

## Electrodialysis reversal (EDR) and ion exchange as polishing treatment for perchlorate treatment

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### Abstract

Due to the development of a new analytical method that lowered the perchlorate detection limit to 4 µg/L, perchlorate has been detected in many drinking water sources. Perchlorate contamination is now recognized as a widespread concern affecting many water utilities. Furthermore, perchlorate is a very stable substance in aquatic systems and is therefore difficult to remove with conventional treatment processes. Magna Water Company in Utah, USA, provides chlorinated groundwater as potable water to the northwest section of Salt Lake County. The groundwater of one of their wells is contaminated with low levels of perchlorate and concentrations are expected to rise due to plume migration. High hardness, alkalinity, and TDS characterize this groundwater. An electrodialysis reversal (EDR) pilot unit was installed at an uncontaminated well. Various perchlorate levels were spiked into the feed water to test the full range of possible perchlorate concentrations. This paper provides EDR performance and cost data for perchlorate treatment. Based on perchlorate removal, the production cost varies between \$1.10 and \$1.50 per 1000 gal (\$0.30 and \$0.40/m<sup>3</sup>). The presented data allow comparison with other treatment processes.

*Keywords:* Electrodialysis; Ion exchange; Perchlorate

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### 1. Introduction

A new analytical method developed by the California Department of Health Services (CDHS) in April 1997 decreased the perchlorate detection limit from 400 µg/L to 4 µg/L [1] resulting in perchlorate detection in many drinking water sources. Recent detection of

perchlorate and lack of treatment information is a cause of concern for many water utilities. Based on existing health effects data, California has established an action level of 18 µg/L for perchlorate [2]. Regulatory levels in other states and the US Environmental Protection Agency (USEPA) have not been established. However, perchlorate is listed for USEPA regulatory review.

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The Magna Water Company provides potable water to the northwest sections of Salt Lake County. The groundwater in one of their well fields has shown detectable levels of perchlorate, and concentrations are expected to rise due to contaminant plume migration. Due to current cost and potential future cost escalation of purchased water, as well as the general need to protect and utilize available water resources, it is desirable to maintain use of these well fields.

Currently available treatment options for perchlorate are discussed in light of Magna source water quality and treatment requirements. Preliminary results of pilot testing of the most prominent candidate process, electro dialysis reversal (EDR), and cost estimates for a range of source water perchlorate concentrations and finished water quality goals are presented.

Table 1  
Comparison of potential perchlorate treatment processes

| Process   | Advantage   | Limitations   |
|---|---|---|
| Chemical reduction, with bisulfite or reduced common metals   |   | <ul style="list-style-type: none"> <li>• Too slow for <i>ex situ</i> treatment</li> </ul>   |
| Electrochemical reduction:<br>reduction of perchlorate occurs at anode  | <ul style="list-style-type: none"> <li>• Well understood</li> <li>• No toxic by-products</li> </ul>   | <ul style="list-style-type: none"> <li>• High capital and O&amp;M costs</li> <li>• Electrolysis of water</li> <li>• Safety</li> <li>• Not proven for drinking water applications</li> </ul>                               |
| Biochemical reduction:<br>enzymes from perchlorate-reducing bacteria purified and used as heterogeneous or homogeneous catalyst | <ul style="list-style-type: none"> <li>• Fast reaction</li> <li>• High efficiency</li> </ul>  | <ul style="list-style-type: none"> <li>• Enzyme identification, production and extraction are expensive</li> <li>• Difficult implementation</li> <li>• Not commercially available</li> <li>• Not proven</li> </ul>        |
| Biological reduction:<br>similar to biological denitrification  | <ul style="list-style-type: none"> <li>• Fast reaction</li> <li>• Possible to achieve in existing biofilters</li> </ul>   | <ul style="list-style-type: none"> <li>• Regulatory/public acceptance</li> <li>• Process stability</li> <li>• Unproven for drinking water applications</li> <li>• High capital and O&amp;M costs (potentially)</li> </ul> |
| Ion exchange:<br>Similar to nitrate removal   | <ul style="list-style-type: none"> <li>• Reasonable cost (in general)</li> <li>• Easy implementation</li> </ul>   | <ul style="list-style-type: none"> <li>• Waste disposal</li> <li>• Resin life</li> <li>• TDS (in particular sulfate) competition limits applicability at Magna</li> </ul>   |
| Membranes:<br>RO/NF/EDR   | <ul style="list-style-type: none"> <li>• High removal efficiency</li> <li>• Low cost</li> <li>• Easy implementation</li> <li>• Promising preliminary results</li> </ul> | <ul style="list-style-type: none"> <li>• Waste disposal</li> <li>• Elevated silica limits RO/NF applicability at Magna</li> </ul>   |

## 2. Background

At conditions typical of drinking water treatment, perchlorate exists as a monovalent anion ( $\text{ClO}_4^-$ ). It exhibits limited sorption and negligible volatilization potential [3]. Chemically similar to nitrate, treatment alternatives for perchlorate are also similar. Table 1 summarizes perchlorate treatment options and associated issues in general and with regards to Magna.

Kinetic constraints limit the effective application of chemical reduction, and current commercially available alternatives include:

- biological reduction through processes similar to denitrification
- ion exchange using nitrate-specific resin
- membrane desalting technologies, i.e., reverse osmosis (RO), nanofiltration (NF), and EDR

Biological reduction, while effective and appropriate for wastewater applications, has several drawbacks for drinking water treatment. First, the process requires that a carbon source be added to the water, potentially leading to elevated microbial substrate availability or other impairment of the finished water quality. Second, operating a biological process in a drinking water application poses potential problems from a public acceptance perspective. In addition, biological reduction of perchlorate occurs under anoxic conditions and production of sulfides and other reduced compounds could be problematic. Finally, in general, biological reduction tends to be less stable and lacks the reliability of physical/chemical processes.

Ion exchange can be quite effective for perchlorate removal. However, Magna well water has elevated concentrations of total dissolved solids (TDS) (approximately 1300 mg/L) limiting the feasibility of direct application of ion exchange at Magna. Membrane desalting technologies offer reliable treatment of perchlorate-contaminated drinking water. In general, RO/NF would be cost competitive with EDR. However, with silica concentrations of approxi-

mately 80 mg/L, recovery would be unacceptably low (on the order of 50%). However, silica is not concentrated by EDR, and silica levels have no impact on EDR recovery. While perchlorate removal by EDR would be expected to correspond to other anions with similar charge density (e.g., nitrate), no data were available when this study was initiated.

In light of the above discussion, the specific objectives of this study were to:

- perform a characterization of water quality at Magna to confirm treatment process selections
- determine rejection characteristics of perchlorate by EDR
- develop conceptual designs and cost estimates for a range of EDR staging and implementation options
- evaluate feasibility and cost implications for ion exchange

## 3. Approach

EDR pilot testing was conducted to evaluate perchlorate removal and confirm design criteria for EDR treatment of the Magna groundwater. Fig. 1 shows a process flow diagram of the pilot system.

The EDR pilot unit was an Ionics Aquamite III, generally characterized by the following attributes:

- 7.4 gpm production capacity operating at 70% recovery;
- two electrical stages and four hydraulic stages with Mark IV spacers;
- contained in 20' long by 8' wide by 10' high standard shipping container;
- container including a feedwater tank, feedwater pump, multimedia filter, 10-micron cartridge filter, chemical feed systems, and a product water tank.

Feed water for the pilot system was taken from an uncontaminated production well.

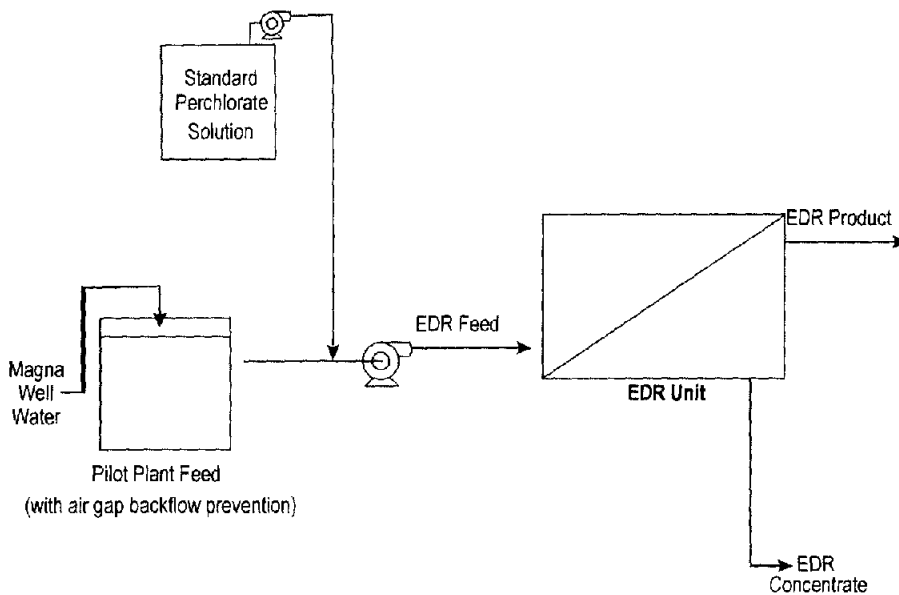


Fig. 1. EDR pilot study process flow diagram.

Table 2  
Experimental conditions for EDR piloting

| Duration (weeks) | Operating conditions  | Objectives   |
|------------------|---|--|
| 1                | <ul style="list-style-type: none"> <li>Set-up EDR</li> <li>Performed preliminary runs</li> <li>Ran during day for only 4 days</li> <li>Continuous operation began June 7, 1999</li> </ul> | <ul style="list-style-type: none"> <li>Start-up system</li> <li>Verified proper performance of system components</li> <li>Performed operation, maintenance, and sampling training</li> </ul> |
| 5                | <ul style="list-style-type: none"> <li>Dosed perchlorate to achieve 130 <math>\mu\text{g}/\text{L}</math> in EDR feed</li> </ul>  | <ul style="list-style-type: none"> <li>Obtained baseline perchlorate removal data</li> <li>Collected data for ion-exchange evaluations</li> </ul>  |
| 4                | <ul style="list-style-type: none"> <li>Dosed perchlorate to achieve 60 <math>\mu\text{g}/\text{L}</math> in EDR feed</li> </ul>   | <ul style="list-style-type: none"> <li>Monitored for concentration dependent perchlorate removal rate</li> </ul>   |
| 3                | <ul style="list-style-type: none"> <li>Dosed perchlorate to achieve 15 <math>\mu\text{g}/\text{L}</math> in EDR feed</li> </ul>   | <ul style="list-style-type: none"> <li>Quantified perchlorate removal after extended period of operation</li> <li>Evaluated low level removal performance</li> </ul>                         |
| 2                | <ul style="list-style-type: none"> <li>Discontinued perchlorate dosing</li> </ul>   | <ul style="list-style-type: none"> <li>Monitored for perchlorate release from EDR membranes</li> </ul>   |
| 1                | <ul style="list-style-type: none"> <li>Demobilization</li> </ul>  | <ul style="list-style-type: none"> <li>Collected membrane samples for analysis</li> <li>Prepared unit for return shipment</li> </ul>   |

Perchlorate was added using an ammonium perchlorate stock solution, and testing was conducted at various feed concentrations as indicated in Table 2.

Daily monitoring included the following parameters: pH, conductivity, temperature, pressure, flow rate, voltage and current. Samples of feed, product, and brine were collected weekly and analyzed for TDS, chlorine, sulfate, and perchlorate. The EDR process model was verified using pilot data and used to evaluate a range of full-scale conditions. Ion-exchange treatment was considered using the Calgon ISEP ion-exchange process model.

**4. Results**

Table 3 summarizes raw water quality parameters. The groundwater quality at Magna is quite stable and variability in feed water characteristics was minimal during testing.

Figs. 2–4 show perchlorate, chloride, sulfate, and TDS removal efficiency when perchlorate was dosed at 130, 60, and 15 µg/L, respectively. TDS, sulfate, and chloride exhibited relatively constant removal efficiency over the entire study period. Perchlorate removals decreased from

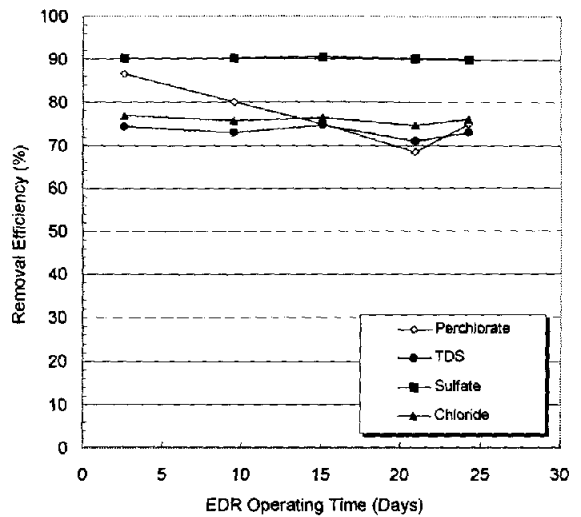


Fig. 2. Removal efficiency of perchlorate and other ions (dosing 130 µg/L perchlorate).

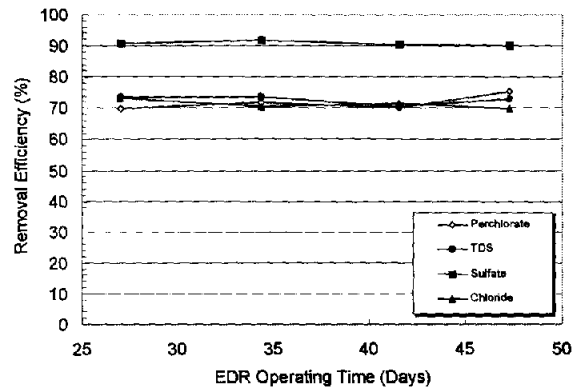


Fig. 3. Removal efficiency of perchlorate and other ions (dosing 60 µg/L perchlorate).

Table 3  
Typical well water quality

| Parameter                                   | Value |
|---|-------|
| TOC, mg/L                                   | 1.10  |
| UV 254, cm <sup>-1</sup>                    | 0.020 |
| pH  | 7.7   |
| Temperature, °C                             | 16.   |
| Turbidity, NTU                              | 0.12  |
| Total alkalinity, mg/L as CaCO <sub>3</sub> | 390   |
| Hardness, mg/L as CaCO <sub>3</sub>         | 520   |
| Manganese, mg/L                             | 0.066 |
| Iron, mg/L                                  | 0.069 |
| TDS, mg/L                                   | 1300  |

87%, initially, to percent removals in the low 70s (Figs. 2 and 3). Perchlorate removals appeared to stabilize in this range for the following 3 weeks of operating time. The decrease in perchlorate dosing level from 130 µg/L to 60 µg/L did not impact percent removals (Fig. 3). However, perchlorate removals dropped to about 60% before returning to the low- to-mid-70s, following the decrease in dosing level from 60 µg/L to 15 µg/L (Fig. 4). Moreover, brine concentrations

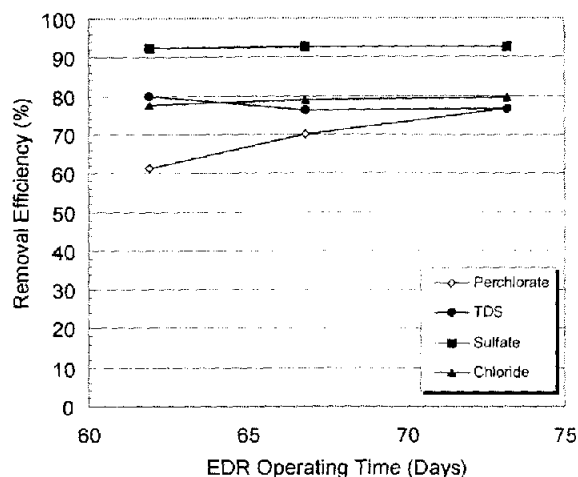


Fig. 4. Removal efficiency of perchlorate and other ions (dosing 15  $\mu\text{g/L}$  perchlorate).

were higher than expected for a 2–3-week period following this change (data not shown).

The membranes in the EDR stack were constructed from ion-exchange resin material. Perchlorate has a reasonably high affinity for certain ion-exchange resins. Therefore, the higher perchlorate removal efficiency at the start of the study (Fig. 2) may have been because removals occurred by two mechanisms: ion exchange and EDR operation. As the ion-exchange capacity of the membranes became exhausted, removals decreased to that which could be achieved solely by EDR operation. The observed decrease in performance following the change from dosing 60  $\mu\text{g/L}$  to 15  $\mu\text{g/L}$  was likely caused by the desorption of perchlorate from the EDR membranes as a new equilibrium was established at the lower perchlorate concentrations. The drop from 130  $\mu\text{g/L}$  to 60  $\mu\text{g/L}$  was apparently insufficient to cause observable changes in the perchlorate removal efficiency. The phenomena of sorption and desorption of perchlorate are expected to be more important in the brine stream due to the greater concentrations of anions which compete for ion exchange sites. Therefore, these phenomena are not expected to

Table 4  
Removal efficiency for various edr system configurations

|             | Removal efficiency, % |         |         |
|-------------|-----------------------|---------|---------|
|             | 2-stage               | 3-stage | 4-stage |
| Perchlorate | 71                    | 88      | 94      |
| Sulfate     | 84                    | 93      | 97      |
| Chloride    | 81                    | 91      | 96      |
| TDS         | 75                    | 88      | 94      |

Table 5  
EDR facility cost estimates

| Cost                | 2-stage   | 3-stage   | 4-stage    |
|---------------------|-----------|-----------|------------|
| EDR equipment, \$   | 3,591,000 | 4,481,000 | 6,190,000  |
| Capital, \$         | 7,850,000 | 9,175,000 | 11,765,000 |
| Annual O&M, \$/y    | 658,000   | 590,000   | 682,000    |
| Production, \$/kgal | 1.16      | 1.20      | 1.41       |

be of concern for product water concentrations, unless influent perchlorate concentrations are highly variable with rapid changes in feed concentrations.

A process model was used to extend these pilot-scale results to evaluate several full-scale configurations. Table 4 summarizes removal efficiencies for perchlorate and other anions for systems comprised of two to four stages. Table 5 lists equipment, construction, annual operation and maintenance, and overall production cost estimates for each system configuration using a design feed flow rate of 5 mgd and average production flow rates of 3.45 mgd for two stages, 3.0 mgd for three stages, 2.8 mgd for four stages.

Ion-exchange system design criteria and construction costs tend to be relatively insensitive to the feed water perchlorate concentration and

Table 6  
Ion-exchange polishing cost estimates

| Pretreatment                           | 2-stage EDR | 3-stage EDR | 4-stage EDR |
|--|-------------|-------------|-------------|
| Ion-exchange equipment, \$             | 3,000,000   | 3,000,000   | 3,000,000   |
| Ion-exchange capital <sup>a</sup> , \$ | 4,600,000   | 4,600,000   | 4,600,000   |
| Ion-exchange annual O&M, \$/y          | 390,000     | 300,000     | 240,000     |
| Ion-exchange production, \$/kgal       | 0.81        | 0.71        | 0.62        |
| EDR production, \$/kgal                | 1.16        | 1.20        | 1.41        |
| Total production, \$/kgal              | 1.97        | 1.91        | 2.03        |

<sup>a</sup>Note that the capital cost for ion-exchange polishing excludes equipment and facilities included in the EDR facility. Capital cost for a stand-alone ion exchange facility would be greater than a polishing application.

the finished water perchlorate goal when used as a polishing system. For a 5mgd system to be added after at least two stages of EDR, equipment cost is approximately \$3,000,000 and the total capital cost is \$4,600,000. As background ionic strength increases, regeneration requirements and operational costs increase. Table 6 lists ion-exchange system and production costs for a range of EDR staging conditions.

## 5. Conclusions

Results of pilot testing indicate that, for the water quality observed at Magna, EDR provides effective removal of perchlorate and the removal efficiency of perchlorate is similar to that of chloride. Some sorption of perchlorate to the EDR ion-exchange membranes appeared to occur although this effected brine perchlorate concentrations to a much greater extent than the product water.

Unless very high perchlorate removal is required, additional stages of EDR provide a more cost-effective alternative than ion-exchange polishing. Should ion-exchange polishing be required, three-stage EDR appears to provide the optimal pretreatment based on economic considerations.

## References

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