

Antimony Trioxide Free Flame Retardant Polymer Composition

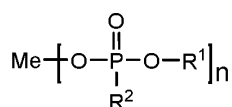
The present disclosure relates to flame retardant additives for thermoplastic compositions and more specifically to a flame retardant additive combination of at least one brominated flame retardant and at least one phosphorus-containing flame retardant as described herein
 5 for thermoplastic polymers.

BACKGROUND

Halogenated organic compounds, including oligomeric and polymeric materials, are widely
 10 used and are highly effective flame retardant additives for polymer resins. To meet high flame retardancy standards in thermoplastics, these flame retardant systems are typically based on a combination of brominated flame retardants with antimony trioxide as synergist. While antimony trioxide is an efficient synergist, it tends to significantly increase the smoke yield, which can impair visibility and create problems for safe evacuation in the case of fire.
 15 Furthermore, antimony trioxide can negatively impact polymer properties in molded parts and is generally associated with increased costs. Moreover, recent environmental standards have restricted use of antimony trioxide in thermoplastic parts. Although there is a clear need for low antimony trioxide or antimony trioxide free flame retardant plastics, the same usually requires a significant increase in the loading of brominated flame retardant.

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US Patent No. 9,475,933 discloses antimony trioxide free flame retardant thermoplastic compositions containing a combination of at least one brominated flame retardant and at least one metal phosphonate or metal phosphinate flame retardant of the following general formula:

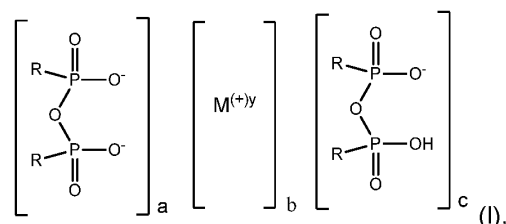


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where Me is a metal, R¹ and R² are the same or different linear or branched or cyclic alkyls having up to 6 carbons atoms, or benzyl, n is a metal valency from 1 to 4, and x is 1 for metal phosphonates and 0 for metal phosphinates. Aluminum methyl methylphosphonate (AMMP) and aluminum diethylphosphinate (DEPAL) are preferred and exemplified in the
 30 disclosure. However, the reported thermal stability of AMMP, such as in US Patent No. 8,889,773, may indicate limitations on its use in thermoplastic polymers that are processed and/or used at high temperatures.

SUMMARY

- In accordance with the present disclosure, thermally-stable phosphorus-containing flame retardants have been developed which in combination with one or more brominated flame retardants provide a highly effective flame retardant additive for thermoplastic polymers without requiring the use of antimony trioxide. Such flame retardant thermoplastic compositions are useful over a wide range of applications, such as in electrical and electronic applications. The phosphorus containing flame retardants of the present disclosure, which are also described in the present Applicant's co-pending patent application nos. PCT/US2019/067184 and PCT/US2019/067230, provide the additional benefit of being compounded into thermoplastic polymers at high temperatures, such as high temperature polyamides and polyterephthalate esters, without decomposing due to the high thermal stability of the phosphorus-containing flame retardants. The additive composition of the present disclosure is therefore useful over a wide range of thermoplastic applications, particularly in thermoplastic polymers that are processed and/or used at high temperatures.
- 15 The present disclosure is directed to an antimony trioxide free flame retardant thermoplastic composition comprising: (a) at least one thermoplastic polymer, (b) at least one brominated flame retardant, and (c) at least one phosphorus-containing flame retardant of empirical formula (I):



- 20 wherein R is H, an alkyl, aryl, alkylaryl, or arylalkyl group, M is a metal and y is 2 or 3, such that $\text{M}^{(+y)}$ is a metal cation where (+)y represents the charge formally assigned to the cation, a, b, and c represent the ratio of the components to which they correspond relative to one another in the compound, and satisfy the charge-balance equation $2(a)+c=b(y)$, and c is not zero.

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Also disclosed is a process of making a flame retardant thermoplastic composition comprising blending (a) at least one thermoplastic polymer, (b) at least one brominated flame retardant, and (c) at least one phosphorus-containing flame retardant of empirical formula (I) above.

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The preceding summary is not intended to restrict in any way the scope of the claimed invention. In addition, it is to be understood that both the foregoing general description and

the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

BRIEF DESCRIPTION OF THE FIGURES

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FIG. 1 shows the result of thermogravimetric analysis (TGA) of an exemplary phosphorus-containing flame retardant material produced according to Example 1 of the present disclosure.

10 FIG. 2 shows the result of thermogravimetric analysis (TGA) of an exemplary phosphorus-containing flame retardant material produced according to Example 7 of the present disclosure.

DETAILED DESCRIPTION

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Unless otherwise specified, the word “a” or “an” in this application means “one or more than one”.

The term “alkyl” in this application includes “arylalkyl,” unless the context dictates otherwise.

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The term “aryl” in this application includes “alkylaryl,” unless the context dictates otherwise.

The term “phosphonic acid” as used herein refers to unsubstituted or alkyl or aryl substituted phosphonic acid, unless the context dictates otherwise.

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The term “pyrophosphonic acid” as used herein refers to unsubstituted or alkyl or aryl substituted pyrophosphonic acid, unless the context dictates otherwise.

30 In accordance with the present disclosure, the combination of one or more phosphorus-containing flame retardant compounds as described herein with at least one brominated flame retardant compound provides a highly effective flame retardant additive for thermoplastic polymers without requiring the use of antimony trioxide.

35 The at least one thermoplastic polymer may be a thermoplastic polyester, polyamide, polystyrene, including high impact polystyrene (HIPS), polyolefin, polycarbonate, polyurethane, polyphenylene ether, or other thermoplastic polymer. In many embodiments, the thermoplastic polymer comprises a polyester (e.g., a polyalkylene terephthalate) or

polyamide. More than one thermoplastic polymer (thermoplastic polymer blends) can be used. The thermoplastic polymer may be unreinforced or reinforced, for example, glass reinforced, such as a glass-filled polyester (e.g., glass-filled polyalkylene terephthalate) or a glass-filled polyamide.

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Examples of thermoplastic polyesters include homopolyesters and copolyesters obtained by polycondensation of an acid component and a diol component or polycondensation of a hydroxycarboxylic acid and a lactone component. For example, suitable polyesters may be chosen from polybutylene terephthalate and polyethylene terephthalate.

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The diol component may contain one or more of the following glycols: ethylene glycol, trimethylene glycol, 2-methyl-1,3-propane glycol, 1,4-butylene glycol, hexamethylene glycol, decamethylene glycol, cyclohexane dimethanol, or neopentylene glycol. The acid component may contain one or more of the following acids: terephthalic acid, isophthalic acid, 2,6-naphthalenedicarboxylic acid, 2,7-naphthalenedicarboxylic acid, 1,5-naphthalenedicarboxylic acid, 4,4'-diphenyldicarboxylic acid, 4,4'-diphenoxyethandicarboxylic acid, p-hydroxybenzoic acid, sebacic acid, adipic acid and polyester-forming derivatives thereof.

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In many embodiments, the thermoplastic polyester is chosen from poly(ethylene terephthalate), poly(1,3-trimethylene terephthalate), poly(1,4-butyleneterephthalate), and blends thereof. For example, thermoplastic polyester blends can comprise from about 1 to about 99 parts by weight of one polyester and from about 99 to about 1 part by weight of a different polyester based on 100 parts by weight of both components combined. The poly(1,4-butylene terephthalate) may be one obtained by polymerizing a diol component which is comprised of at least 70 mol %, e.g., at least 80 mol %, of 1,4-butylene glycol, with an acid component which is comprised of at least 70 mol %, e.g., at least 80 mol %, of terephthalic acid and/or polyester-forming derivatives thereof.

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Thermoplastic polyamides include polyamides derived from a diamine and a dicarboxylic acid, polyamides obtained from an aminocarboxylic acid, including in combination with a diamine and/or a dicarboxylic acid, and polyamides derived from a lactam, including in combination with a diamine and/or a dicarboxylic acid. Examples of suitable polyamides include aliphatic polyamides such as polyamide-4,6, polyamide-6, polyamide-6,6, polyamide-6,10, polyamide-6,12, polyamide-11 and polyamide-12; polyamides obtained from an aromatic dicarboxylic acid, such as terephthalic acid and/or isophthalic acid, and an aliphatic diamine, such as a hexamethylenediamine or nonamethylenediamine; polyamides obtained

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from aliphatic dicarboxylic acids, such as adipic acid and/or azelaic acid, and aromatic diamines, such as meta-xylylenediamine; polyamides obtained from both aromatic and aliphatic dicarboxylic acids, such as both terephthalic acid and adipic acid, and an aliphatic diamine, such as hexamethylenediamine; polyamides obtained from adipic acid, azelaic acid, and 2,2-bis-(p-aminocyclohexyl)propane; and polyamides obtained from terephthalic acid and 4,4'-diaminodicyclohexylmethane. Mixtures and/or copolymers of two or more of the foregoing polyamides or prepolymers thereof, respectively, may also be used.

The polyamides may be made by any known method, such as via polymerization of a monoaminomonocarboxylic acid or a lactam thereof having at least two carbon atoms between the amino and carboxylic acid group, of substantially equimolar proportions of a diamine which contains at least two carbon atoms between the amino groups and a dicarboxylic acid, or of a monoaminocarboxylic acid or a lactam thereof as defined above, together with substantially equimolar proportions of a diamine and a dicarboxylic acid. The dicarboxylic acid may be used in the form of a functional derivative thereof, for example, a salt, an ester or acid chloride.

Polyamides with melting points of at least 280°C are used extensively for producing molding compositions which make possible the production of molded articles, e.g. for the electrical and electronics industry, with excellent dimensional stability at high temperatures and with very good flame-retardant properties. Molding compositions of this type are demanded for example in the electronics industry for producing components which are mounted on printed circuit boards according to the so-called surface mounting technology, SMT. In this application, these components must withstand temperatures of up to 270°C for short periods of time without dimensional change.

Such high temperature polyamides include certain polyamides produced from alkyl diamines and diacids, such as polyamide 4,6. Further, many high temperature polyamides are aromatic and semi-aromatic polyamides, i.e., homopolymers, copolymers, terpolymers, or higher polymers that are derived from monomers containing aromatic groups. An aromatic or semi-aromatic polyamide may be employed or blends of aromatic and/or semi-aromatic polyamides may be used. Blends with aliphatic polyamides may also be used.

Examples of suitable high temperature aromatic or semi-aromatic polyamides include polyamide-4,T, poly(m-xylylene adipamide) (polyamide-MXD,6), poly(dodecamethylene terephthalamide) (polyamide-12,T), poly(decamethylene terephthalamide) (polyamide-10,T), poly(nonamethylene terephthalamide) (polyamide-9,T), hexamethylene

- adipamide/hexamethylene terephthalamide copolyamide (polyamide-6,T/6,6),
 hexamethylene terephthalamide/2-methylpentamethylene terephthalamide copolyamide
 (polyamide-6,T/D,T); hexamethylene adipamide/hexamethylene
 terephthalamide/hexamethylene isophthalamide copolyamide (polyamide-6,6/6,T/6,I);
 5 poly(caprolactam-hexamethylene terephthalamide) (polyamide-6/6,T); hexamethylene
 terephthalamide/hexamethylene isophthalamide (polyamide-6,T/6,I) copolymer; and the like.

- Certain embodiments of the invention are thus to compositions comprising a polyamide that
 melts at high temperatures, e.g., 280° C or higher, 300°C, or higher, or 320°C or higher. In
 10 some embodiments, the polyamide has a melting temperature from 280 to 340°C, such as
 polyamide 4,6 or the aromatic and semi-aromatic polyamides described above.

- Preferred polyamides are polyamide-6, polyamide-6,6, polyamide-11, polyamide-12,
 polyphthalamides, such as polyamide-4,T, polyamide-6,T/6,6, and polyamide-6,6/6,T/6,I
 15 copolymers, glass-filled polyamides thereof, and blends thereof. For example, thermoplastic
 polyamide blends
 can comprise from about 1 to 99 parts by weight of one polyamide and from about 99 to
 about 1 part by weight of a different polyamide based on 100 parts by weight of both
 components combined..

- 20 In some embodiments, the polymer is a thermoplastic elastomer (e.g., thermoplastic
 polyolefins or thermoplastic polyurethanes. In some embodiments, the thermoplastic
 elastomer is a thermoplastic polyurethane.

- 25 At least one inorganic filler may be added to the flame retardant thermoplastic composition
 for the purpose of reducing the molding shrinkage coefficient and linear expansion
 coefficient of a resultant molded article and improving high and low heat shock property.
 Various fillers in the form of fiber or non-fiber (e.g., powder, plate) may be used depending
 on the desired article. Some examples of fibrous filler, which are types of inorganic filler, may
 30 be those such as, glass fiber, glass fiber having a non-circular cross section, such as flat
 fiber, carbon fiber, silica fiber, silica alumina fiber, zirconia fiber, boron nitride fiber, silicon
 nitride fiber, boron fiber, potassium titanate fiber, and further, metal fibrous substances such
 as stainless, aluminum, titanium, copper and brass. Typical fibrous filler is glass fiber or
 carbon fiber. Alternatively, the inorganic filler may be a powdery filler, such as carbon black,
 35 graphite, silica, quartz powder, glass bead, glass powder, calcium silicate, kaolin, talc, clay,
 diatomaceous earth, silicates, such as wollastonite, metal oxides, such as iron oxide,
 titanium oxide, zinc oxide and alumina, metal hydroxides, metal carbonates, such as calcium

carbonate and magnesium carbonate, metal sulfates, such as calcium sulfate and barium sulfate, silicon carbide, silicon nitride, boron nitride and various metal powders. Another example of inorganic filler is plate-like filler such as mica, glass flake and various metal foils. These inorganic fillers can be used alone or in combination of two or more. In use, the
5 inorganic fillers are desirably treated previously with a sizing agent or surface treatment agent, if necessary.

The amount of the at least one inorganic filler in the antimony trioxide free flame retardant thermoplastic composition may be from about 1 to about 50 weight percent, e.g., from about
10 5 to about 50 weight percent, from about 10 to about 40 weight percent, or from about 15 to about 30 weight percent, based on the total weight of the flame retardant thermoplastic composition.

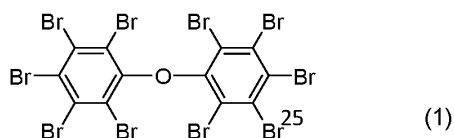
Other ingredients typically employed in amounts less than 10 percent by weight of the flame
15 retardant thermoplastic composition, e.g., less than 5 percent by weight, include non-limiting examples such as antioxidants, UV stabilizers, lubricants, impact modifiers, acid scavengers, heat stabilizers, pigments, dyes, optical brighteners, anti-static agents, anti-dripping agents, and other additives used to enhance the properties of the resin. Typically, transesterification inhibitors are used in amounts from 0.01 percent to 0.5 percent by weight and include
20 monozinc phosphate, zinc phosphate, or other types of inhibitors. Conventional stabilizer additives are often used in amounts from 0.01 to 5 percent by weight of the total flame retardant thermoplastic composition and include examples such as hindered phenols and antioxidants. Typical anti-drip agents include tetrafluoroethylene polymers.

25 The at least one brominated flame retardant and the at least one phosphorus-containing flame retardant are present in the flame retardant thermoplastic composition in flame retardant effective amounts.

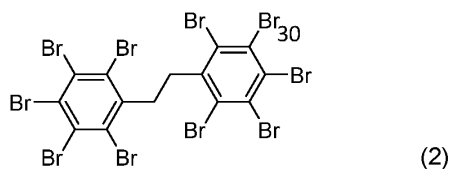
In many embodiments, the antimony trioxide free flame retardant thermoplastic composition
30 comprises the at least one thermoplastic polymer (a) in an amount of from about 30 to about 95 weight percent, the at least one brominated flame retardant (b) in an amount of from about 3 to about 30 weight percent, and the at least one phosphorus-containing flame retardant (c) in an amount of from about 1 to about 10 weight percent, all based on the total weight of the flame retardant thermoplastic composition. In a further embodiment, the
35 antimony trioxide free flame retardant thermoplastic composition comprises the at least one thermoplastic polymer (a) in an amount of from about 30 to about 90 weight percent, the at least one brominated flame retardant (b) in an amount of from about 5 to about 30 weight

- percent, and the at least one phosphorus-containing flame retardant (c) in an amount of from about 1 to about 10 weight percent, all based on the total weight of the flame retardant thermoplastic composition. In some embodiments, the flame retardant thermoplastic composition further comprises at least one inorganic filler in an amount of from about 1 to about 50 weight percent, based on the total weight of the flame retardant thermoplastic composition. Often, the at least one inorganic filler is present from about 5 to about 50 weight percent, e.g., about 10 to about 40 weight percent or about 15 to about 30 weight percent, based on the total weight of the flame retardant thermoplastic composition.
- Non-limiting examples of suitable brominated flame retardant compounds include decabromodiphenyl oxide, decabromodiphenyl ethane, tetrabromobisphenol A, tetrabromobisphenol A bis (2,3-dibromopropyl ether), tris(tribromophenoxy)triazine, tris(tribromoneopentyl) phosphate, brominated polyacrylate, brominated polystyrene, polybromostyrene, Poly (Dibromophenylene oxide), brominated styrene-butadiene-styrene copolymers, brominated epoxy polymers, end capped brominated epoxy polymers, phenoxy-terminated carbonate oligomer of tetrabromobisphenol A, tetrade cabromodiphenoxybenzene, ethylenebistetrabromophthalimide, tetrabromobisphenol S bis (2,3-dibromopropyl ether), 2-ethylhexyl tetrabromophthalate ester, and bis (tribromophenoxy) ethane:

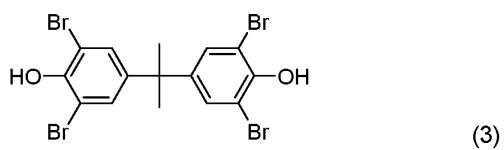
Decabromodiphenyl oxide



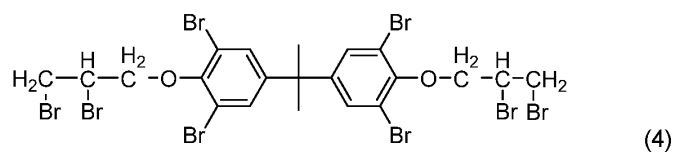
Decabromodiphenyl ethane (such as sold under the trade name Firemaster 2100R)



- Tetrabromobisphenol A (such as sold under the trade name BA-59P)

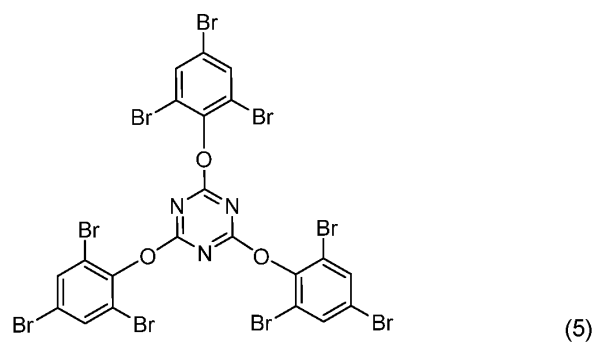


Tetrabromobisphenol A bis (2,3-dibromopropyl ether)

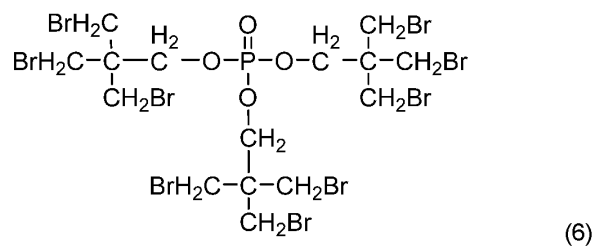


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Tris(tribromophenoxy)triazine

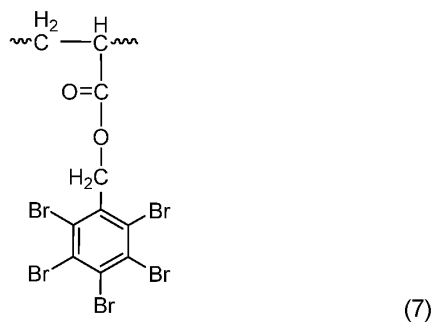


Tris(tribromoneopentyl) phosphate

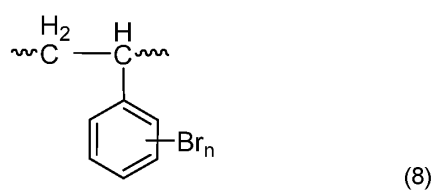


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Brominated polyacrylate

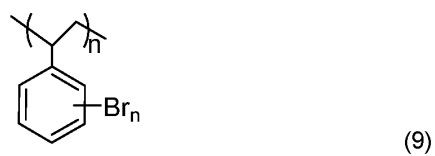


Brominated polystyrene

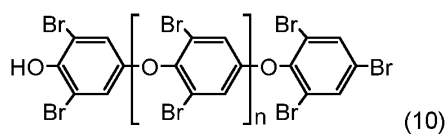


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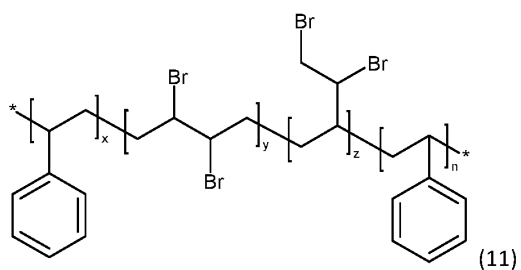
Polybromostyrene (such as sold under the trade names PDBS-80 and Firemaster PBS-64HW)



10 Poly(dibromophenylene oxide) (such as sold under the trade name Uniplex FRP-64)

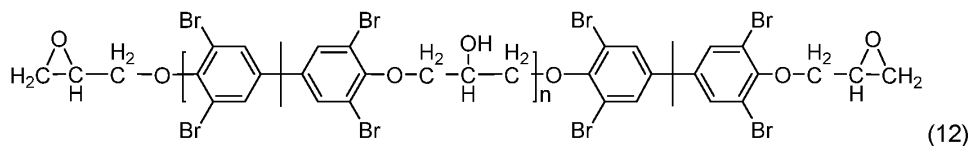


Brominated styrene-butadiene polymer (such as sold under the trade name Emerald Innovation® 3000)

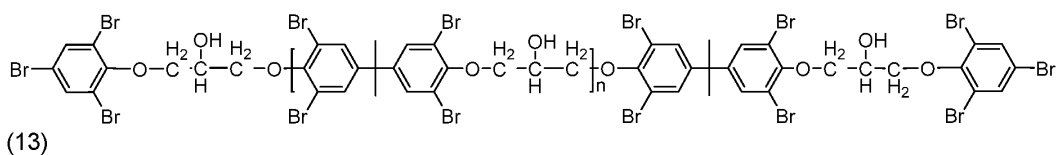


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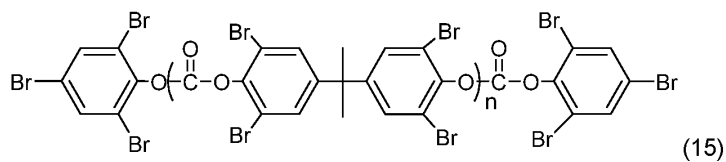
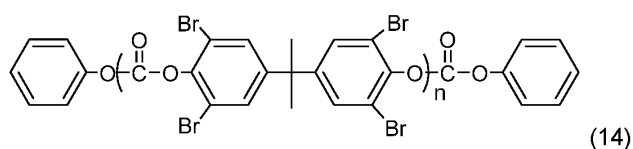
Brominated epoxy polymers



5 End capped brominated epoxy polymers

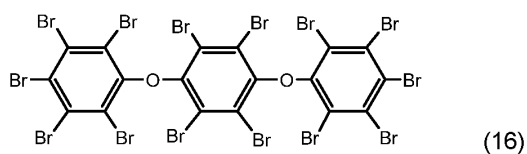


10 Phenoxy-terminated carbonate oligomer of tetrabromobisphenol A (such as sold under the trade names BC-25 and BC-58)

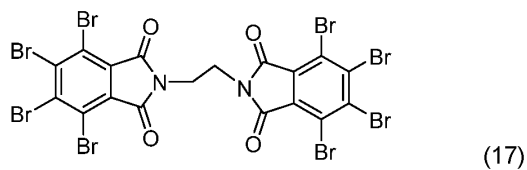


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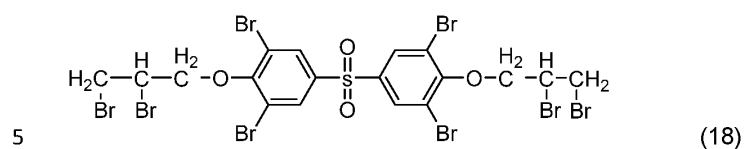
Tetradecabromodiphenoxybenzene



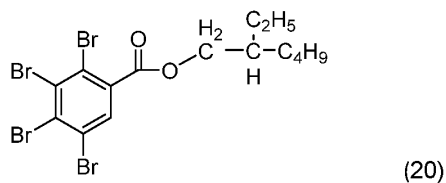
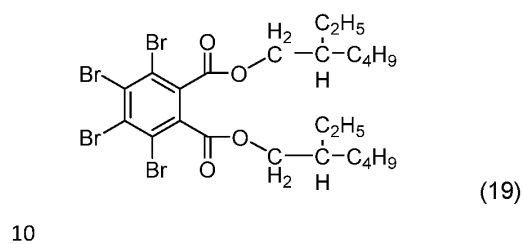
20 Ethylenebistetrabromophthalimide



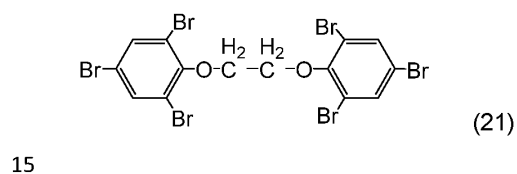
Tetrabromobisphenol S bis (2,3-dibromopropyl ether)



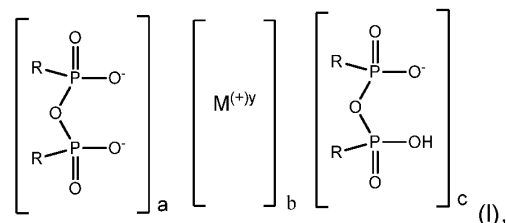
2-ethylhexyl tetrabromophthalate ester (such as under the trade names Uniplex FRP45 and Firemaster BZ-54)



Bis(tribromophenoxy) ethane



The at least one phosphorus-containing flame retardant of the present disclosure has the following empirical formula:

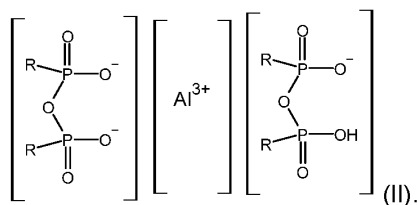


wherein R is H, an alkyl, aryl, alkylaryl, or arylalkyl group, M is a metal and y is 2 or 3, such that $\text{M}^{(+y)}$ is a metal cation where (+)y represents the charge formally assigned to the cation, a, b, and c represent the ratio of the components to which they correspond relative to one another in the compound, and satisfy the charge-balance equation $2(a)+c=b(y)$, and c is not zero. Often, a is 0, 1, or 2 (e.g., 0 or 1), b is from 1 to 4, e.g., 1 or 2, and c is 1 or 2, and the product is charged balanced. Examples of suitable metals (M) include, but are not limited to, Al, Ga, Sb, Fe, Co, B, Bi, Mg, Ca, and Zn.

As is common with inorganic coordination compounds, formula (I) is empirical or idealized such that the compounds may be coordination polymers, complex salts, salts where certain atomic valences are shared, etc. For example, in many embodiments, empirical formula (I) represents a monomer unit (i.e., coordination entity) of a coordination polymer, the extended coordination polymer structure thereby forming the phosphorus-containing flame retardant of the present disclosure.

In certain embodiments, y in formula (I) is 2 (i.e., $\text{M}^{(+y)}$ is a di-cationic metal), a is 0, b is 1, and c is 2. In certain embodiments, the di-cationic metal M is Mg, Ca, or Zn. In other embodiments, y in formula (I) is 3 (i.e., $\text{M}^{(+y)}$ is a tri-cationic metal), a is 1, b is 1, and c is 1. In certain embodiments, the tri-cationic metal M is chosen from Al, Ga, Sb, Fe, Co, B, and Bi. In certain embodiments, the tri-cationic metal M is Al, Fe, Ga, Sb, or B.

In one example, M is Al and y is 3 and the phosphorus-containing flame retardant has the following empirical formula:



As shown herein, the absence of subscripts a, b and c in an empirical formula indicates that the subscripts are each 1, signifying a 1:1:1 ratio of the di-anionic pyrophosphonic acid ligand, metal atom, and mono-anionic pyrophosphonic acid ligand. In many embodiments,

empirical formula (II) represents a repeating monomer unit (i.e., coordination entity) of a coordination polymer, the extended coordination polymer structure thereby forming the phosphorus-containing flame retardant of the present disclosure.

- 5 Often, R is H, C₁₋₁₂ alkyl, C₆₋₁₀ aryl, C₇₋₁₈ alkylaryl, or C₇₋₁₈ arylalkyl, wherein said alkyl, aryl, alkylaryl, or arylalkyl are unsubstituted or are substituted by halogen, hydroxyl, amino, C₁₋₄ alkylamino, di-C₁₋₄ alkylamino, C₁₋₄ alkoxy, carboxy or C₂₋₅ alkoxy carbonyl. In some
embodiments, said alkyl, aryl, alkylaryl, or arylalkyl are unsubstituted C₁₋₁₂ alkyl, C₆ aryl, C₇₋₁₀ alkylaryl, or C₇₋₁₀ arylalkyl, for example, C₁₋₆ alkyl, phenyl, or C₇₋₉ alkylaryl. In some
10 embodiments, R is substituted or unsubstituted C₁₋₆ alkyl, C₆ aryl, C₇₋₁₀ alkylaryl, or C₇₋₁₂ arylalkyl, e.g., C₁₋₄ alkyl, C₆ aryl, C₇₋₉ alkylaryl, or C₇₋₁₀ arylalkyl. In many embodiments, R is unsubstituted C₁₋₁₂ alkyl, e.g., C₁₋₆ alkyl. In many embodiments, lower alkyl phosphonic acids are used, e.g., methyl-, ethyl-, propyl-, isopropyl-, butyl-, t-butyl- and the like.
- 15 R as alkyl may be a straight or branched chain alkyl group having the specified number of carbons and includes e.g., unbranched alkyls such as methyl, ethyl, propyl, butyl, pentyl, hexyl, heptyl, octyl, nonyl, decyl, undecyl, dodecyl, and branched alkyl such as isopropyl, isobutyl, sec-butyl, t-butyl, ethyl hexyl, t-octyl and the like. For example, R as alkyl may be chosen from methyl, ethyl, propyl, isopropyl, butyl, isobutyl, sec-butyl, and t-butyl. In many
20 embodiments, R is methyl, ethyl, propyl or isopropyl, for example methyl or ethyl.

- Often, when R is aryl it is phenyl. Examples of R as alkylaryl include phenyl substituted by one or more alkyl groups, for example groups selected from methyl, ethyl, propyl, isopropyl, butyl, isobutyl, sec-butyl, t-butyl, and the like. Examples of R as arylalkyl, include for
25 example, benzyl, phenethyl, styryl, cumyl, phenpropyl and the like.

- In many embodiments, R is chosen from methyl, ethyl, propyl, isopropyl, butyl, phenyl and benzyl. In certain embodiments, R is methyl, ethyl, propyl, isopropyl or butyl and M is Al, Fe, Zn or Ca.

- 30 The phosphorus-containing flame retardant of the present disclosure can be a mixture of compounds of empirical formula (I).

- The phosphorus-containing flame retardant of the present disclosure has a high phosphorus
35 content (i.e., a higher ratio of phosphorus atoms to metal atoms (P to M)) as compared to phosphorus-containing flame retardants described in the art. For example, tri-cationic metals (e.g., aluminum) and di-cationic metals (e.g., zinc) are known to form tri-substituted

and di-substituted charge balanced compounds, respectively. As seen in the art, tris-phosphonate aluminum salts—having a phosphorus to aluminum ratio of 3:1—and di-phosphonate zinc salts—having a phosphorus to zinc ratio of 2:1—are known as flame retardants. However, in accordance with the pyrophosphonic acid ligand formation of the present disclosure, the ratio of phosphorus to metal in the flame retardant product is higher. For example, as demonstrated in the Examples disclosed herein, the ratio of phosphorus to aluminum, or the ratio of phosphorus to iron, in the resulting flame retardant product was 4:1.

The phosphorus-containing flame retardant of empirical formula (I) may be prepared by a process referred to herein as the solvent method or by a process referred to herein as the molten state method.

Preparing the phosphorus-containing flame retardant via the solvent method

The phosphorus-containing flame retardant of empirical formula (I) may be prepared by reacting a metal or suitable metal compound with an unsubstituted or alkyl or aryl substituted phosphonic acid. The process includes (i) preparing a reaction mixture, the reaction mixture comprising (a) an unsubstituted or alkyl or aryl substituted phosphonic acid, (b) a solvent for the phosphonic acid, and (c) a metal or suitable metal compound; and (ii) heating or reacting the reaction mixture at a reaction temperature of 105 °C or higher for an amount of time sufficient to produce the phosphorus-containing flame retardant. In the reaction, the metal is oxidized and may be represented in its corresponding cationic form by the formula $M^{(+y)}$ where M is a metal, (+y) represents the charge of the metal cation, and y is 2 or 3. The suitable metal compound may be represented by the formula $M_p^{(+y)}X_q$, where M is a metal, (+y) represents the charge of the metal cation, y is 2 or 3, X is an anion, and the values for p and q provide a charge balanced metal compound.

In another embodiment, the phosphorus-containing flame retardant may be prepared by reacting a metal or suitable metal compound with an unsubstituted or alkyl or aryl substituted pyrophosphonic acid. The process includes (i) preparing a reaction mixture, the reaction mixture comprising (a) an unsubstituted or alkyl or aryl substituted pyrophosphonic acid, (b) a solvent for the pyrophosphonic acid, and (c) a metal or suitable metal compound as above; and (ii) heating or reacting the reaction mixture at a reaction temperature of 20 °C or higher for an amount of time sufficient to produce the phosphorus-containing flame retardant.

- The reaction product typically forms as a slurry as the resulting phosphorus-containing flame retardant product precipitates from the reaction mixture. Phosphonic acid, pyrophosphonic acid, and/or solvent remaining after the reaction can be removed along with any possible byproducts by filtration and/or washing, e.g., with water. In many embodiments, a
- 5 substantially pure flame retardant material is produced, e.g., a flame retardant comprising essentially a single compound with flame retardant activity or essentially a mixture of active compounds. Conversion based on the metal or metal compound is typically high, and the product can be readily isolated and optionally further purified if desired.
- 10 Typically, the molar ratio of the phosphonic or pyrophosphonic acid to the metal or suitable metal compound in the reaction mixture is higher than 2:1, such as about 3:1 or higher, about 4:1 or higher, about 5:1 or higher, about 6:1 or higher, about 7:1 or higher, or about 8:1 or higher. Often larger molar excesses of the phosphonic or pyrophosphonic acid to the metal or suitable metal compound are used in the reaction mixture, such as about 10:1 or
- 15 higher, about 15:1 or higher, about 20:1 or higher, about 25:1 or higher, about 30:1 or higher, or any range therebetween. A large molar excess of the phosphonic or pyrophosphonic acid relative to the metal or suitable metal compound may be used. For example, the molar ratio may be up to about 50:1, up to about 100:1, up to about 300:1, up to about 500:1, or any range therebetween. However, as would be understood, process
- 20 efficiency may suffer at certain large molar excesses, e.g., product precipitation from the reaction mixture may be hindered. In many embodiments, the molar ratio ranges from about 4:1, from about 5:1, from about 6:1, from about 8:1 or from about 10:1 to about 100:1 or to about 50:1, such as from about 8:1, from about 12:1, from about 16:1 or from about 20:1 to about 50:1 or to about 40:1.
- 25
- The reaction mixture is heated at a reaction temperature for an amount of time sufficient to produce the flame retardant product. As used herein, the step of "heating the reaction mixture at a reaction temperature for an amount of time sufficient to produce the phosphorus-containing flame retardant" and the like include, but are not limited to,
- 30 embodiments where all or substantially all of component (b) of the reaction mixture—i.e., the solvent for the phosphonic or pyrophosphonic acid—boils off from the reaction mixture during the course of heating the reaction mixture to or at the reaction temperature. It is therefore understood that the "reaction mixture" described herein is still said to be heated at the reaction temperature even where all or substantially all of the solvent component (b)
- 35 boils off during the course of heating the reaction mixture to or at the reaction temperature.

- The reaction temperature for producing the phosphorus-containing flame retardant of the present disclosure according to the solvent method should be chosen to facilitate the formation of pyrophosphonic acid ligands in the reaction product. For a phosphonic acid, a reaction temperature of 105 °C or higher is used. Without being bound by a particular
- 5 theory, the reaction temperature is chosen to produce pyrophosphonic acid ligands via dehydration reaction(s). In many embodiments, the metal or suitable metal compound and the phosphonic acid are reacted at temperatures higher than 105 °C, such as about 115 °C or higher, about 120 °C or higher, about 130 °C or higher, about 140 °C or higher, about 150 °C or higher, about 160 °C or higher, about 170 °C or higher, about 180 °C or higher,
- 10 about 200 °C or higher, about 220 °C or higher, about 240 °C or higher, about 260 °C or higher, about 280 °C or higher, or any range therebetween. The reaction temperature may be higher than those described above, such as up to about 350 °C, up to about 400 °C, or higher, but it typically does not meet or exceed the boiling temperature of the phosphonic acid. In many embodiments, the reaction temperature ranges from about 110 °C to about
- 15 350 °C, from about 115 °C to about 300 °C, from about 125 °C to about 280 °C, or from about 140 °C to about 260°C. Through the dehydration reaction(s), water is formed, which can potentially lead to the undesirable reverse (hydrolysis) reaction. Thus, in some embodiments, the reaction system is designed to facilitate removal, such as the continuous removal, of water from the reaction mixture. For example, the reaction temperature may be
- 20 chosen above the boiling temperature of the water to the extent necessary to boil off at least a portion or desired amount (e.g., a majority, substantially all, or all) of the water from the reaction. Additional means, such as a gas purge, vacuum, and/or other known means, may be used to facilitate removal of water from the reaction system.
- 25 For a pyrophosphonic acid, a reaction temperature of 20 °C or higher is used. As dehydration is unnecessary for pyrophosphonic acid, the reaction temperature can be lower than that described above for phosphonic acid. In many embodiments, the metal or suitable metal compound and the pyrophosphonic acid are reacted at temperatures higher than 20 °C, such as about 40 °C or higher, about 60 °C or higher, about 80 °C or higher, about 100
- 30 °C or higher, about 140 °C or higher, about 180 °C or higher, about 200 °C or higher, or any range therebetween. The reaction temperature may be higher than those described above, such as up to about 300 °C, up to about 400 °C, or higher, but it typically does not meet or exceed the boiling temperature of the pyrophosphonic acid. In many embodiments, the reaction temperature ranges from about 25 °C to about 350 °C, from about 25 °C to about
- 35 280 °C, from about 30 °C to about 260 °C, from about 40 °C to about 260°C, or from about 60 °C to about 240°C. Depending, for example, on the metal compound used to react with the pyrophosphonic acid, water may be generated from the reaction. As described above, in

some embodiments, the reaction system is designed to facilitate removal, such as the continuous removal, of water from the reaction. For example, the reaction temperature may be chosen above the boiling temperature of the water to the extent necessary to boil off at least a portion or desired amount (e.g., a majority, substantially all, or all) of the water from the reaction. Additional means, such as a gas purge, vacuum, and/or other known means, may be used to facilitate removal of water from the reaction system.

The reaction may, but need not, be run under reduced pressure or vacuum.

In some embodiments of the solvent method, the solvent is a protic solvent (e.g., water) and the reaction system is designed to facilitate removal, such as the continuous removal, of the protic solvent during heating of the reaction mixture. For example, the reaction temperature may be chosen at or higher than the boiling temperature of the protic solvent to the extent necessary to boil off at least a portion or desired amount (e.g., a majority, substantially all, or all) of the protic solvent during heating of the reaction mixture. In certain embodiments, the solvent is water and the reaction temperature is about 110 °C or higher, about 115 °C or higher, about 120 °C or higher, about 130 °C or higher, about 140 °C or higher, about 150 °C or higher, or about 160 °C or higher, such as the exemplary ranges described above. The reaction temperature may also be chosen at or higher than the melting temperature of the phosphonic or pyrophosphonic acid, such as further described herein.

Typically, the flame retardant product will precipitate from the reaction mixture such that the reaction is run for a time sufficient to achieve such precipitation. In general, the amount of time required to achieve at least substantial conversion to the flame retardant product, based on the metal or suitable metal compound in the reaction mixture, will depend on the reaction temperature, with higher temperatures generally resulting in shorter reaction times. Often, heating or reacting occurs at the reaction temperature for from about 0.1 to about 48 hours, such as from about 0.2 to about 36 hours, from about 0.5 to about 30 hours, from about 1 hour to about 24 hours, e.g., from about 1 hour to about 12 hours, from about 1 hour to about 8 hours, or from about 1 hour to about 5 hours, although other durations may be used.

The reaction mixture can be prepared in any manner suitable for combining or mixing (a) the unsubstituted or alkyl or aryl substituted phosphonic or pyrophosphonic acid, (b) the solvent for the phosphonic or pyrophosphonic acid, and (c) the metal or suitable metal compound. For example, the components may be combined simultaneously or at different times. In some embodiments, the metal or suitable metal compound (c) is added to a mixture, such as a solution, of the phosphonic or pyrophosphonic acid (a) and solvent (b). The metal or

suitable metal compound (c) can be added to the reaction mixture all at once or in portions. Similarly, the phosphonic or pyrophosphonic acid (a), solvent (b), or mixture, such as a solution, of the phosphonic or pyrophosphonic acid (a) and solvent (b), can be added to the reaction mixture all at once or in portions.

5

In preparing the reaction mixture, the phosphonic or pyrophosphonic acid (a), the solvent (b), and the metal or suitable metal compound (c) may be combined at a preparation temperature below the reaction temperature. The reaction mixture is subsequently heated to the reaction temperature. A preparation temperature may be chosen, for example, to facilitate dissolution of the phosphonic or pyrophosphonic acid (a) in the solvent (b) or to otherwise form a homogenous liquid or solution of the phosphonic or pyrophosphonic acid (a) and the solvent (b). At the preparation temperature, and depending on the metal compound (c), the reaction mixture may form a solution, suspension or slurry, such as a homogenous or substantially homogenous suspension or slurry. In some embodiments, such as at higher preparation temperatures, the reaction mixture may form a solution. Often, near or at the reaction temperature the reaction mixture will present as a solution. In many embodiments, the preparation temperature is about 0 °C or higher, but often below 150 °C, such as below 125 °C, below 115 °C, below 100 °C, below 85 °C, or below 65 °C. For example, the preparation temperature may range from about 0 °C to about 65 °C or from about 15 °C to about 40 °C. In some embodiments, the reaction mixture is prepared at room temperature (e.g., from about 15 °C to about 25 °C). In some embodiments, the solvent (b) is preheated to the preparation temperature and combined with the phosphonic or pyrophosphonic acid (a) and the metal or suitable metal compound (c). In some embodiments, a mixture of the solvent (b) and the phosphonic or pyrophosphonic acid (a) is preheated to the preparation temperature and is combined with the metal or suitable metal compound (c).

The reaction mixture may alternatively be prepared at the reaction temperature. That is, the reaction mixture is prepared by combining (a) the phosphonic or pyrophosphonic acid, (b) the solvent for the phosphonic or pyrophosphonic acid, and (c) the metal or suitable metal compound at the reaction temperature. For example, in some embodiments, preparing the reaction mixture comprises preheating a mixture of the solvent (b) and the phosphonic or pyrophosphonic acid (a) to the reaction temperature and combining with the metal or suitable metal compound (c).

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In some embodiments where the reaction temperature is higher than the melting temperature of the phosphonic or pyrophosphonic acid and residual phosphonic or

pyrophosphonic acid is present in the product reaction mixture after desired conversion, e.g., full or substantially full conversion, to the flame retardant product is achieved, the product reaction mixture is cooled to a temperature above or no less than the melting temperature of the residual phosphonic or pyrophosphonic acid to ensure that the phosphonic or

5 pyrophosphonic acid remains in liquid form. This may be particularly useful in embodiments where an appreciable amount of the solvent for the phosphonic or pyrophosphonic acid (i.e., component (b)) boils off as a result of the heating such that remaining excess phosphonic or pyrophosphonic acid may have a greater tendency to come out of solution. The excess phosphonic or pyrophosphonic acid and the solvent if present in the product reaction mixture

10 can be removed by filtration/washing and optionally recovered. The recovered excess phosphonic or pyrophosphonic acid and/or solvent may be recycled, e.g., back into the reactor in which a metal or suitable metal compound (c) reacts with the phosphonic or pyrophosphonic acid (a). After conversion to the reaction product, a solvent for the phosphonic or pyrophosphonic acid, which may but need not be the same as the solvent

15 component (b), may optionally be added to dissolve or otherwise help remove excess phosphonic or pyrophosphonic acid. The phosphorus-containing flame retardant product is often isolated by filtration, optionally followed by additional work up (e.g., washing, drying, sieving, etc.). The resulting phosphorus-containing flame retardant product, which is generally in the form of a powder or small particles, is readily processable, i.e., without

20 requiring or necessitating grinding, milling, or other such physical processing before use. It should be understood that producing the phosphorus-containing flame retardant product "directly" as a powder or small particles permits workup of the reaction product, such as isolating the flame retardant product (e.g., separating the flame retardant product from remaining solvent), which may include, e.g., processing the reaction product by filtering,

25 sieving, washing, drying, and the like.

The solvent for the phosphonic or pyrophosphonic acid may be any solvent capable of dissolving the phosphonic or pyrophosphonic acid component, should be inert or substantially inert to the reaction between the phosphonic or pyrophosphonic acid and the

30 metal or suitable metal compound, and may further be chosen taking into account other reaction parameters, e.g., the preparation and/or reaction temperature or the type of metal or suitable metal compound, such as to prepare a homogenous or substantially homogenous reaction mixture. In some embodiments, the solvent may be a combination of solvents for the phosphonic or pyrophosphonic acid. Often, the phosphonic or pyrophosphonic acid is

35 substantially or completely dissolved in the solvent. For example, the phosphonic or pyrophosphonic acid and the solvent may form a solution. In some embodiments, the phosphonic or pyrophosphonic acid may be partially dissolved and partially suspended or

dispersed in the solvent. The type of solvent, the amount of solvent relative to the phosphonic or pyrophosphonic acid, and the mixing conditions can be chosen to achieve the desired level of dissolution of the phosphonic acid, such as to obtain a high concentration of phosphonic or pyrophosphonic acid in the mixture while maintaining the phosphonic or pyrophosphonic acid in solution. Often, the ratio of the acid to the solvent ranges from about 10:1 to 1:10, about 5:1 to 1:5, or about 3:1 to 1:3, by weight. In some embodiments where the acid is partially dissolved and partially suspended or dispersed in the solvent, the preparation temperature or reaction temperature may be selected at or higher than the melting temperature of the acid to liquefy the acid which is suspended or dispersed in the solvent.

As described above, depending on the reaction temperature and the boiling temperature of the solvent for the phosphonic or pyrophosphonic acid, at least a portion of the solvent may boil off from the reaction mixture while heating to or at the reaction temperature. In some embodiments, all, substantially all, or at least a majority of the solvent boils off from the reaction mixture during heating. The solvent may be high-boiling (e.g., sulfolane or dimethyl sulfoxide (DMSO)) or low-boiling (e.g., chloroform or tetrahydrofuran (THF)). For example, in some embodiments, the solvent boils at a temperature at or below the reaction temperature such that at least a portion of the solvent boils off during heating of the reaction mixture, e.g., where all, substantially all, or a majority of the solvent boils off. The reaction temperature may be selected at or higher than the melting temperature of the phosphonic or pyrophosphonic acid to ensure that the same remains in liquid form as the solvent boils off. In this way, use of a larger excess of phosphonic or pyrophosphonic acid in the reaction mixture may allow the phosphonic or pyrophosphonic acid to serve as both a reactant and a solvent for the reaction.

In still other embodiments, the solvent has a boiling temperature higher than the reaction temperature, ensuring it will remain in the product reaction mixture, from which the flame retardant product of the reaction can be isolated, as described herein. In some embodiments, the reaction temperature is selected below the melting temperature of the phosphonic or pyrophosphonic acid.

Suitable solvents may be organic or inorganic. Examples of suitable solvents for the phosphonic or pyrophosphonic acid include, but are not limited to, water, sulfones, sulfoxides, halogenated (e.g., chlorinated) hydrocarbons, aromatic hydrocarbons, and ethers. For example, in some embodiments, the solvent may be chosen from water, sulfolane, dimethylsulfone, tetrahydrofuran (THF), dimethoxyethane (DME), 1,4-dioxane,

dimethyl sulfoxide (DMSO), 1,2-dichlorobenzene, chloroform, carbon tetrachloride, xylene and mesitylene. In some embodiments, the solvent comprises water. In some embodiments, the solvent comprises an aqueous solution. In some embodiments, the reaction mixture is an aqueous reaction mixture.

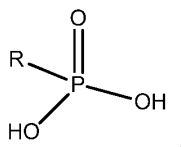
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The solvent may be protic or aprotic. In many embodiments, the solvent for pyrophosphonic acid is an aprotic solvent.

In some embodiments, the solvent (b) comprises a sulfone of the formula $R_1R_2SO_2$, wherein R_1 and R_2 are independently chosen from C_{1-6} hydrocarbon groups, e.g., C_{1-3} hydrocarbon groups, or R_1 and R_2 taken together with S form a ring having 2, 3, 4, or 5 carbon atoms, which ring may be unsubstituted or C_{1-3} alkyl-substituted. In some embodiments, R_1 and R_2 taken together with S form a di-, tri-, tetra-, or penta-methylene ring. In some embodiments, R_1 and R_2 are independently chosen from C_{1-6} alkyl. In some embodiments, R_1 or R_2 is C_{1-6} alkyl and the other is C_{1-3} alkyl. In some embodiments, R_1 and R_2 are independently chosen from C_{1-3} alkyl. The alkyl groups may be branched or straight-chained. In some embodiments, R_1 and R_2 are both methyl, both ethyl, or both propyl. In other embodiments, R_1 or R_2 is methyl and the other is ethyl or propyl. In other embodiments, R_1 or R_2 is ethyl and the other is propyl. In some embodiments, the sulfone is sulfolane.

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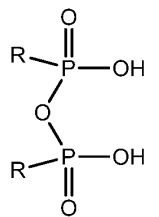
The phosphonic acid may be represented by the following formula:



wherein R is H, alkyl, aryl, alkylaryl, or arylalkyl. In many embodiments, R is H, C_{1-12} alkyl, C_{6-10} aryl, C_{7-18} alkylaryl, or C_{7-18} arylalkyl, wherein said alkyl, aryl, alkylaryl, or arylalkyl are unsubstituted or are substituted by halogen, hydroxyl, amino, C_{1-4} alkylamino, di- C_{1-4} alkylamino, C_{1-4} alkoxy, carboxy or C_{2-5} alkoxy carbonyl. In some embodiments, said alkyl, aryl, alkylaryl, or arylalkyl are unsubstituted C_{1-12} alkyl, C_6 aryl, C_{7-10} alkylaryl, or C_{7-10} arylalkyl, for example, C_{1-6} alkyl, phenyl, or C_{7-9} alkylaryl. In some embodiments, R is substituted or unsubstituted C_{1-6} alkyl, C_6 aryl, C_{7-10} alkylaryl, or C_{7-12} arylalkyl, e.g., C_{1-4} alkyl, C_6 aryl, C_{7-9} alkylaryl, or C_{7-10} arylalkyl. In many embodiments, R is unsubstituted C_{1-12} alkyl, e.g., C_{1-6} alkyl. In many embodiments, lower alkyl phosphonic acids are used, e.g., methyl-, ethyl-, propyl-, isopropyl-, butyl-, t-butyl- and the like.

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The pyrophosphonic acid may be represented by the following formula:



wherein R is as described above.

The process for preparing the phosphorus-containing flame retardant may employ more than one phosphonic acid, more than one pyrophosphonic acid, or a combination of phosphonic and pyrophosphonic acids. In some embodiments, the phosphonic acid or pyrophosphonic acid is generated in situ. For example, preparing the reaction mixture may include preparing phosphonic or pyrophosphonic acid, such as by hydrolysis of higher oligomer phosphonic acid and/or cyclic phosphonic acid anhydride starting materials.

10

As used herein, "suitable metal compound" and the like refer to a compound of the formula $M_p^{(+y)} X_q$, where M is a metal that forms a cation of 2+ or 3+, and X is any anion that provides a charged balanced compound with metal M. Suitable examples for X include, but are not limited to, anions that, together with the metal M, form oxides, halides, alkoxides, hydroxides, carbonates, carboxylates, and phosphonates. The values for p and q provide a charge balanced metal compound, for example, alumina, Al_2O_3 . In some embodiments, an unsubstituted metal, M, is used as described herein. Examples of suitable metals (M) include, but are not limited to, Al, Ga, Sb, Fe, Co, B, Bi, Mg, Ca, and Zn. In some embodiments, M is chosen from Al, Fe, Mg, Zn, and Ca.

20

Suitable metal compounds include, but are not limited to, compounds having a metal-oxygen bond, metal-nitrogen bond, metal-halogen bond, metal-hydrogen bond, metal-phosphorus bond, metal sulfur bond, metal boron bond, etc., for example, oxides, halides, alkoxides, hydroxides, carboxylates, carbonates, phosphonates, phosphinates, phosphonites, phosphates, phosphites, nitrates, nitrites, borates, hydrides, sulfonates, sulfates, sulfides, etc., of Al, Ga, Sb, Fe, Co, B, Bi, Mg, Ca, and Zn, for example, oxides, hydroxides, halides, or alkoxides of Al, Fe, Mg, Zn, or Ca.

25

In some embodiments, the metal, M, of the metal or suitable metal compound is aluminum or iron. In some embodiments, the suitable metal compound is chosen from halides, oxides, hydroxides, alkoxides, carbonates, carboxylates and phosphonates of aluminum. In some embodiments, the suitable metal compound is chosen from halides, oxides, hydroxides, and

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alkoxides of aluminum. In some embodiments, the suitable metal compound is chosen from alumina, aluminum trichloride, aluminum trihydroxide, aluminum isopropoxide, aluminum carbonate, and aluminum acetate. In other embodiments, the suitable metal compound is chosen from halides, oxides, alkoxides, carbonates, and acetates of iron. In some

5 embodiments, the suitable metal compound is chosen from iron(III) oxide, iron(III) chloride, iron(III) isopropoxide, and iron(III) acetate.

In some embodiments, the suitable metal compound is a metal phosphonate salt. The metal in the metal phosphonate salt may be a metal, M, as described herein. In some

10 embodiments, the metal phosphonate salt is prepared from the reaction of an initial metal compound and a phosphonic acid with a solvent (e.g., water) for the phosphonic acid. The initial metal compound may be a compound according to the suitable metal compound described herein. In some embodiments, the initial metal compound and the phosphonic acid are reacted at a temperature at or around room temperature or at a temperature

15 ranging from about 0 to about 20 °C. The resulting metal phosphonate salt may then be used as the suitable metal compound. For example, a phosphonic acid, e.g., one or more than one alkyl phosphonic acid as above, and a solvent (e.g., water) may be stirred to form a homogeneous solution. The solution may be cooled, e.g., from about 0 to about 20 °C, and an initial metal compound, such as a metal oxide, halide, alkoxide, or hydroxide, is added to

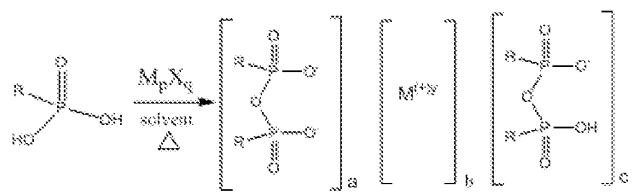
20 react with the phosphonic acid. A metal phosphonate salt is formed, which is then used as the suitable metal compound for preparing the phosphorus-containing flame retardant.

The preparation process may yield mixtures of phosphorus-containing flame retardant compounds, but in many embodiments the process produces the phosphorus-containing

25 flame retardant product as one, or predominantly one, compound, with high conversion based on the metal or metal compound, such as at least 70%, 80%, 85%, 90%, 95%, 98% or higher conversion, or any range therebetween, as opposed to the mixtures of compounds that are obtained by the prior art processes involving heat treatment of metal phosphonate salts, such as disclosed in US Patent No. 9,745,449.

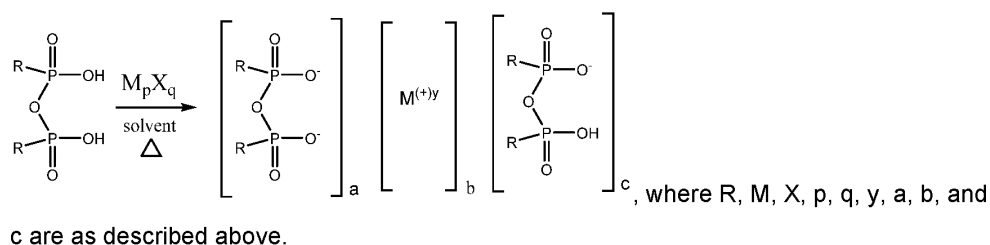
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The reaction according to the solvent method proceeds generally as shown:



wherein M is a metal and y is 2 or 3, such that $M^{(+)y}$ is a metal cation where (+)y represents the charge of the cation; X is an anionic ligand or ligands attached to the metal and the stoichiometry of M and X (i.e., p and q) provides a charged balanced metal compound; R is H, an alkyl, aryl, alkylaryl or arylalkyl (as described herein); a, b, and c represent the ratio of the components to which they correspond relative to one another in the reaction product, and satisfy the charge-balance equation $2(a)+c=b(y)$, and c is not zero. Often, a is 0, 1, or 2 (e.g., 0 or 1), b is from 1 to 4, e.g., 1 or 2, and c is 1 or 2, and the compound is charged balanced. In certain embodiments, R as shown herein is methyl, ethyl, propyl, isopropyl or butyl and M is Al, Fe, Zn or Ca. In further embodiments, X is an oxygen, hydroxy, alkoxy or halogen.

The general reaction scheme with a pyrophosphonic acid can be represented as



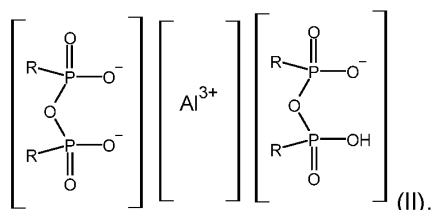
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As discussed above, as is common with inorganic coordination compounds, the formula for the reaction product is empirical or idealized such that the product may be a coordination polymer, complex salt, salt where certain atomic valences are shared, etc. In many embodiments, the reaction product above represents a monomer unit (i.e., coordination entity) of a coordination polymer, the extended coordination polymer structure thereby forming the phosphorus-containing flame retardant of the present disclosure.

In certain embodiments, y is 2 (i.e., $M^{(+)y}$ is a di-cationic metal), a is 0, b is 1, and c is 2. In certain embodiments, the di-cationic metal M is Mg, Ca, or Zn. In other embodiments, y is 3 (i.e., $M^{(+)y}$ is a tri-cationic metal), a is 1, b is 1, and c is 1. In certain embodiments, the tri-cationic metal M is chosen from Al, Ga, Sb, Fe, Co, B, and Bi. In certain embodiments, the tri-cationic metal M is Al, Fe, Ga, Sb, or B. In certain embodiments, M is aluminum (i.e., the reaction product is produced using aluminum or one or more aluminum compounds, such as those described herein) or iron (i.e., the reaction product is produced using iron or one or more iron compounds, such as those described herein).

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In one example, a phosphorus-containing flame retardant compound is produced having the following empirical formula:



As shown herein, the absence of subscripts a, b and c in an empirical formula indicates that the subscripts are each 1, signifying a 1:1:1 ratio of the di-anionic pyrophosphonic acid ligand, metal atom, and mono-anionic pyrophosphonic acid ligand.

5

Often, the phosphorus-containing flame retardant compound, which in many embodiments is an extended coordination polymer as described herein, makes up all, substantially all, or at least a majority of the phosphorus-containing flame retardant product, such as at least 75%, 85%, 90%, 95%, 98%, or higher, or any range therebetween, by weight of the flame

10 retardant product.

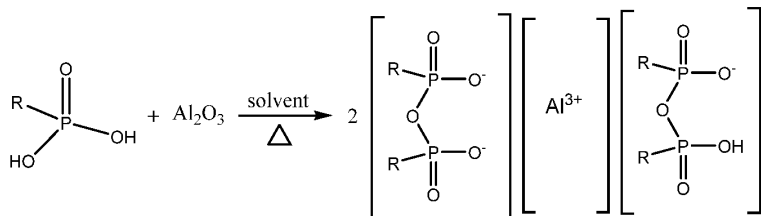
The product reaction mixture formed from the reaction, often presenting as a slurry, may be combined with an additional solvent, which may be the same or a different solvent than the solvent used in the reaction mixture. The additional solvent may, for example, be chosen from those described herein for the solvent component for the phosphonic or pyrophosphonic acid. The additional solvent / slurry mixture may be agitated as desired to break up any clumps that may have formed. The solid product may be isolated by filtration, optionally washed and dried, to yield the product in the form of a powder or small particles. In some cases, the product may be sieved to refine the particle size.

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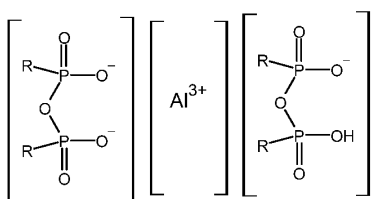
The reaction may optionally be facilitated with a seeding material. For example, use of a seeding material may reduce the time to achieve conversion to the phosphorus-containing flame retardant product and may lead to increased consistency in the product's physical characteristics. Thus, in some embodiments, the reaction mixture further comprises a seeding material. Often, the seeding material is added to the reaction mixture upon or after heating to the reaction temperature. In many embodiments, the seeding material is added before conversion to and/or precipitation of the flame retardant product occurs. In some embodiments, the seeding material comprises a phosphorus-containing flame retardant produced according to a method disclosed herein. The seeding material may be selected or refined to have a desired particle size.

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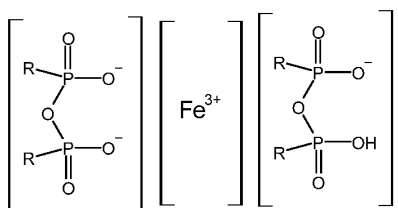
In some embodiments of the solvent method, the suitable metal compound is alumina, and the phosphorus-containing flame retardant product is produced as follows:



- 5 In one example, a reaction mixture comprising a phosphonic acid, such as a C₁-C₁₂ alkyl phosphonic acid (e.g., methyl, ethyl, propyl, iso-propyl, butyl or t-butyl phosphonic acid), a solvent for the phosphonic acid, such as water, and an oxide, hydroxide, halide, alkoxide, carbonate or carboxylate of Al, such as alumina, aluminum trichloride, aluminum trihydroxide, aluminum isopropoxide, aluminum carbonate or aluminum acetate, is heated to
- 10 a reaction temperature as described herein, such as about 115 °C or higher, about 125 °C or higher, about 150 °C or higher, or about 165 °C or higher. Typically, a slurry forms as the reaction proceeds, and the solid phosphorus-containing flame retardant product may be isolated by filtration to yield the product in the form of a powder or small particles. Additional workup on the product reaction mixture may be performed prior to isolating the solid product,
- 15 such as cooling the product reaction mixture above or no less than the melting point of excess phosphonic acid and combining with an additional solvent as described herein, e.g., water. The additional solvent / slurry mixture may be optionally agitated as described above. The solid phosphorus-containing flame retardant product may be isolated by filtration, optionally washed with additional solvent and dried, to yield the product in the form of a
- 20 powder or small particles. The flame retardant product contains phosphorus and aluminum in a 4:1 ratio of phosphorus to aluminum according to the following empirical formula:

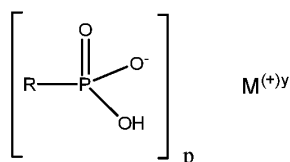


- In a further example, the example described directly above is performed with iron or a suitable iron compound, such as halides, oxides, alkoxides, carbonates, or acetates of iron, e.g., iron(III) oxide, iron(III) chloride, iron(III) isopropoxide, or iron(III) acetate. The flame retardant product contains phosphorus and iron
- 25 in a 4:1 ratio according to the following empirical formula:



Often, the compound of the empirical formulas above (which in many embodiments is an extended coordination polymer as described herein) makes up all, substantially all, or at least a majority of the phosphorus-containing flame retardant product, such as at least 75%,
 5 85%, 90%, 95%, 98%, or higher, or any range therebetween, by weight of the flame retardant product.

In a further embodiment, the suitable metal compound is a metal phosphonate salt of the following formula:

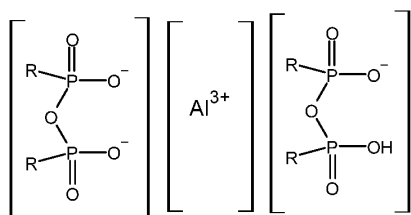


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wherein R and M are as described above, p is 2 or 3 and y is 2 or 3 so that $\text{M}^{(+)\text{y}}$ is a metal cation where (+)y represents the charge formally assigned to the cation and the metal phosphonate salt is charge balanced (i.e., $p=y$). The metal phosphonate salt may be prepared according to methods known in the art.

15

In one example, a phosphonic acid, such as an alkyl phosphonic acid (e.g., methyl, ethyl, propyl, iso-propyl, butyl or t-butyl phosphonic acid) is combined with water (e.g., about 1:1 by weight) and is stirred and cooled to below room temperature (e.g., cooled to or below 10 °C, such as about 0 °C). An initial metal compound is added to the mixture of phosphonic acid
 20 and water to form a metal phosphonate salt. The metal phosphonate salt is then used as the suitable metal compound to produce the phosphorus-containing flame retardant product in the form of a powder or small particles. In embodiments involving an aluminum phosphonate salt as the suitable metal compound, the flame retardant product contains phosphorus and aluminum in a 4:1 ratio of phosphorus to aluminum according to the
 25 following empirical formula:



The compound of the empirical formula (which in many embodiments is an extended coordination polymer as described herein) typically makes up all, substantially all, or at least a majority of the flame retardant product, such as at least 75%, 85%, 90%, 95%, 98%, or higher, or any range therebetween, by weight of the flame retardant product.

Preparing the phosphorus-containing flame retardant via the molten state method

The phosphorus-containing flame retardant of empirical formula (I) may be prepared by reacting a metal or suitable metal compound with a stoichiometric excess of an unsubstituted or alkyl or aryl substituted phosphonic acid. The reaction temperature is 105 °C or higher, the phosphonic acid is in a molten state at the reaction temperature, and the molar ratio of the phosphonic acid to the metal or suitable metal compound in the reaction mixture is higher than 4:1. In the reaction, the metal is oxidized and may be represented in its corresponding cationic form by the formula $M^{(+y)}$ where M is a metal, (+)y represents the charge of the metal cation, and y is 2 or 3. The suitable metal compound may be represented by the formula $M_p^{(+y)}X_q$, where M is a metal, (+)y represents the charge of the metal cation, y is 2 or 3, X is an anion, and the values for p and q provide a charge balanced metal compound.

In another embodiment, the phosphorus-containing flame retardant of empirical formula (I) may be prepared by reacting a metal or suitable metal compound with a stoichiometric excess of an unsubstituted or alkyl or aryl substituted pyrophosphonic acid. The pyrophosphonic acid is in a molten state at the reaction temperature, and the molar ratio of the pyrophosphonic acid to the metal or suitable metal compound in the reaction mixture is higher than 2:1.

As used herein, "stoichiometric excess" of the unsubstituted or alkyl or aryl substituted phosphonic or pyrophosphonic acid relative to the metal or suitable metal compound refers to an amount of the phosphonic or pyrophosphonic acid which exceeds that stoichiometrically required for the reaction between the metal or suitable metal compound and the phosphonic or pyrophosphonic acid. The stoichiometric excess is typically

represented by a molar ratio of the phosphonic or pyrophosphonic acid to the metal or suitable metal compound in the reaction mixture, as described herein.

- The unsubstituted or alkyl or aryl substituted phosphonic or pyrophosphonic acid, used at a stoichiometric excess as described herein, acts as a reagent and solvent for the reaction. The reaction product typically forms as a slurry as the resulting phosphorus-containing flame retardant product precipitates from the reaction mixture. Excess phosphonic or pyrophosphonic acid remaining after the reaction can be removed along with any possible byproducts by filtration and/or washing, e.g., with water. In many embodiments, a substantially pure flame retardant material is produced, e.g., a flame retardant comprising essentially a single compound with flame retardant activity or essentially a mixture of active compounds. Conversion based on the metal or metal compound is typically high, and the product can be readily isolated and optionally further purified if desired.
- Typically, the molar ratio of the phosphonic acid to the metal or suitable metal compound in the reaction mixture is 5:1 or higher, such as about 6:1 or higher, about 8:1 or higher, or about 10:1 or higher. Larger molar excesses of the phosphonic acid to the metal or suitable metal compound may be used in the reaction mixture, such as about 12:1 or higher, about 15:1 or higher, about 20:1 or higher, about 25:1 or higher, about 30:1 or higher, or any range therebetween. A large molar excess of the phosphonic acid relative to the metal or suitable metal compound may be used. For example, the molar ratio may be up to about 50:1, up to about 100:1, up to about 300:1, up to about 500:1, or any range therebetween. However, as would be understood, process efficiency may suffer at certain large molar excesses, e.g., product precipitation from the reaction mixture may be hindered. In many embodiments, the molar ratio ranges from about 8:1, from about 10:1, from about 12:1, or from about 16:1 to about 100:1 or to about 50:1, such as from about 10:1, from about 15:1, or from about 20:1 to about 50:1 or to about 40:1.
- Typically, for pyrophosphonic acid, the molar ratio of the pyrophosphonic acid to the metal or suitable metal compound in the reaction mixture is 3:1 or higher, such as about 4:1 or higher, about 6:1 or higher, or about 8:1 or higher. Often larger molar excesses of the pyrophosphonic acid to the metal or suitable metal compound are used in the reaction mixture, such as about 10:1 or higher, about 12:1 or higher, about 15:1 or higher, about 18:1 or higher, about 20:1 or higher, or any range therebetween. A large molar excess of the pyrophosphonic acid relative to the metal or suitable metal compound may be used. For example, the molar ratio may be up to about 30:1, up to about 50:1, up to about 100:1, up to about 250:1, or any range therebetween. However, as would be understood, process

efficiency may suffer at certain large molar excesses, e.g., product precipitation from the reaction mixture may be hindered. In many embodiments, the molar ratio ranges from about 4:1, from about 5:1, from about 6:1, or from about 8:1 to about 50:1 or to about 25:1, such as from about 5:1, from about 8:1, or from about 10:1 to about 25:1 or to about 20:1.

5

The reaction temperature for producing the phosphorus-containing flame retardant according to the molten state method should be chosen such that the phosphonic or pyrophosphonic acid is in a molten state at the reaction temperature. For example, phosphonic and pyrophosphonic acids (e.g., alkyl substituted phosphonic or pyrophosphonic acids) are often solid at room temperature (e.g., methyl phosphonic acid melts at about 105 °C and ethyl phosphonic acid melts at about 62 °C), and thus heating the phosphonic or pyrophosphonic acid to result in a liquefied physical state (i.e., molten state) is generally appropriate to form a consistent reaction mixture. As one skilled in the art will appreciate, the desired reaction temperature at which the phosphonic or pyrophosphonic acid is in a molten state may vary depending on the chosen reagents and thermodynamic conditions.

The reaction temperature should also be chosen to facilitate the formation of pyrophosphonic acid ligands in the reaction product. For a phosphonic acid, a reaction temperature of 105 °C or higher is used. Without being bound by a particular theory, the reaction temperature is chosen to produce pyrophosphonic acid ligands via dehydration reaction(s). In many embodiments, the metal or suitable metal compound and the phosphonic acid are reacted at temperatures higher than 105 °C, such as about 115 °C or higher, about 120 °C or higher, about 130 °C or higher, about 140 °C or higher, about 150 °C or higher, about 160 °C or higher, about 170 °C or higher, about 180 °C or higher, about 200 °C or higher, about 220 °C or higher, about 240 °C or higher, about 260 °C or higher, about 280 °C or higher, or any range therebetween. The reaction temperature may be higher than those described above, such as up to about 350 °C, up to about 400 °C, or higher, but it typically does not meet or exceed the boiling temperature of the phosphonic acid. For example, the reaction temperature may range from about 150 °C to about 300 °C, such as from about 150 °C to about 280 °C, from about 160 °C to about 260 °C, or from about 160 °C to about 240 °C. In many embodiments, the reaction temperature ranges from about 110 °C to about 350 °C, from about 115 °C to about 300 °C, from about 125 °C to about 280 °C, or from about 140 °C to about 260 °C. Through the dehydration reaction(s), water is formed, which can potentially lead to the undesirable reverse (hydrolysis) reaction. Thus, in some embodiments, the reaction system is designed to facilitate removal, such as the continuous removal, of water from the reaction. For example, the reaction temperature may be chosen above the boiling temperature of the water to the extent necessary to boil off at

least a portion or desired amount (e.g., a majority, substantially all, or all) of the water from the reaction. Additional means, such as a gas purge, vacuum, and/or other known means, may be used to facilitate removal of water from the reaction system.

5 As dehydration is unnecessary for pyrophosphonic acid, the reaction temperature for pyrophosphonic acid may be lower than that described above for phosphonic acid. Generally, the limiting criterion with respect to choosing a suitable reaction temperature when employing a pyrophosphonic acid is the requirement that the pyrophosphonic acid is in a molten state at the reaction temperature. Often, the metal or suitable metal compound and
10 the pyrophosphonic acid are reacted at a temperature of 20 °C or higher. In many embodiments, the metal or suitable metal compound and the pyrophosphonic acid are reacted at temperatures higher than 20 °C, such as about 40 °C or higher, about 60 °C or higher, about 80 °C or higher, about 100 °C or higher, about 140 °C or higher, about 180 °C or higher, about 200 °C or higher, or any range therebetween. The reaction temperature
15 may be higher than those described above, such as up to about 300 °C, up to about 400 °C, or higher, but it typically does not meet or exceed the boiling temperature of the pyrophosphonic acid. In many embodiments, the reaction temperature ranges from about 25 °C to about 350 °C, from about 25 °C to about 280 °C, from about 30 °C to about 260 °C, from about 40 °C to about 260 °C, from about 60 °C to about 260 °C, from about 80 °C to
20 about 240 °C, from about 100 °C to about 240 °C, from about 110 °C to about 240 °C, or from about 120 °C to about 240 °C. Depending, for example, on the metal compound used to react with the pyrophosphonic acid, water may be generated from the reaction. As described above, in some embodiments, the reaction system is designed to facilitate removal, such as the continuous removal, of water from the reaction. For example, the
25 reaction temperature may be chosen above the boiling temperature of the water to the extent necessary to boil off at least a portion or desired amount (e.g., a majority, substantially all, or all) of the water from the reaction. Additional means, such as a gas purge, vacuum, and/or other known means, may be used to facilitate removal of water from the reaction system.

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The reaction may, but need not, be run under reduced pressure or vacuum.

Typically, as the reaction progresses, the product forms as a slurry as the resulting phosphorus-containing flame retardant product precipitates from the product reaction
35 mixture. Thus, the reaction is typically run for a time sufficient to achieve such precipitation. In general, the amount of time required to achieve at least substantial conversion to the flame retardant product, based on the metal or suitable metal compound, will depend on the

reaction temperature, with higher temperatures generally resulting in shorter reaction times. In many embodiments, the metal or suitable metal compound and the phosphonic or pyrophosphonic acid are heated at the reaction temperature for from about 0.1 to about 48 hours, such as from about 0.2 to about 36 hours, from about 0.5 to about 30 hours, from about 1 hour to about 24 hours, e.g., from about 1 hour to about 12 hours, from about 1 hour to about 8 hours, or from about 2 hours to about 5 hours, although other durations may be used.

The metal or suitable metal compound and the molar excess of the phosphonic or pyrophosphonic acid can be combined in any manner suitable to form the reaction mixture. For example, the phosphonic or pyrophosphonic acid and the metal or metal compound may be mixed (e.g., stirred) together, such as to form a homogenous reaction mixture. In some embodiments, the metal or suitable metal compound is added to the phosphonic or pyrophosphonic acid which has been preheated to the reaction temperature. In some embodiments, the phosphonic or pyrophosphonic acid is pre-heated and stirred upon melting, such as under a nitrogen atmosphere or reduced pressure/vacuum. In still further embodiments, the metal or metal compound is added as rapidly as possible without causing a large change in the reaction temperature due to the exothermic nature of the reaction. In some embodiments, the phosphonic or pyrophosphonic acid and the metal or suitable metal compound are combined without preheating the phosphonic acid, or without sufficient heating to liquefy the phosphonic or pyrophosphonic acid, and the components are subsequently heated to the reaction temperature. The full amount of metal or suitable metal compound or phosphonic or pyrophosphonic acid can be added to the reaction all at once or in portions. No additional solvents are needed, as the phosphonic or pyrophosphonic acid, used at a molar excess, acts as reagent and solvent, but additional solvent may be used if desired. In some embodiments, additional solvent is used when employing molar ratios of phosphonic or pyrophosphonic acid to the metal or suitable metal compound that are at or near the lower boundary of the molar ratios disclosed herein.

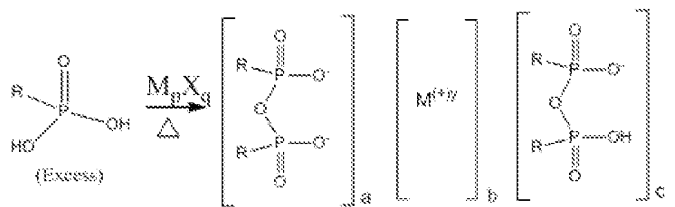
In some embodiments, after desired conversion, e.g., full or substantially full conversion, to the flame retardant product is achieved, the product reaction mixture is cooled to a temperature above or no less than the melting temperature of the excess phosphonic or pyrophosphonic acid to keep the excess phosphonic or pyrophosphonic acid in a liquefied state. The excess phosphonic or pyrophosphonic acid can be removed by filtration/washing and optionally recovered. The recovered excess phosphonic or pyrophosphonic acid may be recycled, e.g., back into the reactor in which a metal or suitable metal compound reacts with the phosphonic or pyrophosphonic acid. After conversion to the reaction product, a

- solvent, e.g., water, an alcohol, and/or another suitable (e.g., polar) liquid, may optionally be added to dissolve or otherwise help remove the excess phosphonic or pyrophosphonic acid. The phosphorus-containing flame retardant product is often isolated by filtration, optionally followed by additional work up (e.g., washing, drying, sieving, etc.). The resulting
- 5 phosphorus-containing flame retardant product, which is generally in the form of a powder or small particles, is readily processable, i.e., without requiring or necessitating grinding, milling, or other such physical processing before use. It should be understood that producing the flame retardant material "directly" as a powder or small particles permits workup of the reaction product, such as isolating the flame retardant product (e.g.,
- 10 separating the flame retardant product from excess phosphonic or pyrophosphonic acid or remaining solvent), which may include, e.g., processing the reaction product by filtering, sieving, washing, drying, and the like. After the reaction, the resulting product reaction mixture, often a slurry, may be cooled to or just above the melting temperature of the excess phosphonic acid and the slurry may be combined with water. The water / slurry mixture may
- 15 be agitated as necessary to break up any large clumps that might have formed. The solid product may be isolated by filtration, optionally washed with water and dried, to yield the product in the form of a powder or small particles. In some cases, the product may be sieved to refine the particle size.
- 20 The phosphonic acid or pyrophosphonic acid used to produce the phosphorus-containing flame retardant may be a phosphonic or pyrophosphonic acid as described above. The process may employ more than one phosphonic acid, more than one pyrophosphonic acid, or a combination of phosphonic and pyrophosphonic acids. In some embodiments, the phosphonic acid or pyrophosphonic acid is generated in situ. For example, preparing the
- 25 reaction mixture may include preparing phosphonic or pyrophosphonic acid, such as by hydrolysis of higher oligomer phosphonic acid and/or cyclic phosphonic acid anhydride starting materials.

Suitable metals and metal compounds for the reaction are as described above.

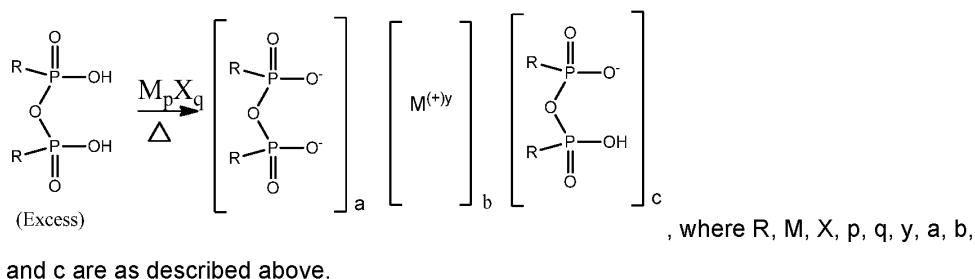
- 30 The preparation process may yield mixtures of phosphorus-containing flame retardant compounds, but in many embodiments the process produces the phosphorus-containing flame retardant product as one, or predominantly one, compound, with high conversion based on the metal or metal compound, such as at least 70%, 80%, 85%, 90%, 95%, 98%
- 35 or higher conversion, or any range therebetween, as opposed to the mixtures of compounds that are obtained by the prior art processes involving heat treatment of metal phosphonate salts, such as disclosed in US Patent No. 9,745,449.

The reaction according to the molten state method proceeds generally as shown:



- wherein M is a metal and y is 2 or 3, such that $\text{M}^{(+y)}$ is a metal cation where (+)y represents the charge of the cation; X is an anionic ligand or ligands attached to the metal and the stoichiometry of M and X (i.e., p and q) provides a charged balanced metal compound; R is H, an alkyl, aryl, alkylaryl or arylalkyl (as described herein); a, b, and c represent the ratio of the components to which they correspond relative to one another in the reaction product, and satisfy the charge-balance equation $2(a)+c=b(y)$, and c is not zero. Often, a is 0, 1, or 2 (e.g., 0 or 1), b is from 1 to 4, e.g., 1 or 2, and c is 1 or 2, and the compound is charged balanced. In certain embodiments, R as shown herein is methyl, ethyl, propyl, isopropyl or butyl and M is Al, Fe, Zn or Ca. In further embodiments, X is an oxygen, hydroxy, alkoxy or halogen.

- 15 The general reaction scheme with a pyrophosphonic acid can be represented as



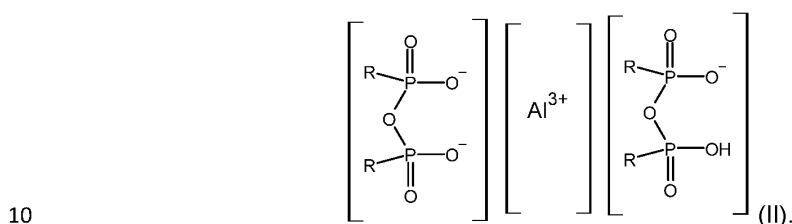
- As discussed above, as is common with inorganic coordination compounds, the formula for the reaction product is empirical or idealized such that the product may be a coordination polymer, complex salt, salt where certain atomic valences are shared, etc. In many embodiments, the reaction product above represents a monomer unit (i.e., coordination entity) of a coordination polymer, the extended coordination polymer structure thereby forming the phosphorus-containing flame retardant of the present disclosure.

25

In certain embodiments, y is 2 (i.e., $\text{M}^{(+y)}$ is a di-cationic metal), a is 0, b is 1, and c is 2. In certain embodiments, the di-cationic metal M is Mg, Ca, or Zn. In other embodiments, y is 3

(i.e., $M^{(+)y}$ is a tri-cationic metal), a is 1, b is 1, and c is 1. In certain embodiments, the tri-cationic metal M is chosen from Al, Ga, Sb, Fe, Co, B, and Bi. In certain embodiments, the tri-cationic metal M is Al, Fe, Ga, Sb, or B. In certain embodiments, M is aluminum (i.e., the reaction product is produced using aluminum or one or more aluminum compounds, such as those described herein) or iron (i.e., the reaction product is produced using iron or one or more iron compounds, such as those described herein).

In one example, a phosphorus-containing flame retardant compound is produced having the following empirical formula:



As described above, the absence of subscripts a, b and c in an empirical formula indicates that the subscripts are each 1, signifying a 1:1:1 ratio of the di-anionic pyrophosphonic acid ligand, metal atom, and mono-anionic pyrophosphonic acid ligand.

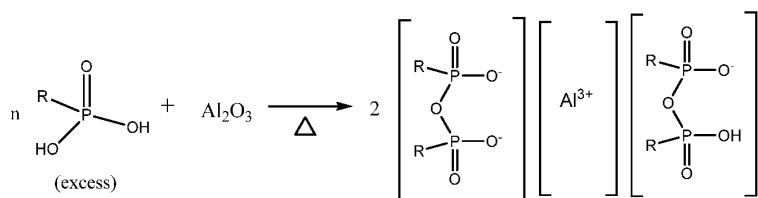
Often, the phosphorus-containing flame retardant compound, which in many embodiments is an extended coordination polymer as described herein, makes up all, substantially all, or at least a majority of the phosphorus-containing flame retardant product, such as at least 75%, 85%, 90%, 95%, 98%, or higher, or any range therebetween, by weight of the flame retardant product.

The product reaction mixture formed from the reaction, often presenting as a slurry, may be combined with a liquid (e.g., water) and agitated as desired to break up any clumps that may have formed. The solid product may be isolated by filtration, optionally washed and dried, to yield the product in the form of a powder or small particles. In some cases, the product may be sieved to refine the particle size.

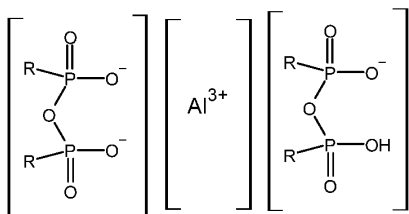
The reaction may optionally be facilitated with a seeding material. For example, use of a seeding material may reduce the time to achieve conversion to the phosphorus-containing flame retardant product and may lead to increased consistency in the product's physical characteristics. Thus, in some embodiments, the reaction mixture further comprises a seeding material. Often, the seeding material is added to the reaction mixture upon or after heating to the reaction temperature. In some embodiments, the seeding material comprises

a phosphorus-containing flame retardant produced according to a method described herein. The seeding material may be selected or refined to have a desired particle size.

In some embodiments of the molten state method, the suitable metal compound is alumina, and the flame retardant material is produced as follows:

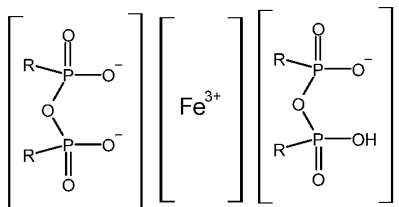


In one example, a phosphonic acid, such as a C₁-C₁₂ alkyl phosphonic acid (e.g., methyl, ethyl, propyl, iso-propyl, butyl or t-butyl phosphonic acid) is heated to or above its melting point, 105 °C, such as to 115 °C, 125 °C, 140 °C, 150 °C, 160 °C, 180 °C, 200 °C, 220 °C, or 240 °C or higher, with stirring (e.g., under nitrogen) upon melting. An oxide, hydroxide, halide, alkoxide, carbonate or carboxylate of Al, such as alumina, aluminum trichloride, aluminum trihydroxide, aluminum isopropoxide, aluminum carbonate or aluminum acetate, is added with stirring at a stoichiometric excess of the phosphonic acid, such as at a molar ratio of phosphonic acid to the metal compound as described herein, e.g., 5:1 or higher, 10:1 or higher, or 15:1 or higher. Typically, a slurry forms as the reaction proceeds, and the solid flame retardant product may be isolated, such as by filtration, washing, etc. to yield the product in the form of a powder or small particles. Additional workup on the product reaction mixture may be performed prior to isolating the solid product, such as cooling the product reaction mixture above or no less than the melting point of the excess phosphonic acid and combining with a liquid, e.g., water, and optionally agitated as described above. The solid flame retardant product may be isolated by filtration, optionally washed with additional solvent and dried, to yield the product in the form of a powder or small particles. The flame retardant product contains phosphorus and aluminum in a 4:1 ratio according to the following empirical formula:



In a further example, the example described directly above is performed with iron or a suitable iron compound, such as halides, oxides, alkoxides, carbonates, or acetates of iron, e.g., iron(III) oxide, iron(III) chloride, iron(III)

isopropoxide, or iron(III) acetate. The flame retardant product contains phosphorus and iron in a 4:1 ratio according to the following empirical formula:

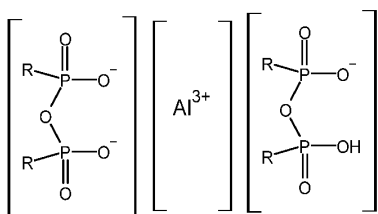


- 5 Often, the compound of the empirical formulas above (which in many embodiments is an extended coordination polymer as described herein) makes up all, substantially all, or at least a majority of the phosphorus-containing flame retardant product, such as at least 75%, 85%, 90%, 95%, 98%, or higher, or any range therebetween, by weight of the flame retardant product.

10

In a further example where the suitable metal compound is a metal phosphonate salt, the metal phosphonate salt is prepared by mixing a phosphonic acid, such as an alkyl phosphonic acid, e.g., methyl, ethyl, propyl, iso-propyl, butyl or t-butyl phosphonic acid, and a solvent (e.g., water) to form a homogeneous solution. For example, any convenient ratio of water to phosphonic acid may be used, e.g., 10:1 to 1:10 by weight, such as 5:1 to 1:5 by weight or 2:1 to 1:2 by weight. The solution may be cooled to, e.g., in the range from about 0 to about 20 °C, and an initial metal compound, such as a metal oxide, halide, alkoxide, or hydroxide, is added to react with the phosphonic acid. A metal phosphonate salt is formed, which is then used as the suitable metal compound for producing the phosphorus-containing flame retardant. For instance, a molar excess of phosphonic acid as described herein (such as at a 5:1 molar ratio of phosphonic acid relative to the metal phosphonate salt) is preheated to a molten state and is reacted with the metal phosphonate salt to form the phosphorus-containing flame retardant product. In embodiments involving an aluminum phosphonate salt as the suitable metal compound, the flame retardant product contains phosphorus and aluminum in a 4:1 ratio of phosphorus to aluminum according to the following empirical formula:

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The compound of the empirical formula (which in many embodiments is an extended coordination polymer as described herein) typically makes up

all, substantially all, or at least a majority of the flame retardant product, such as at least 75%, 85%, 90%, 95%, 98%, or higher, or any range therebetween, by weight of the flame retardant product.

5 **Preparing the flame retardant thermoplastic compositions**

The present invention is not limited by any particular method of blending the components of the presently disclosed flame retardant thermoplastic compositions. Suitable compounding and blending techniques known in the art may be used. For example, one method
10 comprises blending the thermoplastic polymer and flame retardant additives in powder or granular form and melt-mixing the blend (e.g., using a twin-screw extruder). Optionally, other additives including but not limited to fillers, e.g., glass fibers or other types of fillers, are also extruded together. The thermoplastic polymer, flame retardant additives, and other additives are typically pre-dried before melt-mixing. The extruded blend may be comminuted into
15 granular pellets or other suitable shapes by standard techniques. Other melt-mixing process equipment such as a kneader mixer or bowl mixer can be used to compound the flame retardant additives and any additional ingredients with the thermoplastic polymer. In either case, a generally suitable machine temperature may range from about 230° to 330° C, depending on the specific type of thermoplastic selected.

20 The flame retardant thermoplastic compositions can be molded in any equipment suitable for such purpose, e.g., in an injection molding machine. After pelletizing, the granular pellets are typically re-dried before being molded in an injection molding machine suitable for such purpose. Often, the process temperature ranges from about 250° to 280°C, depending on
25 the molding properties of the specific thermoplastic polymer, loading levels of the additives and/or reinforcement filler, and other factors like thickness and gate size of the mold cavity. Those skilled in the art will be able to make suitable adjustments in the molding process to accommodate the composition or tooling differences.

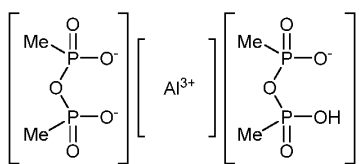
30 In another embodiment, a molded article comprises a flame retardant thermoplastic composition as disclosed herein, such as where the molded article is made by injection molding. The flame retardant thermoplastic composition is useful, for example, in the production of electronic components, such as for connectors, frames, moving parts, transformers and micromotors, and the like. In a further embodiment, injection molded
35 components are provided, e.g., electronic components, comprising a flame retardant thermoplastic composition as disclosed herein.

Further non-limiting disclosure is provided in the Examples that follow.

EXAMPLES

5 Example 1

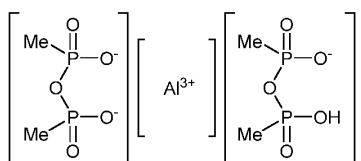
- Methylphosphonic acid (MPA) (3678.8 g, 38.3 mol, 30 eq, 75% aqueous solution) and alumina (130.2 g, 1.28 mol, 1 eq) were mixed at room temperature with limited exotherm observed (about 2 °C increase). The pot temperature was set to 165 °C, with stirrer at 200 RPM under atmospheric pressure, nitrogen purge (4 L/min). When no distillate water was observed at the condenser, 1.0 g of seeding material, which was the flame retardant product produced from MPA and alumina as described herein, was optionally added. The reaction mixture was heated at 165 °C for 3 hours. The product reaction mixture containing a white slurry product was then cooled to about 130 °C and poured into 1.5 L of water in a beaker cooled in an ice water bath. The white slurry was then filtered off, washed by water (500 mL x 3), and dried to yield fine crystals at 92% yield. The product had a 4:1 phosphorus to aluminum ratio (ICP Elemental Analysis) according to the following empirical formula:



- The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product. Thermogravimetric analysis (TGA) of the product is shown in FIG. 1.

Example 2

- A 1 L flask was charged with 800 mL xylenes and set up with a Dean-Stark trap. The solution was heated to 115 °C and methylphosphonic acid (MPA) (33.89 g, 0.35 mol) was added. The acid was allowed to dissolve and the temperature was increased such that the solution began to reflux. Alumina (4.01 g, 0.039 mol) was added in portions over 3 hours. The reflux was maintained at 142 °C overnight. The resulting solid product was isolated by filtration, washed with DMF (100 mL) and Et₂O (2 x 50 mL), and dried to yield a fine powder (18.86 g, 71% yield). The product had a 4:1 phosphorus to aluminum ratio according to the following empirical formula:

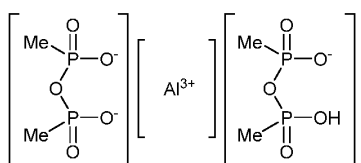


The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

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Example 3

Methylphosphonic acid (MPA) (2216 g, 23.1 mol, 15 eq, aqueous solution) and aluminum trihydroxide (120 g, 1.5 mol, 1 eq) were mixed at room temperature. The pot temperature was set to 165 °C, with stirrer at 200 RPM under atmospheric pressure, nitrogen purge (4 L/min). When no distillate water was observed at the condenser, 1.0 g of seeding material, which was the flame retardant product produced from MPA and aluminum trihydroxide as described herein, was optionally added. The reaction mixture was heated at 165 °C for 3 hours. The product reaction mixture containing a white slurry product was then cooled to about 130 °C and poured into 1.5 L of water in a beaker cooled in an ice water bath. The white slurry was filtered off, washed by water (500 mL x 3), and dried to yield fine crystals at approximately 100% yield. The product had a 4:1 phosphorus to aluminum ratio (ICP Elemental Analysis) according to the following empirical formula:

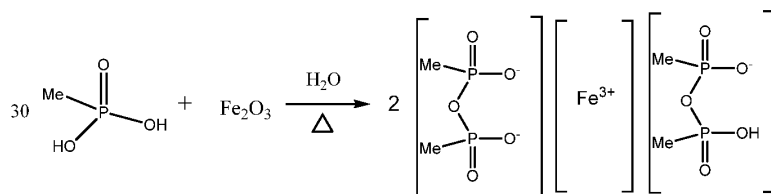


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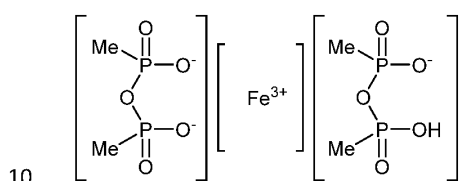
The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

Example 4

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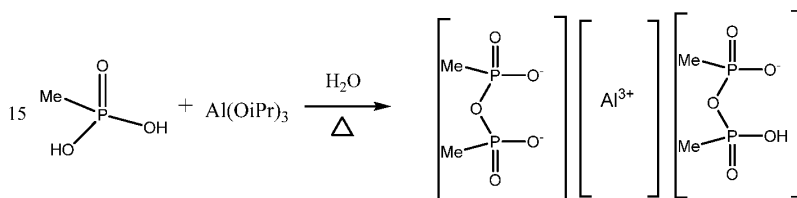


- Methylphosphonic acid (MPA) (1412.6 g, 14.7 mol, 30 eq, 75% aqueous solution) and iron oxide (78.2 g, 0.49 mol, 1 eq) were mixed at room temperature. The pot temperature was set to 130 °C for about 12 hours, with stirrer at 250 RPM under atmospheric pressure, nitrogen purge (4 L/min). The reaction mixture was subsequently heated to 165 °C for 12 hours. The product reaction mixture containing an off-white slurry product was then cooled to about 130 °C and poured into 1.5 L of water in a beaker cooled in an ice water bath. The off-white slurry was filtered off, washed by water (500 mL x 3), and dried to yield fine off-white color crystals at 92% yield. The product had a 4:1 phosphorus to iron ratio (ICP Elemental Analysis) according to the following empirical formula:

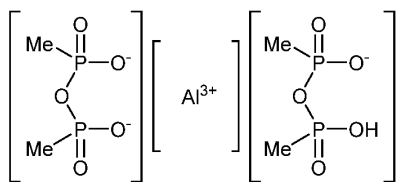


The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

Example 5



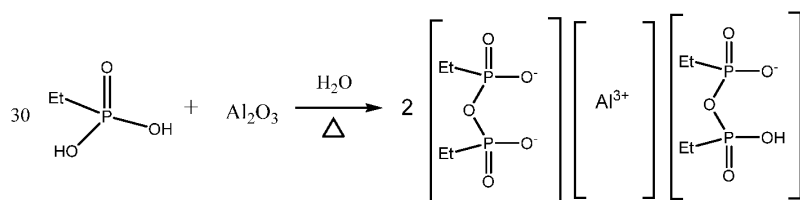
- Methylphosphonic acid (MPA) (1727 g, 18.4 mol, 15 eq, 75% aqueous solution) was cooled to 5 °C in an ice water bath under nitrogen flow (1 L/min). Aluminum isopropoxide (250 g, 1.2 mol, 1 eq) was added in portions as the pot temperature was maintained below 10 degree C. The pot temperature was then set to 165 °C, with stirrer at 250 RPM. At 165 °C, 4.5 g of seeding material, which was the flame retardant product produced from MPA and aluminum isopropoxide as described herein, was optionally added, and the reaction mixture was kept at 165 °C for 3 hours. The product reaction mixture containing a white slurry product was then cooled to about 130 °C and poured into 1.5 L of water in a beaker cooled in an ice water bath. The white slurry was filtered off, washed by water (500 mL x 3), and dried to yield fine crystals at 44% yield. The product had a 4:1 phosphorus to aluminum ratio (ICP Elemental Analysis) according to the following empirical formula:



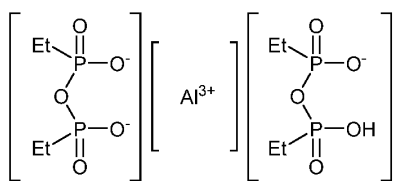
The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

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Example 6

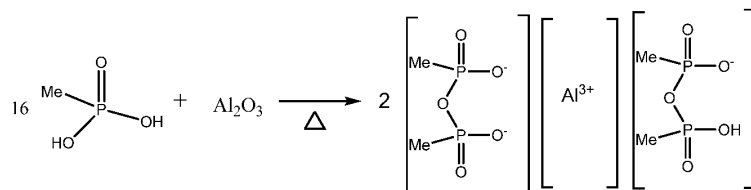


- 10 Ethylphosphonic acid (EPA) (55.0 g, 0.50 mol, 30 eq) and alumina (1.70 g, 17 mmol, 1 eq) were mixed at room temperature with 50 mL of water. The pot temperature was set to 165 °C, with stirrer at 250 RPM under atmospheric pressure, nitrogen purge (4 L/min). The reaction mixture was heated at 165 °C for 3 hours. The product reaction mixture containing a white slurry product was then cooled to about 130 °C and poured into 100 mL of water in a
- 15 beaker cooled in an ice water bath. The white slurry was filtered off, washed by water (50 mL x 3), and dried to yield fine crystals at 76% yield. The product had a 4:1 phosphorus to aluminum ratio (ICP Elemental Analysis) according to the following empirical formula:



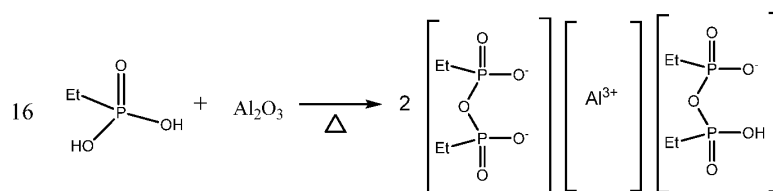
- 20 The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

Example 7



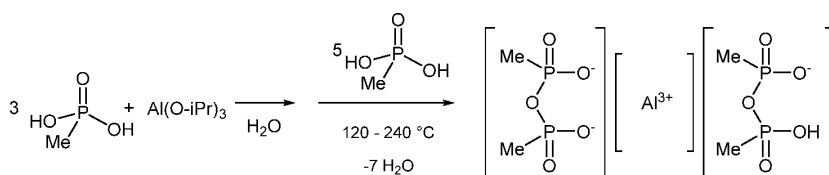
A three-neck 250 mL flask was charged with 114.6 g methylphosphonic acid, which was then heated. At 105 °C the methylphosphonic acid melts, and vigorous stirring was begun under a N₂ blanket. The methylphosphonic acid was heated to 240 °C and 7.78 g of alumina was added as quickly as possible without causing a large exotherm. The slurry was cooled until it was just above the melting point of the excess methyl phosphonic acid, ~110 °C, and then added to 250 mL of H₂O while ensuring that the rate of addition did not cause excessive steam formation. The resulting mixture was agitated to break up any large clumps that might have formed, the product was isolated by filtration, washed with an additional 750 mL of H₂O, and dried to yield 45.08 g of the product as fine colorless crystals at 87% yield. The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product. Thermogravimetric analysis (TGA) of the product is shown in FIG. 2.

Example 8



A three-neck 250 mL flask was charged with 149.8 g ethylphosphonic acid, which was heated to melting, 62 °C. Vigorous stirring was begun under a N₂ blanket, the ethylphosphonic acid was heated to 240 °C and 6.9 g of alumina was added as quickly as possible without causing a large exotherm. The slurry was cooled to ~80 °C, and then added to 250 mL of H₂O while ensuring that the rate of addition did not cause excessive steam formation. The resulting mixture was agitated to break up any large clumps that might have formed, the product was isolated by filtration, washed with an additional 750 mL of H₂O, and dried to yield 49.07 g of the product as fine colorless crystals at 84% yield. The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

Example 9

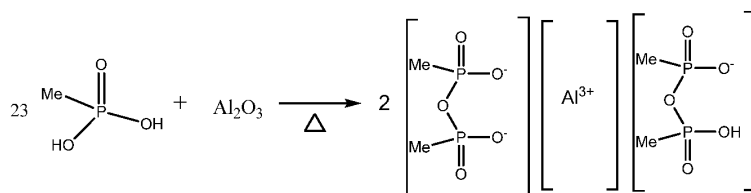


A resin kettle was charged with 83 g of methylphosphonic acid, which was heated to 120 °C.

An intermediate material prepared from 50 g. methyl phosphonic acid and 35.4 g. aluminum tris(isopropoxide) in the presence of water was added to the resin kettle as a syrup. The

- 5 resulting solution contained a 5:1 molar ratio of methylphosphonic acid : aluminum methylphosphonic acid intermediate, which was heated to 240 °C with mechanical stirring. Stirred continued at 240 °C for about 30 min after a solid had formed. 500 mL of H₂O was added and the mixture was stirred for 16 h while a uniform slurry was made. As above, the product was isolated by filtration, washed with an additional 750 mL of H₂O, and dried to
- 10 yield 64.3 g of the product as fine colorless crystals at 93% yield. The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

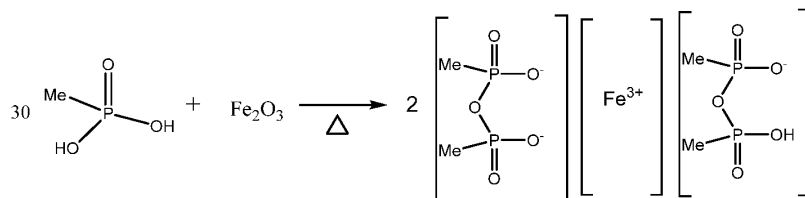
Example 10



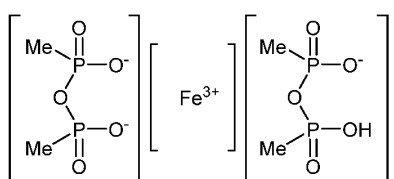
- 15 A three-neck 1 L flask was charged with 1305 g methylphosphonic acid, which was then heated. At 105 °C the methylphosphonic acid melted, and vigorous stirring was begun under vacuum. The methylphosphonic acid was heated to 180 °C and 61 g of alumina was added as quickly as possible without causing a large exotherm or excessive foaming. The slurry
- 20 was cooled until it was just above the melting point of the excess methyl phosphonic acid, ~110 °C, and then added to 1 L of H₂O while ensuring that the rate of addition did not cause excessive steam formation. The resulting mixture was agitated to break up any large clumps that might have formed, and the product was isolated by filtration, washed with an additional 1.5 L of H₂O, and dried to yield 408 g of the product as fine colorless crystals at 84% yield.
- 25 The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

The products from each of Examples 7-10 had a 4:1 P to Al ratio (ICP Elemental Analysis).

Example 11



- A 1 L reaction vessel was charged with 1412.6 g methylphosphonic acid, which was then heated to 165 °C under nitrogen purge (4L/min) at 250 RPM stirring. 78.2 g of iron oxide was added in portions without causing a large exotherm. The reaction mixture was heated at 165 °C for about 24 hours. The product reaction mixture containing an off-white slurry product was then cooled to about 130 °C and poured into 1.5 L of water in a beaker cooled in an ice water bath. The product was isolated by filtration, washed with an additional 500 mLx3 of water, and dried to yield fine off-white color crystals at 83% yield. The product had a 4:1 phosphorus to iron ratio (ICP Elemental Analysis) according to the following empirical formula:



- The product empirical formula above represents repeating monomer units (i.e., coordination entities) of a coordination polymer forming the pure crystalline product.

Example 12

- Flame retardant polymer compositions were compounded and molded into 1.6 mm bars and evaluated for flame retardant activity under UL-94 testing according to Table 1 below. A twin screw extruder was used to compound the below formulas at barrel temperature between 250 and 260°C. Formulation 1 contained a blend of 470 grams of glass-filled polyamide-6 (Durethan® B30S from LANXESS), 250 grams of glass fiber (ChopVantage® 3540 from PPG), 220 grams of poly(dibromostyrene) flame retardant (sold under the trade name Firemaster® PBS-64HW from LANXESS) and 60 grams of the phosphorus-containing flame retardant produced according to Example 7 above (Phos-FR). Formulation 2 was the same, except that the phosphorus-containing flame retardant was produced according to Example

1 above. An injection molder was used to prepare 1/16 inch (thickness) UL-94 specimens for each formulation at 250-260°C for barrel temperature and mold temperature at 80°C.

Table 1

Formulation #	1	2
PA 6 wt%	47	47
Glass wt%	25	25
Phos-FR (Ex. 1) wt%	-	6
Phos-FR (Ex. 7) wt%	6	-
PBS-64 HW wt%	22	22
UL 94 @ 1/16" (1.6 mm)	V-0	V-0

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Although particular embodiments of the present invention have been illustrated and described, it will be apparent to those skilled in the art from consideration of the specification and practice of the present disclosure that various modifications and variations can be made without departing from the scope of the invention, as claimed. Thus, it is intended that the

10 specification and examples be considered as exemplary only, with a true scope of the present invention being indicated by the following claims and their equivalents.