Approved Fume Exhaust Duct – Beyond Minimum Requirements

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Abstract

Facility cost and building code requirements impose more stringent criteria on fume exhaust duct design for semiconductor fabrication facilities than is generally seen in the rest of the chemical process industry. This article summarizes the requirements. Lined stainless steel and fiberglass—reinforced plastic choices available to the designer or facility manager to satisfy these requirements are compared and contrasted. Significant differences in performance in flammability, smoke generation and corrosion resistance are noted.

NEED FOR FIRE-SAFE MATERIALS

Fabs, as a group are chemical process facilities that use some of the most aggressively corrosive and, in many cases, toxic substances seen in industry. Differentiating these fabs from most other chemical process industry (CPI) manufacturing plants is the fact that CPI plants are typically built outdoors, while fabs contain most equipment inside buildings. In addition, the cost of fabs, currently in the neighborhood of US $2 billion, greatly surpasses that of most traditional CPI facilities.

Increased cost generates increased loss risk. Factory Mutual (FM) has estimated the cost of small incidents in fabs at US $2.5 million, compared with $ 250,000 for other industries (10x the exposure!) [1]. Fires in Taiwan in 1996 and 1997 caused $200-$500 million each in damage [2].

This combination of extremely high facility cost and inside-building location for equipment has two dramatic impacts on facility design. First, local building codes generally require a much higher standard for flame spread and, particularly, smoke generation to protect personnel (employees as well as fire fighting personnel) during fires. Secondly, insurance underwriters for the fabs, with billions at stake, usually insist on the use of agency-approved materials of construction for process and support services.

All fabs have fume exhaust systems that are used to convey corrosive and toxic process by-product gases to an environmental control system such as a scrubber or incinerator. These fume exhaust systems are usually quite extensive within the facility and may total several kilometers in overall length. Materials of construction for these fume systems have in the past included traditional fire-retardant materials include glass-reinforced vinyl ester or polyester resin, and thermoplastics such as fire-retardant polypropylene (FRPP), polyvinyl chloride (PVC) or chlorinated polyvinyl chloride (CPVC). Catastrophic fires such as those mentioned above, however, convinced insurers; end-users and designers alike to rely on inherently safe approved materials for construction of fume removal ducts.

DEVELOPMENT OF CURRENT STANDARDS

Factory Mutual was one of the first organizations to address the approval of materials for corrosive-smoke and fume ducts in semiconductor fabs. With the assistance of several end-users, FM developed tests, which more closely approximated duct fire propagation than did other tests in use at the time. The result, the FM 4922 test protocol, subjects actual duct to real fire conditions and measures flame propagation, smoke generation and temperature rise in both horizontal and vertical duct configurations.

Flame propagation 0and smoke generation potential is further characterized by the use of flat-panel tests to ASTM E-84 (NFPA#255) ASTM values of Flame ≤25 and smoke development ≤50 are required for classification as as Class 1 flame – smoke-resistant material.

Underwriters Laboratories (UL), also concerned with issues of personnel and capital investment protection, developed protocols of its own for approving flame – and smoke-safe duct. In contrast to FM, UL requires a Class 1 smoke development (≤50) value on both the inside and the outside of the duct. Products that successfully pass the UL battery of tests receive a listing, which is generally recognized by building-code organizations such as the IBC.

As a result of the test protocols above, FM in the early 1980's approved for use fiberglass-reinforced duct utilizing proprietary resin systems. In the 1990's additional options were approved by FM, including alternative fiberglass-reinforced resin systems and fluoropolymer-lined stainless steel duct.

The year 1997 saw the introduction of the FM 4910 protocol for Clean Room Approved materials. Several manufacturers have since qualified their duct offerings to both FM 4922 and FM 4910, which provides additional assurance to end-users that duct materials installed in the clean room will not contribute unnecessarily to fire or contamination from fire.

An important distinction to make is that the 4922 protocol qualifies duct for use without internal sprinklers, while 4910 qualifies materials to be used in the clean room. A 4910 Approval by itself does not allow use as a non-sprinklered duct, since many of the 4910 Approved materials (I.e. wet-bench materials) would fail the 4922 tests if subjected to them, owing to mechanical failure, sagging, dripping or other reasons.

The balance of this article will discuss some of the key similarities and differences between these approved glass/fiberglass-reinforced plastic (GRP/FRP) and coated stainless steel offerings.

FM APPROVED – COATED STAINLESS OR GRP?

Corrosive-fume and smoke exhaust duct, as its name suggests, must first be corrosion resistant. It also has to be flame-retardant and must not generate smoke when exposed to fire conditions. All the FM 4922 Approved duct systems satisfy these basic requirements, although with some important differences. There are FM 4910 Approved options for both coated stainless steel and fiberglass-reinforced duct systems.

There are key differences in how each of these systems is installed and, of course, cost, both initial and life cycle, plays a role as well. Users may have criteria, such as relative ease of in-plant modification, which can strongly influence the choice of one system versus another.

CHOICES FOR COATED STAINLESS STEEL

Fluoropolymers are organic chain polymers that contain fluorine. PTFE, the original Teflon® material, is familiar to most, but there are many different fluoropolymers, including ETFE (ethylene-tetrafluoroethlylene copolymer) one of many polymers in the Teflon family, and ECTFE (ethylene-chlorotrifluoroethylene copolymer0, commonly known as Halar®. Fluoropolymers are known to offer outstanding corrosion resistance. In addition, they are inherently flame retardant and generate little smoke (figure 1). FM Approved coated stainless steel duct can be divided into two groups – those that use ECTFE as a liner, and those that use ETFE. Properties to be compared for each include fire resistance, adhesion, toughness, surface smoothness, and implications for liner thickness and ultimately corrosion resistance. On the basis of an analysis of the data following, a compelling argument can be made that ECTFE is the better choice for flame, smoke and corrosion-resistant lined stainless steel duct.

Fire Resistance of ECTFE versus ETFE

To support combustion, you must have heat, oxygen and a source of fuel (figure 2). To stop a fire, one of these three components must be removed. One of the easiest and most effective tests is the determination of the limiting oxygen index (LOI). This test (ASTM S2863) determines the percentage amount of oxygen required for the tested material to ignite (the higher the LOI, the harder it is to ignite). The LOI of ETFE ranges from 30 to 40, while the LOI of ECTFE is 60 [3].

Another simple test is the determination of the auto-ignition temperature of a material (ASTM D1929). The auto-ignition temperature for ECTFE is 655°C (1,211°F), while for ETFE it is 500°C (925°F) [4].

To understand the reason for the superior flame resistance of ECTFE compared with ETFE, the various reactions, including depolymerisation, random chain scission, elimination and cross-linking reactions must be taken into account. Owing to differences in competing reaction rates and activation energies, ECTFE generally loses chlorine to dehydrochlorination (elimation) prior to other reactions taking place. The chlorine loss by ECTFE actually helps prevent flame spread by reacting with the free radicals that would otherwise produce flame. ETFE, owing to the higher bond energy of C-F compared with C-Cl, instead probably first suffers chain scission, which in turn generates smaller, free-flowing particles. These smaller particles then drip and burn, ultimately leading to lower char formation for ETFE than for ECTFE. Char is a cross-linked carbon mass, and char formation is important because it provides a barrier to slow down the oxygen and heat penetration required to burn fresh polymer.

Dripping and melting are critical, as flaming drips can quickly help spread a fire. The dripping and flow become severe when a burning polymer undergoes chain scission reactions and quickly produces products of lower molecular weight, which enhance flow, Char formation, if present, helps prevent this dripping (Figure 3).

Figure 3 shows a controlled test burn of both polymers supported on a wire grid above a flame. The ETFE has visible burning drips, while the ECTFE does not, and in fact the ECTFE did not drip throughout the entire experiment. The ability of ECTFE to form a much heavier char layer, inhibiting burning, is visually demonstrated in photos taken at the end of the test, also shown in Figure 3.

A thermal gravimetric analysis of the residual char is shown in the graph in Figure 4. This graph supports the visual evidence of more rapid and complete combustion of the ETFE samples [5].

In addition to the tests described above, various reported results of tests by Factory Mutual are noted here. Factory Mutual requires that duct tested to the 4922 protocol maintain a temperature less than 538°C (1,000°F) near the duct exit [6].

One manufacturer has recently qualified an FM 4922 duct with a fluoropolymer liner significantly thicker than available previously. In tests at FM, Pure Guard SS, with an ECTFE liner, at an average thickness of 0.40mm (0.016in.), reached a maximum temperature of only 395°C (744°F) on the horizontal test and 452°C (846°F) on the vertical-horizontal test, while ETFE, at a greatly reduced liner thickness of 0.25mm (0.010in.), reached much higher maximum temperatures of 454°C (850°F) on the horizontal test and 510°C (950°F) on the vertical-horizontal test, marginally passing the FM requirement for this test [7,8]. Even though the ECTFE-lined stainless steel contained approximately 60% more orgnaic material than did the KETRE-lined stainless steel, the ECTFE product generated far less heat.

In the 4922 Protocol, FM also uses small-scale tests to generate a critical-heat-flux and thermal-response parameter for prospective duct materials. The critical heat flux is the flux at which ignition is not expected to occur. For ECTRE this value is typically > 60kW/m^2 , while for ETFE the value is 20kW/m^2 or less.

Indeed, for the recently introduced 0.40mm ECTFE-lined duct, no ignition at all was obtained in this critical-heat-flux test [4,7,8].

A test of heat release rates for varying liner thickness also demonstrates much lower heat release rates for ECTFE over a broad range of thickness compared with ETFE [4]. Analysis of the chart shown in Figure 5 suggests that the thickness of ECTFE could be increased substantially without suffering degraded flammability performance. The same cannot be said for ETFE, for which the flammability increases dramatically, in practical terms limiting liner thickness for ETFE.

In tests of flame and smoke generation by ASTM E-84 test methods, ETFE at 0.21mm (0.008in.) coating thickness generated a flame spread of 10 and a smoke development of 15, compared with ECTFE at 0.30 – 0.50mm (0.012 – 0.016in.) thickness, which generated numbers of 5 – 15 and 15 – 35, respectively [7,9]. Additional data on these and other tests are available in the referenced source documents.

Adhesion of ECTFE/ETFE to Stainless Steel

Fluoropolymer-coated stainless steel duct is currently manufactured using electrostatic spray coating. The stainless steel substrate is heated, and then the ECTFE or ETFE powder is sprayed through an electrostatic gun, which applies a charge to the polymer powder. The particle charge generated is a function of variables including the particle size, the dielectric constant of the material and other factors.

Stainless steel duct is usually coated in a multi-step process consisting of first a prime coat application, followed by multiple top coats to achieve the final desired thickness. Parts are oven cured between steps to ensure proper adhesion of the coating to the metal substrate and to itself.

Good long-term performance of the coating is a function of good substrate preparation as well as of the adhesion characteristics of the polymer itself. This is no different from any other coating application, where a substandard job of surface preparation almost guarantees an inferior product in use. Adhesion is important because when fluoropolmer coatings fail, they often fail by delamination form the stainless steel substrate.

Controlled tests of liner adhesion on stainless steel for both ECTFE and ETFE have been completed and the results are shown in Figure 6. In the tests, coatings were applied per manufacturer's guidelines. The coating was then pulled off the substrate perpendicular to the surface using an Instron tensile tester.

In addition to showing the adhesion advantage of Halar ECTFE relative to ETFE, the chart in Figure 6 alos shows the critical importance of curing the liner properly during the manufacturing process. As can be seen, properly primed and cured ECTFE generated greater peel strength than primed and cured ETFE, while the difference was even more striking in the unprimed samples (30 versus 5) [10].

Surface Smoothness of ECTFE/ETFE

Surface roughness is usually considered in the mechanical design of duct systems (pressure drops), but is often overlooked in relation to its effect on corrosion resistance. In reality, the surface of any material under the proper magnification will be a series of peaks and valleys. The more peaks and valleys, the more exposed surface per unit area of duct, andalsothe more peaks and valleys that must be filled for pinhole-free coating application. In essence, a greater roughness correlates with more surface area for pinholes and corrosive attack.

With this in mind, surface measurements were run on similarly prepared stainless steel substrates, using ECTFE and ETFE liners. While the measured mean roughness (Ra) for ECTFE was 21.9nm, the corresponding values for ETFE ranged from 53.7 to 63.8nm. These results indicate that the ECTFE-lined substrate has fewer sites for corrosive attack than has ETFE [4].

Liner Toughness of ECTFE/ETFE

In addition to providing a smoother liner, ECTFE produces a tougher surface than does ETFE. Various hardness measurement were conducted, including thjose for Shore D (ASTM D2240), the Pencil Scratch Test (ASTM D3363) and Cut Through (ASTM D3032). In all cases the ECTFE samples outperformed the ETFE, as shown by the data in Figure 7 [4].

Implications for Corrosion Resistance of ECTFE versus ETFE

The discussion above has shown that Halar ECTFE-lined stainless steel has better flame properties than has ETFE. In addition, it has shown that ECTFE results in a smoother, tougher surface, resulting in less opportunity for pinholes or corrosive attack.

The effect of the difference in flame properties is to allow the use of thicker coatings for ECTFE than for ETFE on Approved duct systems, In fact, FM Approved ETFE-coated systems generally provide only 80% of the coating thickness of FM Approved ECTFE-coated ducts, while one recently approved ECTFE-lined duct offers 60% more corrosion-resistant liner [7,9].

CHOICES FOR FIBERGLASS-REINFORCED PLASTIC (FRP/GRP)

The two predominant FM Approved fiberglass-reinforced duct options both involve the use of proprietary resin systems. The oldest predominant technology uses a vinyl ester resin liner reinforced with a veil and chopped glass strands to a maximum thickness of 1.5mm (0.060 in.). Over this liner, a structural jacket is placed, consisting of additional fiberglass saturated with a proprietary phenolic resin system. This results in as dual-resin laminate with two distinct layers, making up a composite duct system.

The predominant competing system (Dual Guard 2000) uses a Halar and fiberglass-reinforced liner with a nominal thickness of 2.5mm (0.100 in.). Over the liner, a structural jacket is placed. The entire composite, liner as well as structure, is formulated using the same proprietary copolymer resin system, resulting in a single, uniform structure.

Both of the above systems have seen widespread use in fabs. Installation for each is similar, with odorless resin bonding systems and relative ease of field tap installation and modification. Several other GRP systems have in the past received FM 4922 Approval, but none has seen widespread use, owing to various commercial and technical issues. As with the coated stainless steel products, there are significant differences between the competing fiberglass technologies that need to be taken into account.

Flame Spread and Temperature Rise

The flame spread values for all FM Approved fiberglass duct systems are very good. The flame-spread values obtained according to ASTM E-84 are 15 and 5 for vinyl ester liner and structural jacket of the dual-resin system, and 5 and 5 for the Dual Guard 2000 product [9]. All the results above are good enough to generate a Class 1 listing for flammability (≤25 is required). However, the vinyl ester liner has a flame spread value three times higher, or 300% of that of the competing product.

Test results for the FM 4922 horizontal duct test are equally enlightening. The criteria for testing the fiberglass duct are identical to those described above for the coated stainless steel. At the outlet of the horizontal duct test, the Dual Guard 2000 product generated a maximum temperature of 337ºC (679ºF). This compares very favorably with the alternative-technology vinyl ester-lined fiberglass duct, which tested at 477ºC (890ºF). The Dual Guard 2000 product passed this test with three times the margin of safety of the vinyl ester-lined system [12,13].

Smoke Development

Perhaps the biggest difference between the competing systems is the smoke development of each. The values for ASTM E-84 smoke development are 375 on the vinyl ester inside liner, and 5 on the outside structure. The values for the Dual

Guard 2000 product are 10 and 10 [9]. These values for Dual Guard 2000 have been confirmed by Underwriters Laboratories, resulting in a LU 181 Listing as a Class 1 material, and confirming suitability for use in accordance with the National Fire Protection Association (NNFPA) 90A standard [14].

With a Class 1 rating for smoke generation (≤50), Dual Guard 2000 meets the commonly accepted building code regulations such as those of the IBC. These typically require a smoke development of ≤50 on both the inside and the outside of the duct. Otherwise, either sprinklers must be installed or a variance must be sought [15].

Corrosion Barrier and Laminate Construction

As noted above, the vinyl-eater-lined product has a liner reinforced with a veil and chopped glass strands to a maximum thickness of 1.5mm (0.060 in.). Dual Guard 2000 is constructed with a Halar and fiberglass reinforced liner witth a nominal thickness of 2.5mm (0.100 in.). Halar provides better corrosion protection than does alternative liner reinforcements, and overall the corrosion barrier, which meets the thickness and construction standards of the chemical corrosion industry, is approximately twice the thickness of that in the competing dual-resin system.

In summary, of the two predominant fiberglass-reinforced plastic options for FM 4922 and FM 4910 approved duct, the Halar-reinforced Dual Guard 2000 offers better performance from a flame and smoke standpoint, as well as offering a thicker corrosion liner that meets the recommended minima for the SPI.

SUMMARY

Several organizations including Factory Mutual and Underwriters Laboratories, have developed test and approval criteria for non-sprinkled corrosive-fume and smoke exhaust ducts used in semiconductor fabs and clean rooms. Even though these approval criteria provide dramatic improvements over earlier duct installation practices, significant performance differences among approved duct materials remain. In general, Halar ECTFE-lined stainless steel has advantages over ETFE-lined stainless steel, while Halar reinforced FRP/GRP duct has advantages over non-Halar reinforced FRP/GRP duct. Engineers and end-users are well advised to consider these performance differences when specifying new equipment.

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