Health Risk Assessments for Alumina Refineries

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Objective: To describe contemporary air dispersion modeling and health risk assessment methodologies applied to alumina refineries and to summarize recent results. **Methods:** Air dispersion models using emission source and meteorological data have been used to assess ground-level concentrations (GLCs) of refinery emissions. Short-term (1-hour and 24-hour average) GLCs and annual average GLCs have been used to assess acute health, chronic health, and incremental carcinogenic risks. **Results:** The acute hazard index can exceed 1 close to refineries, but it is typically less than 1 at neighboring residential locations. The chronic hazard index is typically substantially less than 1. The incremental carcinogenic risk is typically less than 10^{-6} . **Conclusions:** The risks of acute health effects are adequately controlled, and the risks of chronic health effects and incremental carcinogenic risks are negligible around referenced alumina refineries.

Health risk assessments (HRAs) based on air dispersion modeling of alumina refinery emissions have proved useful to assess and communicate risks. The aims of this article are to outline the methodology of air dispersion modeling and HRA, discuss the choice of air dispersion models, describe the general features of alumina refinery air emissions, and give the results of recent HRAs at alumina refineries.

METHODS

Air Dispersion Modeling

Monitoring of emission sources and ambient receptors cannot provide complete geographic and temporal coverage of the distribution of air emissions in an environment surrounding a refinery. It is, therefore, desirable to use air dispersion modeling techniques to more fully describe and document the likely distribution of air contaminant values in space and time. The approach most commonly adopted is to document the sources and substances emitted in an emissions inventory, then to input the emission rates to atmospheric dispersion models to provide predictions of ground-level concentrations (GLCs) of substances that could potentially cause or contribute to health effects.

Sometimes HRAs are based solely or primarily on ambient air monitoring data, rather than air dispersion modeling data—particularly where complex air sheds involve multiple industrial

facilities. See, for example, Queensland Health¹; an assessment that took into account a number of industrial sources in a region, including coal-fired power stations, alumina refining, and aluminum smelting.

Choice of dispersion model to be used can be critical in determining the accuracy and reliability of GLC predictions. For point and fugitive area sources, a range of models is typically used on the basis of suitability for the conditions, terrain, and source types. The Australian Aluminium Council sponsored a review of best practice modeling techniques in the alumina industry (PAE Holmes Ltd, 2009), and the practice of HRAs in Australia has generally followed the recommended dispersion models and techniques as reviewed.² Terrain effects are taken into account either directly via wind field modeling and use of models with complex terrain capabilities, such as Calmet/Calpuff or “The Air Pollution Model,” or by quantification of speed-up factors that are then applied to wind data.² Computational fluid dynamics modeling has been used in recent applications to quantify areas of high or low wind speed that may be important in determining dust (high-wind speed effect) or odor (low-wind speed effect) behavior.

Uncertainties in modeled estimates of exposure arise from various sources, including combined emission value uncertainty, model uncertainty, and meteorological variability. Uncertainty of modeled versus observed GLCs is typically within $\pm 50\%$ at the 95% confidence level for substances with substantial emissions data sets.³ The US Environmental Protection Agency (EPA) has concluded that errors in modeled highest estimated concentrations are typically between $\pm 10\%$ and $\pm 40\%$.⁴

Where HRA outcomes approach or exceed guideline values, it becomes important to test assumptions underlying dispersion models by conducting sensitivity analyses to such issues as assimilation of predicted winds with local observations, uncertainty of emission rate estimates, and choice of model and parameter settings within the model. For example, dispersion over warm and weakly buoyant sources such as refinery cooling ponds was observed from computational fluid dynamics modeling to be highly direction dependent according to the incident wind variation to pond orientation (length to width ratios).⁵ This behavior, in turn, influenced the initial plume rise that occurred, such that there were marked differences in downwind GLCs across-axis compared with along-axis.

Health risk assessments of Alcoa refineries have tended to predominantly use the air dispersion models Calpuff and The Air Pollution Model, with The Air Pollution Model used mainly for point sources, including tall buoyant sources with minimal wake effects, whereas Calpuff has been the model of choice for large-area sources where emission rates are driven by wind processes, such as fugitive dust generation.⁶ Where two models are used for different types of sources, it becomes necessary to add the outputs hour by hour and at each grid point.⁶ Care must be taken to ensure that the model time steps used match exactly, so that statistics generated by the combination of outputs are representative and comparable. For example, the conditions that lead to maximum fugitive dust exposures are frequently associated with strong winds, conditions that tend to lead to lower GLCs for releases from tall point sources. If outputs are not matched exactly in time and, instead, maximum values of different source contributions to a location were simply added, it would erroneously attribute a combined effect that, in practice, would not happen.

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Health Risk Assessment

Ground-level concentrations generated by air dispersion modeling are used to assess three types of health risks:

- Risks of acute health effects
- Risks of chronic health effects
- Incremental carcinogenic risks

Short-term GLCs are used to assess the risks of acute health effects. Typically 99.9th percentile 1-hour average GLCs and 99.5th percentile 24-hour average GLCs are used, to represent an estimate of near worst-case conditions, which by definition occur infrequently. Annual average GLCs are used to assess the risks of chronic health effects and incremental carcinogenic risks.

The risks of acute health effects and chronic health effects are assessed by calculating the acute hazard index (AHI) and chronic hazard index (CHI), respectively. These are each calculated as the sum of hazard quotients for each compound, where the hazard quotient is calculated as the GLC divided by the relevant health-based ambient air quality guideline concentration—for the relevant averaging period. This approach assumes additive relationships, conservative, given the diversity of toxicological properties of the compounds under assessment.

Unit risk factors, published by agencies such as the US EPA and the World Health Organization, give, for each carcinogen of interest, the upper-bound probability of cancer that would be expected with continuous exposure to an inhaled concentration of $1 \mu\text{g}/\text{m}^3$ over 70 years.^{7,8} Incremental carcinogenic risk (ICR) is the incremental upper-bound probability of an individual developing cancer as a result of lifetime exposure to a carcinogen at a specified concentration. This incremental probability is over and above the probability of cancer occurring as a result of other factors—that is, the background incidence rate of cancer. The ICR of each compound is calculated by multiplying the relevant unit risk factor by the annual average GLC. The total ICR is then calculated by summing the ICRs for each compound. This again assumes additive relationships, conservative, given the specificity generally shown by carcinogenic agents for particular types of cancer. The US EPA “de minimis” ICR is 1×10^{-6} . This incremental risk, which equates to less than one person in a million, is regarded as negligible from the US EPA regulatory perspective. Tolerable ICRs vary among regulatory jurisdictions, typically between 10^{-6} and 10^{-4} , with 10^{-5} gaining acceptance in some jurisdictions.^{9,10}

Hazard indices and ICRs are computed for each point on a grid around the refinery. Corresponding contours are often plotted on maps or aerial photographs, representing the AHI, CHI, and ICR at locations/receptors near to the refinery. This can aid presentation to stakeholder groups. Health risk assessment methodology has been described in more detail by the enHealth Council of Australia.¹¹

Noninhalation Pathways

Alumina refinery HRAs conducted to date have concentrated mainly on the air inhalation pathway. Inhalation is expected to represent the most significant exposure route for atmospheric emission sources. Compounds tending toward the particulate phase have been investigated as potential candidates for multipathway exposure, as these may deposit on surfaces and so become available for ingestion.

The Hot Spots Analysis and Reporting Program (HARP) methodology, developed in consultation with various Californian environmental agencies, was applied in the Wagerup and Pinjarra refinery HRAs.^{12–14} The analyses considered the following indirect exposure pathways:

- soil ingestion
- dermal absorption
- vegetable ingestion
- water ingestion

The HARP assessment found that exposure by pathways other than inhalation had potential to be significant only for the metals arsenic and cadmium. Cadmium made only a very minor contribution to the CHI, and as the maximum CHI itself was so small, exposures via dermal absorption and ingestion would not make any appreciable difference to the overall CHI, justifying the exclusion of alternative pathways for cadmium. Arsenic exposure via inhalation was a significant contributor to the predicted ICR, however; so it received further evaluation. The HARP program indicated that the inhalation exposure pathway was likely to account for approximately 75% of the carcinogenic exposure to arsenic. The remaining 25% of the exposure was predicted to occur as a result of soil ingestion (14%), vegetable ingestion (8%), dermal absorption (2%), and drinking water ingestion (1%). Incorporating these additional pathways in the Wagerup refinery assessment meant that the total ICR for all compounds would have increased from 0.63×10^{-6} to 0.72×10^{-6} at the maximum receptor, which is less than the US EPA “de minimis” level of 1×10^{-6} . Therefore, the alternative exposure pathways for arsenic were not expected to have contributed significantly to the ICR at the maximum receptor and would have contributed even less at other receptors. Noting that the assumptions inherent in the HARP are designed to err on the side of health protection to avoid underestimation of risk to the public (Office of Environmental Health Hazard Assessment¹³), it is reasonable to confine the HRA pathways to the inhalation route, in the knowledge that other pathways will not significantly affect the overall assessed risk level.

RESULTS

Emission Sources

Alumina refinery sources may be divided into point and fugitive sources. Point sources include stacks, vents, open-top tanks, and vessels in the Bayer process areas of the refinery, as well as stacks and cooling towers associated with powerhouse sources, boilers, and gas turbines. Point sources may be further divided into low- and high-level sources, buoyant and nonbuoyant releases, and low- or high-moisture content sources. Some of these sources are relatively complex to reliably measure and derive reliable emission rates for, particularly, low-level, nonbuoyant, and high-moisture content sources.

Fugitive sources include area sources, such as bauxite residue-storage areas, cooling ponds, bauxite stockpiles, and loading and transfer areas, such as train- and ship-loading facilities. These types of sources also involve difficult measurement, estimation, and/or release intermittency challenges.

When assumptions are made about emission sources, both point sources and fugitive sources, as part of the HRA process, they are deliberately conservative and precautionary—tending to overestimate the effect on point risk estimates.

Case Studies in Australia

There have now been at least five HRAs undertaken for alumina refineries in Australia, with reports publicly available on the Internet. See, for example, the Wagerup refinery, Pinjarra refinery, and Pinjarra residue HRAs undertaken on behalf of Alcoa, the Worsley refinery expansion HRA undertaken for BHP Billiton, and the QAL Gladstone refinery HRA undertaken for Queensland Alumina Limited.^{12,14–17} The outcomes of these HRAs were as follows.

Acute and chronic hazard indices tend to be dominated by a few compounds or substances, with many other substances adding only very marginally to the cumulative hazard profile. For example, the criteria pollutants nitrogen dioxide, sulfur dioxide, and particulate matter (expressed as PM_{10}) were found to comprise most of the AHI in each of the Wagerup, Pinjarra, Worsley, and Gladstone alumina refinery HRAs.^{12,14,16,17} Up to 70 individual compounds were included in the HRAs, including criteria pollutants, air

toxics, heavy metals, and persistent/bioaccumulative compounds. In nearly all the cases considered, the AHI at the maximum receptor was found to be comfortably less than unity.^{12,14,16,17} The few exceptions were only marginally more than unity, an issue of no concern, given the conservatism built into the methodology. More than 95% of the AHI at the maximum receptor for the Pinjarra refinery HRA was accounted for by PM₁₀, nitrogen dioxide, mercury, sulfur dioxide, formaldehyde,* and carbon monoxide.¹⁴ The CHI results were well less than unity at all receptors.^{12,14,16,17} More than 95% of the CHI at the maximum receptor for the Pinjarra refinery HRA was accounted for by nitrogen dioxide, mercury, acetaldehyde,[†] formaldehyde,[‡] cadmium, ammonia, and manganese.¹⁴

In an assessment of the health risk from fugitive dust from bauxite residue storages (Pinjarra refinery HRA, 2008), the contribution of PM₁₀ was found to dominate the AHI.¹⁵ Constituent metals present in bauxite residue dust typically made up less than 2% of the AHI. The CHI and ICR results were small. These findings suggest that short-term PM₁₀ exposures are the most relevant determinant of health risk in relation to bauxite residue storages, just as for many other sources of crustal dusts, such as unsealed roads, farming operations, or engineering construction activities. They also complement more recent findings from a study conducted after a bauxite residue impoundment failure in Hungary (Gelencser et al¹⁸), notably: “Based on its size distribution and composition, red mud dust appears to be less hazardous to human health than urban particulate matter.”

ICR estimates from cumulative lifetime exposures at neighboring residential properties, due to refinery and residue storage emissions, were found in the referenced studies to generally achieve the US EPA “de minimis” risk criterion of 1×10^{-6} , an indicator of negligible risk (nearly all receptors were well below this level, with a few cases just marginally above it).^{12,14,16,17} More than 95% of the ICR at the maximum receptor for the Pinjarra refinery HRA was accounted for by formaldehyde,[§] polycyclic aromatic hydrocarbons, chromium VI, acetaldehyde,[¶] and arsenic.¹⁴

Typical ranges of hazard indices and ICR estimates across two example HRAs—Wagerup and Pinjarra refineries—are shown in Table 1. A selected sample of contour plots for the AHI, CHI, and ICR are given in Figures 1 to 3 for the Pinjarra refinery HRA. Uncertainties in modeled versus observed GLC predictions have been reported as within $\pm 40\%$ for Worsley refinery and -50% to $+100\%$ (at the 95% confidence level) for Wagerup refinery—where there is topographical complexity.^{3,16}

DISCUSSION

The results of HRAs at alumina refineries to date suggest that of the three types of health risks, acute, chronic and carcinogenic, only the risk of acute health effects is of any practical relevance. The AHI can exceed 1 close to refineries, but is typically less than 1 at neighboring residential locations. As explained earlier, there are layers of conservatism embedded in HRAs, so that marginally exceeding an AHI of 1 does not imply that acute health effects can occur. Also, it is worth remembering that an AHI of 1 implies all of the compounds in the HRA have high percentile (typically 99.9th percentile 1-hour average and 99.5th percentile 24-hour average) GLCs less than their respective health-based ambient air quality guideline concentrations. The CHI results are substantially less than

*It should be kept in mind, however, that the contributions of formaldehyde and acetaldehyde are likely overstated, as the dispersion modeling did not account for atmospheric decay of these carbonyl compounds that are known to have relatively short atmospheric lifetimes.

†See the first footnote.

‡See the first footnote.

§See the first footnote.

¶See the first footnote.

TABLE 1. Typical Ranges of AHI, CHI, and ICR: Two Example HRAs

Distance From Plant	AHI	CHI	ICR
3 km	0.3–1.1	0.02–0.04	0.1×10^{-6} – 1.2×10^{-6}
5 km	0.2–0.7	0.01–0.02	0.05×10^{-6} – 0.6×10^{-6}

AHI, acute hazard index; CHI, chronic hazard index; HRA, health risk assessment; ICR, incremental carcinogenic risk.

FIGURE 1. Acute hazard index contours, Pinjarra refinery health risk assessment, 2008.

1, so the risk of chronic health effects is negligible. The ICR results are also small and typically less than the US EPA “de minimis” level of 1×10^{-6} . An ongoing longitudinal study of employees at Alcoa’s three alumina refineries in Western Australia has found no increase in cancer incidence attributable to working at the refineries.¹⁹ This observation is reassuring, given that occupational exposures to emissions are typically higher than environmental exposures.

One of the benefits of undertaking air dispersion modeling and HRAs is that the effects of changing mass emission rates, stack heights, emission control technologies, and buffer zone areas can be assessed. This can help determine the potential impact of an expansion proposal and the beneficial effect of any associated control measures. For example, Figures 1 to 3 contain isopleths (contours) for both the existing Pinjarra refinery in 2008 and a proposed upgrade, which was subsequently completed.

Undertaking HRAs at isolated facilities in rural settings, such as at Pinjarra refinery and Wagerup refinery, is relatively straightforward. It is of course much more complicated if a complex air shed involving multiple industrial facilities is to be assessed, or if there are substantial diffuse background exposures to consider, such as from urban static and mobile sources. Under these circumstances air dispersion modeling would require emission data from several different companies and need to incorporate assessments of background exposures by using ambient monitoring data.

Community concerns about air emissions from Wagerup refinery resulted in a comprehensive range of investigations, including

FIGURE 2. Chronic hazard index contours, Pinjarra refinery health risk assessment, 2008.

FIGURE 3. Incremental carcinogenic risk contours, Pinjarra refinery health risk assessment, 2008.

intensive ambient air quality monitoring, air dispersion modeling, HRA, and complaints analyses.^{20,21} These investigations found that the risks of health effects were negligible, but that refinery odor could be detected occasionally. Odor perception and environmental worry have been found in other settings to be synergistic determinants of symptom reporting. These and other issues are discussed in an article reporting the Wagerup refinery experience.²⁰ Presentations of HRA

results by using isopleths on aerial photographs (or maps) such as in Figures 1 to 3 have proven useful in communicating with community members and other stakeholders.

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