

Comparison of the Constituents of Two Jet Engine Lubricating Oils and Their Volatile Pyrolytic Degradation Products

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Leaking oil seals in jet engines, at locations prior to the compressor stage, can be a cause of smoke in the cabins of BAe-146 aircraft. Compressed combustion air is bled off to pressurize the cabin and to provide a source of fresh air. Bleed air is diverted from a location just prior to the combustion chamber at a temperature around 500 °C. To prevent oil breakdown products from entering the cabin air, catalytic converters have been used to clean the air. During an oil seal failure this device becomes overloaded and smoke is observed in the cabin. Some aircraft companies have removed the catalytic converters and claim an improvement in air quality. During an oil seal failure, however, the flight crew is potentially exposed to the thermal breakdown products of the engine oils. Because very little is known regarding the thermal breakdown products of jet engine lubrication oils, two commercially available oils were investigated under laboratory conditions at 525 °C to measure the release of CO, CO₂, NO₂, and HCN as well as volatiles which were analyzed using GC-Mass spectrometry in an attempt to see if the neurotoxic agents tricresyl phosphates (TCPs) and trimethyl propane phosphate (TMPP) would be present or formed. TMPP was not found in these experiments. Some CO₂ was generated along with CO which reached levels in excess of 100 ppm. HCN and NO₂ were not detected. GC compositions of the two bulk oils and their breakdown products were almost identical. The presence of TCPs was confirmed in the bulk oils and in the volatiles. Localized condensation in the ventilation ducts and filters in the air conditioning packs are likely the reason why the presence of TCPs has not been demonstrated in cabin air. It was recommended that this needed to be verified in aircraft.

Keywords Jet Engine Lubricating Oils, Tricresylphosphates, TCP, TMPP, Pyrolysis, Neurotoxins, Inhalation Exposure, Aircraft Air, Air Quality

The presence of smoke in the cabin has been classified as a pilot's nightmare.⁽¹⁾ It was therefore not surprising that episodes of smoke in the cabin during flight of a number of BAe-146 aircraft raised the anxiety of the flight crews exposed.⁽²⁾ Eventually the source of the smoke coincided with the recent use of a less expensive engine oil, Castrol 5000, which did not appear to be as compatible with the engine oil seals as Exxon 2380 which was used prior to oil switching. This resulted in excessive amounts of engine oil leaking into the compressed airstream. Under normal conditions air from the compressed engine combustion air is bled off and used for ventilation air and cabin pressurization. Because minor oil contaminants are unavoidable, air destined for the cabin passes through catalytic converters which, at a temperature of 500 °C, are capable of oxidizing sporadic contaminants to carbon dioxide and water. When abnormal amounts of oil enter the ventilation air, however, the system is likely to become overloaded, resulting in a number of contaminants entering the cabin air. These potentially include elevated carbon monoxide and carbon dioxide levels, as well as the presence of unconverted, or semi-converted, hydrocarbon oil constituents which present themselves in the form of smoke. In addition, a heavy chemical load on the catalytic converters is likely to increase their oxygen demand at the expense of the oxygen concentration in the air delivered to the cabin.

Some companies operating the BAe-146 have removed the catalytic converters and claim an improvement of air quality. In these aircraft the presence of leaking oil seals would result in the direct contamination of air destined for the cabin. As this air is diverted from the engine combustion airstream immediately prior to entering the combustion chamber, the temperature is estimated to be in excess of 500 °C. This air is cooled in the engine pylons to 200 °C before it is ducted through the spine of the aircraft to two air pack units situated in the rear of the aircraft. These units filter and condition the air to 50–60 °C before it enters the cabin.

Because both jet engine lubricants of interest contain up to 3 percent tricresyl phosphates (TCPs) as an anti-wear agent,⁽³⁾ inhalation exposure to these agents cannot be ruled out.

It has been reported that inhalation exposure to TCPs in a manufacturing plant has resulted in toxic polyneuritis.⁽⁴⁾ Long-term inhalation exposure of chickens to concentrations between 23 and 110 mg/m³ produced neurotoxic effects.⁽⁵⁾ It has also been suggested that humans are 10 to 100 times more sensitive than chickens.⁽⁶⁾ Although the neurotoxic effects of TCPs have been associated with the ortho isomer which, for that reason, has been kept below 1 percent in these lubricants,⁽³⁾ the observed neurotoxicity in laboratory studies cannot be explained by the presence of the ortho isomer alone. This has been demonstrated by one recent study which reported an unexpected high neurotoxic potency associated with aviation engine lubricants containing 3 percent TCP levels and less than 0.02 percent of the ortho isomer.⁽⁷⁾

There also has been a recent report⁽⁸⁾ that has drawn the attention to the potential generation of an additional neurotoxin, trimethyl propane phosphate (TMPP, i.e., 4-ethyl-1-oxo-2,6,7-trioxy-1-phospha-bicyclo(2.2.2)octane, CAS Registry Number 1005-93-2) that is produced at temperatures of 350–650°C⁽⁹⁾ from TCP and trimethylolpropane esters (TMPE), both of which are common constituents in jet engine oils.

This article reports on the constituents of two commonly used jet engine lubricating oils, their volatile components, and their pyrolytic products at 525°C, the optimum temperature that has been reported by Wyman et al. for TMPP production.⁽⁹⁾ Little information is available that describes how under these circumstances the oxygen, carbon monoxide, and carbon dioxide levels may be affected. Wyman et al.⁽⁹⁾ did report an increase in CO and CO₂ that was co-incident with a decrease in O₂. The source of these observations was thought to be the diesel fuel used to generate the elevated temperature conditions rather than the lubricant oil under investigation. Another investigation of the pyrolysis of Exxon 2380 under non-flaming conditions, using an electric heating unit, indicated that high levels of CO can be generated under these conditions.⁽¹⁰⁾

As it was not possible to make measurements during a flight with leaking oil seals and without the presence of catalytic converters on the engine, a laboratory simulation was done using both oils.

METHODS

Two commercially available jet engine oils were compared, Castrol 5000, which had been implicated in the air quality problems, and Exxon 2380, which had been used without major problems until it was temporarily replaced with Castrol 5000.

The general behavior of each oil was investigated by visual observation after a 0.5-mL sample of the oil was placed on a piece of aluminum foil on top of a ceramic hot plate which was heated to temperatures beyond 250°C at a rate of approximately 10°C/min. until only charred material remained.

The generation of potential volatile oil components at 525°C was investigated using a stainless steel chamber 54 × 64 × 71 cm

(W × L × H). A hotplate with a ceramic top was put at the bottom of this chamber and allowed to reach 525°C while the top lid was open. A surface thermometer (Model 573C Pacific Transducer Corporation, Los Angeles, CA) was placed on top of the hot plate to monitor the temperature. A direct reading multigas monitor TMX-412 (Industrial Scientific Corporation, Oakdale, PA) with data logging capabilities for NO₂, O₂, CO, and LEL was suspended at the top and inside the chamber, as well as a YES-204A monitor (Young Environmental Systems, Richmond, B.C., Canada), capable of recording temperature, relative humidity, and CO₂ concentration.

Both instruments were turned on before a 0.5-mL sample of the oil to be investigated was introduced onto a 5 cm × 5 cm piece of aluminum foil with the edges slightly curled up. This sample was put directly on top of the hot plate at 525°C. The lid was closed and, to prevent the direct reading instruments from thermal damage, the hot plate was kept at this temperature for one additional minute, at which time it was allowed to cool off. Sampling for volatiles was done using a midget impinger filled with a 10-mL ethanol and isopropyl alcohol mixture (95/5%) kept at 0°C and using an air sampling pump running at 1 L/min. Hydrogen cyanide (HCN) was measured using Workers' Compensation Board of British Columbia laboratory procedure 0700⁽¹¹⁾ using midget impingers and sampling pumps running at 1.6 L/min. The chamber had a 10-mm entry port, allowing free access to laboratory air, and a 8-mm exit port to which the impinger was attached. Sampling for all agents was continued for a period of 15 minutes after the introduction of the oil sample. Prior to each experiment a control sample was taken using the identical procedure, as described previously, except that no oil was present on the aluminum foil.

The impinger and bulk oil samples were analyzed using GC/MS. The GLC (Varian model 3400) was equipped with a Supelco PTE-5 column 30 meters in length and .25-mm ID. The injector temperature started at 60°C, was held for 1 minute, followed by 180°C/min. increments up to 280°C, where it was maintained to the end of the run, 50 minutes. The column temperature started at 70°C, was held for 2 minutes followed by 15°C/min. increments up to 280°C, where it was maintained at that temperature to the end of the run. The Mass spectra obtained (Varian Saturn 2) were compared to the National Institute of Standards and Technology (NIST) library.⁽¹²⁾ A para-tricresyl phosphate standard was obtained from ACROS chemicals (Fisher).

RESULTS

Both oils had similar appearance and consistency, with Castrol 5000 being slightly more orange in color. Close observation of the oils during heating from room temperature showed white smoke from Exxon 2380 at 275°C, darkening of the oil at 300°C, with the beginning of charring at 310°C. For Castrol 5000, visible white smoke appeared at 285°C, with darkening of the oil at 310°C, but no charring was observed until the temperature was above 350°C.

When oil samples were introduced onto the hot plate with its surface at 525°C inside the chamber, smoke was liberated which

TABLE I
Summary of gaseous constituents, and conditions, in the air from two turbo jet engine oils at 525°C

Agent/condition	Castrol 5000		Exxon 2380	
	Control	Oil	Control	Oil
NO ₂ (ppm)	<0.09	<0.09	<0.09	<0.09
CO ₂ (ppm)	370–420	390–509	365–420	395–510
CO (ppm)	0.0	0.0–141	0.0	0.0–120
O ₂ (%)	21.6–21.6	21.6–21.4	21.6–21.6	21.6–21.4
LEL (%)	0.0	2	0.0	3
Temp, (°C) ^A	35.7	34.5	36.8	35.7
% RH	20–25	21–28	20–28	20–25
HCN (ppm)	<1.1	<1.1	<1.1	<1.1

^ATemperature at the top of the chamber at the location of the recording instruments.

was similar in smell to what was noticed in aircraft with leaking oil seals. At the end of the experiments, except for some charred brown material, no oil was remaining on the aluminum foil.

The results obtained from the data logging monitors for CO₂, CO, NO₂, LEL, temperature, and relative humidity as well as HCN have been summarized in Table I.

As can be observed in this table no evidence was found for the generation of NO₂ and HCN. CO₂ levels increased throughout the 15-minute experimental regime from a low of 365 (control) to a high of 509 ppm (Castrol 5000). Similarly, CO reached a high of 141 ppm when Castrol 5000 was investigated compared to a high of 120 ppm for Exxon 2380.

The GC traces for the two bulk oil sample analyses and their corresponding traces for the volatiles released at temperatures of 525°C have been summarized in Figure 1. The bulk oil traces showed virtually identical patterns as well as the relative proportions of their constituents. The pyrolyzed oils were very similar in general but differed somewhat between scan number 1200 and 1350 which showed more pronounced peaks for Castrol 5000.

The corresponding GC/MS analyses of the peaks in Figure 1 have been summarized in Table II. The various peaks show virtually identical retention times and mass spectra. The corresponding compounds that match these mass spectra have also been identified in Table II, along with their fit and CAS number. Where possible, only those compounds that were identical in both analyses as being present in peaks of comparable retention times have been shown. Other possible compounds can therefore not be excluded.

DISCUSSION

Visual observation of the two oils during heating indicated slightly different behavior. Castrol 5000 appeared to generate smoke at a slightly higher temperature than Exxon 2380, that is, 285°C versus 275°C. The major difference was that Castrol 2000 did not produce charred remains until 350°C compared to 310°C for Exxon 2380. A published report⁽¹⁰⁾ on a 1983 Exxon 2380 sample indicates visible traces of condensate at

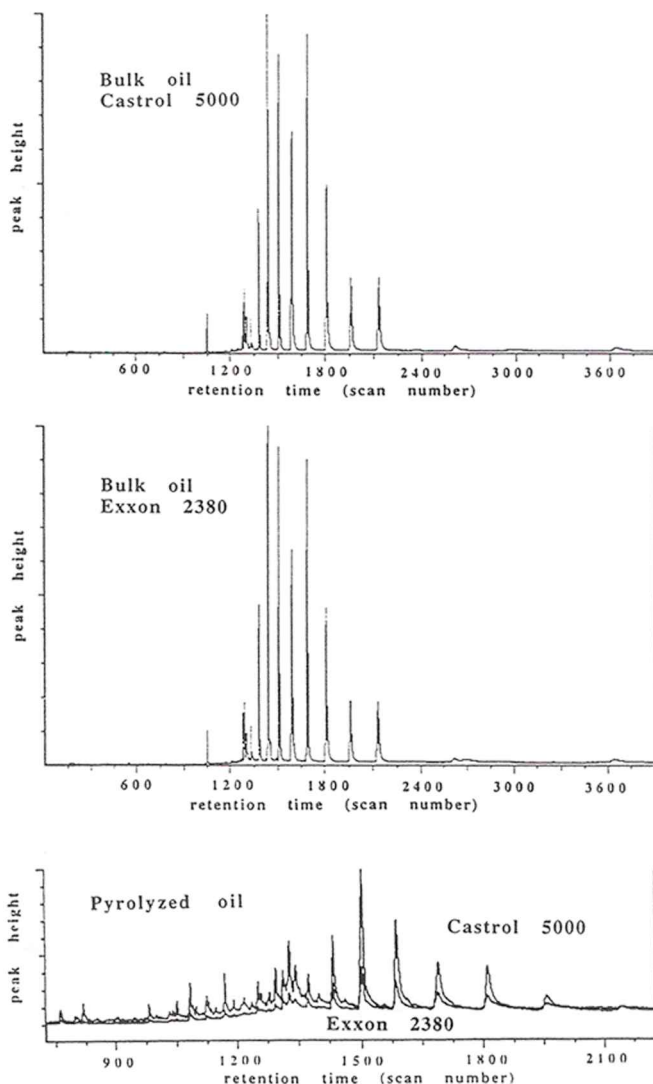


FIGURE 1

Gas chromatograph scans of two turbo jet engine oils and their volatile products produced at 525°C.

208°C, with a dramatic increase in smoke at 306°C which was coincident with the generation of CO, which reached a high of 10,600 ppm at 533°C. A level of 14,300 ppm of CO was reported when an Exxon 2380 oil sample was placed directly in

an environment at 375°C under non-flaming conditions. The CO concentration in our current experiments indicated a high CO concentration of 120 ppm for Exxon 2380. When one takes the different loading characteristics into account, that is, 4.2 L/cc

TABLE II
Bulk oil constituents and volatile products at 525°C from two turbo jet engine oil lubricants

Bulk oil analysis			
Ret. time	Compound	Fit	Cas #
Castrol 5000			
1049	8-Benzylquinoline	972	28748-19-8
	2-naphthylamine, N-phenyl-	963	135-88-6
1274	Phosphoric acid, tris(3-methylphenyl)ester	989	563-04-2
1287	Phosphoric acid, tris(3-methylphenyl)ester	986	563-04-2
1301	Phosphoric acid, tris(3-methylphenyl)ester	984	563-04-2
1316	Phosphoric acid, tris(4-methylphenyl)ester	968	78-32-0
	Phosphoric acid, tris(3-methylphenyl)ester	966	563-04-2
1328	1,3-Dioxane, 5-(hexadecyloxy)-2-pentadecyl-,trans-	892	34315-34-9
1378	3,3-dimethyl-5-(2,2-dimethylpropyl)tetrahydrofuran-2-one	978	0-00-0
1436	Gallium, tetraethyl-di.mu.-1-piperidinyldi-Silane derivative	899	42777-03-7
		845	56771-62-1
1504	1,8-Dihydroxyanthraquinone	897	7336-68-7
1590	Decanoic acid, 1,2,3-propanetriyl ester	864	621-71-6
1690	Decanoic acid, 1,2,3-propanetriyl ester	813	621-71-6
1807	1,8-Dihydroxyanthraquinone	891	7336-68-7
1957	8-methoxy-2-(p-methoxyphenyl)-1,2,4,5-tetrahydro-1-benzazocine-3,6-dione	903	90732-26-6
	Decanoic acid, 1,2,3-propanetriyl ester	837	621-71-6
2132	4-hydroxyanthraquinone-2-carboxylic acid, di-TMS	868	0-00-0
2615	Methanone, (4-ethoxy-3-methoxyphenyl)(6-methyl-1,3-benzodioxol-5-yl)-	863	52828-42-9
3639	Octadecanoic acid, 8,9,11,12-tetrakis[trimethylsilyloxy]-, methyl ester	840	35437-04-8
Exxon 2380			
1051	8-Benzylquinoline	973	28748-19-8
	3-Benzylquinoline	970	37045-16-2
	2-naphthylamine, N-phenyl-	958	135-88-6
1275	Phosphoric acid, tris(3-methylphenyl)ester	987	563-04-2
1288	Phosphoric acid, tris(3-methylphenyl)ester	987	563-04-2
1303	Phosphoric acid, tris(3-methylphenyl)ester	984	563-04-2
1318	Phosphoric acid, tris(4-methylphenyl)ester	968	78-32-0
	Phosphoric acid, tris(methylphenyl)ester	966	1330-78-5
1330	1,3-Dioxane, 5-(hexadecyloxy)-2-pentadecyl-,trans-	890	34315-34-9
1379	3,3-dimethyl-5-(2,2-dimethylpropyl)tetrahydrofuran-2-one	975	0-00-0
1438	Gallium, tetraethyl-di.mu.-1-piperidinyldi-Silane derivative	898	42777-03-7
		845	56771-62-1
1506	1,8-Dihydroxyanthraquinone	900	7336-68-7
1591	Decanoic acid, 1,2,3-propanetriyl ester	851	621-71-6
1693	Decanoic acid, 1,2,3-propanetriyl ester	824	621-71-6
1809	1,8-Dihydroxyanthraquinone	924	7336-68-7
1958	8-methoxy-2-(p-methoxyphenyl)-1,2,4,5-tetrahydro-1-benzazocine-3,6-dione	882	90732-26-6
	Decanoic acid, 1,2,3-propanetriyl ester	827	621-71-6
2133	Naphthalene, 2-(1,1-dimethyl)decahydro-4a-methyl	873	54934-96-2
	4-hydroxyanthraquinone-2-carboxylic acid, di-TMS	871	0-00-0
2615	Methanone, (4-ethoxy-3-methoxyphenyl)(6-methyl-1,3-benzodioxol-5-yl)-	887	52828-42-9
3639	Octadecanoic acid, 8,9,11,12-tetrakis[trimethylsilyloxy]-, methyl estert	843	35437-04-8

TABLE II
Bulk oil constituents and volatile products at 525°C from two turbo jet engine oil lubricants (*Continued*)

Pyrolyzed oil analysis			
Ret. time	Compound	Fit	Cas #
Castrol 5000			
737	diethyl phthalate	967	84-66-2
793	hexane, 1,1'-oxybis	815	112-58-3
958	hexane,2,2,3,4,5,5-hexamethyl-, meso	848	55258-16-7
1059	3-benzoquinoline	937	37045-16-2
1098	2-t-butyl-2,3-dimethyl-3-buten-1-ol	906	0-00-0
1144	5,6-decanedione	847	5579-73-7
1166	Butanimidamide, N-(1-chloro-2-methyl-1-butenyl)-2-monochloride	938	40645-73-6
1189	5-decen-1,ol (Z)-	977	51652-47-2
1269	anthraquinone, 1-p-tolyl	943	20600-74-2
1288	Phosphoric acid, tris(methylphenyl)ester	937	1330-78-5
1301	Phosphoric acid, tris(methylphenyl)ester	961	1330-78-5
1317	Phosphoric acid, tris(methylphenyl)ester	942	1330-78-5
1349	dodecane,1-isocyanate	790	4202-38-4
1375	piperazine, 1-(aminoacetyl)-	868	77808-88-9
1409	3,3-dimethyl-5-(2,2-dimethylpropyl)tetrahydrofuran-2-one	947	0-00-0
1478	Silane, methyltriphenoxy	801	3439-97-2
1562	1,8-Dihydroxyanthraquinone	818	7336-68-7
1664	1,1,3-Tri(alloxy)propane	822	0-00-0
1789	Phenylethylamine, N-Methyl-.beta.,3,4-tris-(trimethylsiloxy)	824	10538-85-9
1933	Benzo[g][I]benzothiopyrano[4,3]-indole	752	10023-23-1
Exxon 2380			
739	diethyl phthalate	969	84-66-2
794	hexane, 1,1'-oxybis	844	112-58-3
958	hexane,2,2,3,4,5,5-hexamethyl-, meso	902	55258-16-7
1056	3-benzoquinoline	970	37045-16-2
1099	2-t-butyl-2,3-dimethyl-3-buten-1-ol	913	0-00-0
1145	5,6-decanedione	872	5579-73-7
	2-nitro-2-methylcyclohexanone	954	0-00-0
1268	anthraquinone, 1-p-tolyl	927	20600-74-2
1286	Phosphoric acid, tris(methylphenyl)ester	817	1330-78-5
1301	Phosphoric acid, tris(methylphenyl)ester	859	1330-78-5
1317	Phosphoric acid, tris(methylphenyl)ester	946	1330-78-5
1350	1-piperidinecarboxaldehyde	897	2591-86-8
1407	3,3-dimethyl-5-(2,2-dimethylpropyl)tetrahydrofuran-2-one	977	0-00-0
1475	Silane, methyltriphenoxy	755	3439-97-2
1559	1,8-Dihydroxyanthraquinone	845	7336-68-7
1665	1,1,3-Tri(alloxy)propane	750	0-00-0
1789	Phenylethylamine, N-Methyl-.beta.,3,4-tris-(trimethylsiloxy)	677	10538-85-9
1931	Benzo[g][I]benzothiopyrano[4,3]-indole	764	10023-23-1

of oil⁽¹⁰⁾ compared to 490 L/cc of oil in our experiments, the concentration of 14,300 ppm referred to above corresponds to 123 ppm under the loading condition that we used. This shows good agreement with the value of 120 ppm CO that we measured at 525°C. There is a possibility that some of the constituents of Exxon 2380 might have been modified or replaced since 1983, and could be responsible for small differences in the CO concentration generated as well as the difference in temperature at

which visible smoke was observed in our experiments, that is, 208°C versus 275°C.

The levels of CO₂ also increased during the experiment, whereas O₂ decreased slightly as expected. These results indicate that these oils, when exposed to elevated temperatures, are sources of CO and CO₂. The CO produced could become a hazard to the flight crew when operating aircraft with leaking engine oil seals. It could be argued that the production of CO in

these experiments is a result of limiting oxygen conditions which are not likely to be present in the combustion air of the aircraft. The oxygen measurements during pyrolysis do not appear to support this argument since only a .2 percent change in oxygen concentration was noted. In contrast, much wider variations in aircraft oxygen concentrations have been reported.⁽²⁾

NO₂ and HCN were not produced under the conditions of the experiment which is consistent with the fact that these gases are produced from atmospheric nitrogen only at temperatures associated with actual flame conditions which are well in excess of 1000°C.⁽¹³⁾ HCN can also be formed at lower temperatures from combustion of nitrogen-rich materials such as wool, silk, polyurethane, and polyacrylonitrile.⁽¹⁴⁾ Based on our analysis of the two oils, the nitrogen content appears to be minimal.

It is also apparent from Figure 1 that the process of heating the oils to above 500°C produces volatile compounds that are not present in the oil itself. These volatiles appeared to be similar between the two oils. In addition, some of the components in the bulk oils that were retained at 1950 and longer retention times were not found in the pyrolyzed samples.

The chamber experiments indicate that the cresyl phosphates were volatilized and could therefore potentially enter the cabin of an aircraft. It is interesting to note that previously reported HPLC analysis of aircraft air with leaking oil seals could not demonstrate the presence of cresyl phosphates above 80 ug/m³.⁽²⁾ It is therefore likely that under the conditions present in an aircraft one expects that a number of oil constituents that were pyrolyzed and/or volatilized will condense out of the airstream at different locations along the ventilation ducts depending on the local temperature. The more volatile components are expected to travel through the ventilation system and enter the cabin, resulting in exposure to the passengers as well as the flight crew.

The principle of localized condensation has also been observed by Rubey⁽¹⁵⁾ during the incineration of engine oils containing TCP. In that investigation the neurotoxic TMPP was not found in the gaseous effluent but was identified in the scrapings of the boiler walls. Because the incinerator temperature was likely higher than what would be encountered in an aircraft ventilation system, it is unlikely that TMPP, if it were produced, would be encountered in the aircraft supply air. It would appear therefore that the catalytic converters on the engines, localized condensation along the ventilation system, and conditioning by the airpack units of the aircraft are capable of modifying and filtering out most compounds that could potentially contaminate the cabin air. It would nevertheless be prudent to verify these hypotheses under the conditions present in an aircraft with either actual or simulated engine oil leakage.

Localized condensation will lead to accumulation of the condensation products in the ventilation system. This could result in the release of these agents into the air when duct temperatures, for some reason, become elevated, causing an air quality problem at a time when there is nothing wrong with the mechanical system of the aircraft.

It should be emphasized that the compounds identified in Table I should be interpreted with caution because other com-

pounds not shown had similar, or closely related, mass spectra. Because the ingredients of these two oils are proprietary information, the accuracy of our analysis could not be confirmed with appropriate standards for most of the components identified and their retention times could not be compared. For this reason some of the compounds in Table II may have been associated with quite different retention times such as, for instance, 1,8-dihydroxyanthraquinone for the Exxon 2380 analysis.

Only a standard would identify the correct peak and its retention time; the other peaks, which were identified with the same compound, are likely associated with closely related derivatives of the compound identified. This was particularly apparent with the large numbers of phosphoric acid derivatives with retention times between 1274 and 1381. Each one of these refers to one of the 10 possible isomers of TCP. The companies did indicate that TCP is present at a 2–3 percent level. This was confirmed in our analyses with a p-cresyl phosphate standard. Identification of the other components was mainly done to identify similarities and to search for the presence of TMPP which could not be demonstrated under the conditions of the experiment and using the NIST library, which does contain a spectrum for TMPP. The identification of TMPP was also hampered by the fact that a standard for this compound could not be obtained.

It has been pointed out⁽¹⁰⁾ that the resulting products from the thermal breakdown of agents is highly dependent on the conditions under which this is achieved. The current observations should therefore be interpreted with caution. Nevertheless, it was also suggested by the same authors that the non-flaming conditions provided by an electric heating system is a reasonable model to study the degradation of turbo engine oils.

CONCLUSIONS

The two jet engine oils investigated appear almost identical in their chemical composition. Pyrolysis at 525°C resulted in the release of CO₂ and CO, as well as a large number of volatiles. Of these, CO and volatilized components as well as pyrolysis products could pose a potential hazard to the flight crews of BAe-146 aircraft experiencing engine oil seal failure. Although TCPs were found in both bulk oils as well as in the air, the presence of neurotoxic TMPP could not be demonstrated. It was postulated that some of the volatilized components, as well as pyrolysis products that were generated in our experiments, would likely condense out of the airstream onto the interior surface of the aircraft ventilation system and not reach the cabin unless the duct temperature is increased. It was therefore recommended that this hypothesis needed to be investigated under actual aircraft conditions.

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