BIOLOGICAL FILTRATION FOR IRON AND MANGANESE REMOVAL: SOME CASE STUDIES

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In an earlier paper\textsuperscript{1}, the author reviewed the physical-chemical processes conventionally used to remove iron and manganese from groundwater and explained how the process most commonly used in France (aeration + filtration) led to the discovery of coincident biological phenomena. These were subsequently applied to enhance the performance of certain existing units and, especially, to serve as a basis for a new generation of biological treatment plants offering sharply improved performance levels.

These general considerations will be illustrated by a number of examples, selected among nearly two hundred existing facilities.

REVIEW OF BASIC PRINCIPLES AND THE MERITS OF THESE BIOLOGICAL PROCESSES

The principle of biological iron and manganese removal can be easily explained with reference to the stability diagram [Eh - pH]: to oxidize iron and manganese prior to filtration when they are present in the reduced, soluble stage (Fe\textsuperscript{2+} and Mn\textsuperscript{2+}) in groundwater deprived of dissolved oxygen, the conventional treatment by physical-chemical process, for reasons related to the reaction kinetics, demands conditions of intensive oxidation. These give the water an Eh value much higher than that which differentiates the respective stability fields of the reduced and oxidized forms. In practice, these physical-chemical treatments require intensive aeration at pH > 7.2 to remove the iron, along with the use of a potent oxidant (O\textsubscript{3}, KMnO\textsubscript{4}, ClO\textsubscript{2}) to remove manganese. Furthermore, they are relatively costly and are often plagued with serious operating problems\textsuperscript{1}.

It was subsequently discovered that under conditions of limited oxidation creating conditions at the boundary between the reduced (dissolved) and oxidized (precipitated) forms of iron and manganese (see Fig. 1), specific bacteria would develop and catalyze the oxidation reaction of these two metals, thanks to the secretion of extracellular enzymes or polymers. At the same time, the precipitates that formed were more compact and consequently, less clogging. A new concept for iron and/or manganese removal from groundwater emerged from these observations, based on biological treatments offering sharply enhanced performance. However, in order to implement these processes, certain constraints must be taken into account:

- The plant must be designed with two-stage filtration in the event of simultaneous presence of iron and manganese. Indeed, Fig. 1 shows that the fields of biological iron and manganese removal are completely separate from one another. There can be some exceptions to this rule, as will be developed below.

- The treatment line must be adapted or changed if other unfavorable parameters prevail (such as H\textsubscript{2}S, NH\textsubscript{4}\textsuperscript{+}, dissolved color, certain heavy metals like zinc, etc.).

- Sufficient natural seeding by autochthonous bacteria must be allowed to occur when the unit is started up. This requires a few days for biological iron removal, and several weeks for biological manganese removal.
Thus, these microorganisms, formerly considered only as a source of problems (clogging wells, causing corrosion, deteriorating water supply quality) have now been "domesticated." Their use in biological iron and manganese removal plants has revealed the many advantages of biological processes over conventional processes for the upgrade of existing units or the design of new projects.

\[ \text{EH (mV/H}_2\text{)} \]

![Graph showing the relationship between EH (mV/H2) and pH, with points labeled MnO2, Mn2+, Mn2O3, Fe(OH)3, Fe2+, and numbers 1 and 2 indicating specific points.]

Fig. 1: Comparative requirements of iron and manganese bacteria
1. Field of biological iron removal
2. Field of biological manganese removal

UPGRADE OF EXISTING PLANTS

In several existing plants, physical-chemical units have been converted to biological treatment through the implementation of one or more of the following measures: modification of pH; change in aeration conditions; elimination of a powerful oxidant or more generally, any reagents added at the head of the treatment line; postponement of chlorination until the end of the treatment line; change in the filter media and/or the nozzles. These simple modifications, when performed under appropriate conditions, have always produced spectacular improvement in treatment efficiency in terms of product water quality, operating costs (longer filter runs, decreased labor requirement, savings on backwash water, partial or total reduction in the use of costly reagents), or both. Operating costs can be cut by as much as 50 to 80 percent.
Two examples of such conversions are shown in Table 1. For both upgrades, the objective was to improve product water quality and reduce operating costs. In other applications, the use of biological processes has allowed substantial increases in capacity. Some 20 conventional treatment plants have now been converted to biological processes.

<table>
<thead>
<tr>
<th>PLANT</th>
<th>LASSAY (30 m³/h = 0.2 mgd)</th>
<th>SAINT-CLAUDE (200 m³/h = 1.3 mgd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Water: pH Fe²⁺</td>
<td>6.2 - 6.5</td>
<td>7.05</td>
</tr>
<tr>
<td></td>
<td>4 - 7 mg/L</td>
<td>0.6 mg/L</td>
</tr>
<tr>
<td>Filtration Rate</td>
<td>6 m/h = 2.5 gpm/sq.ft</td>
<td>9.5 m/h = 4 gpm/sq.ft</td>
</tr>
<tr>
<td>Treatment Mode</td>
<td>Physical-chemical</td>
<td>Biological</td>
</tr>
<tr>
<td></td>
<td>Physical-chemical</td>
<td>Biological</td>
</tr>
<tr>
<td>Chemicals</td>
<td>Chlorine: 5 ppm</td>
<td>KMnO₄: 0.5 ppm</td>
</tr>
<tr>
<td></td>
<td>Alginate: 0.5 ppm</td>
<td>Alginate: 0.2 ppm</td>
</tr>
<tr>
<td>Filter Runs</td>
<td>20 hrs</td>
<td>85 - 120 hrs</td>
</tr>
<tr>
<td>Iron retained</td>
<td>0.7 kg Fe/m²</td>
<td>3-5 kg Fe/m²</td>
</tr>
<tr>
<td>Backwash Water:</td>
<td>4 %</td>
<td>0.7 - 1 %</td>
</tr>
<tr>
<td>- Percentage</td>
<td>Treated</td>
<td>Raw</td>
</tr>
<tr>
<td>- Origin</td>
<td>1.1 %</td>
<td>0.15 - 0.2 %</td>
</tr>
<tr>
<td></td>
<td>Treated</td>
<td>Raw</td>
</tr>
</tbody>
</table>

**THE NEW GENERATION OF IRON AND/OR MANGANESE REMOVAL PLANTS**

The discovery of the potential offered by iron and/or manganese bacteria led above all to the design of a new generation of treatment plants operating by biological process. These facilities offer many advantages over conventional plants:

- much higher filtration rate (between 10 and 50 m/h, or 4 to 20 gpm/sq.ft, depending on the iron or manganese concentration of the raw water) thereby allowing a reduction in the filtration bed area and consequently, in the number and/or size of the filters.

- oxidation and filtration occur practically simultaneously, allowing for even more compact plants and dispensing with certain requisite equipment of conventional plants, such as oxidation columns, contact tanks, settlers, etc.

- possibility of increasing the effective size of the sand (to about 1.5 mm), thus offsetting the higher head loss normally associated with a higher filtration rate.
high iron and manganese retention capacity (expressed in kg/m² retained between two backwashes; this capacity is approximately five times higher than in physical-chemical treatments).

- economical backwashing, requiring about one-fifth the quantity of wash water needed by physical-chemical processes; feasibility of backwashing with raw water in certain cases.

- improved product water quality (iron and manganese absent or occurring in trace amounts only), elimination of interference phenomena due to inorganic anions (particularly silica).

- operational flexibility; feasibility of intermittent operation (although there are limitations regarding manganese removal).

- sludge is easier to thicken and dewater when necessary.

- reduction in capital costs (savings of up to 40% in comparison with a physical-chemical treatment) and operating costs (elimination of certain chemicals, lower backwash frequency, less supervision).

These types of treatment are often implemented at small or medium-sized installations, which explains why pressure filters are more frequently used than concrete gravity filters. Figure 2 illustrates the basic principle of a pressurized biological iron removal unit. The air flow introduced in the initial aeration step ahead of the filter (FERAZUR® reactor) must be adjusted such that it can maintain precisely the right conditions of dissolved oxygen concentration and Redox potential to allow optimal development of the iron bacteria. In certain types of water, where the dissolved O₂ concentration at the filter inlet must be precisely monitored and maintained to within a tolerance of a few tenths or hundredths mg/L, the initial aeration step can be replaced by recycling a small quantity of treated water, oxygenated to approximately the oxygen saturation level. According to the water quality and local conditions, either non-chlorinated treated water or raw water may be used for filter backwash.

![Diagram of pressurized biological iron removal unit](image)

**Fig. 2: Typical pressurized biological iron removal unit**

The diagram of a pressurized biological manganese removal plant is identical, except that there is only one aeration step (involving raw water, to achieve near-saturation level of dissolved O₂ immediately). Additionally, pH adjustment may be necessary to yield a threshold level of around 7.5. MANGAZUR® reactors are used.
A number of alternative designs are available in which gravity filters, of either steel (open or closed) or concrete construction are preceded by spray, cascade or bubble aeration.

Several examples will be examined, including cases of plants equipped with two-stage filtration (in the event of simultaneous presence of iron and manganese); intermediate nitrification, etc.

**CASES OF WATER CONTAINING IRON ONLY**

**Case No. 1 (representative of a situation which has occurred at several different sites):**

The objective is to build a pressurized plant with a capacity of 100 m$^3$/h (0.63 mgd), to treat feedwater having the following characteristics:

$$
\begin{align*}
\text{pH:} & \quad 7.2 \\
\text{Fe}^{2+}: & \quad 3.5 \text{ mg/L} \\
\text{dissolved silica:} & \quad 25 \text{ mg/L (as SiO}_2) \\
\text{dissolved O}_2: & \quad \text{nil}
\end{align*}
$$

A comparison between biological and conventional solutions points to the following conclusion (see Fig. 3):

a) **Physical-chemical process**

The conventional treatment applied in France would consist of the following steps:

- aeration in an oxidation column at a velocity of 30 to 40 m/h (12.3 to 16.4 gpm/sq.ft). Therefore, the diameter of the column would have to be at least 1800 mm;

- addition of chemical(s) to prevent interference resulting from the presence of dissolved silica: KMnO$_4$ and/or flocculant (alginate or polyelectrolyte),

- filtration at a maximum rate of 7 m/h (2.9 gpm/sq.ft), e.g., on three vertical filters with diameter of 2500 mm. The effective size of the sand must be consistently smaller than 1 mm (0.95 mm is generally used),

- disinfection.

b) **Biological process**

There is no need for the oxidation tower. The plant flow diagram, prior to final disinfection, is comparable to that shown in Fig. 2, with a single, 2400 mm-diameter filter (which would then operate at a rate of 22 m/h or 9 gpm/sq.ft), filled with sand of E.S. = 1.35 mm and adjacent to small air mixers on either side.

Fig. 3 highlights the value of the biological process.
Fig. 3: Pressurized iron removal plant design: biological vs. physical chemical process, a case study (100 m³/h)

**Case No. 2: L'ISLE ADAM plant, France (300 m³/h = 1.9 mod)**

Results of the raw water analysis are as follows:

- **temperature:** 15°C
- **pH:** 6.8 - 7 (pH₃)
- **alkalinity:** 340 ppm CaCO₃
- **hardness:** 485 ppm CaCO₃
- **calcium:** 440 ppm CaCO₃ (=176 mg Ca/L)
- **Fe²⁺:** 0.2 - 0.8 mg/L

Like in the previous case, a physical-chemical process would have called for the use of a potent oxidant (Cl₂, KMnO₄...) because the pH is too low for the dissolved oxygen provided by aeration alone to allow sufficiently rapid kinetics of the oxidation reaction, and the pH cannot be raised without making the water scale-forming.

For these reasons, the biological process was chosen, using two 3000 mm-diameter vertical filters, for a filtration rate of 21 m/h (8.7 gpm/sq.ft) on a 1.5-m depth of sand with E.S. = 1.3 mm. This plant was France's first to be designed for this process. Subsequent knowledge has indicated that the filtration rate could have been twice as high.

During the plant's start-up phase, a period of three days was required for seeding and complete removal of the residual iron from the product water.
Case No. 3: SEIGNOSSE, France (75 m³/h = 0.48 mgd)

The previous example shows that in addition to its other advantages, biological iron removal can yield good results at pH < 7. There is, however, a minimum threshold below which it is chemically impossible to achieve effective iron removal. (It must be remembered that the mechanism of bacterial activity is purely catalytic and therefore has no effect on the final state of the chemical reactions). This threshold lies around 6.5, as demonstrated by the case of the Seignosse plant, which had been designed based on the following contractual parameters:

\[
\begin{align*}
pH: & \quad 6.8 - 6.9 \\
Fe^{2+}: & \quad 2 - 3 \text{ mg/L}
\end{align*}
\]

In view of these parameters, it was decided to apply biological iron removal at a rate of 24 m³/h (10 gpm/sq.ft). By the time of start-up, the pH had already dropped to 6.3. It continued to drop in the ensuing days, bottoming out around 5.5, while the iron content of the water had climbed to 3.5 mg/L. Biological iron removal was no longer possible in such an acidic medium. The problem was solved simply by shifting a portion of the caustic dosage (for correction of the carbonic aggressivity of the product water) upstream of the iron removal step, thus restoring the pH to the range of 6.5 to 7 and allowing efficient iron removal.

Two conclusions may be drawn from this experience:

- there is a minimum threshold pH at which this process can be effective;
- representative samples must be available (sufficient pumping time) for the analyses to be used as meaningful design criteria for future projects; this, of course, is an age-old issue in groundwater treatment.

Case No. 4: WEST PINCHBECK, UK (1500 m³/h = 9.5 mgd)

One might also wonder whether biological iron removal can be applied to waters with a very low dissolved iron concentration. An affirmative answer to this question was provided in the form of the WEST PINCHBECK plant (UK) built for Anglian Water.³

The plant was designed for a capacity of 1125 m³/h (7.13 mgd), but its capacity was in fact raised to 1500 m³/h (9.5 mgd). Key analytical data were the following:

\[
\begin{align*}
temperature: & \quad 14 - 15^\circ\text{C} \\
pH: & \quad 7.0 - 7.7 \\
Fe^{2+}: & \quad 0.15 \text{ mg/L on average} \\
Mn^{2+}: & \quad < 0.001 \text{ mg/L} \\
dissolved O_2: & \quad 0 - 0.1 \text{ mg/L}
\end{align*}
\]

The guaranteed level of residual iron in treated water was 0.05 mg/L, in line with the guide level stipulated in the European directive.

The physical-chemical and biological processes were compared³ after confirming the feasibility of biological iron removal on pilot filters:

<table>
<thead>
<tr>
<th>Reagents / Process</th>
<th>Physical-chemical process</th>
<th>Biological process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtration rate</td>
<td>yes 7.1 - 8.5 m/h</td>
<td>no 20 - 40 m/h</td>
</tr>
<tr>
<td>Type of filter</td>
<td>anthracite/sand/garnet</td>
<td>sand</td>
</tr>
<tr>
<td>Number of filters</td>
<td>12</td>
<td>5 or 6</td>
</tr>
<tr>
<td>Wash water</td>
<td>treated</td>
<td>raw</td>
</tr>
<tr>
<td>Capital cost</td>
<td>approx. £ 3 million</td>
<td>approx. £2 million</td>
</tr>
</tbody>
</table>
Among other advantages, the capital cost of the biological process was about 33% lower than that of the physical-chemical process. The biological process also appeared to yield considerable savings on operating costs.

The plant was therefore built and equipped with five FERAZUR® reactors with a unit bed area of 9.6 m². Although the design rate was only 23.4 m³/h or 9.6 gpm/sq.ft (totaling 1125 m³/h for the five filters), it was able to be increased to 31 m³/h or 12.7 gpm/sq.ft (totaling 1500 m³/h for the five filters) and even 39 m³/h or 16 gpm/sq.ft (1125 m³/h for three filters, when one is out of order and another is in the backwash cycle), with no deterioration in product water quality. Furthermore, a test at 52 m³/h (21.3 gpm/sq.ft) showed that even this rate did not reach the limits of the process.

The plant was started up in December 1994. Seeding took about three days and since that time, the iron concentration of the product water has been consistently below or equal to 0.01 mg/L.³

GRAVITY DESIGN ALTERNATIVES FOR IRON REMOVAL

Case No. 5: SAINT-ANDRE DE CUBZAC, France (160 m³/h = 1 mgd)

In this case, the raw water analysis yields the following results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature</td>
<td>23°C</td>
</tr>
<tr>
<td>pH</td>
<td>6.5 - 6.7</td>
</tr>
<tr>
<td>alkalinity</td>
<td>60 ppm CaCO₃</td>
</tr>
<tr>
<td>hardness</td>
<td>65 ppm CaCO₃</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.6 mg/L</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.02 - 0.03 mg/L</td>
</tr>
<tr>
<td>dissolved O₂⁻</td>
<td>nil</td>
</tr>
</tbody>
</table>

Hydrogen sulfide is generally an impediment to biological iron removal (difficulties in raising the Eh; inhibiting action on iron bacteria). In this case, the H₂S level approaches the maximum admissible concentration.

However, calculations and experimentation have shown that atmospheric pressure spray aeration could get rid of the H₂S and raise the dissolved oxygen level of the water, yet without the risk that CO₂ loss would cause pH to rise to a level incompatible with biological iron removal. This phenomenon was linked to the low alkalinity of the water; this solution would have been impossible for water with a higher bicarbonate concentration.

The treatment designed consisted therefore of spray aeration followed by filtration at a rate of 25.5 m³/h (10 gpm/sq.ft) on two closed filters (FERAZUR® reactors) of steel construction, located beneath the aeration tank. This design, illustrated in Fig. 4, appeared preferable to concrete filters due to the limited feedwater flow through the filters. In contrast, gravity plants designed to handle high flows are often equipped with concrete filters, as will be discussed in the following case.
Case No. 6: LOME, Togo (2200 m³/h = 14 mgd)

At the end of 1987, in conjunction with a project to increase the water supply of the city, a biological iron removal plant was installed in the Togolese capital city, Lomé. This marked the first African application of modern biological treatment technologies to groundwater.

The resources consisted of water from three aquifers (Continental Terminal, Paleocene and Maastrichian), which presented significant chemical differences. The characteristics of the combined waters (Table 2) pointed to the need for iron removal; neutralization of CO₂ aggressivity by the physical removal of CO₂ or the use of alkaline reagents, or both; and final disinfection.

Table 2
Lomé Plant: Typical composition of raw water mixture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>30 to 31</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.15 to 6.5</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>ppm CaCO₃</td>
<td>90 to 150</td>
</tr>
<tr>
<td>Dissolved iron</td>
<td>mg/L Fe</td>
<td>0.4 to 1.1</td>
</tr>
<tr>
<td>Manganese</td>
<td>mg/L Mn</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Ammonia</td>
<td>mg/L NH₃</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Dissolved silica</td>
<td>mg/L SiO₂</td>
<td>20 to 25</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>mg/L O₂</td>
<td>0 to 0.7</td>
</tr>
<tr>
<td>Free CO₂</td>
<td>mg/L</td>
<td>75 to 150</td>
</tr>
</tbody>
</table>

Furthermore, in the case of a physical-chemical process, the presence of a high concentration of dissolved silica dictated the use of additional chemicals to prevent interference due to the formation of an iron-silica complex.
The biological process was compared with the physical-chemical treatment and was selected due to the obvious advantages it offered (Fig. 5). The treatment line was designed as follows (Fig. 6):

- three-step cascade aeration with a total drop of 1.5 m and a partial bypass to calibrate the dissolved oxygen content to exact process requirements;
- filtration on four concrete gravity filters with unit bed area of 24.5 m², filtration rate of 22 - 23 m³/h (9 to 9.4 gpm/sq.ft); aerodynamic control system by partialized siphon; filter medium consisting of 1.4 m depth of sand of 1.35 mm E.S., and raw water backwash;
- finishing treatment with lime water from a saturator and chlorine (calcium hypochlorite solution).

![Diagram of treatment process]

Fig. 5: Lomé plant design: biological vs physical-chemical processes
Fig. 6: Schematic diagram of the gravity biological iron removal plant at Lomé

The lack of an available outlet for the discharge of filter backwash water offered an opportunity to draw maximum benefit from the intrinsic advantages of biological iron removal processes (generation of small quantities of wastewater, containing denser, more settleable sludge): a wash water treatment and recycling system was installed (Fig. 7).

- At the filter outlet, the waste wash water is collected in two tanks located below the filter battery (one tank for two filters) (Fig. 7 [no. 4]);

- Each tank can hold enough water for one complete wash; the water is stored and left to settle naturally without reagents;

- The low frequency of filter backwashes provides for settling times of at least 12 hours. This factor and the good settleability of biological sludge, make for excellent separation of thick sludge from clear supernatant;

- At the end of the settling period, clear water is slowly recycled (5) to the head of the plant (2), and sludge is channeled by gravity flow (6) toward a recovery tank (8) which also receives the lime impurities from the saturator (7);

- An automatic electric pump conveys the mixture of sludge from the filter wash and saturator into a concrete thickener of 3.5 m diameter (9).

- The clear water from the thickener is in turn recycled by gravity to the treatment line. The thick sludge is periodically extracted by gravity and sent to the drying beds (5 x 70 m²)(10);

- Therefore, wash water losses in the plant are negligible, being essentially confined to the interstitial water in the thick sludge.
Fig. 7: Flow diagram of the Lomé plant

When the plant was started up, the sand in the filters was rapidly seeded by iron bacteria of the *Gallionella ferruginea* species. The residual iron content of the filter effluent was:

- 0.1 mg/L after 10 hours
- < 0.03 mg/L after 1 day
- trace amounts after 2 days.

The filter runs last well over 48 hours. The total duration of a backwash cycle is only 8.5 minutes (including 1.5 minutes of air scour + water and 4 minutes of rinsing). Backwashing consumes 2.5 m³ of water for each m² of filter bed area, which amounts to less than 0.2 % of the product water. Moreover, with most of the wash water being recycled to the plant as previously described, there is little net water loss.

**FIRST BIOLOGICAL IRON REMOVAL PLANT IN THE U.S.**

The Brookside treatment plant (Toms River Water Company) treated 160 m³/h (1 mgd) of water with an iron concentration of 2 to 3 mg/L. When confronted with the need to
increase plant capacity to a maximum of 480 m³/h (3 mgd), the Toms River Water Company decided to compare the performance of the existing physical-chemical line with those obtained by a pilot biological iron removal plant.

The biological treatment proved to offer many advantages over the conventional solution: improvement in filtered water quality; more rapid return to equilibrium following a backwash sequence; longer filter runs despite a three- or four-fold increase in the filtration rate; savings on wash water (0.25% of biological product water, against 1.6% of physical-chemical product water).

In light of these excellent results, the Toms River Water Company decided to treat the entire plant flow using the biological process, and commissioned the INFLICO-DEGREMONT company to deliver two steel FERAZUR® reactors (dia.: 14' or 4.3 m) to be incorporated into the following treatment line:

- pH correction using lime (from the raw water pH of 6.1 to at least 6.5 required for the process);
- in-line aeration in a static baffle mixer;
- pressure filtration at a rate of 16 m/h (6.8 gpm/sq.ft).

This facility sets a precedent in the United States and is now being installed for start-up in the course of 1996.

**BIOLICAL REMOVAL OF MANGANESE (ALONE)**

**Case No. 7: SORGUES, France (1200 m³/h = 7.6 mgd)**

In this case, treatment concerned water containing manganese as virtually the only contaminant:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.2 - 7.5</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0 - 0.1 mg/L</td>
</tr>
<tr>
<td>Mn²⁺</td>
<td>0.7 - 1 mg/L</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>0.2 mg/L</td>
</tr>
</tbody>
</table>

After completion of pilot testing, the plant became one of the first and leading French references for biological manganese removal. The treatment line (Fig. 8) consists of pressurized in-line aeration; four filters (MANGAZUR® reactors) operating at a maximum rate of 31 m/h (12.7 gpm/sq.ft); a tank for storage of non-chlorinated filter backwash water; a chlorine disinfection stage using chlorine gas; and a treated water storage tank. Sludge generated during treatment is thickened, conditioned with a polymer and dewatered by centrifuge.

Fig. 9 summarizes the measurements taken during start-up of the plant. It reveals that when one filter is seeded with sludge from the waste wash water of other filters used for biological manganese removal, maximum treatment efficiency is reached, in this specific case, within 35 days, compared to two months without seeding.

Mean operating results are as follows:

- Mn: less than 0.02 mg/L in filtered effluent
- Mn retention between two washes: 3.75 kg of Mn per m² of filter bed area.

The sludge, thickened to a concentration of 80 g/L in a thickener, is conditioned with 1 kg of anionic polymer per metric ton of dry solids. The final dry solids content after centrifugation is 23%.
Finally, an experimental study has shown that following a two-month shutdown, the manganese removal capacity of a filter could be completely restored in just 5 days, approximately.

**WATER CONTAINING BOTH IRON AND MANGANESE**

Due to the differences in the optimum treatment conditions for iron and manganese removal respectively (Fig. 1), two filtration steps are usually required. There are, however, certain exceptions, such as the case of the PONCEY-LES-ATHEE plant
(3000 m²/h = 19 mgd), where extensive pilot testing (6 months) confirmed the fact that the moderate iron and manganese levels, along with favorable pH and Eh levels in the raw water provided an exceptional set of conditions conducive to simultaneous iron and manganese removal. However, the filtration rate had to be limited to around 15 m/h (6.15 gpm/sq.ft).

In this case, the selected treatment line consisted of:

- open cascade aeration designed based on the characteristics of the raw water,
- biological iron and manganese removal in a single stage using six sand filters (at a rate of 16.7 m/h = 6.8 gpm/sq.ft),
- intensive aeration,
- polishing on six granular activated carbon (GAC) filters, due to the presence of objectionable tastes as well as pollution by atrazine.

The plant was commissioned at the end of 1994. Despite severe disruptions to operations (frequent shut downs), iron removal has been complete from the outset. In contrast, manganese removal only reached full efficiency after two months. An example of physical-chemical analysis of the raw water and sand-filtered water is presented in Table 3.

Table 3
Poncey-les-Athee: Analytical results (August 21, 1995)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Raw water</th>
<th>Filtered water</th>
<th>Guarantee</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7</td>
<td>7.3</td>
<td>-</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>4.3</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Iron (mg/L)</td>
<td>0.93</td>
<td>&lt; 0.02</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>Manganese (mg/L)</td>
<td>0.47</td>
<td>&lt; 0.002</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>Ammonium (mg/L)</td>
<td>0.23</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Nitrites (mg/L)</td>
<td>0.02</td>
<td>&lt; 0.02</td>
<td></td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>0.52</td>
<td>&lt; 0.5</td>
<td></td>
</tr>
</tbody>
</table>

With these exceptions, the treatment of water containing both iron and manganese requires two-stage filtration, based on the following process design:

- initial aeration (designed for biological iron removal);
- initial filtration (biological iron removal);
- secondary aeration and/or pH correction (using lime, caustic or sodium carbonate to raise pH);
- secondary filtration (physical-chemical manganese removal with complementary oxidant, or biological manganese removal).

Some twenty plants have already been designed based on this principle of two-stage filtration. Table 4 summarizes the operating conditions of a few of them.

At the outlet from each of these plants, the iron and manganese levels of the treated water remain consistently below 0.02 mg/L, and sometimes below 0.001 mg/L.
### Table 4
Examples of biological iron and manganese removal plants

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity (mgd)</th>
<th>1st stage rate (biological iron removal)</th>
<th>2nd stage rate (manganese removal)</th>
<th>Type of manganese removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochfelden</td>
<td>3.8</td>
<td>37 m/h (15 gpm/sq.ft)</td>
<td>10 m/h (4 gpm/sq.ft)</td>
<td>Gravity; physical-chemical then converted to biological</td>
</tr>
<tr>
<td>Ramelshausen</td>
<td>1</td>
<td>40 m/h (16.4 gpm/sq.ft)</td>
<td>21 m/h (8.6 gpm/sq.ft)</td>
<td>Pressurized; physical-chemical then converted to biological</td>
</tr>
<tr>
<td>Blaye</td>
<td>0.8</td>
<td>39 m/h (16 gpm/sq.ft)</td>
<td>24 m/h (9.8 gpm/sq.ft)</td>
<td>Pressurized; biological</td>
</tr>
<tr>
<td>Bischwiller</td>
<td>0.4</td>
<td>25 m/h (10 gpm/sq.ft)</td>
<td>16 m/h (6.5 gpm/sq.ft)</td>
<td>Pressurized; physical-chemical</td>
</tr>
<tr>
<td>Ploudaniel</td>
<td>0.54</td>
<td>22.5 m/h (9.2 gpm/sq.ft)</td>
<td>10 m/h (4 gpm/sq.ft)</td>
<td>Pressurized; biological</td>
</tr>
</tbody>
</table>

For example, Fig. 10 shows the process flow diagram of the Hochfelden plant. But it must be noted that the most frequent combination for low- or medium-capacity plants involves two successive stages of pressure filtration.

![Figure 10: The Hochfelden plant (France)
Capacity: 600 m³/h (3.8 mgd)
EXAMPLES OF NON-APPLICABILITY

The process design engineer must be able to identify situations in which construction of a biological iron and/or manganese removal plant would not yield the desired results. Three such examples are provided below:

Case No. 8: SOUFFLENHEIM, France

The raw water analysis showed:

\[
\begin{align*}
\text{Fe}^{2+}: & \quad 1 - 5 \text{ mg/L} \\
\text{Mn}^{2+}: & \quad 0.15 \text{ mg/L} \\
\text{NH}_4^+: & \quad 0.2 - 0.3 \text{ mg/L} \\
\text{H}_2\text{S}: & \quad 0.25 \text{ mg/L} \\
\text{Zn}: & \quad 0.5 \text{ mg/L}
\end{align*}
\]

The ammonium level already approached the maximum admissible for biological removal of manganese. Above all, the H$_2$S and zinc concentrations absolutely ruled out biological treatment, as proven by pilot plant testing. Accordingly, a conventional physical-chemical treatment was selected.

As this plant, located in the Alsace region of France, is operated by the same company as the Ramelshausen and Hochfelden facilities mentioned above, the economics of the two treatment processes could be compared.

<table>
<thead>
<tr>
<th>Type of treatment</th>
<th>Physical-chemical</th>
<th>Biological (2 stages)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>Soufflenheim</td>
<td>Ramelshausen</td>
</tr>
<tr>
<td>Cost in French francs/m$^3$:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- capital</td>
<td>0.59</td>
<td>0.55</td>
</tr>
<tr>
<td>- operating</td>
<td>0.81</td>
<td>0.08</td>
</tr>
<tr>
<td>Total</td>
<td>1.40</td>
<td>0.63</td>
</tr>
</tbody>
</table>

These figures highlight the advantage of biological treatments where applicable (despite the need for two-stage filtration, in the present example).

Case No. 9: TOUL-ROSIERES, France

The relevant raw water characteristics were as follows:

\[
\begin{align*}
\text{pH}: & \quad 7.2 \\
\text{Fe}^{2+}: & \quad 5 \text{ mg/L} \\
\text{Mn}^{2+}: & \quad 4 \text{ mg/L} \\
\text{NH}_4^+: & \quad 2.5 \text{ mg/L (European standard: 0.5 mg/L)}
\end{align*}
\]

This case involved water containing a very high concentration of the ammonium ion (much higher than the maximum admissible in the European Union). Moreover, the ammonium had to be nitrified before biological manganese removal could be possible. Furthermore, the high Fe$^{2+}$ and Mn$^{2+}$ concentrations dictated the following treatment line:

- biological iron removal at the head of the treatment line to avoid fouling the nitrification reactor;

- an aerated nitrification reactor (NITRAZUR N$^\text{®}$) for biological oxidation of this high NH$_4^+$ loading;
a final filtration step to remove any zooglaee of nitrifying bacteria that may have escaped from the nitrification reactor, while completing the biological manganese removal begun just prior to the nitrification outlet. In such cases, the filtration rate must not exceed 10 to 15 m/h (4 to 6 gpm/sq.ft).

Case No. 10: BUDAPEST, Hungary (6250 m³/h = 40 mgd)

In addition to the excessive levels of iron and manganese (up to 0.5 mg/L of each, a portion of which was already oxidized due to the oxygen content of the borehole water), the raw water contained ammonium at concentrations (0.2 to 0.6 mg NH₄⁺/L with peaks in excess of 2 mg/L) which might have posed numerous problems for biological treatment, as discussed in the preceding section. As a result, sizing of the filtration unit had to be governed by the criterion of complete nitrification.

Moreover, a substantial population of bacteria and microinvertebrates (protozoans, Nematoda and Oligochaeta) had to be taken into account, requiring that the treatment line include a disinfection which would have been incompatible with biological processes but whose absence would have allowed an unacceptable colonization of the filters by the bacteria and anaerolcula.

To determine the most appropriate treatment line, the raw water was subjected to several years of testing in a 30 m³/h pilot plant which provided comparative data for several oxidation treatments (aeration and/or chlorination, ozonation) ahead of the filtration step. The results of this highly comprehensive study conducted by the Budapest water authority, were recently published.

Out of this study emerged the definition of a treatment line that has since been built and consists of:

- cascade aeration for pre-oxidation (leading to savings on the chemical oxidant used downstream) and to impart the dissolved oxygen level needed for nitrification in the filters and the formation of the protective layer in pipes;

- ozonation (with dosage on the order of 1 g/m³) followed by addition of other optional products (K₂MnO₄, flocculant); the ozone fills the dual role of oxidant for the manganese and partial disinfectant acting on microflora and microfauna;

- sand filtration at a rate of 6.5 m/h or 2.7 gpm/sq.ft. (on 10 AQUAZUR V® filters with unit bed area of 102 m²) to capture the precipitated iron and manganese and trigger nitrification;

- GAC filtration at a rate of 13 m/h or 5.3 gpm/sq.ft. (9 MEDIAZUR GH® filters with unit bed area of 57 m²) to complete the nitrification and enhance the quality of product water;

- final disinfection using chlorine.

This case is therefore a good example of a complex raw water for which several factors ruled out the use of biological treatment (partial precipitation of the iron and manganese in the raw water, presence of ammonium, biological problems) and for which an appropriate treatment could only be defined through comprehensive testing.

CONCLUSION

Biological iron and manganese treatments offer the advantages of simplicity and economy. However, they must be designed case by case; the expertise of an experienced water treatment engineer is absolutely necessary in selecting the best treatment based on the characteristics of the raw water (representative samples of which must also have been studied in comprehensive analyses) and in determining the operating conditions in which the treatment will yield the anticipated results.
Furthermore, biological treatments are not applicable to all cases, particularly when the raw water features:

- characteristics considered unfavorable for these processes, *i.e.*, presence of iron and/or manganese as precipitates, high $\text{H}_2\text{S}$ and/or $\text{NH}_4^+$ concentrations, excessively low or high pH, toxic elements (*e.g.*, certain heavy metals);

- other parameters which do not comply with standards and dictate the use of a different type of treatment, although this technology can also constitute a viable pretreatment option in drinking water or industrial water treatment lines.

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1. **MOUCHET, P.** From Conventional to Biological Removal of Iron and Manganese in France. *Jour. AWWA*, 84 (4) : 158 (Apr. 1992)


5. **GISLETT, P.** Personal Communication (1993)