Technical Research

CoREZYN Premium Vinyl Ester Molecule

Modifying
Fire Resistant Vinyl Ester Resins
for Marine and Corrosion
Applications

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Thermoset Resins Division

ABSTRACT

Fiberglass reinforced plastics/glass reinforced plastics (FRP/GRP) composites offer substantial weight reductions, increased strengths, corrosion resistance, plus noise, temperature, and vibration control when compared to metal substrata. However when fire and corrosion resistance properties are simultaneously required from the composite, choosing them over metal raises concerns.

Interplastic Corporation has extensive experience in designing proven resin formulas that will successfully incorporate fire and corrosion resistance simultaneously for composite ducting, pipes, walls and structures, transportation equipment and marine applications.

The scope of this paper is to provide a better understanding of flammability factors and to illustrate the advantages of using Interplastic fire resistant vinyl ester resins in applications also requiring corrosion resistant properties.

INTRODUCTION

All organic polymers are combustible. In fact, once their ignition temperatures are reached, most oxidizable materials will burn if enough surface area is subjected to a sufficient amount of an oxidant.

Carbon, hydrogen and oxygen molecules largely comprise most of the polymeric materials used in today's composites industry. Most polyesters are the result of a condensation reaction of organic dihydric alcohols and dibasic acids. A special family of polyesters called vinyl esters is processed via additional reaction using organic di-epoxides and unsaturated acids.

Since both polymers contain a high degree of carbon and hydrogen bonds, decreasing the flammability properties of these resins must be accomplished by other methods. Incorporating halogens, metal oxides and hydrated fillers into the polymer matrix are commonly used to affect flame properties.

Using the CoREZYN® CORVE8440 series fire resistant vinyl ester resin, Interplastic evaluated pigment grade antimony trioxide, NYACOL® Nano Technologies' APE1540, a non-aqueous colloidal antimony pentoxide dispersion formulated as a flame retardant synergist; and NYACOL APE3040, a patented colloidal antimony pentoxide dispersion

formulated for use as a flame retardant synergist.[1] The results are contained in Figure 1.

An "additive" that we will discuss using, is one of the highly specific physical forms of alumina trihydrate. It accomplishes its fire resistant enhancement by subliming off its three waters of hydration at a specific heat, helping to cool the combustion. It also replaces, volumetrically, part of the resin in the reinforcement volume fraction thereby reducing the combustibles.

COMBUSTION CHEMISTRY

Polymer degradation through thermal oxidation is described by a myriad of complex chemical equations that take place in solid, liquid and gaseous phases. This process is initiated:

1. when an ignition source is applied to the organic polymer substrate, and
2. volatile fragments or radicals form and then participate in a series of oxidation reactions, and then
3. enter the gaseous phase adjacent to the substrate surface.

The combustion or oxidative process is propagated by volatile polymer fragments ($R\bullet$) and oxygen containing radicals, ($O\bullet$ and $OH\bullet$), which are created in the pyrolysis zone as depicted in the following schematic:

1. R (vinyl ester or polyester polymer) $+ O_2 \longrightarrow R\bullet + OH\bullet$

2. $R\bullet + OH\bullet \longrightarrow CO + CO_2 + H_2O + R'$

3. $CO + OH\bullet \longrightarrow CO_2 + H\bullet$

4. $H\bullet + O_2 \longrightarrow OH\bullet + O\bullet$

Understanding the combustion process is easier when it is broken down into individual stages. Many flammability test methods describe the effect fire has on specific materials by illustrating the burning process in a sequence of steps. Since there may be as many flammability test methods as there are types of fires, we'll use a more pragmatic approach to first identify the components of flammability and then correlate common laboratory fire tests with those specific combustion phases.

THE SCIENCE OF FIRE

THREE FIRE STAGES

Initiation (or ignition) is the first phase of the burning process. Ignition sources may involve high temperature surfaces, heated air, immense electrical output and flames. Upon ignition, chemicals in the vapor phase near the ignition source will flame due to sustained evolution of heat from combustible gases (CO) and gaseous radicals (OH$\bullet$, H$\bullet$) or from decomposition of the polymer (R$\bullet$).

Propagation (or flame spread) occurs when the polymer decomposes and provides fuel for the flame in the presence of a sufficient amount of oxygen. The distinction between initiation and propagation is somewhat ambiguous since a flame spread can also be thought of as a series of ignitions. Fuel is in the form of polymeric free radicals (R$\bullet$) and combustion gases (CO, CH_4, C_2H_6, etc.). Propagation continues as long as there is oxygen and sufficient fuel available to liberate enough heat for transfer to adjacent polymer surfaces. Smoke is formed as polymer solids and polymer gases are generated throughout the entire combustion process.

Termination (or extinction) is the final phase of the burning process. A flame will extinguish when either the polymer decomposition products are unable to participate in the oxidative chemical reactions (loss of fuel to the flame) or the concentration of oxygen is too low to support initiation or ignition of adjacent polymer composite surfaces.

FLAMMABILITY TESTS

Flammability test procedures have been devised to help predict material performance on a laboratory scale. (It is beyond the scope of this paper to thoroughly discuss each test method and to assess the results of how they comply with the many fire standards that exist today.) The methods commonly used in the FRP/GRP industry are tabulated in Figure 1.

Suitable combustion behavior predictions can be made about composite materials if combinations of these test methods are chosen that describe the three major components of the burning process. The results of these tests are not meant to quantify the complexities of a real fire. They only attempt to examine a fragment of the combustion process for material comparisons and screening for large-scale tests, such as the United States Navy's open environment full-scale test or the N-Gas model smoke and toxicity tests.

SUPPRESSION

There are four key aspects of polymer combustion chemistry that can be suppressed using fire retardant chemicals. They are to:

1. decrease the concentration of polymer free radcals or fuel from entering the flame;

2. minimize the quantity of oxygen available in the pyrolysis zone;

3. alter the heat of combustion of the gaseous phase; and

4. increase the activation energy of combustion of the polymer.

After removing the ignition source, the substrate might continue to burn, it might smolder or the combustion reaction sequence might terminate. The flame might terminate because a thermal barrier, formed by carbonized polymer or ash deposit polymer radical, was created on the polymer's surface. The termination may be induced by water evolution from an additive such as alumina trihydrate, which can also function as an internal heat sink. Degradation of the substrate's surface due to melting, which occurs as combustible material dissipates from the heat source, may also terminate the burning process.

The most common method of suppressing flammability is by using halogens. Halogens are the Group VIIA elements iodine, bromine, chlorine, and fluorine. These chemicals are electron-rich with one vacancy in their outer valence shell. Halogens are superior free radical scavengers due to their strong tendency to add an electron or free radical to complete their shell.

CHEMICAL SUPPRESSION

WHAT DOESN'T WORK

Iodine is an exceptional free radical scavenger but it exhibits inferior thermal stability and becomes ineffective in the volatile phase due to rapid bond dissociation.

Fluorine, on the other hand, bonds so tightly to carbon that it does not dissociate and interfere with oxidative reactions in the vapor phase of combustion.

WHAT DOES WORK

Bromine-containing polymers (such as the CoREZYN

CORVE8440 series) on a molar basis are the most effective fire suppressants in the halogen family.

Chlorinated polymers are also commonly used as fire retardant agents, however bromine has more than twice the molecular weight of chlorinated polymers, making this an economically feasible selection. Choosing bromine as the halogen source for CoREZYN CORVE8440 vinyl ester resins results in it being a more dense polymer for fire and corrosion resistance and therefore, a better choice than a less expensive by weight, chlorinated polymer.

HOW THESE HALOGENS WORK

Upon ignition, bromine-containing polymers and chlorinated polymers dissociate and form acid halides (HX). Acid halides volatilize, enter into the vapor phase and become free radical scavengers. When enough acid halides evolve into the gaseous phase, they can effectively eliminate the highly exothermic, oxidative free radicals. Initiation and propagation of the flame front is ceased by decreasing the concentration of fuel entering the flame, minimizing the quantity of oxygen available in the pyrolysis zone, and lowering the heat of combustion in the gaseous phase.

The following chemical reactions illustrate this interaction.

1. RX (halogen, polymer) $+ O_2 \longrightarrow R\bullet + OH\bullet + HX$ (acid halide)

2. $HX + OH\bullet \longrightarrow H_2O + X\bullet$

3. $X\bullet + R \longrightarrow HX + R\bullet$

When specific metal oxides are added to a halogen-containing polymer system, the efficiency of the above chemical reactions is greatly increased. The synergy between oxides and halogen significantly reduces flammability. Metal oxides are relatively inert in the burning process, however in the presence of halogen, metal oxy-halogens are formed in the vapor phase. As the reaction progresses, metal tri-halides are generated. These compounds are called Lewis Acids. They are thermally stable, with high densities that doubly function as potent free radical scavengers and aid in the formation of a vapor barrier or as a char former. (A char is a carbonized or ash residue formed on the polymer surface that negatively affects heat transfer to adjacent surfaces and further hinders the supply of polymer fragments [or fuel] from entering the flames.)

The following sequence of chemical reactions illustrates the synergy between antimony trioxide and chlorine.[4]

1. $Sb_2O_3 + 2HCl \longrightarrow 2SbOCl + H_2O$
   250°F (121°C)

2. $5SbOCl \longrightarrow Sb_4O_5Cl_2 + SbCl_3$
   245 - 280°F (117 - 138°C)

3. $4Sb_4O_5Cl_2 \longrightarrow 5Sb_3O_4Cl + SbCl_3$
   410 - 475°F (208 - 244°C)

4. $3Sb_3O_4Cl \longrightarrow 4Sb_2O_3 + SbCl_3$
   475 - 565°F (208 - 293°C)

The formation of antimony tri-chloride ($SbCl_3$) is generated over a wide temperature gradient resulting in a very effective flame suppressant. Organo-phosphates are also effective synergists with halogens but react somewhat differently than the metal oxides. Again, phosphorus tri-halides are formed and participate in the chemical reactions of the vapor phase but seem to have a higher affinity to form a vapor barrier, possibly due to the generation of polyphosphoric acid.

Other polymer compositions with high levels of aromaticity (ring structures) and very little carbon-hydrogen bonding outside these aromatic rings yield excellent flammability resistance. Polymers of this type have minimal levels of oxidizable constituents.

Phenolics are polymers derived from a reaction of phenol and formaldehyde. They exhibit low flame spread indices and low smoke evolution. Although phenolics are not user-friendly in the FRP process, they offer the composite engineer an alternative to halogen-containing resins.

Other analogs of highly aromatic polymers are polyamides, polyarylates, and polyphenylene sulfone. Many of these polymers offer excellent fire resistance properties but are difficult to handle, lack good mechanical properties due to rigidity, and are not economical.

THE COMPONENTS OF A SUPERIOR RESIN

GLASS TRANSITION TEMPERATURE (Tg)

Temperature capability is related to how the composite maintains its corrosion resistance and strength when exposed to ambient or process temperatures (Table 5). The higher glass transition temperature of the vinyl ester means it will retain more of its inherent corrosion resistant and physical properties when the

composite is heated by direct or infrared heat sources than, for example, a fire resistant isophthalic or terephthalic polyester will.[8] Table 3 shows the glass transition temperature as is on CORVE8441 with NYACOL APE3040 and with antimony pentoxide.

ELONGATION

Fire resistant vinyl ester resins have proven to be tougher, as shown in the stress strain curves in Figures 2 and 3. As the tensile elongation of orthophthalic and isophthalic polyester resins increases, their glass transition temperatures will decrease. Vinyl ester resins have the ability to absorb tensile and flexural stresses better than polyester resins with the same temperature capabilities. The higher elongation of the fire resistant vinyl ester (3.5 - 4.5%) relates to increased flexibility, meaning that a composite made with a vinyl ester can yield to more stress before failing.

Fire resistant unsaturated polyester resins, such as orthophthalic or isophthalic resins are another group of products used in the fire resistant or corrosion resistant/fire resistant applications. They have tensile elongations of 1 to 2% combined with higher glass transition temperatures of up to 220°F/103°C. The orthophthalic and isophthalic resins are both fairly rigid and in fatigue testing, fail more easily than the tougher vinyl ester resin.

FATIGUE PERFORMANCE

The toughness of the vinyl esters previously mentioned also improves the fatigue performance of the composite. These tougher vinyl esters have longer service lives because they can absorb more stress than a more rigid isophthalic or orthophthalic resin. We typically choose resins with tensile elongations over 3% for fatigue applications because the fiberglass strands used in the knitted and woven fabrics used in marine applications have elongations of 2 to 3% in the tensile mode. The higher elongation allows the composite to transfer more of the stress to the reinforcement, which makes their performance more dependent upon the reinforcement.

TEST DATA

A comparison of ASTM D3479 fatigue performance was previously done for four different resins – a vinyl ester resin, a hybrid/modified vinyl ester resin, a specially designed isophthalic resin and a typical orthophthalic resin.[6] The vinyl ester, modified vinyl ester and isophthalic polymers had tensile elongations over 3%. The orthophthalic had approximately a 2% elongation. Figure 4 shows that the projected lines for the three polymers with elongations over 3% were in a fairly tight grouping while the resin with a 2% elongation

had significantly poorer performance at the same stresses. The correlation factors of the linear models for the four groups of data were 0.87 for the polymer with 2% elongation and 0.93 to 0.97 for the three polymers with over 3% elongation.Flexural fatigue data was run on these same four resins according to ASTM D671.[7] Figure 5 shows that the vinyl ester and hybrid resins were very close in performance, while the isophthalic was significantly lower and the orthophthalic was lower yet. The correlation factors of the four sets of data ranged from 0.84. to 0.92.

CORROSION AND FIRE RESISTANT VINYL ESTERS FOR ENGINEERING COMPOSITES

Brominated vinyl ester resins were chosen over unsaturated polyester resins for corrosion resistant applications. They have a combination of superior physical characteristics, such as tensile elongation of 3% or higher; a glass transition temperature of over 230°F/109°C; excellent performance in the tensile and flexural modes as well as in fatigue; and excellent prolonged resistance to degradation by corrosion attack.

The invention of a brominated vinyl ester resin by Interplastic Corporation in 1975 provided an ideal answer to the question of how to enhance with fire resistance properties, the excellent physicals and corrosion resistance of the bisphenol A-epichlorohydrin vinyl ester. Incorporating bromine into the backbone of the epoxy vinyl ester gives superior corrosion resistance, high fatigue properties, and predictable fire resistance and smoke generation performances.

For example, the increased electron density surrounding the polymer network in a fire resistant vinyl ester resin provides improved resistance to the demanding service conditions found in the paper and pulp industry.[8]

SYNERGISTS AND ADDITIVES: ANTIMONY TRIOXIDE AND ANTIMONY PENTOXIDE

Adding various forms of antimony oxides to fire resistant CoREZYN vinyl ester resin has been thoroughly evaluated by Interplastic Corporation. The fire resistant resting was accomplished at NGC Testing Services.[2] These additives, used as synergists for fire resistance, have proven themselves to be very effective.

Using the CoREZYN CORVE8440 series fire resistant vinyl esters, Interplastic evaluated pigment grade antimony trioxide (Sb_2O_3); NYACOL Nano Technologies' APE1540, a non-aqueous colloidal antimony pentoxide dispersion formulated as a flame

retardant synergist; and NYACOL APE3040, a patented colloidal antimony pentoxide dispersion formulated for use as a flame retardant synergist.[1] The results are contained in Table 1. Table 3 shows the effects of these additives on the Tg of the resin.

FIRE RESISTANT VINYL ESTERS AND GEL TIME DRIFT WITH ANTIMONY AND COLLOIDAL ANTIMONY

The previous industry experiences of rapid gel time drift and filler settle-out using powder Sb_2O_3 have been alleviated by using the NYACOL APE3040. The suspension is stable and requires only occasional mixing to maintain its integrity. Also,the effect on the cobalt-based initiator systems is considerably less than previous antimony compounds allowing larger batches to be compounded at the fabricator. Rechecking gel and cure parameters is suggested as batches age (between shifts, daily).

THE EFFECTS OF ADDING ALUMINA TRIHYDRATE

We pursued additive technology for the fire resistant vinyl ester CORVE8441 by adding J.M. Huber SB432 alumina trihydrate.[3] The results were revealing. It appears that we are near an interesting relationship of resin-to-reinforcement filler volume ratios. Both tests resulted in a fire/smoke of 25 in the Steiner Tunnel Test ASTM E-84. This will only approximate results of other composites in different geometries, but does give an excellent example of the Interplastic CORVE8440 series resins with the high bromine content in a composite with alumina trihydrate. The data is compiled in Table 2.

The CORVE8401B and CORVE8441B vinyl ester resins have Mil-R-21607 qualifications suitable for use in fire resistant FRP composites used in boats, tanks, pipe work, supports and other naval applications. Figure 6 depicts the resin capabilities required for low pressure laminating fire resistant resins.

CORROSION RESISTANT RESIN DESIGN

Hydrolysis is a form of chemical corrosion involving mass transfer of the water molecule into a composite with subsequent scission of polymer reactive sites. The rate of hydrolysis in FRP composites is controlled by the extent of cure, polarity of the polymer and water temperature. Water absorption at the composite's surface was discovered to be fairly rapid and to follow a logarithmic rate.[9] A saturation point is soon reached and if the polymer is non-polar or inert to water, equilibrium exists. If the polymer has a high degree of polarity or contains many ester linkages, it can be chemically attacked and made soluble. A decrease in weight is evidenced as polymer frag-

ments are leached out of the composite and replaced with water.

Vinyl ester resins only have two ester functional groups located at the end of each polymer. These reactive sites are not readily hydrolyzed due to a steric hindrance from a methyl group and adjacent vinyl unsaturation where crosslinking occurs. In contrast, polyesters contain many reactive ester sites throughout the polymer and are more susceptible to trans-esterification.

CORROSION RESISTANCE WITH FIRE RESISTANT ADDITIVES

ResinWizard® (www.resinwizard.com) is a searchable database within the Interplastic website (www.interplastic.com) where you can learn about the corrosion resistant capabilities of our fire resistant vinyl ester resins. Obviously the addition of any material to the composite changes the expected capability of the originally tested resin. Usually it lessens the corrosion resistant capabilities of the composite in some fashion. Interplastic is carefully evaluating many of the combinations in ASTM corrosion testing.

Using alumina trihydrate in a corrosion resistant composite will lessen its corrosion resistant properties by increasing the surface area exposed to the corrosive environment. The alumina itself is resistant to various corrosive environments, and an excellent filler to consider when considering fire retardancy and acid resistance. However, basic chemical resistance is more critical to consider due to the susceptibility of the alumina and the increased surface area.

The effects of the colloidal products are a little harder to predict. The product consists of an unsaturated resin used as a dispersing and suspending vehicle. While the relatively small amount of the antimony pentoxide used will have small effect on the overall resin system, that amount of resin as an additive is detrimental to the overall chemical resistance of the system. Therefore, Interplastic recommends considering corrosion environments at 20°F/6.7°C lower than the recommendations listed in ResinWizard or product literature when these additives are used.

IMPACT OF CURE

Independent of polymer design, an under-cured composite will also be subject to hydrolysis. For example, a fully cured isophthalic polymer can exhibit better hydrolytic resistance than a severely under-cured vinyl ester. Unsaturation sites are located in the terminal positions of each vinyl ester polymer and therefore are more accessible for free radical polymerization with reactive diluents than their polyester counterparts. In general, a high extent of cure should be

easier to obtain with more accessible terminal unsaturation sites. Obviously, the degree of cure directly relates to achieving the fire resistant capability you desire.

CONCLUSION

Fire performance, corrosion resistance, and the mechanical properties of FRP articles are very important considerations in material selection for corrosion applications. The test methods chosen to characterize these performance properties are equally important.

The effect of using a synergist, such as NYACOL APE1540 or APE3040 is extremely effective and has minimal effect on the corrosion resistance we recommend. We have documented here the increase in fire resistance to a <25 in an ASTM E-84 tunnel test.

The use of a fire retardancy enhancing filler, such as the J.M. Huber alumina trihydrate SB432, is predictably effective in reducing combustibility, reducing cost and increasing modulus. NGC Testing Service demonstrated repeatable results when incorporating several levels of the alumina trihydrate.

A solid understanding of flammability is vital when selecting construction materials along with the appropriate fire tests to adequately predict performance properties in actual fire conditions. A combination of small-scale test methods is necessary before proceeding to large-scale testing. Location of the flame, heat source, and the geometry of the specimen are important considerations when choosing a fire test or series of tests as they relate to a specific end-use application.

Static and dynamic physical properties also favor using vinyl ester resins in corrosion applications. Tremendous impact and cyclic stresses are imposed on vessels in everyday use. Vinyl ester resins, with their high tensile elongation and superior strength, withstand these stresses extremely well.

Corrosion resistance is particularly relevant in the marine industry. Vinyl esters exhibit superior hydrolytic capabilities. Interestingly, fire resistant vinyl ester resins have improved water resistance over standard vinyl ester polymers. This was illustrated in an ASTM D570 water absorption study conducted at ambient, 150°F/65°C, and 200°F/93°C temperatures.[9]

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3. Huber SB432 by Huber Engineered Materials, part of J.M. Huber Corporation, 333 Thornall Street, Edison, NJ 08837-2220; Phone: (732) 549-8600.

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9. Burrell, P., McCabe, T., Herzog, D., "A Study of Permeation Barriers to Prevent Blisters in Marine Composites and a Novel Technique for Evaluating Blister Formation," 42nd Annual Conference, SPI Reinforced Plastics/Composites Institute, 1987.

TEST DATA

Table 1: Fire Resistant CORVE8440 - 8441 With 0, 1.5, 3, and 5 % Antimony and Colloidal Antimony in the ASTM E84 Test

Fire Resistant Vinyl Ester*	Sb$_2$O$_3$	Nano NYACOL APE1540	Nano NYACOL APE3040	Flame Spread	% Glass
CORVE8440	1.5%			19	24
CORVE8440	3%			19	24
CORVE8440		5%		21	24
CORVE8440	0%	0%	0%	60	33
CORVE8440	3%			12	33
CORVE8440			3%	19	33
CORVE8440		1.5%		21	33

*For the purposes of this test, CORVE8440 and CORVE8441 are equivalents.

Table 2: Fire Resistant CORVE8440 with Alumina Trihydrate in the ASTM E84 Test

Fire Resistant CoREZYN Vinyl Ester	Alumina Trihydrate Huber SB432	Ignition, Seconds	Flame Front	Smoke	Flame Spread	Glass Content %
CORVE8440 55%	45%	104	7 ft (2.13 m) @ 241 seconds	315	25	25
CORVE8440 50%	50%	93	8.5 ft (2.6 m) @ 422 seconds	320	25	20

Table 3: Glass Transition Temperatures of CORVE8441 and Additives

PRODUCT	CORVE8441	CORVE8441 with 3.5% NYACOL APE3040	CORVE8441 with 1.5% Sb$_2$O$_3$
Glass Transition (Tg), °F/°C	262/128	259/126	262/128

TEST DATA

Table 4: Physical Properties of CORVE8441 and Additives

ASTM Method	Description	CORVE8441		CORVE8441 with 3.5% NYACOL APE 3040		CORVE8441 with 1.5% Sb_2O_3	
		Casting	Laminate	Casting	Laminate	Casting	Laminate
D-790-00	Flexural Strength, psi (MPa)	19,800 (137)	35,000 (241)	20,100 (139)	31,400 (217)	18,400 (127)	34,700 (239)
D-790-00	Flexural Modulus psi x 10^5 (GPa)	4.9 (3.38)	11.0 (7.59)	4.98 (3.43)	12.1 (8.34)	5.27 (3.63)	12.2 (8.41)
D-638-00	Tensile Strength psi (MPa)	11,700 (80.7)	18,600 (128)	12,000 (82.8)	18,900 (130)	11,800 (81.4)	18,000 (124)
D-638-00	Tensile Modulus, psi x 10^5 (GPa)	4.95 (3.41)	14.3 (9.86)	5.08 (3.50)	13.7 (9.45)	4.98 (3.43)	13.4 (9.24)
D-638-00	Elongation, %	4.4	1.9	4.3	1.9	3.89	1.8
D-548-00	Heat Distortion Temperature, °F (°C)	206 (97)		205 (96)		206 (97)	
D2583-95	Barcol Hardness 934-1	34 - 36	40 - 46	34 - 36	44 - 46	34 - 36	44 - 46
D2584	Glass Content %		32		29.9		34.1

Table 5: Flexural Strength as a Function of Temperature
Panel Construction: VEIL/MAT/MAT/WR/MAT/WR/MAT
1.5 oz MAT, 24 oz Woven Roving (WR)

Resin Type	Percent Retention 150°F/66°C	Percent Retention 200°F/93°C	Percent Retention 250°F/121°C	Percent Retention 300°F/149°C
Isophthalic	100	83	12	
CORVE8300	97	83	15	
CORVE8730-36	97	83	80	45
CORVE8770	95	90	78	58
CORVE8440	81	79	34	13

Table 6: Common Laboratory Fire Tests

Identification	Description	Sample Size	Sample Orientation	Flame Direction	Results	Phase
HLT-15	Hooker's Intermittent Flame, in. (cm)	8 x ½ x 1/8 (20.3 x 1.27 x 0.32)	Vertical	Upward	Average of five ignitions: 20, 40, 60, 80, 100%	Initiation
UL-94	Underwriters' Laboratory Vertical, Section 3, in. (cm)	5 x ½ x 1/8 (12.7 x 1.27 x 0.32)	Vertical	Upward	Two 10 second ignitions; V-O, V-1, V-2	Initiation
ASTM E162	Radiant Panel, in. (cm)	6 x 18 x <1 (15.2 x 15.7 x <2.54)	45 degree angle to radiant heat source	Downward	Flame spread index, heat evolution	Propagation
ASTM E662	NBS Smoke Chamber, in. (cm)	3 x 3 x <1 (7.62 x 7.62 x 2.54)	Vertical	Upward	Optical density, non-flaming and flaming modes	Propagation
ASTM D635	Horizontal Burn Test, in. (cm)	5 x ½ x 1/8 (12.3 x 1.27 x 0.32)	Horizontal	Horizontal, end-to-end	30 second flame; burn rate and extent	Propagation
ASTM E1354	Ohio State U, cone calorimeter, in. (cm)	4 x 4 (10.16 x 10.16)	Horizontal and Vertical	Upward, downward radiance	Time to ignition, heat release and mass loss rate	Initiation Propagation Termination
ASTM D2863	Limiting oxygen index (LOI), in. (cm)	6 x ¼ to ½ x 1/8 (15.2 x 0.64 to 1.27 x 0.32)	Vertical	Downward	Minimum oxygen concentration index to support combustion	Termination
ASTM E84 *	Steiner Tunnel Test, ft (m) panel	25 x 20 (7.62 x 0.51)	Horizontal with air flow	Horizontal, end-to-end	10 minute flame; flame spread, smoke density	Initiation Propagation Termination

*ASTM E84 is considered a large-scale test.

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Figure 1: Flexural Stress/Strain Curve
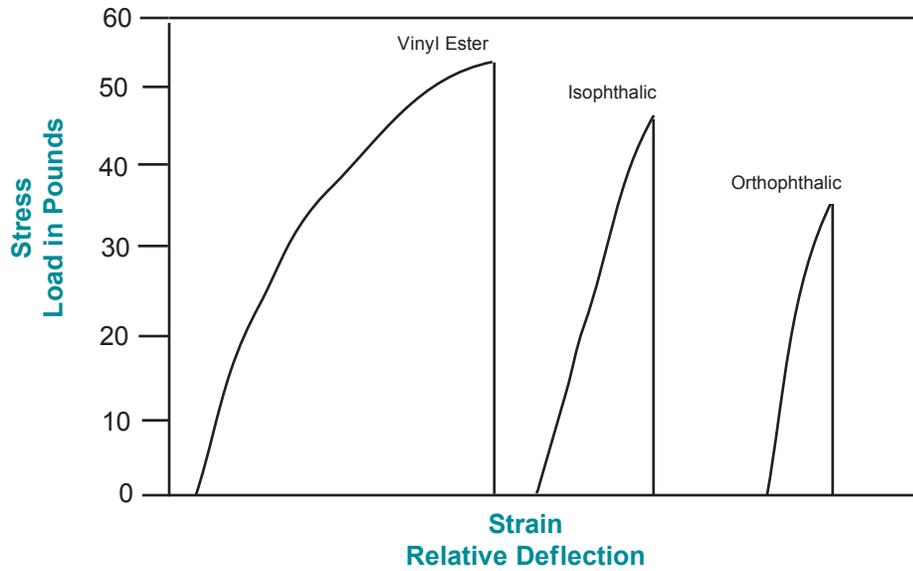
Figure 2: Tensile Stress/Strain Curve

Figure 3

Tensile Fatigue
Curve Fit - ASTM D3479 at 30 Hertz

Figure 4

Flexural Fatigue
Curve Fit - ASTM D671 at 30 Hertz
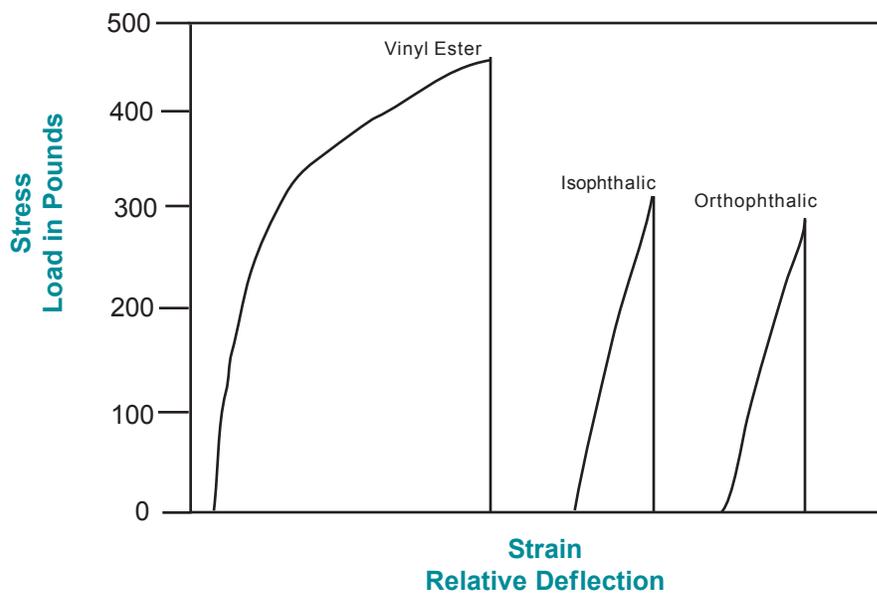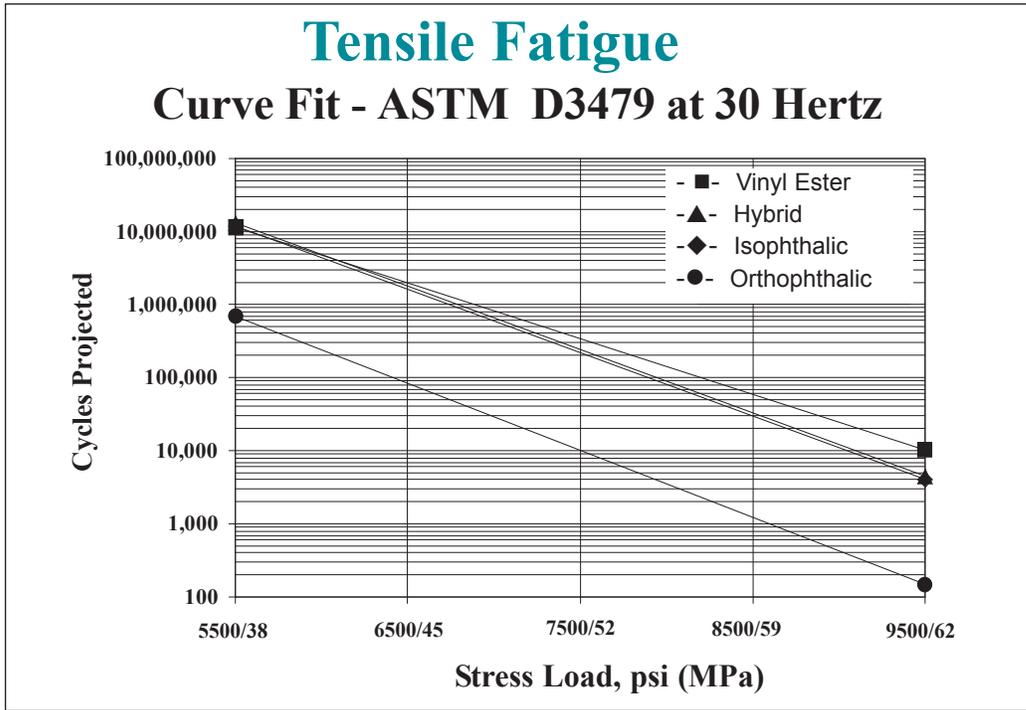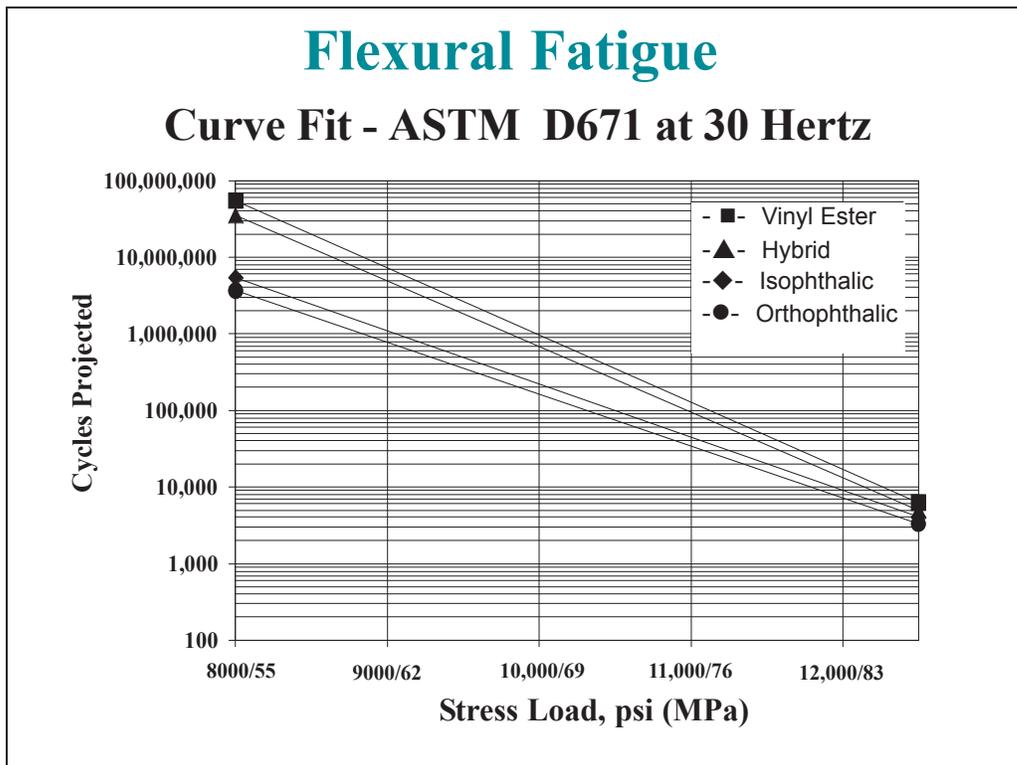
Figure 5: MIL-R-21607 Spec Physical Properties Requirements

	Spec	VE8401B	VE8441B
Standard Conditions Testing			
Flexural Strength, psi/MPa	50,000/345	69,400/479	68,400/472
Flexural Modulus, psi/GPa	2,700,000/18.6	3,180,000/21.9	2,780,000/19.2
Tensile Strength, psi/MPa	40,000/276	46,000/317	41,700/288
Compressive Strength, psi/ MPa	35,000/241	48,700/336	49,400/341
Flammability, inches per min ute	1.0 max	Non-burning	Non-burning
H$_2$O Absorption, 24 hr, % wt	+0.5 max	0.03	0.12
Barcol 934	55	60-65	55-60
Specific Gravity	Not Required	1.9231	1.6064
Resin Content	Not Required	36.18	36.69
Wet Testing, After 2 hr. in Boiling Water			
Flexural Strength, psi/MPa	45,000/310	58,500/403	60,800/419
Flexural Modulus, psi/GPa	2,500,000/172	2,720,000/18.8	2,760,000/19
Tensile Strengt h, psi/MPa	38,000/262	49,800/343	49,900/344
Compressive Strength, psi/GPa	30,000/207	43,100/297	45,000/310
Tested at 160°F/70°C			
Flexural Strength, psi/MPa	40,000/276	65,400/451	63,300/437
Flexural Modulus, psi/GPa	2,300,000/15.9	2,810,000/19.4	2,750,000/19 .0
Tests After Immersion in Chemical Fluids			
Hydraulic Fluid			
Weight change, %	0.2 max	0.06	0.09
Thickness change, %	0.2 max	0.06	0.11
Flexural Strength, psi/MPa	Not Required	59,300/409	60,400/417
Isopropyl Alcohol			
Weight change, %	0.1 max	0.01	0.02
Thickness change, %	0.1 max	0.02	0.02
Flexural Strength, psi/MPa	Not Required	60,800/419	62,500/431
Hydrocarbon Types III			
Weight change, %	0.1 max	0.01	0.01
Thickness change, %	0.1 max	0.03	0.05
Flexural Strength, psi/MPa	Not Required	62,200/427	64,100/442
Tests After 1 Year Weathering			
Flexural Strength, psi/MPa	45,000/310	58,200/401	67,000/462
Flexural Modulus, psi/GPa	2,500,000/17.2	2,610,000/18.0	2,730,000/18.8
Flame Testing, Fed Method 2023, Std. 406			
Initial:			
Average Ignition Time, seconds	55 min.	86	96
Average Burning Time, seconds	125 max	99	84
After One Year Weathering:			
Average Ignition Time, seconds	55 min.	157	116
Average Bur ning Time, seconds	125 max	93	91
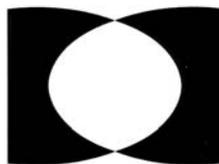
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