DUST AND AMMONIA EMISSIONS FROM UK POULTRY HOUSES

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ABSTRACT This project successfully characterised poultry dust, quantified emission levels, and assessed the potential of emission abatement techniques and the potential impact on human health. Measured in-house concentrations and emission factors of PM<sub>2.5</sub> and PM<sub>10</sub> were within the range of previous measurements, but the average was significantly lower than the average of former studies, especially for broilers. Surprisingly high emission factors were found for housing emissions of free-range layers, for which literature data are sparse. Using the emission factors derived here, overall UK emissions of PM<sub>10</sub> from poultry were 1.865 t.yr<sup>-1</sup>, reduced by fourfold compared with the NAEI. Ammonia emissions were also in the range of previous estimates, but average emission factors were 50% higher than those used to calculate the official UK emission estimates. Abatement using either two baffles and water bath outside the fans (U-bend principle) or a StuffNix filtration system, removed 22% and 67% of PM<sub>10</sub>, respectively. Bioaerosol concentrations, quantified as bacteria, fungi and endotoxin, were also in line with previous results. In-house concentrations are of potential concern to poultry workers. However, due to dilution and dispersion effects, concentrations approach background values at a distance of about 100 m downwind. The bacterial and fungal composition was typical for agricultural areas and E.coli was only identified during one farm visit.

Keywords: poultry, emission dust, ammonia, abatement, human health.

INTRODUCTION Elevated concentrations of atmospheric dust have been associated with an increase in a range of human health problems, such as respiratory and cardiovascular disease. In Europe (and thus in the UK), exposure to inhalable dust (ID) is regulated by setting Air Quality Standards for the mass of particulate matter contained in particles < 10 µm aerodynamic diameter (PM<sub>10</sub>) and in particles < 2.5 µm (PM<sub>2.5</sub>), two metrics for which epidemiological associations have been reported.

Agricultural activity contributes to the primary emission of dust with an absolute contribution that is thought to have remained largely constant over past years. Although making a moderate contribution to the national UK primary dust (PM<sub>10</sub>) inventory overall, the contribution of animal housing to total primary emissions of PM<sub>10</sub> is estimated to have grown from 2.8% in...
1990 to 5.2% in 2000 (RAINS, 2005), with the latest (2006) official UK estimate being 5.9%. Emissions from animal housing are thought to be dominated by poultry livestock operations, followed by pig husbandry. Kilmont and Amann (2002) estimate that the poultry sector is responsible for 57% of PM$_{10}$ and 50% of PM$_{2.5}$ emissions from animal housing, while RAINS (2005) estimates contributions of 40% and between 35 and 45%, respectively. However, these estimates are based on a very sparse database of PM emission factors (Takai et al., 1998; UNECE/EMEP, 2007). There is growing concern that dust from livestock buildings can cause exceedance of UK Air Quality Standards locally. In addition, the presence of bioaerosols (micro-organisms, predominantly fungi and bacteria, and bacterial endotoxins) poses a significant but, to date, largely unknown and unquantified risk to the human population in the vicinity of poultry farms.

In the UK, farms operating with an Environmental Permit in 2008 are obliged to demonstrate some measure of dust management, such as simple control-at-source methods. More complex dust abatement systems, for example, dry filters or wet bio-scrubbers are rarely used in the UK compared with elsewhere in Europe. Control-at-source methods, such as good quality feed pellets and feeders that do not break up the feed, are commonly used but are limited in the amount of dust they can remove. However, more specific management techniques to reduce dust, such as humidification or spraying with oil, will only be adopted if they are proved to have no adverse effect on general management or bird welfare in a commercial situation. External, end-of-pipe technologies are currently limited to diverting dust from the roof or ground to a form of bio-filter, or dispersion and dilution into the atmosphere.

**METHOD** The following main types of poultry production system were selected for monitoring:

- Litter systems (broilers), two off
- Egg production from layers in cages, two off
- Egg production from free-range layers, two off
- Abatement: dust trapping system “U-bend with incorporated water bath”
- Abatement: dry filter system (StuffNiX)

Each selected farm was sampled twice, once in winter and once in summer. The monitoring sites were selected for their production system and secondly on criteria that would make the practical aspects carrying out the monitoring straight forward. Preference was given to large modern commercial farms with powered ventilation, without obstructions down-wind, no or low external sources of dust up-wind of the farm, access to the extractor fans for sampling, access for the mobile laboratory and an adequate power supply for the instrumentation. Specifically, broiler houses were clear-span, constructed from a steel frame with insulated composite panels, fitted with pan feeders and modern nipple drinking system. Caged housing was fitted with belt-cleaned (enriched) cages with manure drying facilities and automatic egg collection. Free-range houses were constructed from wooden frame and cladding, with two-thirds slat and one-third litter on the floor and an automated nest system.

In broiler production, dust concentrations were expected to be at or near peak towards the end of the 35-42 day crop (Roumeliotis and Van Heyst, 2007). Therefore, the broilers age was between 25-30 days old at the start of monitoring, so that the birds were large enough to be a representative sample, whilst avoiding thinning events (usually at 32 days of age). The layers were adult and in full lay.
Measurements were made in ambient air outside (upwind and at several locations up to 400 m downwind) the chicken houses, inside the chicken houses and at one or two ventilation fans. Measurements were made during the light (day time) and dark (night time) periods for the birds over a period of two to three days.

The aerosol mass loading was measured with a TEOM Ambient Particulate Monitor with a PM$_{10}$ head (Thermo Electron), and by gravimetric analysis of samples from two PM$_{2.5}$ and two PM$_{10}$ low volume samplers (Partisol 2000, R&P) as well as two 8-stage Micro Orifice Uniform Deposit Impactors (MOUDI Model 100, MSP Corporation). Particle size distributions were measured with two Aerodynamic Particle Sizers (APS), 0.7 to 20 μm (TSI APS 3321). For measurements at the fan outlets, short sample air inlets were mounted into the air flow, with diameters chosen to provide approximately isokinetic sampling conditions. The flow from the inlet was then directed into the MOUDI, the low volume sampler (via a PM$_{2.5}$ cyclone and a Chemcomb PM$_{10}$ inlet) and the APS samplers. However, as the fan speed was often variable, some non-isokinetic sampling was to be expected.

Bioaerosol samples were taken using static samplers (six-stage Anderson impaction and Partisol samplers, models 2000 and 2005). The Partisol filters were used for endotoxin analysis and microbial enumeration. Predominant bacterial and fungal colonies were identified by gross morphology, microscopic examination and DNA analysis using polymerase chain reaction (PCR) techniques.

The building ventilation rate was measured with a constant release tracer technique (Demmers et al., 2009). The release rate was controlled using mass flow controllers (Bronckhorst High Tech B.V.) and the tracer sulfurhexafluoride (SF$_6$) measured using a gas chromatograph, at the air outlets and corrected for the ambient concentration. Ammonia concentration was measured using a chemiluminescence NO$_x$ analyser, following catalytic conversion of ammonia to nitric oxide (NO) at 750 °C. Emission factors were calculated by multiplying concentration (corrected for background concentration) with the ventilation rate and where required corrected for live weight.

The efficacy of the dry filter was quantified from the difference in concentrations upstream and downstream of the abatement technique. In the case of the U-bend baffle, the downstream concentration was corrected for dilution with clean air using the measured tracer gas concentration at the same location.

**MEASURED INDOOR PM AND BIOAEROSOL CONCENTRATIONS** The mass concentrations measured using all particle instruments, segregated according to lighting regime and season (Figure 1), showed that broilers gave the highest PM$_{10}$ and PM$_{2.5}$ concentration, reaching 2990 μg/m$^3$ during the summertime when the lights were on and 655 μg m$^{-3}$ (winter-time dark period), respectively. The lowest PM$_{10}$ (20 μg m$^{-3}$) and PM$_{2.5}$ (23 μg m$^{-3}$) were measured at a caged-layer farm.

The particle size distribution was unimodal at all farm types, and yet peaked at different particle sizes 5.8, 5.0 and 4.3μm for free-range layers, broilers, and caged layers, respectively. These differences may be partially explained by sampling location and litter conditions, but the consistency within farms of the same type indicated differences between the farm types may be equally important, e.g. the movement freedom and physical condition of the birds resulting in more larger particles being generated.
Figure 1: The mean PM$_{10}$ concentration (on the left) and mean viable bacterial counts (on the right) measured at locations inside the house, at the exhaust and at various distances downwind of the broiler, caged egg layer and free range houses, respectively (logarithmic scale). Where applicable the standard deviation is also given.
Compared to the Partisol filter samples, the Andersen samples yielded 10-100x more cfu. This was as expected due to direct impaction onto agar and no loss due to sample manipulation downstream of sampling. Results were more variable for the Anderson sampler than the Partisol samplers, possibly reflecting the short sampling time and thus greater susceptibility to fluctuations in bioaerosol concentrations. The results from the Partisol samplers (Figure 1) indicate that, similarly to particle size, the highest concentrations were found at broiler farms (10^8 to 10^9 cfu m^{-3}), followed by free-range farms, ranging from 10 to 10^5 cfu m^{-3}. Lowest airborne bacteria concentrations were found at the layer farms 10^3 to 10^4 cfu m^{-3}. Both free-range farms had much lower concentrations in the winter than the summer period, contrary to prior expectations. Increased summer concentrations could be influenced by more birds being out on the range, hence the average ventilation rates during the summer were about the same as in winter, despite higher ambient temperatures. However, this did not explain in full the high levels during the summer, as lower animal numbers generally also impact on the dust generation, i.e. lower the dust concentration.

**PM_{10} and bioaerosol concentrations downwind of poultry houses** Although an effort was made to work on isolated poultry houses where possible, the results of the external sampling using either the Partisol or Anderson samplers will be affected by the unquantified emission from neighbouring sheds and/or other sources on the site or in the vicinity of the experimental shed. This must be taken into account when interpreting the results.

The concentration of PM_{10} emitted from poultry houses was highest for the broiler houses and this is evident from the higher concentrations of PM_{10} measured close to these buildings (Figure 1). However, in almost all cases the concentration of PM_{10} had dropped to background levels (measured 50 m upwind) at 100 m and for all cases at 200 m distance downwind from the buildings.

The concentrations of bacteria upwind, and downwind measured using the Partisol sampler, are summarised in Figure 1. In general, the results demonstrated that due to the emission of bacteria from the building (10^3 to 10^6 cfu m^{-3}) the bacterial concentrations at 50 m downwind (10^1 to 10^4 cfu m^{-3}) were significantly higher than background (1 to 10^2 cfu m^{-3}) and generally declined to background again by 200 m downwind, in line with PM_{10} concentrations. Similar concentration profiles were found for the concentrations of fungi and endotoxins.

**Abatement** The achieved reductions in dust, ammonia and bioaerosol concentration for both abatement systems are summarised in Table 1. The StuffNiX dry filter was far more effective than the U-bend baffle in removing dust. The PM_{10} result compares favourably with the manufacturer’s stated claim of 70% “dust” removal and unpublished PM_{10} data showing a 62% reduction in PM_{10} (BigDutchman, 2009). The effect of either abatement technique on bacterial and fungal concentration was disappointingly low, compared with the reduction in both PM_{10} and PM_{2.5}. This might be due to the bacteria and fungi being associated with fine particles (below PM_{2.5}) that are not captured in either system. The results clearly indicate that neither the dry filter nor the deflector had any effect on ammonia concentration and thus ammonia emission. This was expected for the dry filter system, as the gaseous ammonia will pass straight through (analyser does not measure particulate ammonia). In the case of the U-bend dust trapping system a small reduction in ammonia concentration was expected, but the lack of water in the bath made this unlikely.

Table 1. Efficiency of abatement measures on aerial pollutant emissions.
Emission factors To allow direct comparability with other installations and study results, emission factors (EF) are presented calculated per bird (Table 1). PM$_{2.5}$ and PM$_{10}$ EFs spanned a wide range, two orders of magnitude, with the free-range layers displaying the maximum EF of 15.34 mg/(bird hr). The lowest EF of 0.02 mg/(bird hr) was measured at a battery layer farm.

Table 2. Average particle size, ammonia, bacteria and fungi emission factors for each farm type

<table>
<thead>
<tr>
<th>Farm type</th>
<th>PM$_{2.5}$</th>
<th>PM$_{10}$</th>
<th>Ammonia</th>
<th>Bacteria</th>
<th>Fungi</th>
<th>Endotoxin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg animal$^{-1}$ day$^{-1}$</td>
<td>gNH$_3$-N animal$^{-1}$ day$^{-1}$</td>
<td>cfu animal$^{-1}$ day$^{-1}$</td>
<td>EU animal$^{-1}$ day$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broilers†</td>
<td>5.1</td>
<td>0.29</td>
<td>6.8 10$^5$</td>
<td>2.5 10$^3$</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>Caged layers</td>
<td>6.9</td>
<td>0.06</td>
<td>3.2 10$^5$</td>
<td>5.8 10$^3$</td>
<td>2.3 10$^2$</td>
<td></td>
</tr>
<tr>
<td>Free-range layers</td>
<td>36.4</td>
<td>1.52</td>
<td>1.8 10$^6$</td>
<td>6.4 10$^3$</td>
<td>2.7 10$^3$</td>
<td></td>
</tr>
</tbody>
</table>

†Broiler data were corrected for average bird weight over entire crop cycle. Units were converted from this study using recorded numbers and weights of birds.

The ammonia emissions fell within the published range of values for their type, but measured 50% higher than the current emission factors in the UK ammonia inventory, i.e. 0.12, 0.3 and 0.12 g N (kg lw)$^{-1}$ d$^{-1}$ for belt cleaned cages, free-range layers and broilers on litter, respectively (Misselbrook, 2006). Notable exemptions were a free-range unit with very high ammonia emissions in both summer 2.75 gNH$_3$-N animal$^{-1}$ day$^{-1}$ and winter 1.19 gNH$_3$-N animal$^{-1}$ day$^{-1}$, due to the wet manure under the slats (27% DM) and as a result a high level of ammonia cal-N in the manure. Similarly, the emission from one caged egg unit was relatively high for same reason, despite the fact that the manure was removed weekly. However, the manure on the belts was 5 to 6 days old at the time of the measurements. Surprisingly, the emission from broilers farms was high (0.98 and 1.07 gNH$_3$-N animal$^{-1}$ day$^{-1}$) on two occasions. The litter conditions were relatively poor at one location, potentially explaining the higher emission, but perfect at the other (>71% DM) with very low ammoniacal-N content. Hence, the higher emission was difficult to explain in that case.

The highest emission for bacteria and fungi was from a free-range farm during the summer, at 5.3 x10$^6$ and 1.6 x 10$^4$ cfu animal$^{-1}$ day$^{-1}$, respectively. However, the other farms had similar emissions ranging from 1.8 x10$^5$ to 1.1 x10$^6$ cfu animal$^{-1}$ day$^{-1}$ for bacteria and 3.5 x10$^4$ to 1.1 x10$^4$ cfu animal$^{-1}$ day$^{-1}$ for fungi. Although emissions were expected to be slightly higher in summer compared to winter, in analogy to ammonia emissions, this was not always the case.
DISCUSSION This paper reports on part of a study aimed to improve understanding of (i) the physical and chemical characteristics of poultry related particles, (ii) their emission factors, (iii) the ability of abatement systems to reduce concentrations and (vi) assess the impact on human health. The measurement database against which the results can be compared is limited and the particle transmission of the respiratory system is not directly related to the metrics used for air quality assessment (PM$_{2.5}$ and PM$_{10}$). The EMEP/CORINAIR Emissions Inventory guidebook (UNECE/EMEP, 2007) assumes PM$_{2.5}$ and PM$_{10}$ to be representative to respirable dust (RD) and inhalable dust (ID) respectively. For comparison with published data, our measurements were converted to RD and ID, using derived ratios of PM$_{10}$/ID of 1.08 and PM$_{2.5}$/RD of 0.36.

PM and bioaerosol concentrations In general, our measurements showed much lower concentrations of PM$_{10}$ for all farm types whilst PM$_{2.5}$ measurements were of a broadly similar magnitude (Schneider et al. 2005, Lim et al., 2003, Takai et al., 1998). Measurements by Lim et al. (2003) were made using a TEOM and provide a relatively comparable dataset to our measurements, but display slightly higher concentrations for PM$_{10}$ and lower concentrations for PM$_{2.5}$. The comprehensive study by Takai et al. (1998) again has a wide range of concentrations for both ID and RD and these are consistently higher for PM$_{10}$ measurements than our data, but our PM$_{2.5}$ data are within their measured RD range. For the broiler farms, the data of Takai et al. (1998) also displayed higher concentrations than our measurements, with differences again more so for the PM$_{10}$ concentrations rather than PM$_{2.5}$; by contrast our measurements are higher than the averages measured by Roumeliotis and Van Heyst (2007).

Bioaerosol samples taken inside poultry houses were of similar order of magnitude than those reported by Seedorf et al. (1998) for layers and broilers in northern Europe (including the UK). Concentrations of airborne bacteria, fungi and endotoxin were generally greater during light periods than dark in correspondence with earlier findings (Seedorf et. al., 1998). This reflected the likely levels of activity of the birds, with more bird movement during daylight hours creating greater disturbance of litter and associated contaminants.

The general trend in all studies, including this one, is for broilers to display the largest dust concentrations, whilst battery cage layer farms display the least, but within each farm type there are wide ranges of dust concentrations measured. This is unsurprising given the differences between building size, ventilation method, litter composition and management and lighting regime employed across the farms featured in the aforementioned studies. A consistently lower result in this study may simply be the product of better farm management practises within the past 10 years designed to limit exposure to dust and potentially reflects the fact that this study focussed on relatively modern installations.

Emission factors A recent study (Roumeliotis and Van Heyst, 2008) reviewed the available particulate EFs for poultry farms globally. For the broiler farms, the PM$_{10}$ EF data from Lacey et al. (2004) agrees well with our measurements, whilst those of Roumeliotis and Van Heyst (2008) are 50% lower, but still within one standard deviation of our collective measurements. The measurements of Takai et al. (1998) are used in the latest edition of the EMEP/CORINAIR Emission Inventory Guidebook (UNECE/EMEP, 2007) as a basis for poultry particulate EFs and are much larger than our converted ID EFs. It is not apparent at which stage in the broilers’ life cycle the measurements from Takai et al. (1998) were conducted; if only mature birds were considered then their emission estimates would be elevated with respect to the entire crop cycle. Similarly to our PM$_{10}$ and ID results, the PM$_{2.5}$
measurements from broiler farms are twice as high as the measurements of Roumeliotis and Van Heyst (2008) and the converted RD data are roughly half those measured by other researchers. At caged layer farms, PM$_{10}$ measurements and equivalent ID results were towards the lower end of the published range of EFs, whilst our PM$_{2.5}$ and RD results were approximately twice as high as other reported values. There is a lack of measurements of PM emission factors from free-range layer farms in the literature. The results presented here indicate that free-range emit more particles per bird than broilers and substantially more than caged layers. It should also be noted that no allowance was made for the proportion of birds outside during measurements. An attempt was made to estimate the total annual emissions from UK poultry houses based on the results of this study. The resulting estimate is significantly lower than the estimates presented by the UK National Emissions Inventory (NAEI) by factors of approximately 4 for both PM$_{2.5}$ and PM$_{10}$, reflecting the use of larger emission factors used in the NAEI calculations, especially for broilers. It should be noted that the study presented here focussed on modern poultry houses. The ban on cages in the egg laying sector will inevitably lead to a substantial increase in the overall annual emission from poultry houses.

Bioaerosol emissions are within the range reported by Crook et al. (2009) for agricultural and related industries. Seedorf et al. (1998) reported emissions for bacteria, $2.3 \times 10^8$ and $0.5 \times 10^6$ cfu.kg$^{-1}$day$^{-1}$ and fungi, $3 \times 10^6$ and $4.8 \times 10^6$ cfu.kg$^{-1}$day$^{-1}$ for broilers and layer buildings, respectively. The latter results for broilers are substantially higher than the emissions measured in this study in line with the results for PM. The concentration of fungi measured in this study was lower for both broilers and layers.

Whilst poultry dust emissions from poultry houses significantly contributed to bioaerosol levels at short distances (50 m) from source, bioaerosol concentrations generally declined rapidly with distance from source. At the maximum distances from source ($300 - 400$ m) numbers were generally similar to upwind background. This may be expected because of the dispersion and dilution effect in open air. In some instances, bioaerosol numbers were greater than upwind background, but this may have resulted from innate variation in environmental bioaerosol measurement or the influence of other bioaerosol sources in the vicinity, e.g., from other agricultural operations. Concentrations at 200-400 m from the building were generally low compared to previously published data (Crook et al., 2008).

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Abatement Efficiency  The dry filter abatement method was the most efficient way to remove particles, with reduced PM$_{10}$ concentrations up to 70% observed. Despite the water bath not being used, the baffle system removed ~15-25% of measured particles. Nevertheless, in absolute figures, this house still had some of the largest emissions observed during this study, which may be more related to high ventilation rate and litter conditions. Both abatement techniques had very limited success in reducing bioaerosol emissions. The disappointingly low efficiency is difficult to explain for the StuffNiX system especially, as both PM$_{10}$ and PM$_{2.5}$ efficiencies were substantial. The only reason might be that the bacteria and fungi are associated with an even lower size fraction that is not affected by the filter. Neither abatement system had any effect on ammonia emissions. Integrating ammonia reduction techniques in the dry filter method will be very difficult, whereas it should be possible to integrate a simple wet scrubber to remove ammonia into the air deflection baffle method, potentially improving the dust removal efficiency.

Assessment of the human health implications  EC Directive 2008/50/EC requires PM$_{10}$ particle concentrations not to exceed a daily mean of 50 μg m$^{-3}$ on more than 35 times per year, judged against a scale in which bands 1 to 3 (0 to 49 μg PM$_{10}$ m$^{-3}$) are rated low; 4 to 6 (50 to 74 μg PM$_{10}$ m$^{-3}$) are rated moderate, 7 to 9 (75 to 99 μg PM$_{10}$ m$^{-3}$) are rated high and band 10 (100+ μg PM$_{10}$ m$^{-3}$) is rated very high (AEA, 2007). At 100+ m downwind of poultry houses PM$_{10}$ concentrations fell into the low rating. At 50 m downwind, out of 21 sets of measurements only 4 would be rated moderate or high, one of these rating as very high. All of the higher rated values were associated with broiler houses.

Bioaerosol concentrations measured at vents from poultry houses were generally of a similar order of magnitude as bioaerosol concentrations measured in poultry houses (Crook et al., 2008). Therefore, in close proximity to vents from poultry houses it could be argued that bioaerosol emissions represent a risk to human health through respiratory allergy comparable to that for workers inside the houses. However, as discussed previously, the dilution and dispersion of those bioaerosols means that within a relatively short distance (100 m) the risk to human health is significantly reduced. This is consistent with findings from another study that showed a reduction in dust and ammonia levels at ~13 m distance from poultry houses compared to ~3 m feet distance, although reduction in bacterial levels was less clear in that study (Davis and Morishita, 2005). Of the chosen specific enteric pathogens in our study, only verocytotoxict E. coli could be isolated and only on one farm.

It is therefore unlikely that people other than workers on commercial poultry farms will receive long term exposure to bioaerosols sufficient to trigger respiratory allergy or disease

CONCLUSION  This work represents one of the most comprehensive studies to quantify PM emissions from poultry housing to date, comparing a total of eight farms. Large variations between farm management practises, lighting regimes, litter conditions, and meteorology contributed to variability in emissions, even for the same type of farm. The broiler installations were associated with the largest indoor air PM$_{2.5}$ and PM$_{10}$ concentrations (655 μg m$^{-3}$ and 2990 μg m$^{-3}$, respectively) and the highest bacterial and fungal counts. Concentrations of particulate matter and bioaerosols were the lowest at battery farms. Free-range farms had the highest emission per animal of PM$_{2.5}$, PM$_{10}$ and bioaerosols. Bioaerosol concentrations in the building represent a risk to poultry workers in terms of respiratory allergy or disease, but were reduced to background levels by 100 m downwind of even the highest emitting poultry houses, and therefore are unlikely to pose a risk to those living in the vicinity of poultry operations. Of
the abatement systems tested, the baffle had a low efficacy for PM$_{10}$ removal of 22%, whereas the dry filter (StuffNiX) method was far more effective at 67%. Neither affected the emission of ammonia.

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