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EFFECTS OF ADDITIVES ON FIRE PROPERTIES OF POLYETHYLENE

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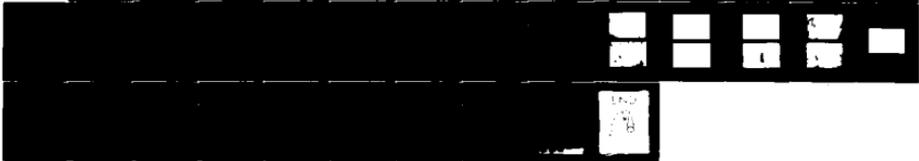
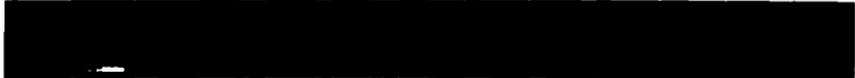
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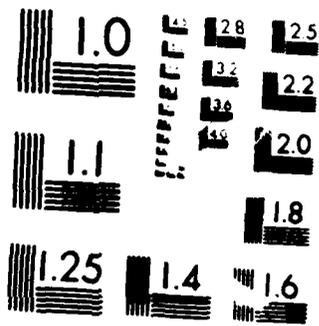
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A. J. Christopher

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EFFECTS OF ADDITIVES ON FIRE PROPERTIES OF POLYETHYLENE

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SUMMARY

Low-density polyethylene, with and without an antimony-bromine synergistic fire retardant or aluminium hydroxide, was subjected to standard fire tests and to experiments which determined the smoke and harmful fumes emitted on overheating.

Both additives improved most fire properties but the fire retardant increased the smoke generated by intense radiant heat.

The onset of smoke, flammable gas, carbon monoxide and acids was generally delayed by the additives. The total amounts and maximum values of these volatiles were lessened. Sample weight and form affect the results from these experiments.

Observations during heating show that the additives reduce spreading of the melt, thus reducing the surface area available for oxidation.

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1 INTRODUCTION

Polymeric materials must often pass flammability and smoke-emission tests when they are to be used in particular applications, *eg* aircraft interiors. A considerable variety of standard tests exists according to application and country and it has been shown that there is little correlation between them¹. The tests generally relate to flaming or intense radiant heat conditions.

In cases where fire tests indicate that a polymeric material is unsatisfactory, additives are often incorporated to improve the performance in the tests specified for the applications envisaged. Whilst the fire and smoke properties tested are improved, unspecified properties such as toxic hazard and irritancy of combustion products may be worsened by the additives. Similarly, there is no guarantee that the behaviour of the material under different fire or overheat conditions will not be impaired.

To attempt to gain some understanding of the effects of such additives on the performance of materials under the rather different conditions of gradual overheating, *eg* in electrical faults and the early stages of fires in aircraft, a number of polymers with and without known additives were compounded and tested. Low-density polyethylene (LDPE) was selected as the first polymer for study because it has a simple carbon chain structure. Examination of the volatile products of the formulations subjected to controlled overheating in air showed that some improvement is brought about by the additives.

2 MATERIALS

Formulations were selected and made, on the basis of literature and advice from polymer and additive manufacturers, by the Rubber and Plastics Research Association (RAPRA).

Materials were pre-mixed in a single-screw extruder fitted with a RAPRA Cavity Transfer Mixer and extruded as strips. The strips were granulated and injection moulded at 150-260° into 3mm thick sheets.

The additives selected were an antimony-halogen synergistic pair and aluminium hydroxide.

Halogen compounds, of which bromine is the most effective, are often incorporated into polyethylene to reduce flammability². Antimony trioxide synergistically increases the efficiency of the halogen so a mixture of antimony trioxide and decabromodiphenyl-oxide, one of the most common fire retardants for polyethylene, was selected for the first formulation.

Aluminium hydroxide³ is used to reduce flammability and smoke in many polymers without introducing potentially toxic materials, so this was incorporated in the other formulation.

The formulations used and their elemental analyses, performed at Birmingham University, are shown in Table 1. For the pure polyethylene (LDPE) and the fire-retarded composition (LDPE + FR), good agreement between elements calculated and found is shown. In the case of polyethylene containing aluminium hydroxide (LDPE + AH), high analysis results for carbon and hydrogen were obtained. This is consistent with loss of water from the aluminium hydroxide during processing: if all the water were lost, 66% carbon and 11% hydrogen would be expected. Aluminium hydroxide releases most of its water over the temperature range 220-350°C, so some loss might be expected during extrusion and moulding.

3 EXPERIMENTAL

3.1 Standard fire tests

The Underwriters' Laboratories UL94 flammability test⁴ is an important acceptance test for electrical and other plastics goods in the USA. A flame is applied to a horizontal specimen and the burning rate measured. A more severe, vertical test is also carried out.

The limiting oxygen index test to ASTM 02863⁴ defines the percentage of oxygen needed in the atmosphere to just sustain candle-like burning of a strip of material. The temperature index is the temperature at which the oxygen index is 21%, i.e. the concentration of oxygen in air.

The ignition temperatures determined to ASTM D1929⁴ are the temperatures at which flammable volatiles are ignited with and without a pilot flame (flash- and self-ignition temperatures).

The Civil Aviation Authority (CAA) Specification No.8 test⁵ is the acceptance test for interior materials for civil aircraft registered in the United Kingdom. The test is suitable for satisfying the Joint Airworthiness Requirements and is very similar to tests applied in the USA and many other countries. A flame is applied to horizontal, vertical or 45° specimens according to the use of the material in the aircraft. Burn length, after-flame and after-glow times and flame time of drips are observed.

The National Bureau of Standards (NBS) smoke test to ASTM E662⁴ is the most commonly used smoke emission test. Specimens are subjected to intense radiant heat with and without a pilot flame and the maximum optical density of smoke accumulating in the test chamber is measured.

RAPRA carried out all the standard fire tests except the CAA8 tests, which were performed at Yarsley Technical Centre.

3.2 RAE smoke and fume apparatus⁶⁻⁷

A small sample of material is heated from ambient to 500°C at 20°C/min in flowing air. Initiation temperatures and amounts of smoke, flammable gas and carbon monoxide (CO) are measured. The sample temperature and the pH of a water bubbler are also monitored. The apparatus has been interfaced with data-logging equipment by RAPRA and is now operated by them.

3.3 RAE acid and alkali titration apparatus⁸

The sample is heated in the same way as in the RAE smoke and fume apparatus. Volatile products are passed into a water bubbler in which a glass electrode senses any pH change. A proprietary two-way pH-stat system titrates acids or alkalis as they are sensed in the bubbler to give a continuous record as the sample temperature is raised.

3.4 Ion chromatography

To determine individual acids titrated as above, the contents of the bubbler after titration are subjected to two separate ion chromatographic techniques using a Dionex 2120i ion chromatograph. Ion chromatography with an HPIC-AS4 column and 0.0028M sodium bicarbonate/0.00225M sodium carbonate eluent is used to analyse inorganic anions arising from hetero-elements in polymers or additives. Ion chromatography exclusion with an HPICE-ASI column and 0.001M hydrochloric acid eluent is used for organic anions from the thermo-oxidation of polymer chains. Hollow-fibre suppression is used for both systems. No pretreatment of the bubbler samples except membrane filtration is needed.

3.5 Thermogravimetric analysis

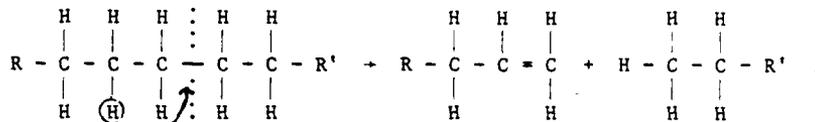
Samples are heated in a Stanton Redcroft TG 760 thermobalance at 20°C/min from ambient to 500°C or 1000°C in moving air. Integral and differential weight loss curves are recorded against temperature. The apparatus is operated by Birmingham University.

3.6 Hot-stage microscopy

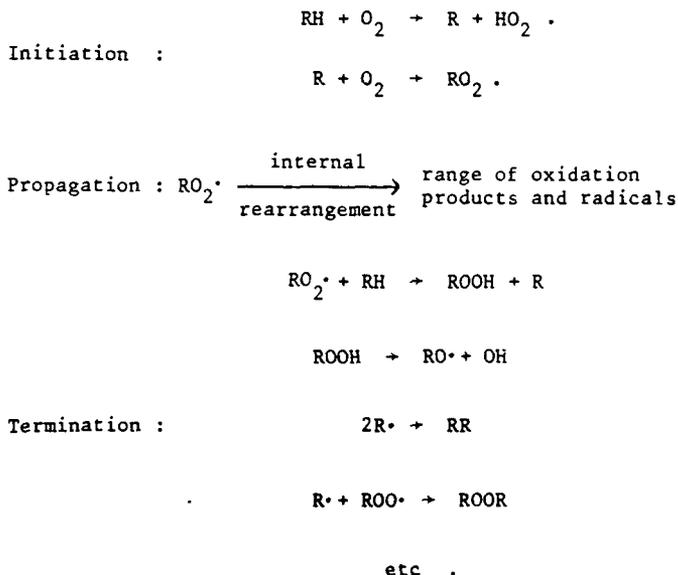
Samples are heated at 20°C/min from ambient to 1000° in an Inconel dish in a Stanton Redcroft HSM-5 high-temperature hot stage with air flowing through it. Behaviour is observed microscopically by reflected light.

4 FIRE BEHAVIOUR OF POLYETHYLENE

When polyethylene is heated, thermal stresses on the polymer chains cause random scission² and hence give rise to a mixture of saturated and unsaturated hydrocarbons with randomly distributed chain lengths:



In air, these fragments can be oxidised through free-radical chain reactions to form acids, *eg* as below

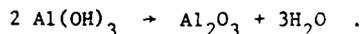


Oxidation products produced by these mechanisms can include aldehydes, ketones, acids, heterocyclic compounds, etc.

The hydrocarbon fragments from the pyrolysis are tars, liquids and flammable gases, according to their chain lengths. Spontaneous or piloted ignition of the gases leads to fire. The acids and aldehydes produced by oxidation are irritant to the eyes, nose and throat and can also induce deep-lung effects⁹. Another major oxidation product is CO which is the main source of toxic hazard by virtue of its narcotic action⁹.

Antimony-bromine synergistic fire retardants are thought to act through the formation of a volatile antimony compound, probably SbBr_3 (boiling point 280°C)². Free radical reactions could then give rise to HBr which can react with radicals formed in the propagation reaction and inhibit it. In other words, another termination mechanism is provided at a reaction rate competitive with that of the propagation. However, HBr is also known to catalyse some oxidation reactions. In addition to these gas-phase effects, some char-promoting action is thought to be likely in the solid phase. Much work has been done in attempts to elucidate the mechanism by which these fire retardants act, but no firm conclusions have been drawn.

Aluminium hydroxide³ reduces flammability, and sometimes smoke, by its endothermic decomposition in the temperature range $220\text{--}350^\circ\text{C}$, in which water is released:



This can be observed by thermogravimetric analysis (Fig 1). A high loading of this additive is necessary.

5 EFFECTS OF ADDITIVES ON STANDARD FIRE TEST PERFORMANCE

The standard fire test performance of the three materials is shown in Table 2.

In the UL 94 test, all three materials fail the vertical burning test but gain 'HB' ratings in the horizontal version. Both additives reduce the burning rate from 25 to 0 mm/min. However, in the CAA8 (horizontal) test, which is very similar, only LDPE + AH gives a better result. This may be due to the sizes of flames used in the tests: although the specimen width is the same in each, the UL 94 test uses a 25 mm flame applied for 30 seconds whereas the CAA8 test uses a 38 mm flame for 15 seconds. The smaller flame of the UL 94 test may not raise the specimens to their flash-ignition temperatures whereas the lower flash ignition temperature of LDPE + AH may be reached in the CAA8 test (see ASTM D1929 test results in Table 2). The self-ignition temperatures of the materials with additives are both 20°C higher than that of the LDPE itself.

In the CAA8 (vertical) test, the specimens of LDPE and LDPE + AH burn over their entire length (305 mm) but the burn length of LDPE + FR is only a tenth of this. The after-flame time and flame time of drips of LDPE + FR are also greatly reduced but the AH gives some improvement as well. In the 45°

version of the test no penetration by the flame of any of the materials occurred.

The FR improved the oxygen index sufficiently for the LDPE + FR to be considered fire retarded but AH made only a slight difference. Sobolev and Woycheshin³ quote 30.2 as the oxygen index for an AH-filled polyethylene but the loading was 60%. It seems that a very high proportion of AH is needed to improve the performance of polyethylene significantly in most flammability tests. As would be expected, the temperature indices of LDPE and LDPE + AH are around ambient because their oxygen indices are about 21. The LDPE + FR melts below its temperature index, so this measurement cannot be made.

In the NBS smoke test, the LDPE + FR produces more smoke than LDPE (much more in the flaming mode) whereas the AH has no effect.

To summarise, FR gives considerably reduced flammability but increases smoke production. AH gives slight, if any, improvement in flammability but does not increase smoke production.

6 EFFECTS OF ADDITIVES ON VISIBLE BEHAVIOUR

As a glass furnace was used for the RAE experiments⁶ it was possible to observe the behaviour of the materials during runs. It was evident that the LDPE sagged and flowed from its support on the thermocouple and spread over the combustion tube wall whereas the other materials tended to swell to a globule which did not flow.

In order to investigate this difference in behaviour more closely and conveniently, a Stanton Redcroft high-temperature hot stage was used to heat very small fragments of the materials in different atmospheres for microscopical observation. In air, the behaviour was similar to that observed in the combustion tube. Figs 2 to 4 show how LDPE spreads to a thin smear in the pan of the hot stage at 300°C whereas the other materials spread much less; a skin appears to form and prevent the spread.

To see whether this difference was due to pyrolysis or oxidation reactions, the experiment was repeated in atmospheres of nitrogen and oxygen. In nitrogen (Figs 5 to 7), little spread occurred for any of the materials but in oxygen (Figs 8 to 10), LDPE spread as in air. The skins which formed appeared to be more charred in the presence of oxygen.

Due to the greater surface area of the melt, LDPE is thus likely to give rise to more smoke and fumes, resulting from oxidation reactions at temperatures

above the melting point, than the materials with additives. It seems that the spreading of LDPE melt is due to surface oxidation reactions and that these are somehow inhibited by FR and AH.

7 EFFECT OF ADDITIVES ON SMOKE AND FUME EMISSION

7.1 Sample weight and form

The RAE procedures measure temperatures of initiation of selected volatiles and their amounts relative to the sample weight. From previous work⁶ it was suspected that the amounts found per unit weight varied with the sample weight and that the geometrical form might also have an effect. Using the acid/alkali emission apparatus, because it gave a wider determinable range than the smoke apparatus and was simpler, these effects were checked for LDPE.

Fig 11 shows the effects of both sample weight and form on acid emission from LDPE. For a powder, three times as much acid was emitted per gram for a 100 mg sample as for a 1000 mg sample. Far less sample-weight effect was seen for lumps and cable sheath, and virtually none for a thin film. This suggested that the surface area before melting exposed to oxidative degradation was important as well as that after melting.

Fig 12 shows the relations between area per unit volume and volumes calculated for approximations of the shapes of LDPE tested. If the amount of acid emitted is proportional to the sample surface area, these plots should be similar to those actually found. The model solids used to simulate the samples were:

- (a) a cube to represent a lump sample;
- (b) a cone of constant height 10 mm with its curved surface only exposed to air; this simulates the lump sample, partially molten, sagging from the thermocouple support on to the combustion tube;
- (c) a rod, 2 mm in diameter, to simulate a cable sheath;
- (d) a flat film, thickness 0.3 mm, one surface exposed to air;
- (e) cubes, side 0.1 mm, distributed on a 0.1 mm grid so that alternate spaces are occupied, then with the spaces fully occupied; then additional layers; this simulates a milled sample.

The plot for the simulated milled material is seen to be considerably steeper than those for the other forms, corresponding to the 'acid against sample weight' plots (Fig 11). This supports the idea that the acids are formed by the oxidation of chain fragments at the surface of the polymer by the reactions

described earlier. Only results for equal weights of the same geometrical form of materials should be directly compared for ranking purposes. All the RAE experiments described were done on lump samples.

7.2 Acid emission

After titration, ion chromatographic techniques were used to determine the anions in the bubbler. It was found necessary to carry out the ion chromatography exclusion as soon as possible after titration because the concentrations found increased with time (Fig 13), presumably due to oxidation of aldehydes. It should, in fact, be feasible to deliberately oxidise the aldehydes and determine them ion chromatographically as the corresponding acids, and it is proposed to attempt to develop such a technique for future use.

Table 3 shows the acid emission results. Both additives increased the temperature at which acid is first evolved. The FR reduced the total acid emitted per unit weight of material but the AH had little, if any, effect.

About 5% of the bromine in the FR was recovered as bromide in the bubbler and atomic absorption spectroscopy showed a corresponding amount of antimony. This suggests that most of the FR is active in the solid rather than the gas phase.

The amount of acid accounted for by the acetate found by ion chromatography exclusion was very similar for all three materials, but both additives drastically reduced the amount of formate found. Formate is much more readily oxidised than other fatty acid anions so promotion of oxidation by the additives is suggested. The materials with additives gave a good final ionic balance of titrated hydrogen ion against total anions found, whereas for LDPE, the 'extra' formate was not accounted for by hydrogen ion. The 'missing' cation may be a carbonium ion. 60 mg of paraformaldehyde (solid mixed low polymers of formaldehyde) was heated under the usual conditions in the titration apparatus to generate formaldehyde gas. No titration resulted, and no formate was found by ion chromatography exclusion, so the 'extra' formate does not seem to be formed by oxidation of formaldehyde between titration and injection on to the chromatograph.

The small amounts of sulphate and nitrate found must be due to additives or impurities.

7.3 Smoke and fume emission

Table 4 lists results obtained with the RAE smoke and fume apparatus.

Fig 14 shows the effects of additives on temperatures of smoke and fume initiation and maximum concentration: generally the FR increases these considerably and the AH to a lesser extent, *ie* both have beneficial effects. This delay in smoke and fume emission is presumably related to the skin formation and spread reduction brought about by the additives. The amounts of smoke and flammable gas (measured as hexane), per gram of material, corrected for additive contents, are reduced to some extent. The FR appears to reduce CO emission per gram of material but the results for AH are variable.

Figs 15 to 17 show actual traces obtained for smoke, flammable gas and CO emissions. In each case the addition of FR shifts the peak to a higher temperature, reduces its height and adds another, partially resolved, minor peak after the LDPE peak. AH shifts the main peak temperature higher still, reduces its height more and adds minor peaks before and after it. The fact that these effects apply to all three types of emission strongly suggests that the smoke, flammable gas and CO are all products of the same major decomposition process which is affected by the additives.

As might be expected and as earlier work had indicated⁶, differential thermogravimetric analysis gives curves which quite closely resemble the smoke and fume emission curves (Fig 18). The maximum rate of weight loss is compared with smoke, flammable gas and CO maxima in Table 5. The FR appears to increase the maximum weight loss rate but decrease the maximum values for smoke, flammable gas and CO. The maximum weight loss rate for LDPE + AH is about the same as for LDPE but maximum values for smoke, flammable gas and CO are all considerably reduced. Thus the FR and AH seem to have the effect of modifying decomposition reactions to give less smoke, flammable gas and CO and more of other volatiles. Now in the ion chromatography exclusion determinations it was found that the additives greatly reduced the formate produced. It therefore seems likely that the skin formation, associated with the additives in air, inhibits formation of formate in oxidation reactions.

8 SUMMARY OF RESULTS

LDPE and formulations of it with antimony trioxide plus decabromodiphenyl oxide (FR) and with aluminium hydroxide (AH) were subjected to standard fire tests and RAE smoke and fume emission experiments. The results are summarised in Table 6.

In standard fire tests, FR decreased flammability but increased smoke produced by intense radiant heat. AH gave only slight reduction in flammability but did not increase smoke.

Observations during heating showed that little spreading of the melts of any of the materials occurred in nitrogen but, in atmospheres of air and oxygen, the LDPE melt spread whilst the others did not.

Production of acidic volatiles per unit weight of LDPE heated in air was proportionately greater for smaller weights, except when the sample was a thin film. A milled sample gave the most marked sample-weight effect; lumps and cable sheath gave lesser effects.

Both additives increased the temperature at which acid was first evolved. FR reduced the total acid evolved per unit weight but AH had less effect. Both additives greatly reduced the amount of formate ion evolved.

FR and, to a lesser extent, AH increased the temperatures at which smoke, flammable gas and carbon monoxide were evolved. The amounts of these emissions and their maximum values were reduced.

FR increased the maximum rate of weight loss but AH made no difference.

9. CONCLUSIONS

An antimony-bromine fire retardant and aluminium hydroxide generally reduce the flammability of LDPE and the smoke and harmful fume emissions from it. However, the fire retardant increases smoke under intense radiant heat conditions.

In an oxidising atmosphere, both additives encourage the formation of a skin on the polymer melt, reducing its surface area. This effect delays the onset of smoke, flammable gas, carbon monoxide and acids and, to some extent, their amounts.

Sample size and geometrical form should be constant for materials being compared in overheating experiments.

Further materials should be studied to see the effects of additives on emission of harmful volatiles.

A method for the determination of aldehydes should be developed, based on their oxidation to acids and determination by ion chromatography exclusion.

Acknowledgments

The author is grateful to Dr M. Gale and Dr K.T. Paul of the Rubber and Plastics Research Association for compounding and fire testing the materials, to Dr A.M.G. Macdonald and Mr K. Scott of the University of Birmingham for thermogravimetric and elemental analyses, and to Mr E. Soja and Mr N.T. Rowan of the Yarsley Technical Centre for CAAS tests.

Table 1
FORMULATIONS AND ELEMENTAL ANALYSES

	LDPE	LDPE + FR	LDPE + AH
Formulation:			
Polyethylene	100 (100)	100 (93.0)	100 (64.9)
Antimony trioxide	-	1.9 (1.7)	-
Decabromodiphenyl oxide	-	5.6 (5.2)	-
Aluminium hydroxide	-	-	54 (35.1)
Analyses:			
Percentage of carbon found	85.8	81.1	61.1
Percentage of carbon calculated	85.6	80.4	55.6
Percentage of hydrogen found	14.1	14.0	10.7
Percentage of hydrogen calculated	14.4	13.4	9.5
Percentage of bromine found	-	4.1	-
Percentage of bromine calculated	-	4.3	-

NB The formulations are given in parts per hundred of polymer by weight (unbracketed) and per cent by weight (bracketed).

The calculated hydrogen analysis for LDPE + AH includes 0.2% which would be released as water from the AH.

Table 2
RESULTS OF STANDARD FIRE TESTS

	LDPE	LDPE + FR	LDPR + AH
UL 94	HB(25)	HB(0)	HB(0)
ASTM 02863 (Oxygen index)	19	27	21
Temperature index	<23	(melts)	23
ASTM D1929:			
Flash ignition temp.	340	350	300
Self ignition temp.	360	380	380
CAA8 (vertical):			
After-flame time	518	3	302
After-glow time	0	0	0
Burn length	305	30	305
Flame time of drips	903	0	538
CAA8 (horizontal):			
Burn rate	21	0	23
CAA8 (45°):			
After-flame time	0	0	0
After-glow time	0	0	0
Flame time of drips	0	0	0
Penetration	None	None	None
ASTM E662 (NBS smoke test):			
Flaming	75	203	76
Non-flaming	176	255	163

Table 3
RAE ACID EMISSION TEST RESULTS

	LDPE		LDPE + FR		LDPE + AH	
	250°	260°	300°	340°	290°	270°
Temperature at which acid first titrated	250°	260°	300°	340°	290°	270°
Total H ⁺ titrated (A)	0.36	0.44	0.29 (0.31)	0.27 (0.29)	0.25 (0.39)	0.22 (0.34)
Ion chromatography:						
Formic acid	0.51	0.60	0.13 (0.14)	0.11 (0.12)	0.17 (0.26)	0.12 (0.18)
Acetic acid	0.10	0.11	0.09 (0.10)	0.11 (0.12)	0.07 (0.11)	0.05 (0.08)
Sulphuric acid	0.01	0.01	0.01 (0.01)	0.01 (0.01)	0.01 (0.02)	0.01 (0.02)
Hydrobromic acid	0.00	0.00	0.02 (0.02)	0.03 (0.03)	0.00 (0.00)	0.00 (0.00)
Nitric acid	0.00	0.00	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.01 (0.02)
Total acid found by:						
IC(B)	0.62	0.72	0.25 (0.27)	0.26 (0.28)	0.25 (0.39)	0.19 (0.29)
(A-B)	-0.26	-0.28	+0.04 (+0.04)	+0.01 (+0.01)	0.00 (0.00)	+0.03 (+0.05)

Results in brackets are corrected for additive content.
Results are in milli-equivalents per gram of material.

Table 4
SMOKE AND FUME TEST RESULTS

	LDPE		LDPE + FR		LDPE + AH	
Temperature at which pH change detected	240	240	230	255	265	260
Temperature at which smoke first detected	205	135	350	315	265	270
Smoke maximum temperature	380	390	410	390	405	410
Temperature at which flammable gas first detected	240	240	370	365	-	280
Flammable gas maximum temperature	385	395	415	405	-	415
Temperature at which CO first detected	270	280	370	375	295	300
CO maximum temperature	395	405	445	415	415	420
Smoke number	9.8	7.8	6.6 (7.2)	7.0 (7.5)	5.1 (7.8)	4.2 (6.5)
Hexane number	4.5	6.1	4.3 (4.7)	4.5 (4.9)	-	2.7 (4.1)
CO number	210	220	150 (164)	160 (174)	120 (182)	180 (274)

Table 5COMPARISON OF WEIGHT LOSS WITH MEASURED VOLATILES

Material	Normalised maximum values of			
	Smoke	'Hexane'	CO	Weight loss rate
LDPE	1.00	1.00	1.00	1.00
LDPE + FR	0.76	0.89	0.68	1.89
LDPE + AH	0.46	0.46	0.46	0.94

All results are corrected for additive content

Table 6
EFFECTS OF ADDITIVES ON FIRE PROPERTIES

		FR	AH
Smoke emission (RAE test) - amount	initial temperature	+	+
	maximum temperature	+	+
Smoke emission (NBS test) - flaming	non-flaming	-	0
Acid emission - total	formic	+	0
	acetic	+	+
	initial temperature	0	0
		+	+
Weight loss on heating - maximum rate	initial temperature	-	0
		+	+
Spread of melt		+	+
CO emission - amount	initial temperature	+	0
	maximum temperature	+	+
		+	+
Flammable gas emission - amount	initial temperature	0	0
	maximum temperature	+	+
		+	+
Flammability - UL94	oxygen index	+	+
	temperature index	+	+
	flash ignition temperature	(melts)	+
	self ignition temperature	+	-
	CAA8 (after flame time)	+	+
	CAA8 (burn length)	+	0
	CAA8 (flame time of drips)	+	+
		+	+

+ = better
- = worse
0 = no effect

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Fig 1

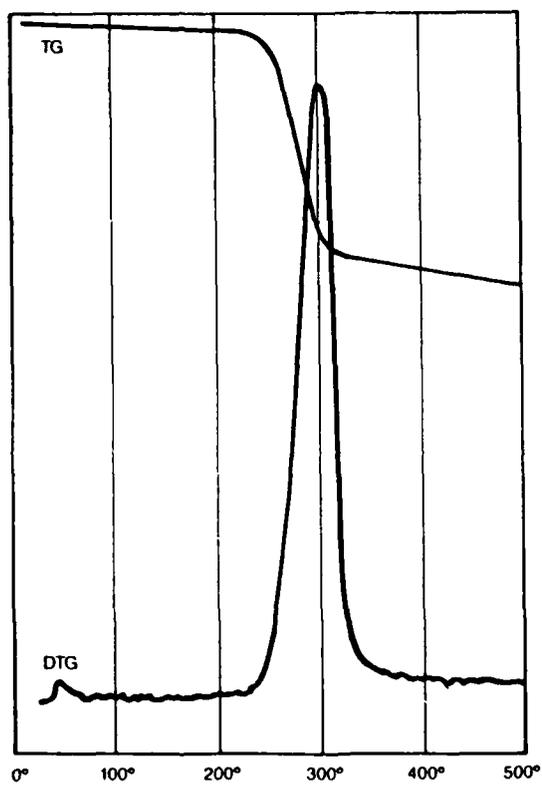


Fig 1 Thermogravimetric and differential thermogravimetric curves for aluminium hydroxide

TM MS 1096

Figs 2&3



Fig 2 LDPE in air at 300°



Fig 3 LDPE + FR in air at 300°

Figs 6&7

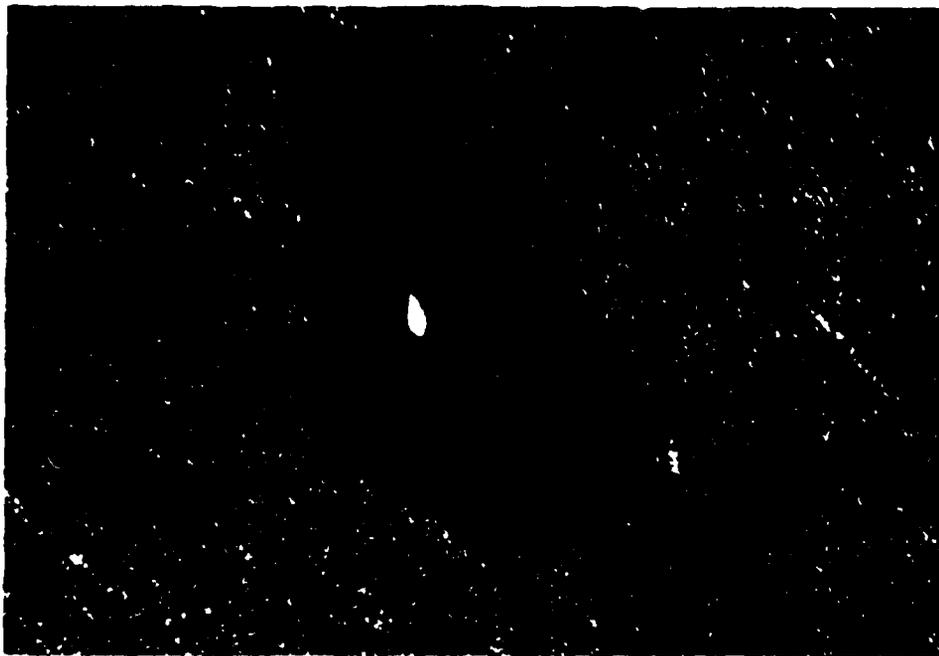


Fig 6 LDPE + FR in nitrogen at 300°



Fig 7 LDPE + AH in air at 300°

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Fig 4 LDPE + AH in air at 300°



Fig 5 LDPE in nitrogen at 300°

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Fig 8 LDPE in oxygen at 300°



Fig 9 LDPE + FR in oxygen at 300°

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Fig 10



Fig 10 LDPE + AH in oxygen at 300°

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Fig 11

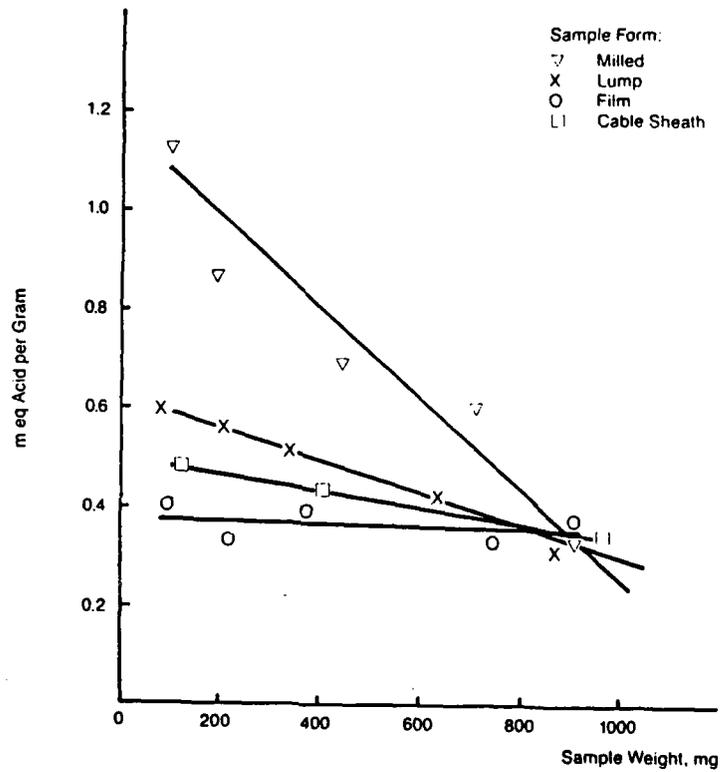


Fig 11 Effects of sample weight and physical form

. Fig 12

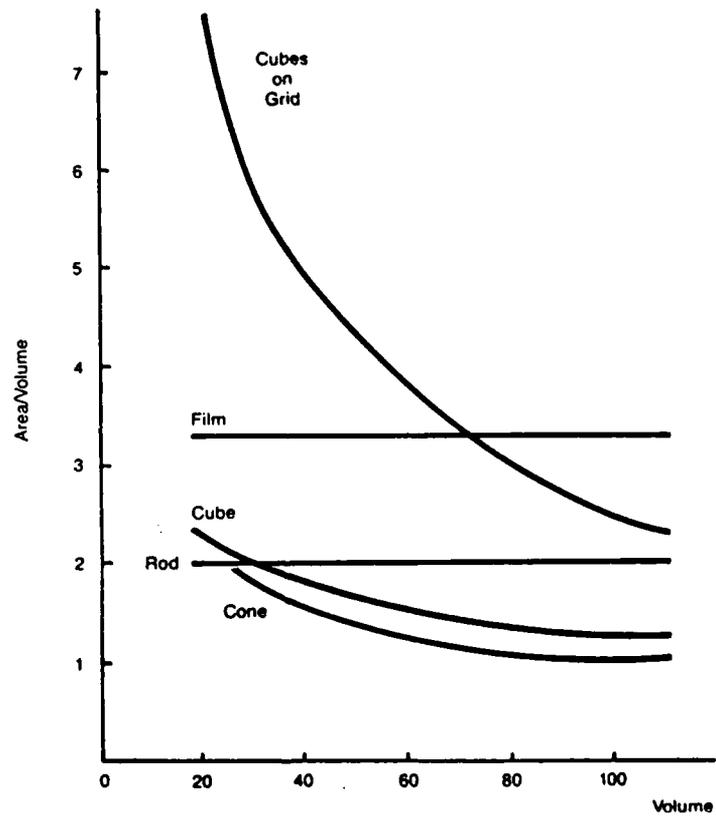


Fig 12 Area/volume ratios in relation to volumes of solids

Fig 13

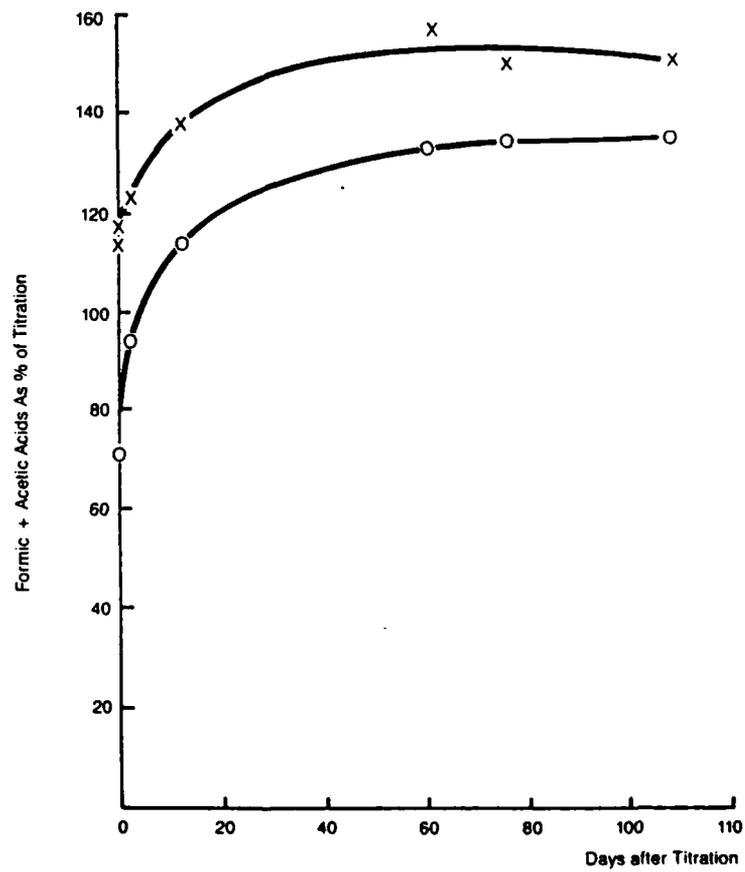


Fig 13 Increase of acetic and formic acid concentrations with time

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Fig 14

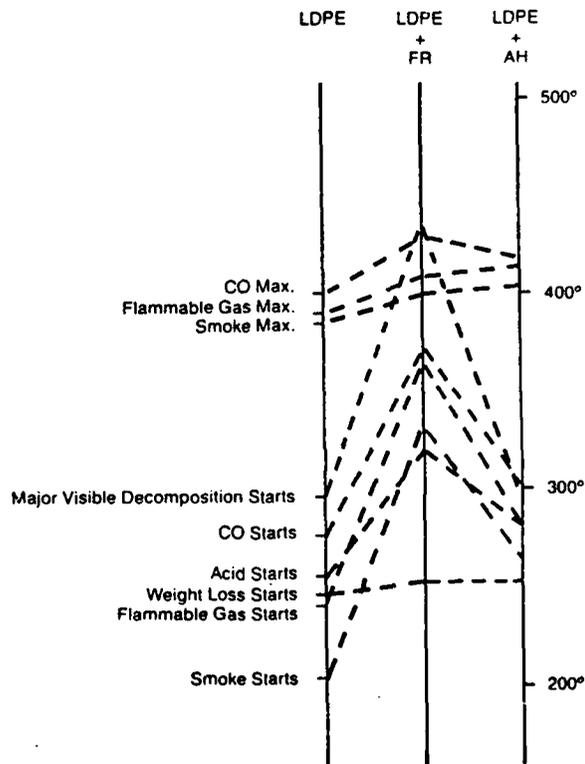


Fig 14 Effects of additives on smoke- and fume-initiation temperatures

Fig 15

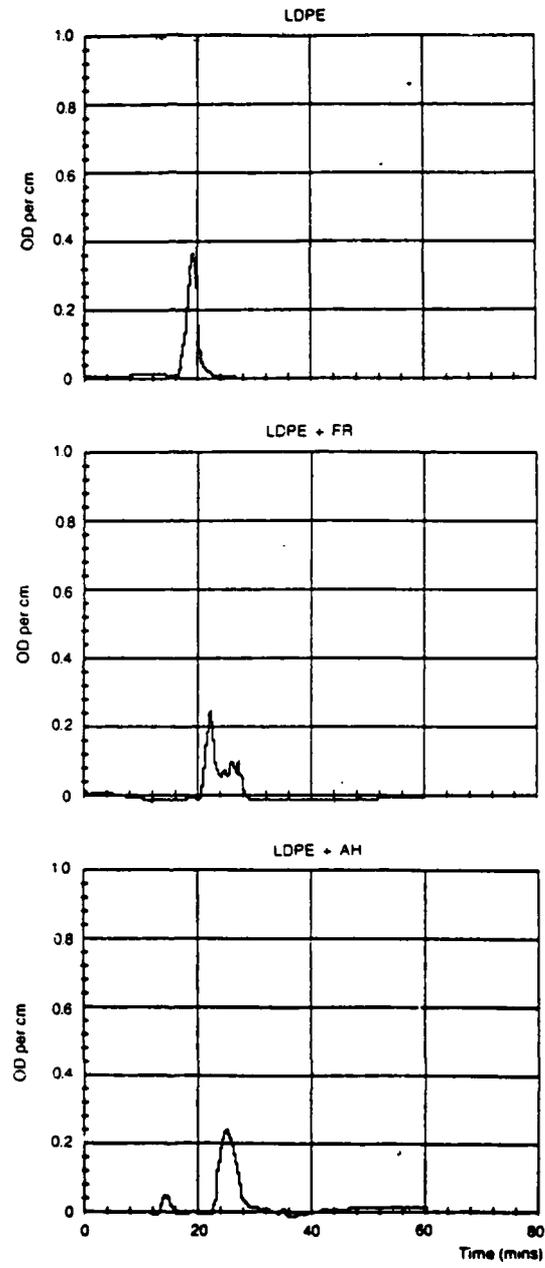


Fig 15 Emission of smoke

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Fig 16

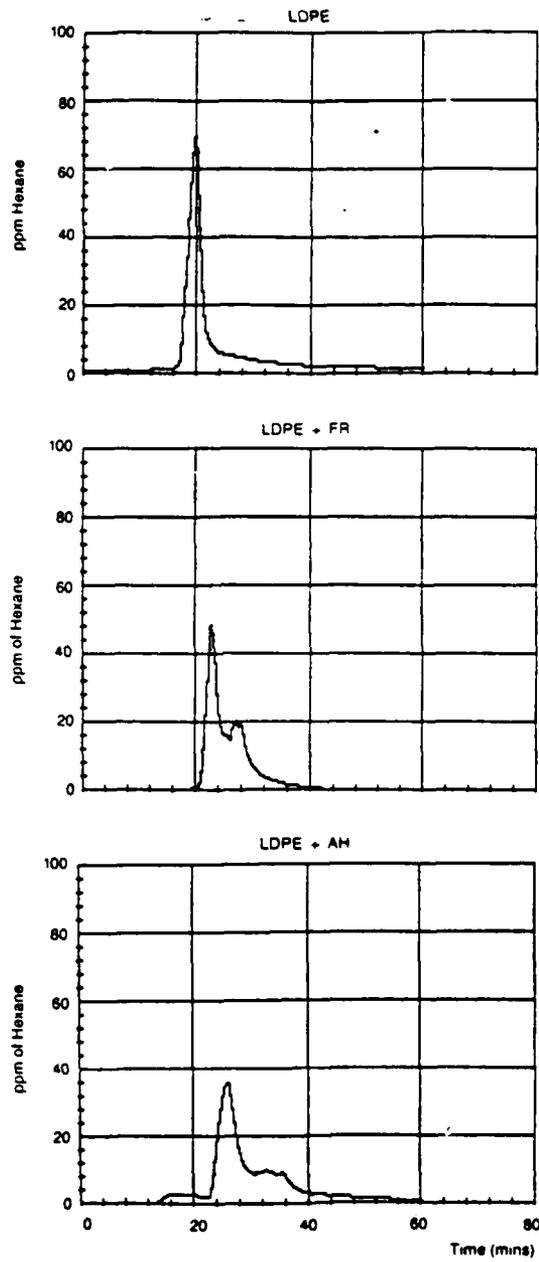


Fig 16 Emission of flammable gas

Fig 17

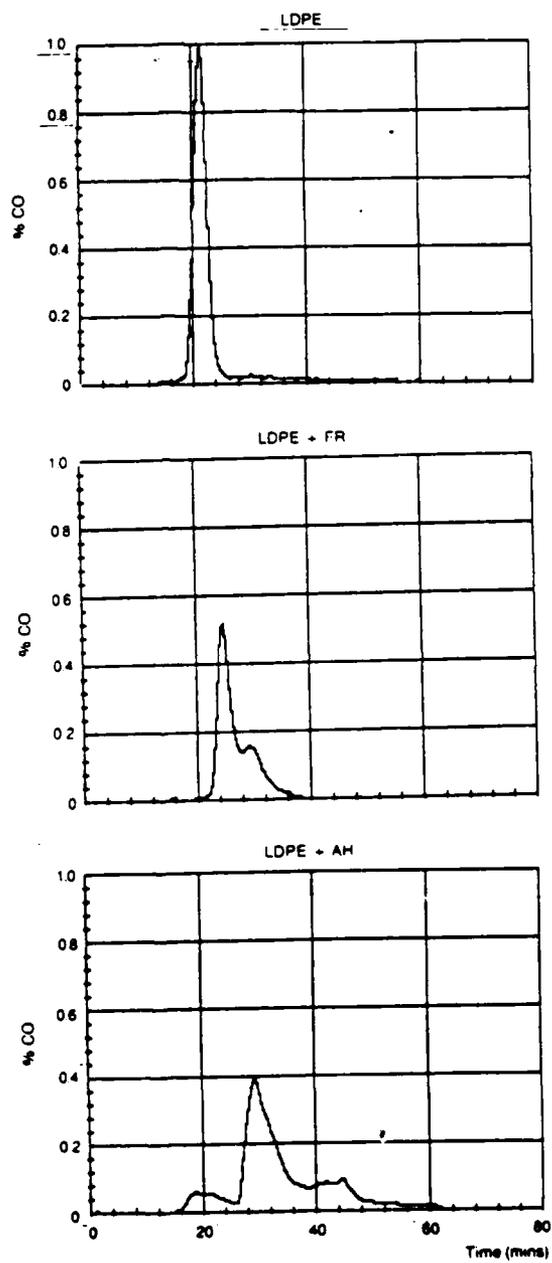


Fig 17 Emission of carbon monoxide

Fig 18

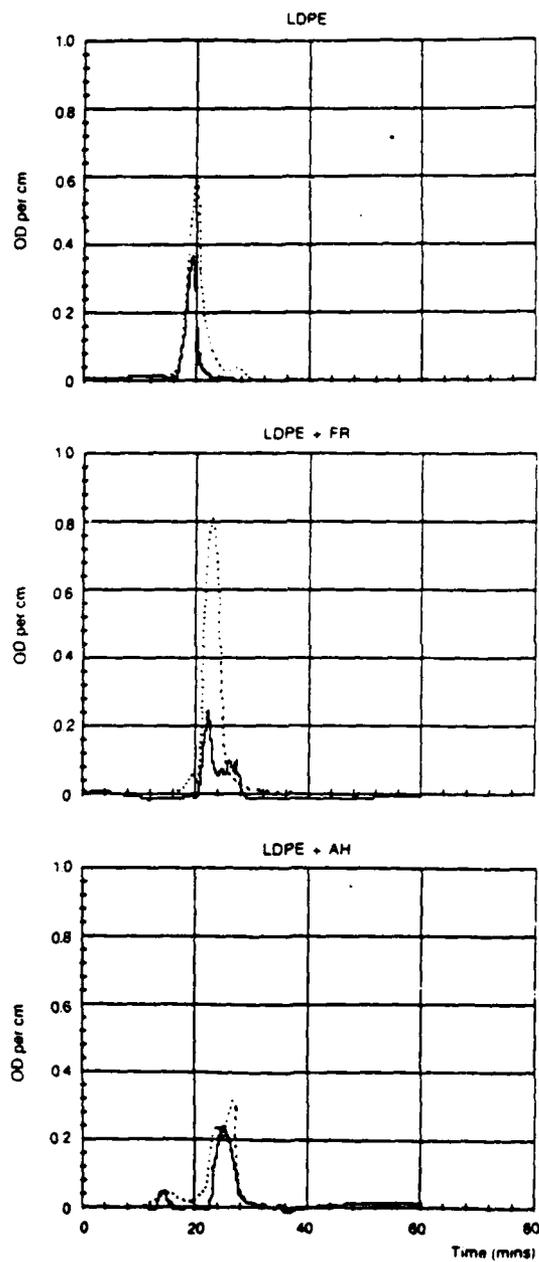


Fig 18 Comparison of smoke-emission (solid) and DTGA (dotted) curves

REPORT DOCUMENTATION PAGE

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST) Polyethylene. Fire. Smoke. Fumes. Fire retardant. Overheating. Acids.			
17. Abstract <p>Low-density polyethylene, with and without an antimony-bromine synergistic fire retardant or aluminium hydroxide, was subjected to standard fire tests and to experiments which determined the smoke and harmful fumes emitted on overheating.</p> <p>Both additives improved most fire properties but the fire retardant increased the smoke generated by intense radiant heat.</p> <p>The onset of smoke, flammable gas, carbon monoxide and acids was generally delayed by the additives. The total amounts and maximum values of these volatiles were lessened. Sample weight and form affect the results from these experiments.</p> <p>Observations during heating show that the additives reduce spreading of the melt, thus reducing the surface area available for oxidation.</p> <p>This memorandum has been submitted to the journal <i>Fire and Materials</i>.</p>			

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