AN ASSESSMENT OF MERCURY IN THE FORM OF AMALGAM IN DENTAL WASTEWATER IN THE UNITED STATES

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Abstract. An assessment was conducted of the discharge from dental facilities of mercury in the form of amalgam to surface waters in the United States. Two pathways were examined – effluent from publicly owned treatment works (POTWs) and air emissions from sewage sludge incinerators (SSIs). The annual use of mercury in the form of amalgam in the U.S. is approximately 35.2 tons (31.9 metric tons). It was estimated that 29.7 tons (26.9 metric tons) of mercury in the form of amalgam are annually discharged to the internal wastewater systems of dental facilities during amalgam placements and removals. Based on the partial capture of this amalgam in conventional chair-side traps and vacuum filters, the discharge of mercury in the form of amalgam from dental facilities to POTWs was estimated to be 6.5 tons (5.9 metric tons). The discharge of mercury to surface water via POTW effluents and SSI emissions was estimated to total approximately 0.4 tons (0.4 metric tons). A cost-effectiveness analysis determined that the annual cost to the dental industry to reduce mercury discharges through the use of amalgam separators would range from $380 million to $1.14 billion per ton.

Keywords: amalgam separator, biosolids, dental amalgam, dentistry, mercury, publicly owned treatment works, wastewater

1. Introduction

Amalgams (often referred to as silver fillings) have been the primary restorative material used by dentists in the United States for over 150 years (Yuming *et al.*, 1998). Amalgam has historically contained approximately 50% by weight mercury (Anusavice, 2003). Due to the growing concern regarding mercury as a persistent, bioaccumulative, and toxic (PBT) substance, the use of mercury in many industries and products in the United States has decreased substantially since the early 1980s (USEPA, 1997; Sznopek and Goonan, 2000). Although the available data indicate that the use of mercury in dental amalgams has also decreased during this period, the dental industry remains one of the largest consumers of mercury in the United States (ADA, 2002; Sznopek and Goonan, 2000).

The placement and removal of dental amalgams generates small amounts of amalgam particles in a dental facility's wastewater. This wastewater flows through a chair-side trap and, in the majority of dental facilities, a filter that protects the vacuum pump, prior to being discharged. Although chair-side traps and vacuum filters capture amalgam particles in the dental wastewater stream, some particles remain in the wastewater (MCES and MDA, 2001). Because the majority of dental facilities in the United States are connected to sewerage systems, this wastewater is primarily received and managed by publicly owned treatment works (POTWs). The concern regarding mercury as a PBT in the United States has prompted reductions in mercury discharges to surface waters from point sources, including POTWs. Therefore, the dental industry is currently facing increasing regulatory scrutiny at the national, state, and local levels regarding the mercury content of dental wastewater (AMSA, 2002).

Through the early 1990s, little data existed to accurately estimate the use of amalgam in dentistry and the resulting mercury content of dental wastewater. Researchers noted that the relative contribution of dental offices to the mercury load is not well documented and that the data on the amount of the different mercury contaminated waste categories produced in dentistry are sparse (Fan *et al.*, 1997; Arenholt-Bindslev and Larsen, 1996). Because of this lack of data, researchers recognized that initial assessments were dominated by rough estimates and assumptions (Arenholt-Bindslev, 1992; Arenholt-Bindslev and Larsen, 1996). Over the past several years, a number of studies have been conducted on the use of mercury in the dental industry and the attendant mercury content of dental wastewater, resulting in the generation of a substantial volume of data.

The objectives of the present study were to assess, through a comprehensive review of the available data, (1) the quantity of mercury used in amalgam in the United States, (2) the amount of mercury in the form of amalgam discharged from dental facilities to surface waters via POTW effluent and mercury emitted from sewage sludge incinerators (SSI), and (3) the cost-effectiveness of reducing these discharges through the installation and use of amalgam separators in dental facilities. This study was limited to the discharge of mercury in the form of amalgam to surface waters via the primary pathways of POTW effluent and mercury emissions from SSIs.

It was recognized that additional indirect pathways may exist for the discharge of mercury to the environment due to its use in dental amalgam. Other indirect pathways may include the volatilization of mercury from land-applied biosolids and the leaching of mercury from landfills. The scope of the present assessment was specifically to examine the discharge of mercury in POTW effluent and emissions from SSIs. However, in the course of conducting this assessment, a number of studies were identified that the authors believe provide initial or preliminary data to support that these indirect pathways are minimal sources of mercury.

Key among these is the highly bound form of mercury in the amalgam, which also plays a role in the calculations presented throughout this publication. The calculations presented herein assume that mercury remains in the form of amalgam throughout the wastewater conveyance and treatment process. This assumption is based on studies conducted by Kunkel *et al.* in 1996 and Okabe *et al.* in 2003, among others. Kunkel *et al.* studied the potential release of mercury from amalgam in aerobic and anaerobic wastewater treatment systems and did not detect soluble mercury, even when amalgam particles were introduced into the systems at concentrations on the order of 1,000 times the expected concentration of POTW influents. Okabe *et al.* evaluated the release of mercury from amalgam into continuously replenished water and acidic solutions (pH = 1) over 1 month and identified slow release rates that decreased exponentially over time. Preliminary calculations based on these release rates and the anticipated size and shape of discharged amalgam particles indicate that an insignificant fraction of mercury is released from dental amalgam in the tested solutions. Although more work is needed in this area, the authors have reasonably assumed that that the significant fraction of mercury in dental amalgam remains amalgamated through the wastewater conveyance and treatment process. As a result, mercury in the form of amalgam particles that are land-applied with POTW biosolids or landfilled are still relatively immobile as compared to many other sources of mercury (for example, background levels of mercury in soils).

Beyond the highly bound form of the mercury in the amalgam particles, other factors are likely to limit the quantity of mercury reaching surface waters from land-applied and landfilled amalgam particles. These include the reaction and fixation of any mercury released from amalgam particles with other compounds in soil and waste matrices, the application of additional layers of biosolids over land-applied amalgam particles over time, and the containment provided by landfill covers and leachate collection systems. Accordingly, the authors focused on direct discharges of mercury in the form of amalgam to surface waters and the incineration and ultimate deposition of mercury from amalgam particles present in biosolids as the primary pathways during this assessment.

2. Use, Capture, and Discharge of Mercury in the Form of Amalgam

2.1. Use of Mercury in the Form of Amalgam

The assessment focused on identifying and evaluating the mercury discharges to surface waters in the United States from the use of amalgam by general dentists and specialists in private practice. According to surveys conducted by the ADA, the United States dental industry comprised 166,611 active, licensed dentists in 2001. Approximately 92%, or 153,116, of these dentists were in private practice, with the remainder consisting of professors, graduate students, and federal employees. General dentists account for 122,320 of the dentists in private practice (ADA, 2002). Surveys conducted by product manufacturers indicate that approximately 76% of general dentists reported using amalgam in 2001, down from 88% in 1997 (White, 2001). It was estimated, therefore, that 92,957 (76% of 122,320) general dentists in private practice in the United States currently use amalgam.

According to the ADA, pediatric dentists, prosthodontists, and endodontists were the only specialists that reported using amalgam in 2001. These dentists constituted 10,739 of the 30,804 specialists in private practice in the United States (ADA, 2002). No data were available regarding the fraction of these specialists that used amalgam. It was therefore conservatively assumed that all 10,739 of these specialists used amalgam in their practice.

The ADA estimated that a total of approximately 71 million restorations were conducted using amalgam in 1999, down 29% from the 99.5 million amalgam restorations estimated by the ADA in 1990 (Berthold, 2002). The ADA's estimate correlated well with most recent estimates of mercury use in dentistry conducted by the USGS, which identified a decrease of 30% from 1990 to 1996 (Sznopek and Goonan, 2000). According to the ADA, general dentists performed approximately 66.3 million of the 71 million amalgam procedures conducted in 1999, and pediatric dentists, prosthodontists, and endodontists performed the remaining 4.7 million procedures (Berthold, 2002).

Based on the data presented above, it was estimated that general dentists that use amalgam annually perform an average of 713 amalgam placements per dentist, and the pediatric dentists, prosthodontists, and endodontists annually perform an average of 440 amalgam placements per specialist. The amalgam placement rate estimated for general dentists correlated well with data collected in the early to mid-1990s by various domestic municipalities, including the Municipality of Metropolitan Seattle, Washington; the Metropolitan Council Environmental Services (MCES) in Minneapolis-St. Paul, Minnesota; and the Western Lake Superior Sanitary District (WLSSD) in Duluth, Minnesota. The annual placement rates reported by these municipalities for general dentists averaged approximately 710 amalgam placements per general dentist when adjusted for the decrease in amalgam use throughout the 1990s (Municipality of Metropolitan Seattle, 1993; MCES, 1995; WLSSD, 1992). No comparable data for specialists were identified.

Stone *et al.* (2001) reported the average mercury content per double spill of amalgam to be approximately 450 mg. Combined with the 71 million restorations reported by the ADA in 1999, it was estimated that the United States dental industry currently uses approximately 35.2 tons (31.9 metric tons) of mercury in the form of amalgam each year. This quantity correlates well with the USGS' most recent estimate of mercury consumption by the dental industry of 34.2 tons (31 metric tons) in 1996 (Sznopek and Goonan, 2000). Given the decrease in amalgam use in recent years, it was recognized that the use of 35.2 tons (31.9 metric tons) provided a conservative, upper-bound estimate of the current, annual consumption of mercury by the dental industry in the United States.

2.2. Release of mercury in the form of amalgam to dental wastewater

The mercury used as amalgam by the dental industry is primarily placed in teeth as a restorative material. However, dentists commonly triturate excess amalgam during each procedure to ensure that sufficient mixed amalgam is available to complete the restoration of the tooth prior to the hardening of the amalgam. The leftover amalgam from this process is often identified as "non-contact" amalgam because it has not been in contact with a patient's mouth. The Florida Center for Solid and Hazardous Waste Management (1997); Arenholt-Bindlsev (1992); and Barron (2001) estimated that 15% to 50% of the amalgam triturated for placement is collected by dentists and recycled as non-contact amalgam. Barron's estimate of 25% was used as an approximate average of the percentages reported in the literature. Applying this percentage, it was estimated that 8.8 tons (8 metric tons) of the mercury used by the dental industry in the United States becomes non-contact amalgam. The remaining approximately 26.4 tons (24 metric tons) of mercury is used in amalgam placements, for an average of approximately 340 mg of mercury used per placement. Barron (2001) estimated that 9% of amalgam, or about 30 mg of mercury per placement, is ultimately discharged to the internal wastewater systems of dental facilities during amalgam placements, such that only 310 mg is actually placed in the tooth. This percentage was applied to the estimated 26.4 tons (24 metric tons) of mercury used in amalgam placements to estimate that approximately 2.4 tons (2.2 metric tons) of mercury are annually discharged as amalgam particles to the internal wastewater systems of dental facilities in the United States during amalgam placements.

Recent data were not available regarding the number of amalgams removed by the dental industry. However, five municipal studies that had evaluated amalgam removal rates in the early to mid-1990s were identified, including the three studies noted previously by the Municipality of Metropolitan Seattle, Washington (1993); MCES (1995); and WLSSD (1992), and two studies conducted by the City of San Francisco (Rourke, 1993) and the Massachusetts Water Resources Authority (Bering, 1997). These studies reported amalgam removal rates on daily and weekly bases; therefore, data regarding the work schedule of the dental industry was obtained from the ADA in order to compare annual rates. For 1999, the ADA reported that the average dentist spent 1,600 h per year conducting patient examinations and restorative procedures, and worked an average of 48 weeks per year (ADA, 2001). Normalizing the data from the available studies, the average amalgam removal rate was approximately 710 removals per general dentist per year. Data were not available regarding the removal rate for specialists. It was estimated, therefore, that specialists remove amalgams at a rate similar to the placement rate of approximately 440 amalgams per specialist per year. Further, it was assumed that all of the general dentists, pediatric dentists, prosthodontists, and endodontists in the United States removed amalgam in their practices. Considering the numbers of active general dentists and specialists estimated above and their respective removal rates, it was estimated that approximately 91.5 million amalgam removals are currently conducted in the United States each year.

The USGS estimated the average life of a dental amalgam as approximately 8–9 years in its evaluations of the cycling of mercury as a commodity in the United

States (Sznopek and Goonan, 2000). As a result, it was anticipated that the amalgam placement rates of 1990 would generally approximate the amalgam removal rates for 1999 (i.e., the typical amalgam placed in 1990 would likely be removed in approximately 1999 for replacement with an amalgam or composite). According to the ADA, 99.5 million amalgam placements were conducted by general dentists in 1990 (Berthold, 2002). This generally correlates with the 91.5 million amalgam removals estimated from the municipal studies.

The mass of amalgam originally placed in a tooth will be greater than that ultimately removed from the tooth at the end of the amalgam's useful life due to losses associated with wear. Barron (2001) estimated that 90% of the mercury originally placed in amalgam is present at the time of removal. With an estimated amalgam life of 8–9 years, this percentage was in general agreement with the annual mercury loss rates predicted by Skare (1995) and the United States Agency for Toxic Substances and Disease Registry (ATSDR, 1999). When applied to the estimated average mass of mercury originally placed as amalgam (310 mg), this percentage indicated that the average amalgam would contain approximately 280 mg of mercury when removed from the tooth. This estimate was slightly lower than the results of a study of amalgam conducted by Watson *et al.* (2002). During the study, amalgam was removed from 152 human and dentoform teeth. Although the age of the removed amalgam was not identified during the study, the data indicated that an average of approximately 320 mg mercury was present in each removed amalgam.

Each amalgam currently removed by dentists in the United States was estimated to contain an average of 300 mg of mercury based on the studies conducted by Barron (2001) and Watson *et al.* (2002). Combined with the estimated 91.5 million amalgam removals conducted each year, it was estimated that approximately 30.3 tons (27.5 metric tons) of mercury in the form of amalgam are removed annually. Barron (2001) estimated that 90% of mercury in the form of amalgam is released to the internal wastewater systems of dental facilities during the removal procedures. Therefore, it was estimated that approximately 27.2 tons (24.7 metric tons) of mercury in the form of amalgam are annually discharged to the internal wastewater systems of dental facilities during removal procedures.

By summing the discharge estimates for both amalgam placements (2.4 tons or 2.2 metric tons) and removals (27.3 tons or 24.8 metric tons), it was estimated that a total of approximately 29.7 tons (26.9 metric tons) of mercury in the form of amalgam are discharged to the internal wastewater systems of dental facilities in the United States each year.

2.3. Capture of mercury in the form of amalgam in dental facilities

Dental wastewater generated from restorative procedures flows through a chair-side trap and, in the majority of dental facilities, a filter that protects the vacuum pump, prior to discharge (MCES and MDA, 2001). Drummond *et al.* (1995) identified a capture efficiency for chair-side traps of 60% based on sampling data, while Naleway *et al.* (1994) estimated that chair-side traps capture 75% of amalgam in dental wastewater based on particle size distribution studies. An average chair-side trap capture efficiency of 68% was selected based on the capture efficiencies reported by these studies.

Based on studies conducted in Minneapolis-St. Paul, Minnesota, the MCES and MDA reported that approximately 71% to 88% of the surveyed dental facilities were equipped with vacuum filters (MCES, 1995; MCES and MDA, 2001). These estimates are similar to those reported in a study conducted by Watson *et al.* (2002), which estimated that approximately 90% to 95% of dental facilities in Ontario, Canada were equipped with vacuum filters. Approximately 80% of the dental facilities in the United States were estimated to be equipped with vacuum filters based on the average of the results of the MCES and MDA studies.

In 2001, the MCES and MDA conducted a detailed evaluation of the efficiency of vacuum filters in capturing amalgam particles that pass a chair-side trap, and identified an overall capture efficiency of 42%. Particle size distribution studies conducted by Batchu *et al.* (1995) and Cailas *et al.* (1994) indicated that capture efficiencies for vacuum filters range from 25% to 50%. An average vacuum filter capture efficiency of 40% was estimated based on the average of the capture efficiencies identified from these studies.

The industry-wide capture efficiency of mercury in the form of amalgam was calculated using the data identified in the literature for the capture of chair-side traps and vacuum filters. Dental facilities equipped with both a chair-side trap and vacuum filter were estimated to capture approximately 81% of the amalgam particles in dental wastewater due to the combined capture of both devices, while dental facilities equipped with only a chair-side trap were estimated to capture 68% of the amalgam particles. An estimated 80% of the dental facilities in the United States are equipped with both chair-side traps and vacuum filters and 20% are equipped with chair-side traps only. A weighted average was utilized to estimate an industry-wide capture efficiency for dental facilities in the United States of approximately 78%. This capture efficiency assumes that dentists manage chair-side traps and vacuum filters appropriately, as has been emphasized by the ADA in recent years through education and outreach efforts and recently updated ADA best management practices for amalgam waste (ADA, 2004).

The industry-wide capture efficiency of 78% was applied to the estimated 29.7 tons (26.9 metric tons) of mercury annually discharged in the form of amalgam to the internal wastewater systems in dental facilities to estimate the mass of mercury captured each year. Based on this capture efficiency, it was estimated that chair-side traps and vacuum filters capture approximately 23.2 tons (21 metric tons) of mercury in the form of amalgam, and that the dental industry discharges approximately 6.5 tons (5.9 metric tons) of mercury in the form of amalgam each year.

2.4. Capture of mercury in the form of amalgam in POTWs

In the United States, the wastewater generated by dental facilities is discharged to either POTWs or septic systems. The Maine Dental Association recently conducted a survey of its constituents, and estimated that 86% of the dentists in Maine discharged wastewater to POTWs and that the remainder is discharged to septic systems (F. Miliano, personal communication). Little additional data regarding this distribution was identified from a review of the literature. In order to be conservative in the estimate of mercury loading to POTWs, it was assumed that all of the dental facilities in the United States discharge to POTWs.

A review of the open literature was conducted to identify POTW capture efficiencies for mercury and mercury in the form of amalgam. Although substantial data were identified regarding the capture of mercury by POTWs, little data was identified for the capture of mercury in the form of amalgam. The capture of a particle, such as amalgam, by a POTW is largely a function of particle density and size (Tchobanoglous and Burton, 1991). The density of amalgam is approximately 10 times that of water (Fan *et al.*, 2002b). Analyses of the particle size distribution of amalgam generated from dental procedures conducted by the American, Dutch, and German Dental Associations in support of the development of a representative amalgam sample for International Organization for Standardization (ISO) Standard 11143 have indicated that amalgam particles are generally larger than the other forms of mercury captured in POTWs. These analyses determined that approximately 98% of the particles generated from amalgam placements and removals are larger than 5 μm (ISO, 1999). In comparison, a study of mercury entering a POTW in St. Paul, Minnesota reported that 85% of the mercury entering the POTW from all sources was associated with particle sizes greater than 5 μm (Balogh and Liang, 1995). Although these data indicate a higher POTW capture efficiency for mercury in the form of amalgam than for other forms of mercury, it was conservatively estimated that all forms of mercury are captured at the same efficiency.

A number of recent studies have reported mercury capture efficiencies for POTWs ranging from 95% to 99%. The most comprehensive of these studies was conducted by AMSA (2002), and included of a review of 15 POTWs ranging in capacity from approximately 4 million gallons per day (MGD) to 375 MGD. The AMSA study identified an average mercury capture efficiency for POTWs of 95%. Independent studies conducted by the MCES in 1995 and 1998 identified mercury capture efficiencies for three POTWs of 96%, 98%, and 99%, respectively (Balogh and Liang, 1995; Balogh and Johnson, 1998). Based on the comprehensive data reported in the AMSA study, an average POTW capture efficiency of 95% for mercury and mercury in the form of amalgam was used.

2.5. Discharge of mercury to surface waters

The average POTW capture efficiency of 95% was applied to the estimated 6.5 tons (5.9 metric tons) of mercury annually discharged in the form of amalgam to POTWs to estimate that approximately 6.2 tons (5.6 metric tons) of mercury in the form of amalgam are annually captured by the POTWs. Approximately 0.3 tons (0.3 metric tons) of mercury in the form of amalgam are discharged by POTWs to surface waters.

Particles captured in POTWs are either removed with the grit solids or biosolids. Grit solids are typically removed from the wastewater stream through the use of horizontal-flow, aerated, or vortex grit chambers (Tchobanoglous and Burton, 1991). A study conducted by the MCES in 1998 identified mercury capture efficiencies for aerated and vortex grit chambers of 7% and 48%, respectively (Balogh and Johnson, 1998). These data were compared with a theoretical capture analysis for amalgam of approximately 20% in a horizontal-flow grit chamber based on design specifications reported by Tchobanoglous and Burton (1991) and the amalgam particle size distribution identified by ISO (1999). Based on these data and personal communication from AMSA (K. Kirk, personal communication), it was estimated that 25% of mercury in the form of amalgam captured by POTWs is transferred to the grit solids, and that 75% is transferred to the biosolids. This distribution was applied to the estimated 6.2 tons (5.6 metric tons) of mercury in the form of amalgam that is captured by POTWs to estimate that approximately 1.6 tons (1.5 metric tons) of mercury is transferred to the grit solids and 4.6 tons (4.2 metric tons) to the biosolids.

Approximately 22% of the biosolids generated in the United States are managed through incineration in SSIs (USEPA, 1999). Applying this percentage, it was estimated that approximately 1 ton (0.9 metric ton) of mercury in the form of amalgam present in biosolids is annually incinerated by SSIs. The emissions from SSIs are treated by wet scrubber systems to control particulate emissions, and capture some particulate forms of mercury. From approximately 1988 to 1995, the United States Environmental Protection Agency (USEPA) developed representative emissions factors for SSIs, commonly referred to as AP-42 factors, the average of which represented a mercury capture efficiency for SSI emission controls of about 79% (USEPA, 1995). This capture efficiency was used for SSIs to estimate that approximately 0.2 tons (0.2 metric tons) of mercury from dental amalgam is annually emitted to the atmosphere from SSIs as a result of the incineration of biosolids.

In 1997, the USEPA estimated that approximately one-third of the mercury emissions originating from the United States were deposited within the country (USEPA, 1997). This percentage was used to estimate that less than 0.1 tons (0.1 metric tons) of the mercury is annually deposited in the United States from the incineration of biosolids containing amalgam. It was conservatively estimated that all this mercury will enter surface waters. This deposition estimate was combined

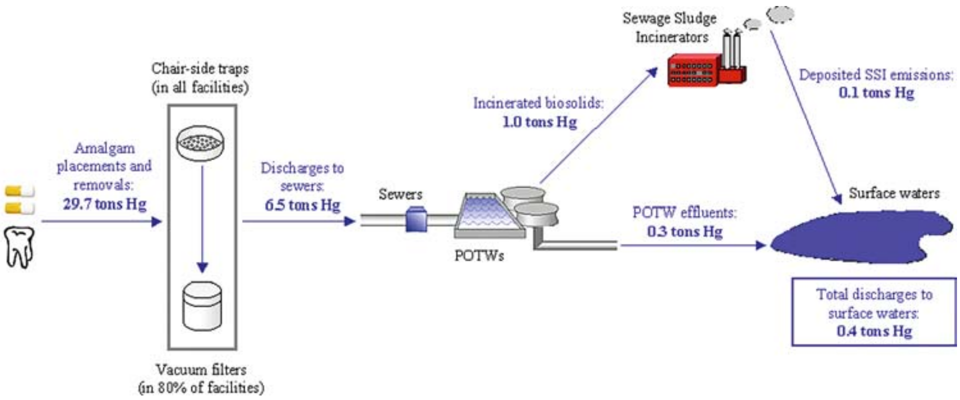

Figure 1. Summary of the fate of mercury used as amalgam in the United States.

with the discharge estimate for POTW effluents of approximately 0.3 tons (0.3 metric tons) to estimate that approximately 0.4 tons (0.4 metric tons) of mercury from dental facilities are annually entering surface waters in the United States via POTW effluents and SSI emissions.

Figure 1 summarizes the results of this assessment.

3. Cost-Effectiveness Analysis

The cost-effectiveness analysis focused on identifying the unit cost of reducing the discharge of mercury through the use of amalgam separators at dental facilities. The costs associated with the purchase, installation, and operation of amalgam separators were identified from a review of recent studies, as well as vendor quotes. The effectiveness of separators was evaluated as the incremental capture attained by the separator beyond that already attained by chair-side traps and, where present, vacuum filters. The behavior of the amalgam fraction not captured by the separators in the receiving POTWs was evaluated in order to determine the actual reduction in discharges to surface waters via the POTW effluent and SSI emission pathways. Due to the limited data regarding this behavior, two scenarios of incremental POTW capture were considered in the final cost-effectiveness calculations.

3.1. Cost of amalgam separation equipment

From 2000 to 2002, the ADA, the MCES and MDA, and the Palo Alto RWQCP conducted studies of the costs associated with utilizing amalgam separation equipment in dental facilities in the United States (Fan *et al.*, 2002a; MCES and MDA, 2001; Johnson, 2000). The results of these studies were reviewed and supplemented with commercial vendor quotes to estimate the current cost of purchasing and operating

TABLE I

Summary of amalgam separator purchase and operating costs

Vendor	Model	Type	Purchase price	Annual operating costs
AB Dental Trends, Inc.	890–1000	Sedimentation, filtration, ion exchange	$1,190	$476
	890–4000	Sedimentation, filtration, ion exchange	$1,650	$610
	890–6000	Sedimentation, filtration, ion exchange	$667	$441
	A 1000	Sedimentation	$750	$1,150
Air Techniques, Inc.	Durr 7800/7801	Centrifuge	$4,000	$495
Avprox, Inc.	Asdex filter	Filtration	$215	$1,360
DRNA	BullfroHg	Sedimentation	$0	$1,200
	MRU	Sedimentation, filtration, ion exchange	$0	$1,800
Maximum Separation Systems, Inc.	MSS 2000	Sedimentation	$3,000	$596
Metasys	ECO II	Sedimentation	$260	$428
R&D Services	Amalgam collector	Sedimentation	$350	$540
Rebec Environmental	RME 2000	Sedimentation	$1,895	$474
SolmeteX	Hg5	Sedimentation, filtration, ion exchange	$695	$496

an amalgam separator for the average dental facility in the United States. Table I summarizes the separator purchase and operating costs estimated for the cost-effectiveness analysis.

Based on a review of the cost studies and vendor quotes, it was estimated that the cost to purchase and install an amalgam separator(s) would typically range from roughly $1,000 to $2,000 per dental facility. It was estimated that the cost to operate the separator(s) would typically range from $700 to $1,000 per dental facility per year.

In order to prepare a conservative estimate of the nationwide costs associated with amalgam separators, only the installation and operation of separators in those dental facilities operated by general dentists were considered in the cost calculations. In 2001, the ADA reported that approximately 66% of all dentists in private practice in the United States maintained a solo practice, and that the remaining 34% of dentists worked in practices staffed by an average of 2.9 dentists per facility (ADA, 2001). These percentages were applied to the 122,320 general dentists that manage amalgam (through placements and/or removals) to estimate that amalgam procedures are currently conducted in approximately 95,066 dental facilities in the United States.

The range of costs for the purchase and installation of amalgam separators of approximately $1,000 to $2,000 per dental facility were applied to the estimated 95,066 dental facilities in the United States to calculate an estimated capital cost for the installation of amalgam separators in these facilities of approximately $95 million to $190 million. Similarly, the operation and maintenance of separators in these dental facilities was estimated to require approximately $67 million to $95 million per year. For the purposes of the cost-effectiveness analysis, the capital cost was spread evenly over a 10-year assumed separator life to estimate an annual cost of approximately $76 million to $114 million for the purchase, installation, and operation of amalgam separators in dental facilities in the United States.

3.2. Performance of amalgam separators

The MCES and MDA recently completed a 2-year study on the capture efficiency of amalgam separators in several dental facilities located in Minnesota. This study identified incremental capture efficiencies for amalgam separators of approximately 94% beyond the capture already achieved in facilities equipped with chair-side traps and 89% beyond the capture achieved in facilities equipped with both chair-side traps and vacuum filters (MCES and MDA, 2001).

The ADA recently conducted a bench study of the amalgam capture efficiency of 12 amalgam separators in accordance with ISO Standard 11143. From the study, the ADA identified an average overall amalgam capture efficiency of 99%. However, the amalgam sample utilized in these studies was prepared in accordance with the ISO standard, and consisted of amalgam particles ranging up to 3,150 μm in size, 60% by mass of which were greater than 500 μm in diameter (Fan *et al.*, 2002b; ISO, 1999). As noted, dental facilities in the United States are equipped with chair-side traps that have pore sizes of 700 μm, and many are also equipped with vacuum filters that have pore sizes ranging from 210 μm to 400 μm. Therefore, had the ADA's tests been conducted in actual dental facilities, much of the ISO amalgam sample utilized in the tests would have been captured by the chair-side traps and vacuum filters prior to entering the amalgam separators. As a result, the incremental amalgam capture efficiency achieved from the use of the separators in these dental facilities would be less than 99%.

In order to determine the incremental capture efficiency of the amalgam separators tested by the ADA under ISO Standard 11143, the fate of a 100-mg representative ISO amalgam sample was considered. As discussed previously, it was estimated that 80% of the dental facilities in the United States are equipped with both chair-side traps and vacuum filters, for which average capture efficiencies of 68% and 40%, respectively, were identified in the open literature. In those dental facilities equipped with both a chair-side trap and vacuum filter, an estimated 68 mg of the ISO amalgam sample would be captured in the chair-side trap, with approximately 32 mg passing on to the vacuum filter. The incremental capture of the vacuum filter, at 40%, would retain approximately 13 mg of the 32 mg of amalgam that passed the chair-side trap. Therefore, an estimated 81 mg of the original amalgam sample would be captured from the combination of the chair-side trap and vacuum filter. The remaining 19 mg of the amalgam sample would pass on to the amalgam separator, which would capture some portion of the 19 mg. According to the ADA sampling results, if the entire 100 mg sample were run through the amalgam separator at the average 99% ISO capture efficiency, the separator would not have captured 1 mg of the sample. This 1 mg would consist of the smallest and most difficult amalgam particles to capture, and, having passed the chair-side trap and vacuum filter, would be part of the 19 mg left under this illustration. Therefore, the ADA data indicate that, in a typical dental facility equipped with both a chair-side trap and vacuum filter, the average amalgam separator would capture 18 mg of the 19 mg of amalgam that reached the device, for an incremental capture efficiency of approximately 95%. Similarly, in the estimated 20% of dental facilities that are only equipped with chair-side traps, approximately 68 mg of the ISO amalgam sample would be captured in the chair-side trap, with about 32 mg passing on to the amalgam separator. In these dental facilities, the separator would capture 31 mg of the 32 mg that reached the device, for an incremental capture efficiency of approximately 97%.

Based on the MCES and MDA study and the ADA bench tests, an average incremental capture efficiency for the use of amalgam separators of approximately 95% was used in the cost-effectiveness analysis. At this efficiency, amalgam separators would reduce the estimated discharge of 6.5 tons (5.9 metric tons) of mercury in the form of amalgam to POTWs in the United States to approximately 0.3 tons (0.3 metric tons). As noted, this 0.3 tons would consist of the smallest and most difficult amalgam particles to capture. Amalgam separators primarily employ the same physical processes to remove amalgam particles as the processes utilized at POTWs to remove particulates (i.e., sedimentation and centrifugation), and can generally be expected to remove the same types of amalgam particles. Indeed, the amalgam capture efficiencies identified for both POTWs and separators from the open literature are both approximately 95%. Therefore, it is unlikely that a significant amount, if any, of the 0.3 tons of mercury in the form of amalgam particles not captured by amalgam separators would subsequently be captured by the downstream POTWs (i.e., the 0.3 tons of mercury in the form of amalgam not captured by the separators would consist of the same 0.3 tons that is already estimated not to be captured by POTWs). Under this scenario, the only benefit attained through the use of separators would be the virtual elimination of the deposition to surface waters of an estimated 0.1 tons (0.1 metric tons) of mercury from the incineration of amalgam in SSIs in the United States, at an estimated annual cost of reduction of approximately $760 million to $1.14 billion per ton.

A second scenario of the potential reductions in mercury discharges from the use of amalgam separators was considered for the purposes of the cost-effectiveness analysis. AMSA is currently conducting a study to evaluate whether separators have an effect on the mercury discharged in POTW effluents. From this study, AMSA has generated some preliminary data regarding average mercury concentrations in the effluent from the POTWs operated by the City of Wichita, Kansas. Although the data appear relatively inconclusive, AMSA has reported that the use of amalgam separators reduced mercury effluent concentrations from the City of Wichita's POTWs by approximately 29% (C. Hornback, personal communication). Despite the preliminary nature of this data, a hypothetical situation was considered for the cost-effectiveness analysis in which the use of amalgam separators decreased the mercury concentrations in the effluent from POTWs nationwide by approximately 30%. Assuming this hypothetical situation, the mercury discharges from POTWs to surface waters in the United States would be reduced by at most 0.2 tons (0.2 metric tons) per year, at an annual cost of reduction of approximately \$380 million to \$570 million per ton.

4. Discussion

The results of the present study correspond well with independent estimates of mercury use by the dental industry in the United States, the mercury discharged in the form of amalgam to POTWs, and the mercury emitted from SSIs as a result of the incineration of biosolids. The estimate of the use of mercury in amalgam by the dental industry of 35.2 tons (31.9 metric tons) per year from this assessment generally agrees with the USGS' most recent estimate of 34.2 tons (31 metric tons) per year. It is noted, however, that the USGS' estimate was prepared in 1996, while the estimate from the present study was intended to represent the current use of mercury in amalgam. Due to the decreased use of amalgam in the 1990s, the 35.2-ton (31.9-metric ton) estimate from this assessment may be an overly conservative one.

The estimate that approximately 6.5 tons (5.9 metric tons) of mercury in the form of amalgam is discharged to POTWs from dental facilities in the United States generally agrees with the results of POTW influent studies conducted by AMSA in 2002 and the USEPA in 1996. The AMSA study identified an average mercury concentration in POTW influents of approximately 225 ng/L (AMSA, 2002). The USEPA estimated that, in 1996, the total wastewater flow to POTWs was approximately 32 billion gallons per day (1.4 million liters per second) (USEPA, 1999). Based on forecasting methods used by the USEPA for the Clean Water Needs Survey, it was estimated that the current flow of wastewater to POTWs has increased since 1996 to approximately 36 billion gallons per day (1.6 million liters per second). At an average mercury concentration of approximately 225 ng/L, this flow rate equates to a total mercury load to POTWs of approximately 12.3 tons (11.2 metric tons) per year. At approximately 6.5 tons (5.9 metric tons), the present study's estimate of the discharge of mercury as amalgam from dental facilities to POTWs corresponds to approximately half of the estimated total mercury load to POTWs in the United States. This percentage is slightly higher than the dental contribution estimated by AMSA of approximately 35 to 40% (K. Kirk, personal communication). This is to be expected considering the conservative assumptions used in this assessment, particularly that all dental facilities discharge to POTWs.

Similarly, the estimate that approximately 0.3 tons (0.3 metric tons) of mercury in the form of amalgam is annually discharged to surface waters in the United States via POTW effluents also agrees with the data collected during AMSA's 2002 study. AMSA identified an average mercury concentration in POTW effluents of approximately 12 ng/L. When applied to the estimated wastewater flow rate of 36 billion gallons per day, this equates to a total discharge of mercury to surface waters via POTW effluents of approximately 0.6 tons (0.5 metric tons). When an estimated dental contribution of approximately half is applied to this total discharge estimate, the resulting 0.3 tons (0.3 metric tons) attributable to dental facilities agrees with the 0.3-ton discharge estimate from the present study.

Finally, the estimate of the emission of mercury as amalgam from SSIs also correlates well with estimates of total SSI emissions. The USEPA estimated that a total of approximately 0.9 tons (0.8 metric tons) of mercury were emitted from SSIs in 1994 (USEPA, 1997). At that time, the USEPA estimated the mercury concentration of biosolids as approximately 5.2 parts per million (ppm) (USEPA, 1995). According to AMSA, the concentration of mercury in biosolids currently ranges from approximately 1 ppm to 3 ppm (K. Kirk, personal communication). Assuming an average mercury concentration of approximately 2 ppm, the total mercury emissions from SSIs can be estimated at approximately 0.4 tons (0.4 metric tons) of mercury per year. When a dental contribution of approximately half is applied to this total emissions estimate, the resulting 0.2 tons (0.2 metric tons) of emissions associated with the use of mercury as amalgam agrees with the 0.2-ton emissions estimate from the present study.

Figure 2 illustrates the correlation of the results of this assessment with the data obtained from the AMSA and USEPA studies.

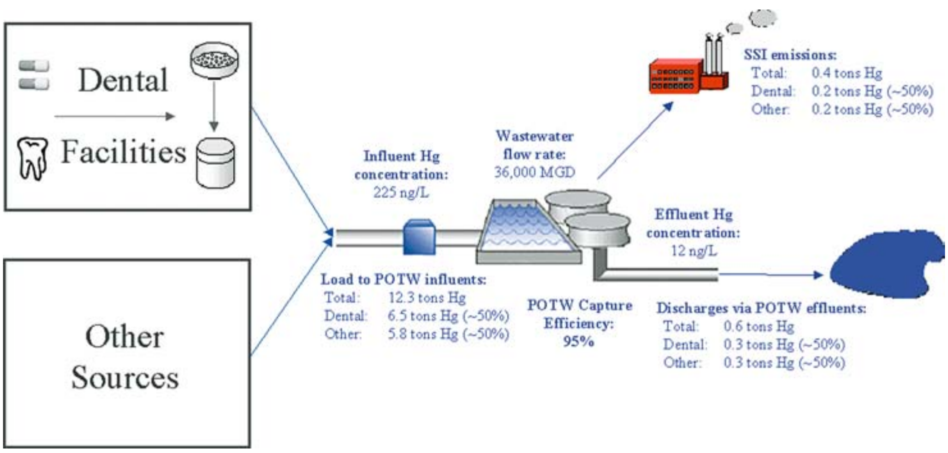

Figure 2. Summary of the flow of total mercury and mercury from dental amalgam in the United States.

5. Conclusions

An assessment was conducted to quantify the use of mercury in the form of amalgam by the dental industry in the United States and to estimate the discharge of that mercury from dental facilities to surface waters via POTW effluents and SSI emissions. The annual use of mercury as amalgam by the dental industry in the United States was estimated at approximately 35.2 tons (31.9 metric tons). It was estimated that approximately 29.7 tons (26.9 metric tons) of mercury in the form of amalgam are annually discharged to the internal wastewater systems of dental facilities during amalgam placements and removals. Due to the partial capture of this amalgam in conventional chair-side traps and vacuum filters, the discharge of mercury in the form of amalgam from dental facilities to POTWs was estimated at 6.5 tons (5.9 metric tons), or approximately half of the estimated total mercury load to POTWs throughout the United States. The discharge of mercury from dental facilities to the surface waters of the United States via POTW effluent and SSI emissions were estimated to total approximately 0.4 tons (0.4 metric tons). When approximately half of the total mercury in POTW influents, POTW effluents, and SSI emissions was attributed to wastewater discharges associated with the use of mercury as amalgam in dental facilities, the results of the present study correlated well with data from studies conducted by AMSA and the USEPA. A cost-effectiveness analysis based on these results determined that the annual unit cost to reduce these mercury discharges through the use of amalgam separators would range from $380 million to $1.14 billion per ton.

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