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Product Quality and an Assessment of a Chemical Formulation for an Insulator

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Abstract: Materials can be insulators, semiconductors or conductors based on their ability to conduct electrical and thermal current. An insulator is a substance that retard and block the flow of thermal and electrical current, it's a poor conductor and a non-conducting material. Insulator material include rock wool, mineral wool, fiberglass, and cork. Conductors are materials that conduct electrical and thermal current such as metals, copper, zinc, gold, silver…etc. Semiconductors are a different class of materials that have conductivity between insulators and conductors, silicon, germanium…etc. The objective is to find the reason behind the off gassing of the finished product at high temperatures and if sprayed with water for cooling purposes and suggest methods to minimize its off- gassing to improve its quality. It has been found that some chemical compounds in the current formulation are either hygroscopic, extremely soluble or are reactive towards other chemical compounds in the formulation. Soluble starch, ammonium sulfate and boric acid are water soluble chemical compounds having hygroscopic properties. It isn't recommended the usage of starch, and ammonium sulfate in the current formulation. Treating ammonium sulfate with water would result in the formation of ammonia gas, and there is high possibility of the reaction of starch with boric acid when exposed to water increasing its acidity. It's recommended the use of other insoluble chemical compounds, antimony III oxide or zinc borate and the more branched Dextrins instead.

Keywords: Insulator, Finished Product, Product Quality, Off-Gassing

1. Introduction

A chemical company in the USA is looking to improve the quality of the insulator finished product. The finished product shows off-gassing when used in certain areas within the US. It shows off-gassing when used in the mid-western and the south-western areas of the unites states, CA, TX, and MI, these regions of the unites states that are known to have high levels of humidity. The insulator consisted of the following chemical compounds, Ammonium sulfate, boric acid, starch, fertilizer, soybean oil, gray fiber, and brown fibers, mixed at temperature between 57.2- 73.9°C. The amount of each chemical compounds in the formulation are, 81% fiber, 10% ammonium sulfate and 10% boric acid, starch, fertilizer and soybean oil.

Materials can be insulators, semiconductors or conductors based on their ability to conduct electrical and thermal current. Electrical insulator has high resistivity than semiconductors or conductors, the electric current doesn't flow freely, and they don't conduct electricity. [1, 2]

An insulator is a substance that retard and block the flow of thermal and electrical current. It's a poor conductor and a non-conducting material. Insulator material include rock wool, mineral wool, fiberglass, and cork. Mineral wool is made by blowing steam through limestone or siliceous rock or through slag. Their opacity to heat breaks up heat-flow path. The thermal conductivity varies with temperature for a given material. Increasing temperature leads to decreasing the thermal conductivity. [3]

Fibrous insulator prevents heat transmission through convection and it works by capturing air within the fiber. It limits heat conduction between gas molecules minimizing collision between particles. Fibrous insulator is porous in structure and their structure are flexible that can be made

rigid by using some additives. [4]

Types of common fibrous insulators are natural fiber, plastic fiber, cellulose, mineral wool, and fiberglass, each type is of different properties. Natural fibers include wool, cotton, and straw used as insulator materiel. Both cotton and wool must be treated with borate to make them flame retardant. Cotton insulation is more-costly than fiberglass, and borate treated wool can hold large amounts of water that makes it lose its flame-resistant coating. Plastic fibers are similar to fiberglass, and they are made of recycled PET plastic bottles, mostly treated to make it more fire resistant. Cellulose is made of recycled paper products; mineral borates can be added to increase its fire resistance. Mineral wool contains large amount of industrial recycled content and natural minerals, and it doesn't require additional chemical treatments to make it fire resistant. Fiberglass is made from fine fibers of molten glass. [5]

Superior thermal insulators are made of foamed plastics. Plastic parts with increased thermal conductivities are sometimes required, as low thermal conductivity can limit cooling, heating rates, and limit processing speed. Mineral fillers have greater thermal conductivities than polymers as they increase composite conductivity. Heat conductivity is directly related to the material being able to conduct photons not electrons. Thermal conductivity depends on the amount of heat conductive material added, the thermal conductivity of polymer matrix, thermal conductivity of added material, and the presence or absence of interfacial gaps most critical barrier to heat transfer. Fillers material, materials like talc and calcium carbonate, speeds heating and cooling operations by increasing thermal conductivity. Best results are obtained by using specialty fillers, beryllium oxide, boron nitride (cubic and hexagonal), graphite, alumina, metals, and diamonds. A good example for such applications is their use in electronic devices to reduce heat. [6]

Insulators can be either in a solid or a liquid form. Solid insulators are usually present as thin layer on which the conducting layer sits. Some common solid insulators are silicone dioxide, glass, ceramics, porcelain, paper, fiberglass, rock salt, plastics, asphalt, graphite, rubber, and thin carbon foils. Silicone, oils, and natural esters are examples for liquid insulators. [7]

Fire retardants are substances that can be added to products such as furniture or electronic devices to limit the spread of fire or prevent fire from occurring. It reduces the risk associated with fire. Currently fire retardants are used in the furnishings, transportation, electronics, building and construction materials. Chemical compounds used as fire retardants are Hexabromocyclododecane (HBCD), Ethane, 1,2-dibromo, Antimony oxide (Sb2O3), Triphenyl phosphate (TPP), Tricresyl phosphate (TCP), and Phenol, isopropylated, phosphate (3:1) (PIP 3:1). Hexabromocyclododecane (HBCD) is used in construction applications and buildings, Ethane, 1,2-dibromo isn't used in conumer products, and it is used in chemical resistant clothing, and modified acrylic fibers. Antimony oxide (Sb2O3) increase the effectiveness of some hydrogenated fire retardants to enhance their effectiveness. Triphenyl phosphate (TPP) is known to be used in glues, casting resins, hydraulic fluids, electronics and PVC. Tricresyl phosphate (TCP) is used in chloroprene rubber, vinyl resins, and in plasticizers. Phenol, isopropylated, phosphate (3:1) (PIP 3:1) is used in electronics, consumer and industrial applications, and in automotive. [8] Antimony trioxide (Antimony III Oxide) is known to be used as a fire retardant in combination with other smoke suppressants and fire retardants. At an early stage of combustion, it forms a protective layer of surface as it melts, it isolates air, and it reduces combustion temperature. It dilutes air oxygen concentration as it vaporizes at high temperatures, and act as a fire retardant. Its solubility in water is 2.7 mg/L at 25 C. [9]

2. Experimental

Ammonium sulfate a compound with chemical formula of $(NH_4)_2SO_4$, and a molecular weight of 132.14 g/mol. It's white solid at room temperature, highly soluble in water with a solubility of 70.6g/ 100g of water. It's hygroscopic in nature as the solid absorbs water vapor from air. It's used as a food additive, and it's considered safe by the US, FDA. It's also used in addition to chlorine in disinfection and in the treatment of water. It's used as flame retardant, it decreases the maximum weight loss rate, increase combustion temperature of materials, and it increases the production of residue or char. It has been used in the past as wood preservative, and it was discontinued due to its hygroscopic nature, and its causing metal corrosion. [17]

Boric acid, a compound chemical formula of H_3BO_3, a molecular weight of 62.02 g/mol, and a melting point of 170.9 °C, and 339.6 °F. It's a week acid used as flame retardant, antiseptic, and as an insecticide. It inhibits the growth of microorganisms on the external surface of the body. It exists in the form of water-soluble colorless crystals or in the form of a white powder, slightly soluble in water, with a solubility of 4.72 g/100 mL of water. [18] It has a variety of applications in pharmaceuticals and cosmetics, flame retardants, glass and fiberglass, and it's also used as a nutritional supplement. In the pharmaceutical industry, it's used in eye disinfectants, vaginal remedies, contact lens solutions, anti-aging preparations, and in baby powder [19, 20]. It's used as a nutritional supplement as a source of boron in over-the-counter supplements. It's used a fire retardant as it reduces combustion by releasing chemically bonded water, and it inhibits the release of gases from burning paper-based materials, wood, and cotton. It's used in insulation, and gypsum board, mattresses, furniture, Futons, textiles, and Plastics as a flame retardant. It's used to increase the chemical and temperature resistance of the glass and fiberglass. It's also used as a natural insect and fungus control product, and as a wood preservative. It has been known to be used instead of chlorine in swimming pools. [21] It's a weak acid with ka value of $5.8* 10^{-10}$ [22], its acidity increases by 5 order magnitude in the presence of cis-vicinal diols (organic compounds containing similarly oriented OH groups), like glycerol or mannitol (a naturally occurring

alcohol in vegetables and fruits). The increase in the acidity is due to the formation of stable anion esters of five-member −B−O−C−C−O− rings, called mannitoborate ester anions, shifting the equilibrium to the right. The PH of a neutral solution containing boric acid is lowered by the addition of mannitol, and it can be titrated by a strong base as NaOH, a method used to determine the borate content of aqueous solutions. [23, 24]

$$B(OH)_3 + 2\ H(HCOH)_6H \rightleftharpoons [B(H(HCOH)_2(HCO-)_2(HCOH)_2H)_2]^- + 3\ H_2O + H^+$$

Equation 1: Overall reaction of mannitol with boric acid to form stable anion esters containing one or two five-member −B−O−C−C−O− rings.

Solid boric acid decomposes at high temperatures to form different boron compounds with different water solubility. Heating boric acid to 170 °C leads to forming slightly water soluble meta-boric acid, heating it to 300 °C, leads to forming water soluble tetra-boric acid, and heating it to above 330 °C, leads to forming boron tri-oxide, with a solubility of 1.1g/ 100g of water. [15-28]

$$H_3BO_3 \rightarrow HBO_2 + H_2O$$

(Meta-boric Acid)

$$4HBO_2 \rightarrow H_2B_4O_7 + H_2O$$

(Tetra-boric Acid)

$$H_2B_4O_7 \rightarrow 2B_2O_3 + H_2O$$

(Boron tri-oxide)

Figure 1. *Decomposition Reactions of Boric Acid at Different Temperatures.*

Starch, is a chemical compound with formula of $(C_6H_{10}O_5)_{n.\ 1}$t is a white granular chemical compound produced my most plant. It's insoluble in alcohol and insoluble in water. The starch molecules would dissolve in water upon heating. Starch is used in brewing, paper manufacturing, paper bags, tape, gummed paper, and in textile industry as wrap sizing. It's a thickening agent. It increases the strength of paper. [29] At normal atmospheric pressure, starch is a hygroscopic substance that absorbs (10-17%) of moisture. 30Starch can be used as adhesives in the paper industry. Starch has a good heat resistance, and is of low cost. Additives may be used to improves its properties, biocides may be used to inhibit fungal growth, urea formaldehyde may be used to improve its moisture resistance, and polyvinyl acetate and polyvinyl alcohols may be used to improve resistance to cold water. Dextrins dry faster than starch as they have higher solid composition, they are suitable for bonding paper-based material, and they supports higher line speed. Dextrins are the de-polymerized products of starch by heat or acid treatments, and its re-polymerization, and it is highly branched and soluble in water product. Borated dextrins contain borax to increase tack. [30,43, 47].

Ammonium polyphosphate, is a chemical compound with formula of $[NH_4\ PO_3]_n$, where n can be greater than 1000, and it's a flame retardant. Linear and short APPs (n < 100) are less thermally stable, decomposes at 150°C and more water sensitive (hydrolysis) compared to the long chain APPs (n >1000), which decomposes at 240 °C, almost 300°C to form ammonia and polyphosphoric acid. The long chain APPs are very water insoluble, its solubility is less than 0.1 g/ 100 ml. Properties of long chain APPs can be easily modified by using additive to make them suitable for certain applications. [31]

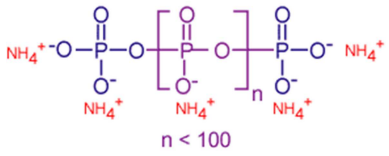


Figure 2. *General structure for Linear and short APPs.*

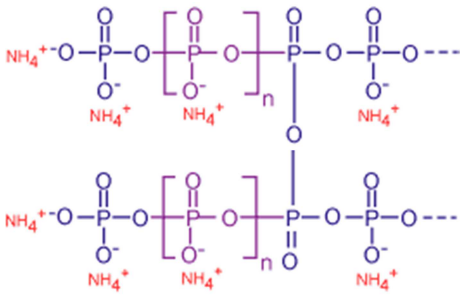


Figure 3. *General structure for long chain and branched APPs.*

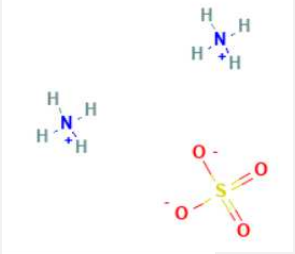
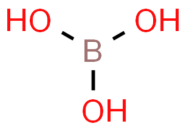
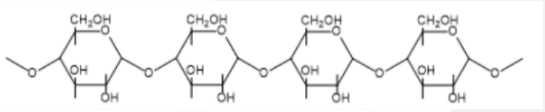
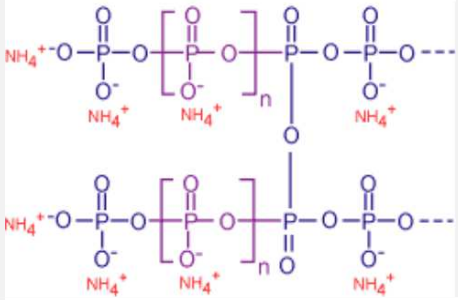
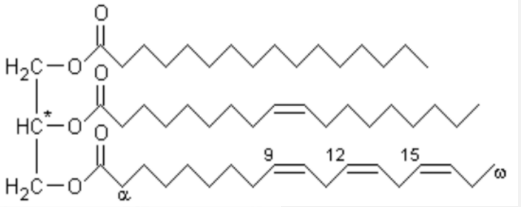
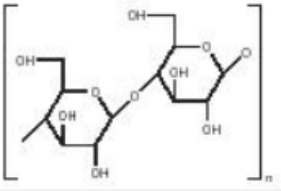
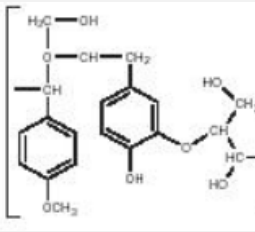
The dehydration of carbon-based poly-alcohols, for example cellulose in wood is catalyzed by the phosphoric acid forming heat-unstable phosphate esters. The phosphoric acid catalyst is regenerated by the decomposition of the esters and the release of carbon dioxide gas. The oxygen of the air is diluted by the release of non-flammable carbon dioxide gas, and the char produced shields the polymer from further reacting with oxygen of air. It has a potential to be widely used as a flame retardant instead of halogen compounds flame retardants due to its environmental profile. [32, 33]

Soybean oil, is a chemical compound with formula of $C_{55}H_{98}O_6$ and an average molecular weight of 92g/mol. Is a liquid mixture of triglycerides, and it contains 23% of monounsaturated fat, and 58% of polyunsaturated fat, and 16% of saturated fat. It's an electrical insulating fluid. It's mostly used in the food industry in frying and baking. [34, 35, 36].

The fundamental unit of which fabric is made is called fiber. It resembles hair in appearance, and it used in the making of clothes. [37] Fibers can be either natural or synthetic. Natural fibers are either plant or animal based or inorganic fibers. Cellulose (cotton) is an example of a plant-based fiber, and wool and silk are animal-based fibers. Animal fibers are known to be used in production of ropes, weaving and insulation. Some Natural fibers are made of inorganic materials. Examples for inorganic fibers are fiberglass, carbon fibers, and steel fibers. Spun glass makes fiberglass. Steel fibers are known for their abrasive quality. Synthetic fibers are made of either polyamides or polyesters.

Orlon, polypropylene, dacron, and nylon are synthetic fibers. [37-42]

Table 1. *Lists Chemical name, chemical structure, molecular formula, molecular weight and usages for chemical compounds used in the current formulation.*

Chemical Name	Chemical Structure	Molecular Formula	Molecular Weight (g/mol)	Properties and usage.
Ammonium sulfate [10]		$(NH_4)_2SO_4$	132.14	Buffer in the food industry, and a fire retardant
Boric acid [11]		H_3BO_3	62.02	Insect control, anti-fungal, and fire retardant
Starch [12, 13]		$(C_6H_{10}O_5)n$	Variable 5	Adhesive and a flame retardant
Fertilizer (ammonium polyphosphate Solution) [14]		$[NH_4\ PO_3]_n$	97.01	Flame retardant
Soybean oil [15]		C55H98O6	920	Electrical insulating fluid.
Fibers [16]	 Cellulose fiber  Lignin Fiber	Variable.	Variable.	Insulating material.

3. Discussion

Most insulators are solid, unreactive, and water insoluble chemical compounds, such as rubbers, glass, oil, dry wood, and plastics. The known strong insulators include Dry paper, Ceramics, and Quartz. The chemical compounds in the formulation should be insoluble and unreactive.

The formulation contains solids which are soluble in water, causing the solids dissolve and possibly to react when mixed/ sprayed with water or when there is high humidity meaning large amount of water vapor in air, and the result of the reaction is the formation a gaseous product. Most reactions are known to increase by increasing temperature, more gas product is formed. Starch, and fibers are mainly insoluble in water, fertilizer (ammonium polyphosphate Solution) is only slightly soluble in water with a solubility of less than 0.1 g/ 100 ml, which is nearly insoluble in water.

The current formulation consists water-soluble chemical compounds, boric acid, and ammonium sulfate. Boric acid is slightly water-soluble and a hygroscopic chemical compound with a solubility of 4.72 g/100 mL of water, whereas ammonium sulfate is a very water-soluble chemical compound, hygroscopic solid with a solubility of 70.6g/ 100g of water. There are some forms of soluble starch possibly used in the current formulation. Also, insoluble starch becomes soluble with increasing temperatures.

The PH of 0.1M of ammonium sulfate is almost 5.5. [17] Increasing the PH to 7 by spraying with tap water or by absorbing water would result in the formation of ammonia gas, the bubbling. [44] Also, upon heating the solid in an open system, it decomposes at almost 150°C, forming ammonium bisulfate (NH_4HSO_4), and ammonia gas. [45-47] Boric acid is known to be used as antifungal agent and a fire retardant. It's not recommended the use of ammonium sulfate as a fire retardant in the current formulation as it's very water soluble, hygroscopic, and it was discontinued as wood preservative years ago.

Starch is a hygroscopic polysaccharide consisting of glucose monomers in α 1,4 linkages. The reactivity of starch arises from the free poly-hydroxyl functional groups in the constituent glucose monomers. The hydroxyl groups at position C-2, C-3 and C-6 are free from the bond-linkages and pyranose ring formation, and are free for substitution reactions involving either the entire hydroxyl group or the attached hydrogen. 46 Acid hydrolysis of starch due to mineral acids such as H2SO4, HCl (Ka= 1.3 * 10^6), HNO3, and H3PO4 at temperatures below the gelatinization temperature can occur (between 55-85^o C, based on the type of plant).

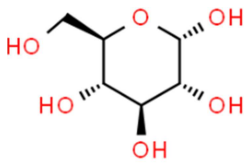


Figure 4. *Structure for α-D Glucose.*

With polyols containing cis-vicinal diols, such as glycerol and mannitol, the acidity of the boric acid solution is increased. With different mannitol concentrations, the pK of B(OH)3 extends on five orders of magnitude (from 9 to 4): This is due to the formation of a boron-mannitol chelate, [B(C6H8O2(OH)4)2]−, also known as mannito-borate complex, according to the following complexation reaction releasing a proton:

$$B(OH)_3 + 2\ C_6H_{14}O_6 \rightleftharpoons [B(C_6H_8O_2(OH)_4)_2]^- + 3\ H_2O + H^+$$

boric acid mannitol mannitoborate complex

It's not recommended the use of both boric acid and soluble starch in the same formulation due to possible side reactions. Boric acid is known to be used as antifungal agent and a fire retardant in current chemical industry. It's recommended the use of a more branched adhesive than starch, Dextrins. More branched adhesive compound would have less available free poly-hydroxyl groups, minimizing the reactions and therefore minimizing the off-gassing. Dextrins dry faster than starch as they have higher solid composition, they are suitable for bonding paper-based material, and they support higher line speed.

4. Conclusions

It is not recommended the use of ammonium sulfate in the formulation as it is very water soluble, hygroscopic, chemically reactive compounds, and it was discontinued as a fire retardant and in the wood preservative industry. Other fire retardants may be used.

It's recommended the use of 10% antimony III oxide or zinc borate instead. Both antimony III oxide and zinc borate are good fire retardants. Zinc borate is used as a fire retardant in in plastics and cellulose fibers, paper, rubbers and textiles, and it is a very water insoluble compound with a solubility of 0.1%.

Also, it's not recommended the use of soluble starch in the current formulation, the free poly-hydroxyl functional groups in the constituent glucose monomers of the starch polysaccharide makes the molecule reactive for substitution reactions involving either the entire hydroxyl group or the attached hydrogen. Also, boric acid acidity increases by five folds in the presence of cis-vicinal diols.

It's recommended the use of the more branched Dextrins. More branched Dextrins adhesive would have less available free poly-hydroxyl groups, minimizing the reactions and therefore minimizing the off-gassing.

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