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Comparison of hydrofluorosilicic acid and pharmaceutical sodium fluoride as fluoridating agents—A cost-benefit analysis

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ABSTRACT

Water fluoridation programs in the United States and other countries which have them use either sodium fluoride (NaF), hydrofluorosilicic acid (HFSA) or the sodium salt of that acid (NaSF), all technical grade chemicals to adjust the fluoride level in drinking water to about 0.7–1 mg/L. In this paper we estimate the comparative overall cost for U.S. society between using cheaper industrial grade HFSA as the principal fluoridating agent versus using more costly pharmaceutical grade (U.S. Pharmacopeia – USP) NaF. USP NaF is used in toothpaste. HFSA, a liquid, contains significant amounts of arsenic (As). HFSA and NaSF have been shown to leach lead (Pb) from water delivery plumbing, while NaF has been shown not to do so. The U.S. Environmental Protection Agency's (EPA) health-based drinking water standards for As and Pb are zero. Our focus was on comparing the social costs associated with the difference in numbers of cancer cases arising from As during use of HFSA as fluoridating agent versus substitution of USP grade NaF. We calculated the amount of As delivered to fluoridated water systems using each agent, and used EPA Unit Risk values for As to estimate the number of lung and bladder cancer cases associated with each. We used cost of cancer cases published by EPA to estimate cost of treating lung and bladder cancer cases. Commercial prices of HFSA and USP NaF were used to compare costs of using each to fluoridate. We then compared the total cost to our society for the use of HFSA versus USP NaF as fluoridating agent. The U.S. could save \$1 billion to more than \$5 billion/year by using USP NaF in place of HFSA while simultaneously mitigating the pain and suffering of citizens that result from use of the technical grade fluoridating agents. Other countries, such as Ireland, New Zealand, Canada and Australia that use technical grade fluoridating agents may realize similar benefits by making this change. Policy makers would have to confront the uneven distribution of costs and benefits across societies if this change were made.

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1. Background

The first recommendation to use fluoride for the purpose of reducing dental caries was made in the United States, but not adopted, in 1939 (Cox, 1939). Cox had studied the effect of fluoride on caries formation in rats, which followed research carried out earlier (e.g., Dean, 1938) on caries incidence in humans. In 1945 the program of adding fluoride to public water supplies for this purpose was begun on an experimental basis. The amount of fluoride in drinking water supplies of three cities, Newburgh, N.Y., Grand Rapids, MI and Brantford, Ontario, Canada was adjusted upward to approximately 1 mg/L. Later, the recommended amount of fluoride to be achieved in public water supplies was set by the U.S. Public Health Service at 0.7–1.2 mg/L, depending on local climate. In January 2011, the U.S. Department of Health and Human Services proposed lowering the recommended optimal target concentration to 0.7 mg/L (DHHS, 2011). At the time fluoridation began, the form of fluoride used was technical grade NaF. Since 1947 when NaSF was introduced (McClure, 1950), the dominant fluoride source has become HFSA itself. NaSF and HFSA together are commonly referred to as silicofluorides (SiFs). Some European countries along with some regions of Canada, New Zealand and Australia, among others countries, followed the American lead in instituting fluoridation programs using these agents. It is beyond the scope of this article to go deeply into the historical development or the economic and health public implications of fluoridation programs on an international scale. Our work is focused on information from the U.S. experience with this practice.

HFSA arises in a by-product stream from production of phosphate chemicals through the presence of various silicates, calcium fluoride and calcium fluorapatite in the phosphate ore (Denzinger et al., 1979). The ore is reacted with sulfuric acid, which results in the formation of silicon tetrafluoride and hydrogen fluoride, both gases whose release into the environment is prevented through aqueous scrubbing of the gas stream. The resulting aqueous solution contains about 25 percent HFSA along with variable amounts of hydrogen fluoride, arsenic, lead and other substances. EPA considers use of this by-product as “an ideal environmental solution to a long-standing problem. By recovering by-product fluosilicic (sic) acid from fertilizer manufacturing, water and air pollution are minimized, and water utilities have a low-cost source of fluoride available to them.” (EPA, 1980). Arsenic levels in this HFSA product vary substantially (e.g. Pollock, 2011), but are typically about 30–35 mg/kg (see [Supplemental Material Appendix A](#)). It is noteworthy that HFSA arising from phosphate production in China is at least under consideration for use in the U.S., and may be under consideration – or currently being used – in other countries with fluoridation programs.

The most common form of NaF used in tooth paste in the U.S. is made by a different process and contains markedly less arsenic (Phibro, 2009 see [Supplemental Material Appendix B](#)). It is produced by reacting high purity calcium fluoride with sulfuric acid to produce hydrogen fluoride, which is then neutralized with high purity sodium carbonate or sodium hydroxide (Pollock, personal communication – email and phone – December 2, 2010).

The EPA (EPA, 2011) has set the health-based, non-enforceable drinking water standards, known as Maximum Contaminant Level Goals (MCLGs), for both As and Pb at zero. The enforceable standards, known as Maximum Contaminant Levels (MCLs) are 10 $\mu\text{g/L}$ and 15 $\mu\text{g/L}$, respectively. While EPA does not regulate the amount of either contaminant that can be introduced to drinking water by substances added to water supplies, in practical terms the amount of As and Pb entering drinking water supplies in this way is regulated by NSF, Inc. and the American National Standards Institute via the NSF/ANSI Standard 60 (CDC, 2011a,b). This standard sets the maximum amount of any substance that can be added to drinking water for which EPA has established an MCL at less than 10 percent of that MCL, or less than 1 $\mu\text{g/L}$ for As and less than 1.5 $\mu\text{g/L}$ for Pb.

In the [Supplemental Material Appendix A](#) provides examples of the variability of the arsenic content of HFSA along with substantiation of our assertion that our use of 30 mg/kg As as an average for typical HFSA is reasonable. We show in [Section 3](#) how this average As level in HFSA leads to an As level in finished water of 0.078 $\mu\text{g/L}$. [Supplementary Material Appendix C](#) contains a statement by the former National Fluoridation Engineer, Thomas Reeves of the U.S. Department of Health and Human Services, Centers for Disease Control and Prevention (CDC) Oral Health Division, that As levels in finished drinking water found by the entity responsible for overseeing compliance with legal requirements governing drinking water treatment chemicals, NSF, Inc., averaged 0.43 $\mu\text{g/L}$ (IFIN, 2001). In our calculation of comparative risks we use both the 0.078 $\mu\text{g/L}$ and 0.43 $\mu\text{g/L}$ As levels as well as the maximum level that could arise from use of HFSA that complies with the NSF/ANSI Standard 60, viz. 0.99 $\mu\text{g/L}$.

There appears to be little or no concern by officials responsible for implementing water fluoridation, at least in Wellington, Florida., over the health consequences of adding as much as 1.1 $\mu\text{g/L}$ of As to the local water supply via HFSA because that amount is much “less than the MCL of 10 $\mu\text{g/L}$ (ppb) set by the USEPA and deemed safe for human consumption over extended periods of time.” (Riebe W, personal communication – email – to Charlene Arcadi-pane, February 21, 2011. See [Supplementary Material Appendix D](#)).

It is noteworthy that if the assertion made by Riebe is correct, then the HFSA used in Wellington, Florida that resulted in adding that much As to the community water supply was in violation of the NSF/ANSI Standard 60 (NSF, 2011), because it added more than 10 percent of the MCL for As to that drinking water supply. The above information about the Wellington, Florida water supply is in the second paragraph of [Supplementary Material Appendix D](#). The City of Wellington officially reported its drinking water in 2009 to have a total As content of 1.6 $\mu\text{g/L}$ (Wellington, 2009).

An independent study of operations at the South Central Connecticut Water Authority published by the American Water Works Association (Weng et al., 2000) showed that HFSA contributed about 90 percent of As found in finished water. The study showed that the “normal” amount of As contributed by HFSA in that community was 0.114 $\mu\text{g/L}$.

2. Objective

In comparing the overall costs for U.S. society between using cheaper industrial grade HFSA as the principal fluoridating agent versus using more costly pharmaceutical grade NaF the simplest component of comparison, and the one which is the subject of this paper, involves the cost of treating As-related lung and bladder cancer cases associated with HFSA versus USP NaF. We used information on numbers of cancers associated with exposure to As in drinking water and their treatment costs published by EPA when it established its current MCL for arsenic (EPA, 2001).

Another component of social cost, increased blood-lead levels and their sequelae associated with use of SiFs as fluoridating agents, has been addressed by others (Edwards et al., 2007; Maas et al., 2007; Masters and Coplan, 1999; Masters et al., 2000; Masters, 2003; Shapiro and Hassett, 2012) and is not part of our analysis. These latter costs to society may well exceed those associated with cancer treatments.

3. Method

While a larger number of cost comparisons could be made, we chose to present only four comparisons of costs associated with the As-related cancer risks presented by the two alternative fluoridating agents:

1. Typical levels of As in both agents. Calculations based on this case are shown below in this section.
2. Typical levels of As in HFSA and maximum level in USP NaF (Phibro, 2009).
3. Maximum allowed As level for HFSA permitted under NSF/ANSI Standard 60 and typical levels for USP NaF (Phibro, 2009).
4. Average level of As reported by NSF in finished water and level of As in finished water using typical USP NaF (Phibro, 2009). See [Supplementary Material Appendix C](#).

3.1. Estimation of comparative fluoridation costs

We calculated the amount of each agent required to increase the fluoride level in water by 0.5 mg/L to reach 0.7 mg/L, and used sale prices (Boulder, 2007; Pollock, personal communication, 2010) for each agent to determine the cost of artificially fluoridating one liter of water. Then we calculated the size of the U.S. population receiving water fluoridated with HFSA based on available data (See below). Next we calculated the total cost in the U.S. to fluoridate the water used by the population currently receiving fluoridated water using EPA data on daily water use per capita (EPA, 2009), U.S. Department of Commerce data (DOC, 2010) on U.S. population and U.S. Public Health Service data (CDC, 1993, 2008a, 2008b) on the fraction of the U.S. population affected.

3.1.1. Estimation of 2010 exposed population

We used available data from CDC to estimate the number of U.S. citizens receiving water containing HFSA, employing a

compromise between strict adherence to significant figure usage and maximum use of available population data. In 1992, the last year in which CDC made such data available (CDC, 1993), 10,006,000 U.S. citizens received naturally fluoridated water. We assumed that the number receiving naturally fluoridated water was unlikely to grow faster than the general population, which was 256,500,000 in 1992 (CDC, 1993). In 2010 the U.S. population was estimated at 312,000,000 (DOC, 2010). So the number receiving naturally fluoridated water in 2010 was estimated at $10,006,000 \times 312,000,000/256,500,000 = 12,170,000$.

We used CDC data (CDC, 2008a) on the U.S. population on public water systems receiving fluoridated water (which includes both natural and adjusted fluoride levels meeting the CDC criteria for fluoridated water) in 2008, the last year such data were made available. These data showed 269,912,000 people on public water systems, of which 72.4 percent received fluoridated water. This number is 195,500,000. We adjusted this number the same way the naturally fluoridated population was adjusted, by multiplying that value by the ratio of the 2010 U.S. population to the 2008 U.S. population (CDC, 2008a), arriving at this value: $195,500,000 \times 312,000,000/304,060,000 = 200,600,000$ people receiving fluoridated water. Then we subtracted the number receiving naturally fluoridated water from the total fluoridated population: $200,600,000 - 12,140,000 = 188,460,000$ to estimate the population receiving any fluoridation chemical.

We used data (CDC, 1993) from the last report by CDC on the populations receiving each of the three major fluoridating agents. These data showed 62.6 percent of people receiving adjusted fluoride were exposed to HFSA. Thus we estimate that currently $188,460,000 \times 0.626 = 118,000,000$ people are exposed to HFSA. We think this number may be lower than the actual number exposed. For instance, in Bexar County, TX prior to the 1992 fluoridation census there were 70,000 people exposed to HFSA (CDC, 2008b). Data from the 2008 census show that 1,474,000 additional people in Bexar County were receiving water fluoridated with HFSA (CDC, 2008b).

3.2. Estimation of per capita water use

EPA (2002) provides information on a variety of public water systems and their efforts at water conservation. The following 1998 per capita water uses for a sample set of systems – Albuquerque, NM 200 gal/day; Ashland, OR 150 gal/day; New York City 167 gal/day; Massachusetts Resources Board 136 gal/day; Seattle, WA 115 gal/day.

EPA (2009) cites household per capita water use as approximately 87 gal/day.

Considering the data from these two EPA sources we settled on the per capita value of 100 gal/day for use in our analysis.

3.3. Risk estimation method

We used Unit Risk values computed from EPA's Arsenic in drinking water final rule (EPA, 2001) to calculate the anticipated number of cancers attributable to use of each fluoridating agent along with estimated benefit values for

cancer cases avoided (EPA, 2001, 7013–7019) to estimate the total cost of treating those cancers. Rather than use the unit risk as published (EPA, 2011), we instead used a lower risk factor derived from EPA's analysis presented in its Final Rule (EPA, 2001, 7008) for Arsenic in Drinking Water. This lower risk factor employs the central tendency risk rather than the upper 95 percent confidence limit risk and leads to a lower number of cancer cases attributable to As in drinking water. A further measure to avoid over estimating cases of cancer was that we did not consider As transferred to foods or beverages made or processed with fluoridated water. We followed EPA's example (EPA, 2001, 7004) by rejecting a sub-linear dose-response hypothesis in calculating the number of cancer cases that could be attributed to the use of each agent from the amount of As in each. We then compared the costs of fluoridating and treating cancers attributable to each fluoridating agent.

3.3.1. Modified unit risk calculation (data from table III D-2[a], EPA, 2001, 7008)

As level ($\mu\text{g/L}$)	Mean exposed population risk	Unit risk [pop. risk/ $(\mu\text{g/L})$]
3	$9.3\text{--}12.5 \times 10^{-5}$	$3\text{--}4 \times 10^{-5}$
5	$16.3\text{--}20.2 \times 10^{-5}$	$3\text{--}4 \times 10^{-5}$
10	$24.1\text{--}29.9 \times 10^{-5}$	$2\text{--}3 \times 10^{-5}$

From the above a Unit Risk value of $3.5 \times 10^{-5}/(\mu\text{g/L})$ was derived and used below

3.4. Sample comparative costs calculation – case 1

3.4.1. Typical HFSA and typical NaF As Levels in drinking water

HFSA mixture: HFSA has a typical level of 30×10^{-6} g As per g HFSA (as delivered as 24% assay H_2SiF_6) (see [Supplementary Material Appendix A](#)). The product's density is 1.24 g/mL, and H_2SiF_6 is 79.2% (w/w) fluoride. Therefore $1.24 \text{ g/mL} \times 0.24 \times 0.792 = 0.235 \text{ g fluoride/mL HFSA}$ (235 mg fluoride/mL HFSA). And $1.24 \text{ g HFSA/mL} \times 30 \times 10^{-6} \text{ g As/g HFSA} = 37.2 \times 10^{-6} \text{ g As/mL HFSA}$

One needs about 0.5 mg fluoride/L of water to reach target fluoride level from typical surface water fluoride levels of about 0.2 mg/L. So one needs:

0.5 mg fluoride/235 mg fluoride/mL of HFSA = 2.1×10^{-3} mL HFSA.

That much HFSA delivers $2.1 \times 10^{-3} \text{ mL} \times 37.2 \times 10^{-6} \text{ g As/mL} = 7.8 \times 10^{-8} \text{ g As} = 7.8 \times 10^{-2} \mu\text{g As/L water}$.

NaF: One needs about 1.1 mg NaF to yield 0.5 mg fluoride/L of drinking water.

1.1 mg USP NaF $\times 0.76 \times 10^{-6} \text{ mg As/mg NaF} = 0.84 \times 10^{-6} \text{ mg} (0.84 \times 10^{-3} \mu\text{g}) \text{ As/L water}$

3.4.2. Population cancer risks: As concentration \times unit risk

HFSA: $7.8 \times 10^{-2} \mu\text{g As/L} \times 3.5 \times 10^{-5}/\mu\text{g As/L} = 2.7 \times 10^{-6}$

NaF: $8.4 \times 10^{-4} \mu\text{g As/L} \times 3.5 \times 10^{-5}/\mu\text{g As/L} = 2.9 \times 10^{-8}$

3.4.3. Cancer cases: population risk[3.4.2] \times exposed population[3.1.3]

HFSA: $2.7 \times 10^{-6} \times 118 \times 10^6 = 320/\text{yr}$

NaF: $2.9 \times 10^{-8} \times 118 \times 10^6 = 3.4/\text{yr}$

3.4.4. Cancer treatment costs (in \$Millions)

HFSA: $320 \text{ cases/yr} \times \$3,500,000/\text{case}$ (EPA, 2001, 7013–7019) = \$1120/yr

NaF: $3.4 \text{ cases/yr} \times \$3,500,000/\text{case} = \$12/\text{yr}$

NaF advantage: $\$1120 - \$12/\text{yr} = \$1,108/\text{yr}$

3.4.5. Annual fluoridation costs

Per capita water use: 100 gal. = 380 L [3.2]

Total daily water use by exposed population $380 \text{ L/day} \times 1.18 \times 10^8 = 4.5 \times 10^{10} \text{ L}$

HFSA: Sales price \$500/ton; \$0.25/lb (Boulder, 2007)

Need $2.1 \times 10^{-3} \text{ mL/L H}_2\text{O} \times 1.24 \text{ g/mL} \times 1 \text{ lb}/454 \text{ g} \times \$0.25/\text{lb} = \$1.4 \times 10^{-6}/\text{L}$

$\$1.4 \times 10^{-6}/\text{L} \times 4.5 \times 10^{10} \text{ L/day} \times 365 \text{ day/yr} = \$23 \times 10^6/\text{yr}$

NaF: Sales price \$3/lb (Pollock, 2010, personal communication)

Need $1.1 \times 10^{-3} \text{ g/L} \times 1 \text{ lb}/454 \text{ g} \times \$3/\text{lb} = \$7.3 \times 10^{-6}/\text{L}$

$\$7.3 \times 10^{-6}/\text{L} \times 4.5 \times 10^{10} \text{ L/day} \times 365 \text{ day/yr} = \$120 \times 10^6/\text{yr}$

HFSA advantage (\$Millions): $\$120 - \$23/\text{yr} = \$97/\text{yr}$

3.4.6. Annual total social costs (\$Millions)

HFSA Cancer treatment cost [3.4.4] plus fluoridation cost [3.4.5]

$\$1120 + \$23 = \$1143/\text{year}$

NaF: Cancer treatment cost [3.4.4] plus fluoridation cost [3.4.5]

$\$12 + \$120 = \$132/\text{year}$

NaF advantage: $\$1143 - \$132 = \$1011/\text{year}$

4. Results

The additional cost of purchasing and using pharmaceutical grade NaF over technical grade HFSA is about \$97 million annually. Cancer risk reduction factors, based on the ratio of the As level in HFSA fluoridated water to the As level in NaF fluoridated water are in [Table 1](#). The corresponding numbers of cancers along with the estimated treatment costs associated with each fluoridating agent are in [Table 2](#). In [Table 3](#) the realistic net annual social cost savings by using NaF is shown to range from about \$1 billion (Case 1) to about \$6 billion (Case 4) as shown in [Table 3](#).

We show in the [Supplementary Material](#) that with As levels that would pass the NFS/ANSI Standard 60, i.e. 380 ppm As, the savings could be as great as \$14 billion/year, and that based on the reported actual amount of As delivered to the Wellington, FL water system (Riebe, 2011), the savings would be about \$16 billion/year.

Additional social cost savings would be realized through avoidance of the consequences of elevated blood lead levels. We did not attempt to assess these additional social cost savings because of the complexities and uncertainties associated with the resulting effects, especially on lowering IQ of children exposed to higher lead levels. Nevertheless, based on one very limited example that has been analyzed (Masters, 2003), we recognize that there are potentially greater social cost savings attributable to avoiding this effect than from lowering cancer rates associated with As exposure.

Table 1 – Comparison of expected cancer cases HFSA vs. U.S.P. NaF.

Case	Fluoride source	mg As/kg source	µg As/L H ₂ O	Cancer risk per million	Lung/bladder Cancers
1	Typical HFSA	30	0.078	2.7	320
	Typical NaF	0.76	0.00084	0.029	3.4
2	Typical HFSA	30	0.078	2.7	320
	Max. NaF	1.5	0.0017	0.06	7
3	Max. HFSA ^a	380	0.99	35	4100
	Typical NaF	0.76	0.00084	0.029	3.4
4	NSF HFSA	nd ^b	0.43	15	1800
	Typical NaF	0.76	0.00084	0.029	3.4

^a Maximum As level permitted under NFS/ANSI Std 60.

^b As reported by NSF, Inc in terms of average As level in treated water. As level in the HFSA used was not reported (Reeves in IFIN, 2001; see Supplementary Material Appendix C).

Table 2 – Comparison of cancer treatment costs.

Case	Fluoride source	Lung/bladder cancer cases	Treatment cost (\$Millions)	Cost savings (\$Millions)
1	Typical HFSA	320	1120	
	Typical NaF	3.4	12	1108
2	Typical HFSA	320	1120	
	Max. NaF	8	24	1096
3	Max. HFSA ^a	4100	14,350	
	Typical NaF	3.4	12	14,338
4	NSF HFSA ^b	1800	6,300	
	Typical NaF	4	12	6388

^a Maximum As level permitted under NFS/ANSI Std 60.

^b As reported by NSF, Inc in terms of average As level in treated water. As level in the HFSA used was not reported (Reeves in IFIN, 2001; see Supplementary Material Appendix C).

Table 3 – Comparison of total social costs.

Case No.	Fluoride source	Chemical cost (\$ Millions)	Cancer treatment cost (\$ Millions)	Total social cost (\$Millions)	Social cost saving (\$ Millions)
1	Typical HFSA	23	1120	1143	
	Typical NaF	120	12	132	1011
2	Typical HFSA	23	1120	1143	
	Max. NaF	120	24	144	999
3	Max. HFSA ^a	23	14,350	14,373	
	Typical NaF	120	12	132	14,241
4	NSF HFSA ^b	23	6300	6323	
	Typical NaF	120	12	132	6191

^a Maximum As level permitted under NFS/ANSI Std 60.

^b As reported by NSF, Inc in terms of average As level in treated water. As level in the HFSA used was not reported. (Reeves in IFIN, 2001; see Supplementary Material Appendix C)

5. Conclusions

Our analysis shows that if local governments that currently add HFSA to their drinking water wish to continue delivering fluoride to their citizens and at the same time reduce the number of lung and bladder cancers among their citizens, they could do so with a significant net benefit to society by switching to USP NaF for fluoridation. We note that with respect to As added to water supplies by fluoridation additives, NSF/ANSI Standard 60 allows for significant cancer treatment costs, up to \$14 billion annually, to be incurred by society.

It is obvious that the benefits and cost associated with a switch from HFSA to the grade of fluoride used in tooth

paste are distributed unevenly across a society organized as is the U.S. That is, local governments that would purchase the more expensive fluoridating agent are unlikely to be the direct beneficiary of reduced cancer treatment costs. We cannot go further in this paper than to recommend that in the U.S. our results stimulate a study, perhaps by the Congressional Research Service, of how our society would deal with the cost/benefit distribution question.

The last Congressional review of the national program of water fluoridation in the U.S. took place over thirty years ago, and a great deal of new knowledge has been developed during that time. What we have presented here is but a small, but we think important, portion of that new knowledge.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.envsci.2013.01.007>.

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