RDF AS A KILN FUEL

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ABSTRACT

Refuse derived fuel (RDF) has been experimented with and/or proposed for use in kilns for the production of portland cement, lime and expanded shale (a form of lightweight aggregate). Technological issues affecting the use of RDF in kilns are reviewed.

INTRODUCTION

One approach to recovering energy from municipal solid wastes is the production of a refuse derived fuel (RDF). Such fuels can take a variety of forms which have been proposed for use in several types of combustion units, including boilers to raise steam and rotary kilns to produce cement and other construction materials. The types and potential uses of RDF have been reviewed. [1]

As mentioned, one of the potential uses for RDF is as a kiln fuel. Three of the major types of construction materials produced in rotary kilns are portland cement, quicklime and expanded shale (lightweight) aggregate. Each of these requires substantial amounts of energy for production and there is understandable interest among kiln operators in finding new sources of inexpensive fuels. Trial burns of RDF have been conducted in several kilns with promising results.

The purpose of this report is to investigate the potential for the use of RDF as a kiln fuel. The report reviews the results of trials and discusses the major research issues that need to be resolved en route to commercial use of RDF in kilns.

REFUSE DERIVED FUEL

Refuse derived fuel (RDF) is produced by the mechanical processing of municipal solid waste. For use in a kiln, a typical processing scheme for production of RDF might include shredding, screening and air classification of the wastes.

The fuel properties of RDF vary somewhat among plants and processing schemes but in comparison with typical coal properties, refuse derived fuels are generally lower in calorific value and sulfur content but higher in chlorine content. [2-6] The low sulfur content of RDF is a desirable feature because sulfur dioxide emissions from kilns are subject to air pollution regulations and the use of a low sulfur fuel facilitates meeting these regulations. Also, sulfur is considered a contaminant of some products made in kilns (e.g., lime) and kiln operators prefer to minimize the addition of sulfur to their kilns.

In addition to the chemical composition of the RDF itself, the chemical composition of the ash resulting from combustion of RDF is also important. RDF and coal ash are similar in silica (SiO₂) and alumina (Al₂O₃) content. RDF ash is generally lower in sulfur (SO₃) and iron oxide (Fe₂O₃) but higher in the alkaline oxides (Na₂O, K₂O) than coal ash. The importance of alkali content is discussed later in this report as a concern when using RDF in cement kilns.

PORTLAND CEMENT

Portland cement is an inorganic powder which,
when mixed with water and an aggregate, forms the construction material, concrete. On the average, the production of cement* has been reported to require 6.3 million Btu of energy per ton of product (i.e., 7.3 GJ/t cement) [7, 8].

THE CEMENT MAKING PROCESS

The principal chemical elements required as feed for cement making are calcium, silicon, aluminum, and iron [7, 9]. Calcium is supplied as calcium carbonate (CaCO₃) usually in the form of limestone. Silicon and aluminum are usually added either as oxides (e.g., silica sands) or as silicates (e.g., from clays and shales). Iron, as iron oxide, may be introduced as iron ore or, in some cases, steel mill scale [10].

The thermal processing of the mixed raw materials may be viewed in three stages: drying, calcining and clinkering. The first stage, drying, requires temperatures in the neighborhood of 212 F (100 C). The second stage, calcining, is the controlled heating of the mixture in order to dehydrate the materials and to drive off carbon dioxide from the limestone. Calcining temperatures are in the range 1000-1800 F (550-1000 C). Clinkering (sometimes called "burning") is the term for the chemical reactions that convert the raw materials into hardened granular masses (typically up to 1 in. or 25 mm in diameter) of calcium silicates, calcium aluminates and calcium ferrites. The clinkering reactions take place at temperatures in the range of 1800-2700 F (1000-1500 C). The resulting clinker is then air-cooled and ground to a fine powder (90 percent < 200 mesh) for use as portland cement.

*Although there are several types of cement other than portland cement, for the purposes of this report, the terms "cement" and portland cement are used interchangeably.

For most (about 80 percent) cement production in the U.S., all three stages of thermal processing take place in rotary kilns such as those depicted in Fig. 1. The wet or dry mixture of raw materials enters the rotating cylinder at the upper (or back) end of the kiln and proceeds through zones of drying, calcining and clinkering until it reaches the lower (front) end of the kiln where it exits as clinker. Heat for the operation of the kiln is supplied by suspension firing of fuels through burners located at the lower end of the kiln. As indicated in Fig. 1, the flow of the heated gases in the kiln is countercurrent to the flow of the raw materials.

Approximately 80 percent of the energy required for cement production is used in fueling the kiln [11]. Among the fuels used in cement production in 1978, pulverized coal accounted for 63 percent, natural gas for 20 percent, oil for 9 percent, electric power 7.8 percent and other fuels such as petroleum coke for 0.2 percent. In recent years, there has been increasing conversion of cement plants from the use of gas and oil to the use of solid fuels, primarily coal.

There are two features of cement kilns that make them unusual as furnaces for the combustion of coal. First is the fact that much of the ash from combustion of coal becomes incorporated into the clinker. It is a standard practice in the cement industry to adjust the raw material feed to account for the incorporation of coal ash into the clinker [12]. Second is the fact that the kiln itself acts somewhat as a scrubber for sulfur oxides, thus removing some potential pollutants from the exhaust gases. This scrubbing effect is partially present in the calcining zone of the kiln where calcium carbonate is converted to calcium oxide (lime) which can react with the sulfur oxides to form calcium sulfite and sulfate. This scrubbing effect permits the kilns to use relatively high sulfur fuels (reportedly up to 3-4 percent sulfur) without exceeding air...
pollution codes [11]. Generally speaking, high sulfur coal can be purchased at prices below those paid for low sulfur (1 percent or less) fuels.

Despite the incorporation of much of the coal ash and sulfur dioxide into the clinker, the exhaust stream leaving the upper end of the kiln must undergo air cleaning before discharge to the atmosphere. Most modern cement plants employ electrostatic precipitation or baghouses, often with mechanical collection, to remove particulates from the exhaust gases. Most of the particulates (perhaps 90 percent) are fine particles of cement or raw materials rather than particles of fly ash from the fuel [13]. In some cases, the collected dusts are recycled through the kiln but in other instances—for reasons discussed later in this report—the dusts are considered detrimental to the chemistry of the process and are, therefore, discarded as wastes.

PROPERTIES OF CEMENT

The important properties of portland cement can be classed either as physical or chemical. These properties are summarized in Table 1 and are discussed below.

### PROPERTIES OF CEMENT

The important properties of portland cement can be classed either as physical or chemical. These properties are summarized in Table 1 and are discussed below.

#### TABLE 1 SPECIFIED LIMITS FOR SELECTED PHYSICAL AND CHEMICAL PROPERTIES OF CEMENT*

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Specified Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Min. Compressive Strength</strong></td>
<td></td>
</tr>
<tr>
<td>3 day</td>
<td>1800 psi (12.8 MPa)</td>
</tr>
<tr>
<td>7</td>
<td>2600 psi (18.5 MPa)</td>
</tr>
<tr>
<td>28</td>
<td>3800 psi (27.0 MPa)</td>
</tr>
<tr>
<td><strong>Time of Set (Vicat)</strong></td>
<td></td>
</tr>
<tr>
<td>Initial (min.)</td>
<td>0.75 hr.</td>
</tr>
<tr>
<td>Final (max.)</td>
<td>8 hr.</td>
</tr>
<tr>
<td><strong>False set, final penetration (min.)</strong></td>
<td>50%</td>
</tr>
<tr>
<td><strong>Autoclave Expansion (max.)</strong></td>
<td>0.80%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemical Properties</th>
<th>Max. Allowable Weight Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalies</td>
<td>0.6</td>
</tr>
<tr>
<td>Chloride</td>
<td>2.0</td>
</tr>
<tr>
<td>Lead Oxide (PbO)</td>
<td>0.001</td>
</tr>
<tr>
<td>Magnesium Oxide (MgO)</td>
<td>5</td>
</tr>
<tr>
<td>Sulfate (SO₄)</td>
<td>3</td>
</tr>
</tbody>
</table>

*Source: Reference 14.

**PHYSICAL PROPERTIES**

A number of physical parameters are used as indicators of the strength and durability of the cement. The compressive strength of the cement is the most important physical parameter [14]. It is a measure of the force that can be applied to the cement before failure occurs. The time of setting is important because a cement that sets too quickly will stiffen before it can be placed. Air content of concrete up to 5 percent increases resistance to frost and to sulfates and improves the workability of the concrete mix. Higher air content can lead to increased thermal expansion and drying shrinkage of the concrete.

**CHEMICAL PROPERTIES**

Among the chemical requirements for cement, three which merit discussion in this report are sulfur compounds, alkalies (Na₂O, K₂O), and chlorides.

Although the ability of cement kilns to remove sulfur dioxide (SO₂) from exhaust gases permits cement plants to use relatively high sulfur coals, there are limits on the amounts of sulfur which can be acceptably incorporated into the clinker. Excessive sulfate levels in cement have been associated with a condition known as "efflorescence" during service. The incorporation of sulfur compounds into the clinker effectively limits the cement manufacturer's ability to add calcium sulfate (e.g., as gypsum) to control the setting time of the cement product. The formation of deposits (known as "rings") in the middle of the kiln is sometimes attributed to cake inducing salts such as calcium sulfate and/or alkalies [15].

The principal reason for limiting the alkali content of cement is prevention of the so-called "alkali-aggregate" reactions. It has been reported that certain aggregates, especially silicious aggregates such as opal-bearing rocks, chert and quartz, can react with alkalies in cement [16]. The reaction leads to formation of an alkali silicate gel which creates expansive forces within the concrete and has been associated with cracking and failure of concrete sections. In order for the reaction to occur, both a relatively high alkali content in the cement and the presence of sufficiently reactive constituents in the aggregate are necessary [17].

*Efflorescence is the loss of water of hydration from a soluble salt which has migrated to the surface of concrete; efflorescence results in a white coating on the surface of concrete [15].

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Despite this fact, it is common for cement users to specify "low alkali" cement whether reactive aggregates are used or not. ASTM Standard C-150 limits the alkali content of "low alkali" cements to 0.6 percent by weight.

Concern for chloride levels in cements is particularly important for cements to be used with steel reinforcing bars because of the effects of chlorides on the corrosion of steel. Small quantities of chlorides are acceptable in concrete and a chloride level of 2 percent or less in cement is often specified.

**MAJOR RESEARCH ISSUES**

When considering the use of RDF in cement plants, there are several major research issues of interest. These include:

a. Handling properties of the fuel.

b. Ability to control temperature in the kiln (or precalcining furnace).

c. Effect of RDF combustion products on kiln coatings.

d. Effect of RDF combustion products on clinker chemistry.

e. Changes in physical properties of clinker and cement.

f. Effect of using RDF on air emissions.

These issues are discussed in the following paragraphs.

**HANDLING PROPERTIES OF THE RDF**

Refuse derived fuels are different in form and appearance than fuels commonly used in cement plants. RDF's are primarily composed of fibrous materials and are in the form of thin plate-like particles (e.g., shredded newspaper), unlike coal which is primarily crystalline and in the form of spherical (or nearly spherical) particles. Generally speaking, cement kiln fuels are fed pneumatically, hence the need to design the RDF feeding system for pneumatic firing.

The pneumatic firing of RDF is not unique to the use of RDF in kilns. Refuse derived fuels have been pneumatically fed to both suspension and semi-suspension fired boilers [2,3,18-21]. In some cases, RDF has been used as the only boiler fuel but in others, RDF has been cofired with coal.

**ABILITY TO CONTROL TEMPERATURE**

Temperatures in the clinkering zone of a cement kiln are controlled to within ± 100 F (55 C) [22]. The sensitivity of the clinkering reactions to variations in kiln temperature makes temperature control an important requirement for proper kiln operation. Variation in the amount and composition of fuels fed to the kiln can affect temperature and these effects need to be controlled.

**EFFECT ON KILN COATINGS**

Cement kiln operators maintain a coating or layer of deposits along the inside lining of the kiln. The coating layer serves to insulate the shell of the kiln from the high temperatures maintained within. The coating is primarily composed of silicates and is similar in composition to clinker [12]. For proper furnace operation it is important that this coating layer neither be built up excessively nor sloughed off. Although there is no specific feature of RDF which suggests any particular effect on the coating layer, there is a need to establish whether the use of RDF is likely to affect the kiln coating.

**EFFECT OF RDF ON CLINKER CHEMISTRY**

Because of the interaction among fuels and raw materials that takes place within a kiln, the chemical properties of the cement clinker are affected by the chemical composition of the fuel, especially the composition of the ash. As discussed previously, RDF is typically higher in ash and chlorine content but lower in sulfur content than most coals. The elemental composition of RDF ash is quite similar to reported compositions for coal ash, but combustion of RDF produces more ash per unit of energy supplied than does coal. Thus, RDF may contribute a disproportionately high amount of ash to the cement clinker.

Of particular interest are the potential effects of using RDF on the alkali and chloride content of the clinker. Estimates of the alkali contribution from RDF ash can be made based on reported deposition rates for fuel ash in the kiln and on the following assumptions. An average energy consumption of 6 million Btu/ton (6.9 GJ/t) of clinker produced is assumed. A coal with a calorific value of 12,000 Btu/lb (28 MJ/kg) [23] is used as well as a refuse derived fuel with a calorific value of 5500 Btu/lb (13 MJ/kg). Midrange reported values for alkali content (predominantly K2O) of cement-making limestone and clay are 0.12 and 1.4 percent respectively [24]. A typical coal ash has an alkali content of 2.3 percent. Based on the results of
RDF trials conducted at cement plants (without dust recycling), it is estimated that 90 percent of the total available Na₂O and 50 percent of the total available K₂O in the raw materials and fuel is incorporated into the clinker [25].

Given these simplifying assumptions, the alkali content of clinker produced by replacing 30-40 percent of the fuel with RDF, ranges between 0.45 and 0.64 percent as shown in Table 2. Except for the worst case assumptions, it can be seen in Table 2 that alkali levels in the clinker do not exceed the ASTM specification of 0.6 percent. The assumptions made are judged to be conservative, and, indeed, in actual RDF trials, the reported alkali content of the clinker has been consistently lower in alkalis than might be anticipated based on calculations such as those reflected in Table 2. Of course, the actual raw material contribution of alkalis is site specific and, where local clays contain high concentrations of alkali, cements may well exceed the 0.6 percent level — with or without using RDF as a kiln feed.

From the calculation shown above, it can be concluded that the RDF itself (at up to 40 percent of the energy input to the kiln) is not likely to contribute alkalies in excess of specified limits. For cements already approaching or at the alkali limit, however, the use of RDF could theoretically contribute sufficient alkalis to exceed the limit.

In assessing the effects of using RDF on alkali content, it is important to note that there are methods of controlling alkali build-up through modifications in kiln operations. The bypassing of some of the exhaust gas stream, for example, removes some of the entrained fuel ash particles from the kiln and thus lessens the opportunity for ash to become incorporated into the clinker. The discarding of collected cement dusts, which are rich in alkalis, is another approach to reducing the buildup of alkalis.

The relatively high chlorine content of RDF, as compared with most coals, raises concerns for the potential effect of using RDF on chloride levels of the clinker. Sodium and potassium chlorides (NaCl, KCl), either present in the RDF or formed by reactions between the fuel and the clinker can become volatilized at clinkering temperatures and then redeposited in molten form in the lower temperature zones of the kiln. Such deposition would tend to increase the chloride content of the clinker and can also create so called “sticky” conditions within the kiln coating layer. This “sticky” condition can lead to formation of rings within the kiln — an undesirable disruption of kiln operation.

**CHANGES IN PHYSICAL PROPERTIES OF CLINKER OR CEMENT**

Although there is no specific reason to suspect that RDF may adversely affect any of the physical properties of clinker or cement, there are at least two physical properties of research interest. First is the grindability of the clinker. Any decrease in grindability would increase the energy needed to grind the clinker and would, therefore, offset a portion of the energy savings due to the use of RDF. Second is the strength (1 day, 7 day and 28 day strength) of the cement. Strength is an important property of cement and one which cement manufacturers are understandably hesitant to jeopardize.

**TABLE 2 CALCULATED EFFECT OF USING RDF ON ALKALI CONTENT OF CEMENT CLINKER**

<table>
<thead>
<tr>
<th>RDF Properties</th>
<th>Calculated Alkali Content of Clinker</th>
<th>RDF as 30% of Kiln Fuel</th>
<th>RDF as 40% of Kiln Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash Content</td>
<td>Alkali Content of Ash</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15%</td>
<td>6%</td>
<td>0.45%</td>
<td>0.50%</td>
</tr>
<tr>
<td>15%</td>
<td>8%</td>
<td>0.49%</td>
<td>0.54%</td>
</tr>
<tr>
<td>20%</td>
<td>6%</td>
<td>0.49%</td>
<td>0.60%</td>
</tr>
<tr>
<td>20%</td>
<td>8%</td>
<td>0.54%</td>
<td>0.64%</td>
</tr>
</tbody>
</table>

*Note: See text for discussion of the assumptions.*
EFFECT ON AIR EMISSIONS

As mentioned, the ash resulting from combustion of RDF may differ in quantity (per calorific unit) and in composition from the ash resulting from combustion of other fuels. Some of the ash becomes entrained in the air flow through the kiln and is processed through the air pollution control system of the plant. A research concern, therefore, is whether the differences between RDF and other fuels will affect the amount or composition of ash particles either entering the air pollution control equipment or exiting the control system as emissions from the plant.

Reports on the cofiring of RDF with coal as a boiler fuel suggest that there are increases in total particulate emissions when compared with firing coal alone [25]. It should be noted, however, that the actual moment of particulate emissions may be affected more by site-specific features such as furnace operations and efficiency of air pollution control equipment than by fuel mixture. Also, the RDF's that have been used in these reported cofiring trials were relatively high ash fuels. There is a trend in the design and operation of resource recovery plants towards the production of lower ash RDF and this may affect the amount of fly ash resulting from RDF combustion.

TRIALS USING RDF IN CEMENT KILNS

Over the past five years, eight portland cement companies have conducted trials in which RDF was used as a fuel in their rotary kilns. Four of the trials lasted for one week or less and did not result in any published reports [26-30]. Among the conclusions from these trials were that pelletized RDF should not be pulverized with coal in a ball mill (the milled pellets swell and clog the pulverizer; that fluff RDF [particle size less than 2 in. (51 mm)] could be pneumatically fired into a kiln for as long as 72 continuous hours; and that, with RDF supplying up to 30 percent of the energy to the kiln, there were no observed changes either in chemical or physical properties of the clinker or in operating performance of the kilns.

More extensive trials have been — and are continuing to be — conducted at four cement plants, two in the U.S., one in Canada and one in the U.K. These are discussed below.

Blue Circle Group

In the U.K., the Blue Circle Group of the Associated Portland Cement Manufacturers Ltd. has been experimenting with the use of RDF for several years. The Blue Circle Group has patented their process for using RDF in cement kilns but has not published detailed data on the results of their trials [31]. RDF has been used at several of the Blue Circle cement plants and has been reported to produce clinker of satisfactory quality [32, 33, 34]. Experiments at Blue Circle's Westbury plant began in 1974 with trial runs of up to five days. In 1977, the plant contracted with Wiltshire County to receive municipal solid waste on a daily basis. At the cement plant, the refuse is shredded, magnetically separated and pneumatically fed into the coal-fired kiln to provide approximately 14 percent of the kiln's energy requirements. To date, more than 30,000 tons (27,200 t) of RDF have been utilized in this way and no significant buildup of alkali (or other chemical constituent) has been observed.

The RDF produced and used by Blue Circle is generally lower in calorific value and higher in ash (per unit weight) than RDF's produced in the U.S. Consequently, it requires larger quantities of the Blue Circle RDF to supply a given amount of energy to a cement kiln than it would require if a more processed form of RDF were used. This may account for the fact that Blue Circle's practice has been to limit the use of RDF to replacement of 10-20 percent of the primary energy source. The only major problem expressed by Blue Circle has been the need for more reliable shredders — a problem not unique to the use of RDF in kilns.

Canada Cement Lafarge Ltd.

A full year of trials using RDF as 10 to 50 percent of the energy input to a wet process cement kiln is being conducted at a Cement Lafarge plant in Woodstock, Ontario [35]. The kilns at this plant are units fired with coal during the winter (October through March) and natural gas during the summer (April through September). The trials are managed and financially supported by the Ontario Ministry of the Environment.

Refuse derived fuel for the kiln trials is produced at the Toronto resource recovery facility, owned by the Ontario Ministry of the Environment and operated by Browning Ferris Industries. Refuse is shredded to a nominal 6 in. (152 mm) particle size and then air classified. The air-classified lights are then baled and truck hauled to the Woodstock
analyses of raw materials balance, RDF ash quality, and components of the clinker were not significantly conducted in a wet process, gas-fired cement affected (see Table 3), and specified ASTM restrictions on chemical and physical properties of cement were never exceeded.

The 1975 and 1977 trials conducted by BFI RDF for use in these trials was produced in the Gulf Coast Portland Cement plant, it was noted that the dusts collected were coarser than the dusts produced during firing of natural gas alone. Although particulates increased during RDF firing, total particulate emissions remained within federal standards for cement kilns \( [93-94 \text{ lb/hr}] (12.2-12.6 \text{ kg/h}) \). During the emissions testing at the Gulf Coast plant, it was noted that the dusts collected by the electrostatic precipitator during RDF firing were coarser than the dusts produced during firing of natural gas alone.

The Gulf Coast/BFI trials have been suspended since 1977, but are scheduled to be continued in 1980, again with the support of the U.S. DOE [36]. Since the last series of trials, the Gulf Coast plant has made the conversion from gas to coal as their primary kiln fuel. One objective of the scheduled trials will be to determine whether the problems experienced when RDF was used as 40 percent of the kiln fuel were related to the use of RDF or were simply the result of defective temperature controls within the kiln. The new series of trials will also enable comparisons between using RDF in coal-fired and gas-fired kilns.
<table>
<thead>
<tr>
<th>Chemical Properties</th>
<th>Trial Results</th>
<th>ASTM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% RDF</td>
<td>20% RDF</td>
</tr>
<tr>
<td>Alkalies (%)</td>
<td>0.04</td>
<td>0.47</td>
</tr>
<tr>
<td>Chloride (%)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Lead Oxide (%)</td>
<td>negligible</td>
<td>0.01</td>
</tr>
<tr>
<td>Magnesium Oxide (%)</td>
<td>0.74</td>
<td>0.99</td>
</tr>
<tr>
<td>Sulfate (SO₃) (%)</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Free Lime (%)</td>
<td>0.9</td>
<td>n.r.*</td>
</tr>
</tbody>
</table>

* n.d. = not detected
n.r. = not reported

Physical Properties

<table>
<thead>
<tr>
<th>Min. Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>28</td>
</tr>
</tbody>
</table>

Time of Set (Vicat)

| Initial (min., hrs.) | 3.0  | 2.7  | 1.2  | 1.8  |
| Final (max., hrs.)   | 4.8  | 4.0  | 3.3  | 2.8  |

False set, final penetration (min. %) 73 70 76 72 50

C-185 Air Content, Hydraulic Cement Mortar, (max. %) 6.1 6.5 7.0 7.6 12

Autoclave Expansion (max. %) 0.011 0.078 0.187 0.250 0.8

^ n.d. = not detected
n.r. = not reported

Note: Conversion factor = psi x 6.895 = kPa
Lehigh Portland Cement Co.

A series of trials using RDF in a dry process, coal-fired cement kiln began in November, 1979 at the Lehigh Portland Cement Co. plant in Union Bridge, Maryland [37]. The trials were managed by Teledyne National, who also supplied the fuel. Financial support for the trials was from the U. S. Environmental Protection Agency and the Maryland Environmental Service.

The RDF for the trials was produced at the Baltimore County (Md.) resource recovery plant at which refuse is shredded, magnetically separated and the nonmagnetics are air classified. For the cement plant trials, the air classified light fraction was screened in a trommel to recover a 1½ x ½ in. (38 x 13 mm) fraction which was re-shredded to a nominal 1 - ½ in. (25 - 13 mm) size then transported to the cement plant in compactor trucks. At the cement plant, the RDF was refluffed using rotating lump breakers and fed through an air lock into a 9 in. (229 mm) pneumatic duct leading to the front end of the kiln. Air pressure in the duct was ½ - 1 psi (5.3 kPa - 7.1 kPa) and the duct entered the kiln directly below the coal feed pipe. The trial was designed to be a full month of continuous use of RDF. The objective was to use RDF as up to 40 percent of the energy input of the kiln. During the trials, cement chemistry and physical properties were monitored by the Lehigh Co. and by the Portland Cement Association; air pollution monitoring was performed by an EPA contractor. The trial was in progress during the writing of this paper and the results were therefore not available.

LIME

Lime is a chemical used for a variety of applications including steel manufacturing, water and wastewater treatment, chemicals production, and paper manufacturing [38, 39].

BASIC PROCESS

The major step in lime production is calcination, which is the controlled heating of carbonate rock to drive off volatile components including carbon dioxide (CO₂) [38]. For lime production, a source of calcium carbonate, either limestone or shell, is fed into a furnace or kiln and heated to 1800-2400 F (480-1300 C) so that calcination can occur [40]. The kiln product, quicklime, can be converted to hydrated lime by adding enough moisture to satisfy the affinity of quicklime for water. The hydrated lime product is a dry, fine powder.

Several types of furnaces or kiln systems are used to produce lime. Approximately 85 percent of the commercial lime produced in the U. S. is made in rotary kilns. Although a variety of fuels can be fired in a rotary lime kiln, the trend here, as in other industries, is to convert from natural gas to coal. The energy consumed in producing lime in a rotary kiln is approximately 7 million Btu/ton (8.1 GJ/t) of lime [8].

The quality and commercial value of quicklime is affected by the amount of impurities present. Chemical specifications differ among the potential uses of lime but, generally speaking, precautions are taken to limit the incorporation of fuel ash into the product and to avoid use of limestone high in silica, alumina or iron oxide. These limestone contaminants may result in the formation of undesirable cementitious products such as calcium silicates, aluminates, and ferrites. Such products may contaminate the lime and/or cause the coating layer within the kiln to build up excessively, resulting in disruption of kiln operation. Impurities such as phosphorous and sulfur may also be present in small quantities in limestone.

The single largest consumer of lime in the U. S. is the steel industry. Most of this lime is used as a flux to purify steel in basic oxygen furnaces (BOF). Any silica, alumina, sulfur, and phosphorous that are originally present in the lime are undesirable and the lime must meet tight chemical specifications to be used for steel-making.

MAJOR RESEARCH ISSUES

When considering the use of RDF in lime plants, there are two major research issues of interest. These are:

a. Effect of RDF combustion products on kiln coating layer.

b. Effect of RDF ash on the chemical composition of the lime product.

COATING LAYER

The coating layer within a lime kiln differs in thickness and chemical composition from that in a cement kiln. Typically, lime kiln coatings are ¼ in. (13 mm) thick while cement kiln coatings are up to 12 in. (305 mm) thick. Lime kiln coatings are primarily calcium oxide while cement kiln coatings
are composed primarily of silicates [41]. The differences in kiln coatings may affect the acceptability of RDF for use in the kiln. As discussed earlier, about 50 percent of the ash from RDF (and also from coal) is silica which, at kiln temperatures, reacts with other components of the fuel and feedstock to form silicates. Such silicates are not undesirable in cement kilns because they are chemically compatible with both the clinker and the coatings. Conversely, the incorporation of silicates into the lime kiln coatings (or into the lime itself) is not desirable because the lime kiln coatings are low in silicates and the incorporation of silicates could lead to the formation of rings in the kiln.

A critical factor in determining the effect of using RDF on the coating layer of a lime kiln is the behavior of RDF ash within the kiln. The ash from RDF has been reported to soften at temperatures below flame temperatures in a lime kiln and also below the softening point of the ash from many coals [2, 5]. Thus, at least within the flame itself, it is probable that RDF ash will be in a softened, if not molten, state. As the ash particles leave the flame zone and proceed towards the back end of the kiln, they are cooled. Although the ash particles tend to be carried along in the gas flow through the kiln, the particles may impact the coating layer at some point in the kiln. If the ash particles are in a softened or molten state when they impact, they are likely to be retained on the coating layer, thus potentially affecting the chemistry and thickness of the coating [42]. If the buildup of ash particles occurs in a localized region of the kiln, rings of deposits may be formed which disrupt kiln operations. It is conceivable that such a ring might form near the hottest area of the kiln, i.e., where there is the shortest distance between the flame and the kiln wall and where the ash is most likely to be molten. This phenomenon could be especially pronounced in newer kilns with narrower kiln diameters and hence more confined heat release zones than some older kilns [43]. Although effects such as deposition of softened RDF ash particles can be hypothesized or speculated upon, there is at present no reported information on actual behavior of RDF ash in a lime kiln (there have been no RDF trials in lime kilns), nor has there been an analysis of the likelihood for RDF ash particles to be softened or melted on contact with kiln coatings.

**EFFECT OF RDF ON LIME QUALITY**

The value of lime is affected by its chemical purity. Some lime plants use only gas or oil as fuels, rather than coal, to minimize the addition of undesirable chemicals (e.g., sulfur, silica). Of particular interest in coal-fired kilns are the effects of increased ash content attributable to the use of a solid fuel. The use of RDF, another solid fuel, would also raise concerns about the effects of ash on the lime making process and product. On a calorific (rather than weight percent) basis, RDF contains more silica, alumina, and iron oxide but less sulfur than coal. The levels of these substances must be minimized for most applications of lime. Investigations are needed to quantify the extent to which ash (either coal or RDF) becomes incorporated into the lime product.

Table 4 presents a simplified analysis of the calculated effects of RDF ash on the silica and metal oxide (Al₂O₃ and Fe₂O₃) contents of lime. The calculations are based on several assumptions described in the following paragraph.

The energy required to produce a ton of lime is approximately 7 million Btu (8.1 GJ/t). Coal and RDF are assumed to have calorific values of 12,000 Btu/lb (28 MJ/kg) and 5500 Btu/lb (13 MJ/kg) respectively. Ash content of coal is assumed to be 10 percent by weight. Although quantities vary with the type of limestone, about 1.7 ton (1.5 t) of limestone are needed to produce 1 ton (0.9 t) of lime [24]. RDF is assumed to provide 30 percent of the energy input to the kiln. Approximately 15 percent of the coal ash and 25 percent of the RDF ash are assumed not to be entrained in the flue dust, and may therefore be incorporated into the lime [41]. The silica content of the coal ash is 55 percent, a typical midrange value, and the silica content of the RDF ash is 50 percent. A typical value for the silica content of limestone is 0.5 percent [24]. Typically, coal ash is 22 percent Al₂O₃ and 14 percent Fe₂O₃.

### TABLE 4 CALCULATED SILICA AND METAL OXIDE (Al₂O₃ PLUS Fe₂O₃) CONTENTS OF LIME WHEN USING RDF AS A KILN FUEL

<table>
<thead>
<tr>
<th>RDF Ash Content (% by weight)</th>
<th>Silica Content (% by weight)</th>
<th>Metal Oxide Content (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.27</td>
<td>0.67</td>
</tr>
<tr>
<td>15</td>
<td>1.38</td>
<td>0.72</td>
</tr>
<tr>
<td>20</td>
<td>1.50</td>
<td>0.76</td>
</tr>
</tbody>
</table>

*See text for discussion of assumptions*
A typical RDF ash might contain 10 percent Al₂O₃ and 4 percent Fe₂O₃ [2, 3, 6].

The use of lime in the manufacture of steel requires that silica (SiO₂) in the lime not exceed 1.5 percent by weight. Other uses of lime do not require such stringent limitations on the silica content. As seen in Table 4, the 1.5 percent limit on silica in lime is reached but not exceeded under the given assumptions.

A reasonable restrictive upper bound on the metal oxide content of lime is the 1 percent (by weight) limit imposed for use in the manufacture of calcium carbide [44]. The calculations reflected in Table 4 suggest that the metal oxides contribution from RDF and coal ash would not, by themselves be expected to cause failure of the lime to meet the 1 percent upper limit.

Table 4 suggests that, when RDF is used as 30 percent or less of the kiln fuel, limits on the silica and metal oxide content of lime can be met. In those cases where the lime product already approaches contaminant limits (due to limestone impurities, for example), the use of RDF could theoretically contribute sufficient impurities to cause the product lime to exceed the limits. The same could also be said of coal ash.

EXPANDED SHALE (LIGHTWEIGHT AGGREGATE)

Lightweight aggregates include a variety of natural (e.g., vermiculite) and manufactured (e.g., expanded shale) mineral and rock materials that, when mixed with cement, are used to form lightweight concrete building blocks and other products. As their name implies, lightweight aggregates are lower in density than sand, gravel, and other mineral aggregates commonly used in construction. “Expanded shale” is a name frequently used to describe shale, clay, and slate processed in a kiln for use as a lightweight aggregate [45]. More than half of the total lightweight aggregate used in the U.S. is expanded shale, most of which is used in construction block [46, 47].

BASIC PROCESS

In the U.S., most of the production of expanded shale aggregate is accomplished by the controlled heating of crushed shale, clay or slate in a rotary kiln. In the first section of the kiln, temperatures are maintained in the range 1200-1800°F (650-980°C) so that the material becomes softened and a viscous airtight seal is formed over voids within the clay or shale [46]. Towards the exit end of the kiln (the front end), temperatures rise to 2200°F (1200°C) or so. At these elevated temperatures, heat penetrates the material and gases are generated from certain carbon and sulfur compounds. The escape of these gases, as well as water vapor, is blocked by the airtight coating and “bloating” occurs. As a rule of thumb, the material expands to approximately twice its volume during the bloating process. Before shipment, the material is crushed and graded to a specified size range.

Within the kiln, temperatures and flame length must be maintained in a rather narrow range so as to insure bloating but to prevent fusion of the clay particles. Fusion of the particles leads to formation of large clinkers or rings which disrupt kiln operation and must be removed. As an indication of the importance of temperature control in expanded shale plants, one plant operator reports maintaining the kiln within 10°F of 2100°F (1150°C ± 5.5°C) [48].

The kiln is the major consumer of energy in the expanded shale industry. An average of 2.9 million Btu’s (3.1 GJ) is required to produce 1 ton (0.9 t) of expanded shale. As with other industries, expanded shale manufacturers are accelerating the conversion to coal from natural gas and oil. As of 1977, 51 percent of the industry used coal and 42 percent used gas. Oil and waste oil accounted for about 4 percent of the energy consumed.

MAJOR RESEARCH ISSUES

When considering the use of RDF in expanded shale plants, the major issue is the effect of RDF on the ability to closely control kiln temperature. Expanded shale kilns may well be more sensitive to variations in kiln temperatures than either cement kilns or lime kilns. For successful use of a fuel, such as RDF, that varies in moisture content and calorific value, strict monitoring of kiln temperature and control over fuel feed rates would be required.

Generally speaking, the characteristics of the expanded shale itself are not significantly affected by the incorporation of fuel ash into the product. In part, this is because much of the ash is either entrained in the flue dust or screened out of the product during cooling.

EXPANDED SHALE TRIALS

To date, the only trials in which RDF has been
used in an expanded shale kiln took place at the Lehigh Portland Cement Company's plant in Woodsboro, Maryland [48]. The trials were arranged by Teledyne National.

The first trials were conducted in February and March of 1977 in a coal-fired kiln. Shredded, air-classified light fraction was shipped to the expanded shale plant where it was to be reshredded and fired pneumatically into the kiln. Shredder operation at the expanded shale plant was a limiting factor, however, as breakdowns, fires, and maintenance problems kept the system from sustained continuous firing of RDF. During the times that RDF was fired into the kiln, minor problems keeping the flame at a proper length occurred, but there were no problems with product quality or ring formation. RDF supplied 30 percent of the energy for the kiln.

A second series of test runs was conducted in 1978. For this series of trials, secondary shredding of RDF was performed at the resource recovery plant and the RDF was shipped to the expanded shale plant. The RDF was fed through an air lock into a pneumatic duct leading to the kiln. Air pressure within the pneumatic duct was reportedly too high with the result that the flame became too long. Attempts were made to dampen the air flow but the flame continued to be too long which increased the length of the "bloating" zone — an undesirable effect. The final product was judged satisfactory in quality, however, despite the feeding and flame length problems.

OVERALL REVIEW AND CONCLUSIONS

There is no question that the cement, lime and aggregate industries employ energy intensive processes and are in search of cheaper fuels. Much has been learned about the potential for the use of RDF as a kiln fuel through the various trials and other research efforts discussed above. Despite the apparent needs of the industry and despite the trials, however, there are no kilns in the U. S. using RDF on a regular basis. The reasons for the failure of RDF to be adopted as a kiln fuel differ among the construction material industries but two general reasons can be given. They are: (a) the limited availability of RDF at reasonable distances from operating kilns; and (b) the need for research and/or demonstrations to establish kiln operator confidence in the use of RDF.

Table 5 presents a summary of the size of the potential market for RDF in cement, lime and expanded shale kilns. The size of the market depends on the number, location and fuel consumption of the kilns in which RDF may be used. As reflected in Table 5, the cement and lime industries offer larger potential markets for use of RDF than the expanded shale industry. There are 157 cement plants, 32 of which are located within 50 miles (80 km) of a major U. S. urban area. On the average and assuming RDF is used as 30 percent of the energy input to the kiln, a cement plant could consume 164 tons/day (149 t/d) (seven day week) of RDF; a lime plant 190 tons (172 t). By contrast, there are only 34 expanded shale plants in the U. S., seven near urban areas. A typical expanded shale plant (say 1000 tons/day (900 t/d) of aggregate) could consume no more than 50 tons/day (45 t/d) of RDF, again assuming 30 percent replacement of the normal kiln fuel.

Table 5 reflects the fact that kilns may provide a large potential market for the future use of RDF. The results of the trials which are now underway together with additional research/demonstration projects (e.g., an RDF trial in a lime kiln) should provide an answer to whether this market potential can be realized.

ACKNOWLEDGMENTS

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In preparing this report, a number of persons (researchers, kiln operators, etc.) were consulted and many of these contacts are referenced within the report. The assistance provided by these people has been greatly appreciated.

REFERENCES

TABLE 5  POTENTIAL CONSUMPTION OF RDF/DAY

Assume: 30% substitution of fuel source by RDF
12,000 Btu/lb (27.9 MJ/kg) coal
5500 Btu/lb (12.8 MJ/kg) RDF
plants operate 300 days/yr

Cement Plants - Assume energy consumption of 6 million Btu/ton
(7 GJ/t) product

<table>
<thead>
<tr>
<th>Capacity  tons/day</th>
<th>No. of Plants</th>
<th>Approx. RDF requirement tons/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1350</td>
<td>43</td>
<td>&lt;210</td>
</tr>
<tr>
<td>1350-2300</td>
<td>65</td>
<td>210-380</td>
</tr>
<tr>
<td>2300-3300</td>
<td>29</td>
<td>380-540</td>
</tr>
<tr>
<td>&gt;3300</td>
<td>20</td>
<td>&gt;540</td>
</tr>
</tbody>
</table>

Lime Plants - Assume energy consumption of 7 million Btu/ton
(8.1 GJ/t) product

<table>
<thead>
<tr>
<th>Capacity  tons/day</th>
<th>No. of Plants</th>
<th>Approx. RDF requirement tons/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;510</td>
<td>104</td>
<td>&lt;100</td>
</tr>
<tr>
<td>510-970</td>
<td>26</td>
<td>100-185</td>
</tr>
<tr>
<td>970-2200</td>
<td>26</td>
<td>185-400</td>
</tr>
<tr>
<td>&gt;2200</td>
<td>8</td>
<td>&gt;400</td>
</tr>
</tbody>
</table>

Expanded Shale Plants - Assume energy consumption of 2.9 million Btu/ton (3.4 GJ/t) product. Total number of plants is 28.

<table>
<thead>
<tr>
<th>Capacity  tons/day</th>
<th>Approx. RDF requirement tons/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>170-340</td>
<td>13-27</td>
</tr>
<tr>
<td>340-670</td>
<td>27-55</td>
</tr>
<tr>
<td>670-1700</td>
<td>55-135</td>
</tr>
</tbody>
</table>

Note: Conversion factor – tons/day X 0.9 = t/d


[46] Lightweight Concrete, Bethesda, Maryland, Expanded Shale Clay and Slate Institute, 1971.


Key Words
Plant — Industrial
Refuse Derived Fuel
Rotary Kiln