A Review of the Effectiveness of Respirators in Reducing Exposure to Polycyclic Aromatic Hydrocarbons for Coke Oven Workers

Joanne O. Crawford¹*, Ken Dixon¹, Brian G. Miller² and John W. Cherrie¹

¹Research Management, Institute of Occupational Medicine, Research Avenue North, Riccarton, Edinburgh EH14 4AP, UK
²Statistics and Toxicology, Institute of Occupational Medicine, Research Avenue North, Riccarton, Edinburgh EH14 4AP, UK
*Author to whom correspondence should be addressed. Tel: +0131-449-8037; fax: +0131-449-8084; e-mail: joanne.crawford@iom-world.org
Submitted 13 December 2013; revised 8 May 2014; revised version accepted 28 May 2014.

ABSTRACT

Objectives: In 2011 recommendations for the prescription of lung cancer in coke oven workers were made in the UK. In the 1970s, a powered helmet respirator, the Airstream helmet, was introduced to the UK coking industry with the aim of reducing exposure to polycyclic aromatic hydrocarbons (PAH) aerosols and consequent lung cancer risks for workers on the coke oven tops. This review set out to identify the level of protection afforded by the Airstream helmet, when the helmets could be considered to have provided effective protection and whether the levels of protection have been maintained to the current time.

Methods: Five approaches were taken to identify review material, including searching the peer-reviewed and grey literature; searching material held in the National Archive; using a Freedom of Information to the Health and Safety Executive; interviews with employees involved in the introduction of the Airstream helmet; and acquisition of company reports.

Results: The two principal companies involved in coke production in the UK took different approaches to the introduction of the Airstream helmets. Because of this, it can only be considered that effective wearing occurred in the industry as a whole from 1982 onwards. Exposure measurements made by British Steel in the late 1970s suggested that the mean protection factor of the Airstream helmet was ~10 (5th percentile ~2.5), regardless of whether exposure was assessed as the inhalable aerosol or other measures more specific to aerosol of PAH. More recent data collected using biological monitoring has identified that average urinary levels of 1-hydroxypyrene (1-HP) generally correspond with the inhalation occupational exposure limit for benzene soluble material. Although on occasions, relatively high air concentrations in-mask and urinary 1-HP concentrations have been identified, underlining the necessity to maintain close supervision of workers wearing respirators.

Conclusions: Overall, we concluded that the wearing of helmet respirators has effectively controlled long-term average exposure to PAH for most workers on coke ovens since 1982.

KEYWORDS: coke ovens; polycyclic aromatic hydrocarbons; powered respirators
INTRODUCTION
In September 2011, the UK Industrial Injuries Advisory Council recommended that lung cancer in coke oven workers should be a prescribed disease (Industrial Injuries Advisory Council, Department for Work and Pensions, 2011). The recommendations were based on a review of the epidemiological literature of lung cancer in coke oven workers as a result of exposure to polycyclic aromatic hydrocarbons (PAH) and these recommendations updated a previous review published in 1986. On the basis of the available research it was identified that there was a more than doubling of the risk of lung cancer after 5 years of working on a coke oven top or >15 years employment in general coke oven work.

In Britain, there were two principal organisations involved with coal carbonization: the British Steel Corporation and National Smokeless Fuels (NSF), which was a subsidiary of the National Coal Board (NCB) (later known as British Coal). NSF had been previously been known as the Coal Products Division of NCB. In the 1960s, these companies operated >50 coking plants and there were over 6000 men employed in the industry (Hurley et al., 1991).

Since the early 1970s, when the risk of lung cancer became evident, there were a number of developments aimed at reducing exposures for coke oven workers including improved coke oven design and maintenance. One of the main developments led to the introduction of the powered helmet respirator, which was originally developed by the Safety in Mines Research Establishment and described by Greenhough (1975). This device was eventually commercialized by Racal as the Airstream helmet, although since this time there have been further products developed including the Cobra and Pureflo helmet respirator designs. Airstream helmets were introduced into the coke industry in the late 1970s and early 1980s. The assessment of levels of protection provided by helmet respirators was mostly carried out in a laboratory setting rather than in the workplace where other influences, such as the behaviour of the individual, could impact on the effectiveness. However, from the information available at that time it appeared as though these devices could reliably reduce worker exposure.

This review was carried out to:

- Assess the likely reduction in exposure to PAH in the coal carbonization industry achieved by wearing a powered helmet respirator;
- Identify the jobs in the coal carbonization industry where powered helmet respirators were required to be worn;
- Determine at what date the powered helmet respirators were considered to be effectively worn by the majority of workers;
- Evaluate the evidence that powered helmet respirators have continued to provide effective protection in the industry to the current day.

METHODOLOGY
Five approaches were taken to identify relevant information for this review. Firstly, a literature search strategy was developed including relevant search terms and search combinations [this is available from the research report (Crawford et al., 2012)]. Searches were carried out using databases including Medline, Highwire, and Google Scholar and identified publications were stored in the RefWorks software package.

Secondly, we searched archived material held by UK National Archives in relation to powered helmet respirators and their use in the British coal carbonization industry. The search was further extended to examine other industries where powered helmet respirators were known to have been worn including the steel, coal, construction, welding, pharmaceutical, and chemical (powder handling) industries. The archive documents were screened for relevance and then collated into the review.

A Freedom of Information (FoI) request was sent to the UK Health and Safety Executive (HSE) asking for information on the use of powered helmet respirators (Airstream helmets) principally in the coke industry, but also in other industries where powered helmet respirators were used.

Interviews were carried out with individuals employed in or involved with the British coking industry and the implementation of Airstream helmets in the 1970s and 1980s. These included occupational hygienists and coke plant managers who were involved in the introduction and evaluation of the Airstream helmet at the British Steel Corporation and NSF Ltd. The aim
of the interviews was to corroborate the information obtained from the literature searches and the timeline of events. Three semi-structured interviews were carried out by telephone or face-to-face. The interview content aimed to identify the time period in which the participant was involved with either of the companies, feedback on the timeline of events produced from the literature review and corroboration or rejection of the information identified by Institute of Occupational Medicine from the historical material.

Finally, relevant archive material was obtained from Tata Steel, the successor of the British Steel Corporation, and Corus, a later owner of the coking plants, which included documents and reports from the 1970s to 2010 in relation to the use of powered helmet respirators in the industry.

To aid in the understanding of the protection factors obtained within the research, respirator protection factors (RPFs), i.e. the ratio of the measured in-mask to ambient concentration, were summarized as geometric means, with 95% confidence intervals (CIs) calculated from the geometric standard deviation assuming an underlying log-normal distribution. A 5th percentile was estimated using bootstrap estimation, in which repeated random samples of the same size as the data set are taken, with replacement (Efron and Tibshirani, 1993). This was done 2000 times to build an empirical distribution for the 5th percentile, from which were estimated a geometric mean and an empirical 95% CI. All calculations used the statistical package GenStat (VSN International, 2012).

RESULTS

Information searches
The search of the bibliographic databases identified 77 publications in the peer-reviewed and grey literature related to powered helmet respirators or the Airstream helmet. These were screened as to whether they contained relevant information, which resulted in the inclusion of 19 publications for review. A further 11 scientific reports were received from Tata Steel, which had been prepared as company documents by either the British Steel Corporation or Tata Steel. Additional materials were also provided by a former employee of British Steel Corporation, as a consequence of enquiries made by Tata Steel.

Approximately 2000 National Archive files and documents were screened during the review process. Relevant materials were abstracted and summarized to aid the development of the chronology of implementation of the helmet respirators.

The FoI request to HSE did not result in any usable material for the review.

Introduction of powered helmet respirators into the British coking industry
Epidemiological studies in the coking industry had been on-going through the 1960s and the potential link between lung cancer and coke oven workers in the US steel industry was recognized in the early 1970s (Lloyd, 1971). At this time there was considerable economic and political turmoil with reduction in the demand for coke and industrial change in the coal industry.

The historical documentation and interview material show that the introduction of the Airstream helmet into the industry was not straightforward. The National Archive material started in 1972. The material showed that when management in the industry recognized that there was a cancer risk from the coke emissions it was quickly decided that the most effective way to protect workers was to provide a suitable form of respiratory protection. The recently invented Airstream helmet respirator seemed to offer an appropriate solution and the two main operating companies, in discussion with the HSE, decided to investigate their use on coke ovens. Helmets were being reportedly worn in some parts of the industry from around 1976.

The British Steel Corporation and NSF took very different approaches to the introduction of respiratory protection. Fig. 1, presents a timeline of events within both British Steel and NSF. British Steel Corporation moved quickly to purchase powered helmet respirators and to train staff in their use, whereas NSF proceeded more slowly through a number of small-scale trials. Workers on the battery tops and sides, where exposures were known to be highest, were provided with helmets and were encouraged to wear them. However, at this stage there appears to have been little enforcement of wearing powered helmets in NSF. During the initial introduction several problems were identified, e.g. faults in the equipment owing to the high temperatures on top of the oven, scratching of visors, poor battery performance, and the fact that individuals could still smell ‘fumes’, which were all likely to have reduced initial wearer acceptance and incentive to use the respirators. The helmet manufacturer dealt
with these problems, but they clearly delayed effective implementation of the respirators.

The interviews with individuals working in the industry at the time of these events corroborated the archive material and identified several other factors that may have influenced effective wearing of the respirators. The servicing of powered helmet respirators in NSF was not carried out centrally until the mid-1980s. This raises questions about the ability of individuals to service their own equipment and how frequently this was carried out. There was no archive material either to support or refute these issues.

In 1981 the HSE took steps to enforce the wearing of helmet respirators on oven tops. In August there were discussions between the British Steel Corporation, NSF Ltd, and HSE about the issuing of a cautionary leaflet, which stated, ‘respiratory protection such as ventilated helmets must be worn at all times with the visors down over the face.’ In November of the same year, the HSE wrote a letter was sent to NSF regarding the printing of leaflets to which the wording ‘Employees are reminded that failure to wear the respiratory equipment may in certain circumstances be considered an offence under Section 7 of the Health and Safety at Work Act 1974’ had been added. The NCB Coal Products Limited Annual Review of Safety (1981/1982), noted the publication of the HSE’s guidelines ‘Reduction Operator Exposure to Fumes and Smoke from Coke Ovens’ (Health and Safety Executive, 1982). Where it was stated in the document ‘respiratory protective equipment shall be worn at all times by persons on the battery tops. Employees are reminded that failure to wear the respiratory equipment may, in certain circumstances, be considered an offence under Section 7 of the Health and Safety at Work etc. Act 1974.’

From 1989 to 1993 there was an occupational exposure limit of 0.2 mg m\(^{-3}\) for aerosol emissions from coke ovens measured as benzene (and later cyclohexane) soluble material until 1993 when it was eventually replaced with a biological monitoring benchmark value for 1-hydroxypyrene (1-HP) based on measurement of end-of-shift urine samples of 4 µmol 1-HP mol\(^{-1}\) creatinine (Unwin et al., 2006).

The peer-reviewed scientific literature on the effectiveness of helmet respirators

Early studies of the Airstream helmet mainly focussed on laboratory assessments of the device. Treaftis et al. (1981), from the US Bureau of Mines, evaluated the filter elements from two models of Airstream helmet (the AH1 and AH5) against coal and silica dust. The authors say the main difference between the two devices was that the AH5 helmet had a more powerful
blower and a more efficient fine filter compared to the AH1 helmet evaluated. These tests showed that >99% of dust was filtered from the air when the device was challenged with relatively high concentrations of ‘total’ dust, i.e. 9–176 mg m\(^{-3}\). There was little evidence of any difference in performance between the two types of respirator filter. Cecala (1981), from the US Mine Safety and Health Administration, tested the Airstream helmet worn by a mannequin in a wind tunnel and carried out a number of tests in a mine where the helmets were worn by workers or the scientific investigators. In the laboratory, effectiveness was assessed using a tracer gas measured both inside and outside the helmet. At an air flow of 400 fpm (feet per minute), equivalent to 2.03 m s\(^{-1}\), the protection factor was 10 or greater, but this decreased to <4 at 1600 fpm (8.13 m s\(^{-1}\)). In the mine tests, respirable dust was measured using two samplers inside the Airstream visor and a single sampler outside the helmet visor. The average protection factor was 6.2 at relatively low ventilation airflow (<2 m s\(^{-1}\)) but this reduced to a mean protection factor of 2 in a high airflow mine (i.e. ~8 m s\(^{-1}\) airflow). The investigators noted that there were consistently higher concentrations inside the visor on the windward side of the helmet (4.5–66% higher), which they attributed to air being forced between the face and the visor seal on this side of the helmet.

Parobeck studied the acceptability of the Airstream helmet in coalmines in the USA (Parobeck et al., 1989). They noted that the miners did not always keep the visor down in use and that there were minor issues with battery life and the filters. It is clear that with the visor lifted the helmet provides no protection to the wearer. Miners also did not wear the helmet respirator when doing heavy work, e.g. shovelling, because of the visor fogging.

A study of 24 smelter workers exposed to lead who had access to Airstream helmet respirators was undertaken by Ulenbelt et al. (1991); refinery workers also studied did not have helmet respirators. In a statistical analysis of the data collected, 38% of the variation in lead in blood levels was attributed to the percentage of time Airstream helmets were worn, frequency of spitting, smoking, and the concentration of lead in air. The reduction in blood lead concentration attributed to the Airstream respirator was statistically significant, but the data were not presented in a way that allows the magnitude of the reduction in exposure to be determined. The same group of researchers also reported on the determinants of exposure to the lead battery plant and a smelter (Meijman et al., 1996); in the latter workplace the workers had Airstream helmet respirators. Use of the Airstream helmet was negatively correlated with lead in blood levels (independently of air concentration), showing that it was protective. However, it was again not possible with the data presented to assess the reduction in exposure.

Two published studies have focussed on the effectiveness of helmet respirators in reducing effects of airborne contaminants on the health of workers. A study by Kongerud and Rambjør looked at the effect of wearing a helmet respirator in an aluminium pot room on worker lung function and respiratory symptoms (Kongerud and Rambjør, 1991). They used a randomized cross-over study design where workers wore either an Airstream helmet or a 3M disposable respirator for a 2-week period and then during a second period wore the other type of respirator. There were 25 male workers enrolled, but six dropped out before the end of the study (24%). Lung function and symptoms were recorded on a daily basis. The authors concluded there was a small statistically significant improvement in peak flow when the helmet respirators were used but no corresponding change in symptoms’ scores. They attributed the improved lung function to the greater comfort in wearing the helmet respirator and the likelihood that they were worn more consistently than the disposable respirators, although they had no objective data to support this contention.

Taivainen investigated the effect of wearing four different types of helmet respirator on lung function and respiratory symptoms of a group of 33 asthmatic agricultural workers (Taivainen et al., 1998). Participants were monitored for 3 months without the respirator and for 10 months with the respirator. There was a small but statistically significant increase in morning peak expired airflow rate and daily variation of peak flow amongst atopic workers wearing the respirators was significantly reduced, but there was no change in either evening or mean peak flow. Wearing the helmet respirator did not affect the farmers with non-atopic asthma. The helmet respirators also reduced sputum production but did not result in any statistically significant changes in other respiratory symptoms in the atopic patients.

Davies, carried out a study to assess the magnitude of reduction in exposure provided by these devices when used by coke oven workers, although the main focus of
the paper was a general description of exposure measurements made on the plants (Davies et al., 1986). They found that the mean protection factors for dust were 12 on one survey and 7 on another, while for benzene soluble material (BSM), used as a marker of PAH exposure, the corresponding mean protection factors were 15 and 7. The authors do not present information about the variability in the protective effect or any further details of how the measurements were made.

Measurements of exposure inside and outside airstream respirators
Tata Steel provided 11 technical reports describing trials on the Airstream helmet and other helmet respirators, carried out between 1976 and 2010. In addition, summary data sheets were provided by Tata Steel for additional studies where air contaminant concentrations had been measured inside and outside Airstream helmets.

Data from measurements made, inside and outside the respirator during normal work activities, to assess the effectiveness of the device, were abstracted for statistical analysis. There were 51 sets of measurements where dust, BSM, and benzo-a-pyrene (B[a]P), which is also commonly used as a marker for PAH mixtures, had been measured over a full working shift. These were collected on five coke works from men mostly working on the battery top or sides, with a small number of measurements being obtained from the scientists undertaking the investigation. There was no information about whether the respirator visors were always kept down or not. All of the ambient dust and BSM measurements and the in-mask dust measurements produced detectable levels. However, a proportion of the other measurements were below the limit of detection (LOD): ~4% of the ambient B[a]P; 16% of the in-mask BSM, and 40% of the in-mask B[a]P values. LOD values varied depending on the sample duration.

The geometric mean and 5th percentile of the calculated RPF are shown in Table 1, including the impact of excluding the measurements less than the LOD.

Scatter plot comparing ambient and in-mask dust concentration measurements
Contours of RPF are shown as dotted lines. The scatter plots show no strong relationship between ambient and in-helmet concentrations. The geometric mean protection factor is 10, with 95% CI 7.8–12.6; the 5th percentile is 2.9 (CI: 2.2–4.3).

Fig. 2 shows the same comparison, for measurements of BSM. Data points where one measurement was recorded as below the LOD have been replaced with a value half of the LOD, and these data are shown as filled symbols.

Again, the data do not suggest a strong relationship, although there is better association between ambient and in-mask BSM concentrations than for dust. It should be noted that ~24% of the measured in-mask concentrations were above the exposure limit (0.2 mg m\(^{-3}\)). The geometric mean protection factor is 9.6, with 95% CI: 7.4–12.4. Omitting the filled points, which may be distorting the mean, the geometric mean protection factor is reduced somewhat to 8.2, with 95% CI: 6.3–10.7. The corresponding estimates of the 5th percentile are 2.5 (CI: 1.8–3.2) and 2.4 (CI: 1.8–3.1).

Fig. 3 compares the B[a]P data from ambient and in-mask samples. There were more values here below the LOD compared to Figs 2 and 4. Taking all values assuming half the LOD for non-detects, the geometric mean protection factor is 20.2, 95% CI 13.4–30.5.

Table 1. Estimated geometric mean and 5th percentile of the RPFs

<table>
<thead>
<tr>
<th>Aerosol</th>
<th>N</th>
<th>Geometric mean RPF</th>
<th>5th percentile RPF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Estimate</td>
<td>95% CI</td>
</tr>
<tr>
<td>Dust</td>
<td>51</td>
<td>10.0</td>
<td>7.8</td>
</tr>
<tr>
<td>BSM</td>
<td>51</td>
<td>9.6</td>
<td>7.4</td>
</tr>
<tr>
<td>BSM</td>
<td>Excluding &lt; LOD</td>
<td>42</td>
<td>8.2</td>
</tr>
<tr>
<td>B[a]P</td>
<td>50</td>
<td>20.2</td>
<td>13.4</td>
</tr>
<tr>
<td>B[a]P</td>
<td>Excluding &lt; LOD</td>
<td>30</td>
<td>11.6</td>
</tr>
</tbody>
</table>
Omitting the filled points brings this down to 11.6, 95% CI: 8.3–16.2. The corresponding estimates of the 5th percentile are 2.0 (CI: 1.0–4.5) and 2.3 (CI: 1.6–4.6). Here, imputing the <LOD points has probably inflated the mean protection factor considerably and we consider that the latter protection factor excluding the non-detectable values is more reliable.

Two reports were provided by Tata Steel describing small trials of the effectiveness of the Airstream helmet to reduce exposure in a powder handing task. Although this activity was not associated with coke ovens it was informative, not only because it has relevant quantitative data but the measurement survey had a unique design where for one set of data the sampling system was set up so that the air samples were only collected when the visor was down. There was no suggestion of a strong relationship between in-helmet and ambient concentration in either investigation and there was no difference between the protection factors when the samples were collected only with the visor down. Overall the mean protection factor was 10.5, which is consistent with the data from coke ovens described above.

There was one additional report from the British Steel Corporation of an investigation of the performance of Airstream helmets in a foundry. However, we have excluded these data because the measurements made inside and outside the helmet were made with different sampling systems (a cyclone respirable dust sampler on the workers lapel and an in-line filter with a short length of tube to sample behind the respirator visor) and these are considered to be not comparable because of the relatively coarse nature of the airborne dust in this workplace.

**Other relevant environmental monitoring reports from the industry**

In 1993 and 1995 the British Steel Corporation carried out investigations to assess the filtration efficiency
of Airstream filter elements (and an alternative Dustmaster unit) for a range of aromatic compounds. Two types of filter were included: the conventional Airstream filter (AH1) and filters containing charcoal granules intended to adsorb volatile compounds (AH60 or Dustmaster). The filters were cut into 25-mm diameter discs and these were located in filter holders with a sampling filter and sorbent tube placed in series behind. Ambient air samples were collected alongside the test rigs. The tests were carried out on the top of a coke oven battery. Both sets of filters and tubes were analyzed for a range of aromatic compounds (in the first study there were 16 PAHs plus benzene, toluene, and xylene, in the second set of measurements xylene and toluene were not analysed). In the first tests 10 sets of results were obtained over a 5-day period while in the second series there were eight data sets from eight days.

The results are summarized in Table 2 as the mean percentage penetration (and range) through the filter media for the 1-ring, 2-ring, etc. compounds. There were large numbers of analyses that were below the LOD, particularly for the higher molecular weight compounds. In these cases the authors of the reports assumed that the penetration was <3%, which was almost certainly a considerable overestimate of the true penetration.

Note that some of the percentage penetration figures are >100, but this is probably because of random errors in the measurement of the concentration and the absence of any filtration effect because of the low molecular weight of the compounds, i.e. they were in vapour form.

In all cases the filter penetration for 4, 5, and 6-ring PAH compounds was <3% on average and almost all results for PAHs in samples collected behind the respirator visor were below the LOD. For 2- and 3-ring compounds, such as naphthalene and anthracene, the simple AH1 particulate filter had no clear effect but the charcoal filter media reduced the concentration
of these compounds to <5% of the ambient levels for 3-ring compounds and less than ~15% for 2-ring compounds, on average. For benzene (toluene and xylene) the effect of the charcoal filter differed between the two trials, with <1% on average passing through the filter on the first occasion and 80% passing through during the second investigation. It is unclear why there was such a large difference in the test results, since the methodology was similar in both cases.

The British Steel Corporation also carried out a number of tests in 1995 to assess the acceptable duration of use of the filters in Airstream helmet respirators and other competitor equipment. Tests on the MSA Technostat

Table 2. Percentage penetration through helmet respirator filter media for groups of aromatic compounds—mean (range)

<table>
<thead>
<tr>
<th>Aromatic compounds</th>
<th>Study in 1993</th>
<th>Study in 1995</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Airstream AH1</td>
<td>Charcoal AH60</td>
</tr>
<tr>
<td>1-ring (e.g. benzene)</td>
<td>49 (24–87)</td>
<td>0.5 (&lt;0.1–1.3)</td>
</tr>
<tr>
<td>2-ring (e.g. naphthalene)</td>
<td>62 (40–107)</td>
<td>13 (6.9–20)</td>
</tr>
<tr>
<td>3-ring (e.g. anthracene)</td>
<td>59 (22–125)</td>
<td>3.8 (&lt;1.5–7.8)</td>
</tr>
<tr>
<td>4-ring (e.g. pyrene)</td>
<td>&lt;3 (&lt;3–1.9)</td>
<td>&lt;3 (&lt;3)</td>
</tr>
<tr>
<td>5 and 6 ring (e.g. B[a]P)</td>
<td>&lt;3 (&lt;3)</td>
<td>&lt;3 (&lt;3)</td>
</tr>
</tbody>
</table>

4 Compares the dust concentrations measured inside the helmet (y-axis) with the ambient dust concentration (x-axis), both expressed as mg m$^{-3}$. 

![Dust concentration graph](image)
filter element (used in the MSA Cobra helmet respirator) showed that after 5 days the filtration efficiency for BSM decreased. As a consequence it was recommended these filters should be changed every 30 h. Similar conclusions were arrived at for Airstream filter media.

In 1995 the MSA Cobra helmet respirator was made available in the British Steel Corporation as an alternative to the Airstream helmet. In 2010 Tata Steel carried out a review of helmet respirators for use on coke ovens. The evaluation was based on the helmet respirator:

- Providing a high standard of performance (i.e. high protection factor);
- Incorporating a charcoal filter along with a P3 aerosol filter (Filters at least 99.95% of airborne particles according to the appropriate European standard test);
- Having good usability; and
- Being suitable for use on coke ovens.

The company intended to choose a single device for use in all coke ovens. Four devices were assessed: Pureflo, 3M Jupiter, the Sundstrum SR 500, and 3M Versaflo.

The Sundstrum helmet respirator was subsequently recommended for use across Tata Steel oven plants because it met the initial performance criteria, was available in an intrinsically safe model, i.e. can be used in areas where there may be flammable gases present, and it had been successfully used in other coke plants owned by the company. The respirator also had a proven history of acceptable use in the coke oven environment. The authors of this report also quote a protection factor of 438 against B[a]P based on experimental tests using a mannequin to sample inside and outside the visor (presumably the mean of a number of measurements, although this is not stated).

Biological monitoring data from British coke workers

Biological monitoring using 1-HP in urine as an indicator of exposure to PAH is now widely accepted. The HSE have published a biological monitoring benchmark value for exposure to PAH as measured by 1-HP in urine as 4 µmol 1-HP mol⁻¹ creatinine (Unwin et al., 2006). Biological monitoring assesses exposure by all routes into the body and so these data reflect uptake by inhalation, skin contact, and ingestion, e.g. hand-to-mouth contacts. Biological monitoring levels also reflect the protection offered by respirators or other personal protective equipment.

We were provided with three reports by Tata Steel dated 2009, which summarized biological monitoring results from periodic surveys undertaken among coke workers on Teesside. There were data for 52 workers from four work areas (charger, pusher, guide, coke car and miscellaneous jobs, including heater operators, shift managers, and others working around the ovens). The arithmetic average level was 3.8 µmol 1-HP mol⁻¹ creatinine, but the levels for charger operators were much higher than for the other groups (arithmetic average 9.8 µmol 1-HP mol⁻¹ creatinine) and 10 of the 12 samples in this group were above the HSE’s benchmark level. Investigation of the reasons for the high levels among the charger operators revealed that by making changes to the work clothing worn (clean underwear provided by the employee and overalls provided by the company every shift), changes to the process operation and the operators wearing the helmet respirator correctly throughout the shift (visor only raised at the battery ends) resulted in exposure levels below the biological monitoring benchmark level. Clearly the implication is that dermal exposure has contributed some of the 1-HP in the biological monitoring samples. The author of this report concluded that it was possible to control exposures below the benchmark level, but ‘to achieve this, a whole package of control measures is required spanning clothing, respiratory protection, personal hygiene, operating procedures and personal discipline. In effect, the additional effort put into achieving these [lower] results must become the norm’.

As part of the 2010 review of helmet respirators carried out by Tata Steel, a limited amount of biological monitoring data was provided for men wearing a range of helmet respirators. The difference in level between samples collected at the end and start of the working week ranged from 0.6 to 6.6 µmol 1-HP mol⁻¹ creatinine (31 measurements from nine workers wearing up to four different helmet respirators). The arithmetic average across all workers and helmet types was 2 µmol 1-HP mol⁻¹ creatinine, with ~95% of measurements below the HSE’s benchmark level.

The HSE carried out a biological monitoring survey of PAH-exposed workers with data for three sets of British coke oven workers (Unwin et al., 2006).
These data showed the mean 1-HP levels ranged from ~1.8 to 2.6 µmol 1-HP mol$^{-1}$ creatinine, Table 3. The measurements were presumably made with workers wearing powered helmet respirators, although this is not explicitly stated in the paper.

**DISCUSSION**

There is very little information in the peer-reviewed scientific literature to substantiate the effectiveness of helmet respirators in reducing exposure, either on coke ovens or in other workplaces. However, the British Steel Corporation collected data on the effectiveness during the 1970s by simultaneously measuring the concentration of dust, BSM, and B[a]P inside and outside the visors of Airstream helmets worn by coke oven workers. These data showed that the helmet respirators probably reduced average exposure for workers on coke oven tops and sides by about a factor of 10 and in-helmet levels presented in this paper were mostly below the British occupational exposure limit of 0.2 mg m$^{-3}$ as BSM, although about a quarter of individual measurements exceeded the limit. We have no data on within and between worker variability in exposure but it seems reasonable to assume that on average most workers would have their exposures reduced by about this magnitude, i.e. the average protection over time is similar for all workers. The minimum protection provided by the Airstream helmet to a single worker on a single work shift was a reduction in exposure level by 50% (5th percentiles for RPFs for all three exposure metrics were between 2 and 2.9).

The question of when ‘effective wearing’ occurred within the industry was difficult to answer. In the context of this paper, we have considered this to be when the vast majority of men on the oven tops and sides (>90%) were wearing reliable Airstream helmet respirators with the visor down for at least 75% of the time. From the material available it appears that this occurred from ~1982 onwards, after action was taken by the British Factory Inspectorate to enforce the use of the respirators. The evidence from biological monitoring data and from interviews with company staff suggests that effective wearing of the Airstream helmets or other powered helmet respirators has generally continued to the current time, and that this has reduced average exposure below the 4 µmol 1-HP mol$^{-1}$ creatinine guidance value. However, as with the airborne exposure measurements a proportion (<10%) of the individual measurements exceeded the limit.

This study has also identified a number of issues in relation to the introduction of powered helmet respirators into the industry. These include issues with regard to the design of the respirators; when this is not at an optimum then individuals are less likely to use them effectively. For example, the weight of the respirator and the impact on vision with scratched visors causing workers to raise the visor therefore reducing protection. Also there was a perception that the powered respirators did not work because people could still smell fumes which is likely to have been a further barrier in the effective use of the equipment. This is most likely because the filters removed only particulate, the higher molecular weight PAHs, and allowed more volatile PAHs to pass into the worker’s breathing zone. These factors would have impacted on acceptance and effective use of the powered respirators and identify the importance when trying to change behaviour of ensuring that those affected are consulted and equipment trialled and modified. It is probable that incorrect wearing of helmet respirators on occasion has reduced the protection, but we judge on the basis of the biological monitoring data summarized in this

<table>
<thead>
<tr>
<th>Site</th>
<th>Description</th>
<th>Number of measures</th>
<th>B[a]P (µg m$^{-3}$)</th>
<th>1-Hydroxypyrene (µmol mol$^{-1}$ creatinine)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>11</td>
<td>Coke oven</td>
<td>11</td>
<td>2.14</td>
<td>0.13–6.21</td>
</tr>
<tr>
<td>14</td>
<td>Coke oven</td>
<td>13</td>
<td>0.79</td>
<td>0.02–4.08</td>
</tr>
<tr>
<td>2</td>
<td>Coke oven (low temperature)</td>
<td>13</td>
<td>1.13</td>
<td>0.01–2.91</td>
</tr>
</tbody>
</table>
paper that over the longer term these devices have continued to be effective.

The archive material sourced for this study was incomplete with records of various meetings missing. However, the use of interviews with those involved in all aspects of the introduction of powered respirators enabled some areas to be further explored and new issues identified. The interviews also gave more in-depth context to the industry at the time of the introduction of powered respirators. We received reports from Tata Steel, successor to the British Steel Corporation, but it is not known whether these comprise all of the relevant material because there is no systematic archive from the period of interest. Despite the likely incomplete nature of all of the materials studied the picture they paint is coherent and is corroborated by other data, e.g. the HSE biological monitoring studies in the industry.

In conclusion, the limited data on the use and effectiveness of respiratory protection, and the available biological monitoring data suggest that that the wearing of helmet respirators has effectively controlled long-term average exposure to PAH for most workers on coke ovens since 1982.

**Funding**
This work was funded by Tata Steel Europe.

**Acknowledgements**
Tata Steel Europe funded this work. The company provided material for the review and assisted in identifying interviewees for the study. They were given the opportunity to comment on the draft paper, although the authors reserved the right to amend the text as they considered appropriate. We would like to thank the interviewees and all others who provide assistance in identifying material used in the review. We are particularly grateful for support from Dr Sally Williams, from Tata Steel and Iain Archibald, Andy Gillies, Robin Howie, David Wilcox, Andrew Coleman, and Geoff Smith, and to our colleagues Dr Martie van Tongeren and Alice Davis for their advice. Tata Steel reviewed the submitted work but no material changes were made as a result of this review.

**References**