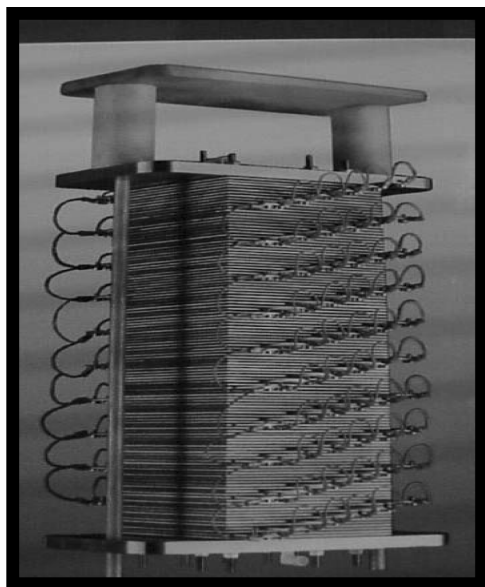


Fig. 2. LLNL laboratory module.

were then cut/trimmed and typically had the following dimensions:

Length	301.24 mm (11.86 inches)
Width	158.75 mm (6.25 inches)
Thickness	0.8128 mm (0.032 inches)

Various numbers of electrodes were tested and the final bench scale unit (MK-8A) contained 24 sheets of electrodes (12 Cathodes + 12 Anodes). This means that the total electrode area inside the unit, accessible to ions (cations and anions), was 2.29 m² (24.7 ft²) or 1/40th of a future full scale industrial unit. The aerogel produced during this research had also the following characteristics:

- BET surface area: >600 m²/g
- Bulk resistivity: 20 m ohm cm
- Specific capacitance: >2 Farad/cm²

5.2. Phase 2: cell/module development

Once the aerogel electrodes manufacturing process has been successfully established, the electrodes needed to be connected as individual cells.

Fig. 3 illustrates the final prototype, with individual cells connected in a durable polypropylene housing.

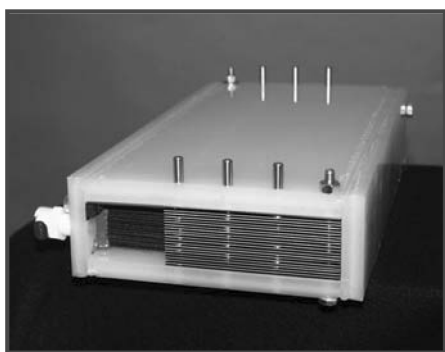


Fig. 3. Section: Bench Scale CDT™ industrial prototype unit.

5.3. Phase 3: control system development

With an industrial bench scale module successfully manufactured, an overall control system was needed to switch between the two main cycles, which is operation and regeneration. During this phase the researcher interpreted water treatment efficiency for an instrumentation and control specialist. Water samples were taken during operational and regeneration cycles, analysis was conducted and the data was used to optimize instrumentation and control specifications.

Once the basic treatment unit was optimized, it was wired to an overall control system and a direct current power supply. Two basic flow paths were used: a once through scenario and a recycle scenario. Fig. 4 illustrates the overall control system set-up used for test runs.

6. Methodology

Fig. 4 illustrates the typical set-up for test work during the module development and technology evaluation phases. Conductivity probes in the inlet and outlet lines were used to measure solution conductivity. A volt and an amp meter were used to measure

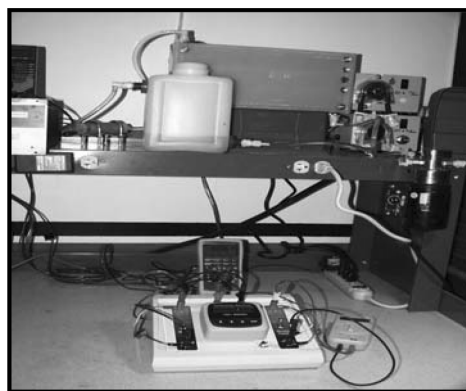


Fig. 4. Bench scale control system.

the electrical data required to determine energy consumption. A control console allowed for rapid change from a production/charge cycle to a regeneration/discharge cycle. Electronic wiring of the control console also allowed for automatic data logging of time, conductivity, bus voltage and current supplied during each test run. Graphical interpretations of typical capacitive deionization test data always have two main cycles, an operational/charge cycle and a regeneration/discharge cycle.

Outlet water stream conductivity is decreased to below the inlet conductivity during the operational cycle, which is a result of ions being adsorbed into the electric-double layer on the electrode surface. The outlet water conductivity increases to above the inlet conductivity during the regeneration cycle, as the adsorbed ions are removed (washed-off) from the electrode surface. Rate of ion adsorption, associated energy consumption, overall water recovery and general operations & maintenance requirements, were used as the fundamental comparative factors in comparing capacitive deionization to other existing desalination technology's.

The following two sections present and discuss the typical test results obtained during the prototype *development* and *evaluation* phases. During the development phase various tests had to be conducted to come-up with an optimum prototype design. Once the development phase results researched set criteria of performance, the optimum prototype was further tested and evaluated in more detail to determine the technologies potential as an industrial desalination technology.

Electrical conductivity probes were used to determine salt content. However for the purpose of comparison the following conversion factor can be used to convert

conductivity to TDS in mg/l. Salt content as a conductivity reading in $\mu\text{S}/\text{cm}$ (microsiemens per centimeter) can be converted to TDS in mg/l by multiplying by 0.7. It must be noted that this factor will differ between source water's, but for most source water's tested during this research project it proved accurate enough.

7. Results: prototype development phase

The main objective of this phase was to develop a prototype, which could be manufactured and operated cost effectively on an industrial scale. Tests on the manufactured aerogel for quality control purposes were already discussed. Results discussed here focus more on the quality control of the overall module development. One of the main challenges during the development phase was to ensure optimum electrical connection between the aerogel electrodes and their associated bus connectors.

Various materials were tested for use in the manufacturing of the bus connectors.

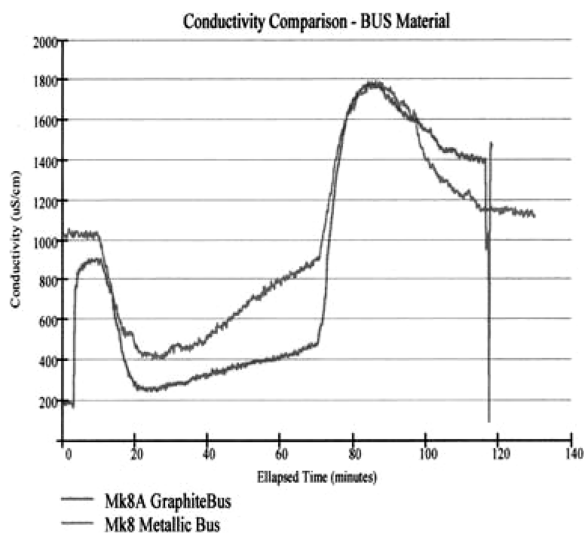


Fig. 5. Effect on ion adsorption by changing bus connection material.

Fig. 5 illustrates the effect of changing the bus connection material from nickel-plated stainless steel (metallic) to graphite. A once-through system set-up conducted test runs for Fig. 5, with conductivity of the output water measured.

Using a MK-8A prototype at a constant flow rate of 50 ml/min generated data presented in Fig. 5. The usage of graphite instead of stainless steel/nickel-plated bus connectors had an improved ion adsorption effect. It is noted that by the time the regeneration cycle was started (around 72.5 minutes), that the MK-8A prototype was not fully saturated as was the case for the metallic bus connector prototype (MK-8).

The next step of comparing bus connector efficiencies was to conduct continuous cyclic tests.

Fig. 6 illustrates the results obtained from repetitive long term testing of two prototype modules, one containing stainless steel nickel plated bus connectors and the other the more efficient graphite connectors. The feed water conductivity was 22 mS/m ($220 \mu\text{S}/\text{cm}$).

The final decision on which prototype design to use in further desalination efficiency testing was made after an ion adsorption test

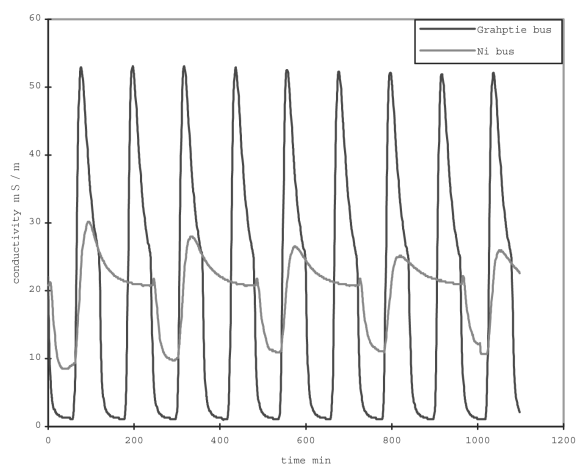


Fig. 6. Repetitive cycle testing for bus connector optimization.

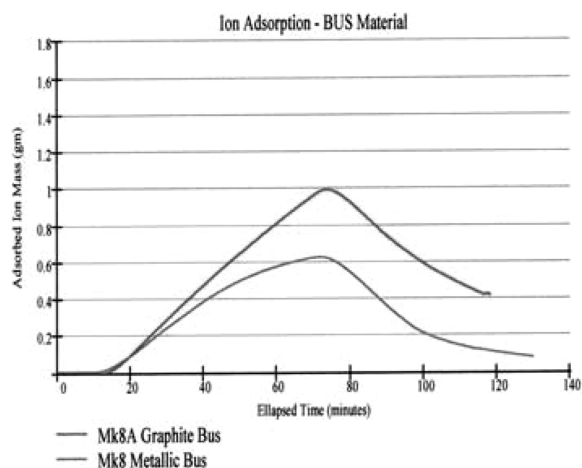


Fig. 7. Ion adsorption efficiency: metallic vs. graphite bus connectors.

run was conducted on the two main prototype alternatives. Fig. 7 represents the cumulative ion adsorption for a single charge/discharge cycle on each prototype alternative. The feed water was a $1\,032 \mu\text{S}/\text{cm}$ NaCl solution at a flow rate of 52.6 ml/min. A potential difference of 1.3 V was used on both alternatives. The MK-8A (graphite bus connectors) prototype adsorbed around 1.6 times more ions at the same energy consumption, as compared to the metallic bus connector prototype.

Power Use

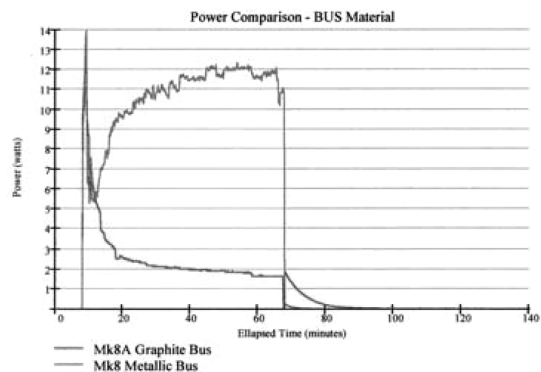


Fig. 8. Energy requirements: Metallic vs. graphite bus connectors.

7.1. Energy requirement

Fig. 8 illustrates a comparative power use/energy requirement test run. The energy/power was calculated by multiplying voltage and current data. Flow was constant at 52,6 ml/min and the feed conductivity was 1032 $\mu\text{S}/\text{cm}$. In this test run the MK-8 (metallic bus connector) prototype developed an increased current draw at approximately 12 minutes, this was not due to a direct short as the module voltage was maintained at 1.3 Volts by the power supply.

The energy requirement graph of the MK-8A prototype (red line) would be typical of a CDTTM industrial module, due to the capacitive behavior of a module. As the capacitors charge up, less and less current is allowed to flow through the capacitors, resulting in the typical exponential decrease of the required energy. Saturation of the electrode surfaces is directly proportional to the overall “charged state” of the various capacitors making-up a CDTTM module. Therefore a fully charged CDTTM module indicates a saturated electrode condition and vice versa.

8. Results: prototype desalination testing phase

This section discusses the results obtained from the following two final overall testing phases:

- General prototype performance testing, and
- Brackish water: application specific testing

8.1. General testing

In order to realistically evaluate capacitive deionization as a potential alternative to existing industrial scale desalination technologies, two main parameters need to be investigated (1) ion adsorption per electrode surface area (percentage water recovery), and (2) energy required to facilitate adsorption. With regard to electrical energy, the

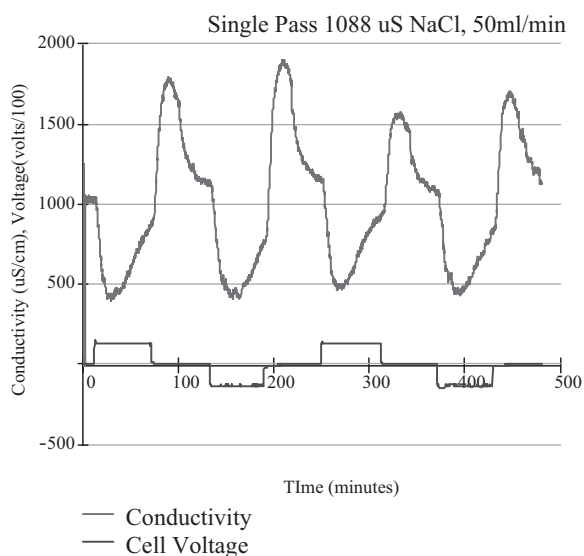


Fig. 9. Typical continuous CDTTM desalination evaluation test run.

typical operational mode of a CDTTM plant would be to switch between charging the cells (ion adsorption) and discharging the cells (ion removal). Fig. 9 illustrates a typical continuous/cyclic once through test run used during this phase of testing, which would also be the typical continuous scenario for a module as part of an industrial size application.

Fig. 9 further illustrates the typical graphical interpretation of time, outlet conductivity and bus voltage/supply current data collected at each test run in this phase.

The feed NaCl solution conductivity for this specific test run was 1088 $\mu\text{S}/\text{cm}$ through a MK-8A prototype module. The blue trace shows the applied voltage as it was switched from +1.3 V to 0 V to −1.3 V. Switching the polarity after each cycle, assists with the regeneration phase.

During the production cycle, with a direct current voltage applied to the module, ions are removed from the water passing through the system; conductivity is reduced below the input level. Conductivity drops for about the

Table 1
Pre-and post treatment results on diluted artificial seawater

		Feed water	Product water	Reduction %
Cation	Sodium as mg/l Na^+	180	39	78.33%
	Magnesium as mg/l Mg^{2+}	20	3.9	80.50%
	Calcium as mg/l Ca^{2+}	4.7	1.1	76.60%
	Potassium as mg/l K^+	16	2.6	83.75%
	Zinc as mg/l Zn^+	0.17	0.14	17.65%
	Boron as mg/l B^+	0.09	0.06	33.33%
Anion	Chlorine as ma/l Cl^-	260	58	77.69%
	Sulfate as mg/l So_4^{2-}	40	9	77.50%
	Bromine as mg/l Br^-	0.36	0.05	86.11%
	Carbonic acid HCO_3^-	120	72	40.00%

first $\frac{1}{4}$ of the production cycle, then increase to again to close to the starting value.

8.2. Application specific testing

Table 1 summarizes the pre- and post treatment results on diluted artificial seawater (sea water intrusion scenario). A MK-8A capacitive deionization prototype module was used to generate data for Table 1. A feed stream of diluted artificially generated seawater at $1000 \mu\text{S}/\text{cm}$ was treated to produce a product stream of $23.4 \mu\text{S}/\text{cm}$ at a flow rate of 50 ml/min.

High ionic specie reduction as shown in Table 1 on artificially prepared brackish water was a good start, however in order to evaluate capacitive deionization in a “real world” scenario, testing on naturally occurring brackish water was needed. Therefore testing on naturally occurring brackish water follows next

In the natural gas industry, a lot of brackish water is generated during well drilling. The brackish type water generated by drilling is called “produced water”.

The first naturally occurring brackish water tested on a CDTTM industrial prototype was samples from the natural gas industry in Wyoming, USA. In these brackish water bicarbonates ($<1900 \text{ mg/l}$) are the main

contaminant. The same test methodology was used as for the laboratory-generated solutions.

During the production cycle a 1.3 Volt potential difference was generated via direct current. During the regeneration cycle the electrodes were grounded. Fig. 10 illustrates the desalination of coal bed methane (CBME) produced water.

During the period from 360 to roughly 390 minutes, the module was filling, so there was no output from the conductivity probe located on

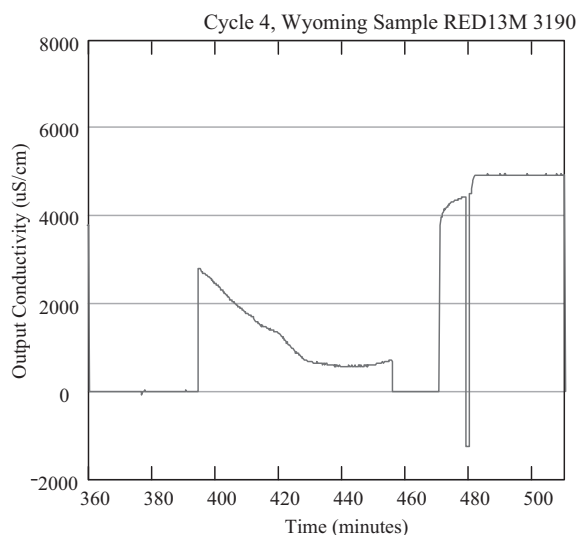


Fig. 10. Desalination of CBME produced water.

the water output line. The input water conductivity was 2095 $\mu\text{S}/\text{cm}$ at 20.5°C. The output conductivity at the start of the cycle was above the input value due to residual rinse water being pushed out the system.

The rinse began at roughly 470 minutes, the zero conductivity occurs during the fill time and is 1/3 the time of the production fill since the rinse flow rate was 3 times the production flow rate. Rinse conductivity saturated at 5000 $\mu\text{S}/\text{cm}$ since this was the maximum range set on the meter. It was increased for subsequent runs.

For this test run the water recovery rate was around 70% and rinse water could be re-used for at least another rinse cycle, before discarding as brine. Reducing the volume of the brine has a major cost benefit in this industry, as it needs to be trucked and pumped underground at specific brine aquifer injection points.

Voltage and current data was used to determine that it would take an estimated 2,25 kWh to treat 1000 gallons (3785 liters) of the produced brackish water to below reinsertion/reuse limits (<1000 mg/l).

This result is significantly higher than the 0.36 kWh per 1000 gallons (3785 liters) predicted by earlier research work from LLNL, however by including energy recovery and improved electrical connection, future industrial modules could approach the laboratory benchmark.

9. Cost: evaluation and comparison

At the time of this research, technology license agreements limited manufacturing to the USA and as the majority of research for this dissertation was conducted in the USA, the currency used in this cost evaluation chapter is the US Dollar.

In order to compare “apples-with-apples” a reference design will be used to compare the

Table 2
Reference design parameters

Parameter	Value
Water supply source	Groundwater
Source water TDS, mg/l	2000
Required produced water TDS, mg/l	500
Finished water quantity, mgd (Ml/d)	1.0 (3785)
Brine concentrate disposal	Surface water body
Intake type	Well feed pump

Data source: AWWA M46: p 93.

costs (capital and operational) of a 1 mgd (3.78 Ml/d) low-pressure brackish groundwater RO desalination facility to a 1 mgd (3.78 Ml/d) CDTTM brackish water facility treating a brackish feed water (TDS: 2000 mg/l) to potable standards. Table 2 summarizes the reference design conditions.

10. Low pressure RO plant description

- Well feed Pump
- Pump to increase pressure to 1 965 kPa (285 psig)
- Cartridge Filters
- 3-Stage RO Membranes
- Degasifier
- Disinfection system
- Storage
- Pump to Distribution System
- CDTTM PLANT DISCRIPTION
- Well Feed Pump @ 413 kPa (60 psig)
- Cartridge Filters
- 3 Parallel CDT Module Trains
- Disinfection
- Storage
- Pump to Distribution System

Table 3 lists the estimated costs associated with the RO reference design.

Table 4 lists the estimated costs associated with the CDTTM plant.

Table 3
Estimated RO costs for reference design

Item	Value
Feed salinity content, TDS in mg/l	2000
Flow rate in mgd (Ml/d)	1 (3785)
Capital/construction costs ^a (Direct and Indirect Costs)	\$3,139,000
Annual Energy + O & M ^b	\$296,535
15-year capital amortization + 10% residual	\$188,340
Total annual costs	\$484,875
Cost per 1000 gallons	\$1.33
Cost per 1000 liters	\$0.35

^asee AWWA, M46: p94 for a detailed breakdown of construction costs.

^bEnergy @ 3.83 kWh/1000 gal (AWWA, M46: p 98) typically is 33% of a RO facility's O & M costs (AWWA, M46: p 5). No blending.

Table 4
Estimated CDTTM Costs for the reference design

Item	Value
Feed salinity content, TDS in mg/l	2000
Flow rate in mgd (Ml/d)	1 (3785)
Number of CDT modules	1500
Capital Cost (modules + 30%) ^a (Direct and Indirect Costs)	\$1 560 000
Annual Energy + O & M ²	\$52 500
15-Year capital amortization	\$93 600
Total annual costs	\$146 100
Cost per 1000 gallons	\$0.40
Cost per 1000 liters	\$0.11

^aData Source: CDT Systems, Inc 2004.

Table 5
Comparative Cost per 1000 gallons for a 1 mgd Brackish water treatment facility^a

CDT			RO		
Capital	O & M	Total	Capital	O & M	Total
\$0.26	\$0.14	\$0.40	\$0.52	\$0.81	\$1.33
\$0.40/1000 gal or \$0.11/1000 liters			\$1.33/100 gal or \$0.35/1000 liters		

^aData Source: CDT Systems, Inc for CDT data.
(AWWA M46, 1999) for RO data.

Table 5 summarizes the above-mentioned cost for the two alternative technologies.

Due to the low energy requirements, CDTTM could be very cost effective as compared to reverse osmosis for brackish water (<1000 mg/l) applications. However, reverse osmosis would be more cost effective for the higher salinity waters. Only by reducing the capital costs for the production of CDTTM modules, would capacitive deionization become a serious competitor for reverse osmosis in higher salinity brackish or seawater applications.

EDR is another competitive brackish water desalination technology. Without energy recovery test work on an industrial type CDTTM module indicated an energy requirement of 2.25 kWh/1000 gallons and EDR utilizes 7.7 kWh/1000 gallons (AWWA M46, 1999) for typical brackish water conditions. It is thus possible for future CDTTM plants to cut the costs to produce desalinated brackish water by 70%, as compared to existing EDR data.

11. Conclusions

The following conclusions can be made regarding the research conducted:

- Aerogel Manufacturing

It is possible to cost effectively manufacture the carbon aerogel electrodes on a large/ industrial scale, by designing and

constructing a small model of a potential future manufacturing facility. To summarize, carbon aerogels are manufactured by polycondensation of resorcinol and formaldehyde in a slightly basic medium, followed by supercritical drying and pyrolysis in an inert atmosphere. The impregnation of carbon cloth with the resorcinol-formaldehyde resin generates monolithic sheets. These monolithic sheets can easily be trimmed to produce the electrode sheets used in module assembly. Future carbon aerogels will be even more human and environmental friendly as material sciences advance.

- Simple construction of industrial modules.

CDTTM only requires simple double-sided planar electrodes, which can be stacked in a low-pressure housing (Plate-and-frame type module).

- Enhanced energy efficiency for treatment of brackish water.

CDTTM can be used to treat brackish water (800–10,000 mg/l). The desalination of brackish source water is becoming increasingly more important. Competing technologies for this application are electrodialysis 2.03 Wh/liter (7.7 Wh/gal) and reverse osmosis 2.25 Wh/liter (8.5 Wh/gal). CDT is more energy efficient at 0.13–0.59 Wh/liter (0.5–2.25 Wh/gal) depending on energy recovery and operation.

- Elimination of wastes from chemical regeneration.

CDTTM uses electrical regeneration, thereby eliminating the need for handling secondary chemical wastes streams. A highly concentrated brine stream is the only waste stream produced.

- Carbon Aerogel is resistant to chemical attack.

Aerogels are resistant to aggressive chemicals like HCl and resistant to oxidizing agents, should de-scaling or de-fouling be required in CDTTM desalination facilities.

- Industrial treatment plants would be fully automated.

The capacitive deionization process is fully automatic. A typical industrial size plant would require a minimum of two treatment trains for continuous operation. While the one train produces desalinated water, the other would be regenerating. Energy captured from the regenerating train could be supplied to the train in production mode.

- Potential to reduce treatment plant disposal costs.

Old membrane modules have no recycle value and thus present a disposal problem. CDTTM has the potential to reduce the overall disposal costs to a treatment plant, as the carbon aerogel electrode lifetime is conservatively estimated in excess of 10 years by LLNL.

In summary, simple design requirements and low energy costs could make CDTTM very competitive to existing membrane technologies such as reverse osmosis and electrodialysis for brackish water applications in the immediate future.

To be competitive for seawater applications, the production costs per capacitive deionization module needs to be reduced before the technology can cost effectively compete with reverse osmosis on such applications.

CDTTM is a young, but very promising technology for the desalination of brackish and potentially seawater sources.

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