TOX/2013/32

COMMITTEE ON TOXICITY OF CHEMICALS IN FOOD CONSUMER PRODUCTS AND THE ENVIRONMENT

DISCUSSION PAPER ON EXPOSURE MONITORING OF THE AIRCRAFT CABIN ENVIRONMENT

INTRODUCTION

1. The Department for Transport (DfT) has asked the Committee on Toxicity (COT) to undertake an independent scientific review of the results of DfT-funded aircraft cabin environment research commissioned in response to recommendations made by COT in 2007. The DfT commissioned four studies relating to air monitoring equipment assessment, air and residues monitoring in aircraft, and a statistical analysis of fume event and operational parameter data in aircraft. The Public Health England (PHE) COT Secretariat and through them the PHE Toxicology Unit, Imperial College, London have been commissioned by the DfT to review the submission and prepare a discussion paper for the COT.

2. Throughout this paper terms relating to an air contamination incident (fume incident, fume event) are intended to refer to incidents with internal sources (e.g. passengers, aircraft components, cleaning materials, dust, disinsection procedures, contaminants arising from aircraft systems such as engine oil). External contamination, such as that arising from ground level air pollution, is not covered in this evaluation.

BACKGROUND

3. Between July 2006 and July 2007, the COT considered a referral from DfT to review data submitted by the British Airline Pilots Association (BALPA) to DfT due to concerns about the possible effects on aircrew health of oil/hydraulic fluid smoke/fume contamination incidents in commercial aircraft and published a statement on its advice and recommendations (Annex 1). The submitted data related to organophosphates (OPs), the cabin air environment, ill-health in aircraft crews and the possible relationship to fume events in aircraft. The objectives for COT were, firstly, to evaluate the submission and data sourced by the Secretariat, assess the risk of exposure of aircraft crews to OPs and oil/hydraulic fluid pyrolysis products in cabin air and determine whether there is a case for a relationship between exposure and the ill-health in aircraft crews. A summary of the data considered by the Committee was provided in the COT statement (Annex 1 paragraphs 29-63). Secondly, to provide the DfT with appropriate advice on any further research required to evaluate this subject.

4. The conclusions of the COT together with some of the data considered by the Committee are reproduced below for ease of reference (paragraphs 5-22).

5. The COT considered as a general point, prior to detailed evaluation of the submitted evidence, that regardless of the cause(s) of the reported adverse symptoms, it would be prudent to take appropriate action to prevent oil or hydraulic fluid smoke/fume contamination incidents (Annex 1 paragraph 28).

6. On the basis of the available evidence, the Committee agreed that it was not possible to conclude whether a causal association existed between cabin air exposures (either general or following incidents) and ill-health in commercial aircraft crews. However, the Committee noted a number of oil/hydraulic fluid fume contamination incidents where the temporal relationship between reports of exposure and acute health symptoms provided evidence that an association was plausible (Annex 1 paragraphs 54 and 74). The Committee agreed that consideration should be given to further research investigating a possible association between exposure to oil/hydraulic fluid pyrolysis products and ill-health in commercial aircrews (Annex 1 paragraph 74).

Exposure Monitoring

7. The COT evaluated the limited number of published laboratory studies of oil and hydraulic fluid pyrolysis (Annex 1 paragraphs 29-30). The thermal degradation of jet oils has been shown to form a diversity of volatile organic compounds (VOCs) including ketones, acids, aldehydes, esters, oxygen-containing heterocyclic compounds, and tricresyl phosphate (TCP) isomers (but not the ortho- isomer) in addition to carbon monoxide, carbon dioxide and ozone. Parameters other than amount of oil released into an engine, such as bleed air temperatures and pressures in compression chambers and airflows, would also have an impact on the chemical contaminants formed during an oil/hydraulic fluid air contamination incident. The temperatures chosen for the evaluation of oil degradation products varied between studies and ranged from 121–371°C. The COT noted the theoretical formation of trimethylolpropanephosphate (TMPP) from trimethylolpropane esters and tricresyl phosphates but that this could not be demonstrated in experiments using realistic pyrolysis conditions. Thus, it was considered that formation of TMPP during fume contaminant incidents on commercial aircraft was unlikely, although appropriate air monitoring data were not available.

8. The thermal degradation of hydraulic fluids has been shown to produce carbon particles, a low level of carbon monoxide, and a variety of short chain hydrocarbons which can rearrange to form condensed ring structures (Annex 1 paragraph 30).

9. Around 90 compounds including alkanes, alkenes and aldehydes were identified in bleed air tests on an ALF502R-5 turbofan engine from a BAe 146 aircraft set up on a test rig (Annex 1 paragraph 34). The concentrations of the

compounds were generally below 12 parts per billion (ppb) at the engine bleed port. Acetone, methylene chloride, carbon monoxide, methane, carbon dioxide, ethylene, 2-methylpentane, 3-methylpentane were detected at varying concentrations above this level. Assuming no significant in-cabin sources, the levels of these chemicals would be expected to be lower in cabin air. The ortho- isomer of TCP was not detected but total isomers of TCP had been detected and quantified.

10. An in-confidence report was obtained for a study undertaken to investigate potential exposure to engine oil, hydraulic fluid, Auxiliary Power Unit (APU) oil and fuel using B757s on the ground (to establish methodology) and during 3 commercial flights (Annex 1 paragraph 37). The B757s selected for this study had been reported previously as having problems with oil smells. The authors reported that there was some limited evidence for the presence of APU oil and hydraulic fluid in cabin air on all the flights but at levels below those expected to induce mild acute symptoms. Around 100 individual organic compounds including VOCs and siloxanes were detected using thermal desorption.

11. Overall, the COT agreed that there was considerable uncertainty regarding the identity of VOCs, semi-volatile organic compounds (SVOCs) and other pyrolysis products released into the cabin air during an oil/hydraulic fluid smoke/fume incident (Annex 1 paragraph 43). Further, that approaches to exposure measurement should address the widest possible range of potential contaminants from oil/hydraulic fluid that could be analysed and should not focus on only a single chemical group or compound (Annex 1 paragraph 66).

12. The Committee agreed that no specific hypothesis regarding which chemicals to monitor could be pursued and thus a staged approach to exposure monitoring and data collection from pilots (e.g. health assessment) would be most appropriate, to enable specific hypotheses to be developed and investigated (paragraph 67).

13. The COT was provided with estimates of the number of flights that would need to be monitored for air quality in order to have a 95 per cent probability of monitoring at least one flight in which an oil/hydraulic fluid smoke/fume incident occurred, assuming the underlying rate of such incidents was 1/100, 1/1000 or 1/10,000 flights. The COT agreed that there would need to be monitoring on approximately 300, 3000 or 30,000 flights respectively (per airframe with a specific engine).

14. Members agreed that the calculated incidence of oil/hydraulic fluid fume contamination was approximately 1% from pilot reports and approximately 0.05% following engineering investigation (although this might vary depending on airframe, engine type and servicing). It was noted that the estimates of incident rates and numbers of sectors required to be monitored were preliminary and should be used for initial guidance only. It was evident from this information that overall a large number of sectors would need to be monitored to have a high degree of confidence of including an engineering-

confirmed oil/hydraulic fluid smoke/fume incident. Members agreed the proposed preliminary estimates of the number of flights required for exposure monitoring per airframe/engine type of more than 100 sectors for background monitoring, and of up to 10,000-15,000 sectors to assess exposures relating to engineering-confirmed oil/hydraulic fluid smoke/fume incidents, depending on the airframe and engine type, APU, rate of oil/hydraulic fluid contamination, air conditioning system operation and engine servicing. Members noted that such a study would also provide more reliable data on background exposure (Annex 1 paragraph 69).

15. Members considered a wide range of analytical techniques, samplers and sensors that could be used or adapted to undertake the initial assessment of the cockpit/cabin environment in conjunction with data presented on oil content and combustion analyses, potential smoke/fume incident rates, the number of aircraft types and the number of flights/sectors that may need to be sampled. The Committee agreed the available options for exposure monitoring and passive sampling of a large number of flights on appropriate aircraft represent the best initial approach (Annex 1 paragraph 70).

16. The COT agreed that a two-stage approach to exposure monitoring needed to be undertaken, with validation and calibration of solid phase microextraction (SPME) fibre technology followed by preliminary air monitoring testing using appropriate B757 and BAe 146 aircraft, the types of aircraft which had been cited most often in the BALPA submission to have been associated with reports of acute health symptoms in aircrew (Annex 1 paragraph 71). Further, that any exposure monitoring approach that is developed would need to link to data recorded by airlines with regard to engineering status of the aircraft and reports of odours and adverse symptoms by pilots. It would also have to take into account the often transient nature of contamination incidents.

17. The COT agreed that carbon monoxide could be used as one potential indicator of burning oil and thus the measurement strategy should include monitoring for carbon monoxide exposure (Annex 1 paragraph 72).

Health

18. The Committee agreed that consideration should be given to further research investigating a possible association between exposure to oil/hydraulic fluid pyrolysis products and ill-health in aircrews. The COT considered that any epidemiological study would need some index of oil/hydraulic fluid air contamination incident exposure in order to be useful.

19. The Committee agreed that in order to address concerns about incident-related acute irritation, a general structure-activity equation might, in principle, be used to evaluate the acute sensory irritancy thresholds of mixtures present in cabin air incidents after independent validation of the approach to sensory irritants (Annex 1 paragraph 78). The outcome of this research would provide an indication/semi-quantitative measure as to whether exposures in commercial aircraft cabin air might be associated with sensory

irritation. Overall, there was insufficient evidence available to the COT to recommend additional epidemiological research on any acute health effects (Annex 1 paragraph 81).

20. The COT confirmed the need to obtain objective measures of exposure in epidemiological studies (Annex 1 paragraph 75) and suggested that these could come from exposure monitoring or through use of validated proxy measures of exposure. The Committee agreed there was insufficient evidence to justify epidemiological research focusing specifically on OPs (Annex 1 paragraphs 80 and 82).

21. The available evidence, although limited, together with information from pilots, supported further investigation of neuropsychological impairment in commercial pilots (Annex 1 paragraphs 58 and 81). However, there was insufficient evidence to recommend any specific additional research for any other acute or chronic health effect with regard to oil/hydraulic fluid contamination incidents on commercial aircraft (Annex 1 paragraph 81).

22. The Committee agreed the most appropriate epidemiological approach to research on neuropsychological status in commercial pilots would be a cross-sectional study to investigate how the prevalence of reported neuropsychological symptoms and the results of neuropsychological testing differ between pilots flying different airframes/engine combinations and between pilots who report, or do not report, air quality incidents, and whether associations differ between countries. Such a study would need the development and use of a validated proxy exposure approach for oil/hydraulic fluid contamination exposure in order to determine whether there is an association between oil/hydraulic fluid smoke/fume contamination and neuropsychological symptoms (Annex 1 paragraphs 82 and 83).

EXPOSURE MONITORING OF THE AIRCRAFT CABIN ENVIRONMENT

23. DfT commissioned 4 studies to address research recommendations made by COT: identification of air monitoring equipment capable of sampling air during fume events in real time (Report 1, Annex 2); a statistical analysis of data relating fume events and operational parameters in aircraft to investigate a potential link between cabin air fume events and aircraft full power take-offs (Report 2, Annex 3); real time in-flight cabin air sampling and data analysis (Report 3, Annex 4); an investigation of aircraft cabin surface residues (Report 4, Annex 5).

REPORT 1: FUNCTIONALITY TEST REPORT (Institute of Environment and Health, Cranfield University 2008) (ANNEX 2)

24. The study was commissioned to test a variety of air sampling devices through the collection of cabin air samples from a BAe 146 aircraft and a Boeing 757 aircraft fitted with an RR535C engine. The aim was to identify suitable equipment capable of detecting a wide range of compounds in a cabin air environment, and of capturing fume events in real time. The research was undertaken by three contractors.

EQUIPMENT TESTED

25. The main equipment assessed was a SPME fibre diffusive sampling system and a hand-held, battery-powered photoionization detector (PID). The equipment had to be capable of monitoring VOC and SVOC compounds across all phases of a flight, and of detecting anomalous elevations of VOC/SVOC concentrations (fume events). Also trialled were diffusive and pumped sampling onto thermal desorption (TD) tubes. The pumped TD tubes were packed with a front layer of Tenax for less volatile chemicals and a back-up layer of Unicarb, a carbon molecular sieve for volatiles. Tenax retains compounds in the range C8-C30, while Unicarb retains compounds in the C3-C7 range. A description of how these pieces of equipment function is provided in Annex 2, page 6, section 3.3. A further piece of equipment based on pumped air sampling was provided by one of the contractors for use in the trial.

26. Consideration was given to the feasibility of using a PID as a method for triggering other VOC/SVOC sampling methods, such as pumped TD, in the event of a fume incident. Consideration was also given to the feasibility of a technically qualified investigator travelling in the aircraft to perform sampling.

TEST SAMPLING ON BAe 146 AIRCRAFT

27. Air monitoring tests were conducted in the cabin of a BAe 146 aircraft whilst on the ground, parked in a hangar. Samples were taken with and without the auxiliary power unit (APU) and environmental conditioning system packs (ECS) running (a description of a generic air conditioning system on aircraft can be found in Annex 1, page 6-7, paragraphs 20-25). Air samples were taken in the aircraft hangar, in the aircraft cabin as background, and in the aircraft cabin while the APU and ECS packs were operating.

28. As a check of the sampling techniques, a test solvent sample containing 90% toluene and 10% xylene was released into the cabin at a pre-determined time while the APU was running. One of the laboratories identified toluene in the sample using pumped TD, at a concentration of 27 mg/m^3 as compared to a previous background level of 0.051 mg/m^3, and also identified increased levels of m- and p-xylene (2.3 mg/m^3 after sample release as compared to a previous background level of 0.0059 mg/m^3). The second

laboratory involved in the analyses reported that 'large concentrations' of toluene and xylene were detected using pumped TD, but did not report specific concentrations.

29. Analysis of all samples was carried out by gas chromatography-mass spectrometry (GC-MS).

Diffusive SPME Fibres

30. The diffusive SPME fibres were tested by one of the three laboratories. Use of these fibres resulted in the detection of nanogram quantities of 8 compounds: benzene, toluene, ethylbenzene, m- and p-xylene, o-xylene, styrene, 1,2,4-trimethylbenzene, and tributyl phosphate (TBP). The SPME fibres were able to register an increase in weight of benzene and toluene when the test sample was released. However, problems were encountered with fibre bleed during injection of samples onto the GC-MS, and a large number of siloxanes and other silicon compounds were also detected, which may have masked the presence of other compounds.

Diffusive TD Tubes

31. The tubes used were Carbograph TD1. Fifteen compounds were detected during sampling with these tubes, in addition to the 8 compounds identified on the SPME fibres, namely C6-C7, C9-C15, and C20-C30+ aliphatic hydrocarbons, 2,5-diphenylbenzoquinone, dioctyl phthalate, tertiary butylphenol, and trimethylpentylphenol. TBP, found in hydraulic fluid, was not detected. The report authors commented that the levels could not be accurately quantified without suitable uptake rates for the analytes detected. Further, the chemical masses collected on the tubes were very low, and the study authors reported that Tenax polymer may have been a better sorbent to use in the tubes to capture the less volatile compounds.

Pumped TD Tubes

32. The sampling for VOCs and SVOCs using pumped TD tubes resulted in detection of the same compounds as diffusive sampling. The pumped TD sampling recorded toluene and xylene in the correct proportions in cabin air on test release (27.0 and 2.3 mg/m^3 respectively).

33. Sampling was also undertaken with a hand held sampler using pumped TD tubes to collect air samples. The analysis focussed primarily on the detection of engine oil, and the SVOCs of Jet 2 engine oil and Hyjet 4 hydraulic fluid used in the aircraft tested. Jet 2 engine oil is reported to contain a range of synthetic esters, 1-3% TCP and 1-2% aromatic amines. Hyjet 4 hydraulic fluid is reported to contain TBP, dibutylphenyl phosphate and butyldiphenyl phosphate. The researchers reported TBP in all of the samples from the aircraft cabin, in concentrations ranging from 23-42 $\mu g/m^3$, compared to a background level in the hangar of 2 $\mu g/m^3$. They also found higher concentrations of Jet 2 engine oil (11-14 $\mu g/m^3$) (measured as a mass spectrometer response to the esters) in the cabin when the APU and ECS

systems were running, compared to background levels in the hangar and in the cabin when the systems were off (2 µg/m^3). Higher concentrations (0.6-1.3 µg/m^3) of total TCP, a component of engine oil, were found when the APU and ECS systems were in operation, compared to background levels of 0.02-0.03 µg/m^3. This laboratory equipment also measured a rise in ultra-fine particle concentrations when the APU and ECS were operating. The laboratory considered that their equipment was suitable to identify and measure low-level airborne concentrations of engine oil and hydraulic fluid, and of their components.

PID

34. The photoionization detector instrument used was a MiniRAE 2000, capable of measurements in parts per million (ppm). Before the release of the test sample the instrument did not register the presence of any VOCs, suggesting that concentrations may have been low, below its detection limit of 1 ppm. It responded to the release of the test sample, registering peaks up to approximately 150 ppm, over a period of about 6 minutes. It was decided to use an instrument with greater sensitivity, measuring in parts per billion (ppb), for the next cabin air test.

TEST SAMPLING ON BOEING 757 AIRCRAFT FITTED WITH RR535C ENGINE

35. Air monitoring tests were conducted on the flight deck of a B757 cargo plane, with the door to the cargo bay closed, while the aircraft was in flight. Sampling was undertaken using SPME fibres, pumped TD tubes and a hand held sampler using pumped thermal desorption. The PID device was changed from the BAe 146 study to one which could register one part per billion. Analysis of a set of samples was undertaken by an independent commercial laboratory to verify the findings.

Fume Event

36. A fume event occurred in the test flight, at the top of the climb phase of flight. It was noticed by both crew and scientists in the cockpit as a distinct oily type odour, which persisted for less than one minute and completely dissipated. A sharp peak in ultra-fine particle concentration of >500,000 particles per cm^3 of air, for particle sizes of 20 nm-1 µm, was registered using a particle monitor for a brief period of around a few seconds. However, the pumped TD sample during this phase of flight was taken over a period of 18 minutes. The mass concentration of the particles would have been extremely small, and did not show an effect on the sample taken. Thus, although a fume event occurred on the flight, the samples were collected over a longer period of time, and could not be regarded as an accurate measure of substances released during the event.

Diffusive SPME Fibres

37. The diffusive SPME fibres were used to take 4 samples, one during aircraft taxiing, one during take-off and climb, one during cruising and the last during descent and landing. The sample duration times ranged from 13 to 25 minutes. The fibres were positioned in the aircraft cabin, to ascertain background conditions in the cabin. Compounds detected during this testing were toluene, heptanal, C9-C15 aliphatic hydrocarbons, C15 aromatic hydrocarbons, and C17 aliphatic hydrocarbons. The weight of the compounds was recorded in micrograms. C9-C15 aliphatic hydrocarbons were below the limit of detection for 3 out of the 4 samples. The report authors noted that SPME fibres cannot be used to quantify concentrations of air contaminants. As with the testing on a BAe 146 aircraft, problems were encountered with fibre bleed during injection of samples, and a large number of siloxanes and other silicon compounds may have masked the presence of other compounds. The fibres were also found to be fragile. This technique was not recommended by the report authors for future investigations of cabin air quality.

Pumped TD Tubes

38. For pumped TD tubes, samples were taken by drawing air at a known flow rate, of 80-100 ml/minute, through a tube packed with Tenax and Unicarb. The sampling pumps used were all SKC Pocketpumps 201-1 002TX air sampling pumps. Samples were taken in the aircraft cabin, at a number of specified stages of the aircraft's flight cycle: at a stand-still prior to engine activation, at a stand-still following engine activation, during taxiing, during take-off and climb, during cruising, during descent, landing, and during final taxi.

39. The compounds detected during the flight were benzene, toluene, m- and p-xylene, o-xylene, 1,2,4-trimethylbenzene, naphthalene, heptanal, C9-C15 aliphatic hydrocarbons, phenol, 3-carene, phenylethyne, C17 aliphatic hydrocarbons, ethyl hexyl phthalate, C20-C30 aliphatic hydrocarbons, and hexadecanoic acid. None of the detected compounds was present at concentrations in excess of 0.2 mg/m^3. The report authors compared the concentrations found with Workplace Exposure Limits (WELs) specified by the Health and Safety Executive (HSE), for compounds for which WELs are available. The concentrations of the detected compunds were below the relevant WELs where applicable (Annex 2, page 45).

40. The results obtained from the TD tubes during the stage of flight in which the fume event occurred did not indicate any prominent compound that was either unique to that stage of sampling, or that was present at a significantly elevated concentration.

41. The hand held sampler with TD tubes detected a higher average concentration of Jet 2 engine oil (5 $\mu g/m^3$) during the stage of flight in which the fume event occurred, compared to that found during other stages of the flight (2 $\mu g/m^3$ or below), although this was lower than some concentrations of engine oil recorded during the tests on the BAe 146 aircraft in the hangar (11-14.5 $\mu g/m^3$), when no fume event had been noted. The average

concentration of total TCP over the flight stage when the fume event occurred was 0.04 µg/m^3, higher than in the other phases of the flight, although the background concentration recorded in the aircraft while stationary before the test flight was 0.05 µg/m^3. These results are presented in Annex 2, pages 70-72). Skydrol hydraulic fluid was found at similar average levels (1-4 µg/m^3) in air samples from all stages of the flight. TBP was found at average concentrations of 2-8 µg/m^3.

42. During the period over which the fume event occurred, the particle monitor recorded high readings over a period of around 2 minutes within the total tube sampling time of 18 minutes. The study authors calculated that if it was assumed the particles emitted account for at least part of the bleed air contamination, then the instantaneous Jet 2/Skydrol concentrations could have been around ten times the average value. The sharp peak in ultrafine particle concentrations indicated that the fume event lasted only a few seconds before being ventilated away. The number of particles measured was >500,000 particles per cm^3 of air and due to their small size of 20 nm – 1 µm their mass concentration would have been low.

PID

43. The PID device used in this flight test was a PhoCheck+ 5000, capable of measurements in parts per billion (ppb). It provided no useful information because it did not register anything above baseline in any phase of the flight. The report authors commented that it was unclear whether the problem was with all PhoCheck+5000 instruments, or with the particular machine used.

Independent Sample Analysis

44. A commercial laboratory analysed 8 pumped TD samples as an independent check on the findings of the two institutions carrying out the sampling. This laboratory highlighted a critical feature of the tubes packed with Tenax and Unicarb - Tenax was the weaker adsorbent at the front of the tube which would retain involatile compounds, whereas the VOCs/SVOCs would pass through the weak adsorbent and be retained on the stronger adsorbent Unicarb at the back. Therefore, it was vital that the tubes were used the right way round. Out of the 8 samples analysed, 3 had been taken from the wrong direction, and very few compounds could be identified in these three samples. Other compounds may have been present, but could not be detected.

45. It was not possible to reconcile the quantitative data from the two institutions and the independent laboratory proposed that this might be as a result of differences in the analytical protocols used. Of the compounds that were quantified, four were consistently found to be present above 0.5 ppb: propanol (ca. 50 ppb), toluene (ca. 3 ppb), alpha-pinene (ca. 2 ppb), and nonanal (ca. 1 ppb).

46. A further concern was raised about validation of the sampling and analysis methodology. The laboratory stated that for a valid analysis of the

compounds present it was necessary to show that all of the compound entering the tube during the sampling period was retained on the tube. This had not been validated. The laboratory stated that, if the project continued, it was a necessity to show that all of the compound was retained for a range of analytes being investigated, and that quantification depended on such confirmation at least for the range C3-C14. It was also necessary to show that all of the compound on the tube at the end of the sampling period was transferred to the GC-MS analysis system when analysed. This criterion had been validated for the range of volatilities of propanol to dodecane by a second desorption of both sample tubes and calibration tubes containing the compounds.

47. Finally, the laboratory commented that the GC method was eluting up to C14 in the time range of the analysis, whereas compounds of C17 had been found in the cabin air. The range of application of the method would need to be extended by ensuring appropriate adsorbent tubes and thermal desorption conditions, and by extending the GC run time.

CONCLUSIONS

48. The report authors concluded that the most suitable methodology was a combination of the use of pumped TD tubes to collect air samples over predetermined phases of flight, and the potential use of a PID (measuring in parts per billion) to indicate when a fume event occurred. If there was evidence of a fume event from the PID, or from observations by crew, a pumped TD tube sample should be immediately collected within the following minute. A technician would need to be present on the flight to collect that sample.

49. Although the PhoCheck+ 5000 did not provide any useful information, the report authors considered that it would be a suitable method for detecting a fume event due to its rapid response to a wide range of compounds, and could be used as a trigger for short duration pumped TD sampling if a fume incident were to occur.

50. The report authors recommended that in any future major data collection study the pilots and research scientist on the aircraft should complete a questionnaire, and that relevant information should also be obtained from the flight data recorder and aircraft maintenance reports for subsequent analysis.

51. QUESTIONS FOR THE COMMITTEE

i. What are Members' views on the approach taken to determine which techniques and equipment are the most appropriate for use in the aircraft cabin environment?

ii. What are Members' views on the results of the test sampling onboard both the BAe 146 and B757 aircraft?

iii. What are Members' views on the results following the fume event?

iv. What are Members' views on the independent analysis of the SPMEs and pumped thermal desorption tube samples?

v. What are Members' views on the techniques and equipment selected for the main air sampling study?

REPORT 2: Oil Smells in Aircraft Cockpits: Findings of Statistical Analysis into Associated Parameters (Institute of Environment and Health, Cranfield University 2009) (ANNEX 3)

52. After the occurrence of a fume event during the functionality test described in the previous section, a statistical analysis of various associated factors was undertaken. The fume event during a trial flight in the functionality test began when the aircraft levelled off at the end of the climb, and started the cruise phase of flight. The rate of climb up to that moment had been very steep. The event occurred as the aircraft handling went from full throttle to very low throttle, and raised the question whether fume events may in some way be related to the handling of the aircraft. A further question was whether any relationship could be established with aircraft maintenance reports.

53. The aim of this exploratory study was to determine whether it was possible to identify any factors associated with an increase in the probability of the occurrence of a fume event. It might then be possible to use such statistical approaches to identify steps which could be taken to reduce the probability of its occurrence, and therefore potentially make changes to standard operating procedures or to maintenance practices. The work is thus also a response to the COT recommendation that '*it would be prudent to take appropriate action to prevent oil or hydraulic fluid smoke/fume contamination incidents*' (Annex 1, page 8, paragraph 28).

54. Data were provided by a commercial airline for 15,468 flights on B757 aircraft, fitted with the RR535C engine; a total of 60 fume events from crew written reports were identified in this flight data. There were 48 flight parameters available for analysis, for example bleed duct temperature, air conditioning pack on/off. Those which showed statistically significant differences between flights with and without a fume event related to the status of the engine bleed air, air conditioning packs, pressure regulating shut-off valve and the pre-cooler temperature (see Annex 1, page 6-7, paragraphs 20-25 for description of a generic air conditioning system). Fume events occurred at 9 out of 12 stages of flight. The detailed data are presented in Annex 3, pages 6-24.

55. The factors showing a positive association with a fume event were generally reactive, reflecting a response of the pilot to isolate the smell and occurred after the fume event itself. Hence, in themselves they were not involved in the production of the event.

56. The authors stated that the study was exploratory, and that the methodology could be improved and refined. The authors suggested, however, that this type of data could support engineering discussions about how to anticipate and possibly mitigate fume events. In particular, oil pressures, duct temperatures, and engine power could merit further investigation. In this study, parameters were investigated individually; the authors stated that further analysis would be needed to determine whether interaction between parameters could be linked to fume events. The report authors concluded that statistical analyses of information from aircraft flight

data recorders could potentially provide useful information to support changes to aircraft systems.

57. QUESTIONS FOR THE COMMITTEE

i. What are Members' views on the methodological approach reported?

ii. Do Members have suggestions on additional factors that might be included in such analyses?

REPORT 3: Aircraft Cabin Air Sampling Study, Final Report Parts 1 and 2. Cranfield Research Report YE29016V. (Institute of Environment and Health, Cranfield University 2011) (ANNEXES 4a and 4b respectively)

58. The aim of this study was to undertake real time in-flight air sampling using the equipment identified as being suitable from the functionality tests (Report 1), and to obtain air samples from the flight decks of commercial aircraft in scheduled operation. In addition to the air sampling pumps, TD tubes, and PID recommended in Report 1, a gas monitor for carbon monoxide (CO) and an ultrafine particle counter were also used. Two institutions were involved in the air monitoring, with one organisation responsible for sampling while the other conducted analysis. Samples were transported via a third institution. Analysis was carried out by gas chromatography/mass spectrometry (GC/MS), using thermal desorption.

SAMPLING PLAN

Overall Sampling Strategy

59. The plan was to carry out air sampling on 100 flight sectors (flights), distributed equally among five different commercial carriers. Sampling was carried out over five periods of time, detailed in Annex 4a, page 6,Table 3, between September 2008 to February 2010. Five different aircraft types were involved: Boeing 757 cargo plane, and four types of passenger plane - Boeing 757, BAe 146, and Airbus A319 and A320/1. All Boeing 757 aircraft were fitted with RR RB211-535C engines and the BAe146 aircraft were all fitted with engines manufactured by Honeywell. The number of flights, aircraft types and tasks of the institutions involved are given in Annex 4a, page 4, Table 1. Information was not provided on the distance of sector and time of day which were previously identified by COT as relevant variables. Reasons for the selection of the flights used were not given by the study authors, nor was there an explanation of how representative the sample was of the airline industry as a whole.

60. A researcher travelled on each flight by prior arrangement with the airline. Samples were taken exclusively in the flight deck. A detailed schedule for sampling was provided to the researcher travelling on the plane (given in Annex 4a, page 6, Table 2), which included 10 phases of flight where samples were to be taken. A sample was taken by pumping air into a TD tube packed with adsorbent material. Air was sampled at a flow rate of approximately 500 ml/min for 5 minutes, giving a total sample volume of 2.5 litres. A small number of samples were of shorter duration, usually because of insufficient time within a given phase of flight. However, because the pump had a data logging capacity, the shorter samples could be identified, their actual duration calculated, and concentrations of the analytes of interest determined.

61. A second pumped air sampler was carried on each flight, identical in specification to the first. If an air quality event occurred during the flight, either

because a smell was reported or a warning came from the other monitoring instruments, the second sampler was to be started immediately to capture the compounds present at that time.

Post-Flight Questionnaire

62. The flight crew and cabin crew (if present) were requested to complete a post-flight questionnaire for all flights, which included questions concerning any fumes or odours they may have noticed during the flight. The same questionnaire was completed by the researcher conducting the air quality measurements.

Target Analyte List

63. The target analyte list consisted of the following 8 compounds:

i. TOCP, one of a number of tri-cresyl phosphate isomers
ii. Other TCP isomers, meta- and para- isomers
iii. TBP, a component of hydraulic fluid
iv. Toluene, a widely occurring VOC which is a component of petroleum based fuels
v. m+p xylene, often occurring with toluene
vi. Limonene, widely used as a fragrance in cleaning products
vii. Tetrachloroethylene (TCE), a solvent used in cleaning products
viii. Undecane, present in fuels

64. A wide range of chemicals were detected in the functionality test, including TCP isomers, TBP, toluene and m+p xylene, and in engine bleed air studies considered previously by COT. The study authors agreed the list of target analytes at the outset of the study. Their rationale was that the list included chemicals indicating sources of hydraulic fluid, aviation fuel and consumer products known to occur widely in indoor environments.

METHODOLOGY

Equipment

TSI Model SP730 air sampling pump and stainless steel sorbent tubes

65. One pump was used to take a series of air samples at each of ten phases of flight, as detailed in Annex 4a, page 6, Table 2. The stainless steel sorbent tubes used to take the air samples were packed with quartz wool and Tenax TA.

66. A second TSI Model SP730 air sampling pump, with an identical configuration to the first, was also carried in the flight deck to be used exclusively for sampling any air quality events. If the other monitoring equipment registered a change potentially indicative of a fume event, or if a

smell was reported by the crew or noticed by the technician, then a sample would be collected using this second pump.

Ion Science FirstCheck+5000 photoionization detector, with a four-channel gas monitor

67. The FirstCheck+5000 was a sensitive monitor capable of measuring in parts per billion (ppb) but the Secretariat noted that its utility was not verified in the functionality test. The PID responds to VOCs in the air, and provides a measure of Total VOC concentration. It also contained a gas monitor to detect carbon monoxide (CO) by an electrochemical cell. The range of CO that could be detected was 0.1-1,000 ppm. Monitoring was continuous throughout each flight at a sampling interval of one second.

TSI Model 8525 P-Trak ultrafine particle counter

68. This instrument was a condensation particle counter, able to detect and record particles with a diameter in the range of 0.02-1.0 µm. The size range included particles that are classified as both fine and ultrafine particles, ultrafine being less than 0.1 µm in diameter. Particle count was logged throughout each sector at a sampling interval of one second.

Thermal desorption and use of Tenax tubes

69. The Secretariat noted that the TD sampling matrix had been changed from that tested in the functionality tests (Tenax and Unicarb) (Annex 2) to one which had not been tested for purpose (Tenax and quartz wool). The study authors reported that sorbent tubes containing Tenax TA had been shown to effectively trap particles in the size range 0.020-0.700 µm, quoting Jamriska and Uhde (2003), and they referred to ISO 16000-6 as advising that quartz wool enhances collection and recovery of SVOCs, particularly those above C22. They reported that their method for sampling and analysis was based on the guidance in the international standards ISO 16000-6 and in BS EN ISO 16017-1.

70. The study authors presented a table of breakthrough volumes of Tenax for five out of eight of their analytes, showing calculated volumes in excess of their sampling volume of 2.5 litres, and considered that this indicated the compounds were well retained on Tenax (Annex 4a, page 10, Table 3a). They provided examples from literature to support the use of Tenax for the other compounds of interest (Annex 4a, page 10). The study authors recognised, however, that the retention of organophosphates on Tenax TA has not been so well investigated, particularly at the high flow rates used in their study (Annex 4a, page 10).

Inter-Laboratory Agreement

71. Sampling and blinded analysis were undertaken by different laboratories to minimise bias and the data re-collated by the contractor with

sector record forms and instrument data-logs. It is unclear from the report which data were used in the final analysis of the results.

72. The analysis was undertaken by two laboratories and the study authors reported that it was important to investigate the comparability of the two sets of data. The authors stated that instrumentation between the two laboratories differed in the mass spectrometer used by each institution. The inter-laboratory comparisons are reported in Annex 4a, pages 73-82, with the 2009 comparison reported in pages 77-82. Out of 7 spiked tubes, one tube had outlier values for several of the analytes tested, with no explanation available for this result. The authors referred to the possibility of contamination before spiking, or during transport or storage. This could give rise to some uncertainty in the interpretation of some of the high values obtained in the study.

Analysis of Blank Tubes

73. During each flight at least one sorbent tube was identified as a blank, and a total of 185 blank tubes were analysed along with the sample tubes from the 100 flights. The results of the analysis of blanks are presented in Annex 4a, page 91. The authors decided, however, not to use the 'generally low blank levels' to adjust the measured values during the flights, and the blank values were not deducted from the analyte values obtained.

RESULTS

Chemicals Determined by TD/GC/MS

All data *(all flight phases for all flights)*

74. A total of 981 samples were collected and analysed. Mean values and percentiles for VOC/SVOC concentrations for all samples, for all 100 flights and all flight phases, were calculated. The results for each analyte were presented in terms of the arithmetic mean, standard deviation, and minimum and maximum values, as well as percentile values from the distribution of data points. Table 4 in Annex 4a, page 12, presents these statistics for all flights, and cumulative frequency diagrams are given on pages 84-88. The most striking observations were that the most abundant chemicals were limonene and toluene, and that the concentrations of TCPs were below the limit of quantification for over 95% of samples.

Each flight *(based on mean of measured values during each flight)*

75. The mean and percentile concentrations were calculated for each target analyte, based on their mean concentration during each flight, and are presented in Annex 4a, page 13, Table 5. The highest values were again recorded for limonene and toluene.

Each phase of flight *(based on percentile, mean, minimum and maximum of each flight phase)*

76. This section of the report presented the mean and percentile concentrations of each analyte across all flights by phases of flight (Annex 4a, pages 14-22). Eleven distinct phases of flight were identified. A sample duration of 5 minutes was selected for each phase. Some phases were of shorter duration than 5 minutes, and where this occurred, the data were allotted to the phase during which sampling was initiated. For TOCP, the highest mean levels occurred during the climb phase (0.24 µg/m^3, page 14). For other TCPs, the highest mean levels occurred during pre-landing (0.32 µg/m^3, page 15). For the majority of the analytes, the highest mean levels occurred during first engine start: TBP (2.06 µg/m^3, page 17); toluene (26 µg/m^3, page 18); m+p xylene (3.77 µg/m^3, page 19); TCE (0.89 µg/m^3, page 21); undecane (4.49 µg/m^3, page 22). For limonene, the highest concentration occurred during taxi out (16.46 µg/m^3, page 20). The results for the mean concentrations by phase of flight are presented as box plots in Annex 4a, pages 93-97. It is possible that in some instances the mean may be driven by one or two high values or outliers.

Each part of study *(i.e. aircraft type, based on all measurements in flight)*

77. Concentrations of the analytes are presented for each of the five aircraft that were used for testing, and the data are shown in Tables 8a-e in Annex 4a, pages 23-25. The mean concentrations of analytes, and 95% Confidence Intervals, are shown in graphs on pages 99-103, and as box plots, including also the phases of flight, on pages 105-110. Part 1, the Boeing 757 cargo plane, had the highest mean concentration of TBP in all stages of flight (page 105). It also had the highest values for mean concentration of other TCPs and TOCP out of all five planes (page 100, Figure K1-3). Part 3, the Airbus A320/1, recorded the highest mean concentrations of limonene and undecane (page 102, Figure K1-7, and page 103, Figure K1-8). The highest mean TCE concentration was recorded for Part 5, the Airbus A319 (page 102, Figure K1-8), and also the highest mean concentration of m+p xylene (page 101, Figure K1-6).

Air Quality Events (Fume Events)

78. Thirty air quality events occurred over the course of the study. These were distributed over 25 flights. Of the 30 events, concentration data were available for 25. Information on the other 5 was not available for various reasons (Annex 4a, page 22). The details of the events are given in Annex 4a, page 23, Table 7. Twenty-one flights experienced a single air quality event, three experienced two, and one flight had three events recorded. The highest number of events recorded was on the BAe 146 (11 events). The other four types of aircraft recorded 4 or 5 events each. Apart from events that occurred during ‘taxi-back’, which occurred at various times after landing and often with the aircraft parked and the doors open to ambient air and odours, the highest number of events occurred during engine start and take-off. Notes on the sampling record form by the researcher on the plane

reported the presence of an 'oily' odour or 'fuel smell' for 19 of the air quality events. The other reports were of changes in the Total VOC or ultrafine particle number as reasons for initiating the sample. It is unclear from the report whether those aboard the aircraft were unaware of any change in air quality where sampling was commenced in response to instrumentation signals.

Ultrafine Particle Count

79. Numbers of ultrafine particles in the cabin air were monitored during each flight by a P-Trak ultrafine particle counter, and a value was logged each second. A summary of the findings is presented in Annex 4a, page 27, Table 9. Mean, minimum and maximum values were recorded for each flight. Table 9 presents some large ranges of particle number, and records 65 flights with values in the maximum range of 100,001 - >500,000 particles/cm^3. It is stated that 5 of these flights had counts over 500,000 particles/cm^3, beyond the range of detection of the instrument. Three of these highest readings occurred on the Boeing 757 cargo plane, and two on the BAe 146 aircraft.

80. A summary of ultrafine particle counts for flights with an air quality event is presented in Annex 4a, page 28, Table 9A. Nineteen out of the 25 flights with an air quality event with concentration data had values recorded in the maximum range of 100,001 - >500,000 particles/cm^3, although the authors reported that none of these exceeded the 500,000 particles/cm^3 limit of the instrument.

81. The data presented in the report did not indicate how the concentrations of specific target analytes linked with the recorded peaks in ultrafine particle numbers, nor whether peaks in the concentrations of individual contaminants occurred simultaneously or individually.

Total VOC by PID

82. Total VOC readings were logged continuously each second during the flights, using the FirstCheck+5000 detector. Peak concentrations of more than 10 ppm were recorded on 19 flights (Annex 4a, page 29, Table 10), but only one air quality event was recorded from these 19 flights. Thirteen out of the 19 peak concentrations occurred during the 'immediate / taxi-out' phase of flight. Overall, the authors stated that the VOC PID data was not a clear indicator of air quality events. They gave one example (Annex 4a, page 30, Figure 4) where they thought there was some evidence for an association between the PID value and report of an oily smell, but also stated that other data showed no evidence of an increase in Total VOC concentration coincident with a reported air quality event. There was also concern that some of the highest PID readings may have reflected isopropyl alcohol released by the P-Trak instrument, which was often in close proximity for logistical reasons.

Carbon Monoxide (CO) by Electrochemical Sensor

83. CO readings were logged continuously each second during the flights. The number of values recorded in ppm are summarised in Annex 4a, page 31, Table 11. There were 7 flights on which maximum concentrations of ≥3 ppm were recorded. On two of these flights, the researcher reported an air quality event. For one of these, the peak of 5 ppm occurred during taxi out and take off, and not during engine start. On the second, a peak of 7 ppm occurred during taxi back, and finished immediately before the collection of an air event sample in response to fuel odour when the doors were opened. The authors commented that there did not seem to be a direct link between CO peak and an air quality event.

Questionnaire Reports of Fume/Smell Events

84. At least one questionnaire was completed for 96 out of the 100 flights, and the total number completed was 552. Questionnaires were completed at the end of the flight and by all crew members, not only those present on the flight deck where air sampling was conducted.

85. A total of 38 flights had fumes/smells reported on the questionnaire by at least one crew member or researcher, which was greater than the number of air quality events (30) identified by the researcher in the cockpit conducting the sampling. The authors commented that the discrepancy may have been due to the location of individuals in the plane, as fumes/smells may have been experienced differently by persons in different parts of the aircraft.

86. Some flights had up to three people reporting a smell/fume, and others only one. A total of 60 questionnaires contained a report of the occurrence of a smell/fume during the flight. Some flights had reports of smells in more than one phase, others only in one. The greatest number were reported to have occurred during engine start, taxi out and take off. Four of the fumes/smells were reported by respondents to have a 'health effect', which in all cases was a headache/slight headache.

87. The main descriptor for the smell was oil or oily smell, which was used in 26 questionnaires. However, none of the fume/smell events reported in the questionnaires triggered the formal airline reporting mechanism.

COMPARISON OF RESULTS TO STANDARDS AND GUIDELINES

88. The authors referred in the report to the European standard BS EN 4628: 2009, which specifies limits for CO and toluene on aircraft. They stated that CO levels did not exceed 10 ppm, which is the 8 hour health limit specified, and that levels of toluene were well below the comfort limit of 153 mg/m^3, the maximum concentration of toluene measured during flight being 0.17 mg/m^3.

89. UK workplace exposure limits (WEL) set by the HSE are reported in Annex 4a, page 36, Table 14 for xylene, TCE, TBP and TOCP. All concentrations measured in the study were well below these limits, the closest

being 0.02 mg/m^3 for TOCP during the climb phase of a flight in Part 2, which was still below the 8 hour WEL of 0.1 mg/m^3 for TOCP.

90. Indoor air quality guidelines are reported in Annex 4a, page 37, Table 15 for limonene, TCE, toluene, xylene, and CO. Measured concentrations of TCE, xylenes and toluene did not exceed any of the guideline values; one measurement of limonene during Part 3 of the study exceeded the long term exposure limit for a short time (540.3 µg/m^3, compared to 450 µg/m^3 as the recommended exposure limit). CO levels did not exceed the BS limit described previously.

91. The report described results of a national survey of indoor pollutants in homes conducted during the 1990s (Annex 4a, pages 38-39). The survey reported concentrations of toluene, xylenes, undecane and limonene in indoor air in homes. The cabin air measurements were found to be lower or of similar magnitude; for example, the 95th percentile measurement for toluene in bedrooms of English homes was reported to be 74.9 µg/m^3 (Annex 4a, page 38, Table 17), while the 95% measurement for toluene in the cabin air study was 50.1 µg/m^3 (Annex 4a, page 12, Table 4). The authors concluded that, broadly, concentrations of these chemicals were of similar magnitude to those reported to occur in homes in developed countries.

CONCLUSIONS

92. The cabin air sampling study completed a range of air quality measurements in five aircraft types for a total of 100 flights. The COT in their statement (Annex 1) estimated the number of flights required for exposure monitoring per airframe/engine type of more than 100 sectors for background monitoring, and considered that several thousand flights (10,000-15,000) would need to be monitored to have a high degree of confidence of including an engineering-confirmed fume incident for a particular airplane/engine combination (Annex 1, paragraph 69).

93. Thirty-eight flights out of the hundred had fumes or smell reported by at least one crew member or researcher in a post-flight questionnaire, although only 30 air quality events were identified by the researcher in the cockpit conducting the sampling. From the sorbent tube samples for VOCs/SVOCs collected by the researcher during these events, it was seen that concentrations of the target analytes were not elevated compared with the routine samples collected in each respective phase of flight (Annex 4a, pages 14-22, Tables 6a-6i, 'AQ event'). There was some evidence of an occasional association between occurrence of peaks in the total VOC concentration and some events, but many peaks occurred during flights without being associated with an event.

94. The mean concentrations of some of the target analytes (toluene, xylenes, TCE, undecane) showed a trend with the phase of flight, with minimum values occurring during the main phases of flight (climb to descent),

and higher values on the ground and during take-off. The trend was not seen for limonene, TOCP, or the other TCP compounds measured.

95. Concerning specific measurements, the following conclusions were made:

- the most abundant target VOCs/SVOCs were generally limonene and toluene
- mean total VOC concentrations measured by the PID were mostly below 2 ppm. There was evidence for a rise in total VOC concentration coincident with two reported air quality events, one of which was equivocal.
- mean ultrafine particle numbers were generally in the range 1,000-100,000 particles/cm^3; on 5 flights the peak concentration exceeded the maximum range of the instrument of 500,000 particles/cm^3.
- maximum CO concentrations were mostly below 2 ppm, and peak concentrations of ≥3 ppm recorded on 7 flights were not associated with reported air quality events.

96. In comparison with standards and guidelines, recorded levels of CO and toluene did not exceed the limits described in the European standard. No concentrations of xylenes, TCE, TBP or TOCP exceeded the WELs. Based on data for VOCs in indoor air in buildings, the concentrations of toluene, limonene, xylenes, undecane and TCE in aircraft cabin air were of similar magnitude to those occurring in homes in developed countries.

97. There appear to be gaps in the data of the report in the following areas:

- reasons for the selection of the flights used were not given
- no explanation was provided as to why analysis was restricted to only 8 compounds in the cabin air study when according to COT discussion paper TOX/2007/20 Annex 4, engine bleed air data for a set of tests on engine model ALF502R-5 were able to identify around 90 compounds, including alkanes, alkenes and aldehydes.
- with regard to methodology, the real-time information from total VOC readings, CO monitoring and ultrafine particle count has not been analysed as a single dataset

98. In summary, samples taken specifically during recorded air quality events did not have notably elevated concentrations of any of the target analytes, and there was no evidence, from the conditions experienced in this study, of the target pollutants occurring in cabin air at levels exceeding available health and safety standards and guidelines.

99. QUESTIONS FOR THE COMMITTEE

i. Do Members have any general comments on the design and analysis of the reported study?

ii. Do Members agree with the report authors that there was no evidence for any differences between background concentrations of the analytes measured and the levels reported during air quality events?

iii. Is there any evidence for air contamination by engine oil/hydraulic fluid on the B757 cargo and passenger planes (Parts 1 and 2 of the study), as suggested in the graphs in Annex 4a, pages 99-100, Figures K1-1 to K1-4, and Tables 8a/8b on pages 23-24?

iv. The report authors have stated that retrospective evaluation of the chromatography data for other air contaminants would be possible (Annex 4a, page 42, 'Further work'). Do Members require further evaluation of the data? If so, which compounds should be selected for evaluation?

v. Do Members agree the conclusions reached by the authors of the report?

REPORT 4: Cabin Air – Surface Residue Study. IOM Research Report TM/11/06. (Institute of Occupational Medicine 2012) (ANNEX 5)

100. This study was commissioned by DfT to complement the cabin air sampling study. The aim of the study was to measure and characterise residues on the internal surfaces of aircraft and other comparable control environments, and to interpret the data in relation to the possible sources of contamination. It was thought that information on chemical surface residues could be an indication of previous fume events. Four organophosphate (OP) compounds were studied: TBP, TCP, butyl diphenyl phosphate (BDPP), and dibutyl phenyl phosphate (DBPP). These four chemicals were chosen because they are common SVOC additives of aircraft lubricants and fluids. The control locations chosen were at airports and in offices.

METHODOLOGY

101. Development and validation of the sampling and analytical methods was undertaken. Analysis was carried out using gas chromatography/mass spectrometry (GC-MS) on a Shimadzu QP2010S instrument. Skydrol hydraulic fluid, commonly used by airline companies, was chosen as the calibration standard for the compounds DBPP and BDPP. A potential problem of contamination of sampling equipment by OPs from the general environment was identified, and low levels of TBP were found on the glass fibre filters to be used for sampling. All batches of filters were therefore washed with ethyl acetate before use.

Removal Efficiency and Absorption Efficiency

102. A number of spiked samples were prepared to check the ability of the glass fibre filters to adsorb acceptable amounts of the desired surface contaminants when wiped across a test surface. Removal efficiencies ranged from 82-100% for the four OP compounds when they were deposited on clean glass plates (Annex 5, page 11, section 4.1.2). Removal efficiencies were lower, however, when samples were removed from plastic surfaces, similar in composition to those found in aircraft fasciae, and ranged from 14-100%. The lowest values related to one plastic in particular.

103. Desorption efficiency of the analytical method was also determined by analysing spiked samples by gas chromatography to identify how much analyte could be recovered. The percentage recovery was lower for TBP and DBPP (59-84/89%) than for BDPP and TCP, which had recovery percentages in the 90s and up to 100% (Annex 5, page 12, section 4.1.3).

OP Stability on Different Surfaces

104. Samples of the four OPs were spiked onto a variety of different plastic surfaces to provide information on the residence time of the materials. It was found that, in general, small but detectable amounts of OPs were detected in analysed samples after 14 days, but much less compound, typically only

about 10%, was present after 21 days. The results suggested that the sampling method would detect any deposits from fume events which had occurred during the previous 14 days, but that after 21 days the recoverable amounts would be very low. The study authors considered that the capture method was appropriate with a maximum of 14 days between collection of initial and follow-up samples.

Analysis of Duplicate Samples by External Laboratory

105. To achieve comparability of analytical methods with the Cranfield cabin air study (Report 3), spiked and 'duplicate' real samples were also sent to one of the laboratories that had been involved in the Cranfield University analyses. These were prepared during the validation phase as well as the sampling periods.

Participants

106. A total of seventeen aircraft, five airport-based vehicles (controls) and two offices were evaluated in the study. The aircraft types sampled were the B737, B757, B767, Airbus 320/321 and one BAe 146 plane. This BAe 146 aircraft carried a large amount of scientific equipment in its rear compartment, and around 20 scientists on board, so was considered unrepresentative of the standard passenger-carrying BAe 146 that was originally sought, but it was included to provide additional data.

SAMPLING STRATEGY AND METHOD

107. Samples were taken both from the flight deck and from the passenger cabin in the aircraft. The locations chosen were relatively smooth surfaces and in areas where surface contact by crew or passengers was considered unlikely. All samples were taken while the aircraft were stationary on the apron, with the majority carried out during flight turnaround periods. Surfaces chosen in the control vehicle and office environments were also relatively smooth, and in areas where there was unlikely to be any disturbance by the occupants. An additional sampling method was undertaken on some sites, where multiple wipes were taken from the same location to determine removal efficiencies from different surfaces at that site. This provided a comparison with removal efficiencies measures in the lab.

108. Statistical regression methods were used to examine associations between levels of TBP, TCP, BDPP and DBPP and type of aircraft or control site, and locations within the aircraft (cockpit or rear). Comparisons of results between laboratories were carried out using paired t-tests, and statistical regression methods.

RESULTS

109. Data were available from 6 sites – 4 airports and 2 control sites. Seventeen aircraft (of five different types), five airport-based vehicles (of two different types), and two offices were included for sampling. A total of 86 samples were collected and analysed for TBP, DBPP, BDPP and TCP.

110. On most aircraft, samples were taken on two occasions, usually two weeks apart. The first sample provided a 'baseline' amount, while the second would represent residues accumulated over the 2-week time period. As the number of flights flown between the two sampling periods was known for most of the planes, a further analysis was made where the 'amount per sector (flight)' could be calculated.

Mean Amounts of TBP by Aircraft Type

111. The limit of detection (LOD) for TBP was 3.3×10^3 ng/m^2. The average mass recovered from the first wipe per area for each of the 86 samples is shown in Annex 5, page 18, Table 3. Results for the B737 aircraft type and for the building control sites were below the level of detection. The highest recorded mean amount was for the BAe 146 plane, 9.3×10^4 ng/m^2, but since the aircraft type was only seen at one site, and the site had only this type of plane, it was not possible to attribute the high level either to the plane type or to the particular site. The next highest mean amount, 5.1×10^4 ng/m^2, was for the Airbus 320. The differences between aircraft types were found to be statistically significant. The distribution of TBP by aircraft / control type is shown, on a log scale, in Annex 5, page 19, Figure 1. The study authors reported that levels in aircraft and control vehicles were also significantly higher than in buildings.

Mean Amounts of DBPP and BDPP by Aircraft Type

112. The results for DBPP and BDPP showed similar patterns to those for TBP, with higher levels detected in aircraft than in control vehicles and buildings (Annex 5, pages 20 and 21). The authors reported that the difference between aircraft and buildings was statistically significant. However, only 2 buildings were sampled. Mean levels in the BAe 146 aircraft were again higher than in the other aircraft types (7.4×10^5 ng/m^2 for DBPP and 1.3×10^5 ng/m^2 for BDPP).

Mean Amounts of TCP by Aircraft Type

113. The mean amounts measured were similar in buildings and control vehicles (mostly <LOD, with one value of 3.0×10^4 ng/m^2), and somewhat higher in aircraft, with the highest recorded mean amount being 3.9×10^4 ng/m^2 in a B757. The levels in B757s were reported to be significantly higher than in other types of aircraft (Annex 5, page 22, Table 6).

Different Locations w ithin Aircraft

114. For all four substances, samples from the passenger compartment of the Boeing and Airbus aircraft were significantly lower than in the cockpit area,

though the reduction was less significant for TCP. For TBP, a larger difference between the cockpit and rear was observed for the Airbus, as compared to the Boeing aircraft (cockpit 6.4 x 10^4 ng/m^2, rear <LOD, Annex 5, page 23, Table 7). The differences for DBPP and BDPP were also highest for the Airbus, followed by the Boeing 757. For TCP, there were no statistically significant differences between plane types. In the BAe 146 aircraft carrying electronic equipment, the levels of TBP, DBPP and BDPP were higher in the rear than in the cockpit.

Analysis of Second Samples

115. In the analysis of the second set of samples only (that is, the samples taken on the second site visit, usually 2 weeks after the first; these samples were taken to determine if there had been any deposition of surface residues in the interim period between visits), there were no statistically significant differences seen between aircraft, control vehicles and buildings for TBP, BDPP and TCP. For DBPP, levels in aircraft were higher than those in buildings.

116. Differences between the cockpit and rear of the aircraft varied significantly by aircraft type for TBP, DBPP and BDPP, with reduction in levels in the rear of the plane significantly greater in the Airbus planes, as in the first set of samples. The amounts detected for all four substances were higher in the rear of the BAe 146 aircraft than in the cockpit.

General Observations on the Analysis of Samples

117. Over the whole period of on-site sampling, it was estimated that around 450 flights were flown in total by the aircraft participating in the study. No fume events were reported in the period between the first and second set of samples. Several events describing odours were traced to on-board ovens, or other non-engine/hydraulics related issues.

118. The amounts of TBP, DBPP and BDPP detected in the initial samples were on average higher than those collected on the subsequent site visit. The initial samples gave an indication of surface residues that had accumulated over time. The second set of samples were considered by the report authors to reflect general deposition of particulate in the intervening time period, and not any specific episode of contamination, since no fume events had been reported. The authors indicated two potential sources of inaccuracy in their sampling results: particulate matter may enter aircraft from the external airport environment, which would tend to increase the levels of residues found on wipes; and the second set of samples may have contained residues that were not completely removed by the first sampling, so not all the recovered residues might have been deposited in the intervening 2-week period between first and second sampling.

FACTORS AFFECTING THE SAMPLING RESULTS

Wipe Sampling Method

119. Several difficulties were encountered during the sampling process. Firstly, the wipe sampling method had achieved satisfactory recoveries during the laboratory-based validation process, with known amounts of analyte in ethyl acetate solution being spiked onto a glass plate, and removed in a standardised manner. Sampling in aircraft cabins and vehicles was more challenging, however, as the majority of surfaces were formed from plastics or polymers rather than glass, and the ethyl acetate carrier solution may have damaged surfaces besides collecting the wipe samples. It was therefore possible that OPs contained within the surface materials may have been dissolved and captured during the sampling.

Interferences and Background Contamination

120. The authors referred to difficulties in the determination of very low levels of OPs in air, as there is potentially interference from background levels of OPs within the general environment, from their use as flame retardants, plasticisers and general product additives. Background interference in IOM's laboratories was found, as significant levels of all four compounds were detected in marker pens used on glassware. TBP was detected in the glass fibre filters during the validation process. All the filters were therefore cleaned with ethyl acetate in an attempt to overcome this problem.

121. Contamination of some laboratory blank filters was found, with low levels of all four OP compounds. For the affected batches, it was impossible to differentiate between blank contamination and material gathered during sampling. The source of contamination could not be identified, and could not be corrected for because it was not systematic. Contamination with TCP was considered most significant, and some of the less reliable TCP results were excluded from the statistical analysis.

Electronic Equipment and Aircraft Cleaning Regimes

122. The report authors noted several studies where TBP was detected in surface wipes taken from office computer covers and screens (Annex 5, page 30, section 6.3.1 (i)) and suggested there may be a contribution to TBP levels from emissions from electronic equipment. This might help to explain why levels determined on cockpit surfaces were generally higher than levels in passenger areas. It might also explain why TBP levels in the BAe 146 aircraft were, by contrast, greater in the rear of the plane, since a large amount of scientific and analytical equipment was carried on this plane in the rear.

123. The authors also remarked that cockpits on aircraft are not cleaned routinely, to minimise the risk of contact of water or other cleaning materials with the electrical and electronic equipment. In contrast, passenger areas are cleaned regularly. Surface deposits are therefore less likely to be removed from cockpit surfaces than from the passenger cabin. This cleaning regime may be a further reason why residue levels were in general found to be higher

in the cockpit than in the rear of the plane, with the exception of the BAe 146, which carried electronic equipment in the rear.

Contribution to OP Levels from External Sources

124. The mean amounts of TBP, DBPP and BDPP detected in all of the types of aircraft studied were similar to those determined in the airport-apron based control vehicles. The study authors considered the likelihood of a contribution to the air within aircraft from the exhaust emissions of other aircraft taxiing or sitting at a gate. They commented that similar ingress of aircraft exhaust emissions is likely to occur also in vehicles operating close to aircraft.

Discrepancies in Inter-Laboratory Findings

125. For 27 of the 86 samples taken, analyses of the four substances were also carried out by an external laboratory. The results were consistently around 1.5 times higher than those reported by the IOM. At the very low levels being measured, the research authors considered that this was not significant and would not lead to a fundamental change in the estimated airborne concentrations which they calculated. They stated the discrepancy may be due to different desorption techniques used by the two laboratories.

ESTIMATED MAXIMUM AIRBORNE CONCENTRATIONS OF TCP AND TBP

126. An estimation was made, from the measured surface amounts, of the theoretical maximum airborne concentrations of TCP and TBP. Calculations were carried out using the maxima of the total of all the wipe samples taken for each aircraft type; they included samples where the TCP amounts were likely to have been reported as significantly higher than the actual amount because of blank contamination, so that a worst case assessment of airborne concentration could be made. The report authors were not able to differentiate analytically between the isomers of TCP, but estimates for TOCP and mono-ortho cresyl phosphate were made using the measured maxima and assumed amounts of the two isomers derived from the literature on oil composition (Annex 5, page 34, paragraphs 5-8), and the results of the calculations are presented on page 35, Table 13. The range of the estimated airborne concentrations of total TCP (all isomers) went from 0.9 µg/m^3 (on the Airbus) to 44 µg/m^3 on the B757. The authors stated that these estimated concentrations were in agreement with those reported in the Cranfield 2011 study for total TCPs (2.08-37.7 µg/m^3, values given in Annex 4a, page 12, Table 4).

127. Calculations for estimated airborne concentrations of TBP are presented in Annex 5, page 35, Table 14. Estimated concentrations ranged from 2.0 µg/m^3 on the B737 to 22 µg/m^3 on the B757 aircraft. A higher value of 41 µg/cm^3 was calculated for the BAe 146 plane. Apart from the latter, the values were again considered to be in agreement with those reported in the

Cranfield 2011 study, 1.96-21.8 µg/cm^3 (values given in Annex 4a, page 12, Table 4).

CONCLUSIONS

128. The report authors considered that the methods they used for collecting and analysing residues were appropriate for the project, although the very low levels of the four OPs of interest created difficulties in sampling and analysis. They also encountered difficulties from background contamination by OPs in the environment, and suggested that additional blank testing, before and during the site work, might have been helpful.

129. The study detected a range of OPs in samples of surface residues collected from a variety of aircraft types. The arithmetic mean data by type of aircraft ranged up to about 3 x 10^4 ng/m^2 for TCP, up to 1 x 10^6 for BDPP, up to 7 x 10^5 for DBPP and up to 9 x 10^4 for TBP. The amounts of all of the OPs detected on surfaces within aircraft and airport control vehicles were higher than those collected in offices. Cockpit levels of the OPs were generally higher than those in passenger areas.

130. The authors considered that maximum estimated airborne concentrations for TBP were low, between about 10 and 40 µg/cm^3. Ortho isomers of TCP could not be determined by their methods, but a theoretical concentration of TOCP was estimated from TCP levels obtained and using data in the literature. The authors considered that maximum estimated airborne concentrations of TOCP were very low, between about 0.0001 and 0.0006 µg/cm^3. These estimated concentrations were in the range found in the aircraft cabin air sampling study (Report 3).

131. QUESTIONS FOR THE COMMITTEE

i. Do Members have any general comments on the design and analysis of this study?

ii. What are Members' views on the levels of the OPs found in the aircraft in this study and the reliability of the measurement?

iii. Do Members consider that the surface residue data suggest contamination occurred from emission of oil/hydraulic fluid into cabin air?

iv. Is it possible to make any assessment by plane type?

UPDATE OF LITERATURE REVIEW ON AIRCRAFT CABIN AIR ENVIRONMENT

132. A literature search was undertaken for the period January 2007 (closing date of the last review) - June 2013, using the search terms shown in Table 2, Annex 6, in the PubMed and Web of Science databases. Around 9,000 peer-reviewed references were retrieved through the database searches. Duplicates were deleted, and the titles were screened against the inclusion/exclusion criteria set out in Table 1, Annex 6. The selection criteria were applied first to the titles of retrieved papers; if the relevance was not clear from the title, the abstract of the paper was evaluated. A list of papers for which the abstracts were considered is provided in Annex 7.

133. From the PubMed and Web of Science searches (Table 2, Annex 6), nine papers appeared to fulfil the selection criteria focussing on exposure monitoring of the cabin air environment in aircraft. Eight of these (Allen 2012, Allen 2013, Christiansson 2008, Denola 2008, Denola 2011, Rosenberger 2013, Solbu 2010, Solbu 2011) reported original data concerning potential contaminants of indoor air on aircraft. One (Chaturvedi 2011) was identified as a review, and the list of references scanned for any further relevant material. No further relevant references were identified.

134. The full text was obtained for the eight relevant papers. When the abstract was read for the Solbu 2010 paper, it was clear that the study concerned exposure of ground personnel at airports to emissions present in outdoor air, not in the aircraft cabin, and that it therefore did not fulfil the selection criteria. It was not evaluated further. The Rosenberger 2013 paper was published in German, so only the abstract has been evaluated. The remaining relevant papers are summarised in the following section.

Laboratory Investigations on the Pyrolysis of Jet Oils

135. The Denola 2008 study concerns the toxicity of ortho-cresyl phosphate isomers of TCP. The authors state that aircraft turbine engine oil contains TCP at concentrations of 2-3%. There are 10 possible structural isomers of TCP, with the maximum allowable human exposure to TCP based on the toxicity of the tri-o-cresyl isomer. In their investigation, the authors separated 9 out of the 10 isomers of TCP using a sensitive technique of pulsed flame photometric detection. They extracted and analysed isomers from 4 samples of aircraft turbine engine oils, and also used a calculation method to check their findings. The concentrations of TOCP and the di-o-cresyl phosphate isomers were found to be below the level of detection, whereas the mono-o-isomers were in the range of 13-150 mg/kg. The authors stated that, because they were able to analyse for the mono-o-cresyl isomers, they found them to be the predominant ortho isomers present, more abundant than the tri-cresyl isomer. They stated that the mono-o-isomers are regarded as the most toxic of the isomers of TCP, and therefore suggest that the measure of toxicity of TCP could be based on the presence and quantity of the mono-o-isomers, rather than the quantity of the less toxic tri-o-cresyl isomer.

Exposure Data from Studies of Jet Aircraft

136. The aim of the Rosenberger 2013 study was to determine levels of mono- and di-ortho tricresyl phosphates in indoor air in aircraft, and to investigate the distribution of the 10 isomers of TCP in 90 air samples collected from two aircraft types and engine oil samples. Only the abstract was reviewed, as the paper is in German. Mono-ortho and di-ortho TCP were not detected. TCP was detected in only 15% of samples taken during normal flight operation, with levels in the range of 2-67 ng/m^3, which the authors say is in the concentration range of the limit of detection. The highest concentrations were recorded in one aircraft in the course of pilot training which included 50 cycles of touch down and go, and these concentrations were 65 ng/m^3 on the flight deck, and 61 ng/m^3 in the rear galley. The engine oils contained <20 µg/kg, or 0.02 ppm, of ortho-TCP per isomer. No other values are reported in the abstract.

137. The Solbu 2011 study considered OP exposure of flight personnel under normal flight conditions. The study included six different types of aircraft, including jet airplanes, from fleets in Norway. For the jet airplanes, two models of plane were used, designated Model A and Model B. The aircraft types were not specified. The aim of the study was to determine the contamination levels of OPs originating from hydraulic and turbine oils in aircraft cabin and cockpit air. The hydraulic oil used in both Model A and B planes contained 40-70% dibutylphenyl phosphate (DBPP) and 20% TBP. The turbine oil used in Model A planes contained <2.5% TCP, and that used in Model B planes 1-5% TCP.

138. Determinations of OPs from all the sampling methods used were performed by gas chromatography-electron ionization mass spectrometry (GC-EI-MS). A Varian VF-5ms capillary column was used for separation of OPs. The limit of detection of the method for OPs in solvent was 3 ng/ml. Total VOCs were determined using thermal desorption and GC-EI-MS, and specific components were determined only in cases where they were distinct in the chromatogram.

139. Several sampling methods were used. Active within-day sampling of OPs from cabin air was performed on both Model A and B planes. There were 30 individual Model A planes used for sampling, and 22 Model B aircraft. On both Model A and B planes, a combined filter/adsorbent method was used for OP collection: a glass fibre filter in a 37 mm closed-faced aerosol cassette was used to retain aerosols, and a Chromosorb 106 glass adsorbent tube to retain vapours. An in-house made pump was used to pump air at a flow rate of 1.5 l/min. Active VOC sampling was performed only on the Model B planes, with VOCs collected on stainless steel thermal desorption (TD) tubes packed with Tenax TA 60/80 mesh adsorbent material, at a flow rate of 50 ml/min.

140. For the active air sampling, samples were taken in Model A airplanes in the cockpit and in the aft galley. In Model B planes, samples were taken in the cockpit and the aft cabin. No fume events were reported on the flights during which sampling took place.

141. Passive long-term sampling was performed using three methods: wipe sampling, activated charcoal cloth sampling, and HEPA (High Efficiency Particulate Air)-filter analysis. This sampling was performed only on Model A planes. For wipe sampling, two aluminium tape wipe areas were established on the cockpit and galley walls in 26 different aircraft. The sampling area was wiped clean with two wipes, and the second sample analysed to ensure it did not contain OPs. The area was exposed for 1-3 months, then wiped, and the wipes were analysed. Two sampling areas were also established for activated charcoal cloth sampling, on the cabin wall in 26 individual planes. The charcoal cloths were exposed for 1-3 months, and were collected at the same time as the wipe samples. For the HEPA filters, new filters were installed into 6 airplanes and left untouched for 1-3 months. Then a 10 g spot sample was cut from the centre of each filter.

142. OPs from the filter samples were extracted with acetonitrile as solvent, giving nearly full recovery with a minimum of 96%. OPs from the wipe samples were extracted with dichloromethane, yielding a minimum recovery of 94%, whereas the activated charcoal cloths, using Zorflex FM50K cloth, were extracted using the optimum solvent combination that could be achieved of 100 ml/l dimethyl formamide in carbon disulphide. Recoveries of aryl phosphates ranged from 25-61%, but alkyl phosphates were nearly fully recovered, in a range of 94-98%.

143. In general, OP levels in the within-day air samples collected in the cabin and cockpit during commercial flights were low. The general limit of quantification for OPs in air was 0.075 µg/m^3. TCP was not detected in the within-day samples from jet airplanes. Other OPs originating from hydraulic oils, such as TBP, were more prominent, although levels were still low: for Model A planes the median was 1.1 µg/m^3, and min-max 0.41-4.1 µg/m^3, while for Model B planes levels were lower still, median 0.16 µg/m^3, and min-max 0.02-1.0 µg/m^3. DBPP levels were also lower in the Model B planes (median 0.046 µg/m^3, min-max <level of quantitation (LOQ) -0.31 µg/m^3) than in Model A planes (median 0.20 µg/m^3, min-max 0.07-0.77 µg/m^3).

144. Total VOC levels were measured on Model A planes only. The authors stated that the Total VOC level has been traditionally used as a general indicator of cabin air quality, and that levels have previously been reported in the range 0.01-4.4 mg/m^3. They reported that Total VOC levels in their study were of a similar order: median 0.72 mg/m^3, min-max 0.46-1.3 mg/m^3.

145. The long-term sampling by wipes was conducted only on the Model A aircraft. TCP was present in 31% of samples, with a min-max of <0.05-1.3 ng/dm^2 per day, median <LOQ. A much higher maximum value was found on the activated charcoal cloth (min-max <1.3-270 ng/dm^2 per day, median <LOQ), but was thought to be a result of contamination of the cloth from an unknown TCP-containing source, thus illustrating the potential vulnerability of the sampling method. DBPP was determined in nearly all wipe samples on the Model A planes, but min-max values were significantly lower for wipe samples (<0.05-20 ng/dm^2 per day, median < LOQ) than for the charcoal cloth (min-max 59-970 ng/dm^2 per day, median 210 ng/dm^2 per day).

146. In the Denola 2011 study the authors monitored TCP in cockpit air in three types of military aircraft: fighter trainer, fighter bomber and cargo transport planes. Only the data relating to cargo transport planes is relevant to this review, as the air conditioning systems in fighter planes are different. The aircraft chosen had a previous history of pilot complaints of fume events. In the cargo planes, crews had observed air contamination at high engine thrusts during take-off, and in ground engine runs at high power.

147. Nine different cargo transport planes were sampled, providing a total of 32 samples. As in the Cranfield study (Report 3), air samples were collected in the cockpit in flight. Denola and colleagues used Porapak Q and cellulose filters to sample aircraft air. Long duration in-flight and ground-based sampling was carried out using sorption tubes and a metring pump such as an Aircheck model 2000, operating at 2 l/min. The stainless steel tubes were packed with around 0.06 g of Porapak Q held in place with glass wool. Some samples were also collected during ground engine runs, with the aircraft in a fixed location on the ground, and air samples taken by the ground crew with the engines at high throttle. For short duration (5-20 minute) air sampling during the ground engine runs, PALL Corporation Metricel 0.8 μm membrane filters were used instead of sorbent tubes, with a battery powered diaphragm pump operated at high volume of 36 l/min.

148. Solvents used for extraction of TCP were iso-hexane and dichloromethane. Recovery of TCP from Porapak Q sorbent was 79-94.8% with iso-hexane and 96.6% with dichloromethane, and similar recoveries were observed for the filters, 76.4-95.6% with iso-hexane, and 95.3-98.4% with dichloromethane.

149. Of the 32 samples taken from cargo transport aircraft, only five showed levels of TCP > the limit of detection (LOD), value given for each measurement). Two of these levels were recorded during ground engine runs, and three in-flight. An odour was noticed on another flight, but no TCP could be detected then.

150. The highest concentrations in the cargo planes were recorded during ground engine runs (mean TCP air concentration 0.26 $\mu g/m^3$, LOD 0.009 $\mu g/m^3$, relative standard deviation (RSD) 6.33%). Tube samples taken from the same aircraft during ground engine runs, over periods of 6 and 2 hours, produced mean TCP concentrations of 0.255 $\mu g/m^3$, LOD 0.009 $\mu g/m^3$, (RSD 6.33%) and 0.123 $\mu g/m^3$, LOD 0.032 $\mu g/m^3$, (RSD 10.62%), respectively. In-flight concentrations taken during cruising were lower – the highest of the 3 mean TCP air concentrations was 0.05 $\mu g/m^3$, LOD 0.017 $\mu g/m^3$, (RSD 0.78%). The PHE Secretariat note that in comparison, the highest total TCP measurement in the Cranfield study was 37.7 $\mu g/m^3$. All measurements were well below the 8-hour time-weighted average exposure limit of 100 $\mu g/m^3$ for TOCP.

Flame Retardants in Cabin Air

151. Several recent papers have addressed the question of whether flame retardants are present in cabin air. In a study by Christiansson (2008), the authors describe the use of polybrominated diphenyl ethers (PBDEs) as flame retardants in a wide variety of consumer products, including in commercial aircraft where fire protection for passenger safety is required. The authors state that there is a concern over PBDEs because they readily adsorb to dust particles, and aircraft crew and passengers could potentially receive significant exposure through inhalation of those particles.

152. Nine adult subjects on intercontinental flights participated in the Christiansson pilot study. They hand-collected one or more samples of cabin dust during the flights on which they were travelling. The details of how this was undertaken are not given, and the paper does not describe what information or reasons for sampling were given to the participants. Four types of aircraft were involved: Boeing 777-200/300; Airbus 340-300; Airbus A330-300; Airbus A319. The dust samples were extracted by tetrahydrofuran solvent, and analysed by gas chromatography/mass spectrometry using an ion trap GCQ Finnigan Mat instrument.

153. Concentrations of eight PBDE congeners (BDE 28, 47, 99, 100, 153, 154, 183, 209) were determined in pmoles per gram of dust, and were compared to levels in household dust reported in scientific literature. The authors reported that cabin dust concentrations of PBDEs varied greatly between individual samples, apparently independent of aircraft type. They cautioned that the sampling procedure was not standardised, and the number of samples was small. PBDE concentrations in aircraft cabin dust samples were generally an order of magnitude higher than concentrations of dust in residences. The study authors reported, for example, BDE 47 had a median of 7,300 pmol/g, range 280-469,000 pmol/g in aircraft in the study (n=20), whereas in US household dust, n=20 (reported in the literature) the median was 840 pmol/g, range 170-6,800 pmol/g.

154. The Allen 2012 study in the US reported results of air samples collected on board in-flight aircraft, and analysed for four PBDE congeners, BDE 47, 99, 100 and 209. A total of 59 air samples were collected between 2009 and 2010, each from a different aircraft. Aircraft types are not given. Sorbent tubes containing polyurethane foam and XAD-2 sorbent were used to collect samples at various pumped flow rates; the tubes were maintained chilled until samples were extracted in dichloromethane or a mixture of hexane and dichloromethane. Analysis was by gas chromatography/mass spectrometry in the multiple ion detection mode using negative ionization.

155. The authors stated that a limitation in their method was the presence of detectable levels of PBDE congeners in the polyurethane foam used for sample collection, so data in the study were blank-corrected. Reporting limits were set as 3 times the standard deviation after blank correction, which led to reporting limits higher than those reported for other studies. They believed this might impact the percent of samples with detectable PBDEs, but not the overall findings of the study.

156. Results for maximum cabin air concentrations of PBDEs in ng/m^3 were compared with values reported in the peer-reviewed literature in industrial electronics facilities, offices, and residences. Overall, cabin air concentrations of BDEs 47, 99 and 100 were similar to concentrations in other occupational studies, but an order of magnitude higher than concentrations in offices and residences. As an example, median and maximum values of BDE 47 measured in the study were 1.3 ng/m^3 and 20 ng/m^3 respectively (95th percentile, 5.1 ng/m^3). Values reported for an electronic recycling plant in Sweden in a dismantling hall were a mean of 1.2 ng/m^3 and a maximum concentration of 2.1 ng/m^3. By contrast, in offices in Sweden and the UK mean concentrations ranged from <0.1-0.69 ng/m^3, and in US homes the mean concentration was 0.23 ng/m^3 with a maximum of 1.4 ng/m^3. For UK residences the median was reported as 0.09 ng/m^3, with a maximum or 1.3 ng/m^3.

157. The authors calculated an average daily dose for the four BDEs, and derived inhalation exposure limits for the congeners in the study for which published reference doses were available (BDEs 47, 99 and 209). They reported that the 95th percentile measured concentrations of PBDEs in aircraft air were <1% of the derived inhalation exposure limits, and concluded that the average daily dose of PBDEs would not be expected to exceed the health-based benchmarks set by the Environmental Protection Agency in the US.

158. The Allen 2013 study analysed dust samples collected in November and December 2010 on 19 commercial planes that were parked overnight at an international airport. The planes represented a wide range of manufacturing dates, from 1986-2008, and were from 5 manufacturers: Boeing, Airbus, Canadair Regional, McDonnell Douglas and Embraer. A total of 40 dust samples were collected, two from each aircraft for the 19 planes, and one plane was re-sampled. The authors analysed BDEs 28, 33, 47, 99, 100, 153, 154, 183 and 209. Apart from BDE 33, which was analysed along with BDE 28, the congeners were the same as those analysed in the Christiansson 2008 study. Dust samples were extracted with a hexane/dichloromethane mixture as solvent, and analysed by gas chromatography/mass spectrometry in electron capture negative ionization mode.

159. Dust samples were collected from two locations in the aircraft, the carpet and air supply return vents near the floor. In general, concentrations in dust collected from the vents were greater than those from carpet dust. Two major manufacturers, Boeing and Airbus, were compared: BDEs 47, 99 and 100 were higher in Boeing than Airbus planes, as well as BDEs 153 and 154, although the latter two did not reach statistical significance. BDE 183 was higher in Airbus planes. The types of Boeing and Airbus planes were not specified.

160. Concentrations of BDEs 47, 99, 100, 153 and 154 were found to be similar to concentrations in US homes, but slightly higher than concentrations in US offices (for example, for BDE 100, the median was 1100 ng/g of dust (range 36-180,000 ng/g) in airplanes, 440 ng/g (range 71-4,300 ng/g) in US

homes, and 200 ng/g (range 13-8,700 ng/g) in US offices). Concentrations of BDE 183 were higher than in homes or offices (median 490 ng/g (range 3.5-190,000 ng/g) in planes, 28 ng/g (range 1.7-230 ng/g) in US homes, 80 ng/g (range 15-13,000 ng/g) in US offices). For BDE 209, median concentrations were 22,000 ng/g (range 440-190,000 ng/g), an order of magnitude higher than in US homes, although ranges were similar (4,500 ng/g, range 790-180,000 ng/g) and US offices (4,200 ng/g, range 910-110,000 ng/g).

161. The Allen 2013 study authors concluded that their research adds to the limited body of knowledge regarding exposure to flame retardants in commercial aircraft. Their findings indicated that 100% of the dust samples they collected from aircraft contained some flame retardants. They found that concentrations of BDE 209, specifically, were elevated by an order of magnitude relative to residential and office environments, and suggested that more research is needed to further analyse their findings.

162. COT DISCUSSION

i. The Committee is asked to consider further the information presented in Annexes 2-8 and to address the questions posed for each study report within the discussion paper.

ii. Do Members have any comments on the new information from the published literature on contaminant levels in cabin air of aircraft?

iii. What overall conclusions can be drawn from the information provided in this report?

iv. Are there any major limitations or data gaps in the work undertaken to date? What are the major uncertainties?

v. In light of the work to date, could Members provide specific recommendations for further research in this area?

PHE COT Secretariat

August 2013

Annexes

Annex 1: Statement on the review of the cabin air environment, ill-health in aircraft crews and the possible relationship to smoke/fume events in aircraft. COT Statement 2007/06. September 2007.

Annex 2: Functionality test report (Institute of Environment and Health, Cranfield University 2008).

Annex 3: Oil smells in aircraft cockpits: findings of statistical analysis into associated parameters (Institute of Environment and Health, Cranfield University 2009).

Annex 4a & 4b: Aircraft cabin air sampling study, final report parts 1 and 2. Cranfield Research Report YE29016V. (Institute of Environment and Health, Cranfield University 2011).

Annex 5: Cabin air – surface residue study. IOM Research Report TM/11/06. (Institute of Occupational Medicine 2012).

Annex 6: Table 1. Literature search inclusion and exclusion criteria; Table 2. Literature search results

Annex 7: Literature considered as part of the review.

Annex 8: Publications: Solbu et al 2011; Denola et al 2011.

References

Allen, J. G., H. M. Stapleton, et al. (2013). Exposure to flame retardant chemicals on commercial airplanes. Environ Health **12**: 17.

Allen, J. G., A. L. Sumner, et al. (2012). Air concentrations of PBDEs on in-flight airplanes and assessment of flight crew inhalation exposure. J Expo Sci Environ Epidemiol.

Chaturvedi, A. K. (2011). Aerospace toxicology overview: aerial application and cabin air quality. Rev Environ Contam Toxicol **214**: 15-40.

Christiansson, A., L. Hovander, et al. (2008). Polybrominated diphenyl ethers in aircraft cabins--a source of human exposure? Chemosphere **73**(10): 1654-1660.

Denola, G., J. Kibby, et al. (2008). Determination of ortho-cresyl phosphate isomers of tricresyl phosphate used in aircraft turbine engine oils by gas chromatography and mass spectrometry. J Chromatogr A **1200**(2): 211-216.

Denola, G., P. J. Hanhela, et al. (2011). Determination of tricresyl phosphate air contamination in aircraft. Ann Occup Hyg **55**(7): 710-722.

Rosenberger, W., S. Netz-Piepenbrink, et al. (2013). Determination of mono- and diortho tricresyl phosphates in indoor air of aircraft. Gefahrstoffe Reinhaltung Der Luft **73**(4): 138-143.

Solbu, K., H. L. Daae, et al. (2011). Organophosphates in aircraft cabin and cockpit air--method development and measurements of contaminants. J Environ Monit **13**(5): 1393-1403.

Solbu, K., H. L. Daae, et al. (2010). Exposure to airborne organophosphates originating from hydraulic and turbine oils among aviation technicians and loaders. J Environ Monit **12**(12): 2259-2268.

Abbreviations

APU	auxiliary power unit
BALPA	British Airline Pilots Association
BDE	brominated diphenyl ether
BDPP	butyl diphenyl phosphate
CO	carbon monoxide
COT	Committee on Toxicity
DBPP	dibutyl phenyl phosphate
DfT	Department for Transport
ECS	environmental conditioning system
GC-EI-MS	gas chromatography- electron ionization-mass spectrometry
GC-MS	gas chromatography- mass spectrometry
HEPA	high-efficiency particulate air (filter)
HSE	Health and Safety Executive
IEH	Institute of Environment and Health
IOM	Institute of Occupational Medicine
LOD	limit of detection
LOQ	limit of quantitation
OPs	organophosphates
PBDE	polybrominated diphenyl ethers
PHE	Public Health England
PID	photoionization detector
ppb	parts per billion
ppm	parts per million

RSD	relative standard deviation
SPME	solid phase microextraction
SVOCs	semi-volatile organic compounds
TBP	tributyl phosphate
TCE	tetrachloroethylene
TCP	tricresyl phosphate
TD	thermal desorption
TMPP	trimethylolpropanephosphate
TOCP	tri-ortho cresyl phosphate
VOCs	volatile organic compounds
WELs	workplace exposure limits