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Technical Paper

Advances in Fine Grinding & Mill System Application in the FGD Industry

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Presented to:
**EPRI-DOE-EPA Combined Utility Air
Pollutant Control Symposium**
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Abstract

Being an integral part of the typical FGD system, the design and performance of the reagent preparation system will influence the overall process effectiveness. In providing the most cost effective and energy efficient FGD system design, the options and advancements in size reduction processes urge consideration. Presented is an analysis of an attrition mill option, which can be used to demonstrate the opportunities available when applying comminution processes to the FGD industry.

Introduction

Horizontal ball mills have dominated as the equipment of choice for limestone grinding functions within wet flue gas desulfurization (WFGD) systems. Recent years have led to a more wide spread investigation and acceptance of alternative mill system designs. Mill types considered within the industry have ranged from a variety of media mills to dry roller mills.

The science and application of size reduction processes is a complex subject. Similarly, the design of the FGD system is also complex and can be influenced by many factors. Determining the most cost effective and energy efficient grinding method for each application can require an exhausting study. The detailing of optional designs with significant capital cost, power and operational information is time consuming to produce and evaluate.

Presented is a review of limestone grinding for FGD systems, with an attrition mill option exemplifying how advancements in comminution processes influence overall FGD system design. Relative grinding energy efficiencies are presented to assess the impact of operational power consumption and installed power. The goal is to shed light on overall objectives and design path alternatives.

Wet FGD Limestone Grinding

The wet horizontal ball mill has typically been the workhorse for limestone slurry preparation within a wet FGD system. Undoubtedly, the horizontal ball mill has certain characteristics that suit it well to FGD service, these primarily being:

- Wet grinding capability
- Large reduction ration capability (ability to take a 1" feed size to a micron range product)
- Resistance to abrasion
- Relatively low operation, control and maintenance requirements

Wet grinding is usually preferred over dry grinding. When looking at the grinding process in isolation, there are pros and cons of wet versus dry. Dry grinding requires more power, yet has less ball and liner consumption than in wet grinding. Additionally, the capacity of a dry mill is typically less per unit mill volume than it is with wet milling.

However, it is the overall FGD system design and use requirements that push the selection in the direction of wet grinding. The two main reasons are that the ground product is utilized in a wet process and that the received condition of the stone can be one of relatively high moisture.

In addition to the higher dry milling energy required, when feed stone surface moisture rises above 2-3% by weight, a heated air source to accommodate drying is typically required. This usually leads to unacceptably high-energy costs. Indeed, in most industries, the increased energy consumption and the capital cost of the equipment can swiftly move the overall economics away from dry grinding when a wet slurry is a desired end product.

A commonly specified FGD limestone size for feed to the mill system is $\frac{3}{4}$ " x 0". This is a loose description of a size distribution which can be thought of as all the particles smaller than $\frac{3}{4}$ " with the distribution extending into a fines range below 20 mesh. Size ranges described in this manner are variable in practice and can have occasional 1" to 3" tramp material and/or higher percentages of fines. The horizontal ball mill is capable of accepting this stone size direct, without any pre-crushing function, thus improving system flexibility, simplicity and reliability. Abrasion is controlled with wear resistant mill liners and by the inherent concentration of the wear in the media.

Alternative Designs

An alternate wet ball mill design that has gained acceptance in the FGD industry is the tower mill or vertical ball mill.

Vertical ball mills are a form of "stirred" ball mill and can be more energy efficient than typical horizontal ball mills. Their increased efficiency is partially explained by placing the grinding action in solids beds that are of a more optimum thickness or porosity. The variation in the transport of the feed through the mill, the distribution of feed in the ball charge media, and the method of energy transfer to the media are also factors which help explain the difference in efficiencies.

Furthermore, tower mills are typically fed with a $\frac{1}{4}$ " x 0" feed size. While this necessitates the use of a pre-crusher when a larger sized stone is received, it allows for the mill to be sized for a smaller reduction ratio and a more optimum media charge size distribution.

Wet FGD Limestone Attrition Milling

Attrition milling is another approach beginning to gain acceptance in FGD. Attrition milling is also not new. Various forms of attrition milling have been used across a wide range of industries and applications, such as paints, pigments, pharmaceuticals, ceramics and coal slurries. The attrition mill could be considered on the other end of the loose generic description of stirred media or stirred ball mills. Similarly, some have classified the vertical ball mill as being in the family of attrition mills.

The tailoring of the mill design to the specific application can be critical with attrition mills, as they operate at higher speeds, smaller volumes and higher localized energy concentrations. This mill type was chosen as an example of how mill system advancement, optional mill system arrangements and sparing philosophies can impact overall system design and process effectiveness.

The mill was designed specifically for limestone grinding with a reduction ratio equivalent to that typically applied to the vertical ball mill in FGD service. This is taken to be the comminution of $\frac{1}{4}$ " x 0" mill feed size to a 95% less than 325 mesh product size. Since the design of the attrition mill is suited to obtaining extremely fine grinding, finer product sizes are possible and are evaluated to some extent later.

The original attrition mill was invented by Dr. Andrew Szegvari in the 1920s. The invention is significant in that it marked the beginnings of agitated media milling. As mentioned earlier, the stirred ball mill term is often used as it depicts a grinding mill, which utilizes a stationary vessel and internally agitated balls. The concept is integral to the design of the attrition mill. Power input is used more directly for agitating the media rather than for rotating a large heavy tank and its contents, as in the case with conventional horizontal ball milling.

Optimal fine grinding requires both impact and shearing force. In the mill, the rotation of the horizontal arms directly imparts energy to the grinding media, thus causing the balls to randomly collided with one another. These collisions create the necessary impact forces to break down individual particles in the slurry. In addition to the impact forces of the media, the balls are also spinning in different directions, thereby creating shear forces on the adjacent slurry. The combination of these impact and shearing forces results in efficient size reduction.

In 1946, Dr. Szegvari embarked on further development of attrition milling and particle size reduction technology. Today, after more than 50 years of continual research and development, there are many different types of attrition mills used worldwide in various industries and research laboratories.

In 1991, a continuous grinding attrition mill for lime slaking applications was produced. These mills have been successfully applied to dry FGD systems where a slaked lime product is required.

Building upon that success, an attrition mill for continuous grinding of limestone was introduced in 1996. The mill was specifically designed with increased grinding capability for continuous wet milling of limestone in wet FGD services.

The system has demonstrated efficient processing of limestone from 6mm down to 95% minus 325 mesh on a continual basis. Within the system boundaries are a separation tank, mill circulation pump, mill product tank, hydroclones and hydroclone feed pumps. (Reference Figure 1 & Figure 2)

During wet milling of FGD limestone, both limestone and water are continuously fed from the top of the mill through a specially designed feed housing. This funnel shaped housing has a cylindrical extension, which projects into the grinding vessel of the attrition mill. The shaft of the mill extends down through the housing and the cylindrical extension with the media agitator arms being disposed just beneath the extension. The rotating shaft utilizes several radially projecting, angled impeller blades, which are within the cylindrical extension. When the shaft rotates, these blades create a pumping action, which forces the limestone and water into the grinding media bed.

Generally, attrition mills use media ranging in size from 3mm to 10mm. However, in the wet FGD application, the mill design was altered to incorporate 12.7mm through-hardened carbon steel balls. The specialized mill design allows the 6mm (1/4") feed size of the limestone. Attrition arm tip speed is approximately 270 m/min.

After the limestone and water slurry has passed through the grinding media bed, the ground limestone slurry overflows and discharges from the top of the mill into a separation tank. A low speed mixer is incorporated into the separation tank, which allows the fines to continuously overflow to the mill product tank while coarse limestone particles settle to the bottom. A mill recirculation pump then carries the coarse limestone particles back to the mill to be re-ground.

The power consumption of these high efficiency attrition mills is relatively low. For example, a mill equipped with a 150hp mill motor produced 9.75 metric tons per hour of 95% minus 325 mesh limestone slurry product when fed with 1/4" x 0" stone feed size. This equates to a specific energy based on the mill installed motor power of only 10.4 kWh per short ton of material processed.

Attrition Mill System Layout Options

Basic Layout

The attrition mill, due to its inherent design, will more effectively grind a larger percentage of fine particles, compared to the horizontal ball mill. This finer grind will result in a smaller recirculation load when designing hydroclones for the final classification. The recirculation load is defined as the ratio of feed to the hydroclone to the overflow of the hydroclone. A typical recirculation load for an attrition ball mill processing limestone with a bond work index of 10 and a feed particle size of 1/4" x 0" is between 140 to 150%. The result is smaller hydroclones than for a typical horizontal ball mill system of similar capacity.

There are two basic recirculation loop methodologies for an attrition ball mill.

- Single Recirculation Loop
- Double Recirculation Loop

The single recirculation loop (Figure 1) is typical for attrition mills as well as conventional horizontal ball mills. This layout relies strictly on the hydroclone to perform the classification function. In this layout, the recirculation load can range from 200 to 250%.

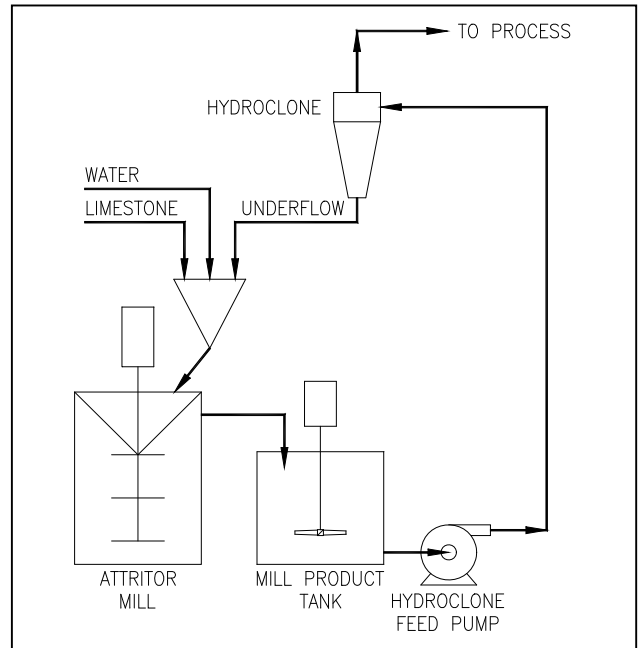


FIGURE 1 Single Recirculation Loop

The double recirculation loop (Figure 2) utilizes a primary recirculation loop to re-grind coarse particles and a secondary recirculation loop for the final classification. In this layout, the recirculation load is in the previously stated range of 140 to 150%.

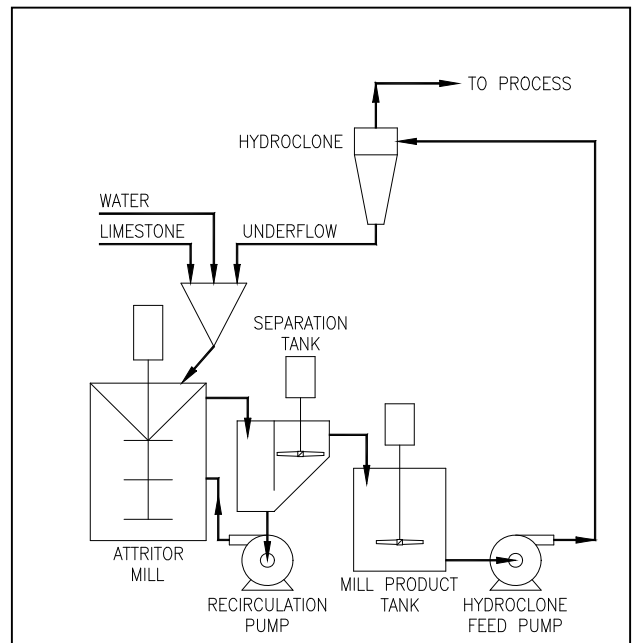


FIGURE 2 Double Recirculation Loop

Overall, the attrition mill system is area and foundation size efficient. In a study performed by Chemco on a wet FGD system, which required two 17.5 ton/hr vertical ball mills versus two attrition mills, the building size and height were reduced. This resulted in substantial savings on the metal building costs as well as the foundations.

Redundancy

Many wet FGD system owners have required 100% redundancy for the limestone grinding system. This is typically achieved by doubling of the equipment, such as feeders, crushers (if incorporated in the design), ball mills, mill product tanks and accessories, such as hydroclone feed pumps and the hydroclone clusters.

Not only does this approach increase the capital expenditures for the process equipment, but it also enlarges the building size and foundations required to house and support the entire 100% redundant limestone grinding system.

An alternate approach to system redundancy is to evaluate the use of multiple mills of a smaller capacity. For example, a 60 tph capacity system could be achieved with the use of four 15 tph capacity attrition mills. One, two or three additional mills could be added to satisfy redundancy needed for the degree of availability sought. In this manner, the mill sizes are reduced to the demonstrated capability range of the attrition mill, thus allowing the significant energy savings possible with attrition grinding technology.

A total system installation can be designed in less floor area and with much less foundation work due to the significantly lower weights and loads of the attrition mill as compared to the horizontal ball mill. This multi-mill redundant system can result in the following advantages:

- Less overall floor space
- Less connected power
- Less operating power costs
- Smaller electrical loads and motor control centers
- Smaller foundations
- Less process equipment costs
- Increased operational flexibility with the capability of bringing mill capacity on line as needed to suit the limestone demand

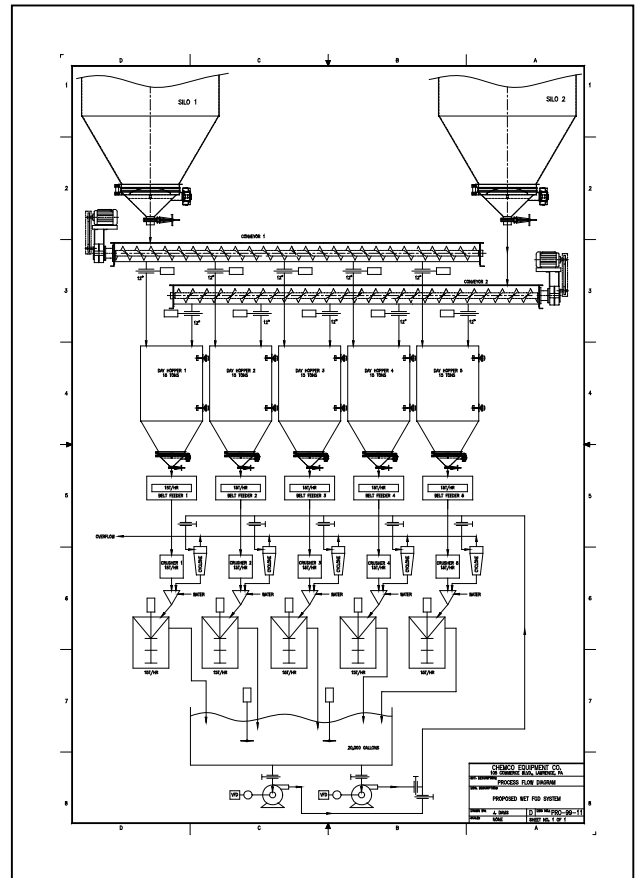


FIGURE 3 Multi-mill Arrangement

Energy Efficiencies

When grinding energy efficiencies are examined over a range of conditions for horizontal ball mill, vertical ball or tower mill, and attrition mill systems, an improved energy efficiency is respectively noted.

When testing for material grindability or mill performance, the 80% passing particle size for the mill system feed (F_{80}) and mill system product (P_{80}) is often used. A typical wet FGD grind requirement is to comminute a $\frac{3}{4}$ " x 0" feed size ($F_{80} \cong 12000$ microns) to a 95% minus 325 mesh ($P_{80} \cong 25$ microns) product slurry at a limestone bond work index of 10 kWh/short ton. In the context of this paper, this is referred to as the "normal grind requirement".

An approximate average system energy efficiency can be determined by dividing the sum of equipment operating brake horsepower by the processing rate.

For the closed circuit wet horizontal ball mill, the majority of the system power is drawn by the main mill motor. Information available from various proposed and actual operating system designs, over a capacity range of 5 to 80 short ton per hour dry limestone processing rate, were evaluated against the normal grind requirement. Design main mill drive brake power requirements averaged around 41 bHP per short ton per hour of dry limestone processed. The secondary power consumers, lubrication systems, tank agitators, and classifier feed pumps, seldom exceed 2 bHP per short ton per hour of dry stone processed. With the additional secondary power consumption, the average wet horizontal closed circuit mill system brake horsepower requirement was estimated at 43 brake horsepower per dry short ton.

When the power consumption is divided by processing rate, an energy dissipated per unit mass of material is given. This is a specific energy value that is indicative of the system grinding energy efficiency.

For horizontal ball mills, when designed or adjusted for the normal grind condition, an average specific energy determined over a range of designs examined is about 32 kWh/dry short ton of limestone processed.

From an energy efficiency standpoint, a general rule in comminution is to crush as fine as you can, then impact as fine as you can, and only then grind. The crushing operation from the ¾" x 0" size to 1/8" x 0" size has a significantly greater energy utilization than the tower mill grinding operation from 1/8" x 0" to the 95 minus 325 mesh product. Since it is easier to fracture a larger particle than a smaller one, the crusher produces far more new surface area per unit of energy than the tower mill does. Crusher power requirements vary, however, many operate in the range of 2-4 kWh/dry short ton.

When continuing the focus on wet grinding, the tower or vertical ball mill system shows improved energy utilization and can typically provide the normal grind requirement at an approximate value of 25 kWh/dry short ton. This includes the crusher power and represents an approximate 20% power savings over the horizontal ball mill installation. The increased grinding efficiencies for tower mills can be explained by the stirred media mill characteristics and the pre-crusher utilized to reduce the ¾" stone to a ¼" to 1/8" range for the tower mill feed.

Attrition mills are showing a further improvement in applied energy requirements. The approximate corresponding applied energy requirement for the attrition mill system, inclusive of all pre-crushing activity, is on the order of 15 kWh/dry short ton. This represents a sizable improvement over the vertical ball mill and a dramatic improvement over the horizontal ball mill. For the most part, an approximate 50% reduction in power consumption is possible when utilizing attrition milling over classical horizontal ball milling at the normal grind condition.

Since the attrition mill is suited towards finer grind capabilities, the option of fine grind performance with energy levels remaining less than that typically achieved with a standard wet FGD ball mill system is possible.

Peripheral System Design

Limestone Storage & Handling

The moisture content of the stone can be controlled somewhat by the upstream handling system design. Covered storage, protecting against direct rainfall, can prove economical if significant drying and/or handling system costs are saved. Purchasing larger "run-of-crusher" stone can reduce the moisture levels in the limestone, as the maximum amount of moisture bulk stone can contain is a function of the fines content. Larger stone sizes with less surface area allow for more natural draining and reduced moisture content. The drawback is the need for an additional pre-crusher. However, pre-crushing operations can improve overall energy efficiency and apply well to the tower mill and attrition mill system designs.

The storage requirements for the ground product can impact the system design capital costs, energy consumption and arrangements.

One cubic foot of limestone slurry at 30% suspended solids weights approximately 77 pounds and contains only 23 pounds of limestone. Whereas, one cubic foot of ¾" x 0" stone weighs about 90 pounds and contains 90 pounds of limestone. This reiterates the knowledge that dry storage is more efficient use of storage volume compared to that with a wet milled product.

A multiple attrition mill system can be more ideally suited to system designs where the limestone is bulk stored on the ground and reclaimed to individual surge bins upstream of each mill. However, incorporation of larger day silos is certainly possible as it is with the typical horizontal ball mill system.

In general, the entire system from limestone unloading to the final milled product should be evaluated to ensure possible synergies are identified and taken advantage of. In this manner, the overall plant storage, processing efficiency and reliability are maximized.

Absorber System Design

Absorber designs can be influenced by mill system performance and operating efficiency. Achieving an equivalent grind with less energy can allow power savings that can be banked or re-allocation elsewhere. Achieving finer grinds at acceptable energy usage can allow tailoring of the grind size to assist in optimization efforts in the wet FGD absorber and dewatering system design.

Wet FGD absorber design often requires the juggling of absorber tank size with limestone dissolution, Ca/S ratio, and gypsum precipitation design factors. Figure 4 provides an indication of how absorber tank size can be influenced by grind size when holding all other factors constant. Taken in isolation, the effect is significant. However, in reality reductions in reaction tank size must be weighed against corresponding influences on the oxidation system design, absorber recirculation pump design, recirculation rates, gypsum precipitation and crystal growth. Yet, even a slight reduction in tank size will translate into capital cost savings. This is especially true if the vessels are constructed of high alloys and/or enclosed in buildings.

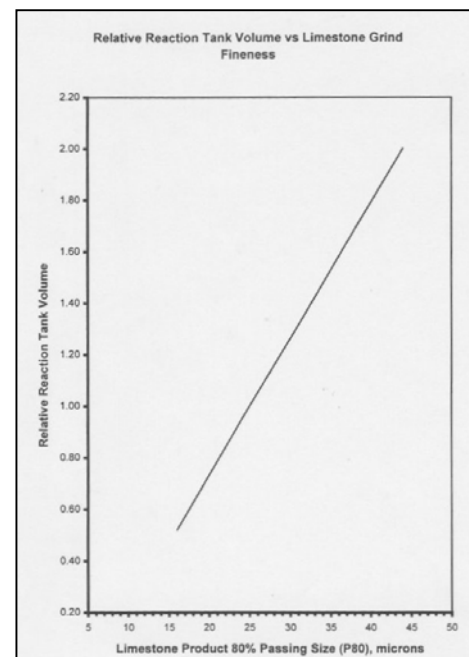


FIGURE 4 Absorber Tank Size vs. Grind Size

With increasing fineness of the limestone grind, classifiers within the dewatering system can more easily produce quality gypsum products while maintaining a higher calcium to sulfur stoichiometric ratio within the absorber loop. This improves absorber performance and/or allows similar performance with reductions in tank size or liquid to gas ratios.

From an evaluated power cost alone, the use of more efficient limestone grinding techniques can provide for significant savings over the life of the plant. Comparing capital and energy costs throughout the FGD system design scope is simplified by placing the values on a common unit basis. Often the quantity per unit of SO₂ removed is used (\$/t, kWh/t, etc.).

A typical ratio of limestone consumption per unit mass of sulfur dioxide removed is approximately 1.8 grams of limestone per gram of SO₂ removed. Using this factor the mill system applied energy in units of kWh per short ton of dry limestone can be corrected to a unit mass of SO₂ removed basis, rather than a unit mass of limestone ground basis.

For example, a mill system operating at 32 kWh per short ton of limestone ground can be converted to an SO₂ removed basis by multiplying by the factor of 1.8.

$$\frac{32 \text{ kWh}}{\text{ton limestone}} \times \frac{1.8 \text{ ton limestone}}{\text{ton SO}_2} = \frac{57.6 \text{ kWh}}{\text{ton SO}_2} \text{ or } 57.6 \text{ kWh/tp SO}_2 \text{ removed}$$

If the project has a power evaluation factor of \$2,500/kW, then the energy costs of the mill system are valued at \$144,000 for each tph of SO₂ removal rate.

Applying this correction, Figure 5 depicts how the mill system design can influence power costs over a range of power evaluation factors.

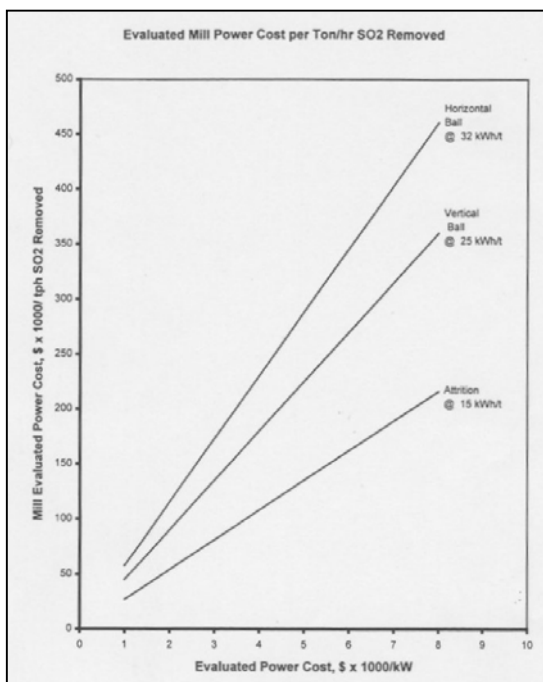


FIGURE 5 Mill System Design vs. Power Costs.

Plots of this type can help in visualizing where and how to optimize the overall plant design capital versus energy costs. The age-old plant design optimization problem.

Summary

While the traditional horizontal ball mill has its place in the industry, alternate mill systems are providing competition. With flexible sparing philosophies, the additional equipment required to feed multiple mill systems can be more than offset by reductions in mill costs and improvements in energy efficiency.

Attrition mills are particularly suited towards this endeavor through their characteristics of compact size and approximate 50% power savings over the traditional horizontal ball mill system. They represent a prime example of how alternate equipment choices can provide for improvements in system design and economics.

In conclusion, when considering non-traditional process equipment, the entire plant site envelope must often be evaluated to ensure maximized gains. With this particular subject, the use of smaller efficient attrition mills can offer space, foundation and energy savings in the reagent preparation area. Furthermore, FGD system design optimization efforts can be enhanced by providing increased flexibility with regard to final grind size.

References

1. P. C. Kapur, T. P. Meloy, "Advances in Size Reduction: Fine and Ultra Fine Grinding". Paper and course work material presented at the Powder & Bulk Solids annual conference, Chicago Illinois, May 6-9, 1991.
2. M. C. Kerr and J. S. Reed, "Comparative Grinding Kinetics and Grinding Energy during Ball Milling and Attrition Milling". American Ceramic Society Bulletin, Volume 71, No. 12, pp 1809-1816, December 1992.
3. A. Szegvari and M. Yang, "Fine Grinding of High-Value-Added Industrial Minerals by Attrition Milling". Paper presented at Les Mineraux Industriels Materiaux des Annees 90, March 9, 1989.
4. A. Szegvari and M. Yang, "Attrition Mill Fine Dry Grinding in Continuous and Batch Modes". Paper presented at the Powder & Bulk Solids annual conference, Chicago Illinois, May 17, 1989.
5. A. L. Just and M. Yang, "Attritor Grinding Mills and New Developments". Paper presented at the Toronto Society for Coatings Technology. Toronto, Ontario, Canada, April 14, 1997.
6. C. Brogren and J. S. Klingspor, "Impact of Limestone Grind Size on WFGD Performance". Paper presented at the EPRI-DOE-EPA Combined Utility Air Pollutant Control Symposium, Washington, DC, August 25-29, 1997.