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THE RISK OF HAZARDOUS WASTE SPILLS FROM INCINERATION AT SEA

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Summary

This paper presents a critical assessment of the risk of spills from hazardous waste incineration aboard ocean going vessels. The *likelihood of spills* is estimated on the basis of recent domestic and worldwide chemical tanker experience. Results indicate that the probability of a spill is significant for projections of future ocean incineration demand. The *severity of spills* is explored using mathematical models of chemical transport and fate. This analysis is site specific and presents upper and lower bounds on the average pollutant concentration from spills of polychlorinated biphenyls in Mobile Bay. Severe impacts on the water quality and marine life in this region would result from spills of less than the capacity of a single incineration vessel. These findings demonstrate some inherent uncertainties in the analysis of these risks which bear strongly on the reliability of the program, the adequacy of contingency plans, and current liability requirements.

1. An introduction to hazardous waste incineration at sea

High temperature incineration is a promising technology for transforming polychlorinated biphenyls (PCBs), DDT, dioxins, and other chlorinated aromatic liquids into hydrochloric acid, carbon dioxide, water, and trace residuals. Incineration at sea is an approach that uses incinerators mounted on specially built chemical carrying ships to burn the wastes far from shore. Ocean basing is designed to take advantage of the buffering capacity of the marine environment and to lessen facility siting problems by decreasing human exposure to the combustion process. Between 1975 and 1983, the Environmental Protection Agency (EPA) issued four permits for a total of thirteen research burns in the Gulf of Mexico and the Pacific Ocean. European experience with incineration at sea totals about 350 burns since 1969.

Despite its intuitive appeal as a means of detoxifying hazardous wastes, incineration at sea has met with substantial public opposition. The concerns raised by groups and individuals range from the possible environmental impact of emissions and spills to questions about monitoring, liability requirements, port site designation, and EPA's overall strategy toward hazardous manage-

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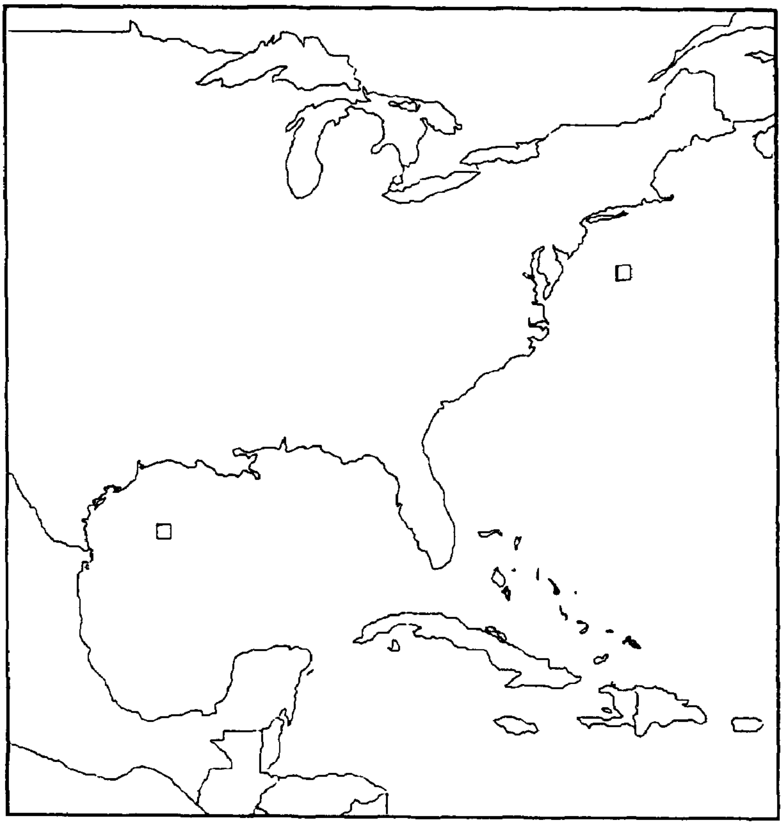

Fig. 1. Designated and proposed incineration sites of the United states.

ment. This sentiment is most apparent in the coastal regions, near port facilities and in communities closest to the potential burn sites. It now seems that incineration at sea faces difficulties in port siting that rival the facility siting problems that it sought to avoid. Figure 1 shows the location of the designated burn site in the Gulf of Mexico, approximately 190 miles off the South Texas coast and a proposed site in the North Atlantic, 140 miles from New Jersey.

Recently, EPA has demonstrated a strong interest in the ocean incineration program. In February 1985, the Agency proposed amendments to the Marine Protection, Research and Sanctuaries Act that would govern the incineration permit process and set performance standards. This was followed by five public hearings in New Jersey, Louisiana, Texas, California, and Alabama. Congressional interest in the program is growing. Bills have been introduced in the House and Senate that call for a three year moratorium on incineration at sea.

This paper presents a critical assessment of the risk of hazardous waste spills from incineration at sea. This research asks two key questions. First, what is the likelihood of one or more spills from this controversial technology? Second, what would be the consequences in the event of a spill? The next section outlines changing views on the significance of this risk issue over the last fifteen years. In Section 3, the chance of a spill is estimated from historical data on marine transportation. Section 4 follows with a characterization of the environmental consequences of a variety of spills. Section 5 is devoted to a discussion of the significance of the findings. Finally, Section 6 summarizes some conclusions about the risks of spills from ocean incineration and recommendations for further study.

2. The risks of spill from incineration at sea

This paper investigates one issue in the controversy over hazardous waste incineration at sea. Ocean incineration poses a unique risk to the coastal environment because the wastes must undergo additional handling and transportation near and through harbors. It is this incremental risk that motivates the following analysis of the potential impacts of hazardous waste spills. Of course, since there are several major issues, the results of this effort are not likely to resolve the conflict between those that favor and those that oppose this technology.

A brief review of previous analyses reveals the evolution of thinking on the risks of spills. In 1978, EPA released a report on the relative merits of land and ocean basing of incineration facilities [1]. The report acknowledged the possibility of accident for any technology but concluded that "the potential for acute adverse effects on the environment is greater at the land based facility due to its close proximity to population centers, and areas of environmental concern".[1] In 1980, the report of an interagency work group of EPA, Maritime Administration, and Coast Guard representatives on the need for and feasibility of a domestic incinerator vessel lent further support [2].

Later the same year and again in 1983, questions were raised about the possible risks entailed by transportation to the burn site [3,4]. Still, no efforts were made to quantify these potential impacts. In the fall of 1983, over six thousand people attended a public hearing in Brownsville, Texas, on future burns in the Gulf of Mexico. This attendance sets the record for the largest turnout at an EPA hearing and registered the intensity of public opposition. However, the concerns expressed at the hearing centered mainly on the chronic release of unburned wastes rather than the catastrophic potential for spills. Perhaps decades of direct industrial dumping to the Gulf made a chance release seem trivial.

Slowly, it has become apparent that both the likelihood and the severity of spill are greatest in the near shore regions.[2] With a minimum of fanfare, EPA's Office of Water commissioned a study of worst case scenarios for ocean incineration [5]. Complete discharge of the ship's contents was considered in port, at an offshore location, and at the Gulf burn site. The report concluded that impacts on marine life could be great, but that the probability of such an event was extremely low. The analysis failed to consider the impacts of more credible spill scenarios.

In April 1985, EPA's Science Advisory Board released its "Report on the Incineration of Liquid Hazardous Wastes" [6]. The document pointed to many scientific uncertainties about incinerator performance and potential effects of process residuals. On the topic of spills, the report directed EPA to prepare "a statistical profile of spills based on historical data, to assess the probability of various exposure scenarios".[3] At the same time, the Office of Policy, Planning, and Evaluation released its "Incineration Study" [7]. This ambitious report addressed the incineration process, emerging technological alternatives, market feasibility, comparative risks, and public opposition. The risk assessment is of particular interest here. Its treatment of spill risks includes an estimate of their frequency and some qualitative description of potential environmental consequences.

The pervasive belief that "farther away is safer" ignores the important logistic differences between treatment at land based and ocean based facilities. Incineration at sea requires an additional transportation link from port facility, through harbor and coastal waters, to the designated burn site. In an effort to reduce human exposure to residuals, the potential for an environmentally damaging release of hazardous material is introduced. This paper will draw on, critique, and extend these previous efforts is assessing the risk of spills from ocean incineration.

3. The likelihood of spills from incineration at sea

3.1 Spill statistics and the Poisson distribution

The following calculations are based on the important assumption that the chance of a spill on any given transit is constant. For large numbers of transits and with low spill probabilities on each transit, such binomial trials are well approximated by the Poisson distribution.[4] This common function maps the rate of events per unit exposure and the period of exposure into a discrete probability distribution over the number of events.

$$P(X \text{ spills} \mid \lambda, n) = \frac{(\lambda n)^X \exp(-\lambda n)}{X!} \qquad (1)$$

The average rate of spills per transit, λ, is the probability of a spill on any given voyage. Equation (1) gives the probability of X spills, $P(X \text{ spills})$, in n transits. The Poisson distribution has received widespread use to describe spill statistics for oil and hazardous materials [8–11]. We will return to this formulation to generate the probability of one or more spills after exploring these

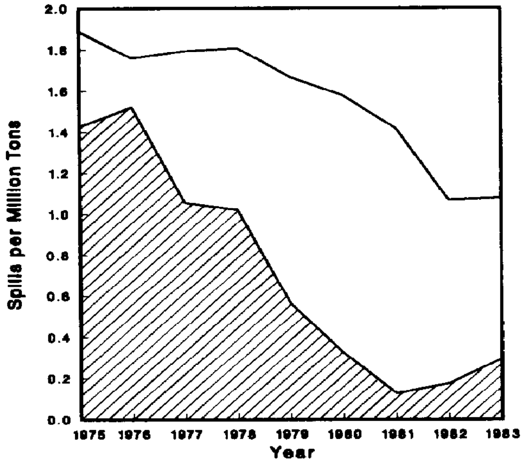

Fig. 2. Spills of petroleum and chemicals per million tons transported by tank ships and barges.

two critical inputs which describe the reliability and the scale of the ocean incineration program.

3.2 Estimating the spill rate for incineration vessels

In any risk assessment, experience is the best predictor of future performance. However, when evaluating the chance of an accident for new technologies, one is forced to rely on the operating record from analogous activities. Since incinerator vessels are required to comply with international standards for bulk chemical carriers, material storage, handling, and transfer practices closely resemble those of other hazardous liquid cargoes. These overriding technical and logistic similarities make marine transportation of hazardous chemical a good proxy for the port and coastal portions of incineration operations. Thus, accumulated experience in bulk hazardous material transportation can provide an insight into the likely transportation risks of ocean based incinerators.

Estimating the spill rate of a ship that has yet to experience a spill is not an easy matter. The Coast Guard maintains a computerized record of reported petroleum and chemical spills to U.S. waters [12]. By combining these data with waterborne commerce statistics, one can form the ratio of the number of spills from tankers and barges to the tonnage moved [13]. Figure 2 shows the generally downward trend in this value for both oil and hazardous materials. For chemicals, this ratio has varied between 1.52 and 0.127 spills per million tons over the period 1975 through 1983. Multiplication by four thousand tons per transit gives crude estimates of λ at 61 and 5.1 spills per ten thousand transits.

It is useful to consider the conclusions of other research into spill statistics.

TABLE 1

Spills per ten thousand transits from marine transportation of petroleum and hazardous materials

λ	Source
61 to 5.1	Range for chemical spills based on Coast Guard and Army Corps of Engineers data scaled for a vessel capacity of 4000 tons per transit
5.5	Meade [14] for 6000 to 20,000 dead weight ton vessels
3.1	Abkowitz [15] for Mobile Bay
1.7	Abkowitz [15] for Delaware Bay
4.1	Abkowitz [15] for aggregated Gulf ports
2.7	Abkowitz [15] for aggregated Atlantic ports
6.1	EPA Incineration Study, base rate
0.91	EPA Incineration Study, adjusted rate for Delaware Bay
0.60	EPA Incineration Study, adjusted rate for Mobile Bay

One source has reported spill rates for vessels (6000 to 20,000 dead weight tons) at 5.5 "pollution causing incidents" per ten thousand port calls [14]. More recent and detailed analysis combines the probability of an accident with the conditional probability of a spill given that an accident has occurred [15,16]. These rates range from 1.7 to 4.1 spills per ten thousand transits depending on geographical location. Each of these estimates of λ can be found in Table 1.

EPA's risk analysis is based on the historical record of similarly sized tankers. Data from worldwide chemical transportation between 1969 and 1982 yield an average rate of 6.1 spills per ten thousand transits. A number of safety factors were introduced to account for unique design features (e.g. double hull construction, bow thrusters) and assumed operating procedures (e.g. Coast Guard escort, day light travel restrictions). Taken together, these result in an adjusted spill rate of 0.60 and 0.91 spills per ten thousand transits for operations out of Mobile Bay and Philadelphia, respectively [17]. Subsequent calculations will carry through EPA's base rate and the adjusted rate for Mobile because they span the range of reasonable estimates for λ.

In their Incineration Study, EPA stopped short of calculating spill probabilities. Instead, they report an alternative measure of the likelihood of spills, the expected waiting time until the first spill, $E[\tau]$. Equation (2) defines this metric which is the reciprocal of the spill rate defined on a per year basis. Assuming fourteen transits per year of a single vessel and using the adjusted spill rate for Mobile of 0.60 spills per ten thousand transits, EPA calculated the expected time until the first spill at roughly 1100 years.^{5}

$$E[\tau] = \frac{1}{\lambda \, n_v \, f} \tag{2}$$

In this form, the number of vessels is n_v and f is the frequency of transits per vessel-year. EPA's calculation assumed one ship only. Regardless of the ap-

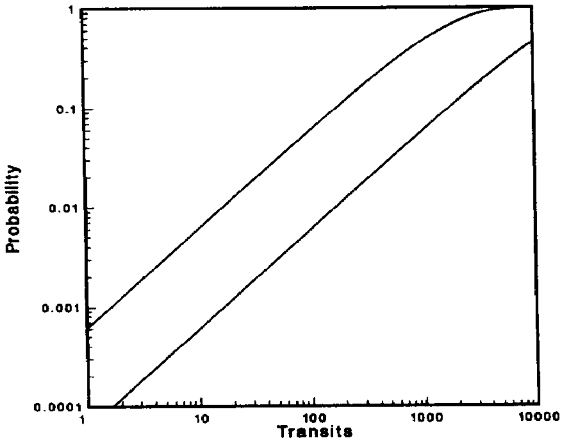

Fig. 3. Probability of a spill versus number of transits for historical and adjusted spill rates.

propriateness of these values, this description of the likelihood of spills is deficient in that it does not include any measure of the time period over which spills could occur. Obviously, the probability of a spill will increase over time, but the expected waiting time is identical whether the program lasts for five years or fifty.

3.3 The probability of spills

The reported value of $E[\tau]$ makes the possibility of a spill appear quite distant. After all, there are very few people concerned with events that occur once a millennium. However, while the expected number of years may be long, there is a finite probability of a spill on each and every transit. By recasting the Poisson distribution into a modified form, it is possible to calculate the cumulative probability of a spill for any number of transits. Figure 3 gives this probability for a λ of 6.1 and 0.60 spills per ten thousand transits.

With estimates of the spill rate, the number of transits, the number of vessels, and the overall duration of operation, t, eqn. (3) permits the calculation of the probability of a spill. For a single vessel that makes twenty transits per year for five years (i.e. 100 transits), the probability of a spill is 5.9 percent using EPA's historical rate and 0.6 percent for the adjusted rate for Mobile. Note that for such limited operations, the spill probability is proportional to the spill rate. Therefore, the order of magnitude safety factor assumed in the Mobile analysis results in an order of magnitude decrease in $P(\text{spill})$.

$$P(\text{spill}) = 1 - \exp\,(-\lambda\, n_v\, f\, t) \qquad (3)$$

For more ambitious projections of incineration at sea, the chance of spills en route increases. If the two Apollo vessels and the two Vulcanus vessels were to follow the same schedule of twenty burns per year each for five years, the probability of a spill rises to 22 percent or 2.4 percent for the historical and adjusted rates, respectively. If one imagines ocean incineration growing to meet EPA's estimated demand equivalent to thirty-three vessels, then $P(\text{spill})$ is 87 percent or 18 percent for the two rates.

Approximately one hundred incineration vessels would be required to accommodate OTA's projected incineration shortfall of 5.0 million tons by 1990 [18]. While no one has realistic expectations of such a fleet, it is worth noting that the probability of spill would climb to 99.8 or 45 percent depending on which spill rate is adopted. Each of these estimates has assumed five years of operation. The reader can easily produce estimates of probability of a spill for other combinations of the number of vessels, the frequency of transits, and the duration of operations.

These results demonstrate the sensitivity of the likelihood of one or more spills to changing assumptions about the reliability and scale of the ocean incineration program. It is interesting to note that in both respects, EPA's analysis is predicated on point estimates that tend to understate the chance of a spill. For example, the calculations are made on the basis of one vessel despite the existence of four and projections of a much greater demand.

As the next section will underscore, the consequences of a hazardous material spill depend strongly on the quantity released. Since all spills are not equal, it is not enough to know the probability of just any spill. This analysis also seeks the conditional probability of different size spills, given that a spill has occurred. The U.S. Coast Guard maintains a computerized record of petroleum and other material spills as part of the Polluting Incident Reporting System [12]. This data base contains information on the size, location, and other circumstances of reported hazardous material spills.

From the Coast Guard data, one can produce a discrete probability density function shown in Fig. 4. The quantity spilled, in metric tons, is shown on a logarithmic scale because it covers several orders of magnitude and takes on only positive values. These data are from 794 self-reported spills of hazardous material from 1979 through 1983. The median spill is approximately 0.4 metric tons with 95% of these spills less than about 27 metric tons. Note that the vast majority of these spills are less than the 4000 tons by the Vulcanus and Apollo vessels. Efforts to characterize the consequences of different size spills in the estuarine environment are described next.

4. The consequences of PCB spills from incineration at sea

4.1 Identifying concentrations for concern

Before describing the models used to predict concentrations from chemical spills, it is important to have some idea of the levels of PCB contamination that are worthy of concern. As it turns out, it is not possible to point to a clear

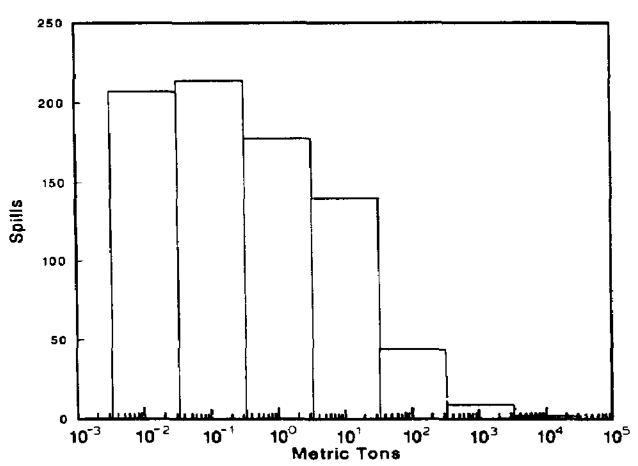

Fig. 4. Spill size distribution for hazardous materials released to U.S. waters.

threshold below which no harm results. However, by reviewing water quality standards, data on effects, and the potential for bioconcentration, one can describe a range of concentrations that help to interpret the following results.

One way to gauge the significance of these concentrations is to consider the effects of different contamination levels on the marine environment [19,20]. Acute toxicity thresholds are one measure, but they are dependent on the chemical, the target species, and the exposure period [21,22]. Fortunately, there is a very substantial literature covering the effects of PCBs and other chlorinated aromatic compounds [23,24]. The toxicity of one mixture of PCBs, Arochlor 1254, on selected vertebrate fishes varies from 0.1 to 10.0 μg/l depending on age [25,26].

The current water quality standard criteria specify ceilings on PCB concentrations to protect salt water life at 0.03 μg/l and fresh water life at 0.014 μg/l [27]. Bioconcentration considerations provide another way to describe the severity of aqueous concentrations. The Food and Drug Administration (FDA) standards limit the sale of vertebrates or shellfish with PCB concentrations in tissue greater than 2 parts per million [28]. For representative bioconcentration factors of 10^4 to 10^5 [29,30], ambient concentration of 0.02 to 0.2 μg/l serve as a threshold for damage to commercial fishing interests. In evaluating the following results, these values will serve as a rough indicator of when PCB concentrations threaten estuary ecosystems.

4.2 The nature of bottom residing spills

Besides their ecological impacts at extremely low concentrations, PCBs have other characteristics that pose particularly challenging environmental threats in nearshore regions. These species are denser than water, relatively insoluble,

TABLE 2

PCB concentrations for concern

Concentration ($\mu g/l$)	Basis
0.1 -10.0	Acute toxicity threshold for several vertebrate fishes
0.03	Federal Water Quality Criteria to protect salt water life
0.014	Federal Water Quality Criteria to protect fresh water life
0.02- 0.2	FDA limit of fish for human consumption (2 parts per million) multiplied by representative PCB bioconcentration factors (10^4 to 10^5)

and readily adsorbed onto sediments [31]. Figure 5 is a schematic representation of the transport and transformation processes of a bottom residing chemical. The material diffuses out of the spill and into the water column where it is transported by currents and tidal motions.

The consequences of a particular spill from incineration at sea are dependent on the quantity and properties of the chemical, the hydrology and ecology of the receiving waters, and other factors like weather and remedial actions. Because the effects are very site specific, this analysis considers consequences in a single location. The Mobile Estuary, shown in Fig. 6, has served as a port for previous waste incinertion in the Gulf of Mexico [32,33]. Similarity of Gulf estuaries make this research meaningful for other possible port sites in Mississippi, Louisiana, or Texas [34].

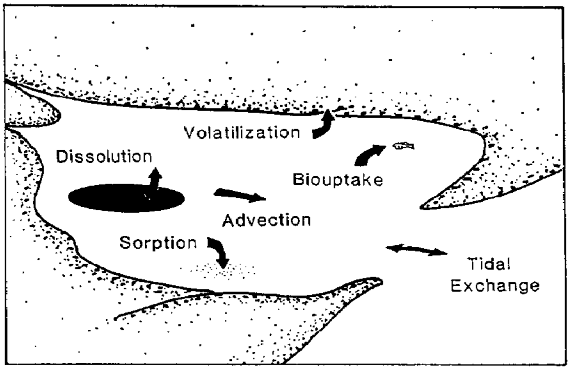

Fig. 5. Transport processes for bottom residing spills.

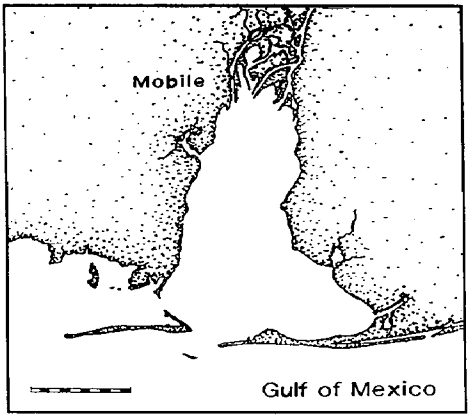

Fig. 6. Mobile Bay, past and potential port site for burns in the Gulf of Mexico.

4.3 Modeling PCB concentrations in Mobile Bay

Mathematical models can provide clues to the behavior of chemicals in environmental systems [35]. Generally, the complexity of analysis is limited by some combination of time, data, and analytic resources. As the following calculations demonstrate, the conclusions drawn from such modeling depend critically on the depth of analysis employed. The two models that follow provide rough upper and lower bounds on the average concentrations that would result from PCB spills in Mobile Bay.

The Instantaneous Mixing Model is based on an algebraic equation that produces an average concentration, $\langle C \rangle$, for a given mass of material spilled, M. Equation (4) shows this simple relationship for an enclosed bay with volume, V_{BAY}. For Mobile Bay, an average volume has been reported at 3.1×10^9 m^3 [34].

$$\langle C \rangle = \frac{M}{V_{\mathrm{BAY}}} \tag{4}$$

The Instantaneous Mixing Model overstates actual concentrations because it assumes that chemicals mix instantly and uniformly throughout the bay. This "mixing bowl" description gives a single, average concentration for given quantities of chemical and water. The two solid lines in Fig. 7 represent results of the Instantaneous Mixing Model for two PCB mixtures. Arochlor 1242 and 1260. Therefore, a one metric ton spill of PCBs would be expected to cause an average concentration of roughly 0.3 μg/l. Since these chlorinated aromatic chemicals are only slightly soluble in water, the results are truncated at the aqueous solubility limit of the chemical. The cross-hatched region marks the concentration thresholds for concern derived from bioconcentration data and FDA contamination standards for PCBs.

The Instantaneous Mixing Model represents an upper bound on the average concentrations in the bay because the entire mass of contaminant is introduced to the system at one time. However, the assumption of complete and instantaneous mixing ignores the long time scale of dissolution [36]. Also, the Instantaneous Mixing Model fails to capture the time variant character of natural estuarine flushing mechanisms. Fresh water from river sources and tidal exchange with saline waters dilute the concentrations in the bay as they transport the chemical to the Gulf of Mexico. The Dissolution Model can overcome some of these shortcomings by taking into account dissolution, mixing, volatilization, and other temporal processes. In this framing, a flat pool of uniform thickness lies on the sediment surface and slowly diffuses into the flowing water body. The flux of material out of the organic phase is controlled by a concentration driving force. The quasi-steady state concentration C_{ss}, is given by solution of eqn. (5).

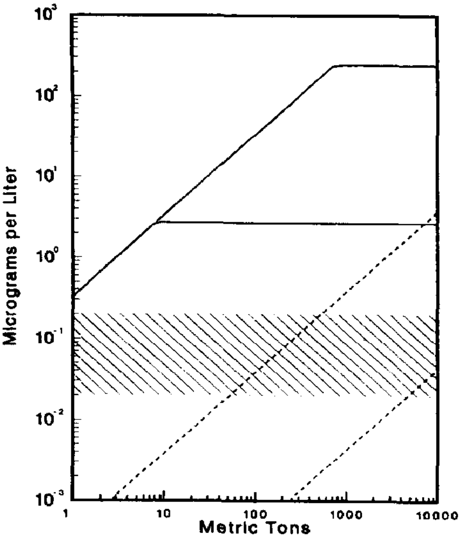

Fig. 7. Upper and lower bounds on average PCB concentrations in Mobile Bay.

$$C_{ss} = \frac{k\,M\,(C^* - C_{ss})}{\rho\,h\,Q} \tag{5}$$

For some time after a spill, but before complete dissolution of the bottom residing sources, the bay may experience quasi-steady state, tidally averaged concentrations[6]. For most of the chemicals proposed for incineration at sea, the duration of the bottom residing pool is nearly proportional to its thickness. This thickness is governed by physical properties of the chemical and the geography of the sediment bed [37]. Reasonable pool thicknesses lead to very long lived pools lasting several decades and longer. While this could facilitate clean up efforts, it leads to concern over chronic impacts, about which little is known [6]. Interactions between sediment and the water column have caused long term, low level contamination in other estuaries [22,38].

The dotted lines in Fig. 7 show these steady concentrations over a range of spills sizes of the same two PCB mixtures. The fresh water flow through the bay, Q, is 1800 m^3/s, the dissolution constant, k, is 1.26×10^{-3} cm/s, and the bulk density, ρ is 1.5 g/cm^3. The thickness of the pool, h, is 0.3 cm, the height of the free surface pool with a surface tension of 40 dyne/cm in water [37]. Here, a 1000 metric ton spill results in a quasi-steady concentration of 0.11, and 0.04 μg/l, respectively. Note that these are many orders of magnitude lower than the predictions of the Instantaneous Mixing Model.

The Dissolution Model is clearly a more realistic representation of the underlying transport process of bottom residing spills. However, actual concentrations could be greater than these results predict. The presence of large quantities of more soluble organic chemicals could increase the overall solubility of the PCBs, speeding the rate of mass transfer. Alternatively, emulsions of chemicals could form increasing transport of the organics by bottom currents and increasing the surface area available for mass transfer.

The Instantaneous Mixing Model and the Dissolution Model can be used to bound the average concentrations that would result from PCB spills in Mobile Bay. Still, both models assume a uniform distribution of contaminant throughout the bay. To say anything quantitative about the distribution of contamination within the estuary requires the use of a spatial model. Based on partial differential equations of the conservation of mass, most current efforts at spatial modeling produce numerical solutions that define multidimensional concentration profiles. For real estuaries, this analysis is a great deal more complicated than the previous two [39]. The data requirements are large and include spatial and temporal description of system boundaries, source terms, flow and mixing patterns.

How do these results compare with EPA's findings? The Agency's Incineration Study states that the impacts of such a spill in Mobile Bay are "uncertain". While true on its face, such comments are insufficient. This paper has shown that more is known about the consequences of a spill. How would the consequences of spills in other settings compare with those in Mobile Bay? Do tidal, climactic, or seasonal variations introduce additional uncertainties? Are local concentration variations, so-called hot spots, a possibility? These and many others issues remain. The next section will interpret the results of this investigation into the likelihood and severity of hazardous waste spills from incineration at sea.

5. Discussion of results

5.1 Uncertainty in the likelihood of spills

Any analysis of the likelihood of potential outcomes is accompanied by uncertainty. As one example, the limited historical experience of ocean incineration provides no real alternative to the use of analogies. The 350 burns without a spill is consistent with a wide range of spill rates. For example, for a rate of 6.1 spills per ten thousand transits, the probability of zero spills is 80.8 percent. With the modified rate of 0.60 spills per ten thousand, the chance of no spills is 97.9 percent. In short, these data are insufficient to make any reasonable inferences about the spill rate.

In this paper, the frequency of spills from chemical tankers forms the basis for estimating the chance of a spill from incineration activities. But despite obvious technical and operational similarities, we can not know how the peculiarities of the incinerator program will influence the likelihood of spills. Almost a decade ago, the prospect of liquefied propane and natural gas transportation by tanker vessel prompted debate over the risks of catastrophic release [40]. Then, too, the spill rate was estimated from other marine accident statistics. High design and operating standards were assumed to add a margin of safety, reducing the expected rate of spills by twenty-five times [41].

EPA's risk assessment followed this same approach. Incinerator operation is assumed to be ten times less prone to spills than the population of chemical carriers [7]. As in the LNG case, this safety factor is unsubstantiable. Neither analysis considers the possibility that the uniqueness of the program might lead to different risks. In fact, regional weather conditions, local port configurations, or even the peculiarly hazardous cargo could offset the effect of proposed safety measures. As shown earlier, this single assumption of a ten fold decrease in spill rate has a considerable influence on the calculated probability of spill. Such optimistic estimates overlook factors that tend to offset or even increase the spill rate [41]. The unique hazards that accompany such operations can turn routine operations into critical ones. In view of the intense public opposition to incineration at sea, the prospect of sabotage or other violent acts should not be discounted.

Subtle and unavoidable biases enter the evaluation through judgements about data, assumptions, methods and interpretation. This paper has given several estimates of the spill rate and demonstrated the relationship between the rate, the number of transits, and the probability of a spill. In contrast, EPA's Incineration Study relied on a single number of transits and used a single value for the spill rate to calculate the expected time until the first spill. Whether intentional or not, this produced the most remote estimate of likelihood which in turn was presented by the potentially misleading metric of expected waiting time. Estimates of the probability of a spill, which require estimates of the number of vessels and years, provide more relevant information for evaluating the overall risks of the program. Finally, because the spill rate λ is such a critical parameter, it should be prominent in EPA's report on these risks, not relegated to the appendices of a multiple volume study. This only increases the difficulty of investigating the implications of different data and assumptions.

Taken together, the sources of uncertainty should inspire a healthy skepticism about any single estimate. Unfortunately, conflicting estimates of the likelihood of spills from incineration can only be resolved by accumulated experience. Yet to gain this experience is to run the very risks that motivate the analysis. In reviewing estimation methods for oil spill risk assessments, Stewart and Lescine suggest that to improve the validity of risk estimates, "the widest possible range of risk estimates should be developed" [42]. Because of the importance of the resources at risk, these probability estimates are useful even if they are based on imperfect data, analogies, and assumptions. The greatest value of such analyses is the development of a general sense of the likelihood. There is room for legitimate dispute over the significance of an 2.4

percent versus an 22 percent chance of spill, but either vlue appears at odds with EPA's assertions that it is "remote" or "extremely small".[7]

5.2 Potential consequences of spills

This investigation advances the understanding of potential impacts of spills from incineration at sea. But, as in the estimation of their likelihood, analysis of environmental consequences of spills encounters many uncertainties. Just as analogies are sought to predict the former, mathematical models are used to characterize the behavior of chemicals released from incineration activities. The two models described in this paper provide upper and lower bounds on the average concentration in the bay.

In the simplest treatment, the Instantaneous Mixing Model provides estimates of the average concentration of a completely and instantaneously mixed spill in Mobile Bay. As an upper bound, spills of 0.1 metric tons of PCBs would create an average concentration greater than the threshold based on water quality standards or food contamination levels life. Because dissolution is a rather slow process, the Instantaneous Mixing Model overstates the average concentration in the bay.

As PCBs diffuse from the organic, bottom residing pool into the water column, fresh water from land and saline water from the Gulf of Mexico mix, further diluting these concentrations. The Dynamic Model accounts for these temporal considerations and gives steady concentrations that are two to four orders of magnitude below the upper bound. The predefined threshold for concern would only be surpassed for spills of a few chemicals in quantities approaching the likely capacity of incinerator vessels.

The Dynamic Model raises two issues that are obscured by the static view of the spill. First, the existence and persistence of bottom residing spills could be a great aid to recovery efforts, provided that dredging is conducted in a timely and effective manner. Second, rapid adsorption of the chemical onto sediments and subsequent desorption could cause extensive, long term contamination of the coastal environment.

Both the Static and Dynamic Models produce average concentrations as though the bay were uniformly mixed. In fact, much higher values are certain to be found in the vicinity of the spill. To anticipate heterogeneities in concentration, attention must turn to spatial distribution of the chemical. Results of the Spatial Model have many practical applications. This is an essential component of responsible contingency plans and development of adequate remedial action plants. Analysis of the consequences of spills in different locations could be used to evaluate competing port sites. Finally, realistic damage estimates are needed to establish meaningful liability requirements.

6. Conclusions

This analysis of the likelihood of spills has implications that extend beyond incineration at sea to other assessments of technological risk. Because of the necessary reliance on imperfect analogies, assumptions, and data, any such analysis contains substantial uncertainties that are, at least to some extent, unavoidable. Biases introduced by the framing of analyses and the packaging of results should inspire a healthy sense of skepticism about any single estimate. Open review and discussion of these analyses is the only realistic way to build a consensus on the dimensions of risk posed by controversial technologies.

In this analysis, the likelihood of spill was reported in several ways. Existing accident statistics are used to arrive at conservative and more optimistic spill rates. The probability of at least one spill is given for different numbers of transits. If four vessels operate continuously over five years, the probability of a spill is 21% and 2.4%, respectively. A scenario with thirty three ships operating for the same period produces estimates of 86% and 18%. Should a spill occur, it is equally likely to be above or below 0.4 metric tons, but there is a five percent chance that it would be greater than 27 metric tons.

To demonstrate the site specific consequences of a range of spills, Mobile Bay was chosen for particular attention. The predominant finding of the research into spill consequences is that hazardous material releases have the potential to cause severe impacts in coastal environments. Physical and chemical properties of chlorinated aromatic wastes can lead to persistent contamination of the biota and sediment in affected areas.

Mathematical modeling provides some estimates of the concentration profiles from different quantities of likely incineration chemicals. The Static and Dynamic Models provide upper and lower bounds on the concentrations that would be experienced within Mobile Bay. The modeling efforts described in this paper provide partial answers to important questions about the site specific impact of hazardous material spills. Both predict that PCB water quality criteria might be exceeded by credibly sized spills from incinerator vessels. There is substantial uncertainty about the concentrations that would result and how they are distributed throughout the bay. Given the seriousness of the environmental threat and the limited understanding, there is a clear need for more research to develop realistic impact assessments. Such information is necessary for contingency planning and for the establishment of liability requirements.

This paper should be seen as one contribution to an overall assessment of hazardous waste incineration at sea. It does point out that in its efforts to reduce this historic reliance on land disposal, EPA should anticipate the sometimes new and different risks engendered by detoxification. Because of the peculiar hazard presented by the cargo of incinerator vessels, compliance with proposed regulations may not guarantee an acceptably low level of risk at the community or regional level. With the important questions of remedial action and liability for damages unanswered, prudence dictates a more cautious and thoughtful approach to hazardous waste incineration at sea.

Notes

[1] U.S. Environmental Protection Agency, Ref. [1], p.6.

[2] The contingency plan for the 1983 PCB permit noted that "the greatest potential for a hazardous substance pollution incident involving the vessel is during loading of the vessel at the [port facility], and during transit of the Mobile River from Chickasaw to the Mobile Harbor Entrance" [43].

[3] U.S. Environment Protection Agency, Ref. [6], p.12.

[4] The Poisson distribution describes spill statistics that satisfy three conditions: the probability of a spill on any given transit is constant (stationarity); the probability of two or more events on any given transit is negligible relative to the probability of one spill (non-multiplicity); and the number of spills is independent of the number of past spills (independence).

[5] There is some minor dispute over the frequency of vessel transits. Waste Management claims that the Vulcanus, which has a capacity of 3,500 metric tons, can burn 80,000 tons of waste per year. This translates into about 21 transits annually. Similarly, the Apollo vessels, which carry 1.33 million gallons, advertise a yearly throughput of 30 million gallons. This is equivalent to over 22 transits per year.

[6] Once the pool is depleted or removed, this model suggests that the average concentration falls exponentially with a time constant equal to the inverse of the net first order loss rate. If estuarine flushing is the dominant mechanism for contaminant disappearance, then this time constant is equivalent to the residence time of the estuary, defined as the ratio of the bay volume to the freshwater flow rate. Using the values given in the text, Mobile Bay has a residence time of twenty days.

[7] EPA's Incineration Study [7] concluded that "... there is a remote probability that ocean incineration operations could result in a ship casualty and spill of hazardous waste" (p.1).

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