

The State of Art of Small Community Defluoridation of Drinking Water

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Summary: Numerous naturally occurring media and products are known to be capable to remove fluoride from water. These can be categorised into three main groups; A) The bone char, activated alumina, clay and similar compounds are sorption media, which are normally packed in columns to be used for a certain operation period. The columns end up saturated, subject to renewal or regeneration. B) Alum and lime in the Nalgonda technique, polyaluminium chloride, lime and similar compounds resemble co-precipitation chemicals, which are normally added batch wise. This precipitation technique produces a daily amount of sludge. C) The calcium and phosphate compounds are the so-called contact precipitation chemicals to be added to the water upstream a catalytic filter bed. In this contact precipitation there is no sludge and no well-defined saturation of bed. However the bed accumulates the precipitate and has to be rejuvenated.

Apart from the contact precipitation all the methods have been known already in the mid-thirties, where fluoride was discovered as the agent behind "The Colorado Stain". There is no universal method that can be sustained under all kinds of social, financial, environmental and technical constraints. On the other hand all the methods mentioned do have advantages and have shown to be capable of removing fluoride at certain conditions. These include: A) The appropriate selection of the method. B) The utilisation of an appropriate design. C) The provision of infrastructural support, and D) The continues motivation and training of users. This paper provides guidelines examples of design of household and small community defluoridation units.

Key words: Defluoridation of water, design, bone char, alum, alumina, clay, contact precipitation, domestic defluoridation, community unit, column filters, bucket filters, drum filters, Nalgonda, advantages, disadvantages, rejuvenation, regeneration, bath treatment, plug flow, breakthrough, taboo limitation, removal capacity, removal efficiency, cost.

Introduction

Occurrence of fluoride at too high levels in drinking water in developing countries is a serious health problem, closely related to the fluoride properties. In the drinking water, fluoride is tasteless, odourless, colourless and totally soluble, i. e. it does not produce any turbidity. Its detection demands analytical grade chemicals and laboratory equipment and skills. Its effects on health are delayed and, to a large extent, commutative and irreversible.

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Similarly, the prevention of fluorosis through treatment of drinking water is a difficult task, which requires favourable socio-economical conditions of knowledge, motivation, prioritisation, discipline and technical and organisational set-ups. Many media and several water treatment methods are known to remove fluoride from water. However, due to lack of such favourable conditions, many initiatives on defluoridation of water have resulted in failures and frustrations⁹. Therefore, in any attempt to mitigate the fluoride problem for an affected community, the provision of safe low fluoride water from alternative sources must be investigated as the first option.

In cases where alternative sources are not available, defluoridation of water is the only measure remaining to prevent fluorosis. However, the defluoridation methods are several and differ from each other. What may work in one community may not work in another. What may be appropriate at a certain time and stage of urbanisation, may not be in another. It is therefore most important to select appropriate defluoridation method very carefully, if a sustainable solution to the fluorosis problem is to be achieved.

This document introduces the basic characterisation of the removal methods. Then the most promising defluoridation methods are presented one by one: bone char, contact precipitation, Nalgonda, activated alumina and clay. Finally the methods presented are compared using indicators, which may be appropriate in developing countries.

Methods of high tech characteristics, e.g. reverse osmosis, electrodialysis and distillation, plus methods based on patented media and natural media of only theoretical interest are left out of the scope of this document. Reference is given to e. g. Heidewiller 1990¹⁸ and Bulusu et al. 1993⁷.

METHOD CHARACTERISATION

Scale & decentralisation. Conventional water treatment, as carried out in both rural and urban areas in industrialised countries, takes place:

- At large scale.
- In a water works without direct involvement of the users.
- Under the supervision of skilled operators.
- Where the treatment affordability is taken for granted.

In such cases the method of treatment is sufficiently characterised by the utilised medium or the process in use. Such a setup may have serious limitations or disadvantages in less-developed countries. Especially in rural areas, where the water supply is scattered or does not exist, treatment may only be feasible at a decentralised level e. g. at community village level or at household level, cf. Table 1.

TABLE 1. Differences in characterisation of water treatment methods in conventional systems as taking place in industrialised and developing countries.

Criteria	In Industrialised Countries	In Developing Countries
Setup & water flow	Always continuous, often in columns.	Often discontinuous in columns. Fill and draw in batch.
Scale & treatment site	Always at water works, often close to water source.	At water works. At village community level. At house hold level.
Treatment media/process	Contact precipitation. Activated alumina. Synthetic resins. Nalgonda. Reverse Osmosis. Electrodialysis. Bone char.	Bone char. Contact precipitation. Nalgonda. Activated alumina. Clay. Other naturally occurring media.

Setup and flow. As water supply in less developed countries is less reliable, the setup may accordingly be different in order to account for the required storage of water and the different feed and withdraw patterns. Filter columns, as used for bone char, activated alumina and clay, are often intermittently fed and operate at various flow rates. Thus there will be a need for a pre-storage container and a control of the flow rate in order to ensure a minimum of contact time. Batch units as in the Nalgonda technique are often fed once a day. In both cases a separate clean water container would be useful or even essential.

Even in situations where the water is supplied through pipe schemes, the decentralised solution may be more advantageous. After all, there is no need to remove the fluoride from the water that is not used for cooking or drinking, because:

- The entire water demand is often more than 10 times the water needed for drinking and cooking. Defluoridation of the total demand would therefore be more costly, and often unaffordable for the community or the household.
- Unnecessary large removal of fluoride from water would result in accumulation of toxic sludge, which is likely to create an environmental health problem.

Thus systems of industrialised countries are normally hydraulically simple and sufficiently characterised by the process in use. The “developing country-systems” are often hydraulically and process-wise more complicated and only sufficiently characterised when the point of treatment and the type of setup in use are given. For example the bone char process can be utilised in water works, in a village plant and at the house level. Also it can be performed in columns or in batch, e.g. water buckets. For a layman the difference between these may look insignificant. Taking into consideration the environmental and socio-economical sustainability of the treatment system, the difference between a centralised system and a house hold system may be much more significant than the difference between bone char and alumina.

Media and process. Defluoridation processes can be categorised into three main groups.

- Bone char, activated alumina and clay resemble *sorption media*, preferably to be packed in columns to be used for an operation period. Sorption processes end up with saturated columns to be renewed or regenerated.
- Alum and lime in the Nalgonda technique, polyaluminium chloride, lime and similar compounds resemble *co-precipitation chemicals* to be added daily and batch wise. Precipitation techniques produce a daily amount of sludge.
- Calcium, and phosphate compounds are the so-called *contact precipitation chemicals* to be added to the water upstream a catalytic filter bed. In contact precipitation there is no sludge and no saturation of bed, only the accumulation of the precipitate in the bed.

Magnesite, apophyllite, natrolite, stilbite, clinoptilolite, gibbsite, goethite, kaolinite, halloysite, bentonite, vermiculite, zeolite(s), serpentine, alkalkine soil, acidic clay, kaolinitic clay, China clay, aiken soil, Fuller's earth, diatomaceous earth and ando soil are among the numerous naturally occurring minerals which have been studied and confirmed to be able to adsorb fluoride from water^{22, 2, 29, 5, 7}. The common feature of these minerals is their contents of metal lattice hydroxyl-groups, which can be exchanged with fluoride:

Ion exchange of a metal compound M:

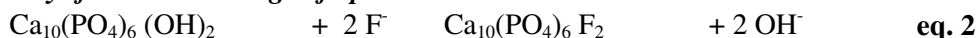


In general, the minerals themselves do have some capacity of fluoride removal. The capacity can be increased through "activation" by acid washing, calcination or air-drying. None of these minerals can fulfil any expectation as a universal defluoridation agent. Should any of them however be found next door to a fluorotic area, and thus be available at low or no cost, it may be considered as the medium of choice for that particular area. In this document clay is used as a prototype for these minerals. Clay has been reported to be appropriate for use in Sri Lanka²⁵.

BONE CHAR

Description. Bone char is blackish porous grains. In contact with water the bone char is able to a limited extent to absorb a wide range of pollutants like colour, taste and smell components. Moreover, bone char has specific ability to take up fluoride from the water. This is believed to be due to its chemical composition, mainly as hydroxyapatite, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$, where one or both the hydroxyl-groups can be replaced with fluoride. The principal reaction is:

Hydroxyl-fluoride exchange of apatite:



If analysed for major components, the bone char would show a contents of calcium phosphate, 57-80 %, calcium carbonate, 6-10 %, and activated carbon, 7-10 %.

Preparation. The preparation of bone char is crucial for its properties as a defluoridation agent and as a water purifier. Unless carried out properly, the bone charring process may result in a product of low defluoridation capacity and/or deteriorated water quality. Water treated with poor bone char may taste and smell like rotten meat, i.e. most unpleasant and repulsive for human sensory. Once the water users are exposed to such a smell or taste, they may reject the bone char treatment process in total and for good. It is therefore essential to ensure that the bone char quality is good not in most cases but always. Even single failures in the production may be fatal for a defluoridation project ¹².

Another potential disadvantage of bone char is related to the problems of supply to local users. Industrially prepared bone char used to be commercially widely available some decades ago. Now a day the commercial distribution of the bone char is much more limited. One option may therefore be to prepare the bone char at a village factory or a household level ¹⁹.

Bone char is prepared by heating ground bone in retorts or in pots piled in furnace resembling potter's kiln, without or under limited admission of atmospheric oxygen. Ground bone materials are prepared industrially by degreasing, boiling, washing and drying, prior to grinding and sifting out. The bone grains are normally available from the manufacturing of bone meal used as fodder additive ²¹. Several attempts on finding optimum heating temperature and duration seem to have failed. Heating to 550 °C for about 4 hours or even less is in principle sufficient, but the process in total, including heating up and cooling down, would take not less 24 hours. Probably the entirely required temperature and duration depend to a large extent on the batch size and the packing rather than the type or the nature of the bone ¹².

At a village level the process can be carried out in a kiln, where the raw bones can be packed directly along with coal. This technique provides an advantage, because crashing of the charred bone material is much less laborious than of the un-charred bones.

Table 2 illustrates that the poor bone char quality would mainly be due to:

- Insufficient charring, i. e. too low temperature and too short duration.
- Admission of oxygen, i.e. running the process as calcination in stead of as a charring.
- Overheating of the bones, especially if oxygen is admitted to the heated bone material.
- Inhomogeneous heating would always result in poor bone char quality.

It must be added that the preparation of bone char may, if not carried out in a properly designed kiln or furnace, cause very nasty smell even in a spacey rural environment ¹⁹. Maintaining odour free or low odour process can be obtained by 1) ensuring a secondary combustion of the produced gasses through special air injection and 2) scraping the smoke exhaust though water.

TABLE 2 Critical parameters for bone char preparation and quality testing, after Dahi & Bregnhøj 1997.

Quality Criteria	Preparation		Reason of Deterioration
	Proper	Poor	
Bone char grains:			
• Defluoridat. capacity	> 4 mg/g	< 3 mg/g	Charring: temp. > 550 °C +oxidation
• Residual organics	Untraceable	Traceable	Charring: low temp./short duration
• Carbon contents	6 –10 %	< 6 %	Charring: oxidation
• Grain size, mm	1-3	<1 or >3	Raw crashing, insufficient sorting
• Non-uniformity	Low	High	Insufficient sorting
• Colour	Black	Grey-White	Charring: temp. > 550 °C +oxidation
• BET m ² /g ^{*)}	120-150	< 100	Charring: temp. > 550 °C +oxidation
Equilibrium water:			
• Taste	Tasteless	Unpleasant	Insufficient charring/too large bulk
• Smell	No smell	Unpleasant	Insufficient charring/too large bulk
• Colour	Colourless	Yellowish	Insufficient charring/too large bulk
• pH	7.5 - 8.5	> 8.5	Charring: temp. > 550 °C +oxidation
• Alkalinity	< 1 meq/L	>1 meq/L	Charring: temp. > 550 °C +oxidation
* BET is the Brunauer, Emmett & Teller index for specific sorption area determination using nitrogen. Its unit is m ² /g.			

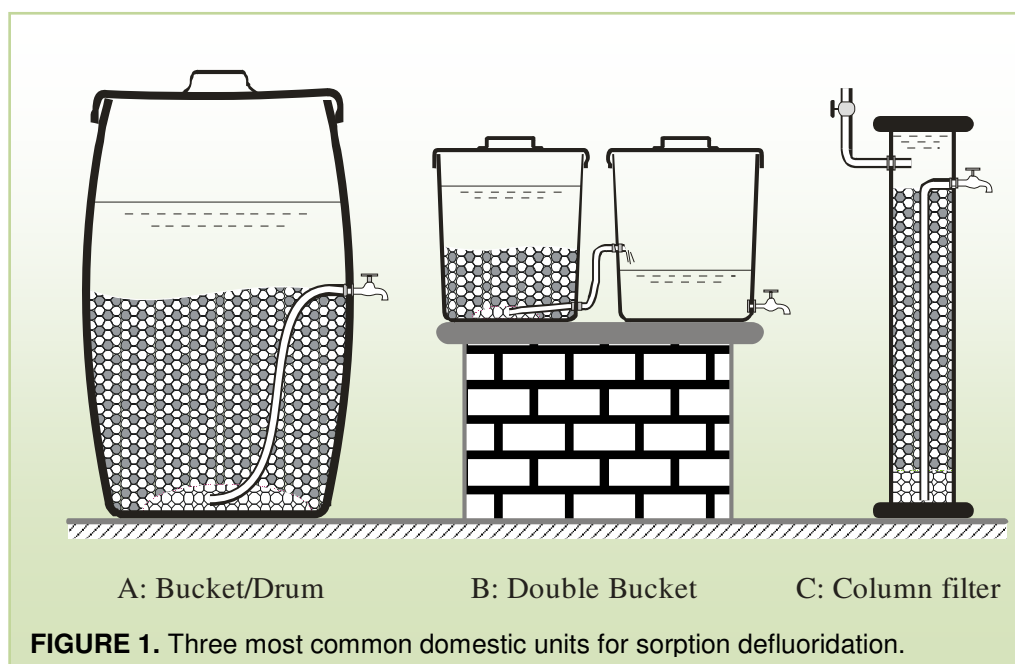


TABLE 3. Comparison of the three types bone char filters illustrated in figure 1.

<i>Advantages:</i>	<i>Drum type</i>	<i>Bucket type</i>	<i>Column type</i>
1. No daily dosage of chemicals	Yes	Yes	Yes
2. Theoretical medium capacity can be utilized at most	No	No	Yes
3. High removal efficiency can be ensured; minimum short circuiting	No	No	Yes
4. Easy to construct, even by the users	Yes	Yes	Yes/No
5. Construction materials are cheap and widely available	Yes	Yes	Yes/No
6. Can be sized for one or several families or e.g. a school	Yes	No	Yes
7. Can be connected to an overhead raw water reservoir (tight cover)	Yes	No	Yes
8. Can be connected to piped water supply (none return valve)	No/Yes	No	Yes
9. Can be made of normal water buckets or purchased ready-made	No/Yes	Yes	No
<i>Disadvantages</i>	<i>Drum type</i>	<i>Bucket type</i>	<i>Column type</i>
10. Medium needs renewal or regeneration at saturation	Yes	Yes	Yes
11. Surveillance of saturation point is difficult; needs monitoring.	Yes	Yes	Yes
12. Low removal efficiency if water is withdrawn at high rate	Yes	Yes	No
13. Risk of medium water drainage, “drying”	No	Yes/No	No
14. Less convenient packing and setting up.	No	No	Yes/No

Technical setup. Figure 1 illustrates three most common types of bone char filters. Table 3 indicates the differences among them. The illustrated technical setups are commonly used for all types of sorption process.

One of the basic differences concerns the water flow in the filter. In the column filter the flow resembles *plug flow*, where the upper parts of the filter bed get saturated at a time where the lower parts are still fresh. Then the saturation zone moves slowly towards the bottom effluent point. This kind of flow allows for saturation of the medium with respect to the high fluoride raw water. Hence the high capacity utilisation in the column systems. In the drum or the bucket filter the flow resembles a *total mix* system, where the medium at saturation point is in equilibrium with the treated water. Hence the low capacity utilisation in the drum and the bucket type filters.

Another technical criterion of the different setups is whether the filter allows for drainage of the medium water in case treated water is withdrawn without taking care of the raw water supply. “Drying” the medium means disturbance of the sorption

TABLE 4. Examples of design of the bone char filters illustrated in figure 1. For simplification the filters are designed assuming the same daily water consumption, raw water and bone char quality.

Parameters:			Design Examples		
			Filter Type		
			Drum	Bucket	Column
<i>Given Parameters:</i>					
		Unit			
D	Daily personal water demand	L/(c•d)	3	3	3
N	Number of users	p	6	6	6
OP	Operation period months	months	12	3	6
Γ_O	Operational sorption capacity	g/kg	2	2	4
σ	Bulk density of medium	kg/L	0.83	0.83	0.83
F_i	Raw water fluoride conc.	mg/L	10	10	10
F_t	Treated water average fluoride conc.	mg/L	1	1	1
$VR_{SW/M}$	Volume ratio supernatant water/medium	-	2	2.5	0.2
$VR_{CW/M}$	Volume ratio clean water container/medium	-	0	3.5	0
<i>Derived Parameters:</i>					
$Q = D \cdot N$	Daily water treatment	L/d	18	18	18
$V_T = OP \cdot Q$	Total volume of water treated in a filter period	L	6500	1600	3200
$F_T = V_T \cdot (F_i - F_t) / 1000$	Total fluoride removal during a period	g	60	15	30
$M = F_T / \Gamma_O$	Amount of medium required for renewal	kg	30	7	7
$V_M = M / \sigma$	Volume of medium in the filter	L	35	9	9
$BV = V_T / V_M$	Number of bed volumes treated in a filter period	-	185	185	370
$V_{SW} = VR_{SW/M} / V_M$	Volume capacity of supernatant water	L	70	22	2
$V_{CW} = VR_{CW/M} / V_M$	Volume capacity of clean water container	L	0	31	0
$V_F = V_M + V_{SW} + V_{CW}$	Total Volume of filter	L	105	62	11
<i>Corresponding dimensions:</i>					
$\emptyset$	Filter diameter (selected as available)	cm	42	32	12
$H_F = V_F / [\pi \cdot (\emptyset/2)^2]$	Total height of the filter	cm	75	75	92

process and more contact time would be required for reestablishment. Unfortunately this point is overseen in many household filter designs.

Regeneration. Upon saturation with fluoride, it is feasible to regenerate bone char. This can be done by allowing equilibrium with 1 % solution of sodium hydroxide and after-wash or neutralisation of the caustic soda surplus ¹. Probably the regeneration is only cost effective at a large scale water works level or in case of constraints in availability of the medium. At village-community and household levels, it is easier and environmentally acceptable to discard the saturated bone char as fertiliser and soil conditioner.

Design Criteria. Apart from the daily water demand, i.e. the load, and the raw water fluoride concentration, the main key parameter of all designs would be the bone char *theoretical defluoridation capacity*, Γ . Γ is expressed as the amount of fluoride absorbed by one gram of bone char at saturation. Unfortunately it is often seen in laboratory studies that Γ is estimated with respect to unrealistically high fluoride concentrations. In water treatment one should use the *operational defluoridation capacity*, with reference to the given fluoride concentration and experimental setup. Obviously, saturation with respect to the raw water fluoride concentration, as in column filters, would result in much larger utilisation of a bone char medium than saturation with respect to the effluent concentration at the end of a filter period, as in bucket filters (drum or bucket filters).

Thus at operational level, Γ depends on the loading pattern, i.e. the variation of water flow through the filter medium, and the *back mix* pattern, i.e. to what extent the water flow resembles a *plug flow* through the filter medium. Different sorption models are developed to simulate the operation of bone char filters and thus to create a rational background for the design of these filters ⁶.

As a rule of thumb it is assumed that:

<i>Operational Defluoridation Capacity in column filters</i>	$\approx$	$2/3$	<i>Theoretical Capacity</i>	<i>defluoridation</i>
<i>Operational Defluoridation Capacity in bucket filters</i>	$\approx$	$1/3$	<i>Theoretical Capacity</i>	<i>defluoridation</i>

Examples of design of bone char filters are given in Table 4. Assuming the theoretical bone char defluoridation capacity is 6 mg/g, the operational capacity would then be 4 mg/g for column filters and 2 mg/g for bucket filters.

Table 4 demonstrates how the dosage equivalent is 2 and 4 g/L for respectively column filter and bucket & drum filters. If the same dosage is added as in batch the residual concentration will be less than average in the filters.

Cost. All three types of bone char filters can be made locally using cheap locally available robust and corrosion resistant materials like plastic, concrete, ferrocement or

galvanised iron sheets. In such cases the unit price would be affordable to most motivated communities.

The price of bone char on the other hand may be significant, depending on the fabrics. F. ex. in 1995 quotations were collected for large scale delivery of bone char *ab fabric* from UK, China and Tanzania. The prices given were 2280, 333 and 167 US\$/ton respectively. Finally it was found out that the bone char could be prepared in a low cost locally made kiln out of free collected bones in the Arusha region in Tanzania by using about 120 kg of charcoal per ton.

Experiences. Bone char is the oldest known water defluoridation agent. It has been used in USA in the 1940's through 1960's, where bone char was commercially widely available, because of its use at large scale in the sugar industry ¹.

The first domestic defluoridators were developed in the early 60ies as column filters similar to the one shown in Figure 1c ^{15,28}. In 1988 the ICOH filter type was launched by WHO ²⁷ and has since been tested both in and outside Thailand. In the contrary to the filter described by ²⁸, the ICOH type filter is enriched with charcoal, and thus has the capacity of removal of impurities in case the raw water quality is poor or in case the of insufficient bone charring. Furthermore the water flow in the ICOH defluoridator occurs by siphoning the raw water from an overhead container. This arrangement allows for manual adjustment of the water flow by using tube clamps, but the unit would need supervision and training in order to avoid the column to run dry and the clean water jar to overflow.

Today the bone char defluoridation in waterworks is replaced by the use of ion exchange resins and activated alumina. At domestic level the bone char defluoridation seems to function in Thailand and Africa, but no wide scale implementation has been experienced yet.

It is experienced that filters are launched commercially at a relatively high price, as packages of medium and a modification of the candle type domestic filters of stainless steel.

Taboos. One of the constraints of the bone char defluoridation is related to possible conviction among some users that any use of animal bones is unethical. In such cases the use of bone char must be avoided.

However, it has been experienced that many users only take aversion to the use of bone char originating from certain animals, like caws among Hindus, pigs among Muslims and Jews, and hyena and dogs among Africans. From a scientific point of view all types of bones are equally good as raw materials for bone char, but in such cases the problem would be solved through information and production of the bone char in accordance with local acceptability.

Irrespective the users conviction, the microbiological, esthetical and psychological complications would be fatal for the acceptability of the bone char defluoridation, if drinking water is allowed to percolate a medium containing organic residuals from animals. It has therefore to be emphasised that this would only happen in case of

incomplete charring. Properly prepared bone char is totally mineralised and, if this is the case, the black colour of the bones is nothing but non-organic activated carbon.

CONTACT PRECIPITATION

Description. Contact precipitation is a recently discovered technique, by which fluoride is removed from the water through addition calcium and phosphate compounds and then bringing the water in contact with an already saturated bone char medium. In a solution mix of calcium, phosphate and fluoride, the precipitation of calcium fluoride and/or fluorapatite is theoretically feasible, but practically impossible due to reaction inertness. It has recently been reported that the precipitation is easily catalysed in a contact bed which acts a filter for the precipitate¹⁰. Using calcium chloride, CC, and sodiumdihydrogen-phosphate, MSP, as chemicals the following equations may illustrate the removal:

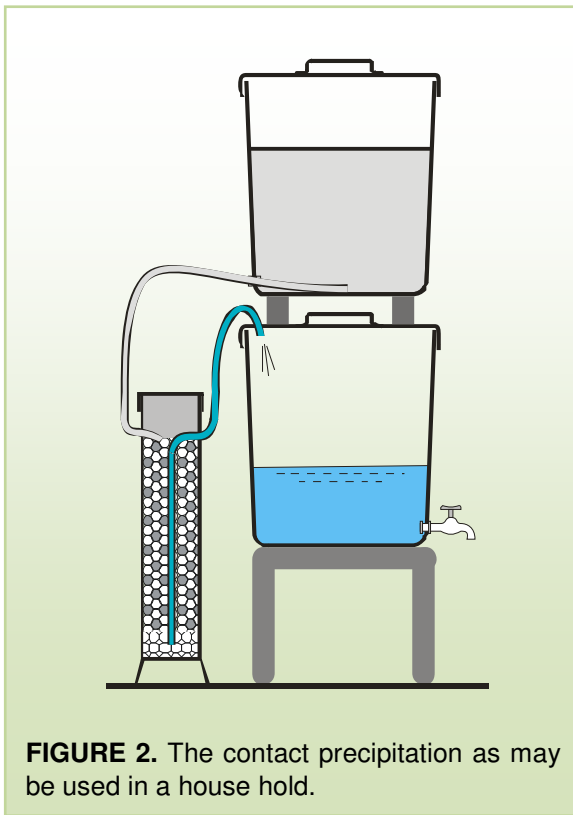
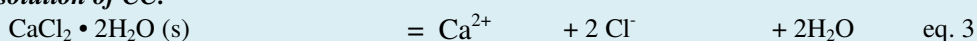
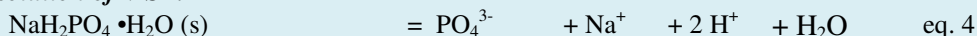


FIGURE 2. The contact precipitation as may be used in a house hold.

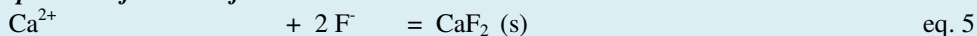
Dissolution of CC:



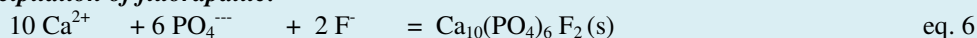
Dissolution of MSP:



Precipitation of calcium fluoride:



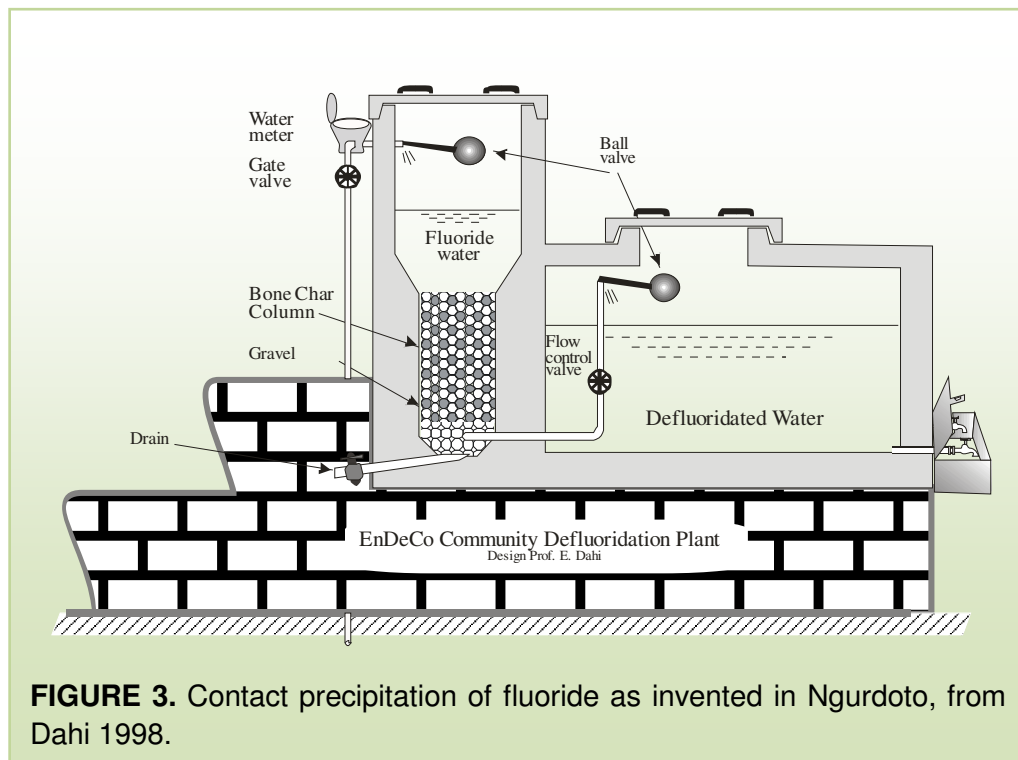
Precipitation of fluorapatite:



From the equations it is seen that the bone char medium, i.e. hydroxyapatite does not take part in the reactions. Hence it does not need to be renewed or regenerated, but it would need to be drained out for de-sludging and refreshment after a certain operation period. The only daily routine required is to add the two chemicals, preferably in stock solutions, along with the water, either continuously as water flows into the unit, or when the water is supplied batch wise for daily consumption.

The process seems to be promising, because it implies: 1) Relatively low daily working load. 2) High reliability without the need of surveillance of flow or effluent

concentration. 3) High removal efficiency, even in case of high raw water concentrations. 4) Low operation cost. 5) No health risk in case of misuse or over-dosage of chemicals.



Technical Setup. Though it has so far only been implemented at village level in Tanzania and Kenya the contact precipitation is probably suitable for implementation at any required level. Figure 2 & 3 show the contact precipitation plant as developed for household and installed at different schools in the rural areas of the Arusha region, Tanzania.

The plants consist of a column, containing a relatively small, saturated bone char contact bed. Gravel, or coarse grain size bone char, is used as bearing medium. Above the bed a relatively large space is left as raw water compartment, in which the chemicals are mixed. From the bed the defluoridated water flows continuously by gravity to a shallow but wide clean water tank. One or more clean water taps are fitted at bottom. The flow from the raw water tank to the clean water tank is constrained by a valve or a narrow tube arrangement to allow for sufficient contact time in the bed. The filter resistance is negligible compared to the flow resistance in through the tube and the valve 11.

In a large scale plant both the contact bed and the defluoridated water tank may be supplied with plastic tubes used as manometers. Both tubes are ended few cm below the upper edges of the tanks in order eventually to avoid overflow.

Chemical Dosage in Stock Solutions: Any calcium and phosphate compounds can be used. It is however important to bring the chemicals in solution prior to mixing with the water. As a calcium compound calcium chloride, **CC**, may be used. As a phosphate compound sodiumdihydrogenphosphate, also called monosodium phosphate or **MSP**, may be used. Both compounds are easily dissolved, quite cheap and widely used. CC is fabricated as technical grade flakes containing 77-80 % calcium chloride. One MSP product is fabricated as Bolifor Granular containing 24 % P and 20 % Na. The bulk density of the chemicals may be 1.04 for CC and 0.95 for MSP.

The chemicals are preferably prepared as stock solutions to be used in aliquots. The two stock solutions may be prepared, e.g. once every month, but should not be mixed before treatment in order to avoid the precipitation of calcium phosphate. Two special measuring cups may be used for volumetric portioning of the chemicals. It is advisable to check the bulk density as it may vary for different brands. The stock solutions Jerry cans, along with the respective chemical bags and the measuring cups and cylinders may be coloured respectively in red and green in order to minimise the risk of exchange and failure dosage.

Operation of the Domestic Unit: Initially the raw water bucket would be empty. The plant caretaker starts closing the flow control valve completely and one and half liters of each of the stock solutions are added to be mixed with a part of the raw water fetched to the raw water column. As the residual raw water is filled into the raw water column, the supernatant water is completely mixed. The flow control valve is then opened, but only to allow slow flow through the contact bed, the average filtration velocity not exceeding 0.5 m/h.

Operation of the Community Plant: Initially the raw water column would be empty. The plant care taker starts closing the flow control valve completely and each of the two stock solution aliquots are added to be mixed with a part of the raw water fetched to the raw water column. As the residual raw water is filled into the raw water column, the supernatant water would be completely mixed. The flow control valve is then opened, but only to allow slow flow through the contact bed, the average filtration velocity not exceeding 0.5 m/h or about 0.5 cm/min.

Design Criteria. The construction of the contact precipitation plants is simple, but the theoretical background for doing it is not. Probably both reactions 5 and 6 play important roles, but it is not well known to what extent each of them does. In the calcium fluoride precipitation, the Ca/F weigh ratio is about 1, equivalent to a CC/F ratio of about 4. In the fluorapatite precipitation, the Ca/F is 11 and the PO_4/F ratio is 15, equivalent to a CC/F ratio of about 39 and a MSP/F ratio of about 23.

Thus the more fluoride is precipitated as calcium fluoride the lower is the required dosage of chemicals. Probably the calcium fluoride precipitation is more dominant the higher the fluoride concentration in the raw water. Long term operation of the contact precipitation technique in Tanzania, where the fluoride concentration is about 10 mg/L, have shown that the process functions perfectly when the dosage ratios are 30

and 15 respectively for CC and MSP. This dosage would ensure at least 65 % precipitation of fluorapatite and a surplus of calcium for precipitation of the residual fluoride as calcium fluoride. This dosage is adopted in table 5, just to be on the safe side. The over-dosage is of no economic or health significance and lower dosage levels may be recommended on trail and error basis.

TABLE 5. Examples of design of domestic bucket and school brick plants for contact precipitation of fluoride, cf. 2 & 4. It is assumed that calcium compound, CC, used is calcium chloride containing about 27 % calcium, and sodiumdihydrogenphosphate, MSP, containing about 65 % phosphate.

<i>Given Parameters:</i>		<i>Design Examples</i>		
		Unit	Domestic	School /Market
D	Daily personal water demand	L/(c•d)	3	0.5
N	Number of users	p	6	500
F _i	Raw water fluoride conc.	mg/L	10	10
F _t	Treated water average fluoride conc.	mg/L	0.4	0.4
ε	Medium porosity	-	0.56	0.56
σ	Medium bulk density	kg/L	0.83	0.83
v	Filtration velocity	m/h	0.5	0.5
t _C	Contact time (=H _C •ε/v)	h	0.3	0.3
t _F	Filtration time (=Q/(v•π•(Ø/2) ²))	h	4	4
VR _{RW/Q}	Volume ration raw water/daily water treated	-	1.1	1.2
VR _{BC/Q}	Volume bone char medium/daily water treated	-	0.3	0.3
VR _{CW/Q}	Volume bone char medium/daily water treated	-	1.1	2
MR _{CC/F}	Mass ratio calcium chloride/daily fluoride loading	-	30	30
MR _{MSP/F}	Mass ratio MSP/daily fluoride loading	-	15	155
<i>Derived Parameters:</i>				
Q	= D • N Daily water treatment	L/d	18	250
F _T	= Q • F _i / 1000 Total daily fluoride loading (≈ removal)	g/d	0.18	2.5
Ø _{BC}	= 2(Q/(t _F • v • π) ^{0.5}) Diameter of contact bed	cm	11	40
H _{BC}	=t _C • v/ε Height of contact bed medium only	cm	27	40
M _{CC}	= F _T • WR _{CC/F} Total daily dosage of CC	g/d	5	75
M _{MSP}	= F _T • MR _{MSP/F} Total daily dosage of MSP	g/d	3	40
V _{RW}	= Q • VR _{CW/Q} Volume of raw water bucket/column	L	20	300
V _{BC}	= Q • VR _{BC/Q} Volume of contact bed medium	L	2.4	33.5
M _{BC}	= V _{BC} • σ Mass of contact bed medium	kg	2	30
V _{CW}	= Q • VR _{CW/Q} Volume of clean water bucket/tank	L	20	500

TABLE 5. Continued.

Corresponding Parameters:		Design Examples		
		Unit	Domestic	School /Market
W_{RW}	$\approx (V_{RW})^{1/3}$ Width of raw water column	cm	-	65
L_{RW}	$\approx W_{RW}$ Length of raw water column	cm	-	65
H_{RW}	$= V_{RW} / (W_{RW} \cdot L_{RW})$ Height of raw water column	cm	-	70
$\varnothing_{CB}$	$= \varnothing_{BC}$ Diameter of contact bed compartment	cm	-	40
H_{CB}	$= H_{CW}$ Height of contact bed compartment	cm	-	65
W_{CW}	$= W_{RW}$ Width of clean water tank	cm	-	65
H_{CW}	$= H_{CB}$ Height of clean water tank	cm	-	65
L_{CW}	$= V_{CW} / (B_{CW} \cdot H_{CW})$ Length of clean water tank	cm	-	120

Cost. Quotations were collected in 1996 for calcium chloride and sodium dihydrogen phosphate *ab fabric* whole sale. The figures given were 283 and 780 US\$/ton respectively.

Experiences. Experiences from the Arusha region have shown that construction of a plant need skilled supervision, at least until a bricklayer team has been through the construction of few plants. The critical points seem to be:

1. Water tight cement or plastic plastering.
2. Proper installation of fittings and
3. Adjustment of the flow rate to meet the given demands of contact time and filtration time.

Once these issues are taken care of, it has been demonstrated that a young school pupil can easily operate the plant satisfactorily.

No bacterial growth or disturbance in the efficiency of the plant has been observed during standing still in a rain season or a summer vacation.

The length of the operation period seems to be different in different setups. More field experiences are needed in order to establish guidelines about the de-sludging procedure.

NALGONDA

Description. The Nalgonda process is the aluminium sulphate based coagulation-flocculation sedimentation, where the dosage is designed to ensure appropriate fluoride removal from the water. Aluminium sulphate, $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$, is dissolved and added to the water under efficient stirring in order to ensure initial total mix. Rapidly aluminium hydroxide micro-flocs are produced and gathered into larger easily settling flocs. Hereafter the mixture is allowed to settle. During this flocculation process all kinds of micro-particles and negatively charged ions including fluoride are partially removed by electrostatic attachment to the flocs, eq. 7 -10.

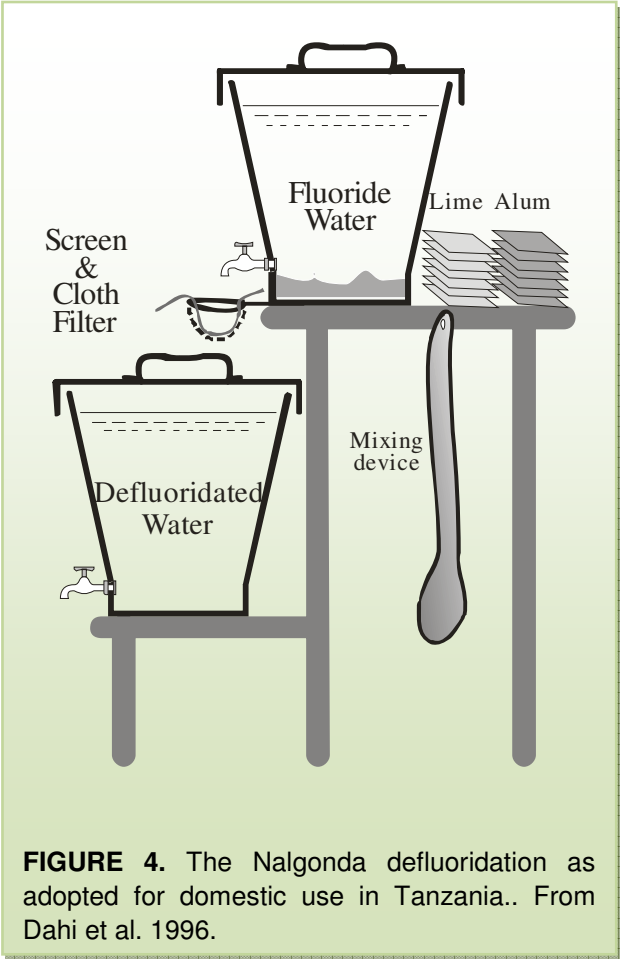
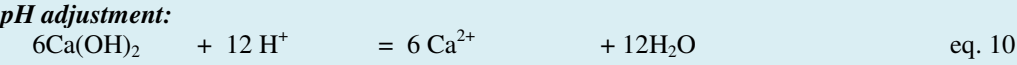
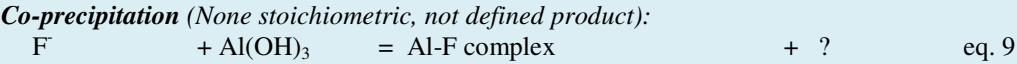
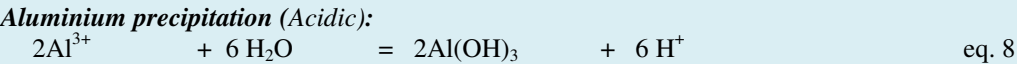
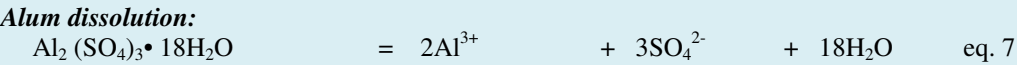


FIGURE 4. The Nalgonda defluoridation as adopted for domestic use in Tanzania.. From Dahi et al. 1996.



Compared to normal water flocculation, much larger dosage of alum is normally required in the defluoridation process. As the alum solution is acidic, simultaneous

addition of lime would often be needed. Lime would ensure neutral pH in the treated water and complete precipitation of aluminium. Surplus of lime is used as a thickener, i. e. to facilitate more complete settling. The treated water can be decanted. Safety filtration is however required, ensuring that no sludge particles escape with the treated water.

Technical setup. The Nalgonda defluoridation has been developed for African households as shown in Figure 4. Alum and lime are sold to the consumers as powders in small sealed differently marked plastic bags. One set of two bags contains the dosage required to defluoridate one bucket of water. The treatment system consists of two locally available 20 L plastic buckets, each supplied with one small brass tap of the type used for domestic filter containers. The taps are fixed 5 cm above the bottom of the buckets in order to enable trapping of sludge. The upper bucket tap is furthermore supplied with a tea sieve on which a piece of cotton cloth is placed, allowing the water to flow directly into the second clean water bucket.

Alum and lime are added simultaneously to the raw water bucket where it is dissolved/suspended by stirring with a wooden paddle. The villagers are trained to stir fast while counting to 60 (1 minute) and then slowly while counting to 300 (5 minutes). The flocs formed are left for settling for about one hour. The treated water is then tapped through the cloth into the treated water bucket from where it is stored for daily drinking and cooking.

It has been shown¹⁴ that the fluoride is bound to the aluminium hydroxide flocs only loosely. That is why it is prescribed to remove the treated water not later than a couple of hours after initiating the flocculation. If not, the fluoride concentration in the water would start increasing quite slowly but surely.

Design Criteria. The above described batch treatment is suitable for a daily routine, where one bucket of water is treated for one day water demand. If a 20 L bucket is used, the bucket should be filled with only 18 L to allow for efficient mixing with chemicals. An estimate of the amounts of alum required may be calculated using the Freundlich based formula as developed by Dahi et al. 1995¹³:

$$A = \frac{(F_r - F_t) \cdot V}{\alpha \cdot F_t^{1/\beta}}$$

Where:

- A is the amount of alum required, g.
- F_r is the fluoride concentration in the raw water, mg/l.
- F_t is the residual fluoride concentration in the treated water, mg/l.
- V is the volume of water to be treated in batch, l.
- α is the sorption capacity constant, $l^{(1-1/\beta)} \text{ mg}^{2/\beta} \text{ g}^{-1}$.
- β is the sorption intensity constant, -.

Any resulting pH between 6.2 and 7.6 is close to optimum. For pH = 6.7 and required residual fluoride between 1 and 1.5 mg/l, $\alpha = 6$ and $\beta = 1.33$. The amount of lime required to achieve optimum pH is difficult to estimate theoretically as it depends on the quality of lime, the alkalinity and pH of the raw water and the fluoride removal itself. Lime addition may be 20-50 % of the alum dosage.

Cost. According to COWI 1998⁹ the price of one of the above buckets in Tanzania is about 3000 TZS or about 3.3 US\$ in 1995 prices. The tap would cost about 1.7 US\$. Seven pairs of alum and lime bags could be made available for 0.15 US\$. In this price 20 % represent the purchase of chemicals. Alum is purchased at a tax free whole sale scale as normally for water works.

Sludge Problem.

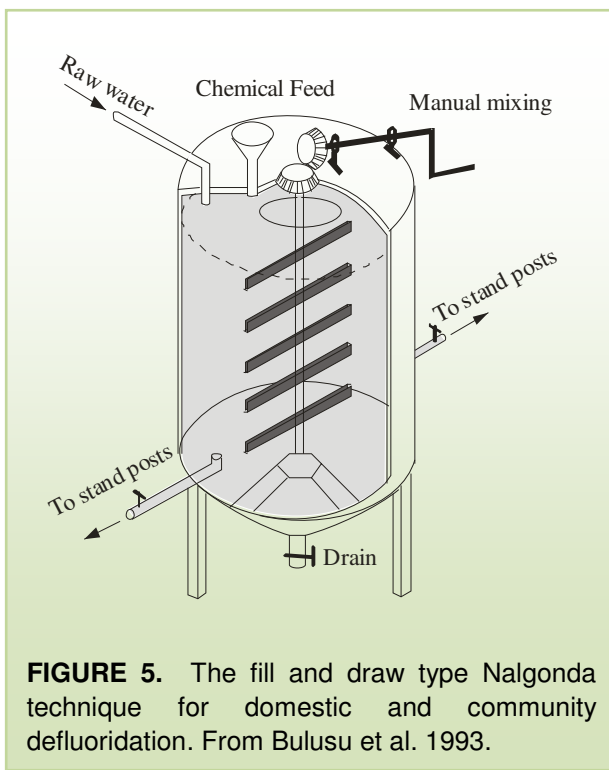
Discarding the sludge from the Nalgonda process is often thought of as a serious environmental health problem. The sludge is quite toxic as it contains the removed fluoride in a concentrated form. The sludge retained in the empty raw water bucket is to be discarded in a pit or a soak away:

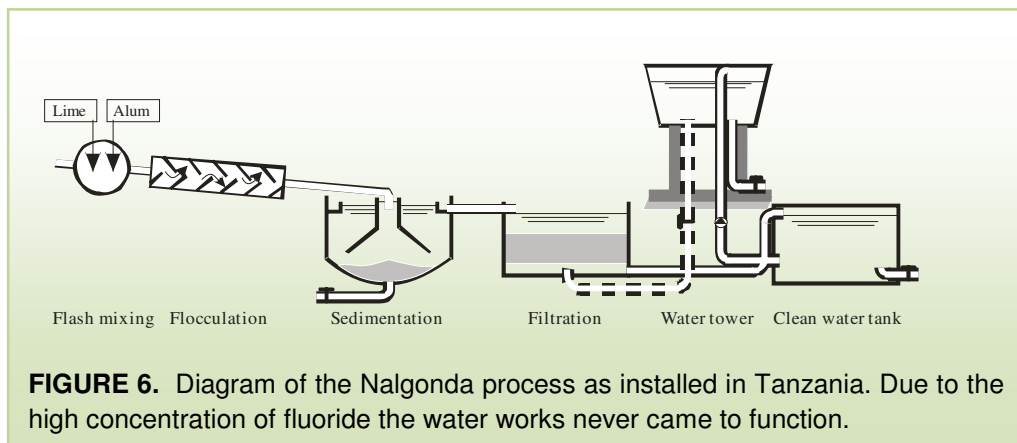
- Inaccessible to children
- Inaccessible to animals
- Remote from kitchen garden and
- Remote from wells which may be used for drinking.

In nature the fluoride would be expected to immobilize rapidly due to weathering processes. The free fluoride ion would then be subject to infiltration to underground or rain run off.

Once these precautions are taken, the sludge would be of low or no environmental health significance, as far as only drinking and cooking water is treated.

Experiences. The alum and lime process was proposed for defluoridation of water as soon as the fluoride occurrence in water became known in US as the agent behind mottling of teeth⁴. Four decades later the process was adopted by NEERI as the Nalgonda technique and developed for low cost use at all levels in India²⁴. Figure 5 & 6 illustrate setups of the Nalgonda technique at village community and water works levels.





The comprehensive studies on the Nalgonda technique at NEERI have resulted in three main achievements:

- The widespread of knowledge about fluorosis and the possibilities of solving the treatment problems at different levels even at very low cost.
- The understanding of the non-stoichiometric co-precipitation mechanisms for removal of fluoride in the flocculation process.
- The dosage design given as a simple table nomogram, indicating the required dosage of alum for given values of water alkalinity and fluoride concentrations. The dosage of lime is fixed to 5 % of the added alum⁷.

Unfortunately the above mentioned design was not found to be useful for African waters of relatively high fluoride and low alkalinity. Furthermore for African waters it was found that lime should be added at much higher dosage in order to ensure pH of optimum removal. Accordingly a more appropriate mathematical tool for the design was developed¹³.

In spite of the fact that the Nalgonda technique has been introduced in many cases and places, it has yet not been demonstrated to be the method of choice. It has certainly the great advantages of being most cheap, most simple and based on most widely available chemicals and materials. Yet experiences have shown that the following may play a role as negative factors:

- The treatment efficiency is limited to about around 70 %. Thus the process would be less satisfactory in case of medium to high fluoride contamination in the raw water.
- Large dosage of alum, up to 700 – 1200 mg/L, may be needed. Thus it reaches the threshold where the users starts complaining about residual sulphate salinity in the treated water. The large dosage is also resulting in large sludge problem in case of water works treatment.
- It is often seen that the users are not properly instructed, resulting in high working load in terms of unnecessary long lasting mixing.

It is often discussed that much care has to be taken to avoid the escape of aluminium in the treated water. Experiences have demonstrated that the risk of water contamination has been highly overstated. Where the aluminium is soluble in the

water, pH would be so extreme that the water would be undrinkable. Practically speaking it is only needed to avoid the escape of flocs. This is easily done by a careful drain of the supernatant water in combination of simple filtration as a second barrier.

ACTIVATED ALUMINA

Description. Activated alumina is aluminium oxide, Al_2O_3 , grains prepared in a way that they have sorptive surface. When the water passes through a packed column of activated alumina, pollutants and other components in the water are adsorbed to the surface of the grains, cf. equation 1. Eventually the column becomes saturated, first at its upstream zone. Later, as more water is passed through, the saturated zone moves down streams and in the end the column gets totally saturated.

The *total saturation* means that the concentration of fluoride in the effluent water increases to the same value as the influent water. The total saturation of the column must be avoided. The column is only operated to a certain *break point*, where the effluent concentration is e.g. 1.5 mg/L at *normal saturation*. The time between the start of operation and the break point of the column is presented by V; the accumulated volume of treated water. When dividing V by the bulk volume of the activated alumina packed, a standard operational parameter is obtained; i. e. the number of Bed Volumes, BV. BV is an expression of the capacity of treatment before the column medium needs to be renewed or regenerated. BV is highly dependent on the raw water fluoride concentration.

Technical setup. The activated alumina process is carried out in sorption filters as shown in Figure 1. A user-friendly unit, cf. figure 7, is made commercially available in Scandinavia through the HOH-Water Technology LTD. In order to avoid the monitoring of the water quality, the unit is supplied with a water meter allowing for direct indication of the cumulative water flow. After treatment of e.g. 2000 L equivalent to 250 BV of water containing about 5 mg/L, the unit is opened for renewal of the 8 kg medium. Alternatively the unit is dismantled for regeneration by the dealer.

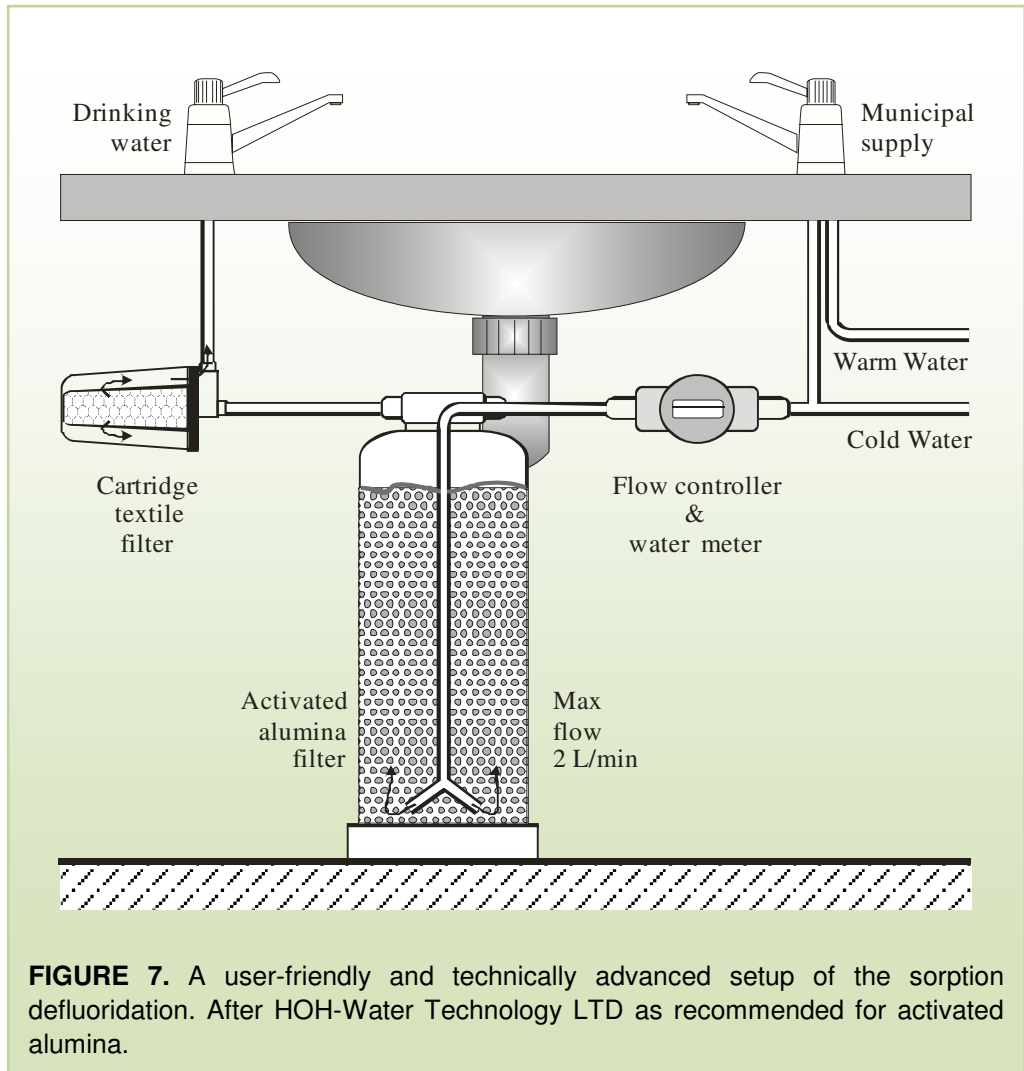
Regeneration. Regeneration of the saturated alumina is carried out by exposing the medium to 4 % caustic soda, NaOH, either in batch or by flow through the column, resulting in a few BV of caustic, high-fluoride contaminated wastewater. Residual caustic soda is then washed out and the medium is neutralised with a 2 % solution of sulphuric acid rinse.

During this process about 5-10 % alumina are lost, and the capacity of residual medium is significantly reduced, 30-40 %. After only 3-4 regenerations the media has to be replaced. Alternatively, in order to avoid on site regeneration, the saturated alumina can be recycled to a dealer, who can take care of standardising the capacity of the activated alumina using an appropriate mixture of fresh and regenerated media.

In development water supply projects where the process is operated at domestic level, the regeneration can not be left to the users. Instead, a central chemical store is set up

in each village, where the users can get the regeneration done along with motivation and encouragement to continue the fluorosis prevention.

It has to be mentioned that the regeneration may result in escape of aluminium and pollution of the drinking water, $> 0.2 \text{ mg/L}$, in case pH is not fully readjusted to normal.



Design Criteria. The alumina process is designed as a sorption process according to same principle as bone char, cf. Table 4. Similar considerations about the flow and the mix are valid. Also in the case of alumina the key design parameter is the operational defluoridation capacity, which may deviate from the theoretical.

According to Hao et al.¹⁷, the fluoride removal capacity of alumina is between 4 and 15 mg/g. Experiences from the field however, show that the removal capacity is often about 1 mg/g⁹. Thus there seems to be a waste difference in the degree of

“activation” of alumina products. One of the explanations may be due to variation in pH. The capacity of alumina is highly dependent on pH, the optimum being about 5. While it may be easy to adjust pH for maximum removal at a water work, one has to depend on the genuine pH of the raw water in domestic and small community treatments. Another explanation is the brand of the product. Most laboratory tests are carried out using pure highly sorptive media and distilled waters, while fieldwork is based on commercially available technical grade media and naturally polluted water. With other words, it is almost impossible to extrapolate laboratory data to field conditions. For the design one has to establish the capacity of the available alumina through testing under authentic conditions. As a preliminary qualified guess the removal capacity of 1 mg/L and the bulk density of 1.2 kg/L may be used.

Cost. Few years ago the activated alumina process, due to high chemical cost and non-availability in markets, was out of consideration in most developing countries. It is no longer the case. Recent experiences mainly from India, Thailand and China indicate that activated alumina may under certain condition be affordable to low income communities.

TABLE 6. Some defluoridation unit prices of an NGO development project in India. From /COWI 1998/.

Item of Activated alumina	IRp	Item of Nalgonda	IRp
Defluoridator /unit + incl. 3 kg AA	1200	Defluoridator /unit	500
Activated alumina /kg	65	Alum /kg	3
Sodium hydroxide /kg	26	Lime /kg	4
Sulfuric acid 92 % /kg	8	Jerry cans, 2 pieces	160
Salary /regeneration of 3 kg	10	Measuring cylinder	60
Defluoridator /unit + incl. 3 kg AA	1200	Defluoridator /unit	500

Experiences. Activated alumina was proposed for defluoridation of water and a drum filter, figure 1a, was patented for domestic use already in 1936¹⁶. Since then the activated alumina has been subject to several patents and, due to commercial interests, one of the most advocated defluoridation methods.

As the ceramic candle domestic filter is well known in some countries, it, or version similar to it, has been used as a unit for the activated alumina defluoridation. In a special modification, the “candles” are replaced with a connection screen and a wing nut for adjustment of the filtration rate.

Activated alumina is a largely available industrial chemical. It is however not widely distributed at grass root level as alum is. Furthermore, its use has been limited by the difficulties of regeneration, the low capacity of less purified technical grade products and the relative high price. During the recent years the activated alumina became less costly and more popular, especially in middle income countries, where it is now a day possible to manufacture.

CLAY

Description. Clay is an earthy sedimentary material composed mainly of fine particles of hydrous aluminium silicates and other minerals and impurities. Clay is fine-textured, plastic when moist, retains its shape when dried and sinters hard when fired. These properties are widely utilised in the manufacture of pottery, brick and tile. Both clay powder and fired clay are capable of sorption of fluoride as well as other pollutants from water. Well known is clay's ability to clarify turbid water. This property is believed to have been commonly known and utilised at domestic level from ancient time, e.g. in Egypt.

Technical setup. Though clay takes up fluoride as in a sorption process, it may be used as a flocculent powder in a batch system like the one shown in figure 4. As clay has a relative high density, e. g. compared to bone char, it will settle and enable decanting or drain of the supernatant water.

The use of clay powder in columns is possible, but troublesome mainly because of difficulties in packing the columns and controlling the flow.

Domestic clay column filters are therefore normally packed using clay chips wasted in the manufacture of brick, pottery or tile. Figure 7 illustrates such a column filter. It resembles the filter used in Sri Lanka and reported by Padmasiri in 1997²⁵. The filter is based on up flow in order to allow for settling of suspended solid within the filter bed. The filter does not have a clean water reservoir and the filtration rate is controlled by slow withdrawal through the tap.

The column described by Padmasiri is stratified with one layer of charred coconut shells and another layer of pebbles above the entire bed of brick chips. Depending on the raw water quality, and on the quality of the brick chips, such an after-filtration through charcoal may be a precondition to get good water quality. As char coal has a low specific density, the pebbles stabilise the stratified bed and are necessary to avoid the escape of char coal grains with the treated water.

Regeneration. Clay and similar media can be regenerated, at least in part. It would however in most cases not be cost effective. The process has therefore to be established on medium renewal at less cost.

Design Criteria. Based on testing of the capacity of clay to remove fluoride from water, different studies reveal different conclusions about the capacity and about the usability of the method in general. Thus Zevenbergen et al. 1996³⁰ conclude that "the Ando soil appears to be an economical and efficient method for defluoridation of

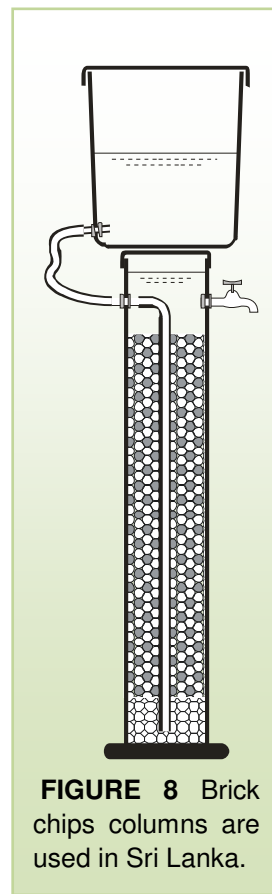


FIGURE 8 Brick chips columns are used in Sri Lanka.

drinking water” while Bulusu et al. 1979⁸ do not find the clay worth mentioning as a defluoridation agent.

According to the study of Zevenbergen et al. 1996³⁰ the defluoridation capacity of Ando soil of Kenya is 5.5 mg/g while Moges et al. 1996²³ find that the capacity of ground and fired clay pot of Ethiopia is no more than 0.2 mg/g. One could conclude that the Ando soil of Kenya is more efficient in defluoridating the water than the clay pot powder of Ethiopia. A close look at the data indicates that this is not the case. If the Ando soil studied by Zevenbergen et al. 1996³⁰ is simulated used under authentic field conditions in a bucket treatment system, it reveals defluoridation capacity of the same order as studied by Moges et al. 1996²³, i. e. about 0.2 mg/g.

Bårdsen & Bjorvatn /1997/ studied the sorption isotherm of clay calcined at 600 °C. They found that the sorption continues to take place even up to 10 days of contact time, but the capacity was as low as 0.07 mg/g at 1 mg/L level. Thus in order to remove 3.4 mg/L of fluoride from water containing fluoride at as high level as 12.5 mg/L, within one hour of contact time, they had to add calcined clay at level of 100 g/L, i.e. batch operational capacity of 0.03 mg/g. Convincing field experiments have been reported from Sri Lanka²⁵ showing an operational capacity of 0.08 mg/g brick chips used in column defluoridators .

According to Jinadasa et al. 1988²⁰, the capacity is known to be at optimum when pH is about 5.6.

For design purposes the operational capacity has to be investigated at first. As a preliminary guideline the capacities of 0.03 and 0.1 mg/g may respectively be used for design of batch and column defluoridators using clay materials, e. g. as shown in Table 7. Because the clay powder in a bucket system is to be added at large dosages, the volume of the treated water wasted along with the sludge has to be encountered.

TABLE 7. Examples of design of bucket flocculation as illustrated in figure 1b and an up flow column filter as illustrated in figure 7. It is assumed that clay powder having capacity 0.03 mg/g and bulk density of 1.5 kg/L in the bucket type filter. The column filter utilizes clay brick grains of 8-16 mm, the capacity being 0.1 mg/g and the bulk density 1.3 kg/L.

<i>Given Parameters:</i>		<i>Design Examples</i>		
		<i>Unit</i>	<i>Bucket type</i>	<i>Column type</i>
D	Daily personal water demand	L/(c•d)	3	3
N	Number of users	p	6	6
OP	Operation period	days	1	180
Γ_O	Operational sorption capacity	g/kg	0.03	0.1
σ	Bulk density of medium (Powder & Chips)	kg/L	1.05	0.86
F_i	Raw water fluoride conc.	mg/L	3	3
F_t	Treated water average fluoride conc.	mg/L	1	1
$VR_{SW/M}$	Volume ratio supernatant water / medium	-	-	1/5
$VR_{AF/M}$	Volume ratio after-filter water / medium	-	-	½
$VR_{S/Q}$	Volume ratio of sludge / water demand	-	1/10	-
$VR_{VS/Q}$	Volume ratio vacant space for mix./ water demand	-	1/15	-
<i>Derived Parameters:</i>				
Q	= D • N Daily water treatment	L/d	18	18
V_S	= Q • $VR_{S/Q}$ Volume of residual sludge	L	2	-
V_T	= OP • Q + V_S Total volume of water treated in a filter period	L	20	3200
F_T	= $V_T \cdot (F_i - F_t) / 1000$ Total fluoride removal during a period	g	0.04	6
M	= F_T / Γ_O Amount of medium required for renewal	kg	1.3	65
V_M	= M / σ Volume of medium in the filter	L	0.9	50
BV	= V_T / V_M Number of bed volumes treated in a filter period	-	-	45
V_{SW}	= $V_M \cdot VR_{SW/M}$ Volume capacity of supernatant water	L	-	15
V_{AF}	= $V_M \cdot VR_{AF/M}$ Volume of after-filter arrangement	L	-	40
V_{VS}	= Q • $VR_{VS/Q}$ Volume capacity of vacant space in bucket	L	1.2	0
V_B	= Q + V_S + V_{VS} ; $V_F = V_M + V_{SW} + V_{AF}$ Total Volume of bucket/filter	L	40	130
<i>Corresponding dimensions:</i>				
Ø	Filter diameter (selected as available)	cm	35	40
H	= $V_B / (\pi \cdot (\text{Ø}/2)^2)$ or $V_F / (\pi \cdot (\text{Ø}/2)^2)$ Total height of the bucket / filter	cm	40	100

From the design examples shown in table 7 it may be seen that the dosages required are estimated to be 73 and 20 g/L respectively. Thus the dosage is much higher than in the other methods, even though the raw water fluoride is as low as 3 mg/L. Furthermore the removal efficiencies are expected to be low i. e. 67 %. Probably the clay process would be of no or at least much less use if the water contains higher concentrations of fluoride or if better removal efficiencies are demanded.

Hygienic precautions. It is well known that clay and most other soil minerals, which demonstrate defluoridation capacities, primarily are cation-exchangers. It is also well known that especially toxic heavy metals and a wide range of other pollutants may be retained in the clay strata when rainwater percolates the soil. Furthermore it is well known that clay is efficient to retain bacteria and virus and most other infectious pathogens. Care has therefore to be taken in order to ensure that any soil material to be used in a defluoridation process:

- The medium should be calcined and stored hygienically.
- The medium loses its defluoridation capacity if calcined to dead burnt temperatures, e. g. 1200 °C.
- The medium should be tested for potential dissolution of toxic materials.
- The medium should not allow for microbial growth due to contents of organic carbon.

Cost. It has been stated by Padmasiri 1997 ²⁵, that the clay process is only cost effective if the freshly burnt broken bricks of good quality are available on site or next door to the users and if the filter is prepared using low cost locally available materials.

Experiences. According to Padmasiri 1997 ²⁵, nearly 80 % of 600 clay columns defluoridators installed in house holds in Sri Lanka were found in operating conditions after being monitored in different periods from 2 years to date. The described technology was found to be sustainable, but only if the uses were motivated through information and motivation campaigns ⁹.

EVALUATION AND SELECTION OF METHOD

The above reporting on the methods of defluoridation reveals that we do not have a universal method that can be sustained under all kinds of social, financial, environmental and technical constraints. This is in agreement with the fact that none of methods has been implemented successfully at a large scale in many parts of the world. This is quite remarkable, especially when taking into consideration, that several defluoridation methods have been studied in details and even reported as appropriate methods, for quite a number of years ^{7, 8, 18, 24, 27, 30}. Apart from the contact precipitation all the methods have been known already in the mid-thirties, where the agent behind “the Colorado stain”, fluoride, was discovered.

This oddity is probably due to the fact that the available defluoridation methods do have disadvantages. Some of these are what may be designated as killer disadvantages, in the sense that the method turn out to be unsustainable under the

given socioeconomical conditions. As killer disadvantages of defluoridation methods may be mentioned:

1. **High Cost-Tech;** i.e. either the price and/or the technology is high, demanding imported spare parts, continuous power supply, expensive chemicals, skilled operation or regeneration and the like. Reverse osmosis, ion exchange and activated alumina may thus be categorised as high cost-tech methods.
2. **Limited efficiency;** i.e. the method does not imply sufficient removal of the fluoride, even when appropriate dosage is used. Like in the Nalgonda technique, the residual concentration would often be higher than 1 mg/l, unless the raw water concentration it self is low.
3. **Unnoticeable break through;** i. e. the fluoride concentration in the treated water may raise gradually or suddenly typically when a medium in a treatment column is exhausted or even when the flow is out of control. Like in the case of bone char and other column filters, these techniques necessitate continuous monitoring of fluoride residual, or at least the rate and the volume of treated water, if the unnoticeable break through or the waste of removal capacity are to be avoided.
4. **Limited capacity;** while the removal capacity of bone char or activated alumina may be about 2 mg fluoride per g of medium, much higher amounts of f. ex. calcined clay or Nirmali seeds, has to be used in order to obtain appropriate removal.
5. **Deteriorated water quality;** some methods like the activated magnesia would by nature result in too high pH-values, normally above 10. The water quality may also deteriorate due to poorly prepared medium (bone char) or due to medium escaping the treatment container, e.g. ion exchangers, alumina, Nalgonda sludge etc..

TABLE 8. General comparison of advantages of the most promising defluoridation methods. BC = Bone char, CP = contact precipitation, Nal = The Nalgonda technique or alum and lime, AA = activated alumina, CI = calcined clay.

“Risk” means in some cases.

+ indicates advantage. – indicates potential disadvantage.

<i>Advantages:</i>	<i>Defluoridation Method</i>				
	<i>BC</i>	<i>CP</i>	<i>Nal</i>	<i>AA</i>	<i>CI</i>
1. No daily dosage of chemicals, i.e. no daily working load	+	-	-	+	+
2. Dosage designed for actual F-conc. independent of unit or plant	-	+	+	-	-
3. No risk of false treatment due to break point	-	+	+	-	-
4. Removal capacity of medium is independent of F-concentration	-	+	-	-	-
5. No regeneration or renewal of medium is required	-	+	+	-	-
6. High removal efficiency can be ensured	+	+	-	+	--
7. Easy to construct, even by the users	+	+	++	+	+
8. Construction materials are cheap and widely available	+	+	++	+	+
9. Can be sized for one or several families or e.g. a school	+	++	+	+	-
10. No risk of medium/chemicals unacceptability	-	-/+	+	+	-
11. No risk of deterioration of the original water quality	-/+	+	-/+	-/+	-

6. **Taboo limitations;** especially the bone char method is culturally not acceptable to Hindus. The bone char origin from pigs may be questioned by Muslims. Even the charring of bones have been reported to be repulsive to villagers in North Thailand.

On the other hand all the methods mentioned do have advantages and have shown to be capable of removing fluoride at certain conditions. Four criteria are essential and may contribute to the success of fluorosis prevention through treatment of drinking water at decentralised level:

The most appropriate method has to be selected to deal with given water quality and social acceptability. Table 8 may be useful in selection of method.

Proper design and process understanding are required at least among the surveillance officers.

Media and unit spare parts have to be made available through an infrastructural setup, like village communities and social and health workers.

Motivation and training of users has to be continued through the same or a similar infrastructure.

ACKNOWLEDGEMENT

The Danish International Development Agency, Danida, has kindly provided financial support for the preparation of this paper.

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