APPLICATION GUIDE

ATLAC®
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Corrosion
Resins
For Power
Generation
Applications

REICHHOOLD
ATLAC and DION™
Performance Polymers For Corrosion Protection
The Use of FRP in Flue Gas Desulfurization Processes

### CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>CURRENT LEGISLATION</td>
<td>1</td>
</tr>
<tr>
<td>TYPES OF PROCESSES</td>
<td>1</td>
</tr>
<tr>
<td>Use of Low Sulfur Fuels</td>
<td>1</td>
</tr>
<tr>
<td>Alternate Combustion Technologies</td>
<td>2</td>
</tr>
<tr>
<td>Regenerable Systems</td>
<td>2</td>
</tr>
<tr>
<td>Processes Yielding Sulfuric Acid</td>
<td>2</td>
</tr>
<tr>
<td>Throwaway Processes</td>
<td>2</td>
</tr>
<tr>
<td>Dry Systems</td>
<td>2</td>
</tr>
<tr>
<td>Wet Systems</td>
<td>3</td>
</tr>
<tr>
<td>PROCESS DESCRIPTION</td>
<td>3</td>
</tr>
<tr>
<td>SO$_2$ ABSORBER CHEMISTRY</td>
<td>4</td>
</tr>
<tr>
<td>SULFURIC ACID</td>
<td>4</td>
</tr>
<tr>
<td>NITRIC ACID</td>
<td>6</td>
</tr>
<tr>
<td>EFFECT OF OXYGEN</td>
<td>6</td>
</tr>
<tr>
<td>LEVELS OF ACIDITY</td>
<td>7</td>
</tr>
<tr>
<td>SCALE FORMATION</td>
<td>7</td>
</tr>
<tr>
<td>INCREASED ALKALINITY SYSTEMS</td>
<td>7</td>
</tr>
<tr>
<td>DIBASIC ACID ADDITION</td>
<td>8</td>
</tr>
<tr>
<td>OTHER ADDITIVES</td>
<td>8</td>
</tr>
<tr>
<td>CHLORIDE ATTACK</td>
<td>8</td>
</tr>
<tr>
<td>EFFECTS ON CONCRETE</td>
<td>9</td>
</tr>
<tr>
<td>CORROSION RESISTANCE</td>
<td>9</td>
</tr>
<tr>
<td>ALTERNATE MATERIALS</td>
<td>11</td>
</tr>
<tr>
<td>Rubber</td>
<td>11</td>
</tr>
<tr>
<td>Brick &amp; Refractories</td>
<td>11</td>
</tr>
<tr>
<td>Thermoplastics</td>
<td>11</td>
</tr>
<tr>
<td>Other Thermosets</td>
<td>12</td>
</tr>
<tr>
<td>CASE HISTORIES</td>
<td>12</td>
</tr>
<tr>
<td>RESIN SELECTION</td>
<td>12</td>
</tr>
<tr>
<td>FLAME RETARDANCY</td>
<td>14</td>
</tr>
<tr>
<td>STATIC ELECTRICITY</td>
<td>14</td>
</tr>
<tr>
<td>COMPOSITE CONSTRUCTION</td>
<td>14</td>
</tr>
<tr>
<td>LINERS</td>
<td>15</td>
</tr>
<tr>
<td>STRUCTURAL COMPOSITES</td>
<td>15</td>
</tr>
<tr>
<td>OTHER COMPOSITES</td>
<td>16</td>
</tr>
<tr>
<td>COMPARATIVE PHYSICAL PROPERTIES</td>
<td>16</td>
</tr>
<tr>
<td>ELEVATED TEMPERATURE PROPERTIES</td>
<td>18</td>
</tr>
<tr>
<td>ELECTRICAL PROPERTIES</td>
<td>18</td>
</tr>
<tr>
<td>THERMAL CONDUCTIVITY</td>
<td>18</td>
</tr>
<tr>
<td>THERMAL EXPANSION</td>
<td>19</td>
</tr>
<tr>
<td>ABRASION RESISTANCE</td>
<td>19</td>
</tr>
<tr>
<td>FURTHER ADVANTAGES TO FRP</td>
<td>19</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>20</td>
</tr>
<tr>
<td>AUTHOR</td>
<td>20</td>
</tr>
<tr>
<td>FIGURE 1: Process Flow Diagram</td>
<td>3</td>
</tr>
<tr>
<td>FIGURE 2: Sulfuric Acid Dew Point</td>
<td>5</td>
</tr>
<tr>
<td>FIGURE 3: Effect of Oxygen with Sulfuric Acid</td>
<td>6</td>
</tr>
<tr>
<td>FIGURE 4: Limestone Utilization vs pH</td>
<td>7</td>
</tr>
<tr>
<td>FIGURE 5: Effects of Chlorides on Alloys</td>
<td>9</td>
</tr>
<tr>
<td>FIGURE 6: Photo of Intermountain Stack</td>
<td>12</td>
</tr>
<tr>
<td>FIGURE 7: Corrosion Barrier</td>
<td>15</td>
</tr>
<tr>
<td>FIGURE 8: High Temperature Properties of Atlac 711</td>
<td>16</td>
</tr>
<tr>
<td>FIGURE 9: High Temperature Properties of Atlac 580</td>
<td>17</td>
</tr>
<tr>
<td>FIGURE 10: Elastic Damping Properties of Atlac 711</td>
<td>17</td>
</tr>
<tr>
<td>FIGURE 11: Temperature Profile in FRP Laminates</td>
<td>18</td>
</tr>
</tbody>
</table>

**REICHOLD**

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INTRODUCTION

When utility companies first began to commercialize the use of SO₂ scrubbers in the late 1960s and early 1970s, there were a great deal of operating problems, primarily scaling, and acid and chloride related corrosion. Because of these problems, removal of SO₂ from flue gas was in jeopardy of not being considered a viable technology.

Since then, a great deal of advancement has been made, thanks to the efforts of owners, fabricators, developers and designers of these systems. Newly developed processes have greatly reduced scaling tendencies, and there is now much more careful consideration of corrosion aspects. Use of Fiberglass Reinforced Plastic (FRP) has contributed to this success, and as further efforts are made to improve efficiencies of SO₂ removal, there will be more demands placed on improved corrosion resistance. As a result, FRP is expected to find even wider use in various desulfurization processes, especially in view of acid rain legislation which is now promulgated.

Increased proliferation of desulfurization processes introduces many corrosion concerns which accompany the direct process itself. For example, in the case of chimney liners, the acidic wet conditions of the treated flue gas make use of ordinary carbon steel increasingly impractical. According to studies done by CICIND (International Committee on Industrial Chimneys), about 90% of the steel chimney failures have historically been based on some form of corrosion. Wet conditions will serve to make the matter worse. Likewise, acid drift can lead to increased corrosion of external stack components, such as concrete, buckstays, and wind caps.

Although the conditions inherent in flue gas desulfurization (FGD) systems can result in exceptionally severe corrosion for carbon and alloy steels, they are typically relatively mild compared with the conditions present in many applications where polyesters and vinyl esters have been successfully used for decades.

However, when it comes to corrosion, nothing should be taken for granted. For successful use of FRP, it is necessary to understand details of resin selection, fabrication, and mechanical advantages and limitations. Specifiers of FRP should avail themselves of testing and technical services offered by resin manufacturers and skilled FRP fabricators before finalizing designs.

For the benefit of fabricators and others without necessary background, a discussion of the key elements of SO₂ removal technologies (especially in regard to corrosion implications) is presented. Likewise, for people with limited FRP experience, some basic description is given of resin selection and corrosion related FRP construction techniques.

CURRENT LEGISLATION

The enactment of the United States Clean Air Act of 1970 provided the first major impetus to the large scale application of various desulfurization processes. From 1970 until 1990, when the Clean Air Act was amended, there were at least 150 utility FGD systems installed, with about 40 more planned or under construction.

The 1990 Clean Air Act Amendments (CAA) represented some major comprehensive and novel approaches directed toward meeting national goals of reducing air emissions. The CAAA is comprised of seven titles, of which the most relevant to utility companies is Title IV, which deals with the specific acid rain precursors, SO₂ and NOₓ.

The CAAA is divided into two phases. Phase I began on January 1, 1995, and involved 110 specific utility companies. SO₂ emissions are limited to 2.5 lbs/MMbtu, which is in the absence of other controls equates to coal of less than about 2% sulfur.

Phase II compliance begins January 1, 2000, and entails emission limits of less than 1.2 lbs/MMbtu, which corresponds to about 1% sulfur coal. The law applies to any site of at least 25 megawatts, and 785 utility companies are affected. This involves in excess of 2,100 stations.

The novel feature of the CAAA is that it represents a departure from traditional command and control strategies. Each emitter is allowed a variety of approaches, ostensibly with the purpose of reducing annual emissions at the lowest overall cost to the consumer. The plethora of details is beyond the scope of this paper, but the following comments can be made on some of the technical options.

TYPES OF PROCESSES

A wide variety of processes exist for that removal of sulfur from combustion of fossil fuels. In a broad sense, there are a number of basic categories:

Use of low sulfur content fuels

The United States is blessed with an abundance of low sulfur coal, and despite higher prices coal switching represented the choice in about 60% of the Phase I decisions. It remains commonplace for utilities in the Midwest that are next to vast deposits of high sulfur Illinois No. 6 seam coal to import low sulfur subbituminous coals and lignite by unit train from the Western areas of the country.

In addition to a frequently higher fuel operating cost, a switch to a low sulfur coal is actually much more expensive than it first seems. This is because most low sulfur coals are characterized by high ash content, which necessitates increased handling and disposal facilities. Furthermore, the ashes tend to be very electrically resistant, and this may require major refits or replacements of electrostatic precipitators.

Nonetheless, coal switching is often less involved than other options, but critics argue that the practice is not in keeping with elements of Federal law dealing with Best Available Control Technology (BACT) or Prevention of Significant Air Deterioration (PSD). Furthermore, there have been some unforeseen and yet unresolved conflicts between Title IV of
the CAAA and other elements of the legislation.

Most notably, this involves Title III, which is directed toward specific air toxins. Some of these toxins include mercury and selenium, which may be commonly affixed to fugitive flyash discharged to the atmosphere. Incomplete combustion products, such as benzene, are other examples. Although modern combustion processes are quite efficient and the concentration of such toxins is exceedingly small, the usage of coal at a typical station is quite high by industrial standards. Scrubbers, critics argue, would serve to reduce these toxins considerably compared to direct combustion.

In the case of residual oil fired units, the higher unit heating value of oil usually made it practical for utility companies to avoid SO2 removal by purchasing oil low enough in sulfur. For many petroleum stocks, this will demand more use of expensive hydrodesulfurization, which, in turn, will direct many of the sulfur removal processes to the refineries themselves. Although sulfur removal in refineries is different from that of combustion processes, many of the costs and corrosion concerns are shared.

Alternate combustion technologies

A common use is the use of so-called fluidized bed boilers. Here, limestone (or preferably dolomite) is injected into the furnace. The material becomes calcined (CO2 is driven off from carbonates) and the calcined species react with SO2 to generate alkali sulfites and sulfates which can be disposed with ash in the coal. This requires fairly large combustion units and the use of lower flame temperatures. Furthermore, the calcination of dolomite is extremely endothermic, which represents a higher heat duty.

The process has the advantage of removing enough sulfur to avoid downstream SO2 removal. However, the degree of sulfur removal is equilibrium controlled and, because this technology is still emerging, it is difficult to predict the extent to which it may be used.

Another example of this basic category is coal gasification, which burns the coal with a deficiency of oxygen to yield a reducing gas. Most of the sulfur is then converted to H2S, which is easier to remove than SO2. After cleaning, the reducing gas (CO and H2) can be used as gaseous fuel, for example in a gas turbine based combined cycle plant.

Regenerative systems, which recover SO2 and then convert it to elemental sulfur

These processes have the distinct advantage of generating a minimal amount of by-product, i.e., sulfur itself. Moreover, the sulfur can be conveniently stored and is quite often higher in purity than ordinary mined sulfur, which makes it a good by-product for sulfuric acid plants. A major disadvantage is the high operating cost.

In order to reduce SO2 to elemental sulfur, a reducing gas (ordinarily hydrogen sulfide) is required. The mechanism of reduction is generally the basic Claus process, which is widely used by petroleum refineries throughout the world:

$$\text{SO}_2 + 2\text{H}_2\text{S} \rightarrow 2\text{H}_2\text{O} + 3/2 \text{S}_2$$

The process is usually conducted over bauxite catalyst and the sulfur is selectively condensed, typically in three sequential steps. However, the Claus reaction is equilibrium controlled and, to recover more than about 90 percent of the sulfur, it is necessary to further treat the tail gas with a series of expensive techniques, one step of which requires absorption of acid gases.

To generate the H2S, it is necessary to directly or indirectly supply hydrogen to the process. This ordinarily comes from steam reforming of methane or other premium fuels. There are many novel direct reduction processes under development, but so far they haven't been widely used by utility companies. This is partly due to the high cost along with the need for sophisticated processing steps.

Processes that convert SO2 to by-product sulfuric acid or ammonium sulfate

A good example is the Wellman-Lord process, in which SO2 is recovered in concentrated form after it is selectively removed from the flue gas by using sodium sulfate. The SO2 is then converted to SO3 over platinum or vanadium catalyst and in turn is used to produce concentrated sulfuric acid. This requires fuel gas for the conversion, and the regeneration of SO2 from sodium bisulfite is energy intensive. So far, the process has been used only in industrial scale operations.

Many other novel processes intended to convert SO2 to sulfuric acid are under development. An example is the lapa process, in which SO2 is reduced directly to sulfuric acid by use of bromine, with the resulting HBr then reconverted to Br2 by electrolysis.

Another timely example is a process developed by General Electric Environmental Systems which absorbs SO2 with ammonia to ultimately produce a salable ammonium sulfate by-product. The ammonium sulfate has a relatively high value which serves to offset much of the cost of desulfurization. Because of net water evaporation and a carefully controlled water balance it is possible to accumulate high levels of chlorides which can restrict the practicality of even expensive high nickel alloys. Recently this process has been installed adjacent to a large coal gasification facility near Bucyrus, North Dakota, and the installation featured total FRP composite construction for all of the key process equipment.

Throwaway or by-product gypsum processes

These are by far the most commonly used processes, and basically involve reacting the SO2 with an alkali material to form sulfites and/or sulfates, which are disposable, or in some cases can be sold into the construction market. There are two types of systems commonly employed.

Dry systems: These normally involve injection of dry soda ash, sodium carbonate or sodium based sequestering agents into the clean flue gas to convert much of the SO2 to sodium sulfite or sulfate cake, which is disposable. Usually these processes are intended for relatively low sulfur Western coals since soda ash is expensive. Furthermore, these processes do not require copious amounts of water, which is a major advantage in the West. Likewise, the limited rainfall in the West can make it practical to contain run-off from the soluble materials being disposed.

Most of the soda ash in this country is obtained from trona mined in Wyoming, and this is more conveniently available to Western utility companies. Although the dry systems do not
employ high levels of water, they often share many of
the same corrosion problems associated with wet scrubbing
operations, as will be discussed in more detail. In fact, many
corrosion aspects of dry scrubbers are analogous to unit
operations of the pulp and paper industry, where FRP has been the
material of choice for many years.

**Wet systems:** Here the SO₂ is absorbed by solubilized
alkaline compounds. What ultimately results is a sludge,
which is de-watered as much as possible and then contained
in a waste disposal area, although the modern developments
are directed at producing salable by-product gypsum. Since
wet systems are the most common SO₂ removal process, it is
the subject of further discussion in this paper.

**PROCESS DESCRIPTION**

Figure 1 is a simplified diagram of a typical SO₂ wet flue
gas desulphurization process. Also depicted are the areas where
corrosion and other problems are usually centered.

The scrubber system is ordinarily placed after the electro-
static precipitator or bag filters so, barring upsets, the enter-
ing gas is essentially free of particulates.

Typically, the gas enters at 250-350°F, depending on load
or efficiency of the steam generating portion of the plant. For
a high sulfur coal, inlet SO₂ concentration is about 2.5 per-
cent by volume. Due to high temperature, ducting for the
incoming flue gas quite typically is tile or refractory lined.

Because the gas is too hot for direct absorption, it is neces-
sary to first quench it with water. This is accomplished by
spraying water into the gas, whereupon evaporation of water
will adiabatically saturate the gas and simultaneously cool it,
typically to 120-140°F, which is a temperature well within the
range of many materials of construction, provided that the
corrosion rate can be accommodated.

The quenched gas is then passed countercurrently through
an absorber equipped with trays specially designed to prevent
foaming. In lieu of trays, efficient spray contact or venturi type
scrubbing zones are provided, depending on allowable pres-
sure drops. Absorbers vary considerably in design.

Within the absorber, SO₂ is absorbed by sulfite, bicarbon-
ate and carbonate alkali compounds dissolved in the recircu-
lating scrubbing liquor. The amount of SO₂ absorbed depends

**Figure 1**

Typical flow diagram for lime or limestone based flue gas desulfurization process. Areas where problems with metals historically occur are indicated.

1 - Localized attack due to chlorides and salts resulting from concentration due to evaporation.
2 - Corrosion by acids and simultaneous erosion.
3, 8, 9 - Dew point attack from condensing sulfuric acid.
4 - Acid corrosion and scaling.
5 - Stress corrosion.
7 - Stress corrosion and fatigue.
9 - Erosion.
10 - Attack of concrete by sulfates.
on many factors, such as available alkalinity, the liquid/gas ratio used in the scrubber and mass transfer characteristics.

Gas leaving the absorber then passes through a mist eliminator to remove entrained water droplets. FRP is commonly used in the construction of these mist eliminators, as is often the case in other utility related operations such as cooling towers. Chevron type mist eliminators can be quite efficient at removing small water droplets, but it is extremely difficult to remove the sub-micron droplets of sulfurous acid mist, as will be explained later. Thus, a consequence of SO$_2$ removal is that it tends to further increase the SO$_3$ concentration, and hence potential metal corrosion in downstream areas such as chimneys.

Gas then passes to a reheater section. Often the reheater is an indirect heat exchanger, although it has been common practice to reheat the gas with some hot inlet gas which bypasses the absorber. This practice is now discouraged or prohibited under some of the provisions of the Clean Air Act Amendments.

There are several major reasons for reheating. First of all, gas is saturated in water vapor and there is still enough SO$_2$ and SO$_3$ in the gas to present acid corrosion problems to downstream equipment. Thus, some superheating of the gas helps in preventing condensation. Secondly, since the gas is cooled, there is not enough natural draft for the flue gas to exit the chimney without excessive pressure drop. For large units, an induced draft fan is required for draft control. Reheating also reduces plume visibility and acid drift in the vicinity of the stack area, which is becoming an increasing problem in some power plants.

The extent of reheating depends on energy and efficiency considerations, as well as concern over corrosion. Metals will last longer when the flue gas is reheated. This is due to the fact that sulfurous acid has a higher dew point than ordinary water vapor, as will be discussed later. On the other hand, the polystyrene and vinyl esters used in FRP composites have excellent acid resistance and can possibly give advantages in flue gas reheating energy savings.

Acidic bisulfite-rich liquor from the scrubber is then sent to a reaction vessel, where the pH is increased with lime or limestone additions. In some designs, the reaction vessel is constructed integrally with the absorber. The function is to dissolve fresh makeup of alkali materials and to also provide the driving force for precipitation of a sludge waste by-product.

In modern designs, an additional technique employed is forced oxidation, wherein air is sparged into the reaction zone or into some portion of the absorber. This converts much of the sulfite to sulfate in a controlled area such that calcium sulfate can be selectively recovered. The practice has also been of great benefit in control of scale in portions of the absorber.

Effluent liquor from the reaction zone is then sent to a thickener for concentration of a sludge sufficiently low in water for disposal. In the case of lime or limestone systems, this sludge is a complex aqueous suspension of:

\[ \text{CaSO}_4 \cdot 1/2 \text{H}_2\text{O}, \text{CaSO}_4 \cdot 2\text{H}_2\text{O}, \text{CaCO}_3 \text{ and Ca(OH)}_2\]

There are different processes involved, however, that affect the types of waste products produced.

Clarified water from the thickener is rich in soluble sulfite and is recycled to the absorber.

**SO$_2$ ABSORBER
CHEMISTRY**

The combustion gas contains two acid gases that are absorbable in water, namely SO$_2$ and CO$_2$, with SO$_2$ being about 30 times more soluble. However, the CO$_2$ concentration in flue gas is much higher than that of SO$_2$. Since SO$_2$ is a stronger acid, its solubility is typically about three times higher than that of CO$_2$ at the pH range and other operating conditions of most scrubbers. This makes selective absorption of SO$_2$ possible.

In SO$_2$ absorption systems, the active soluble alkaline species are sulfite, bicarbonate and carbonate ions. Absorption mechanisms include:

\[ \text{SO}_2 + \text{H}_2\text{O} + \text{SO}_3 = 2\text{H}_2\text{SO}_3 \]
\[ \text{SO}_2 + \text{HCO}_3^- = \text{HSO}_3^- + \text{CO}_2 \]
\[ 2\text{SO}_2 + \text{H}_2\text{O} + \text{CO}_3^- = 2\text{HSO}_3^- + \text{CO}_2 \]

As can be seen, bisulfite ion is continuously formed from SO$_2$ absorbed and, therefore, it is the predominant anion present. It is also a major reason why scrubbing liquors can become corrosive to steel.

In dilute form, the bisulfite ion is weakly acidic:

\[ \text{HSO}_3^- = \text{H}^+ + \text{SO}_3^- \]

Some SO$_2$ also serves to form sulfurous acid:

\[ \text{SO}_2 + \text{H}_2\text{O} = \text{H}_2\text{SO}_3 \]
\[ \text{H}_2\text{SO}_3 = \text{H}^+ + \text{HSO}_3^- \]

However, because of the nature of combustion, dilute sulfurous acid is also formed in FGD systems.

**SULFURIC ACID**

In practice, all fuels require an excess of air to ensure complete combustion. For example, if coal is burned in the furnace with 25 percent excess air, roughly 4 percent oxygen will typically be present in the combustion gas where it is available to oxidize sulfurous acid or sulfite and bisulfite ions to sulfate ions:

\[ 2\text{H}_2\text{SO}_3 + \text{O}_2 = 4\text{H}^+ + 2\text{SO}_4^{2-} \]
\[ 2\text{HSO}_3^- + \text{O}_2 = 2\text{SO}_4^{2-} + 2\text{H}^+ \]
\[ 2\text{SO}_3^- + \text{O}_2 = 2\text{SO}_4^{2-} \]

The oxidation of sulfite to sulfate is a familiar reaction. For example, in the treatment of boiler feedwater, sodium sulfite is frequently added as a way of scavenging free oxygen. As will be explained later, oxygen in flue gas can act as an oxidizing agent, which accelerates corrosion to metals and leads to origins of scale (calcium sulfate) formation.

In modern processes the oxidation of calcium sulfite to gypsum is controlled by direct air injection (forced oxidation), such that the gypsum forms in a particular zone or reaction area where it can be kept in suspension and ultimately recovered. Often this is done integrally in a single, albeit rather sophisticated, vessel, such as in the Chiyoda bubbling jet reactor (CT-121 process). Incidentally, there have been at least two such Chiyoda large-scale reactors field fabricated entirely of FRP. These included the 100 MW Station Yates of Georgia Power, and more recently the delayed petroleum coke scrubbing system of Suncor in Alberta.

An additional effect of the free oxygen is to indirectly provide a source of sulfuric acid:

\[ 2\text{H}^+ + 2\text{SO}_4^{2-} \rightarrow \text{H}_2\text{SO}_4 \]
Sulfuric acid is diprotic and in dilute aqueous form shows all the properties of a strong acid:

\[ \text{H}_2\text{SO}_4 \rightarrow \text{H}^+ + \text{HSO}_4^- \]
\[ \text{HSO}_4^- \rightarrow \text{H}^+ + \text{SO}_4^{2-} \]

There is another major reason that sulfuric acid is formed in the system, namely the presence of traces of sulfur trioxide in the combustion gas. When sulfur is burned at atmospheric pressure, nearly all of the sulfur is converted to sulfur dioxide but a small percentage is also converted to sulfur trioxide.

\[ 2\text{SO}_2 + \text{O}_2 \rightarrow 2\text{SO}_3 \]

Sulfur trioxide has a great affinity for water, combining with it to form sulfuric acid:

\[ \text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4 \]

Oxidizing SO₂ to SO₃ does not occur readily, and in the case of a sulfuric acid plant, it is necessary to conduct the oxidation of SO₂ to SO₃ over catalysts such as platinum or vanadium pentoxide. In a combustion process, however, some small amount of SO₃ coexists in equilibrium with SO₂. For example, if coal containing 3 percent sulfur is burned, the SO₃ contained in the combustion gas will be about 2400 ppm by volume. The level of SO₃, however, will typically range from 20-40 ppm by volume. Levels of SO₃ will vary with the amount of excess air used for combustion and sulfur content of the fuel. For example, typical levels of SO₃ are as follows (ppm by volume):

<table>
<thead>
<tr>
<th>% Sulfur in fuel</th>
<th>% Excess Air</th>
<th>Oil</th>
<th>15</th>
<th>25</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2</td>
<td>12</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>3</td>
<td>15</td>
<td>7</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>4</td>
<td>18</td>
<td>14-28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>5</td>
<td>22</td>
<td>20-40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>6</td>
<td>26</td>
<td>27-54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>6</td>
<td>30</td>
<td>33-66</td>
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</table>

Although it is desirable to limit the excess air used for combustion, this amount is dependent on the reactivity of the fuel, which generally varies inversely with the rank of the coal. Because fuel is the highest operating cost to a utility, the combustion efficiency cannot be sacrificed.

Because of the affinity of SO₃ for water, the net effect is that the dew point of the combustion gas is raised (Figure 2). A typical combustion gas may have a dew point about 200°F higher than that of water vapor. This problem has long been recognized in the operation of steam generating equipment. Some units must keep metal temperatures of economizers and air preheaters as high as 450°F to prevent sulfuric acid condensation and thereby ensure maximum life of the metal. Since efficiency of the unit is inversely proportional to exit temperature of the combustion gas, corrosion is often the major limitation to attaining improved fuel efficiency.

The concentration of sulfuric acid in any condensate is dependent on how far below the dew point the gas is quenched. Based on equilibrium, the first drop that condensates have a concentration as high as 82.5 percent, with only an insignificant amount of water condensed. In reality, upsets will tend to cool the gas well below the sulfuric acid dew point so the acid becomes diluted, which makes it very aggressive toward carbon steel. Some of the most concentrated condensate can form in the outlet ducting and stacks, where collected samples have ranged from 25-50% in concentration of sulfuric acid. In areas where such condensation is likely, it is common practice to line steel ducting with acid-resistant refractory materials. On the other hand, FRP can be quite resistive by itself.

Dilute sulfuric acid can be a particular problem in quench areas before the gas contacts alkali materials. To avoid fouling of spray nozzles, relatively clean water is used. Often corrosion will become localized, and once identified, improved materials can be used in areas that are especially subject to attack.

The actual sulfuric acid dew point varies with the water vapor content of the combustion gas. Oil, for example, generates more water vapor than coal since oil is richer in hydrogen and steam is usually used for atomizing the oil at burners. In an SO₃ scrubber system, however, the combustion gas becomes saturated with water vapor.

If the absorber operates at 120°F, the water vapor content of the exit gas will be about 11.6 volume percent (sea level) and will be about 19.6 volume percent if operated at 140°F. This tends to raise the sulfuric acid dew point compared with the entering combustion gas, but fortunately much of the SO₃ will have been absorbed in the FGD system.

Little data exist on typical levels of SO₃ contained in gas leaving the absorber, however, a reasonable estimate is 5 ppmv. However, as previously mentioned, much of the SO₃ due to its affinity for water will be present as a fine mist of submicron size. Most mist eliminators cannot remove this fine entrainment, and in some stations consideration is given to use of an additional electrostatic precipitator for controlling the sulfuric acid mist. Thus a scrubber may take out nearly all of the sulfur from the combustion gas, but the fly gas can still be exceptionally corrosive to metals.

SO₃ generated during combustion coupled with oxidation of bisulfite ions is often not the only way in which sulfuric acid can form. In many coal fired installations dealing with resistive fly ash, it is common practice to inject sulfur trioxide...
into the gas in order to achieve the proper corona with electrostatic precipitators. Ironically, this most frequently is necessary with ashes typical of low sulfur coals. The SO₂ is first generated by burning molten elemental sulfur and then oxidizing the SO₂ to SO₃ over a small catalyst bed. Although the usage is small, small amounts, as previously discussed, can have significant corrosion effects.

Although carbon steel displays only moderate corrosion rates when exposed to concentrated sulfuric acid (85–98 percent), its rate of corrosion is considerably higher when dilute forms are present due to the relatively high acidity of bisulfate and bisulfite ions. On the other hand, polyesters or vinyl esters used in FRP composites are virtually unaffected by dilute sulfuric acid at the typical operating temperatures of most scrubbers. It is only when concentrated sulfuric acid (greater than 70–80%) is encountered that these polymers reach their limitations. This is a different mechanism of attack, however, involving dehydration of the polymer, which typically produces a charred surface.

Premium quality resins can be used to withstand the required temperatures and sulfuric acid concentrations which might be encountered in outlet ducting and stacks. Furthermore, FRP has the advantage of greatly improved resistance over steel whenever condensed sulfuric acid is diluted with water, as is commonly the case, for example, with mist eliminators or during transient temperature conditions. For this reason, the outlet ducting and breathing has been the most extensive area where FRP has been used in FGD systems. Premium performance resins, including those with flame-retardant properties, have an extensive history of use in elevated temperature exposure to sulfuric and other acidic vapors.

**NITRIC ACID**

Combustion gas also contains oxides of nitrogen. These occur from the combustion of various heterocyclic nitrogen compounds that formed from protein matter during the carbonization of the fossil fuels. Likewise, some NOₓ is formed by fixation of nitrogen in the air used for combustion.

Although combustion methods can be modified to minimize fixed nitrogen, some NOₓ is always present. When exposed to scrubbing liquor some nitric acid is formed:

\[ 3\text{NO}_2 + \text{H}_2\text{O} \rightarrow 2\text{HNO}_3 + \text{NO} \]

Because the combustion gas contains free oxygen the NO can then be bleached back to NO₂, and the process is similar to what occurs in an Ostwald type tower used in nitric acid plants. Because of the amounts generated, there are fewer problems with nitric acid than with sulfuric acid. Nevertheless, it must be considered. Nitric acid is strongly oxidizing, but at the low levels encountered, it does not affect properly constructed FRP.

Generally, scrubbers do not remove much of the NOₓ since most scrubbers operate in an inappropriate acidic range. However, processes which display higher available alkalinity show some promise at affecting some removal of the nitrogen oxides, which in turn may influence corrosion properties of the liquor.

**EFFECT OF OXYGEN**

Free oxygen, originating in the combustion gas, coupled with hydrogen ion resulting from the acids generated during SO₂ absorption can both function as electron acceptors and thus become strong oxidizing agents in the presence of iron:

- **Oxidation (anode)**
  \[ \text{Fe} \cdot 2e^- \rightarrow \text{Fe}^{++} \]
  \[ \text{Fe} \cdot 3e^- \rightarrow \text{Fe}^{+++} \]

- **Reduction (cathode)**
  \[ \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^- \]
  \[ 2\text{H}^+ + 2e^- \rightarrow \text{H}_2 \]

The presence of molecular oxygen and hydrogen ion account for most of the common instances of corrosive attacks on steel, principally through galvanic mechanisms. Because oxygen has a limited solubility in water, its effect is particularly accelerated when there is convection or high velocity at the surface of the metal, which characterizes the situation in typical SO₂ scrubbers. Thus, the combined effect of acid and free oxygen is to make the metal surface quite anodic and subject to oxidation.

Even high nickel alloys which are well regarded for resistance to acids and chlorides (e.g., Monel 400), show much higher corrosion rates with sulfuric acid whenever oxygen is present (Figure 3). Fortunately, polyesters and vinyl esters have long-standing histories of resistance to dilute acids.

![Figure 3](image_url)

**Figure 3**

Free oxygen in the combustion gas can accelerate corrosion rate of sulfuric acid even for high nickel alloys.

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LEVELS OF ACIDITY

Unfortunately, there are many important effects that tend to compete against each other in determining optimal design or operation of SO₂ scrubbers.

To obtain a high degree of solubility of calcium compounds, it is preferable for the system to have a low pH (Figure 4). On the other hand, a high pH will favor the absorption of SO₂.

If the alkali compounds are not fully solubilized, they represent a waste of available material. In the case of limestone, it is necessary to pulverize it extensively to promote solubility and this is expensive. Quite often, slaked or hydrated lime will be used instead of limestone because of its higher efficiency. However, lime is produced by calcining limestone (driving off CO₂ in a kiln), which is expensive and energy intensive. Moreover, lime cannot be stored as conveniently as limestone.

Care must also be taken on the level of magnesium present in the lime or limestone. Although magnesium is much more soluble than calcium, the common ion effect results in less solution of calcium ion and less reactivity of the limestone if magnesium is too high. However, as will be explained later, there are ways of using high-magnesium limes to efficiently increase the available alkalinity of the system.

Perhaps the most important reason for keeping the pH low is to keep a high enough solubility of calcium to avoid scale formation. To avoid scaling in limestone systems, the pH must ordinarily not exceed 5.5. In practice, pH can be as low as 2. It is also important for a variety of reasons to keep the pH in a narrow range. Most absorbers operate in the range of 4-5 pH.

Thus scrubbing waters always tend to be acidic and, therefore, corrosive to metals often used in the construction.

SCALE FORMATION

As previously mentioned, oxygen in the combustion gas serves to oxidize sulfite and bisulfite ions to sulfate. Apart from sulfuric acid, this can lead to the formation of calcium sulfate, which can become hydrated (CaSO₄·2H₂O) and lead to the serious scaling problems that have historically plagued various FGD systems with frequent maintenance and outages. If the pH is too high, calcium carbonate can also precipitate.

Most compounds display increased solubilities with temperature, but many calcium compounds do not. For instance, common scale in hot water pipes is calcium carbonate that results when hard water already saturated in CaCO₃ is heated. This can be offset by use of softening or ion exchange, i.e., replacing calcium ions with more soluble sodium ions.

This inverse solubility, coupled with the low solubility of calcium ion in the first place, demands that portions of the scrubber never be operated under supersaturated conditions for calcium sulfate. This requires a narrow pH range and, as previously mentioned, a low pH, which contributes to corrosion to metals. Another approach to avoiding scale formation is to increase the available alkalinity of the system. As was previously explained, forced oxidation is a modern approach to scale prevention, mainly because the gypsum is forced to form in an area where it can be accommodated and recovered rather than in other portions of the system.

Although scale formation may seemingly serve to protect the metal walls of the scrubber from corrosive or abrasive attack, this is usually not the case in practice. Quite often, metals are subject to severe localized attack from deposits.

Furthermore, every trend of modern design and operation is directed toward elimination of scaling in order to maximize the reliability of the system. As a result, the corrosion resistance of premium polyester resins will earn those materials an increasing role in SO₂ removal processes.

INCREASED ALKALINITY SYSTEMS

Scaling tendencies can be reduced by increasing the available alkalinity of the system. This does not mean that an acidic pH is avoided, it means that the process relies on the higher solubility of magnesium or sodium ions to prevent calcium-related scaling. Key to this approach is the process configuration.

Magnesium sulfate is over 600 times as soluble as calcium sulfate, while sodium sulfate reflects even a greater increase. Whenever the alkali species in the scrubber are magnesium or sodium, the scaling can be avoided and, at the same time, higher scrubbing efficiency can be realized.

The biggest drawback is that sodium or magnesium materials are too expensive to throw away with the sludge. Furthermore, the solubility of these salts is so high that they cannot be economically removed from the water for disposal. Therefore, it is necessary to efficiently treat the liquor leaving the scrubber with calcium (ordinarily using lime) so that a sludge can be precipitated, and the SO₂ present in the com-
bustion gas is effectively converted to predominantly calcium sulfate which is disposable. In the case of magnesium-rich systems, the magnesium bisulfite contained in the scrubber effluent is reacted with lime to generate calcium sulfate:

\[ \text{Mg(HSO}_3\text{)}_2 + \text{Ca(OH)}_2 \rightarrow \text{MgSO}_4 \cdot \text{CaSO}_4 + 2\text{H}_2\text{O} \]

Because of common ion effects, the CaSO₄ will precipitate, and this is normally accommodated by a thickener. Supernatant liquid from the thickener is rich in magnesium sulfate and is recycled to the scrubber. Since the resulting sludge cannot be completely dewatered, even with filtration, the makeup lime must contain enough magnesium to compensate for loss of soluble magnesium compounds.

The system is quite analogous in cases where the increase in available alkalinity is afforded by sodium sulfite or hydroxide. This is commonly referred to as a "dual-alkali" system. The sodium bisulfite from the scrubber is converted by lime addition to predominantly calcium sulfate or calcium sulfate (when air is added to the thickener), with supernatant liquor rich in soluble sodium hydroxide or sodium sulfate recycled to the scrubber. To compensate for sodium loss with the waste product (usually a filter cake), soda ash is used as makeup. This soda ash, however, is expensive.

Although systems such as these are expensive to operate, they have been tremendously successful at reducing scale and improving SO₂ removal efficiency.

**DICARBONIC ACID ADDITION**

To avoid supersaturation of calcium sulfate in portions of the scrubber, a narrow pH range should be employed. However, this is not always easy to do because of load swings and other factors. Some utility companies have had great success at achieving a narrow pH range by using additives that effectively buffer the system. These are commonly dicarbonic organic acids such as adipic, succinic or phthalic acids. To minimize costs, these acids are normally purchased from manufacturers that generate them as by-products. Adipic acid in dilute aqueous solution is most commonly used since it is a by-product of nylon production.

The buffering ability of these acids relates to the relative dissociation constants for the first versus second acid groups. Although the chemistry becomes somewhat involved, addition of organic acids to the system can represent another potential form of attack to metals. On the other hand, polyesters and vinyl esters used in FRP are unaffected by these acids at the concentrations involved.

**OTHER ADDITIVES**

Another way of preventing scale is to inhibit the oxidation of calcium sulfate to calcium sulfate, which is believed to occur by a free radical mechanism. Several utility companies have experienced good success at preventing scale (or solubilizing it once formed) by adding sodium thiosulfate to the system. Some claims have also been made that this improves dewatering of the sludge. Because this method results in prevention of scale, it is possible to improve the efficiency of SO₂ removal.

**CHLORIDE ATTACK**

Because the oxidative corrosion potential of acids toward carbon steel is a major problem in SO₂ scrubbers, the choice has often lead to the use of austenitic stainless steels and high nickel content alloys, e.g., Type 316L stainless steel, Hastelloy, Inconel, or the Haynes series such as C-276. Lately there has also been a trend to use some of the so-called super-austenites which are high in molybdenum content and give good strength, such as type 904. In some cases even titanium has been used.

These alloys are quite expensive. The C-276 alloy is perhaps the most commonly used, and as a frame of reference its cost is roughly four times as much per pound as Type 316L. Obviously, for cost practicality it is necessary to usually install the alloys as cladding or as a thin layer onto steel by a technique known as wallpapering.

These methods introduce obvious potential problems mainly in welded areas for traditional reasons which serve to make the weld anodic to the surrounding environment. Other corrosion mechanisms, such as knife-edge corrosion may come into play. The wallpapering techniques require the strictest of quality control procedures, and even so there can still be serious corrosion problems since the welds are continuously exposed to an environment which is acidic, aerated, and high in chlorides.

The basic problem with use of these alloys has been the high levels of chlorides present in the system. Chlorides serve to break down the passive films that give corrosion resistance to stainless steel. This can result in severe pitting, crevice corrosion and stress cracking due to intergranular attack. The grain boundaries are then depleted of oxygen which causes rapid corrosion.

The problem is especially evident in areas that are oxygen-poor. Although oxygen continuously enters the absorber (reflective of the amount of excess air used for combustion), the sulfite ions present in the system can scavenge much of the dissolved oxygen in wetted areas, leading to localized attack of the stainless steel. This is especially true with the trends toward increased available alkalinity, which can serve to scavenge dissolved oxygen. Investigators have reported that the chloride attack is even more aggressive as the pH is lowered (see Figure 5).

Chlorides accumulate principally as a result of evaporation of makeup water in the system. Flue gas enters the quench portion of the absorber at about 350°F and is then sprayed with water. It is effectively cooled to 120-140°F by evaporation of water, akin to what happens in a cooling tower.

Water is added as makeup to compensate for the increased water vapor content of the gas exiting the flue, as well as for water that accompanies the sludge. The water that leaves with the sludge serves as a blowdown on the system, and the concentration of chlorides in the recirculating water depends on the ratio of net water evaporated to water leaving with the sludge.

For environmental purposes, it is necessary to dewater the sludge as much as possible and recycle the water. The sludge is ordinarily a mixture of hydrated forms of calcium sulfate and sulfite along with calcium carbonate.

Although these sludges are difficult to dewater, there have been advances in the technology such as forced oxidation,
which is reported to be capable of producing wallboard quality gypsum. The trend toward improved sludge dewatering will lead to increasing levels of dissolved chlorides and salts in the system, which limits the use of stainless steel.

There are some reports that chloride concentrations can reach as high as 5 percent in the quench area of the system. Within the absorber section it is not uncommon to see chloride concentrations approaching 15000 ppm, which is a level where only some of the best and most expensive high nickel content alloys may be practical.

Although the FGD system normally follows the electrostatic precipitator, some small amounts of fly ash can still enter the system. Leachable chlorides and other salts from the fly ash represent another area of concern.

Once again, polyesters and vinyl esters have a long history of successful resistance to chlorides and other dissolved salts, along with excellent resistance to dilute and many concentrated acids.
ranged in concentration from 25-50%, and often lower. This is easily tolerable for FRP fashioned from good polyesters or vinyl esters.

FRP also has good resistance to SO₂ or SO₃ vapors and/or fumes whose dew points are within tolerable temperature ranges. For high temperature inlet ducting, where the SO₃ concentration is relatively high (280 °F or higher dew points are not uncommon) refractory materials are frequently used.

### Figure 5

When it comes to constituents encountered in FGD systems, FRP laminates stack up well to metals, including expensive alloys, but care must be taken when dealing with concentrated sulfuric acid dewpoint corrosion. The chart applies to temperature ranges typically encountered.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Chemicals</th>
<th>H₂SO₄ Dil.</th>
<th>H₂SO₄ Conc.</th>
<th>HCl Dil.</th>
<th>HCl Conc.</th>
<th>HNO₃ Dil.</th>
<th>Chloride Salts</th>
<th>NaOH Dil.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steel (1020)</td>
<td></td>
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<td></td>
<td></td>
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<td>Above 85%</td>
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<td>□</td>
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<tr>
<td>316 Stainless</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>□</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Below 5%</td>
<td>Above 85%</td>
<td></td>
<td></td>
<td></td>
<td>□</td>
</tr>
<tr>
<td>Hastelloy C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>□</td>
</tr>
<tr>
<td>High Performance FRP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>□</td>
</tr>
<tr>
<td>Composite Laminate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>□</td>
</tr>
</tbody>
</table>

- Unaffected  □ - Corroded

### Table of Polymeric Materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Examples</th>
<th>Features of Importance in FGD System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bisphenol-A extended epoxy based vinyl ester</td>
<td>Dion 9100 and 9102</td>
<td>Good mechanical and high temperature properties coupled with excellent corrosion resistance to acids and alkaline materials. Good cyclic fatigue resistance. Dion 9102 is TÜV approved for FGD related piping.</td>
</tr>
<tr>
<td>High crosslink density bisphenol-A epoxy vinyl esters</td>
<td>Dion 9200 and Dion 9420</td>
<td>High heat distortion temperatures (&gt; 300°F on castings) coupled with excellent corrosion resistance.</td>
</tr>
<tr>
<td>Urethane modified vinyl ester</td>
<td>Adac 580</td>
<td>Excellent chemical resistance and very good retention of mechanical properties at elevated temperature. TÜV approved in Europe for FGD applications. Very good glass wet-out and excellent for field fabrication. Good toughness and brittle fracture properties.</td>
</tr>
<tr>
<td>Alkoxylated bisphenol-A furanace polyesters</td>
<td>Adac 382 and Dion 6694-Resinized versions also made.</td>
<td>Excellent corrosion resistance to acids and best available resistance to alkali materials. Good candidates for use with many of the alkali constituents of FGD systems.</td>
</tr>
<tr>
<td>Flame-retardant vinyl esters</td>
<td>Dion 9300</td>
<td>Good mechanical properties coupled with flame-retardance.</td>
</tr>
<tr>
<td>Flame-retardant alkoxylated bisphenol-A furanace polyesters</td>
<td>Adac 711 and Dion 6695</td>
<td>Excellent high temperature corrosion resistance coupled with flame-retardant properties. Has been used in ductwork at temperatures of 300°F or higher. Large case history in FGD applications.</td>
</tr>
<tr>
<td>Chlorendic based resins</td>
<td>Adac 797</td>
<td>Excellent resistance to acids and oxidation. Displays flame-retardance. Should not be used in exposure to alkaline materials.</td>
</tr>
<tr>
<td>Rubberized vinyl ester</td>
<td>Dion 9085</td>
<td>High tensile elongation vinyl ester. Good acid resistance and also excellent for profile bonding to various substrates. Good for flooring and other auxiliary applications.</td>
</tr>
<tr>
<td>Novolac based vinyl ester</td>
<td>Dion 9480</td>
<td>Novolac based vinyl ester with good high temperature and toughness properties.</td>
</tr>
<tr>
<td>Liquid Sulfuric Acid Concentration</td>
<td>Atlastic</td>
<td>Dionic 382</td>
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<tr>
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</tr>
<tr>
<td>1%</td>
<td>210</td>
<td>NR</td>
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<tr>
<td>5%</td>
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</tr>
<tr>
<td>80%</td>
<td>NR</td>
<td>NR</td>
</tr>
</tbody>
</table>

NR = Not Recommended

**ALTERNATE MATERIALS**

Most of the preceding discussion has centered on the attributes of FRP and various alloys. However, some comments can be made on other frequently used materials in FGD applications:

**Rubber and various elastomers**

Because rubber has good resistance to sulfuric acid, rubber-lined steel has been frequently used, especially in areas where abrasion resistance is needed, such as in slurry piping. Although there are definite advantages to rubber, there can be some significant disadvantages compared to the use of FRP.

In the case of rubber linings it generally takes very skilled and specialized fabrication, which tends to make it expensive. Many of the linings are very difficult if not impossible to construct around restrictive geometry. It is essential to obtain good bonding to the steel since any permeation behind the lining can quickly corrode the steel. The weight of the rubber makes it difficult to field-bond onto vertical or inverted surfaces. If the lining is damaged by sharp objects, the repairs (unlike FRP) are difficult to conduct.

Although rubber has good chemical resistance the low Tg can restrict its use to moderate temperatures. Suppliers should be carefully consulted to understand any chemical limitations. For example, some rubbers may become embrittled if subjected to cyclic wet and dry conditions. Likewise they can swell in some environments, such as solvents. Generally the hydrocarbon type rubbers can be limited in FGD applications, and there is a trend to rely on a wide variety of synthetic elastomers.

Nevertheless, there are areas where elastomers are essential in power plant applications, such as in bellows type expansion joints. Common types have included Viton® and various bisphenol-A vulcanized fluoroelastomers.

Some fluorocarbon based polymers can be prone to water absorption or loss of abrasion resistance, so specialists should always be consulted.

**Acid resistant brick and refractories**

Both castable and mortar block acid-resistant refractories have of course been used for many years. They are especially advantageous for accommodating high temperature sulfuric acid dew point corrosion.

A disadvantage is the high installation cost, albeit such cost may not be as high as that involved with use of expensive alloys. Castable products must be well bonded or anchored to the steel structure by use of Y-anchors or studs. The refractories are not ductile and concern always exists over cracking or thermal cycling. Block material must be skillfully placed with proper acid mortar.

The high weight can be a big disadvantage in structural support and foundations. Restrictions are also involved in seismic design areas. Failures at times have been catastrophic.

In a wet stack is involved such as from a scrubber, then it is commonplace and often mandatory to use a pressurized membrane to prevent condensation onto the relatively cold steel external skin. This can be considerably expensive.

Some private industry surveys indicate that there are perhaps more than 100 brick stacks in the United States which are leaning or otherwise in need of replacement.

**Thermoplastics**

Many common thermoplastics have good corrosion resistance and can find use in some FGD components, such as mist eliminators, trays, spray headers, and other internals. Examples include polypropylene, ABS, and PVC.

Thermoplastics have quite different properties than the thermosetting resins used in fiber reinforced applications. The thermoplastics have distinct glass transition points and can melt or distort if temperature is too high. Heat distortion properties (HDTUL) are not as good as FRP. They are processed by a variety of techniques such as injection molding and as such are not amenable to the large sizes associated with many utility scale equipment items. Some thermoplastics, however, can be used as spray coatings or as extruded linings subsequently bonded onto various substrates (so-called dual laminates).

Generally cost is higher than FRP except for relatively small or modular parts. Only rarely are thermoplastics reinforced with fiberglass, so they lack the strength of FRP, except perhaps in some cases involving so-called engineering thermoplastics, which are quite expensive. Temperature is the biggest restriction. Water permeation is a also a problem, even for some highly chemically resistant plastics such as fluoropolymers. If cracks occur, especially with materials such as polyethylene, the materials are almost impossible to repair by welding due to the water absorption and other factors.

Molecular weights of thermoplastics are high, but a big
difference is that the resins used in FRP are highly crosslinked upon curing to yield exceptionally good corrosion resistance and high heat distortion properties.

**Other thermosetting resins**

FRP ordinarily features polyesters or vinyl esters which are designed for proper corrosion resistant as well as good thermal and physical properties. In almost all cases, styrene is the crosslinking monomer and the cure is initiated with various peroxides in conjunction with accelerators and promoters. All of the rigid forms of these resins have excellent water and acid resistance, but the less expensive polyesters do not feature good alkali resistance. However, bisphenol-A based polyesters as well as vinyl esters have excellent combined acid and alkali resistance.

Epoxy are another class of thermosetting resins commonly used. They feature good alkali resistance, but acid resistance may be poor. If the pH is less than three (which can occur from condensate in a stack), the practical use of epoxies can be limited or may require specialized versions as well as curing components. A variety of cure systems are used, but most commonly these are amine based.

Epoxy are inherently tough and have good bonding properties. Frequently they are used for relatively thin dielectric protective coatings, especially onto new steel which has been properly prepared. For thick coatings (roughly 30 mils or higher) which require reinforcement, the epoxies can be more expensive than other materials and require special attention to things like wet-out of the reinforcement.

Another common class of thermosetting resins are phenolics which are generally cured with acid catalysts. They tend to be relatively inexpensive, and one of their biggest advantages is in low smoke which is generated in the event of a fire, due to carbonization of the resin during the burning process. However, their biggest disadvantage is poor corrosion resistance in comparison to the polyesters or vinyl esters used in FRP. Like polyesters they can shrink somewhat during cure, but in the case of phenolics the cure can keep extending well after the initial fabrication. This has led to some problems with dimensional stability.

**CASE HISTORIES RELATING TO S0, REMOVAL AND HIGH TEMPERATURE APPLICATIONS**

In some of the following case histories, some company names or locations are omitted for confidentiality. Of course, these products have been used in many more demanding corrosion resistant applications outside of the utility industry.

A key challenge to design is the size of the equipment used. However, skilled fabricators have demonstrated the ability to make large FRP structures. An example is the 685 feet high by 28-foot diameter twin stack liners built by Ershigs, Inc., as part of the Intermountain Power Project in Delta, Utah (Figure 6). The project used flame retardant Atlac 711 and involved field fabrication of the stack in 34-foot long can-like sections using filament winding procedures. Subsequent inspections have shown the lining to be in excellent condition.

**RESIN SELECTION**

There are a variety of mechanisms by which polyesters and vinyl esters can be attacked by corrosive media. However, in most cases, the mechanism revolves around hydrolysis of the ester linkages present within the structure:

R-C-O-R'

Improved corrosion resistance is provided by minimizing the number of ester linkages through the use of large molecular weight components used in the polyester synthesis. Examples involve the use of bisphenol-A or epoxy components. Bisphenol-A fumarate resins such as Atlac 382 or Dion 6694 are extremely corrosion resistant, especially to alkaline materials over a wide range of temperatures.

The ester can be further shielded from attack by stereochrome, i.e., the specific spatial structure of the resin, which makes it more difficult for water or other small molecules to reach and react with the ester linkage. For example, orthophthalic and isophthalic acids are common raw materials in polyester synthesis. Although they have the same empirical formulas, the isophthalic-based polyesters show better resistance because of differences in stereochrome.

Another example of how stereochrome can be important relates to chlorendic resins. The molecular structure in this resin is very dense, which leads to good resistance to acids and oxidizing media. However, chlorendic resins tend to be brittle because of their dense structure and this can limit their application. The chlorendic constituency of these resins makes
<table>
<thead>
<tr>
<th>Company</th>
<th>Date of Installation</th>
<th>Resin Used</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louisiana Pacific</td>
<td>Estimated 1980</td>
<td>Atlas 711</td>
<td>SO₂ scrubber outlet ductwork at 300°F</td>
</tr>
<tr>
<td>LP, Antioch, CA</td>
<td>1979</td>
<td>Atlas 580</td>
<td>Outlet ductwork from an SO₂, HCl scrubber where sodium hydroxide was used; operates at up to 350°F</td>
</tr>
<tr>
<td>Smith Douglas, Plant City, FL</td>
<td>1961</td>
<td>Atlas 382</td>
<td>Stack associated with fluorine, which operates at 300°F</td>
</tr>
<tr>
<td>Elk Falls Co.</td>
<td>1968</td>
<td>Atlas 382</td>
<td>Heat recovery boiler breaching for flue gas and water ranging in pH from 2.5 to 11. Gas contains H₂S and sodium sulfate, with operating temperature of up to 340°F</td>
</tr>
<tr>
<td>Sc. Regis Paper, Jacksonville, FL</td>
<td>1969</td>
<td>Atlas 711</td>
<td>SO₂ and alkali material from outlet of electrostatic precipitator operating at up to 305°F</td>
</tr>
<tr>
<td>Copper smelter in northern Italy</td>
<td>1975</td>
<td>Atlas 382</td>
<td>Stack gas at 175°F from scrubbing of SO₂; where FRP is exposed at temperatures up to 310°F</td>
</tr>
<tr>
<td>Kyments Oy, Finland</td>
<td>1977</td>
<td>Atlas 382</td>
<td>Black liquor heat recovery and SO₂ removal system where FRP is exposed at temperatures up to 310°F</td>
</tr>
<tr>
<td>Kipperfors, Scandinavia</td>
<td>1977</td>
<td>Atlas 382</td>
<td>FRP replaced stainless steel in an SO₂ scrubber associated with a pulp mill. Inlet flue gas temperature was 310°F and outlet was 150°F</td>
</tr>
<tr>
<td>Grays Harbor, Pulp Mill, Hoquiam, WA</td>
<td>Approx. 1980</td>
<td>Atlas 711</td>
<td>Entire system used FRP and replaced stainless steel. Installation included an 8 ft. diameter venturi scrubber and a 32 ft. diameter packed column.</td>
</tr>
<tr>
<td>Kennecott Copper, Garfield, UT</td>
<td>Approx. 1980</td>
<td>Dion 6694</td>
<td>SO₂ scrubber; conditions not known.</td>
</tr>
<tr>
<td>Anaconda Copper, Great Falls, MT</td>
<td>1972</td>
<td>Dion 6693</td>
<td>Ductwork after SO₂ scrubber at temperature up to 170°F</td>
</tr>
<tr>
<td>Guaranteed Products Co.</td>
<td>1981</td>
<td>Dion 6693</td>
<td>Fume exhaust ducts from sulfuric acid at temperatures up to 165°F.</td>
</tr>
<tr>
<td>Standard Oil of California</td>
<td>1973</td>
<td>Dion 6694</td>
<td>Flue gas lining from SO₂ scrubber, temperature up to 212°F.</td>
</tr>
<tr>
<td>Kennecott Copper Magna, UT</td>
<td>1976</td>
<td>Dion 6662T</td>
<td>A 24 ft. diameter x 125 ft. high stack structure at 220°F; One of the biggest FRP structures in the world. Operated nearly 20 years until smelter plant was retired.</td>
</tr>
<tr>
<td>Pennsylvania Power</td>
<td>1973</td>
<td>Dion 6631T</td>
<td>Fume glass lining for ductwork from SO₂ scrubber.</td>
</tr>
<tr>
<td>Alaska Pulp &amp; Paper</td>
<td>Approx. 1972</td>
<td>Atlas 382</td>
<td>SO₂ and SO₂ scrubber system at temperatures up to 200°F.</td>
</tr>
<tr>
<td>Kao Soap Co., Japan</td>
<td>Approx. 1970</td>
<td>Atlas 382</td>
<td>SO₂ and SO₂ scrubber system at temperatures up to 200°F.</td>
</tr>
<tr>
<td>Kennecott Copper</td>
<td>Approx. 1975</td>
<td>Atlas 382</td>
<td>Green butterfly valves handling SO₂ gas mixture at 118°F.</td>
</tr>
<tr>
<td>Revere Sugar, Charleston, MA</td>
<td>Approx. 1971</td>
<td>Atlas 382</td>
<td>Stainless steel and Monel replaced with FRP to handle SO₂ fumes and scrubber liquor at 120°F</td>
</tr>
<tr>
<td>Mitsubishi, Japan</td>
<td>Approx. 1970</td>
<td>Atlas 382</td>
<td>Fume scrubber and 460 ft. stack operating at 170°-195°F</td>
</tr>
<tr>
<td>Pennsylvania Power</td>
<td>1979</td>
<td>Atlas 382</td>
<td>Glass fume linings for 24 carbon steel scrubbers, 150,000 ft. of connecting ductwork, and two 850 ft. fumes operating at high temperature.</td>
</tr>
<tr>
<td>Potomac Electric, Dickerson Station</td>
<td>1980</td>
<td>Atlas 711</td>
<td>Glass fume linings for SO₂ venturi scrubber, mist eliminator, outlet ductwork, thicker tanks at temperatures up to 150°F.</td>
</tr>
<tr>
<td>Saras Refinery Italy</td>
<td>1988</td>
<td>Atlas 580</td>
<td>SO₂ scrubber operating at 1115°F in novel system.</td>
</tr>
<tr>
<td>Emmenbrucke, Switzerland</td>
<td>1994</td>
<td>Atlas 382</td>
<td>Municipal incinerator scrubber at 200°F.</td>
</tr>
<tr>
<td>Ontario Hydro, Lambton Station</td>
<td>1993</td>
<td>Dion 9300</td>
<td>Two unique one-piece composite stack liners associated with FGD system, each 24 feet diameter, over 400 feet tall.</td>
</tr>
<tr>
<td>MTKW-Kempten, Germany</td>
<td>1995</td>
<td>Atlas 580</td>
<td>21 ft diameter by 65 ft high SO₂ absorber</td>
</tr>
<tr>
<td>Intermountain Power Project, Delta, UT</td>
<td>1987</td>
<td>Atlas 711</td>
<td>Structural liner two twin 682 ft. high by 28 ft. diameter flues from an FGD system. Perhaps the largest FRP structure in the world. Annual inspections show no corrosive attack.</td>
</tr>
</tbody>
</table>
them susceptible to attack by alkaline materials. Thus, care should be taken whenever they are considered for FGD systems in view of likely exposure to alkaline compounds. Chlorendic resins also tend to lose their resistance to acids when elevated temperatures are used.

Another important factor that affects corrosion resistance is crosslink density i.e., the number of specific crosslink sites when the resin is cured with a vinyl monomer. Typically, the monomer is styrene, although divinylbenzene and other monomers can be used. The degree of crosslinking is affected by the amount of unsaturation provided in the resin, as well as by its molecular weight. In the case of vinyl esters, the unsaturation is provided at terminal groups of the resin molecule. In general, higher crosslink densities will improve corrosion resistance. However, the crosslink density and distribution affect mechanical properties, which must be considered in design.

The key advantage to polyester and vinyl esters relates to their low viscosity, which permits ease of application yet results in a composite with outstanding properties when cured. Equally important is the need to ensure complete curing of the resin.

**FLAME RETARDANCY**

Although there are no sources of continuous ignition within FGD systems, the organic polymers associated with FRP can ignite. This could occur, for example, due to welding in the area. Once a fire is started, strong natural drafts inside of the ductwork, could accelerate burning and/or make it difficult to extinguish. This is especially a problem in ducting where coal tar or other combustibles may have accumulated.

Therefore, consideration should be given to use of flame-retardant resins, which incorporate halogens into the formulation. Since these resins are still organic, they will burn. However, a key feature is that they will self-extinguish in several seconds once the flame source is removed. Whenever a continuous source of ignition is provided, they will burn at a much slower rate than other polyesters. The degree of flame retardancy can be enhanced by the use of various additives, most commonly antimony trioxides, that act in synergy with the halogen.

The following lists the rate of flame spreads possible as determined by ASTM E84 testing. The indicated flame spread is basically the percentage of its rate of burning compared with that of red oak. Data apply to standard laminates with 25 percent glass. Even lower flame spreads are possible with alternate glass construction.

<table>
<thead>
<tr>
<th>Resin</th>
<th>Additive</th>
<th>ASTM E84 Flame Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aptac 711-05A</td>
<td>NONE</td>
<td>35</td>
</tr>
<tr>
<td>Aptac 711-05A</td>
<td>5% Antimony Oxide</td>
<td>10</td>
</tr>
<tr>
<td>Aptac 711-05A</td>
<td>3% Antimony Oxide</td>
<td>25</td>
</tr>
<tr>
<td>Aptac 711-05A</td>
<td>5% Antimony Oxide</td>
<td>10</td>
</tr>
<tr>
<td>Dico VER 9300FR</td>
<td>5% Antimony Oxide</td>
<td>15</td>
</tr>
<tr>
<td>Aptac 797CT</td>
<td>5% Antimony Oxide</td>
<td>30</td>
</tr>
</tbody>
</table>

**STATIC ELECTRICITY**

Related to fire protection is the need to properly consider electrical potential on the surface of the laminate. Fortunately, the laminates in FGD systems are normally exposed to gas that is rich in water vapor and essentially free of particulates.

In cases where it is necessary to enhance the conductivity of the laminate, consideration can be given to the use of graphite veils or mats in the construction of the corrosion barrier.

Care should be taken in use of copper wire embedded for grounding purposes since copper will inhibit cure and may eventually lead to localized cracks. Preferably graphite or tantalum conductors are used. Surface resistivity of most resin laminates is on the order of $10^6$-$10^8$ ohms. With a proper carbon mat resistivity as low as 10 Ω/ft at 1.5 volts is often possible, but with 20-30% graphite loading it is usually in the neighborhood of 1000 Ω/ft.

**COMPOSITE CONSTRUCTION**

The corrosion protection of an FRP structure is afforded strictly by the resin used. However, resins are too weak to be used without structural reinforcement. Glass flakes or fiberglass are usually used, although more exotic reinforcements can be considered, such as aramid (Kevlar®) or carbon fibers.

When it comes to laminate construction, there are many details that which are outside the scope of this paper. Nonetheless, specifiers and users must take time to learn these matters. Without proper construction, failures can occur. Some generalized principles include:

- The resin must be fully cured. This is generally done by testing the Barcol hardness of the laminate with an instrument (manufactured by Barber Coleman) that measures the force required to penetrate the laminate. This also requires familiarity with curing systems recommended by the resin manufacturer. The resin should be postcured for best performance.
- Since it is the resin that provides the actual corrosion resistance, the composite must not allow exposure to fiberglass reinforcement. Glass is susceptible to chemical attack, especially around alkaline constituents found in FGD systems.
- Laminates must be free of air voids or contamination.
- Glass must be compatible with the resin and well wetted (permeated by the resin) prior to curing. The type of fiberglass to be used is important.
- Oxygen will inhibit curing of the resin on surfaces exposed to the atmosphere. A variety of methods can be used to achieve good surface curing. The most common method involves use of small amounts of paraffin wax in a topcoating formulation.
- It is important to avoid thick layers of resin, which can lead to cracking if not adequately reinforced.
- In general, fillers and other solid additives, including thixotropic agents, detract from corrosion resistance. They should not be used unless necessary for technical reasons.
• Proper safety techniques must be observed.
  For additional information on fabricating FRP structures, refer to Reichold’s Fabricators Handbook.

There are two major types of FRP composites used in FGD systems: liners and fabricated structures.

**LINERS**

Here a reinforced layer of resin is applied by spraying or towelling it onto the metal surface of the vessel or ductwork. Normally, the reinforcement is refractory flaked glass made by a special process. This form of glass has advantages over chopped fiberglass, especially in regard to reducing permeability. The reinforcement and bonding to the flake glass allows thicker linings (up to 100 mils or so), which by itself reduces the permeability. Low permeability is very important to keep water from penetrating to the metal interface, where enormous stresses can develop to disbond the lining through galvanic mechanisms.

In these composites, the glass flakes will align as plate structures, which tend to seal the lining and reduce the permeation. Linings are often composed of multiple layers, for example the layer near the wall may be more flexible than the more corrosion resistant surface exposed to the environment. Furthermore, the flaked glass enhances abrasion resistance, which ordinarily improves when the environment is wet.

The bond between the metal and the composite is extremely important. This requires thorough surface preparation, including sandblasting followed by prompt application of a primer. Quality primers, such as Atprime, which was specifically developed for bonding of polyesters, are suggested. Atprime reacts with the hydroxyl functionality of the resin to provide excellent bonding.

It is also very important to be aware of coefficients of thermal expansion between the metal substrate and the liner. In design and installation of these systems, it is strongly recommended that skilled and experienced fabricators be used. Without proper installation, the lining can fall even though the resin is not chemically attacked. Indeed, failures of some linings relate to inexperience in this regard.

**STRUCTURAL COMPOSITES**

These provide the best available mechanical properties and chemical resistance. As previously mentioned, some very large structural composite parts can be made for FGD systems.

These structures are generally made by filament winding methods, although a number of hand lay-up methods can be used as well.

In filament winding, the wall of the vessel is fabricated by wrapping it with fiberglass rovings that are wetted with catalyzed resin. Many variations exist, including the patterns of glass windings along with use of woven mats.

A key feature is the fabrication of the so-called corrosion barrier, which provides the maximum resistance possible (Figure 7). This requires the use of a surfacing veil, which is ordinarily fabricated of C-glass with a special composition. Synthetic veils can also be used, such as Nexus®. Synthetic veils are made of polyester fabrics or various acrylonitrile-based polymers and copolymers. The veil will reinforce a resin-rich layer exposed to the corrosion medium. The veil layer should be only 10-20 mils in thickness. Excessive thickness may lead to surface cracking.

The veil layer must then be backed up with at least two plies of 1½-oz./sq. ft. chopped strand fiberglass mat. Afterwards, the wall thickness is built up by any accepted practice, depending on desired structural properties. In cases where woven mat is used, it is necessary to alternate the

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**Figure 7**

A properly constructed corrosion barrier provides maximum resistance

- primary corrosion barrier
- side exposed to corrosive media
- alternate mat and roving to desired thickness for strength
- exterior side
- optional

- "C"-glass surfacing veil, 0.010 to 0.020" thick, 10-12% glass content.
- 1 ½ oz. chopped strand mat, 0.100 to 0.125" thick, 20-30% glass content.
- Woven glass roving, 50% glass content.
woven mat with chopped strand mat. Otherwise, interlaminar shear can occur between plies of the woven mat.

Once again, skilled fabricators should be employed for construction, inspection and any necessary repairs.

**OTHER COMPOSITES**

Use of pultruded FRP parts for FGD systems is expected to increase. These parts feature two-dimensional symmetry and high glass loading, with the glass axially oriented. Tensile strength is similar to that of aluminum and about two-thirds that of carbon steel. Applications include tie-rods, bracing, backstays and strapping of various structures. The carbon steel historically used for this purpose often corrodes in FGD applications.

**COMPARATIVE PHYSICAL PROPERTIES OF FRP LAMINATES**

FRP is about 25 percent the weight of carbon steel and slightly lighter than aluminum. FRP composites can be designed to be stronger than steel on an equal weight basis. This property is sometimes called specific strength or strength-to-weight ratio. Depending on the reinforcing materials selected, a wide range of strength properties are available in FRP structures.

As might be expected, the reinforced plastic is not as stiff as steel (Young's modulus or modulus of elasticity). In many applications, such as storage tanks or membranes, this property may be of little importance since most FRP tanks are far thicker than needed. In some applications, however, it is a distinct advantage and FRP is usually not considered for applications where high modulus is required. If stiffness is desirable, it can be obtained by increasing the glass reinforcement or using stiffening ribs in the structure.

The following table compares properties of metals with
Figure 9
Flexural property retentions at elevated temperatures for 1/4" laminates of Atlac 580 urethane modified vinyl esters compared to more conventional Bisphenol-A epoxy type vinyl esters.

Figure 10
Elastic shear modulus ($G'$) and damping ($\Lambda$) properties of Atlac 711-05A flame retardant castings and laminates in temperature range -70 to 200 °C. The peak in the damping curve for unreinforced resin corresponds to the glass transition temperature (Tg). Glass content of laminates is 30%.
those of highly reinforced FRP laminates, i.e., these with 40 percent glass content and containing mat and woven roving construction.

Cost comparisons between these materials have to be examined case by case. In general, FRP represents lower initial cost (especially compared with alloys), as well as lower installation costs. The improved corrosion-resistant properties have obvious cost savings in maintenance and reliability. Furthermore, repairs and replacements are less costly. A variety of field techniques can be used for repairs, including secondary bonding and welding of FRP structures.

**ELEVATED TEMPERATURE PROPERTIES**

Physical properties of materials tend to decrease with elevated temperature. For example, with carbon steel, the elastic properties begin to fall off around 600°F. Figure 8 shows how tensile and flexural properties of laminates made from flame-retardant and highly corrosion-resistant Atlac 711 vary with temperatures up to about 355°F. This must be considered in design, yet the property retention is good compared with most FRP composites.

For improved elevated temperature properties, unique resins have been developed, such as Atlac 580, a urethane-modified vinyl ester. As Figure 9 indicates, Atlac 580 shows better retention of properties than conventional vinyl esters. Atlac 580 also displays excellent brittle fracture properties and toughness due to its urethane component.

Polymers may display both crystalline and amorphous properties depending on temperature. Much of this is related to composition or stereoregularity. As temperature rises, the polymer becomes more plastic in behavior, and when plasticization occurs, limited movement is possible. This can affect performance and behavior, leading to deformation or creep. Plasticization occurs near the glass transition point (Tg) of the polymer. Typically, the Tg occurs about 20°F higher than what is commonly called the heat distortion temperature, i.e., the temperature where deformation is first noted when a static load is applied based on ASTM testing.

Glass reinforcement affects elastic and heat distortion properties as illustrated for Atlac 711 in Figure 10. Castings of Atlac 711 display a Tg of approximately 285°F. As glass reinforcements are increased, so is the retention of structural properties. Structures reinforced with woven roving or filament winding with 40%-50% glass have been known to resist creep at temperatures up to 400°F.

**ELECTRICAL PROPERTIES**

FRP laminates are good electrical insulators, which make them good candidates for use with electrostatic precipitators or other electrical applications. The premium performance corrosion-resistant resins tend to have slightly better properties than other polyesters as a class. Some typical properties are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Atlac 382 Laminates</th>
<th>Atlac 711 Laminates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Constant, ASTM D 150</td>
<td>4.18</td>
<td>3.60</td>
</tr>
<tr>
<td>Dissipation Factor, ASTM D 150</td>
<td>0.0078</td>
<td>0.0075</td>
</tr>
<tr>
<td>Dielectric Strength, Volts/mil, ASTM D 149</td>
<td>&gt; 350</td>
<td>480</td>
</tr>
<tr>
<td>Surface Resistivity, ohm, ASTM E257</td>
<td>8 X 10^11</td>
<td>3.1 X 10^11</td>
</tr>
</tbody>
</table>

**THERMAL CONDUCTIVITY**

Thermal conductivity of FRP composite laminates is only a fraction of that of metals, hence FR provides insulation benefits. Heat conservation in ducting, breachings and linings is crucial in reducing condensation of flue gas vapors, which are highly acidic and corrosive. The low conductivity also increases the temperature gradient across the laminate structure, so that under high operational temperatures, only the surface will be subjected to the full effects of the exposure (Figure 11). Thus, the low conductivity is influential in maintaining good structural integrity in laminates exposed to elevated temperatures.

In some cases, if the inner surface temperature is too high, some people have used carbon at the surface to increase the thermal conductivity in order to reduce the surface temperature.

Although the temperature gradient profile across an FRP lining must be properly considered, the low thermal conductivity can serve to attenuate the shear forces that occur at the metal interface due to coefficient of expansion differences.
THERMAL EXPANSION

FRP composite laminates have higher coefficients of thermal expansion compared with metals. Ducts operating at high temperatures must include expansion joints to take up the considerable movement expected in large FRP structures used in the power and chemical industry.

The anisotropic nature of glass fiber-reinforced laminates leads to differential expansion within the FRP structure, with the cross-sectional thickness displaying three to four times more expansion than in the direction of the fibrous reinforcement. The expansion in the direction of the fiber is restrained by the cohesion between the resin and fiber, whereas there is more freedom in the direction perpendicular to the fibers which is bounded by the resin. This relationship holds when the reinforced structure is measured between 70-200 °F. The coefficient of linear expansion for a 25 percent glass reinforced laminate constructed with a C-veil corrosion barrier is 0.000028 in/in/°F in the fiber direction and 2.7 times this value perpendicular to the fiber. As the reinforcement level is increased to 35 percent, including woven roving, the coefficient of lineal expansion is reduced to 0.000013 in/in/°F in the fiber direction while the expansion perpendicular to the fiber is 3.5 times greater.

ABRASION RESISTANCE

Abrasion has historically been a major problem in FGD, especially for systems involving limestone. However, compared to other solids, limestone is relatively soft, with a Moh hardness of about two. Although there have been many improvements relating to design velocities and reduced scaling, abrasion must nevertheless be considered properly.

Metals in general have better abrasion resistance than FRP composites. However, in corrosive media, this is not necessarily the case. If steel is oxidized, the abrating materials can continuously clean off the oxide coating which accelerates both corrosion and abrasion. A visual inspection of a steel surface may not indicate the problem because the true mechanism of attack is disguised.

A method commonly used to control abrasion in FGD systems is lining the steel with rubber. This has the added benefit that the rubber is resistant to sulfuric acid. Many of the rubber-lined applications have revolved around slurry piping. Although they generally perform well, the linings are expensive to install and often are limited when it comes to elbows and restrictive geometry. Moreover, the linings must be inspected frequently, since leaks can result in corrosive media contacting metal walls, leading to serious damage. Lime and limestone are notorious for containing metal contamination, e.g., nails, wood, angle iron, etc. If these metals cut the rubber lining, it must be repaired promptly, which is usually expensive. This is especially true when cords or reinforcements of the liner are damaged. FRP, on the other hand, is generally easy to repair.

FRP composites generally are not recommended for significantly abrasive conditions. However, there have been a variety of successful techniques used to improve resistance.

One common method is the use of resins that are more flexibilized, exhibiting higher percent tensile elongations. This has the added benefit of improving impact resistance. Flexibilized versions of many resins are available, including Allvac 580. If a more flexible resin is used, care must be taken in the application since more flexible resins have lower heat distortion temperatures and somewhat reduced corrosion resistance.

Silicon carbide and other fillers have also been used successfully to improve abrasion resistance and glass flake also provides good resistance. However, it is necessary to be very careful. Many fillers such as clays or silica may improve hardness and abrasion resistance, but they allow for greater water permeability and detract from corrosion resistance. Glass reinforcements are susceptible to attack by alkaline materials. If the surface of the glass is exposed, rapid deterioration can occur.

Abrasion is never a predictable phenomenon and testing is always necessary. FRP should be considered insasmuch as favorable results are often obtained.

FURTHER ADVANTAGES TO FRP

FRP has a long history or reliable and durable use in utility and other industries, and some of the potential benefits can translate to great practicality or cost savings over and beyond the corrosion resistance properties.

For example, FRP is much lighter in weight than alternate materials. This not only benefits the savings in structural requirements, but can allow installation with helicopter cranes, which can be important for tall structures or remote locations.

FRP can also be installed without the need for hot welding, which can be an advantage in facilities handling combustible materials. Unlike other materials, FRP in general is easy to repair in the field, which can be an advantage in dealing with common physical accidents or equipment modifications.

Perhaps the biggest reluctance to use FRP is an unfounded one, namely lack of familiarity on the part of many designers. Techniques of designing with metals have a long history or expertise and predictability. Composite construction introduces potentially more variables which some people view as overly complicated. However, these variables translate to greater design freedoms.

For example, there are many types of reinforcements ranging from chopped strand mat to woven roving, and there are many ways to configure or arrange the reinforcements in accordance with the anticipated stresses to benefit performance or costs. Some high modulus reinforcements, such as carbon fibers, are becoming increasingly practical to consider, and designers are finding ways of using them more effectively. For instance, the carbon fibers may be used alternatively to fiberglass only in portions of the laminate where they are really needed rather than throughout where some of them may effectively be wasted.

As in any industry, designers of FRP are becoming increasingly sophisticated, and new design standards emphasize the importance of modern finite element stress analysis. Increasingly stringent quality control procedures are also being implemented during fabrication.
From a polymer standpoint, there is always on-going emphasis on improved products with better corrosion resistance, strength, cost, high temperature properties, or environmental improvement.

SUMMARY

It is hoped that people recognize that the conditions and future trends in desulfurization process can represent extremely severe corrosion environments to alloys and other traditional materials of construction used in absorbers, chimneys, ducts, and other facilities in the vicinity of steam generating plants. Indeed there are numerous examples of how serious the corrosion problems have been. FRP has been able to solve these problems, and now has a well-demonstrated history of practical use even at the large sizes needed in these applications. More than anything else, the successful use of FRP hinges on understanding its properties and applications.

AUTHOR

John Kamody currently deals with corrosion-resistant, flame-retardant and other specialty products for the Reactive Polymers Division of Reichhold Chemicals. Since 1968, he has worked for Koppers Company, whose Polyester Division was purchased in 1989 by Reichhold. While at Koppers, his experience included polyester resins, thermoplastics and engineering and construction activities. He holds B.S. and M.S. degrees in chemical engineering from Carnegie-Mellon University, Pittsburgh, Pa., and is a registered professional engineer.