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Does incineration of waste threaten public health? Are the risks untenable? These issues have been the continuing subject of heated debate, scientific and otherwise. Concurrent with increased uses of incineration, there are growing public concerns about the health and ecological impacts of combustion facilities, as well as the levels and costs of environmental controls.

Although today's potentially viable, but controversial, technology emerged from developments over the past century, it has in one form or another been used for much longer. Currently, it is used for destroying contaminated hospital wastes, reducing municipal waste volumes, substantially cutting amounts of hazardous wastes (chemical and biological), and producing energy.

The quantity of material combusted has grown over the past several decades. In the United States, use of the technology markedly increased in the 1980s, when, facing a rapid rise in garbage production, policy makers selected waste incineration as a waste management option. By that time, European nations had already made a strong commitment to adopting the technology.

A National Research Council (NRC) report released last November, Waste Incineration and Public Health, addresses pollutant emissions, exposures, and health risks of incineration (1). It notes that, despite a continuing effort to evaluate the health impacts of emissions, there are still critical data limitations and key inadequacies in current health assessment frameworks (see box, “What the NRC report indicates”).

These limitations and uncertainties occur in several areas. The availability of emissions data, required for characterizing events other than normal operation, is very limited. Moreover, the existing framework used to assess human exposures and health effects from incinerators has focused on local populations but excluded workers and larger regional populations. In addition, a lack of data prevents characterizing intermedia transfers of emitted chemicals from ambient air to food webs and indoor environments.

Burning in the U.S.A.

Although per capita production of municipal solid waste (MSW) increased from 1960 to 1996 from 1.2 to 2 kg/day(1), its growth slowed in the 1990s. Nonetheless, waste production continues to rise because of population growth.

Today, hundreds of incinerators—industrial kilns, boilers, and furnaces—are used to burn MSW and hazardous waste. Approximately 150 commercial, private, and government-operated hazardous waste incinerators, as well as an unknown number of industrial boilers or furnaces and cement or aggregate kilns, currently accept hazardous wastes for combustion. An estimated 3 million tons of hazardous wastes are burned annually (1).

More than 1000 incinerators are used to burn medical waste. Hospitals, which can generate about 12 kg of waste per bed per day, are the largest medical waste producers (1). About 15% of hospital wastes are designated as “red bag” waste and are incinerated or otherwise sterilized to prevent the spread of disease. A rising fraction of medical waste is also burned in municipal waste incinerators (see Figure 1).

Emissions from all incinerators are subject to regulations promulgated through the 1990 Clean Air Act (CAA). The regulations are intended to limit atmospheric concentrations of 188 hazardous air pollutants (HAPs) and six criteria air pollutants—carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide. The list of 188 HAPS is published by EPA's Office of Air and Radiation.

The 1990 CAA Amendments mandate that EPA establish source performance standards for new incinerators and emissions guidelines for existing facilities. This requirement moves regulations from the prior risk-based emissions standards for HAPs to technology-based standards. In response, EPA has defined Maximum Achievable Control Technology (MACT) standards for incinerators and other HAP sources. MACT standards require all pollutant sources within a category, such as incinerators, to attain a level of control that reflects the average of the best-performing (top 12%) of permitted and operating facilities in that category. The residual risk remaining after MACT must also be assessed and held below a target level.

The NRC study notes that MACT standards are intended to address local problems and may not be sufficient to protect workers and regional populations (see Figure 2)—many pollutant exposures can have a local and a regional sphere of impact. For an impacted population, the magnitude of cumulative exposures to incinerator pollutants depends on the proximity to the nearest incinerator and on the number of incinerators and other combustion sources releasing that pollutant into a region. The relative magnitude of local and cumulative exposures depends on the persistence and transport range of the pollutant (2).

Efforts to identify and evaluate potential incinerator health effects require integration of many different kinds of information. The types of pollutants produced as a result of waste combustion must be identified and characterized by their toxicity and chemical properties. Emission rates and locations to which these pollutant emissions travel must be determined. Some emissions are released to the environment from a stack; many are filtered out in pollution control equipment and sent to a landfill; and some emissions are released inside the waste facility itself. Where and how released pollutants spread, transform, and accumulate within the environment must be known for each emission, whether released inside the building, up the stack, or into a landfill. Human contact with waste products and with air, water, soil, and food that have been impacted by these releases must be characterized to assess any potential human health effects. Finally, to assess risk, any observed or predicted exposures must be compared to those exposures associated with adverse health effects.

Characterizing combustion products

Modern incinerators are highly efficient systems for reducing the volume of wastes. The combustion process produces three byproduct streams: stack emissions, ash residue, and residues from pollution control equipment.

The largest volume of material released from an incinerator is in the stack-gas stream, which consists mostly of carbon dioxide and water vapor, as well as smaller amounts of particulate matter and pollutant vapors. Many of the substances detected in these gaseous and particulate emissions are potentially harmful. Among these are fine particulate matter; acid gases; oxides of carbon, nitrogen, and sulfur; dioxins, furans, and other chlorinated compounds; metals; and polycyclic aromatic hydrocarbons (PAHs).

Many organic compounds found in stack emissions and waste residues are products of incomplete combustion (PICs), whose rates of production are controlled by combustion conditions. Their concentrations vary; to understand this, it is helpful to compare incinerators, which are essentially combustion devices, with another more familiar combustion device—the automobile engine.

Regarding those vehicle pollutant emissions, it is well known that the major fraction is produced during startup and periods when the car is speeding up or slowing down (stop-and-go traffic). A well-tuned car moving at freeway speed puts out relatively few emissions. Similarly, the stack of a modern well-tuned incinerator—one that maintains combustion conditions at the appropriate temperature, residence time, and turbulence and operates at constant, uniform feed—can put out a much lower mass of toxic pollutants than its predecessor of 20 years ago. These ideal combustion conditions are needed to maximize the destruction of PICs and minimize the partitioning of heavy metals into vapor and particle-phase emissions that are released out of the stack.

However, addressing changes in health impacts that involve on-site workers as well as local and regional populations requires consideration of source-to-dose relationships that are not necessarily proportional to the mass of toxic stack emissions released during ideal conditions. This is because during start-up and transient events, ideal conditions are unattainable, and pollution emissions can increase significantly. Moreover, analogous to automobiles with their air pollution control devices, equipment failures can significantly increase pollutant emissions (see Table 1).

Understanding the cumulative emissions of an incinerator also requires knowing how much stop-and-go operation takes place. Medical incinerators tend to produce a larger fraction of pollutants per unit mass of waste combusted, in part because these incinerators are operated in a start-and-stop mode. An extreme example of this problem is the large release of dioxins and furans from backyard incinerators (see Figure 3), which are usually simple metal barrels in which people burn garbage (3). Despite the importance of emissions from these intermittent cycles and from nonroutine events, virtually all emissions data used to evaluate incinerator health impacts are derived from routine operations.

Incineration also produces potentially toxic solid wastes. This includes residual ash collected from the furnace, as well as solid wastes collected from precipitators and scrubbers. These produced wastes, which contain quantities of heavy metals, such as lead, cadmium, and mercury, and may contain many of the less volatile PICs, must be placed in landfills. Disposal is particularly expensive because this material is more toxic than ordinary domestic refuse.

Emissions, transport, and exposure

The most important and difficult task for those who evaluate patterns of human exposures to incinerator emissions is tracking the concentration and movement of contaminants, as well as the changes that occur in them as they travel through the environment from the incineration facility to a point of contact with people.

Most incinerator pollutants are released as stack emissions to the atmosphere, where they partition between gas and particulate matter fractions. The partitioning affects downwind transport and deposition. As the pollutants spread through the air, workers at the incinerator and people who live close by can be exposed directly through inhalation. Those who live close by can also be exposed indirectly through ingestion of locally produced foods or water contaminated by pollutant deposition to soil, vegetation, and surface water.

People living at some distance from incinerators are exposed through a different mix of environmental pathways. At these distances, pollutants have sufficient time to go through various chemical and physical transformations and can cycle into and out of soil, vegetation, and surface water. At regional scales, exposures through contact with water, food, soil, and house dust appear to be the most important exposure pathways for the more persistent pollutants such as PAHs, dioxins, furans, polychlorinated biphenyls, mercury, and cadmium.

Unfortunately, multimedia, multipathway exposures remain poorly characterized, and there is a continuing absence of scientific studies, models, and direct measurements of human contact for these indirect pathways.

As discussed in the NRC report and in current literature (1, 4, 5), an obstacle to regional-scale health assessments is the low reliability of both measured data and models used to determine indirect exposures and, in particular, intermedia transfer factors (ITFs). ITFs express the ratio of a contaminant's concentration in one environmental medium to another or in an exposure medium relative to an environmental medium (5). Some examples of ITFs are water/air, soil/air, vegetation/air, vegetation/soil, and indoor/outdoor air partition ratios. Several ITFs are needed for assessing source-dose relationships for incinerator emissions.

Health effects

Historically, the principal health concerns for waste incineration were mainly focused on communities living near the incinerator. The NRC report more comprehensively identifies three potentially exposed populations (1): the local population, which is exposed primarily through inhalation of airborne emissions; workers at the facility, especially those who clean and maintain the pollution control devices; and the larger regional population, who may be remote from any particular incinerator, but who consume food potentially contaminated by one or more incinerators and other combustion sources that release the same persistent and bioaccumulative pollutants.

Workers:

Workers come into close contact with stack emissions. They also have contact with toxic pollutants captured in the air pollution control equipment, including electrostatic precipitators and bag houses. These must be cleaned out periodically, and high concentrations of harmful compounds, for example, dioxins and various metals, have been measured in the air during these operations. Personal and area sampling of workers cleaning out electrostatic precipitators at municipal incinerators reveals exposures greatly in excess of recommended limits for dioxins and metals (arsenic, lead, cadmium, and aluminum) (1, 6). Elevated levels of dioxins and lead have been reported in the blood of municipal incineration workers (1, 7). Higher concentrations of hydroxypyrene in the urine of municipal incineration workers (8) indicate exposure to elevated levels of PAHs; similarly, higher levels of urinary mutagens have been reported among refuse incinerator workers (9).

Results such as these led the NRC committee on health effects of incineration to express substantial concerns about incinerator workers' exposures to dioxin, lead, mercury, other metals, and particulate matter, and a moderate degree of concern about their exposures to acidic aerosols and acidic gases. Because the MACT standards proposed by EPA are intended to reduce emissions from the facility, but not change work conditions, concern for workers will not diminish after implementation of MACT.

Regional Versus Local Health Impacts:

Adverse health effects of lead and particulate matter are now reported at levels previously thought to be safe. These pollutants can be produced by multiple existing sources in communities where incinerators are located. The NRC committee expressed great concern about potential adverse health effects of these pollutants in communities near incinerators. However, because implementation of MACT should reduce these emissions substantially, the committee expressed only minimal concern for release of lead and PM from incinerators operating under MACT.

Similarly, the committee's moderate degree of concern about the emissions of mercury and other metals is reduced to a minimal degree of concern with MACT. When incinerators are operated under MACT, the committee expressed negligible to minimal concern for impacts on the local community but noted that local impacts will vary by pollutant. The committee expressed concern, however, that the MACT standards would not necessarily reduce releases during start-up and nonoptimal operating conditions.

On a more regional level, airborne concentrations of incinerator pollutants will be quite low However, the transport of persistent pollutants from multiple incinerators and other combustion sources can result in elevated concentrations of these pollutants in terrestrial and aquatic food over a wider geographic area. These considerations led the committee to have substantial concerns about the health effects of incinerator-generated dioxins and a moderate degree of concern about incinerator-generated lead, mercury, and other metals on a regional population. The committee did not judge that MACT would reduce these elevated levels of concern (1).

Nagging uncertainties

Characterizing health impacts from incinerators involves the use of large amounts of data coupled with the use of models. Large variability and uncertainty are associated with these evaluations because these data and models must be used to characterize individual behaviors, engineered system performance, contaminant transport, human contact and uptake, and dose among large and often heterogeneous populations. The NRC committee identified the issues of uncertainty and variability as having scientific and policy implications for attributing health impacts to incinerators.

In particular, the committee noted that when the uncertainty and variability become large, it becomes difficult for the stakeholders to interpret or assign relevance to the estimated magnitude of exposure and health risk.

Key uncertainties in the current framework for assessing health impacts derive from factors that are excluded and from a lack of scientific data or understanding. As noted above, one case in which uncertainty derives from exclusion is a health characterization based only on normal operating conditions. Because no data are available to evaluate emissions during start-up and upset conditions, which can be much higher than normal operating conditions, it is not yet possible to evaluate the exposures and consequent potential health risks during these conditions.

Examples of where limited scientific data and inadequate understanding lead to uncertainty are the use of intermedia transfers—particularly, biotransfer factors. Evaluation of methods for measuring and estimating these ITFs reveals that the methods have an error factor in the range of 1.5- to 10-fold (5). The overall variance in estimation methods for ITFs comes from several factors, including variability among experiments; ignorance regarding the processes of chemical partitioning; and the reliability in measures of both the outcome (biotransfer or partition factor) and the explanatory variable, such as Kow.

Future directions

Exposure and health assessments are key steps in the analysis of a link between various incinerator sources and human health risks. If properly conducted and evaluated, these assessments can be useful in the development of an effective risk management strategy. Thus, they might have value for guiding policy directions. However, given the limitations mentioned earlier, they will not be conclusive about specific risk factors.

Managing human exposures to pollutants released from incinerators requires an assessment framework that addresses multiple sources and multiple exposure pathways. More important than an emphasis on predicting exposure and risk, this framework must be able to identify the most significant pollutants, source categories, and exposure pathways. An explicit treatment of the variability and uncertainty in the source-to-dose chain is necessary. As recently noted by Hertwich and co-workers (10), parameter, model, and decision rule uncertainty must all be addressed in multimedia exposure assessments.

If efforts to characterize incinerator health impacts are to be useful for decision makers and the public, two essential research tools—models and measurements—must be better integrated. Models provide the means to integrate and interpret measurements, design hypothesis-driven experiments, and predict the effectiveness of risk management strategies. Measurements, in turn, provide the tools needed for evaluating and improving models.

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