Mercury: the good, the bad, and the export ban*

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May 2009

Abstract

We analyze the bipartisan call to ban US exports of commodity mercury. An export ban can generate positive environmental benefits by increasing the scarcity of mercury in developing economies where significant toxic releases occur. We show, however, that a direct mercury purchase and retirement policy can achieve the same foreign environmental goals without adverse impacts on domestic environmental quality. We present qualitative and quantitative evidence that highlight the potential inefficiencies of a mercury export ban as a method of achieving environmental objectives.

*We thank the organizers and participants of the Commodity-grade Mercury Stakeholder Meetings, sponsored by the USEPA Office of Pollution Prevention and Toxics (Summer 2007). We also thank two referees for very helpful comments. The opinions and conclusions are solely those of the authors.

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1 Introduction

The element mercury has generated enormous benefits to human scientific and industrial endeavors. Mercury is dangerous, however, and the benefits have historically come at high human-health and environmental cost. In fact, mercury was sometimes a deadly and ineffective prescription for various ills in 18th and 19th century medicine. Most modern uses of mercury are much more respectful of its toxic nature. Further, mercury's usefulness to humanity is clearly on the decline. Recent innovations in technology offer safe substitutes for mercury in almost all of its significant applications. Adopting these substitute technologies is pervasive in the developed world, where technology and knowledge capital are relatively cheap and environmental quality is highly valued. Mercury policy must consider its elemental nature. The mercury that was concentrated and put into a thermometer forty years ago still exists somewhere, and as a matter of public policy we encourage its recovery to limit its future environmental impact.

Consistent with canonical theories of international trade, these trends support a growing pattern of net exports of recovered commodity mercury into developing countries. The social problem is that these exports are, themselves, implicated in global environmental degradation and in local human-health tragedies. Artisanal gold miners use mercury in a relatively simple process that separates gold from its ore. A significant quantity of this mercury is released into the environment, and the miners and their communities often suffer the dramatic health consequences of direct exposure. Further, mercury releases in developing countries might show up around the world on any dinner plate in the form of tuna or swordfish with elevated concentrations. Additionally, the facts indicate the future reenforcement of a trade pattern that moves mercury into the economies least likely to control any adverse environmental impact.[1]

[1]Hylander and Goodsite (2005) provide an overview of mercury as a global pollutant. They highlight the unique ability of mercury to be globally transported as a gaseous metal, and that all people and environments

While the focus of this paper is U.S. mercury export policy, it is important to keep in mind that the artisanal miners benefit from mercury use. Gold sales offer the primary source of income in some of the most impoverished communities around the world. The basic drivers behind mercury use (and misuse) in artisanal mining include abject poverty, a lack of access to alternative technologies, and a lack of education concerning the proper use of mercury and the health consequences of long-term exposure. Hilson (2006) argues that appropriate policies to mitigate mercury releases are critically dependent on understanding the fundamentals of the artisanal mining communities.[2] Hinton et al. (2003) provide an overview of the specific technologies and policies that might be applied to mitigate mercury releases by artisanal miners. Regional case studies on artisanal gold mining (and associated environmental problems) are offered by Hilson and Pardie (2006) on Ghana; Vieira (2006) on the Guianas; and Hilson (2009) on sub-Saharan Africa. U.S. export policy cannot address some of the fundamental drivers that make mercury use attractive for artisanal miners, and miners around the world will likely continue to demand mercury as long as substitute technologies are unavailable or are more expensive. The elimination of U.S. mercury from world markets will, however, increase the scarcity of mercury and will likely hasten the adoption of alternatives.

In an effort to keep US mercury off international markets Senator Barack Obama (D-IL) and Senator Lisa Murkowski (R-AK) introduced the Mercury Export Ban Act of 2008 (S.906).[3] The law prohibits the sale of federal stockpiles of elemental mercury and prohibits the export of elemental mercury from the US, effective January 1, 2013.[4] The first provision

are, therefore, affected. Veiga et al. (2006) provide specific details on regional mercury releases from artisanal gold mining activities, and identify international trade in commodity mercury as a contributor to low prices and the general availability of mercury to artisanal miners in less developed countries.

[2]Hilson (2006) explains that education and technical support programs can be more effective than efforts to enforce pollution laws and monitoring of mercury use. The key to effective policy seems to be to enlist the artisanal miners as partners in the effort to mitigate mercury releases.

[3]The bill was introduced March 15, 2007. On the same day, Representative Tom Allen (D-ME) introduced a similar bill to the House of Representatives (H.R.1534). The bill had strong bipartisan support and passed both houses of Congress. It was signed into law October 14, 2008.

[4]The law requires a report analyzing various mercury compounds for inclusion in the export ban. The

simply codifies the current Department of Defense (DOD) and the Department of Energy (DOE) policy of long-term storage and retirement of government mercury stockpiles. In contrast, the ban on exports is a new policy that could dramatically impact the market. The U.S. action follows the European trade ban on mercury passed by the EU Parliament (COD/2006/0206), which bans European exports and imports of mercury effective in 2010.

The U.S. export ban will accomplish the primary goal of further increasing the scarcity of mercury on world markets. To the extent that increased scarcity raises mercury prices faced by artisanal gold miners, it will push them to curb mercury releases and adopt alternative techniques. An export ban, however, has some less than desirable characteristics. First, there is the potential for mercury *leakage* in the form of new primary mercury mining.[5] The increased incentive to extract virgin mercury is a direct result of increased scarcity (higher commodity-mercury prices), and it is practically unavoidable if we restrict ourselves to unilateral policies.

Other undesirable characteristics of an export ban are avoidable and arguably unnecessary. The same level of international mercury scarcity might be achieved more efficiently by a direct purchase and retirement policy. There are two primary problems with an export ban relative to the purchase and retire policy. First, the export ban encourages mercury use in the domestic economy, and, second, it discourages mercury recovery from byproduct and waste sources. In fact, current legal requirements to bring identified mercury waste streams up to commodity-level concentrations combined with pressures to curb the use of mercury in most applications indicate that an export ban will likely result in the destruction of the domestic mercury market. There will likely be a surplus of mercury in the domestic market, even at a zero price. Absent price as a rationing mechanism, public policy will need

bill outlines the creation of the Excess Mercury Storage Advisory Committee, which will produce a report on estimating the costs of mercury retirement and storage.

[5] Large scale primary mining of mercury currently takes place in China and Kyrgyzstan, but the legal, commercial, operations in these countries are likely constrained by capacity and global political pressure. The marginal suppliers of virgin mercury are likely unofficial/illegal artisanal operations.

to wrestle with the problems of administering allocations of mercury to those uses deemed legitimate and the problems of disposing of the mercury surplus. Meeting the problem head on with a direct retirement policy can eliminate the perverse incentives embodied in the export ban and permanently remove significant quantities of mercury from being a future environmental concern.

Another major problem with a US export ban is that it may increase the foreign supply of mercury to artisanal gold miners in developing regions regardless of the mercury mining response. Currently, the US is a significant refiner of byproduct mercury recovered in industrial gold mining around the world. We actually import a significant quantity of commodity mercury, which is refined to a high level of purity for industrial applications around the world.[6] It is hard to imagine this being a viable activity under an export ban. Spatially, it is important to note that byproduct mercury is coincidental to gold deposits. Under a US export ban foreign byproduct mercury is less likely to be refined for industrial applications and some portion will likely find its way onto the local markets that supply artisanal miners.

To our knowledge our analysis of the U.S. mercury export ban, and its domestic environmental implications, is unique in the economic literature. Mercury policy is discussed, however, in the broader literature. Hylander and Goodsite (2005) estimate that avoiding mercury pollution is more cost effective than remediation. To this end, Hylander (2001) suggest that a trade ban by the EU and NAFTA is critical to protecting the environment in places with less strict environmental regulation. While noting that an EU trade ban would result in the closing of the primary mercury mine at Almadén Spain, Hylander does not address the effects on domestic mercury users or the issue of possible new primary mining of mercury in other parts of the world.[7]

[6]For example, Bethlehem Apparatus (a major US mercury recycler) advertises quadruple-distilled mercury, which is at least 99.99995% pure.

[7]In fact, mining at Almadén stopped in 2003 (before the EU trade ban), and Almadén is slated to become a repository for European mercury [U.S. Department of the Interior (2007)].

We believe that models of international trade can add rigor to the debate. As background into fundamental models of international trade and the gains from trade, we suggest a good undergraduate text book like Feenstra and Taylor (2008) or Markusen et al. (1995). Some economic literature does exist on trade bans of other products. In the case of the trade ban on ivory, one study, Fischer (2004), is particularly relevant because she explores the complex set of incentives sparked by the trade ban. Some of these incentives work in favor of the primary environmental goal while others work against it.[8] We see many parallels to the case of the mercury export ban, which also generates a complex set of incentives for domestic and foreign agents.

Our purpose is to identify the implications of an export ban using simple analytical techniques, and to contrast the export ban with a direct mercury retirement program, which achieves the same international environmental impact.[9] We also mockup a numeric model that gives a rough indication of overall scale of the problem in dollars, and identifies groups of winners and losers. Equity considerations are likely important in arriving at a constructive and efficient policy.

2 The Stakeholders

One of the primary stakeholder groups in the debate over US mercury policy is the public. Generally, people in developed countries express a desire, through political action, to limit

[8]Other studies of the trade ban on ivory, which explore similar incentives, include Khanna and Harford (1996), Barnes (1996),Bulte and van Kooten (1999a), Bulte and van Kooten (1999b), and Heltberg (2001).

[9]One might ask why we only consider two policies (the export ban and a direct purchase and retirement policy), and why we do not consider something along the lines of an optimal policy? Finding the optimal policy requires information on the environmental benefits of removing mercury on both world and domestic markets. This is beyond the scope of our study. We only examine unilateral policies that attain a fixed international goal (the elimination of US net exports). In this context we show that an export ban (or equivalently a prohibitive export tax) may, or may not, be superior to the direct purchase and retire policy. We show that the critical parameter for finding the best policy is the assumed domestic environmental valuation. If US agents place enough value on limiting domestic mercury use and/or domestic mercury recovery the direct mercury retirement policy is superior.

mercury use and encourage mercury recovery from the waste stream. While mercury use in Europe and North America is low, relative to historical levels, use of mercury is on the rise in the developing regions of East Asia, Central and South America, and Africa. Many US citizens are concerned with mercury use in developing countries because its use is not well regulated and environmental releases pose a direct and indirect hazard to human health. One problem that people in developed countries face in trying to express their preference for fewer mercury releases in developing regions is the difficulty in regulating agents in different countries. Some unilateral instruments are available, however, and the Mercury Export Ban Act of 2008 (S.906) is an expression of the political pressure to affect the international mercury market.

Another important group of stakeholders are those people engaged in supplying mercury. Primary mercury mining has not taken place in the US since the early 1990s. Mercury is extracted in the U.S. as a byproduct of industrial gold mining, and mercury is recovered through recycling. While there are many companies interested in waste management issues surrounding the collection of mercury-containing products and mercury contaminated waste, there are only a handful of companies that specialize in converting mercury waste into commodity grade mercury. Indeed, the limited number of US companies that specialize in the mercury retort (distillation) process are world leaders. They actually engage in the refining of foreign imported mercury. An export ban could seriously impact the viability of this activity and would favor the emergence of a foreign mercury refining industry.

One industry that would be greatly impacted by the export ban is the chlor-alkali industry. The chlor-alkali process is used to produce chlorine and various alkaline salts. Historically, large quantities of mercury were used in the process, but substitute technologies are currently favored. It is anticipated that the eight remaining US mercury-cell chlor-alkali plants will be decommissioned over the next 10 to 20 years. In the past, mercury from decommissioned plants, or plants that have converted to a mercury-free process, was sold on the open market. If the mercury from the chlor-alkali plants were sold, it would represent approximately 50 tonnes of annualized mercury supply over the next 20 years. This is about 25 percent of annual US supply.[10] It is important to note that mercury revenues offset the costs of decommissioning or converting mercury-cell plants.[11] The chlor-alkali industry is a large player and will be significantly impacted by policies that affect the mercury market.

While US demand for mercury has fallen over the last thirty years due to health and environmental concerns, new technological developments, and direct state-level regulation, mercury is still used in thermometers, electrical switches and relays, dental amalgam, and fluorescent and compact fluorescent light bulbs. It is likely that the general trend of substituting away from mercury in most of its domestic uses will continue. While the price of mercury is not a major driver in the overall trend, recent high prices reinforce the move toward substitutes, and a lower domestic mercury price does not provide the same incentive to not use mercury.

Foreign mercury supply comes from primary and secondary sources. The secondary sources (byproduct in mining and waste recycling) are similar to the US secondary sources. Primary (virgin) mercury, however, is still mined in Kyrgyzstan and China. The naturally occurring ore, cinnabar, is mined and processed to produce mercury. While Kyrgyzstan produces largely for export, China produces for domestic consumption. Additionally, China has a hard-to-quantify amount of artisanal mercury-mining activity.[12] Due to capacity and political constraints, as well as sunk costs, legal mercury mining in China and Kyrgyzstan is likely to be price insensitive. Marginal suppliers, such as the illegal or small scale artisanal operations in developing countries, might be sensitive to market prices and could be an

[10]See the submission of Bruce Lawrence to the USEPA sponsored Mercury Stakeholders Panel [Lawrence (2007)].

[11]See the USEPA background report [USEPA (2007a)].

[12]The Natural Resource Defense Council (2006) estimates that illegal, artisanal, mercury mining in China amounts to between 0 and 200 tonnes per year, based on information from the Chemical Registration Center (CRC) of China's State Environmental Protection Administration (SEPA).

important substitute for some of the US mercury. As the US removes mercury from the international market, small-scale operations—the marginal producers—will likely increase output in response to the higher world price.

Foreign mercury demand comes from many of the same industries as US domestic demand. There are a few differences, however. Mercury can be used as a catalyst in the production of vinyl chloride monomer (VCM). VCM is used in the production of polyvinyl chloride (PVC), a common plastic. In general, this method of PVC production is limited to China and some plants in Russia and India.[13].

The primary foreign users of mercury that we would like to affect are artisanal gold miners. Small-scale artisanal gold mining is profitable in many parts of the developing world. Mercury is used in a relatively simple process that extracts the gold from the ore. Mercury is combined with raw ore or ore concentrate. A mercury-gold amalgam is formed that is easily separated from the rest of the material. When the amalgam is heated the mercury vents off and the gold remains. The direct contact with mercury, the mercury vapor, and its condensates are very toxic to the miners and to their surrounding environment. Use of mercury in artisanal gold mining is extremely difficult to curtail, despite its toxic effects. Mercury has clear short-run benefits to the gold miners. Relative to other processes it is immediate and requires almost no capital. The use of mercury in artisanal gold mining is formally illegal in many countries, but difficult to enforce. Curbing the mercury released by artisanal gold miners is a major focus of national and international environmental efforts.[14]

[13] See Maxson (2006)

[14] For example, the United Nations Industrial Development Organization (UNIDO) initiated the Global Mercury Project in 2002. The Global Mercury Project specifically focuses on mitigating the environmental degradation and adverse health effects resulting from mercury use in artisanal gold mining. See Spiegel and Veiga (2005) for more details on the Global Mercury Project.

3 Analytical Model

This section develops a simple analytical model of the mercury market based on some fundamental behavioral and methodological assumptions. The analysis is intentionally kept at a level of economic principles. Hopefully this will keep it accessible and relevant to the public debate.

3.1 Ground Rules

The model is based on some basic assumptions. These are common tenets of economic analysis, and they form the logical foundation for our qualitative conclusions. First, we assume that efficiency is separable from equity. That is, we frame our analysis around advocacy for aggregate efficiency, not advocacy for any specific agent or group of agents. Every US agent is given equal (dollar-for-dollar) weight in any notion of social welfare. A stockholder in a chlor-alkali plant, a lawyer, a professor, a dentist, or a generic tax payer could all be affected differently by various mercury policies, but which agents win or lose is not a concern (from our perspective). Our concern is to minimize the net social costs, across all agents, of achieving a given environmental goal.[15]

In our market analysis we assume that demand and supply functions are well behaved. The slopes of all demand functions are non-positive, and the slopes of all supply functions non-negative. We consider the extreme cases of perfectly inelastic supply and demand curves, because of our desire to accommodate the views of those who contend that many of the actors are not price sensitive. We note, however, that most of the arguments against price sensitivity are flawed. Anecdotes based on inframarginal transactions cannot indicate price sensitivity on the margin. In fact, economic theory indicates that inframarginal transactions, usually

[15]Formally, this approach to welfare economics is consistent with the Kaldor-Hicks Efficiency Criterion [Kaldor (1939) and Hicks (1940)]. The Kaldor-Hicks Criterion considers a set of hypothetical side payments that would make the policy that minimizes the sum of net costs across agents preferred by all agents. The Kaldor-Hicks Criterion is widely accepted, and applied, in modern economic analysis.

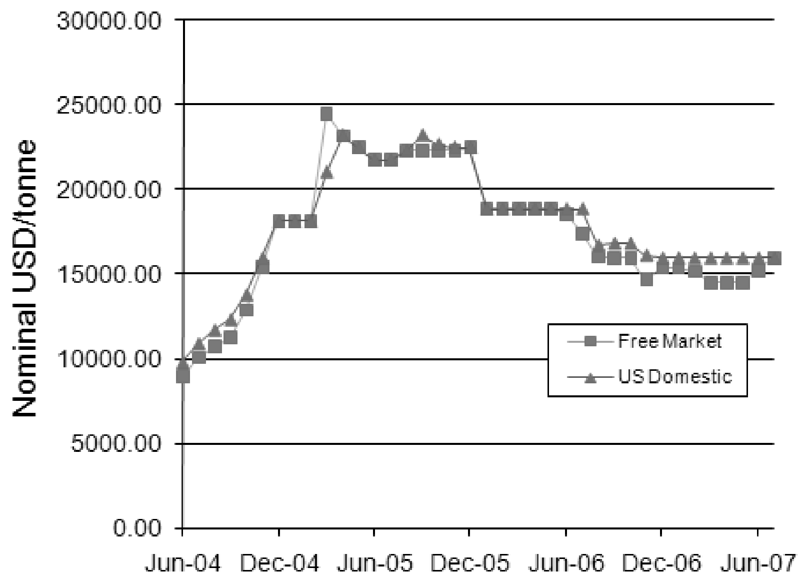
the majority of transactions in a given market, will not be locally sensitive to price. Price simply determines the division of the transaction's surplus between the buyer and the seller. Other arguments against price sensitivity stress the small value of mercury in some larger production activity. It is not clear that small value shares logically indicate anything about price response. Price sensitivity is captured in the (second-order) concepts of substitutability and transformability, not the (first-order) information on value shares.

Consider the case of byproduct mercury from domestic gold mines. Clearly, recovered byproduct mercury is a small value share of any gold mining operation. Some large operations in the US recover byproduct mercury at both the first stage (extraction and beneficiation) and the final stage (retort) of gold mining. Current law, however, exempts the mercury waste generated at the first stage from falling under the regulations of the hazardous waste system.[16] In fact, some smaller companies take advantage of this exemption releasing mercury-containing tailings directly into the environment. The larger mine operators might be recovering the mercury at the first stage for a number of different reasons, including the benefits they get from selling the mercury and the benefits they get from presenting their company as environmentally friendly. Our assumption about the law of supply is critical; even if the large mines are inframarginal sellers a higher mercury price makes it financially easier for them to be *green*, and more importantly might induce the marginal mines into mercury recovery. Clearly, a lower mercury price would not induce more recovery.

The most compelling argument that a market analysis for mercury is appropriate, and that at least some of the parties are price sensitive, is that there is currently an operating market for mercury. Mercury is bought and sold in open markets. If agents were truly price insensitive there would be regular shortages or surpluses. This is not the case. Prices fluctuate and the market clears. Figure 1 shows recent price fluctuations. Late 2004 saw

[16]This is commonly referred to as the Bevill exemption to the Resource Conservation and Recovery Act (RCRA) laws.

Figure 1: Recent Free-market and US Mercury Prices



a run up in the price of mercury due to the closing of primary mercury mines in Spain and Algeria, and increased demand from China. Price peaked in early 2005 and has fallen, leveling out at around $16,000 per tonne.

The final ground rule for our analysis is an assumption that normalizes the mercury content of a given transaction. One problem that is immediately apparent in the data is that there is a great deal of heterogeneity in the unit values of transactions. At an elemental level mercury is homogeneous, but we should not expect to see uniform prices for mercury that is premeasured and prepackaged for dental use versus relatively low-grade commodity mercury imports from mining operations in Peru. We normalize transactions to a common mercury transaction, which is consistent with the metals markets and published commodity price reports.[17] Thus a transaction at a high unit value is presumed to include some characteristic (special packaging or ultrahigh purity) that is tangential to the core

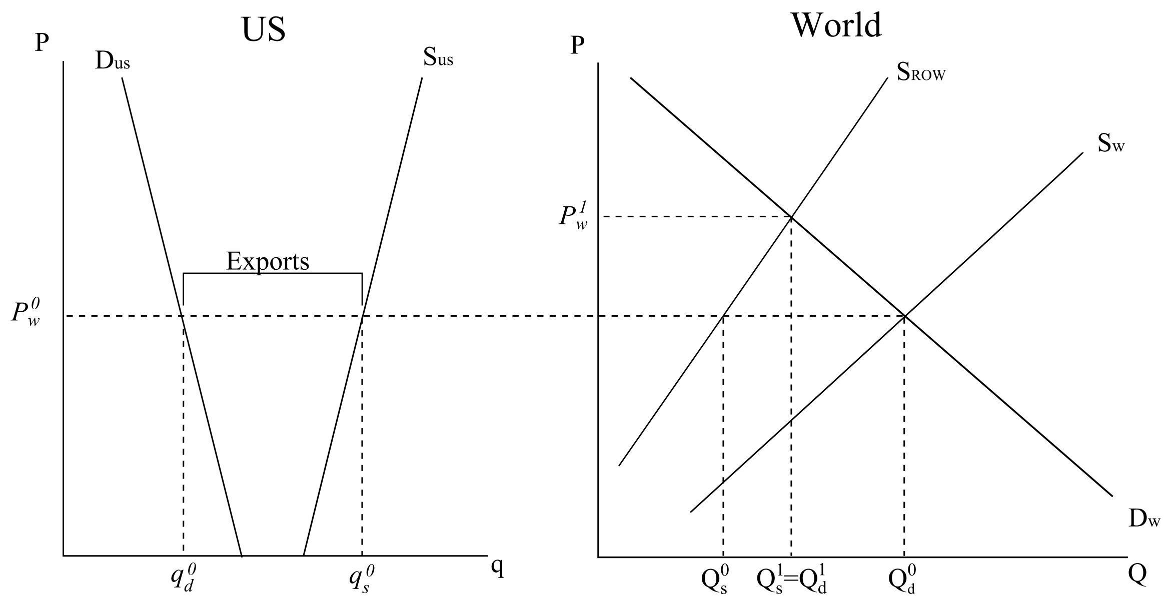
[17]Price data (see Figure 1) was gathered from Platt's Metals Week monthly averages published for June 2004 to July 2007 [Platts (various)].

mercury transaction. Similarly, a transaction at a low unit value is presumed to include some degradating characteristic. In fact—in the case of mercury-containing waste—the party receiving the physical material might also receive the money payment. That is, mercury-containing waste is often a bad, rather than a good, but this does not mean that the embodied mercury is not valued. Current law requires that mercury in the waste stream be brought up to commodity-grade purity (through a retort), at which point the embodied mercury has positive market value. The actual waste that is sent to a retort facility might have a positive or negative value depending on the mercury concentration, and it is our understanding that retort operators compete for this waste. Our assumption to normalize the mercury transactions to a common quality and concentration greatly simplifies the model. This allows us to isolate the mercury transaction from the embedded service components (whether these be, upstream, waste recovery and management services or, downstream, purification and packaging services).

3.2 The model

We start with a simple partial equilibrium model that shows the relationship between an export ban and a direct mercury retirement program. Consider the markets for mercury as represented in Figure 2. In the first panel we plot the quantity of mercury in the US market in relation to the price of mercury. In the second panel we represent the world market. At the benchmark price, P_w^0, US supply exceeds US demand and the difference is exported. At P_w^0 equilibrium demand in the world market, Q_d^0, equals rest-of-world (ROW) supply, Q_s^0, plus US exports $(q_s^0 - q_d^0)$. Given free trade, the total world supply curve (S_w) is given by the sum of the rest-of-world supply (S_{ROW}) and US exports at that price. In the absence of US exports the world market clears at a higher price P_w^1 indicating an increased scarcity of mercury on the world market. With no US exports, rest-of-world supply increases to Q_s^1, which equals the quantity demanded Q_d^1.

Figure 2: US and World Markets for Mercury



In Figure 2 we do not show an intersection of the US demand and US supply curves. This reflects the consensus view of many experts that there will likely be a substantial surplus of mercury in the domestic market if exports are not available.[18] Another peculiarity in Figure 2 is that US supply intersects the horizontal axis at a significant quantity. This reflects a zero marginal cost for much of the US supply. Mercury in the waste stream that is forced to be retorted (because of current regulations) is essentially a free resource. Other sources such as mercury from retired chlorine plants and some mine byproduct mercury may be available in the normalized quality at zero, or very low, marginal cost.

We greatly simplify the analysis by restricting ourselves to linear functions.[19] US demand is given by

$$q_d = a_d + b_d P_{us}, \tag{1}$$

[18]See the minutes from the 2007 Stakeholder Panel for Managing Domestic Stocks of Commodity-Grade Mercury sponsored by the USEPA [USEPA (2007b)].

[19]Restricting the analysis to linear functions has quantitative, but not qualitative implications for the analysis. With linear functions the surpluses can be calculated using simple geometric formulas rather than integral calculus.

where $b_d \leq 0$, and a_d represents the level of demand at a zero price. Similarly we can represent US supply algebraically as

$$q_s = a_s + b_s P_{us}. \tag{2}$$

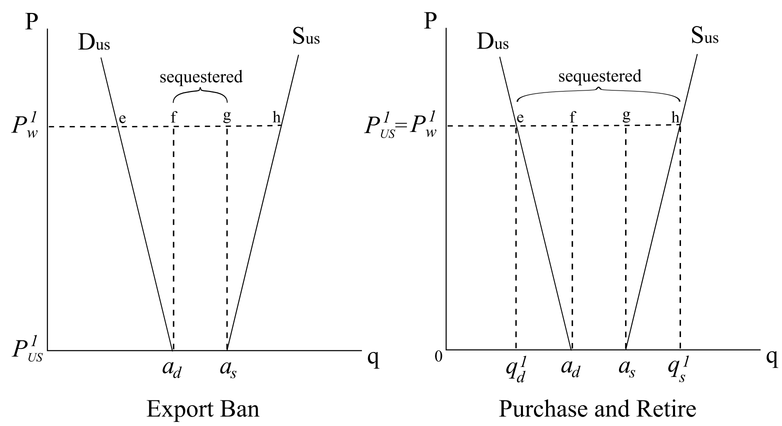
In this case $b_s \geq 0$, and a_s represents the total commodity mercury supplied in the US at a zero price.

We focus on the US market in Figure 3. Areas in the graph represent dollar values, and we can use the concepts of consumer and producer surplus to conduct a simple welfare analysis of various policies. First, consider an export ban. The export ban will achieve an increased level of international scarcity reflected in a world price of mercury of P_w^1 (consistent with $P_w^1 > P_w^0$ in Figure 2). With an export ban, however, the US price would not be P_w^1. As long as $a_s > a_d$ the price in the US market would be driven to zero. As a matter of public policy the surplus, $a_s - a_d$, of mercury would need to be dealt with. Most likely, $a_s - a_d$ tonnes of mercury will be placed in permanent storage, similar to the current DOE and DOD stockpiles. This is indicated in Figure 3 as the quantity sequestered. As a simplifying, but not totally unrealistic, assumption let the annualized cost of mercury storage be negligible relative to the market values.[20] Clearly the export ban generates benefits to US mercury users; the price of mercury is zero and they react by increasing consumption to a_d. On the other hand, those who were selling mercury at a positive price have no market for their product. The quantity supplied drops to a_s, and all producer surplus from mercury sales is lost.[21]

[20] Lehman (2007) presents evidence that the annualized cost of sequestration is on the order of only \$0.05 to \$0.30 per pound. This roughly translates to \$100 to \$600 per tonne. Recent mercury prices are in the range of \$14,000 to \$18,000 per tonne. The cost of sequestration is relatively small, and we ignore it in the qualitative analysis. In the quantitative simulation analysis presented in the next section of this paper we include the estimated sequestration cost.

[21] Mercury retort facilities will still charge for the service they provide to the waste management and other industries, but the resulting mercury will not have any value.

Figure 3: US Market for Mercury: Export Ban versus the Direct Purchase and Retire Policy



Relative to the export ban consider a policy of direct mercury purchase and retirement that achieves the same level of international scarcity. This is represented in the right-side panel of Figure 3. An amount of mercury equal to $q_s^1 - q_d^1$ would need to be purchased at a total cost of $P_w^1(q_s^1 - q_d^1)$ to raise the world price to P_w^1. There would be no net exports of US mercury. Relative to the export ban, mercury users lose a dollar amount equal to the area below P_w^1 and the demand curve: the area of the trapezoid $P_w^1 e a_d 0 = P_w^1(q_d^1 + a_d)/2$. Mercury suppliers, in contrast, gain a dollar amount equal to the area below P_w^1 and above the supply curve: the area of the trapezoid $P_w^1 h a_s 0 = P_w^1(q_s^1 + a_s)/2$. On net, it appears that the direct purchase and retire policy is more costly than the export ban, by the area $\triangle e a_d q_d^1 + \triangle h q_s^1 a_s$, which equals $P_w^1(q_s^1 - a_s)/2 + P_w^1(a_d - q_d^1)/2$.[22] This conclusion, however, places a zero value on the impacts changes in demand and supply quantities of mercury have on domestic environmental quality.

It seems important to consider two different impacts on the domestic environment of the direct purchase and retire policy, which favor it relative to the export ban. First, there will

[22] Relative to the export ban the net impact is the gain to suppliers less the loss to users less the government purchases: $[P_w^1(q_s^1 + a_s)/2] - [P_w^1(q_d^1 + a_d)/2] - [P_w^1(q_s^1 - q_d^1)] = P_w^1(a_s - a_d + q_d^1 - q_s^1)/2 = -(P_w^1(q_s^1 - a_s)/2 + P_w^1(a_d - q_d^1)/2) = \triangle e a_d q_d^1 + \triangle h q_s^1 a_s$. This assumes that the marginal cost of public funds is one and no accounting for domestic environmental quality. We relax both of these restrictive assumptions below.

be social benefits associated with discouraging domestic use of mercury (decreases in the quantity demanded). Denote the marginal benefits of discouraging demand MB_{US}^{d}. Second, there will be social benefits associated with encouraging domestic recovery of mercury from the waste stream (increases in the quantity supplied). Denote the marginal benefit of encouraging recovery on the supply side MB_{US}^{s}. Under the purchase and retirement policy, sequestration increases, indicating benefits along both of these margins (while maintaining the same international outcome as an export ban).

To simplify our analysis of the differences between the export ban and the direct purchase and retire policy, consider assuming that there is a constant marginal social benefit from sequestration (which reduces demand and increases supply). If we denote the marginal benefits of sequestration MB_{US} then our assumption is that $MB_{US} = MB_{US}^{d} = MB_{US}^{s}$. Now consider a specific value for this marginal benefit. Let us assume, for the moment, that the marginal benefit of recovering and sequestering a tonne of mercury from the domestic market is $MB_{US} = 1/2(P_w^1)$. Relative to the export ban the purchase and retirement policy generates social gains from domestic sequestration equal to $MB_{US}[(a_d - q_d^1) + (q_s^1 - a_s)]$. These gains from additional sequestration exactly equal the lost area $\triangle e a_d q_d^1 + \triangle h q_s^1 a_s$. A level of marginal benefits from domestic sequestration equal to $1/2(P_w^1)$ is a key threshold value in our linear model. If the marginal benefit of domestic sequestration is half the world price, the direct purchase and retirement policy is equivalent to the export ban in terms of total welfare.[23]

It is interesting to consider a couple of additional special cases of our simple analytical model. First, consider a case in which US agents are completely unresponsive to prices. The US demand and supply curves are vertical so the areas $\triangle e a_d q_d^1$ and $\triangle h q_s^1 a_s$ go to zero, and there is no increase in sequestration relative to the export ban. If US agents do

[23] Adding nonlinearities that generate strictly convex supply and demand functions (which are common) decreases the areas $\triangle e a_d q_d^1$ and $\triangle h q_s^1 a_s$, and therefore decreases the threshold marginal benefit which results in equivalence between the alternative policies.

not respond to prices there can never be a difference between the export ban and a direct purchase and retirement policy. This result is independent of any assumptions we make about environmental valuation.

Another interesting special case is one in which we assume some domestic price response and that the marginal social benefit of pulling mercury off the domestic market is at least as large as the minimum marginal social benefit of pulling mercury off the foreign market. We can presume that the minimum marginal social benefit from sequestration is the world market price under the export ban (P_w^1). Otherwise, the export ban would not enhance social welfare on the margin.[24] Setting the marginal social benefit from increasing sequestration at P_w^1, or above, indicates that the direct purchase and retire policy is superior to the export ban. In fact, we can weaken the restriction significantly. If the marginal social benefit of domestic sequestration is greater than half the resulting world price ($MB_{US} > 1/2(P_w^1)$), then the direct purchase and retire policy is superior to the export ban regardless of the overall social efficiency of the export ban. Of course, this formal result is dependent on $MB_{US} = MB_{US}^d = MB_{US}^s$; asymmetries between MB_{US}^d and MB_{US}^s will complicate the analysis, but not greatly.[25]

We highlight one additional extension of our analytical model concerning the cost of government mercury purchases. Under the export ban there are no government outlays.[26] Under the direct purchase option the government has to pay for the mercury. This is important because, as a matter of public finance, when the government pays a dollar for mercury (or any other good or service) the cost is generally not a dollar. This is because the govern-

[24]On the margin, the opportunity cost of a tonne of mercury kept off of the international market is the world market price of that tonne. That is, if the marginal social benefit of sequestration were below the world price, social welfare is increased by exporting the marginal unit.

[25]In our linear model the direct purchase and retire policy will remain superior to the export ban as long as the average, weighted by the quantity changes, of the MB_{US}^d and MB_{US}^s is greater than $1/2(P_w^1)$.

[26]There are, in fact, some government outlays under the export ban to cover sequestration costs, but we assume these away in the analytical model. In the numeric simulations that follow we include the sequestration costs.

ment must raise the revenue to purchase the mercury using a distorting tax system (and also considering the fact that the economy starts from a distorted initial equilibrium). Up to this point we have assumed that the marginal cost of public funds (MCPF) is one.[27] That is, we have assumed that a dollar of government outlays on mercury costs the taxpayer one dollar. Any significant MCPF above one puts the direct purchase and retire policy at a relative disadvantage because it escalates its cost, while the export ban does not require any government outlays. The threshold value of MB_{US} that makes the two policies equivalent increases if the government raises revenue using a specific tax instrument with an MCPF > 1 (but the opposite might be true if the government selects a tax instrument with an MCPF < 1, which is a possibility). Without specific information on the actual tax instruments that the government might use to raise the necessary revenue to purchase mercury we simply assume an MCPF of one, and caution the reader that this could potentially bias our comparison of the export ban versus the direct purchase policy.

4 Numeric Simulation

In this section we take the basic lessons from our simple analytical model and apply them in a quantitative simulation model. The model utilizes basic information on the quantities and values in the markets. A number of unknowns remain, however, and we perform sensitivity analysis over the key parameters.

4.1 Model Data and Structure

We adopt the basic structure outlined in Figure 2. We formulate the numeric model as a mixed complementarity problem (MCP) and solve it using the General Algebraic Modeling

[27] The marginal cost of public funds (MCPF) is defined as minus the ratio of the (money metric) welfare change to the increase in government revenues induced by a small tax increase. The MCPF is specific to the particular tax instrument and, starting with a distorted economy, can be above or below one. See the excellent recent book by Dahlby (2008) on the marginal cost of public funds.

System (GAMS) software.[28] Equations (1) and (2) characterize the behavioral responses of the US agents. In addition we have the supply and demand functions for the rest-of-world agents. Let Q_d represent the quantity demanded by foreign agents at various world prices, P_w, such that

$$Q_d = c_d + d_d P_w, \tag{3}$$

where $d_d \leq 0$, and c_d represents the level of rest-of-world demand at a zero price. Similarly we represent rest-of-world supply algebraically as

$$Q_s = c_s + d_s P_w, \tag{4}$$

where $d_s \geq 0$, and c_s represents the level of rest-of-world supply at a zero price.

Next we characterize market clearance as a set of complementarity condition. Associated with the US market price, P_{us}, there is a condition of no excess demand;

$$q_s - q_d - E - G \geq 0 \quad \perp \quad P_{us} \geq 0, \tag{5}$$

where US exports are denoted by the variable E and we add a potential policy instrument G, which represents any direct government purchases of mercury.[29] The $\perp$ symbol is a shorthand method of indicating the complementary slack relationship. In words, we say excess supply may exist when the price is zero, but at positive prices supply is equal to demand. Algebraically condition (5) embodies the following: $q_s - q_d - E - G \geq 0$, $P_{us} \geq 0$,

[28]See Rutherford (1995) for an introduction to MCPs and their operation within GAMS. All programs used in this analysis are available from the authors.

[29]Without specific information on the tax instruments that the government might use to raise the necessary revenue to purchase mercury we assume an MCPF of one. If one assumes an MCPF > 1 the actual cost of G will escalate.

and $P_{us}(q_s - q_d - E - G) = 0$. We have a similar market clearance condition for the world;

$$Q_s + E - Q_d \geq 0 \quad \perp \quad P_w \geq 0. \tag{6}$$

We have a condition that determines the quantity of US exports;

$$P_{us} - P_w \geq 0 \quad \perp \quad E \geq 0. \tag{7}$$

If exports of mercury are allowed, the export activity will arrive at a equilibrium that equalizes the domestic and foreign prices. If the domestic price exceeds the world price, exports will be zero. To implement a simulated export ban, we fix $E = 0$ eliminating condition (7) from the equilibrium system.

The next condition tracks the US surplus if it is not directly purchased by the government:

$$S - q_s + q_d + E + G \geq 0 \quad \perp \quad S \geq 0. \tag{8}$$

In the case of an export ban, $S > 0$ is likely, and we need to track this quantity because its sequestration is costly in the numerical model. If the government purchases mercury directly, $G > 0$, this quantity will also incur sequestration costs.[30] To simulate a direct purchase and retire program we raise the level of G to a point that absorbs the entire excess supply at a world price of $P_w = P_w^1$. That is the world price that would have resulted under the export ban. The condition that determines G is given by

$$P_{us} - P_w^1 \geq 0 \quad \perp \quad G \geq 0. \tag{9}$$

[30] Without specific information on the tax instruments that the government might use to raise the necessary revenue to cover sequestration costs we assume an MCPF of one. If one assumes an MCPF > 1 the actual cost of S will escalate.

When this condition is activated, exports will drop to zero, and we will have the exact same international conditions as an export ban. The domestic equilibrium, however, will be quite different. The domestic price will equal the international price and there will be less domestic demand and more domestic supply. Conditions (1) through (9) form the complete equilibrium system.

The equilibrium system is useful as a quantitative simulation tool once we calibrate the functions to a somewhat realistic benchmark. The data inputs are usually summarized into two groups. There are first-order inputs on quantities and values. The first-order inputs are replicated as the solution to the equilibrium system with no counterfactual policies implemented. The second group of data are summarized in a set of second-order *local* (to the benchmark equilibrium) elasticity assumptions.[31] There is a great deal of uncertainty on the elasticities, given that they are not systematically estimated. We assume a set of central values, which we feel are not unrealistic, and then proceed to a quantitative sensitivity analysis. This illustrates how the results change under different elasticity assumptions.

To calibrate the system we establish rough estimates of the first-order quantities. We utilize the estimates submitted by Bruce Lawrence (President, Bethlehem Apparatus Company, Inc.) to the USEPA concerning the likely near-term (2011) supply and demand quantities for US commodity mercury.[32] Mercury supply in the US is predicted to outstrip domestic demand with an annual export quantity of about 100 tonnes (or 50 percent of US supply). In the world market supply equals demand and is estimated to be approximately 3,000 tonnes [Masters (2006)]. Table 1 summarizes the benchmark reference quantities used to calibrate the demand and supply functions.

In Table 2 we show our unit-value assumptions. The model takes as given a benchmark

[31] The elasticities are *local* because, with linear functions, the elasticities change as we move away from the initial equilibrium.

[32] See the submission of Bruce Lawrence to the USEPA sponsored Mercury Stakeholder Panel [Lawrence (2007)]

Table 1: Benchmark Reference Quantities

		tonnes (t) of mercury
US		
Demand	(q_d^0)	100
Supply	(q_s^0)	200
Exports	$(q_s^0 - q_d^0)$	100
World		
Demand	(Q_d^0)	3000
Supply	$(Q_s^0 + q_s^0 - q_d^0)$	3000

mercury price of \$16,000 per tonne. This is roughly consistent with recent market prices as published by Platts (various), see Figure 1. The second row of Table 2 shows our central assumption about the marginal social benefits of sequestering an additional tonne of mercury from the domestic economy. As we saw in the analytical model this assumption is critical in evaluating the export ban relative to a direct purchase and sequester policy. The final row of Table 2 presents our central assumption on the annualized cost of sequestration. At \$1,000 per tonne we are assuming a value somewhat higher than the estimate of about \$100 to \$600 per tonne made by Lehman (2007). Some might think the Lehman cost estimates are understated, and we adopt a higher value, which is conservative because higher costs work against our argument that the direct purchase and retire policy is superior. We also present these unit values in a per-household metric. We present them as cents per 100 tonnes per US household (assuming 100 million US households). It is important to note the relatively low costs of mercury policy on a household basis. Under our assumptions, the entire quantity of US mercury exports (100 tonnes) could be purchased for about one point six cents per household. This mercury could then be permanently sequestered for an additional one tenth of a cent per household.

The final data that we require to calibrate the functions is an indication of price response (second-order parameters). Given the local elasticities (and the first-order data) the slopes

Table 2: Benchmark Unit-value Assumptions

	\$/t	**¢/100t per US household**
Market Price ($P^0_{us} = P^0_w$)	\$16,000	1.6¢
Annual Marginal Benefit of Domestic Sequestration (MB_{US})	\$10,000	1.0¢
Annual Marginal Cost of Sequestration	\$1,000	0.1¢

and intercepts of the linear functions are determined. To date we have not performed an econometric estimation of these parameters. As an alternative we establish a set of central assumptions based on our experience, and the discussions in the Mercury Stakeholder Panel meetings [sponsored by the USEPA (2007b)]. We then perform sensitivity analysis that attempts to accommodate different views on these key and controversial parameters. Price response is summarized in a local elasticity assumption. The elasticity is the ratio of the percentage change in quantity to the percentage change in price. The equations, (1) through (4), are fully determined by the information on the local elasticity and the benchmark prices and quantities.

Table 3 summarizes the central values of our local elasticity assumptions and the implied intercepts of the demand and supply functions. We assume very inelastic domestic responses. This is consistent with the views expressed in the Mercury Stakeholder Panel meetings. The foreign responses are still inelastic but not as severely restricted. We think it is reasonable to assume that artisanal gold miners respond to price increases by reducing their mercury use (otherwise our export policy would be ineffectual). As a central case, we assume that foreign agents reduce their mercury purchases by 5% given a 10% price increase (for example). This might come in the form of more efficient processes that limit and conserve the mercury used, or it could come in the form of substitute processes.

Table 3: Central Values of Key Response Parameters

		Local Elasticity	Implied Intercept
US			
Demand	(η_{US})	0.1	$110t$
Supply	(γ_{US})	0.1	$180t$
Rest of World			
Demand	(η_{ROW})	0.5	$4500t$
Supply	(γ_{ROW})	0.2	$2320t$

We also assume that the world mercury supply elasticity is twice as large as the US elasticity. This assumption relies partially on our belief that mercury mining is moderately stimulated by higher prices, though this is a point of controversy. There is considerable disagreement about the world supply response among the Mercury Stakeholder Panel members. Some argue that there would be no supply response, while others argue that any US export limit would be offset by new foreign production. David Lennett, a panel member, representing the National Resources Defense Council argues that pulling US mercury off of the world market will have little impact on international primary suppliers.[33] Conversely, Bruce Lawrence, President of Bethlehem Apparatus (a mercury recycler and refiner), believes that the amount of byproduct mercury recovered in the US completely replaces an equivalent amount of primary-mined mercury on the world market.[34] Lennett's argument is probably more consistent with a short-run view, and Lawrence's argument is probably more consistent with the long run. We adopt a central value that is inelastic but does include some response. So, for example, a 10% price increase induces a 2% increase in world supply in our central case. Although this parameter is controversial, it is irrelevant to our central argument concerning a unilateral export ban. The policies that we examine are equivalent with respect

[33]See, for example, the stakeholder meeting minutes [USEPA (2007b)], page 6, May 8. Lennett's statements are attributed to a *participant from a non-governmental organization* in the minutes.

[34]See, for example, the stakeholder meeting minutes [USEPA (2007b)], page 6, May 8. Lawrence's statements are attributed to a *participant from industry* in the minutes.

Table 4: Decomposition of US Welfare Changes (central case)

Account	**Export Ban ($thousands)**	**Direct Purchase ($thousands)**
Consumer Surplus	1,680	-77
Producer Surplus	-3,040	154
Government	0	-1,701
Sequestration	-70	-101
US Environment	-300	14
No Exports	$+X$	$+X$
Total	$+X-$ 1,730	$+X-$ 1,711

to the resulting world price and mercury scarcity; therefore they will have equivalent world mercury supply responses. The more elastic is supply, the less effective both policies are in extracting mercury from the world market.

4.2 Results

With our central assumptions established, we simulate the export ban and direct purchase and sequester policies. Table 4 presents the welfare analysis of these alternative policies. We decompose the aggregate welfare changes into their component impacts on various agents. Presumably there are benefits associated with eliminating US exports and these are indicated by the value $+X$ in the table. If the value of $+X$ is greater than $1.73 million then the policies generate positive net social benefits. To put this in perspective, if the average US household values eliminating exports at a modest 1.73 cents per year the policies are beneficial. For example, if we assume that the average per-household benefit is $1 then $+X =$$100 million, and the net welfare calculation for the export ban would be $100 million - $1.73 million = $98.27 million.

Our assumed value of the marginal benefit of domestic sequestration (at 1 cent per 100t per household per year) is close to the threshold value that yields equivalent net welfare calculations. Given that $+X$ is constant across the policies the direct purchase and sequester policy is favored by \$19,000. We caution that this is a very modest estimate of the social value of sequestration and the differences between the policies is shown to be significantly larger in sensitivity analysis.

We again caution the reader that the results presented in Table 4 are based on assuming an MCPF of one. The government outlays and sequestration costs will escalate if we assume that the government choses a revenue instrument with an MCPF of $\alpha > 1$. In that case, government outlays on mercury become αG and sequestration costs become αS, which makes the direct purchase option more expensive.

Looking only at the aggregate impacts masks many of the important differences in the policies for different agents. Table 4 shows impacts on each group. The export ban has significant benefits for mercury users at the expense of mercury producers. There are no direct government outlays for purchasing the mercury under the export ban, and the sequestration cost is somewhat less given that less mercury is sequestered under the export ban. The row labeled US Environment shows the negative impact of the export ban associated with the demand stimulus and supply contraction. Under the export ban US demand increases to $110t$ and supply contracts to $180t$. Only $70t$ are sequestered relative to the direct purchase and sequester policy, which requires that $101.4t$ be put into permanent retirement (in order to reach the same level of international scarcity).

We use the simulation model to explore the concern about new mercury supplies from the rest of the world given that we limit exports. This concern can be summarized in a *leakage rate*. The leakage rate is defined as the ratio of increased world supply to initial US exports;

$$\textbf{leakage} \equiv \frac{Q_s^1 - Q_s^0}{q_s^0 - q_d^0}. \tag{10}$$

Table 5 shows the leakage rates under various local elasticity assumptions. In the central

Table 5: Mercury Leakage Rates (%) at zero US exports

	Local Supply Elasticity (γ_{ROW})			
	0	**0.2**	**1.0**	**100**
Local Demand Elasticity (η_{ROW})				
0.1	0	66	91	100
0.5	0	28	66	100
1.0	0	16	49	99

case leakage is 28%. The leakage rate falls with the world demand elasticity and increases with the world supply elasticity. Although the leakage rate is sensitive to our assumptions, these cannot affect our qualitative welfare analysis. The value of $+X$ is likely dependent on leakage, but the comparison across the export ban and direct purchase and sequester policies cannot be affected (because $+X$ is the same across the scenarios).

Our welfare analysis, and our comparison across policies, is sensitive to our assumptions about the domestic elasticities and the marginal value of domestic sequestration. Table 6 illustrates the sensitivity. The figures in the body of Table 6 show the difference between the welfare change under the direct purchase policy and the welfare change under the export ban. A negative number indicates that the export ban is more efficient than the direct purchase and sequester policy. As we argued in our analytical model, if the elasticities are zero then there cannot be a difference in the policies (in terms of aggregate welfare). This is shown in the first row. We show that the export ban can be superior to the direct policy if we assume a low enough valuation on domestic sequestration. In general, however, we would argue that the marginal social benefit of domestic sequestration is above $10,000 per tonne, which moves us into the region where the direct policy is superior. How superior the direct policy is largely depends on the domestic supply and demand elasticities. The cost of the

Table 6: Social Cost of the Export Ban relative to the Direct Purchase Policy ($thousands)

Local Elasticities (η_{US}, γ_{US})	**Marginal Social Benefit of Sequestration** (MB_{US}) (¢/100t per US household) 0.5¢	1¢	2¢	3¢	100¢
(0.0, 0.0)	0	0	0	0	0
(0.1, 0.0)	-46	6	111	216	10,382
(0.0, 0.1)	-92	13	223	432	20,765
(0.1, 0.1)	-138	19	334	648	31,147
(0.2, 0.1)	-183	26	445	864	41,530
(0.1, 0.2)	-230	32	556	1,080	51,912
(0.2, 0.2)	-276	39	668	1,296	62,294

export ban escalates as the agents become more responsive to prices.

5 Conclusion

Developed countries find themselves in an uneasy position concerning commodity mercury. Mercury is obviously a beneficial commodity to a number of private agents and their activities. Mercury is, however, a bioaccumulative toxic element. In the US, legislative and regulatory rules require that most mercury-containing or mercury-contaminated waste be treated and the mercury recovered. The recovered mercury is then available to be sold and used again. The evolution of the US economy has put it in a position as a net exporter of mercury. Developing countries import mercury and damage the world environment. The solution to this problem seems obvious: ban mercury exports.

We argue that this policy, while accomplishing its primary goal of eliminating US exports, might have detrimental impacts in the domestic economy and domestic environmental quality. The primary problem that we see with an export ban is that it will encourage domestic activities that use mercury and discourage the recovery of mercury from the byproduct and waste streams. We present an analytical and a quantitative analysis that illustrates our concerns. We also suggest that a direct purchase and sequester policy might be designed to generate the same foreign outcome and a more preferred domestic outcome.

There are a number of reasons we feel our arguments are conservative, and that an export ban might be significantly more costly. First, we assume a relatively low marginal social benefit from sequestration (\$10,000/t). It can be argued that based on current policy the value must be at least as high as the peak market value of mercury (\$23,000/t) in early 2005. The US government currently owns over 5,500 tonnes of commodity mercury, which it has no known use for.[35] The opportunity cost of holding this mercury off of the market in early 2005 was \$23,000/t. Logically, the social value of sequestration must be greater than \$23,000/t or society would have sold some of the mercury. We see our proposed direct purchase and sequester policy as a direct extension and expansion of current US policy.

The second reason that we feel that our analysis is conservative, in that it overstates the costs of the purchase and sequester policy, is that we assume that the US government would have to pay market prices for mercury. The chlor-alkali industry views their mercury as a potentially huge liability. It might be relatively easy to negotiate a complete buy out of this mercury at a less than market price. Similarly, many large mining companies are anxious to advertise their environmental stewardship. These mining companies might be approached as partners in the sequestration process, and the mercury might be purchased at significant discount. The key to avoiding the adverse impacts of the export ban is to maintain a high mercury price for domestic users of mercury and marginal domestic suppliers.

In our analysis we greatly simplify the world markets. A more involved treatment would separate the artisanal mining demand from the industrial uses of mercury. We show an

[35] These are Department of Defense and Department of Energy strategic stockpiles. They no longer have a strategic value. These stockpiles were being sold off until 1993 when the sales were halted because of environmental concerns.

equivalent rest-of-world environmental impact across our scenarios. It can be argued, however, that the significant US imports of mercury keeps mercury out of the hands of artisanal miners, because it is refined for industrial uses. Under an export ban no agents in the US would refine foreign mercury, because the price of the refined mercury would be zero. Absent US imports, this mercury (which is geographically close to gold deposits) might be directly marketed to local artisanal miners. Certainly foreign refining of byproduct mercury will intensify in the absence of US imports. Spatially, this works against the efficacy of the export ban.

Our analysis is useful in that it identifies priorities for future research. We identify key behavioral parameters that might be informed by econometric estimation. Future studies might also focus on the rest-of-world mercury supply activity. A careful analysis of leakage is needed to get an overall assessment of how effective unilateral policies can be. Multilateral efforts are also problematic, but they may be much more effective if leakage rates on unilateral policies are significant.

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