INDOOR AIR QUALITY IN ENGLISH HOMES – INTRODUCTION AND CARBON MONOXIDE FINDINGS

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ABSTRACT
BRE has conducted a national survey of air pollutants in 876 homes in England, to increase knowledge of pollutant levels and the factors associated with high concentrations. Homes were monitored, using passive samplers, for carbon monoxide (CO), nitrogen dioxide, formaldehyde and total volatile organic compounds. Also, in each household an interviewer administered a questionnaire about the characteristics of the home, the occupiers and their activities. This paper describes (a) the survey objectives, design and approach and (b) the findings on 14-day time-weighted average CO levels. Concentrations of CO were higher in kitchens than in bedrooms, but significantly correlated. Higher levels of CO were found in autumn and winter, in urban areas, in homes with a gas oven, homes with unflued fossil fuel heaters, and in smokers’ homes. The CO concentration did not exceed the WHO 8-hour average guideline value in any home.

INDEX TERMS
Carbon monoxide, Homes, Sources, National survey, Diffusive sampling

INTRODUCTION
BRE has conducted a national survey of air pollutants in 876 homes in England. The survey was designed to increase knowledge of pollutant levels and the factors associated with high concentrations. Some data on indoor pollutants in English homes are available from previous studies (e.g. Berry et al, 1996; Wiech & Raw, 1995, 1996; Venn et al, 2001). Although these studies provided valuable information, it could not be assumed that the homes studied were typical of homes across England as a whole. Therefore, the survey reported here was carried out to obtain more representative data. The pollutants monitored were nitrogen dioxide (NO2), carbon monoxide (CO), formaldehyde and other VOCs.

This paper reports the survey objectives, design and approach, and the findings on CO levels. The survey structure and methodology are described in greater detail by Coward et al (2001). Results for the other pollutants are reported in companion papers (Coward et al, 2002; Brown et al, 2002a, 2002b).

METHOD
Selection of homes
The Survey of English Housing (SEH), conducted by the Office for National Statistics (ONS), was used as a vehicle for selecting homes (DETR, 1999). The survey entails visits by interviewers to 20,000 randomly selected homes per year, an equal sample being drawn each month. Our aim was to obtain approximately 1000 sets of measurements in homes over a period of a year, i.e. 80-85 homes per month, visiting each home once only.

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Each interviewer invited the householders at two predetermined addresses (a total of 168 households per month) to participate in the air quality study. Approximately 80 per month accepted but only about 75% of these completed the survey. Consequently, the duration of the survey was extended to 17 months (October 1997 to February 1999). By the end of the study, results had been obtained from 876 homes.

In general the sample was representative of the original SEH sample. However, a few groups were over- or under-represented by 3% or more. Homes in the South East were over-represented and these homes had significantly lower CO levels and kitchen NO\textsubscript{2} than the rest of the country. As a result, it is possible that the mean levels of these pollutants measured in the survey might be approximately 2% lower than in the general population. In other cases, the findings should not have been affected, since pollutant concentrations were not found to be related to the identified groups or variables (householder’s age, type of tenancy, employment status and household composition).

The study procedure
The ONS interviewer administered a questionnaire on behalf of BRE, covering the homes, the characteristics of the occupants and their activities in the home. The interviewer also demonstrated the use of the various diffusive air samplers, and showed the householder suitable locations in which to place them. The interviewer then supplied the address for BRE to send the air samplers by post to the householders, together with instructions for the use of the samplers, self-completion questionnaires about activities during the sampling time and reply-paid envelopes for the return of the samplers and questionnaires.

CO was measured, once in each home, using Dräger colorimetric diffusion tubes, as two-week time-weighted averages in the kitchen and main bedroom of each home. Measurement methods for the other pollutants are described in the companion papers (Op. cit.).

Statistical analysis
The statistical analysis was carried out in three stages, using logarithms of concentrations to correct for skewed distributions. First, descriptive statistics were produced to show population characteristics and the concentrations of pollutants under different conditions (season, type of area etc). Bivariate analysis (analysis of variance (ANOVA) or t-tests) was then used to identify associations between concentrations and possible determinants (e.g. the presence of a gas cooker). ANOVA was then used to show which associations were secondary, in the sense that they could be explained by a factor that more directly determines pollutant levels. The factors reported here are those that emerged as determinants in their own right.

The independent variables used in the analysis were season, region, area type (degree of urbanisation), building date, type of dwelling, presence/type of garage, vehicle fuel, household size, number of habitable rooms, occupant density, cooking fuel, heating system/fuel, heating with portable/unflued heaters or a gas cooker, having an extract fan, amount of cigarette smoking, presence of condensation, damp and mould, presence of particleboard, recent painting and use of toiletries or air fresheners. Only those variables that had a significant effect on CO are mentioned further in this paper.

**CO CONCENTRATIONS**
CO levels were measured successfully in 830 homes, with 821 homes providing results for both kitchens and bedrooms. Minimum, maximum, geometric mean and percentile values are shown in Table 1. Levels were higher in kitchens than in bedrooms. Seasonal CO levels are
shown in Table 2, grouped according to the month when the samplers were opened: spring (March-May); summer (June-August); autumn (September-November) and winter (December-February).

**Table 1.** Statistics for CO concentrations (mg m\(^{-3}\))

<table>
<thead>
<tr>
<th>Room</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Geometric mean</th>
<th>Percentiles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>10%</td>
</tr>
<tr>
<td>Bedroom</td>
<td>&lt;0.01</td>
<td>3.90</td>
<td>0.39</td>
<td>0.12</td>
</tr>
<tr>
<td>Kitchens</td>
<td>&lt;0.01</td>
<td>4.45</td>
<td>0.47</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**Table 2.** Geometric mean CO levels (mg m\(^{-3}\)) by season

<table>
<thead>
<tr>
<th>Room</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchens</td>
<td>0.35</td>
<td>0.27</td>
<td>0.60</td>
<td>0.62</td>
</tr>
<tr>
<td>Bedroom</td>
<td>0.28</td>
<td>0.21</td>
<td>0.53</td>
<td>0.53</td>
</tr>
</tbody>
</table>

The bedroom and kitchen measurements were significantly correlated (r=0.68, p<0.001). Correlations between bedroom and kitchen CO levels were significant in all seasons (p<0.001) but closer in winter (r=0.82) and spring (r=0.71) than in summer (r=0.50) and autumn (r=0.56). It is likely that the closer correlation in winter is due to decreased ventilation. The correlation in spring is higher than in summer and autumn. This could have occurred if the weather was warm enough in spring to use less fossil fuel than in winter, but not warm enough to open the windows.

**DETERMINANTS OF INDOOR CO CONCENTRATION**

**Cooking fuel**

The analysis of cooking fuel compared three groups: homes with a natural gas oven, homes with some natural gas cooking (hob and/or grill) but no gas oven, and homes with no fossil fuel cooking (see Table 3). The difference between the groups was highly significant (kitchens F=98.1, p<0.001; bedrooms F=24.8, p<0.001) with each group significantly different from the other two (except in bedrooms for no gas oven vs no fossil fuel cooking).

**Table 3.** Geometric mean CO (mg m\(^{-3}\)) by cooking fuel

<table>
<thead>
<tr>
<th>Cooking fuel</th>
<th>Kitchen</th>
<th>N</th>
<th>Bedroom</th>
<th>N</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas oven</td>
<td>0.77</td>
<td>335</td>
<td>0.53</td>
<td>332</td>
<td></td>
</tr>
<tr>
<td>Natural gas cooking but no gas oven</td>
<td>0.47</td>
<td>129</td>
<td>0.37</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>No fossil fuel cooking</td>
<td>0.30</td>
<td>349</td>
<td>0.31</td>
<td>347</td>
<td></td>
</tr>
</tbody>
</table>

In homes where natural gas was the only fossil cooking fuel, most homes had either a gas hob, grill and oven, or only a gas hob. These two groups had significantly different CO levels in bedrooms (t=3.3, p<0.01) and kitchens (t=5.7, p<0.001) - see Table 4. Other combinations of gas appliance were found in five homes or fewer.

**Table 4.** Geometric mean CO levels (mg m\(^{-3}\)) with natural gas as the only fossil cooking fuel

<table>
<thead>
<tr>
<th>Gas cooking facilities</th>
<th>Kitchen</th>
<th>Bedroom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>N</td>
</tr>
<tr>
<td>Hob, grill and oven</td>
<td>0.78</td>
<td>326</td>
</tr>
<tr>
<td>Hob only</td>
<td>0.47</td>
<td>125</td>
</tr>
</tbody>
</table>
**Season**
Mean kitchen and bedroom levels are given in Table 2. Bedroom and kitchen CO levels differed significantly between the seasons (bedrooms $F=48.4$, $p<0.001$, kitchens $F=37.5$, $p<0.001$); spring and summer differed significantly from autumn and winter in both rooms, and spring from summer in bedrooms. It is likely that the differences were caused by increased fossil fuel use and decreased ventilation in colder weather.

There was a significant interaction between season and gas appliances in their effect on kitchen CO ($F=2.1$, $p<0.05$). Homes with a gas oven had the highest kitchen CO levels in winter. The other homes had the highest level in autumn (Table 5). Seasonal differences were much greater where there was a gas oven. In homes where no fossil fuel was used and where there were no regular smokers (Table 6), seasonal differences were still significant (bedrooms $F=3.6$, $p<0.05$; kitchens $F=6.0$, $p<0.01$) but much reduced.

**Table 5.** Geometric mean kitchen CO (mg m$^{-3}$) by season

<table>
<thead>
<tr>
<th>Cooking fuel</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas oven</td>
<td>0.61</td>
<td>0.51</td>
<td>0.88</td>
<td>1.06</td>
</tr>
<tr>
<td>Gas cooking but no gas oven</td>
<td>0.41</td>
<td>0.20</td>
<td>0.60</td>
<td>0.57</td>
</tr>
<tr>
<td>No fossil fuel cooking</td>
<td>0.20</td>
<td>0.14</td>
<td>0.44</td>
<td>0.39</td>
</tr>
</tbody>
</table>

**Table 6.** Geometric mean CO levels (mg m$^{-3}$) in all-electric homes with non-smokers

<table>
<thead>
<tr>
<th>Season</th>
<th>Kitchen Mean</th>
<th>N</th>
<th>Bedroom Mean</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>0.14</td>
<td>10</td>
<td>0.13</td>
<td>10</td>
</tr>
<tr>
<td>Summer</td>
<td>0.06</td>
<td>8</td>
<td>0.17</td>
<td>8</td>
</tr>
<tr>
<td>Autumn</td>
<td>0.43</td>
<td>10</td>
<td>0.39</td>
<td>10</td>
</tr>
<tr>
<td>Winter</td>
<td>0.28</td>
<td>8</td>
<td>0.26</td>
<td>8</td>
</tr>
</tbody>
</table>

In a two-way ANOVA of bedroom CO, there was a significant interaction between season and the presence of an extract fan somewhere in the home. Homes with a fan had slightly lower bedroom CO than homes without, except in spring (Table 7).

**Table 7.** Geometric mean bedroom CO (mg m$^{-3}$) by season and extract fan

<table>
<thead>
<tr>
<th>Extract fan in home</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>0.38</td>
<td>0.24</td>
<td>0.58</td>
<td>0.59</td>
</tr>
<tr>
<td>No</td>
<td>0.32</td>
<td>0.29</td>
<td>0.61</td>
<td>0.65</td>
</tr>
</tbody>
</table>

In a two-way ANOVA of bedroom CO, there was a significant interaction between season and dwelling type (Table 8) but there is no obvious interpretation of this.

**Table 8.** Geometric mean bedroom CO (mg m$^{-3}$) by season and dwelling type

<table>
<thead>
<tr>
<th>Dwelling type</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedsit or flat</td>
<td>0.38</td>
<td>0.25</td>
<td>0.44</td>
<td>0.51</td>
</tr>
<tr>
<td>Terrace</td>
<td>0.43</td>
<td>0.29</td>
<td>0.72</td>
<td>0.88</td>
</tr>
<tr>
<td>Semi-detached</td>
<td>0.34</td>
<td>0.36</td>
<td>0.74</td>
<td>0.57</td>
</tr>
<tr>
<td>Detached</td>
<td>0.34</td>
<td>0.18</td>
<td>0.50</td>
<td>0.47</td>
</tr>
<tr>
<td>Bungalow</td>
<td>0.23</td>
<td>0.18</td>
<td>0.42</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Smoking
Householders were asked whether anyone smoked regularly in the home. CO varied significantly with smoking (kitchens t=6.1, p<0.001, bedrooms t=6.4, p<0.001, Table 9). In a two-way ANOVA of bedroom CO, there was a significant interaction between smoking and main heating system (Table 10). Homes with regular smoking had higher bedroom CO than other homes, but the difference was greatest in homes with electric heating.

Table 9. Geometric mean kitchen and bedroom CO (mg m\(^{-3}\)) by smoking

<table>
<thead>
<tr>
<th>Regular smoking in home</th>
<th>Kitchen</th>
<th>Bedroom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>N</td>
</tr>
<tr>
<td>Yes</td>
<td>0.66</td>
<td>242</td>
</tr>
<tr>
<td>No</td>
<td>0.41</td>
<td>585</td>
</tr>
</tbody>
</table>

Table 10. Geometric mean bedroom CO (mg m\(^{-3}\)) by smoking and main heating system

<table>
<thead>
<tr>
<th>Main heating system</th>
<th>Regular smoking in home</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Electric</td>
<td>0.73</td>
</tr>
<tr>
<td>Natural gas or oil central heating</td>
<td>0.54</td>
</tr>
<tr>
<td>Individual natural gas heaters</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Area type
CO is produced outdoors by vehicle exhausts and other sources where there is incomplete combustion of fossil fuels. It would therefore be expected that more CO would enter homes from outdoors in built-up areas than in rural areas. There was a significant difference between area types for kitchens (F=12.4, p<0.001) and bedrooms (F=17.7, p<0.001) - see Table 11. Bedroom and kitchen CO levels were significantly lower in rural areas than in other areas, and bedroom levels were also significantly lower in suburban than in central urban areas.

Table 11. Geometric mean CO levels (mg m\(^{-3}\)) and area type

<table>
<thead>
<tr>
<th>Area type</th>
<th>Kitchen</th>
<th>N</th>
<th>Bedroom</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>0.34</td>
<td>235</td>
<td>0.28</td>
<td>234</td>
</tr>
<tr>
<td>Suburban</td>
<td>0.52</td>
<td>339</td>
<td>0.41</td>
<td>336</td>
</tr>
<tr>
<td>Urban</td>
<td>0.54</td>
<td>222</td>
<td>0.50</td>
<td>220</td>
</tr>
<tr>
<td>Central urban</td>
<td>0.72</td>
<td>31</td>
<td>0.69</td>
<td>31</td>
</tr>
</tbody>
</table>

Unflued heating
The use of an unflued fixed or portable gas heater, including the use of a gas oven for heating, was significantly related to CO levels in kitchens (F=5.8, p<0.001) and bedrooms (F=4.1, p<0.001). Means are shown in Table 12.

Table 12. Geometric mean kitchen and bedroom CO (mg m\(^{-3}\)) by unflued heater use

<table>
<thead>
<tr>
<th>Any use of portable or other unflued heater or gas oven for heating</th>
<th>Kitchen</th>
<th>N</th>
<th>Bedroom</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>0.89</td>
<td>73</td>
<td>0.62</td>
<td>73</td>
</tr>
<tr>
<td>No</td>
<td>0.44</td>
<td>755</td>
<td>0.38</td>
<td>749</td>
</tr>
</tbody>
</table>

COMPARISON WITH HEALTH-BASED GUIDELINE
The 14-day average concentration of CO did not exceed the WHO 8-hour average guideline value of 10 mg m\(^{-3}\) (WHO, 2000) in any home. Monthly mean concentrations were all less
than 1 mg m\(^{-3}\). While it remains possible that the guideline is exceeded in homes over shorter periods, there are no specific health implications of the measurements made in this study.

CONCLUSIONS
The survey identified factors influencing CO levels in homes, i.e. gas cooking, unflued heaters and smoking. The outdoor air was also found to be an important factor, as shown in effects of urban location and season. However, seasonal effects were due largely to indoor sources; this would need to be considered when interpreting time series studies of the effect of outdoor air pollution on health. Extract fans have little effect on CO levels in the kitchen, although they may limit the spread of the gas to other parts of the home.

It is apparent that, in the majority of homes in England, CO levels are very low for most of the time. However, the safe operation and correct ventilation of combustion appliances is essential, to avoid accidental poisoning and death from exposure to high levels of CO.

ACKNOWLEDGEMENTS
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REFERENCES