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DOE/CS/20167-04

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The Use of RDF as a Kiln Fuel

Final Report
October 1980

MASTER

Prepared for:

U.S. Department of Energy

Assistant Secretary for Conservation and Solar Energy

Office of Buildings and Community Systems

Washington D.C. 20585

Under Contract No. AC01-76CS20167

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5285 Port Royal Road
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Price:	Printed Copy:	\$10.00
	Microfiche:	\$4.00

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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 as are the results of trials in which RDF has been used as a kiln fuel. Three future research/demonstration projects for addressing the major unresolved issues are discussed. These projects are: a lime plant trial; a trial in a pre-calcining furnace; and an extended trial in a cement kiln.

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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. Among the forms are: shredded and/or air classified RDF (sometimes called "fluff RDF"); pulverized RDF (e.g., a proprietary fuel trade-marked Eco-Fuel II); and densified, refuse derived fuel (d-RDF). Combustion units for which RDF, in some form, has been proposed for use include: 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. The report concludes with a discussion of three future research/demonstration projects that would address the major unresolved issues and hence speed the commercialization of RDF as a kiln fuel.

In preparing this report, the NCRR has gathered information from many sources. These have included the published literature, operators and managers of several kilns, representatives of trade organizations from the construction materials industry and researchers who have been involved in previous investigations of the use of RDF as a kiln fuel.

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 (see Figure 1) might include shredding, screening and air classification of the wastes. The air classified light fraction consisting primarily of shredded organic materials (e.g., paper, corrugated cardboard, plastics) would be the RDF.

The fuel properties of RDF vary somewhat among plants and processing schemes but two examples of RDF properties are provided by the fuels produced at the St. Louis Demonstration Plant and the Ames, Iowa resource recovery plant.^{2, 3} Properties of the St. Louis and Ames RDF's are shown in Table 1 along with a reported range of properties for bituminous coals.^{4, 5} In reviewing the properties of the St. Louis and Ames RDF's, it is important to note that the design and operation of these two plants were directed towards maximizing the yield of RDF (per input ton on refuse) more so than towards minimizing the ash content of the fuel. RDF produced by processing schemes different from those used in St. Louis and Ames (e.g., the New Orleans fuel fraction also shown in Table 1) may differ in ash content - and other properties - from the St. Louis and Ames fuels.*

* Note: One reason for the relatively low ash content of the New Orleans fuel fraction is the fact that, in the New Orleans plant, raw refuse is processed through a trommel screen before shredding and air classification.⁶ The effect of the trommel screen is to permit separation of glass bottles (and other materials less than 4 3/4 in. in size) from the refuse before the refuse is shredded. The shredding of glass is known to produce fine
(cont. on p. 6)

Figure 1: Simplified Processing Scheme
for Production of RDF

Table 1: Reported Properties of RDF and Coal

	RDF (Ames, Iowa)	RDF (St. Louis, Mo.)	RDF (New Orleans, La.)	Coal (Wyoming, Sub- Bituminous)	Coal (Bituminous- range of reported values)
<u>Properties</u> (as received)					
Calorific value (Btu/lb)	5500	4400	5365	7780	10,000 - 13,500
Moisture	23%	27%	25%	7%	1 - 6%
Fixed Carbon	5%	-	-	30%	45 - 65%
Sulfur	0.43%	0.14%	<0.1	0.4%	0.4 - 6%
Chlorine	0.24%	0.33%	0.26%	-	0.05 - 0.5%
Ash	17%	19%	10%	25%	4 - 20%
<u>Ash Analysis</u>					
SiO ₂	48%	56%	55%	55%	37 - 60%
Al ₂ O ₃	12%	9%	10%	19%	12 - 30%
Fe ₂ O ₃	4%	5%	2%	4%	4 - 29%
MgO	2%	2%	1%	2%	0.6 - 4.0%
Na ₂ O	4%	8%	2%	0.4%	0.2 - 0.8%
K ₂ O	2%	2%	1%	1.8%	0.2 - 1.9%
SO ₃	-	1.5%	1.3%	3.2%	1.4 - 8.9%
Reference No.	3	2	7	4	5

In comparison with the coal properties shown in Table 1, refuse-derived fuels are lower in calorific value and sulfur content but higher in chlorine content. 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 the kilns.

In addition to the chemical composition of the RDF itself, it is also important to review the chemical composition of the ash resulting from combustion of RDF. Table 1 includes a listing of reported mean concentrations of major chemical components in RDF and coal ash (following the usual practice of reporting cations as their oxides). As seen in the Table, RDF and coal ash are similar in silica (SiO_2) and alumina (Al_2O_3) content. RDF ash is generally lower in sulfur (SO_3) and iron oxide (Fe_2O_3) but higher in the alkaline oxides (Na_2O , K_2O) than coal ash. The importance of alkali content is discussed later in this report as a concern when using RDF in cement kilns.

particles, many of which become incorporated into the "light" fraction during air classification thus contributing to the ash content of an air classified RDF. Experience to date in New Orleans suggests that the separation of glass before shredding is effective in reducing the ash content of the shredded material.⁷

Portland Cement

Portland cement is an inorganic powder which, when mixed with water and an aggregate, forms the construction material, concrete. Portland cement is prepared by mixing together calcium, silica, alumina and iron oxide-bearing raw materials and then heating these at elevated temperatures (2400° - 2800°F ; 1300° - 1500°C) to produce hard granular masses known as "clinker."⁸ After the clinker is finely ground (and perhaps some gypsum is added), the resulting product is known as portland cement - or simply as "cement."^{*} 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/Mg cement).⁹

There are a total of 157 cement plants in the U. S., geographically distributed as shown in Figure 2.¹⁰ Total annual cement production in the U. S. is reported to be 67 million tons.⁹ Forty-two percent of this production occurs in the five states of California, Pennsylvania, Texas, Michigan, and Missouri. The remaining production capacity is scattered throughout another 35 states. Table 2 presents a summary of the proximity of cement plants to major population centers (cities of greater than 400,000 people - 1970 census). As shown, there are at least 26 cement plants located within 25 miles of a major urban area. At least 23 of these "urban"

^{*} 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.

ANNUAL PRACTICAL CAPACITY

- UNDER 100,000 TONS
- 100,000 TO 200,000 TONS
- 200,000 TO 400,000 TONS
- OVER 400,000 TONS

SOURCE
ECONOMIC AND MARKET RESEARCH DEPARTMENT
PORTLAND CEMENT ASSOCIATION
5420 OLD ORCHARD ROAD
SIOUX FALLS, S.D. 57108

SCALE
0 50 100 150 200 250 300
MILES

∞

Table 2: Locations and Capacity of Cement
Plants Near Urban Centers*

Plants within
10 miles

Plants within
25 miles

Plants within
50 miles

Phoenix, Ariz.

Phoenix Cement Co.
Phoenix, Ariz.
(1300-2300)

San Jose, Calif.

Kaiser Corp.
Permanente, Calif.
(>3300)

Lone Star Industries
Davenport, Calif.
(<1300)

Los Angeles, Calif.

General Port. Cem.
Colton Calif.
(1300-2300)

Amcord
Riverside, Calif.
(2300-3300)

San Francisco, Calif.

Kaiser Corp.
Permanente, Calif.
(>3300)

Lone Star Industries
Davenport, Calif.
(<1300)

Denver, Colo.

Martin Marietta Co.
Lyons, Colo.
(1300-2300)

*Note: Plants are listed in alphabetical order by state.
Urban centers are defined here as municipalities with
at least 400,000 population.
Approximate plant capacity in tons per day of cement are
shown in parentheses. Source of data is the Portland
Cement Association.

Plants within
10 miles

Plants within
25 miles

Plants within
50 miles

Chicago, Ill.

Universal Atlas
Gary, Ind.
(1300-2300)

Kansas City, Kan.-
Kansas City, Mo.

Lone Star Industries
Kansas City, Kan.
(1300-2300)

Missouri Port. Cem. Co.
Independence, Mo.
(1300-2300)

New Orleans, La.

Lone Star Industries
New Orleans, La.
(1300-2300)

Louisiana Cement
New Orleans, La.
(1300-2300)

Baltimore, Md.

Alpha Portland Cement
Limekiln, Md.
(1300-2300)

Lehigh Portland Cement
Union Bridge, Md.
(2300-3300)

Detroit, Mich.

Peerless Cement Co.
Detroit, Mich.
(2300-3300)

Wyandotte Cement, Inc.
Wyandotte, Mich.
(1300-2300)

Plants within
10 miles

Plants within
25 miles

Plants within
50 miles

St. Louis, Mo.

Alpha Port. Cement Co.
St. Louis, Mo.
(<1300)

Missouri Port. Cem. Co.
St. Louis, Mo.
(2300-3300)

Toledo, Ohio

Dundee Cement Co.
Dundee, Mich.
(2300-3300)

Cincinnati, Ohio

Southwestern Port. Cem.
Fairborn, Oh.
(2300-3300)

Nashville, Tenn.

Marquette Cem. Man. Co.
Nashville, Tenn.
(<1300)

Dallas-Ft. Worth, Tex.

General Portland
Dallas, Tex.
(2300-3300)

Dallas-Ft. Worth, Tex.

Gifford-Hill Port. Cem.
Co.; Midlothian, Tex.
(2300-3300)

Texas Industries
Dallas, Tex.
(>3300)

Houston, Tex.

Gulf Coast Port. Cem.
Co.; Houston, Tex.
(1300-2300)

Ideal Basic Industries
Houston, Tex.
(1300-2300)

Lone Star
Houston, Tex.
(1300-2300)

Plants within
10 miles

Plants within
25 miles

Plants within
50 miles

San Antonio, Tex.

Capitol Aggregates,
Inc.; San Antonio,
Tex.
(<1300)

Kaiser Cem. & Gyp.
Corp.; Longhorn, Tex.
(1300-2300)

San Antonio Port. Cem.
San Antonio, Tex:
(1300-2300)

Seattle, Wash.

Ideal Basic Industries
Seattle, Wash.
(2300-3300)

Lone Star Industries
Seattle, Wash.
(1300-2300)

Milwaukee, Wisc.

Universal Atlas
Milwaukee, Wisc.
(<1300)

plants have annual production capacities in excess of 300,000 tons of cement.

The Cement Making Process

The principal chemical elements required as feed for cement making are calcium, silicon, aluminum, and iron.⁸ Calcium is supplied as calcium carbonate (CaCO_3) 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.

For a typical U. S. cement plant, the raw materials limestone, clay and iron ore are ground to a fine powder (75% < 200 mesh) in a ball mill and are mixed together in approximately the proportions 4 : 1 : .07. The crushing and mixing may either be performed dry as in the so-called "dry process" or as a slurry (30 - 40% water) as in the "wet process." For several years, the wet process has been preferred by U. S. cement manufacturers because of its advantages in control of blending and ease of grinding.⁸ Recently, however, there has been increased conversion to improved forms of dry processing primarily because of the lower energy requirements of the dry process (5.5 million Btu/ton (6.3 GJ/kg) for the dry process as compared with 6.5 million Btu/ton (7.5 GJ/kg) for the wet).^{11, 12}

Figure 3: Simplified Drawing of a Wet Process Cement Kiln

Source: Reference 12

The thermal processing of the mixed raw materials may be viewed in three stages: drying, calcining and clinkering. The first stage, drying, applies primarily to the wet process and requires temperatures in the neighborhood of 212°F (100°C). The second and third stages, calcining and clinkering apply to both the wet and dry process. Calcining is the controlled heating of the mixture in order to dehydrate the materials and to drive off carbon dioxide from the limestone.⁸ Calcining temperatures are in the range 1000° to 1800°F (550° to 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 inch or 25 mm in diameter) of calcium silicates, calcium aluminates and calcium ferrites. The clinkering reactions take place at temperatures in the range 1800° to 2700°F (1000° to 1500°C). The resulting clinker is then air-cooled and ground to a fine powder (90% < 200 mesh) for use as portland cement. Often, gypsum (i.e., calcium sulfate, CaSO_4) is added to the clinker during grinding in order to retard the setting time of the cement.¹³ Gypsum has the effect of lengthening the setting time and cements often contain 5% to 6% gypsum.

For most (about 80%) cement production in the U. S., all three stages of thermal processing take place in rotary kilns such as those depicted in Figure 3. 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

(only for the wet process), calcining and clinkering until it reaches the lower (front) end of the kiln where it exists 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 Figure 3, the flow of the heated gases in the kiln is countercurrent to the flow of the raw materials. Rotary kilns for cement making range in size from 8 to 25 feet (2.4 to 7.6 m) in diameter and from 200 to 600 feet (60 to 183 m) in length and are inclined at approximately $3/8 - 1/2$ inch/ft (1.2 - 1.6 cm/m).¹⁰

Approximately 80% of the energy required for cement production is used in fueling the kiln.¹² Among the fuels used in cement production in 1978, pulverized coal accounted for 63%, natural gas for 20%, oil for 9%, electric power 7.8% and other fuels such as petroleum coke for 0.2%.⁹ 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. To illustrate, the use of coal in cement plants has increased from 36% to 57% over the period 1973 to 1978.

For coal-fired cement plants, the coal is first pulverized (usually in a ball or ring mill) and then blown into the lower end of the kiln where it ignites. Heated air drawn from the clinker coolers is often used as the primary combustion air that conveys the coal and/or as the secondary combustion air injected into the kiln. Fuel and air adjustments are made so as to maintain proper temperatures and flame length within the kiln.

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.^{8, 13} 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 or 4 percent sulfur) without exceeding air pollution codes.¹² 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. As much as 125 tons of particulates may be collected during the production of 1000 tons of cement clinker.¹⁴ Most of these particulates (perhaps 90%) are fine particles of cement

or raw materials rather than particles of fly ash from the fuel. 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.

In the interest of energy conservation and the opportunity to use lower-priced fuels, several U. S. and European cement manufacturers have begun modifying their plants. Other than shifting towards the use of the dry process, most of these modifications involve some separation of the three thermal processing phases carried out in a conventional rotary kiln. Such modifications include the use of preheaters (either suspension or grate-type) and the use of so-called "precalciners" to carry out drying and calcination of the raw materials before the mixture enters the rotary kiln. The rationale for performing the three thermal processing stages in separate furnaces is that each furnace can be designed and operated for a specific use and the rotary kiln can then be used for clinkering alone.

Suspension preheaters are designed to raise the temperature of the raw material mix to 1450°F (790°C) in a series of vertical stages (usually four stages) of cyclonic chambers. Preheaters of this type have been reported to dehydrate the mix and to accomplish 50% of calcination.¹² The thermal energy for these reactions is supplied by the exit gases from the rotary kiln.

Grate preheater systems serve essentially the same function as suspension preheaters with the exception that grate systems usually accomplish a lower degree of calcination than suspension systems. Figure 4 is a drawing of one type of grate preheating system. Raw materials are fed to the grate system (sometimes called the semi-dry process) in pelletized form at a moisture content of 10 to 22%. Drying and partial calcination take place on the grate utilizing hot exit gases from the kiln.

Precalcining furnaces are designed to accept feed from a preheater and to calcine the feed before it enters the kiln. An example of a precalcining furnace (with suspension preheating) is shown in Figure 5. As much as 95% of calcination can take place in precalciners. Temperatures in the precalcining furnace are in the range 1650° to 1800°F (900° to 1000°C).^{15, 16} Unlike most preheating systems, precalcining furnaces utilize their own fuel. It has been estimated that as much as 50 to 60% of total fuel used to produce a ton of clinker may be consumed in a precalciner.¹¹ Exit gases from the precalciner are used in the preheating system.

The incorporation of preheating and/or precalcining systems into the cement making process frees the rotary kiln for use as a clinkering furnace only. In practice this has increased the throughput rate for kilns and/or permitted the use of shorter kilns. U. S. experience in the use of precalciners is somewhat limited (e.g., there are only 2 precalcining

Figure 4: Grate Preheater Kiln System

Figure 5: Precalciner Kiln System

systems in operation at U. S. plants) but the use of preheaters has been adopted at a significant number of cement plants. As of 1978, approximately 20% of total U. S. cement plant capacity is from kilns equipped with preheaters.¹¹

Experience in Europe and elsewhere suggests that the use of a combination preheating/precalcining system can reduce total fuel consumption per ton of clinker by 20 to 35%.^{12, 15-17}

Precalciners facilitate the use of low grade fuels in cement plants. This is both because of the temperatures at which the precalcining furnaces are operated and because of the placement of the precalciner at the back (upper) end of the kiln. Precalcining temperatures are maintained in a range below the temperatures maintained in the clinkering kiln. Also, precalcining furnaces are not as sensitive to temperature variations as are clinkering kilns. The consequence of the less demanding temperature requirements of the precalciner is that the fuel used in the precalciner need not meet the same quality specifications as fuels used in the rotary (clinkering) kilns.

The introduction of fuel in advance of the kiln (as in a precalcining system) reduces the risk of the fuel ash adversely affecting the chemical composition of the clinker. Ash components from fuels can, as mentioned previously, become incorporated into the cement clinker, thus affecting the chemistry of the cement. Often these effects are predictable and can be compensated by adjustments in the raw material

mix. The predictability of the effect, however, depends on the predictability of the composition of the fuel.

Ash components from fuels used in the precalciner are less likely to become incorporated into the clinker than are the ash components from fuels used in the clinkering kiln.¹⁶ There are two reasons for this. First, the lower temperature of the calcining furnace tends to keep fly ash particles in solid form, thus reducing the chance for softened or molten ash to adhere to the raw material mix. The solid ash particles are more likely to stay entrained in the combustion gas stream and thus exit the precalciner. Second, there is less contact time between combustion products and raw materials when a fuel is used in a precalciner than when the fuel is introduced at the front (lower) end of the kiln. Because of the counter current flow of combustion gases and raw materials through a cement plant, any ash (or gaseous combustion product) from the kiln fuel must pass through the entire process flow in order to exit the kiln. Combustion products from fuels introduced in the precalciner, however, need only pass through the precalciner and preheater. In some cement plants, the flow of exhaust gases is shortcircuited so as to bypass one or more of the upstream furnaces. Such bypassing reduces the risk of contaminating the raw materials with undesirable combustion products but at a loss of energy.

Properties of Cement

The important properties of portland cement can be classed either as physical or chemical. These properties are summarized in Table 3 and are discussed below.

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.⁸ It is a measure of the force that can be applied to the cement before failure occurs. ASTM Standard C-150 for Type I portland cement requires a minimum compressive strength of 1800 psi (12.4 M Pa) after three days, 2800 psi (19.3 M Pa) after seven days, and 4000 psi (27.6 M Pa) after 28 days.¹⁸

The time of setting is also an important factor in cement quality. A cement that sets too quickly will stiffen before it can be placed. ASTM C-150 (again, for Type I cement) specifies that the initial set time should not be less than 45 minutes and that the final set time not exceed 8 hours. Set time is determined by the Vicat needle test, which measures the penetration of a steel needle into a specimen of cement.¹⁹ When the needle does not sink into the test specimen, the final setting time is established.

The air content of concrete is an important factor in the cement's resistance to environmental factors. An air content of up to 6% increases resistance to frost and to

Table 3: Specified Limits for Selected Chemical and Physical Properties of Cement*

<u>Chemical Properties</u>	<u>Max. Allowable Weight Percent</u>
Alkalies	0.6
Chloride	2.0
Lead Oxide (PbO)	0.001
Magnesium Oxide (MgO)	5
Sulfate (SO ₃)	3

<u>Physical Properties</u>	<u>Specified Limit</u>
Min. Compressive Strength	
3 day	1800 psi
7	2600 psi
28	3800 psi
Time of Set (Vicat)	
Initial (min.)	0.75 hr.
Final (max.)	8 hr.
False set, final penetration (min.)	50%
Autoclave Expansion (max.)	0.80%

*Source: Reference 18.

sulfates^{8, 13} and improves the workability of the concrete mix. Higher air content can lead to increased thermal expansion and drying shrinkage of the concrete. ASTM Standard C-150 specifies an upper air content limit of 12% for a test specimen of mortar made from cement. The standard also specifies a maximum percentage of expansion of 0.08 in the autoclave expansion test; such expansion is caused by the hydration of CaO or MgO.

Cooled cement clinker usually has a greenish-black color. The rate of cooling can affect clinker color since it determines which crystalline substances are formed. Oxidation during cooling or high crystalline iron compounds can give clinker a brownish-yellow color. Overburning, i.e., burning beyond the point of clinkering, can result in iron undergoing several reduction and oxidation reactions.¹³ This can result in a clinker with a black surface and a yellow core. The presence of certain materials, such as manganese and magnesium oxides, can impart color changes in clinker.

Chemical Properties

Among the chemical requirements for cement listed in Table 3, two which merit discussion in this report are sulfur compounds and alkalies (Na_2O , K_2O).

Although the ability of cement kilns to remove sulfur dioxide (SO_2) 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. ASTM Standard C-150 sets an upper limit of 3 to 3.5% sulfate in cement, depending on the level of tricalcium aluminate in 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.²⁰

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.²¹ 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.²² Despite this fact, it is common for cement users to specify "low alkali" cement whether or not reactive aggregates are

* 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.^{13, 20}

used. ASTM Standard C-150 limits the alkali content of "low alkali" cements to 0.6% by weight.

Control of alkali content can be accomplished in several ways. In some geographical areas, the use of low alkali clays and shales is economical. Alkalies introduced with the raw materials tend to concentrate in the dusts produced in the kiln.^{2, 3} After these dusts are collected in the air pollution control equipment, they are often discarded, rather than recycled, in order to limit the buildup of alkalies in the clinker.¹⁴ There are, of course, energy and raw materials losses that result from discarding the dusts but manufacturers must weigh these losses against the risks of exceeding the 0.6% alkali limit in the cement.

In addition to the chemical composition limits specified in ASTM Standard C-150 (and listed in Table 3), there is also a concern for chloride levels in cements. This 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% or less in cement is specified in ASTM C-150.

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 pre-calcining 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.

The differences in physical properties between coal and RDF suggest the need for modifying existing coal-fired kilns in order to accept RDF. To date, the nature of these modifications has not been fully defined but the principal need is to identify types of equipment and operating practices that will enable RDF to be stored, metered and fed to the kiln. 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, 24-28} In some cases, RDF has been used as the only boiler fuel but in others, RDF has been co-fired with coal.

Ability to Control Temperature

Temperatures in the clinkering zone of a cement kiln are controlled to within $\pm 100^{\circ}\text{F}$ (55°C).²⁴ 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. Thus an important question concerning the use of RDF in cement kilns is whether the fuel will adversely affect temperature control. A similar question can be raised concerning the use of RDF in a precalcining furnace but, in a precalciner, the operating temperature range is usually broader than in a kiln.

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.¹³ 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 coatings.

Effect of RDF on Clinker Chemistry

Because of the interaction between 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/Mg) of clinker produced is assumed.⁹ A coal with a calorific value of 12,000 Btu/lb (28 MJ/kg)²⁹ is used as well as a refuse derived fuel with a calorific value of 5500 Btu/lb (13 MJ/kg). Mid-range reported values for alkali content (predominantly K_2O) of cement-making

limestone and clay are 0.12% and 1.4% respectively.³⁰ A typical coal ash has an alkali content of 2.3%.

Based on trials conducted by Browning-Ferris Industries (BFI) on the use of RDF in cement kilns, it is estimated that 90% of the total available Na_2O and 50% of the total available K_2O in the raw materials and fuel is incorporated into the clinker.³¹ The calculated effects of RDF ash on clinker quality assume no recycling of dusts.

Given these simplifying assumptions, the alkali content of clinker produced by replacing 30% - 40% of the fuel with RDF, ranges between 0.45 and 0.64% as shown in Table 4. Except for the worst case assumptions, it can be seen in the Table that alkali levels in the clinker do not exceed the ASTM specification of 0.6%. The assumptions made are judged to be conservative, and, indeed, the BFI trials produced clinker that was consistently lower in alkalies than might be anticipated based on calculations such as those reflected in Table 4. Of course, the actual raw material contribution of alkalies is site specific and, where local clays contain high concentrations of alkali, cements may well exceed the 0.6% 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% 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

Table 4: Calculated Effect of Using RDF on Alkali Content of Cement Clinker

<u>RDF Properties</u>		<u>Calculated Alkali Content of Clinker</u>	
Ash Content	Alkali Content of Ash	RDF as 30% of Kiln Fuel	RDF as 40% of Kiln Fuel
15%	6%	0.45%	0.50%
15%	8%	0.49%	0.54%
20%	6%	0.49%	0.60%
20%	8%	0.54%	0.64%

Assumptions: *

1. 6 million Btu/ton of clinker produced
2. 12,000 Btu/lb coal; 5500 Btu/lb RDF
3. Ratio of raw materials used to clinker produced is 1:5
4. Alkali content of limestone = .12%; clay = 1.4%
5. 10% ash coal; alkali content of coal ash = 2.3%
6. 90% of the total available Na_2O is incorporated into the clinker
7. 50% of the total available K_2O is incorporated into the clinker
8. No dust recycling

* Note: See text for further discussion of the assumptions.

alkali limit, however, the use of RDF could theoretically contribute sufficient alkalies 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 alkalies, is another approach to reducing the buildup of alkalies. The use of RDF in a precalciner lowers the maximum temperature to which fly ash particles are exposed and thus lessens the probability of ash incorporation into the clinker.

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 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. Thus it is important to investigate whether RDF affects the strength of cement.

Effect of Using RDF in 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 co-firing of RDF with coal as a boiler fuel suggest that there are increases in total particulate loadings (uncontrolled), controlled emissions of total particulates and emissions of lead compounds when compared with firing coal alone.³² It should be noted that the actual amount of particulate emissions was 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 were used in these reported co-firing trials were higher in total ash content than, for example, the fuel fraction recovered at the New Orleans resource recovery plant. Generally speaking 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 flyash resulting from RDF combustion. Stack sampling tests conducted at the Gulf Coast Portland Cement Co. plant (see later discussion) revealed increased particulate emissions (although emissions remained within Federal standards) when RDF was substituted for natural gas in a gas-fired kiln.³³ This is not surprising because natural gas is a very low ash fuel and the co-firing of any solid fuel with natural gas would be expected to increase particulate loadings in the exhaust gas stream.

For the co-firing of coal and RDF in a cement kiln, the effect of RDF on air emissions would depend on the ash content and composition of the RDF, the ash deposition rate within

the kiln and the efficiency of the air cleaning system. As suggested in Table 1, there is enough variability in the ash content and composition of both RDF's and coals that the effect of firing RDF in a coal-fired kiln may well be site specific. That is, the use of a relatively low ash RDF in a kiln fired with a relatively high ash coal may produce no detectable change in air emissions. On the other hand, if the usual kiln fuel is relatively low in ash, an increase in particulate loadings may result from co-firing RDF.

Trials Using RDF in Cement Kilns

Over the past five years, several portland cement plants have conducted trials in which RDF was used as a fuel in their rotary kilns. A summarized list of these trials is presented in Table 5. Discussions of each of these trials follow; the trials are identified by the name of the cement company involved.

Blue Circle Group

The Blue Circle Group of the Associated Portland Cement Manufacturers Ltd. (United Kingdom) 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.³⁴ RDF has been used at several of the Blue Circle cement plants and has been reported to produce clinker of satisfactory quality.^{35, 36}

Table 5: Portland Cement Kiln Trials

<u>Principals (Location)</u>	<u>Date(s)</u>	<u>Comments</u>	<u>Contact</u>
Blue Circle Group Associated Portland Cement Manufacturers, Ltd., United Kingdom			Dr. C. A. C. Haley, Deputy General Manager & Manager, Overseas Project, Commercial Development Division, Blue Circle Industries, Aspdin House, Crete Hall Rd., Northfleet, Kent, DA11 9AA, England
(Westbury, U. K.)	1974	6% RDF & 94% coal successfully used in short trials	
(Westbury, U. K.)	1977	700,000 tpy wet process cement plant uses 14% RDF & 86% coal in daily production. Accept- able clinker quality for over 1 year.	
(Shoreham, U. K.)	1976	8% RDF and 92% coal successfully burned in 5 month full scale trial. Preparations underway to burn 20%-30% RDF and 80%-70% coal in wet process kiln. Plant will eventually use 66,000 tpy in the manufacture of 330,000 tpy of cement.	

<u>Principals (Location)</u>	<u>Date(s)</u>	<u>Comments</u>
(Plymstock, U. K.)	1977	Successful clinker produced in short term trials using dry process kiln with preheater.
(Plymstock, U. K.)	1978	Short term & long term tests planned to burn RDF in preheater duct to kiln.

General Conclusions of Blue Circle Trial

1. Crude refuse must be pulverized to less than 2 in. (50mm) in size to ensure complete burnout.
2. RDF lends itself well to being blown in pneumatically through the kiln hood in the burning zone.
3. Control of primary fuel and raw materials can compensate for variations in RDF.
4. Although lead, zinc, copper, phosphate, and arsenic levels in clinker increased, cement quality not substantially influenced by RDF use.

<u>Principals (Location)</u>	<u>Date(s)</u>	<u>Comments</u>	<u>Contact</u>
Cement Lafarge (Woodstock, Ontario); Ontario Ministry of the Environment, Canada	1979	1 year series of trials to begin in 1979; wet process kilns fired with coal or gas; RDF to be used up to 50%.	Peter Provias, Ontario Center for Resource Recovery, 4375 Chesswood Dr., Toronto, Ontario, M3J 2C2, Canada 416-636-8015.
Gulf Coast Portland Cement Co., (Houston Texas); Browning Ferris Industries; U.S. Dept. of Energy	1977 (ongoing)	Shredded, air classified refuse successfully fed into wet process, gas-fired kiln at 5-8 tph. Acceptable clinker quality using 20% & 30% RDF. Problems of underburning occurring at 40% RDF with consequent decrease in cement strength. Increased particulate emissions but within EPA standards.	James R. Jones, Manager, Systems Engineering BFI, POB 3151, Houston, Texas 77001 713-790-1611
Hercules Cement Co., (Stockertown, Pa.); Vista Chemical & Fiber Products Co., Los Gatos, California	1975	Coal and shredded RDF pellets (5,000 Btu/lb) fed together into kiln successfully. Up to 10% RDF used. No significant increases in alkalies, chlorides, or free lime content of clinker.	Roger Wall, Plant Engineer, Hercules Cement Co., Stockertown, Pa. 18083 215-759-6300
Lehigh Portland Cement Co., (Union Bridge, Md.); Teledyne National, U.S. EPA	1979	1 month trial to begin in Sept. 1979; dry process, coal-fired kiln; RDF to be fired around the clock as 10-40% of energy input.	Carl Weinberger, Teledyne National, 117 Church Lane, Cockeysville, Md. 21030 301-667-4840

<u>Principals (Location)</u>	<u>Date(s)</u>	<u>Comments</u>	<u>Contact</u>
Penn-Dixie Cement Co., (Nazareth, Pa.); Castle Recycling Corp.; National Resource Recovery Corp.	1974	Different mechanisms for feeding coal & fluff RDF (7,000 Btu/lb) experimented with. The two were best fed separately into the kiln. Used 20% RDF for 24 hr. trial. Complete chemical and physical testing demonstrated that clinker was of satisfactory quality.	Harold Mackenzie, National Resource Recovery Corp., POB 1026, Wheaton, Ill. 60187 312-668-2700
Riverside Cement Co., (Crestmore, Calif.); Vista Chemical & Fiber Products Co.	1974	Riverside fed fluff RDF (5600 Btu/lb) through their own coal feeding system with some problems. RDF was successfully used to replace up to 20% of natural gas fuel. In trials using up to 40% RDF, feeding and temperature maintenance problems were experienced.	Charles Bush, V.P. of Operations, Riverside Cement Co., 1500 Rubidoux Blvd., Riverside, Calif. 714-683-3660.
Southwestern Portland Cement Co., (Fairborn, Ohio); Black Clawson Co.	1974	A 24 hr. trial using pulped RDF from Franklin, Ohio was conducted at Southwestern's Fairborn, Ohio plant. The RDF had a moisture content of 40% and calorific content of 4500 Btu/lb. Incomplete fuel burnout in the kiln was noted but overall clinker chemistry was satisfactory.	Jack Dorn, Southwestern Portland Cement Co., Victorville, Calif. 714-245-1681

<u>Principals (Location)</u>	<u>Date(s)</u>	<u>Comments</u>	<u>Contact</u>
Southwestern Portland Cement Co., (Fairborn, Ohio)	1975	Trials were conducted to evaluate the use of a Raymond Mill coal pulverizer to prepare coal & RDF pellets for feeding into a cement kiln. Results were not entirely satisfactory due to feeding problems and incomplete fuel burn-out in the kiln. No data on clinker quality is available.	Jack Dorn (see above for complete address)

Experiments at Blue Circle's Westbury plant began in 1974 with trial runs of up to five days. The Westbury cement plant produces approximately 660,000 tons per year of cement in a wet process kiln. For the trials, RDF fluff (<2 inch nominal particle size) with an average heat value of 4000 Btu/lb (9.3 MJ/kg) provided up to 6% of the total energy input to the kiln. Average RDF usage was 3 1/2 tons per hour. Coal supplied the remaining energy requirements. Clinker quality proved to be quite satisfactory but no details of clinker chemistry have been reported.

In 1977, the plant contracted with Wiltshire County to receive municipal solid waste on a daily basis. Local sanitation authorities were to deliver up to 88,000 tons per year of MSW to the Blue Circle plant and were to pay Blue Circle a tipping fee. At the cement plant, the refuse is shredded, magnetically separated and pneumatically fed into the coal-fired kiln to provide approximately 14% of the kiln's energy requirements (see Figure 6 for a simplified flow diagram of this system). To date, more than 30,000 tons of RDF have been utilized in this way.

Over a one year period of operation at Westbury, clinker quality has been reported to be satisfactory.³⁷ There is no dust recycling at the Westbury plant and no significant alkali buildup has been observed in the clinker. Generally speaking, alkali-aggregate reactions are more of a concern in the U. S. than in the U. K. owing to the presence of more

reactive aggregates in the U. S. Blue Circle hopes to improve the properties of the RDF produced at Westbury through the use of a trommel prior to the shredder and also, perhaps, by shredding to a finer size.

Blue Circle's Shoreham plant produces approximately 330,000 tons per year of clinker in two wet process, coal-fired, kilns. Successful trials were conducted in 1976 using RDF as approximately 12% of the energy input to the kiln. At present, the Shoreham plant uses RDF on a daily basis. Shredded refuse is delivered to the plant five days each week. A mobile solid waste recovery plant on the premises then magnetically separates the refuse and reshreds the material to a nominal 2 inch size at a rate of 16 tons per hour. The refuse is pneumatically fed into the kiln. Figure 6 includes a simplified flow diagram for this system.

Blue Circle's Plymstock plant began using RDF in trial runs in 1977. Plymstock's dry process, oil-fired kilns are equipped with preheaters. The trial runs have been reported to be successful. Continuous runs burning RDF in the preheater duct to the kiln were to have taken place toward the end of 1978. Reports on the results of these tests are not yet available.

The continued testing and use of RDF at Blue Circle's plants is evidence of their confidence in this process. None of their plants report any problems with physical or chemical qualities of the clinker produced. The RDF produced by Blue

Fig. 6: Processing Scheme for Preparation and Use of RDF in Cement Kilns

Blue Circle Group (U.K.) Trial

A) Westbury Plant

B) Shoreham Plant

Circle is generally lower in calorific value and higher in ash (per unit weight) than RDF's produced in the U. S.³⁵ 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% to 20% of the primary energy source. Higher replacement levels have been used in U. S. kilns but not on a continuous basis. 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% of the energy input to a wet process cement kiln will be conducted at a Cement Lafarge plant in Woodstock, Ontario.³⁸ The kilns at this plant are wet process 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 (see Figure 7 for a simplified flow diagram of the process flow for producing and using the RDF in this trial).

Fig. 7: Processing Scheme for Preparation and Use of RDF in Cement Kilns

Cement Lafarge Ltd. (Woodstock, Ont.) Trial

Refuse is shredded to a nominal 6 inch particle size and then air classified. The air-classified lights are then baled and truck hauled to the Woodstock plant. At the cement plant, the bales are broken (using a spike-roll device) and the RDF is then re-shredded to a nominal 3 inch size in a modified knife mill (Shred-Pak). The re-shredded fuel is then dropped through an air lock into a pneumatic duct through which the RDF is fed into the kiln.

During the one year test period, RDF will be used as 10 to 50% of the kiln fuel and will be co-fired with both coal and natural gas. Stack emissions will be monitored as will kiln operations, clinker chemistry and cement properties.

Gulf Coast Portland Cement Company

Browning Ferris Industries, Inc. (BFI) under a contract with the U. S. Department of Energy (DOE), has been investigating the "Co-firing of RDF and Natural Gas in a Cement Kiln."²⁷ Trials were conducted at the Gulf Coast Portland Cement Co. near Houston, Texas in 1975 and 1977.

RDF for use in these trials was produced by BFI at a resource recovery plant in Houston, Texas. Figure 8 is a simplified flow diagram for the processing employed during these trials. At the recovery plant, mixed municipal refuse was first shredded to a nominal 3 to 4 inch size, then magnetic metals were removed and the non-magnetic fraction air classified in a rotary drum air classifier. The light fraction was a

Fig. 8: Processing Scheme for Preparation and Use of RDF in Cement Kilns

Gulf Coast Portland Cement Company. (Houston, Tex.) Trial

fluff-type RDF which represented 50% to 75% (by weight) of the raw refuse. RDF moisture content ranged from 20% to 25%, and bulk density was approximately 5 pounds per cubic foot. The calorific value of the fluff was determined to be approximately 5,000 Btu/lb (11.6 MJ/kg). A typical ash content was 16%.

At the Gulf Coast Portland Cement plant, RDF was pneumatically fed into the kiln using the same feeding system used for firing a utility boiler in the EPA-sponsored St. Louis Resource Recovery Demonstration Project. In this system, conveyors elevated and deposited RDF into a surge hopper that fed a metering bin conveyor. A scalping roll leveled and metered a specified volume of RDF onto the metering conveyor. The RDF then fell from this conveyor to a rotary feeder where a fluffing roll impacted the material to break up any clumps. The fluffed material was then pulled through an air lock and entered the pneumatic duct through which the RDF was fed into the kiln. The gas burner pipe was at the center of the kiln. The RDF firing nozzle was located about two feet from the gas burner pipe and at about 330 degrees (i.e., an "11:00 o'clock" position) from the top of the kiln.

Feed rates in the range of 5 to 8 tons per hour were typical. At these rates, the system worked satisfactorily. Feeder plugging by large pieces of cloth or paper periodically occurred at feed rates approaching 10 tons per hour.

The 1975 and 1977 trials conducted by BFI were conducted in a wet process, gas-fired cement kiln at the Gulf Coast plant. A short test (8 hours) was conducted in 1975 using RDF as 14% to 18% of the energy input to the kiln. The results of the brief 1975 trials were satisfactory enough to permit the longer series of trials in 1977. For the 1977 trials, RDF was used as 20%, 30% and 40% of the kiln fuel feed. Detailed analyses of raw materials balance, RDF ash quality, and clinker quality were made.

At the 20% and 30% substitution levels, results were reported to be satisfactory. Significant increases of the chemical components in the clinker were seldom found (see Table 6), and specified ASTM restrictions on chemical and physical properties of cement were never exceeded. The alkali level in the clinker was approximately 0.45%, within the 0.6% ASTM specification. In a few cases significant increases in the alkali level occurred, but the levels were always below ASTM limits. Alumina and iron oxide levels were also within the ASTM specifications. Other chemical components of the clinker such as chlorides, heavy metals, and sulfates, showed no increase in concentration when RDF was used as up to 30% of the energy input to the kiln.

X-ray diffraction patterns and petrographic examinations performed on the clinker confirmed that no significant differences between "RDF cement" and regular cement existed. Strength of RDF cement is similar to cement made with 100% natural gas

Table 6: Comparison of Specified Limits with Results
of Gulf Coast Cement Co. Trials

<u>Chemical Properties</u>	<u>Trial Results</u>				<u>ASTM</u>
	<u>0% RDF</u>	<u>20% RDF</u>	<u>30% RDF</u>	<u>40% RDF</u>	<u>Specified Limits</u>
Alkalies (%)	0.04	0.47	0.45	0.11	0.6
Chloride (%)	0.01	0.01	0.01	0.01	2.0
Lead Oxide (%)	negligible	0.01	n.d.*	n.d.*	0.001
Magnesium Oxide (%)	0.74	0.99	0.64	0.78	5.0
Sulfate (SO ₃) (%)	0.03	0.03	0.03	0.03	3.0
Free Lime (%)	0.09	-	-	2.2	-
* n.d. = not detected					
<u>Physical Properties</u>					
Min. Compressive Strength (psi)					
1 day	1120	910	1370	1175	-
3	2800	2780	2900	2060	1800
7	4090	4200	4310	3475	2600
14	-	5150	5360	-	-
28	6125	6460	6700	5515	3800
Time of Set (Vicat)					
Initial (min., hrs.)	3.0	2.7	1.2	1.8	0.75
Final (max., hrs.)	4.8	4.0	3.3	2.8	8.0
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

(see Table 6). In a number of cases, RDF cement was superior in compressive strength (a phenomenon also reported by the Blue Circle Group in their trials). Other physical test data such as air content and autoclave expansion were influenced by the use of RDF but not significantly. It is somewhat puzzling, given the higher sulfur content of RDF over natural gas, that cement made with RDF consistently exhibited shorter set times. In the Gulf Coast trials, the setting time was adjusted by adding gypsum to the cooled, crushed clinker - a normal practice in cement manufacturing.

The trials in which RDF was used as 40% of the kiln fuel yielded inconclusive results. Problems of underburning occurred as exhibited by excessive free lime levels in the clinker (see Table 6). It was difficult to maintain adequate kiln temperatures during the 40% RDF trials. In part this was due to a malfunction in the temperature recording device which occurred during this set of trials. It is not certain whether the underburning of the clinker or the inability to control temperature was influenced by the use of RDF.

With the exception of free lime, the chemical analyses of the clinker produced using RDF as 40% of the kiln fuel were acceptable. Alkali levels did not exceed 0.48% (see Table 6). Aluminum and iron oxides were within ASTM specifications. Levels of other chemical components such as chlorides, heavy metals, and sulfates showed no appreciable increase.

There was essentially no difference among the chemical compo-

sitions of the cements produced using RDF as 20, 30 or 40% of the kiln fuel. Overall, the use of RDF seemed to have had a minor effect on clinker chemical composition.

X-ray and petrographic analyses of the clinker (using RDF as 40% of the fuel) confirmed the existence of underburning, and subsequent testing revealed that cement compressive strength had suffered. The compressive strength of the cement at 3, 7, and 28 days was below that of cement made with natural gas alone. The clinker did meet ASTM specifications for air content and autoclave expansion. Again, set time was shorter than for regular cement.

Stack sampling tests revealed increased levels of controlled particulate emissions when RDF replaced a portion of the natural gas. When RDF was used as 20, 30 and 40% of kiln fuel input, particulate emissions increased by 25, 20 and 50% respectively as compared with emissions during firing of natural gas alone. Although particulates increased during RDF firing, total particulate emissions remained within federal standards for cement kilns (93-94 lbs/hr - EPA's New Source Performance Standard). 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 later this year (1979), again with the support of the U. S. DOE.³⁹ 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% 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.

Hercules Cement Co.

A five day trial using RDF in a coal-fired, dry process, kiln was conducted in April, 1975 at the Hercules Cement Company in Stockertown, Pa.⁴⁰ Refuse derived fuel for the trial was supplied by a pilot plant operated by the Vista Chemical and Fiber Products Company of Los Gatos, California. Municipal refuse received at Vista's pilot plant went through primary shredding and magnetic separation. (See Figure 9 for a diagram of the process flow). Secondary shredding, further magnetic separation, and tertiary shredding followed. The refuse was air classified and the light fraction was pelletized and shipped to Stockertown. A California Pellet Mill produced the pelletized RDF that had a bulk density of approximately 35 pounds per cubic foot and a reported calorific value of approximately 6,000 Btu/lb (14 MJ/kg). At first, the RDF pellets were fed with coal directly into a coal pulverizer (a ball mill) but swelling of the milled pellets caused

Fig. 9: Processing Scheme for Preparation and Use of RDF in Cement Kilns

clogging of the pulverizer. As an alternative to ball milling the pellets directly, the pellets were first shredded in a hammermill then mixed with coal and fed to the air swept ball mill. The air stream exiting the ball mill then contained a mixture of pulverized coal and fluff RDF which was fed to the kiln, reportedly without major problems.

Up to 10% of the kiln fuel was replaced by RDF and clinker quality was reported to be satisfactory. Hercules Cement Company concluded that no significant increases in any chemical parameter were found in clinker made with RDF. No physical test data are available. The cement company entered into negotiations with the township and a local private firm to supply RDF on a long term basis but such an arrangement has not yet materialized.

Lehigh Portland Cement Co.

A series of trials using RDF in a dry process, coal-fired cement kiln are scheduled to begin in September, 1979 at the Lehigh Portland Cement Co. plant in Union Bridge, Maryland.⁴¹ The trials will be managed by Teledyne National, who will also supply the fuel. Financial support for the trials is from the U. S. Environmental Protection Agency and the Maryland Environmental Service.

The RDF for the trials will be produced at the Baltimore County (Md.) resource recovery plant operated by Teledyne National. At this plant (see Figure 10), municipal refuse

Fig. 10: Processing Scheme for Preparation and Use of RDF in Cement Kilns

Lehigh Portland Cement Co. (Union Bridge, Md.) Trial

is shredded, magnetically separated and the non-magnetics are air classified. For the cement plant trials, the air classified light fraction will be screened in a trommel to recover a 1-1/2 x 1/2 inch fraction which will be re-shredded to a nominal 1 to 1/2 inch size then transported to the cement plant in compactor trucks. At the cement plant, the RDF will be re-fluffed using rotating lump breakers and fed through an air lock into a 9 inch pneumatic duct leading to the front end of the kiln. Air pressure in the duct will be 3/4 to 1 psi and the duct will enter the kiln directly below the coal feed pipe. Current plans call for one week of trials in early March to be followed by a full month of continuous use of RDF, commencing in September. The objective will be to use RDF as up to 40% of the energy input to the kiln. During the trials, cement chemistry and physical properties will be monitored by the Lehigh Co. and by the Portland Cement Association; air pollution monitoring will be performed by an EPA contractor.

Penn-Dixie Cement Company

During the summer of 1974, the Penn-Dixie Cement Co. conducted several experimental trials using RDF in cement kilns.^{42, 43} The Castle Recycling Corp. of Nazareth, Pa. and the National Resource Recovery Corp. of Wheaton, Ill. provided Penn-Dixie's Nazareth cement plant with refuse preparation and handling equipment. A small, dry process kiln was used. The kiln burned pulverized coal at a rate of 2 tph.

Incoming municipal refuse, received at Castle's recycling plant, was shredded and air classified (see Figure 11 for a simplified flow diagram of the system). The light fraction was trucked 1-1/2 miles to the Penn-Dixie plant where it underwent secondary shredding in a Schutte shredder. The optimal particle size for firing was determined to be less than 1/4 inch. The Schutte shredder was air-swept so that the shredded RDF was pneumatically transported from the shredder to a live bottom feed bin.

At first, RDF was fed from the bin, by means of an auger conveyor, into the air fan that delivered pulverized coal into the kiln. A problem developed, however, in that the auger tended to wad and compact the refuse, producing an RDF that had unsatisfactory combustion characteristics. It was then attempted to add the RDF from the auger feed system into the coal pulverizer. Although it was hoped that the pulverizer would break up the wads, the wads only served to impair adequate pulverizer operation. Finally, RDF (without the auger feed system) was fed directly into the kiln from the bin through a pneumatic feed pipe. The firing nozzle was located at a position about 60 degrees (i.e., "2:00 o'clock") from the top of the kiln. The feed pipe for coal entered the kiln at a position of about 300 degrees ("10:00 o'clock"). Within the kiln, the RDF and coal streams combined and excellent combustion reportedly resulted. The RDF apparently ignited faster than the coal and tended to draw the flame toward the front of the kiln.

Fig. 11: Processing Scheme for Preparation and Use of RDF in Cement Kilns

Penn-Dixie Cement Co. (Nazareth, Pa.) Trial

Until the feed system was fine-tuned, shredded newsprint rather than RDF was used as the supplement to coal. Once a satisfactory feed system was found, RDF at a fuel substitution level of 21% was burned continuously for 24 hours. The RDF was reported to have a 7000 Btu/lb (16.3 MJ/kg) calorific value.

Penn-Dixie conducted numerous chemical and physical examinations of the clinker including x-ray diffraction. Although these data are not available, the Penn-Dixie Research Manager considered the quality of the cement to be satisfactory.⁴³ At the end of the 1974 tests, it was concluded that a test run of 3 to 6 months should be conducted to establish the reliability of the process, but such a trial was never conducted.

Riverside Cement Company

In 1974, a 72 hour trial was conducted at the Riverside Cement Company in California.⁴⁴ Refuse derived fuel for the trial was supplied by a pilot plant operated by the Vista Chemical and Fiber Products Company of Los Gatos, California. Municipal refuse received at Vista's pilot plant went through primary shredding and magnetic separation (see Figure 12 for a diagram of the process flow). Secondary shredding, further magnetic separation, and tertiary shredding followed. The refuse was air classified and the light fraction was shipped to Riverside. The RDF had a density of 5 pounds per cubic foot and a reported calorific value of 5700 Btu/lb (13.2 MJ/kg).

Fig. 12: Processing Scheme for Preparation and Use of RDF in Cement Kilns

Riverside Cement Co. (Crestmore, Calif.) Trial

The Riverside Cement Company assembled their own feeding system to fire the RDF into their dry process, gas-fired kiln. RDF was first emptied into a hopper from which the fuel was gravity fed through an airlock and into a plenum downstream from a 5,000 cfm Buffalo Forge fan. The fluff was blown into the kiln through a nozzle located adjacent to the gas flame. A constant feed rate was difficult to maintain due to reported clogging problems in the hopper. RDF was used as up to 40% of the energy input to the kiln. Although, at times, stable kiln temperatures were reportedly difficult to maintain, clinker quality was reported to be satisfactory at fuel substitution levels up to 20%. No details on clinker chemistry are available.

Southwestern Portland Cement Company

During May of 1974, a 24 hr. test was conducted using RDF at the Fairborn, Ohio plant of the Southwestern Portland Cement Company.⁴⁵ The RDF, from the Black Clawson resource recovery plant in Franklin, Ohio, had a reported calorific value of approximately 4500 Btu/lb (10.5 MJ/kg).

Incoming refuse at the Franklin, Ohio resource recovery plant undergoes wet processing including pulping to produce fuel with a moisture content of almost 50% (see Figure 13 for a simplified diagram of the process flow for producing and firing the RDF). At the cement plant, this RDF was blown into the wet process kiln using a modified Gehl ensilage chopper/blower. The RDF firing nozzle was located directly

Fig. 13: Processing Scheme for Preparation and Use of RDF in Cement Kilns

Southwestern Portland Cement Co. (Fairborn, Oh.) Trial

above the coal feed pipe. RDF was used as approximately 15% of the kiln fuel. Some of the RDF did not burn completely in suspension and continued burning on the kiln floor. Some of the fuel was still burning as it exited the kiln with the clinker.

The kiln was equipped with inadequate temperature control devices. Thus, the effects of RDF on temperature control were not adequately determined. Chemical and physical analyses of the clinker including microscopic and x-ray diffraction tests were performed. There were no significant differences between clinker burned without RDF and clinker burned using RDF as 15% of the kiln fuel.

In 1975, Southwestern Portland Cement experimented with the use of a Raymond Mill coal pulverizer to pulverize and feed coal and pelletized RDF. The Raymond mill was air-swept so that the milled fuel became entrained in the air stream and passed through a cyclone before being blown into the cement kiln. Large, dense particles of fuel became de-entrained in the cyclone and were returned to the mill for regrinding.

The mill handled the mixture of RDF and coal without plugging the cyclone but it was observed that the cyclone seemed to be rejecting larger than normal amounts of coarse coal particles. It appeared that RDF was being selectively accepted by the mill and that the coal was exiting the mill before it was completely crushed. Within the kiln, some of the RDF did not burn completely in suspension and continued burning on the kiln floor. There was no analysis of clinker quality.

Lime

Lime is a chemical used for a variety of applications including steel manufacturing, water and wastewater treatment, chemicals production, and paper manufacturing (see Table 7 for the distribution of lime production by use). Lime is produced by the thermal processing of limestone* in any one of several types of kiln systems at a temperature of approximately 2400°F (1300°C).⁴⁶ The kiln product, quicklime (CaO), may either be sold as is or water may be added to produce hydrated lime, Ca(OH)₂.

Lime is manufactured in 163 plants in 41 states.⁴⁷ Commercial lime plants sell their product on the open market. So-called "captive" lime plants may be owned by large consumers of lime such as steel or chemical companies. Lime plants are concentrated near the steel producing areas of the Great Lakes region, and in the Gulf coast area. Over half of the lime in the U. S. is produced in Ohio, Pennsylvania, Missouri, Texas, and Michigan (see Figure 14).⁴⁸

Table 8 presents a summary of the proximity of lime plants to major population centers. As shown, there are at least 18 lime plants located within 25 miles of a major urban area. Five of these plants are among the 10 largest lime

* Although limestone is the principal form of calcium carbonate used as a raw material for lime kilns, oyster and clam shells are also used at some lime plants.

Table 7: Major Uses of Lime

<u>Use</u>	<u>Percent of Total Lime Production</u>
Steelmaking	42
Potable Water Treatment	10
Refractories	8
Pulp and Paper	7
Wastewater Treatment	4
Other	<u>29</u>
	100

Source: Reference 49

Figure 14

COMMERCIAL LIME PLANTS in U.S. and CANADA

Published by NATIONAL LIME ASSOCIATION, Washington, D.C.

1978

Table 8: Locations of Lime Plants*
Near Urban Centers

A. Commercial Lime Plants

Plants within
10 miles

Plants within
25 miles

Plants within
50 miles

Chicago, Ill.

Marblehead Lime Co.
South Chicago, Ill.

Marblehead Lime Co.
Thornton, Ill.

Vulcan Materials Co.
McCook, Ill.

New Orleans, La.

U. S. Gypsum Co.
New Orleans, La.

Chicago, Ill.

Marblehead Lime Co.
Buffington, In.

Los Angeles, Calif.

Kerr-McGee Chem. Corp.
West End, Calif.

Cincinnati, Ohio

Black River Mining Co.
Carntown, Ky.

Toledo, Ohio

Martin Marietta Corp.
Woodville, Oh.

Ohio Lime Co.
Woodville, Oh.

U. S. Gypsum Co.
Woodville, Oh.

Woodville Lime & Chem.
Co.; Woodville, Oh.

Toledo, Ohio

J. E. Baker Co.
Millersville, Oh.

Pfizer, Inc.
Gibbonsburg, Oh.

* Only those plants with rotary kilns are included. Source of data is National Lime Association.

Plants within
10 miles

Plants within
25 miles

Plants within
50 miles

Philadelphia, Pa.

Warner Co.
Devault, Pa.

Pittsburgh, Pa.

Mercer Lime & Stone Co.
Branchtown, Pa.

Dallas-Ft. Worth, Tex.

Texas Lime Co.
Cleburne, Tex.

San Antonio, Tex.

McDonough Bros., Inc.
San Antonio, Tex.

San Antonio, Tex.

U. S. Gypsum Co.
New Braunfels, Tex.

Seattle, Wash.

Domtar, Inc.
Tacoma, Wash.

B. Captive Lime Plants *

Phoenix, Ariz.

Amstar Corp.
Chandler, Ariz.

Los Angeles, Calif.

Holly Sugar Corp.
Santa Ana, Calif.

San Francisco, Calif.

Holly Sugar Co.
Tracy, Calif.

* Rotary and vertical kilns included. Source of data is National Lime Association.

Plants within
10 miles

Plants within
25 miles

Plants within
50 miles

Denver, Colo.

Great Western Sugar
Co.; Brighton, Colo.

Denver, Colo.

Great Western Sugar
Co.; Longmont, Colo.

Great Western Sugar
Co.; Loveland, Colo.

Great Western Sugar
Co.; Greely, Colo.

Chicago, Ill.

Inland Steel Co.
Indiana Harbor, Ind.

Baltimore, Md.

J. E. Baker Co.
York, Pa.

Bethlehem Steel Corp.
Hanover, Pa.

Detroit, Mich.

BASF Wyandotte Corp.
Wyandotte, Mich.

Cleveland, Ohio

U. S. Steel Corp.
Lorain, Ohio

Republic Steel Corp.
Grand River, Ohio

Toldeo, Ohio

Northern Ohio Sugar Co.
Fremont, Ohio

Houston, Tex.

Champion Inter. Corp.
Pasadena, Tex.

Armco Inc.
Houston, Tex.

plants in the U. S. Approximately 64% of the lime plants have annual capacities of less than 100,000 tons. However, these plants only account for 17% of the lime produced. Most production is attributed to lime plants whose capacities exceed 200,000 tpy.

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 (CO_2).⁴⁶ For lime production, a source of calcium carbonate, either limestone or shell, is fed into a furnace or kiln and heated to $1800^\circ - 2400^\circ\text{F}$ ($480^\circ - 1300^\circ\text{C}$) so that calcination can occur. Temperatures and residence times within the kiln determine the degree of porosity and chemical reactivity of the lime.⁴⁹ Soft-burned lime (having undergone minimal calcination) loses little weight, and is porous, soft, and very reactive. Hard-burned lime loses about 44% of its original weight (as limestone) and is in the form of 1/4 inch to 2 inch "pebbles." After screening, the lime may be sold as pebbles or pulverized to a fine powder. By adding enough moisture to satisfy the affinity of quicklime for water, hydrated lime is produced. The hydrated lime product is a dry, fine powder.

Several types of furnaces or kiln systems are used to produce lime.⁴⁹ Approximately 85% of the commercial lime produced in the U. S. is made in rotary kilns. The percentage is somewhat lower for the captive lime plants. The rotary

kilns in the U. S. generally range between 150 to 200 ft (46 to 62 m) in length and with 8 or 10 ft (2.5 or 3.1 m) internal diameters. 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. Lime plants firing coal generally pulverize the coal first in a ball or ring mill. The pulverized coal is then pneumatically fed into the front end of the kiln where it ignites. Crushed limestone enters the back end of the kiln and undergoes calcination near the front end. As compared with other types of lime kilns, rotary kilns are more efficient for calcining small pieces of limestone and can use a wider variety of fuels. The energy consumed in producing lime in a rotary kiln is approximately 7 million Btu/ton (16.3 GJ/Mg) of lime.⁹ With the use of preheaters, energy consumption can be reduced to 5.5 million Btu/ton (12.8 GJ/Mg) of lime.

Vertical kilns are used by many small lime plants. Vertical kilns are generally used for calcining large pieces of limestone, although some models can accommodate pieces as small as 1 inch or so. Kiln dimensions range up to 25 ft (7.7 m) in diameter and 100 ft (30.8 m) in length. The kilns are usually oil or gas fired, although coal is also used. If oil or gas is used, the fuels are introduced at the base of the kiln and the limestone is fed at the top of the kiln. If a solid fuel is used, both the limestone and the fuel are fed at the top of the kiln. Some vertical kilns

now employ burners directly in the calcining zone to improve kiln efficiency and lime quality. Fuel requirements for vertical lime kilns range from 3.5 to 5 million Btu/ton (8.1 to 11.6 GJ/Mg) of lime product. Other types of lime furnaces include rotary hearth calciners and fluidized bed calciners for producing highly reactive lime.

Most of the energy required to produce lime is consumed in the operation of the furnace or kiln. In 1977, 65% of the lime manufacturers fired their systems with coal.⁹ The remaining plants were fueled with gas or oil. The industry has made improvements in energy efficiency (e.g., 3.3% reduction in energy consumption between 1972 and 1976) by adding preheaters and recuperative coolers to their operations.

Lime quality is affected by the type and composition of fuel used. Some fuels more readily produce a soft, reactive lime while others are more conducive to producing hard-burned, less reactive lime. Fuel selection must take into account the quality of the limestone, kiln design, and the intended use of the product. Today, coal is the major energy source in the lime industry and precautions are taken to limit the incorporation of coal ash into the product.

The value of quicklime is dependent upon its available lime (CaO) content and the amount of impurities present.⁴⁰ Chemical specifications differ among the potential uses of lime. Silica, alumina, and iron oxide are the major impurities found in limestone. In the kiln, excessive levels of silica, alumina, and iron oxides 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 also may be present in small quantities in limestone. Magnesium carbonate, which can be a significant component of dolomitic limestones, may be regarded either as an essential constituent or as an impurity, depending on the use of the lime. Other impurities such as manganese, copper, and potassium (as oxides) occur in such small quantities that they are seldom significant.

The single largest consumer of lime in the U. S. is the steel industry.⁴⁹ Most of this lime is used as a flux to purify steel in basic oxygen furnaces (BOF). The BOF uses about 150 lbs of lime per ton of finished steel. The lime enables impurities (silica, alumina, sulfur, and phosphorous) to melt readily. The impurities then preferentially combine with the lime rather than the steel and produce "slag." 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.

In the production of chemicals, specifications usually require lime to be essentially free of ash and "dirt." In the manufacture of calcium carbide, chemical specifications restrict the phosphorous content in the lime to less than 0.02%. Hydraulic hydrated lime for structural purposes must

meet minimum and maximum specifications for CaO and MgO and maximum specifications for iron and aluminum oxides and carbon dioxide.

Lime is increasingly being used as a so-called soil stabilizer to condition clay subgrade courses of highways and airport runways. In this application, the calcium in the lime reacts with silica and alumina in the clay to form cementing compounds that convert the soil into a hard, water-resistant mass. Chemical specifications for lime used in roadbed stabilization are less restrictive than specifications for use in steelmaking or chemicals production.

Major Research Issues

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

- a) handling characteristics of the fuel;
- b) effect of RDF combustion products on kiln coating layer;
- and c) effect of RDF ash on the chemical composition of the lime product.

Handling Characteristics of the Fuel

Generally, the problems of storing, conveying, and feeding RDF at lime plants are similar to those at cement plants.

Differences in physical properties between RDF and coal, the major energy source of the lime industry, suggest the need

for modifying existing coal-fired rotary kilns in order to accept RDF. There is a need to identify types of equipment and operating practices that will enable RDF to be accommodated in lime kilns. The modifications needed in a rotary lime kiln in order to utilize RDF would essentially be the same modifications required in a rotary cement kiln.

Coating Layer

Lime plants maintain a thinner coating or layer of deposits along the inside lining of the rotary kiln than do cement plants. For proper furnace operation, it is important that this coating layer be neither built up excessively nor sloughed off.⁵⁰

The fragile ash and coating layer interaction may be affected by the use of RDF. There is a need to establish how the silica content of the ash would affect the coating layer. There is also a need to establish the effect of RDF ash (which, in some cases, softens at temperatures below that of coal ash) in a molten state on the buildup of the coating layer. The question of the effect of RDF ash on lime kiln coatings is discussed in more detail later in this report in the description of a lime kiln trial.

Effect of RDF on Lime Quality

As discussed previously, the value of lime is affected by its chemical purity. A number of lime plants use only

gas or oil as fuels to minimize the addition of undesirable chemicals (e.g., sulfur, silica) from coal. 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 9 presents a simplified analysis of the calculated effects of RDF ash on the silica content of lime. Estimates of the silica contribution from RDF ash are based on several assumptions described in the following paragraph.

The energy required to produce a ton of lime is approximately 7 million Btu (16.3 GJ/kg). 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.³⁰ Although quantities vary with the type of limestone, about 1.7 tons of limestone are needed to produce 1 ton of lime.³¹ RDF is assumed to provide 30% of the energy input to the kiln. Approximately 15% of the coal ash and 25% of the RDF ash are assumed not to be entrained in the flue dust, and may therefore be incorporated into the lime.⁵⁰ The silica content of the

coal ash is 55%,⁴ a typical mid-range value, and the silica content of the RDF ash is 50%. A typical value for the silica content of limestone is 0.5%.³¹

The use of lime in the manufacture of steel requires that silica (SiO_2) in the lime not exceed 1.5% by weight. Other uses of lime do not require such stringent limitations on the silica content. As seen in Table 9, the 1.5% limit on silica in lime is only exceeded under the worst case assumptions.

Table 10 shows a simplified analysis of the calculated effects of RDF ash on another set of lime contaminants, the metal oxides, alumina (Al_2O_3) and iron oxide (Fe_2O_3). Estimates of the metal oxide contribution from RDF ash again require making several assumptions which follow.

Generally, the assumptions used in calculating the effect of RDF on silica levels in lime also are applicable in evaluating the effect of RDF on the metal oxide content of lime. Typically, coal ash is 22% Al_2O_3 and 14% Fe_2O_3 .⁴ A typical RDF ash might contain 10% Al_2O_3 and 4% Fe_2O_3 .^{2, 3, 7} Although there is quite a variation in the metal oxide content of limestone, a mid-range value of 0.3% is used.^{31, 49} A reasonable restrictive upper bound on the metal oxide content of lime is the 1% (by weight) limit imposed for use in the manufacture of calcium carbide.⁵¹ The calculations reflected in Table 10 suggest that the metal oxide contribution from

Table 9: Calculated Silica Content of Lime
When Using RDF as a Kiln Fuel
 (Silica content expressed as percent
 by weight of SiO_2 in lime).

RDF Ash Content (% by weight)	Coal Ash Content (% by weight)	
	10	15
10	1.27%	1.35%
15	1.38%	1.45%
20	1.50%	1.60%

Assumptions*

1. Energy consumption approximately 7 million Btu/ton lime produced.
2. 12,000 Btu/lb coal; 5500 Btu/lb RDF.
3. 1.7 tons limestone produce 1 ton lime.
4. RDF provides 30% of the energy input to the kiln.
5. 15% of the coal ash and 25% of the RDF ash become available to product.
6. SiO_2 content of coal ash is 55%; SiO_2 content of RDF ash is 50%.
7. SiO_2 content of limestone is 0.5%.

*See text for further discussion of the assumptions.

RDF and coal ash would not, by itself be expected to cause failure of the lime to meet the 1% upper limit.

Tables 9 and 10 suggest that, when RDF is used as 30% 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.

There are no reasons to believe that any of the specified physical properties of lime would be likely to be adversely affected by the use of RDF as a kiln fuel but properties such as color are important to some lime consumers and it would be useful to test whether there is any effect of using RDF on lime color.

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 with structural concrete to form, for example, lightweight concrete building blocks. As their name implies, lightweight aggregates are lower in density than sand, gravel, and other mineral aggregates commonly used in construction. Lightweight aggregates, such as expanded shale made in rotary kilns, have

Table 10: Calculated Metal Oxide Content of Lime
When Using RDF as a Kiln Fuel
 (Metal Oxide content expressed as percent
 by weight of Al_2O_3 and Fe_2O_3 in lime).

RDF Ash Content (% by weight)	Coal Ash Content (% by weight)	
	10	15
10	0.67%	0.74%
15	0.72%	0.78%
20	0.76%	0.81%

Assumptions*

1. Energy consumption approximately 7 million Btu/ton lime produced.
2. 12,000 Btu/lb coal; 5500 Btu/lb RDF.
3. 1.7 tons limestone produce 1 ton lime.
4. RDF provides 30% of the energy input to the kiln.
5. 15% of the coal ash and 25% of the RDF fuel become available to product.
6. Coal ash contains 22% Al_2O_3 & 14% Fe_2O_3 ; RDF ash contains 10% Al_2O_3 and 4% Fe_2O_3 .
7. Limestone contains 0.3% ($\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$).

*See text for further discussion of the assumptions.

reported densities ranging from 30 to 70 pounds per cubic foot.⁵² This compares with 75 to 110 pounds per cubic foot for gravel.³⁰ The reported advantages of the lightweight concrete are that it possesses better acoustical, insulation, and fire resistant properties than concrete made from common mineral aggregates.⁵³

"Expanded" shale is a name frequently used to describe shale, clay, and slate processed in a kiln for use as a lightweight aggregate. Although competition from natural lightweight aggregates is intense, 55% of all lightweight aggregate used in the U. S. is expanded shale.⁵⁴ Sixty-five percent of expanded shale is used in construction block. Another 25% is used for structural concrete and 10% goes into highway surfacing.

Annual U. S. production of expanded shale is approximately 6 million tons.⁵³ Texas is the leading producer but Arkansas, Indiana, and Iowa are also important producing states. There are 34 expanded shale plants operating in the U.S.

(See Figure 15). The number of plants has been diminishing throughout the 1970's, due to stagnant demand for expanded shale and the apparent economies of scale of operating fewer, but larger, plants. Plants range in capacity from under 60,000 tons per year to over 500,000 tons per year. A typical plant might produce 200,000 tons per year or about 550 tons per day. There are 7 expanded shale plants with production

[illegible]

85

capacities in excess of 200,000 tons per year located within 50 miles of urban areas of the U. S.

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 1,200° - 1,800°F (650° - 980°C) so that the material becomes softened and a viscous airtight seal is formed over voids within the clay or shale.⁵² Care is taken to prevent fusion of the clay particles during this heating process, therefore temperature control within the kiln is a major concern. Towards the exit end of the kiln (the front end), temperatures rise to 2,200°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.

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

* Note: Although most of the expanded shale produced in the U. S. is via the rotary kiln process, four plants in the country use the sintering process to prepare shale, clay, and slate for use as lightweight aggregate. In this process, the raw material is mixed with coarsely crushed coal and is expanded under controlled conditions on a moving grate.

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 $2,100^{\circ}\text{F}$ ($1150^{\circ}\text{C} \pm 5.5^{\circ}\text{C}$).⁵⁵ The cooled product which has been bloated to nearly double its size, is a mass of small, unconnected air cells. Before shipment, the material is crushed and graded to a specified size range.

The kiln is the major consumer of energy in the expanded shale industry. An average of 2.9 million Btu's (6.7 GJ) is required to produce a ton of expanded shale.⁹ The range of energy use in expanded shale kilns lies between 2 million and 5 million Btu's (4.6 to 11.6 GJ) per ton of product. As with other industries, expanded shale manufacturers are accelerating the conversion to coal from natural gas and oil. As of 1977, 51% of the industry used coal and 42% used gas. Oil and scrap fuel oil accounted for about 4% of the energy consumed.

Major Research Issues

When considering the use of RDF in expanded shale plants, two major issues are of interest: handling properties of the fuel and the ability to closely control kiln temperature. As coal is the major fuel source of the industry, the use of RDF would necessitate modifications in the feeding and firing systems of the rotary kiln. As in the cement and lime industries, there is a need to identify types of equipment and operating

practices that will enable RDF to be stored, metered, and fed to the kiln.

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. There is no reason to suspect that the use of RDF would significantly affect the chemical or physical quality of expanded shale.

Expanded Shale Trials

To date, the only trial in which RDF has been used in an expanded shale kiln took place at the Lehigh Portland Cement Company's plant in Woodsboro, Maryland.⁵⁵ The trials were arranged by Teledyne National, operators of the Baltimore County resource recovery plant in Cockeysville, Maryland. The first set of trials were conducted in February and March of 1977 in a coal-fired kiln.

At the resource recovery plant, refuse was first shredded to a nominal 4 inch size, then magnetically separated. The non-magnetic fraction was air classified and the light fraction

shipped to the expanded shale plant where it was to be re-shredded 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, the RDF was fed through a separate feed line operating with a centrifugal fan. Minor problems keeping the flame at a proper length occurred but there were no problems with product quality or ring formation.⁵⁵ RDF was used to provide up to 30% of the energy for the kiln. Generally satisfactory results were obtained.

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 shredded RDF was shipped to the expanded shale plant. There, a conveyor carried the refuse to an air lock box. The RDF passed through the air lock and 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. The RDF was fed at the maximum rate of one ton per hour but with a pressure that would suffice for 20 tons per hour. 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

Factors to be Considered

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, 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 demonstrations of the use of RDF in kilns. The remainder of this report is focused on the second reason, i.e., the need for research/demonstrations.

In assessing the merits of various research/demonstration projects, there are several criteria that can be applied. These are the identification of a clear research objective, the likelihood of succeeding in fulfilling the objective, the likelihood of significantly expanding the market for RDF and the reasonableness of the costs of the project.

Research goals can be identified by comparing the major research issues discussed earlier in this report with the

results of past and current research. Such comparisons are shown in Figure 16, a research needs matrix for the use of RDF in kilns. As seen in the figure, several of the major research questions have already been addressed in previous trials. For example, the use of RDF in cement kilns has consistently been reported to have no ill effects on the strength of portland cement. This being said, however, the longest of the trials was five days thus leaving open the question of whether strength (or some other properties of the cement) deteriorate during extended firing of RDF.

Some of the major research issues are common to all three types of kilns (i.e., cement, lime and expanded shale) and so the trial results from one type of kiln will be transferable to another application. An example is the need for developing reliable RDF feeding systems. There are some differences in the fuel feeding requirements of the various kilns but much of what is learned about feeding cement kilns can be applied to the feeding of lime or expanded shale kilns.

The need to establish the likelihood of success for a research/demonstration project is self evident but defies rigorous analysis. As applied to the use of RDF in kilns, this principle requires that any research/demonstration program be directed at a goal which is reasonable in terms of current industry structure and practices. For example, it seems unreasonable to consider the use of RDF as the only - or even as the principal - fuel for a kiln. Cement plant managers

Figure 16

Research Needs Matrix for the Use of RDF in Cement Kilns*

	Blue Circle Group	Cement Lafarge	Gulf Coast	Hercules	Lehigh	Penn Dixie	Riverside	Southwestern
<u>Type of Kiln</u>	X	X	X					X
Wet Process	X			X	X	X	X	
Dry Process								
<u>Fuel Used</u>	X	X		X	X	X		X
Coal		X	X				X	
Gas								
<u>Research Issues</u>								
<u>Handling Properties</u>								
Storage	X	X	X		X			
Shredding	X	X	X	X	X	X	X	
Feeding	X	X	X	X	X	X	X	X
<u>Firing & Temp. Cont.</u>	X	X	X	X	X	X	X	X
<u>Coatings</u>								
<u>Chemical Quality of Product</u>								
Alkalies	X	X	X	X	X	X		X
Chlorides	X	X	X		X			
Sulfates	X	X	X		X			
<u>Physical Quality of Product</u>								
Strength	X	X	X	X	X	X		X
Grindability	X	X	X		X			
Color			X		X			
<u>Air Emissions</u>	X	X	X		X			
<u>Long Term Effects</u>								
Chemistry								
Strength								
<u>Use of Precalciner</u>								

*Note: x's indicate that the research issue has been addressed in the trial.

are simply not likely to entrust their most critical operation (i.e., the operation of the kiln) to a fuel as unfamiliar and sometimes unpredictable as RDF.

Another factor to consider is the potential size of the RDF market to be affected by the results of any research/demonstration project. Table 11 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 11, 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 of a major U. S. urban area. On the average and assuming RDF is used as 30% of the energy input to the kiln, a cement plant could consume 164 tons per day (7 day week) of RDF and a lime plant, 190 tons. By contrast, there are only 34 expanded shale plants in the U. S., 7 near urban areas. A typical expanded shale plant (say 1000 tons per day of aggregate) could consume no more than 50 tons per day of RDF, again assuming 30% replacement of the normal kiln fuel. Expanded shale plants are potential markets for RDF but they are not likely to be a major user of the RDF produced at any one resource recovery plant and do not merit the same research priority as the cement or lime kilns.

Table 11: Potential Consumption of RDF/day

Assume 30% substitution of fuel source by RDF

12,000 Btu/lb coal

5500 Btu/lb RDF

Plants operate 300 days/yr

Cement Plants - Assume energy consumption of 6 million Btu/ton product

Capacity tons/day	No. of Plants	Approx. RDF requirement tons/day
<1350	43	<210
1350-2300	65	210-380
2300-3300	29	380-540
>3300	20	>540

Lime Plants - Assume energy consumption of 7 million Btu/ton product

Capacity tons/day	No. of Plants	Approx. RDF requirement tons/day
<510	104	<100
510-970	26	100-185
970-2200	26	185-400
>2200	8	>400

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

Capacity tons/day	Approx. RDF requirement tons/day
170-340	13-27
340-670	27-55
670-1340	55-135

Costs for any research/demonstration project are an obvious factor to be addressed. Costs will affect not only whether the various interested parties (government, industry, etc.) can afford to conduct the project but also how the risks should be shared among the parties. For example, one of the costs of any trial is the cost of modifying an existing plant to accommodate the tests. Such modification may, in the long run, become a useful capital asset to the plant, yet, at the start of the tests, a plant may be reluctant to make an investment in a modification that is untried. In such a case, a governmental role may be, in effect, to underwrite the investment risk to the user company by, for example, paying for the initial modification and then being repaid if the modification leads to a successful trial. Similarly, cost-sharing arrangements may be made for other aspects of the trials. The price for the refuse derived fuel could be subsidized so as to make the fuel inexpensive - but not free - to the user. Costs for sampling and analyzing raw materials and products could be split between the user company and the government. In some cases, even the costs of personnel to operate the fuel processing and feeding equipment could be shared in recognition of the fact that the trial would afford an ideal training period for kiln plant employees should the kiln become a long term commercial user of RDF. There is some risk to the cement manufacturer of kiln disruptions, downtime and the production of off-specification cement during the

RDF trial; such risks may require provisions for reimbursing all or a portion of the cement company's losses resulting from the trial.

The Cement Lafarge trial now underway in Ontario, Canada provides an example of an interesting cost-sharing arrangement between the Ontario Ministry of the Environment and the cement company. The Ontario Ministry is an arm of provincial government and is also the owner of the Toronto resource recovery facility, supplier of RDF for the trial. Canada Cement Lafarge, Ltd. is a private company manufacturing cement at several plants including the one in Woodstock, Ontario. For the 1-year trial, the Ontario Ministry agreed to finance the design, purchase and installation of a \$200,000 system for receiving, shredding and firing RDF at the cement plant. The Ministry also agreed to conduct air emission sampling at the cement plant during the trials. Cement Lafarge has agreed to allow the RDF to be used in their kilns, to pay for the RDF (80% of the price of coal on an equivalent calorific basis), to supply all labor required at the cement plant (includes operation of the feeding equipment and sampling of raw materials and products), and to conduct the chemical analyses and physical tests on the product. In addition, Cement Lafarge has agreed to purchase the receiving/feeding system at reasonable market value following successful completion of the trial. As for the risks of unexpected downtime or production of off-specification cement during

the trial, Cement Lafarge has not required the Ontario Ministry to provide any insurance against such risks, but the cement company does retain the option of calling a halt to the trial if technical problems interfere with the production of salable product.

Recommendations for Research/Demonstration Projects

Given the current level of research on the use of RDF in kilns and the potential of the various markets to use RDF, three alternative research/demonstration projects can be considered. The three topics are:

1. Use of RDF in a lime kiln.
2. Use of RDF in a precalciner.
3. Use of RDF in an extended trial at a portland cement kiln.

The three topics are not necessarily listed in order of priority. Each of the topics is discussed in detail below.

Use of RDF in a Lime Kiln. Despite similarities in the production of lime and portland cement, there have been no reported trials using RDF in lime kilns while there have been a number of cement kiln trials. Lime production requires approximately the same amount of energy per unit of product as cement production. Fuel feeding systems in lime kilns are similar to those in cement kilns. Lime is produced at 35 plants that are within 50 miles or so of major urban areas.

Thus there appears to be significant potential to use RDF in lime kilns and to take advantage of much that has been - or will be - learned about firing RDF in cement kilns.

Although there are similarities between lime and cement kilns, there are also major differences which make it unlikely that successful cement kiln trials will guarantee successful use of RDF in lime kilns. Among the major differences are the firing temperatures within the kiln, the characteristics of the coating layer of the kiln and the chemistry of the products.

Maximum temperatures within lime kilns are in the range of 2,200 to 2,400°F (1,200 to 1,315°C) considerably below the maximum temperatures required for producing clinker in a cement kiln (2,700 to 2,900°F or 1,480 to 1,590°C). The lower temperature requirements of lime kilns may make them more tolerant than cement kilns of the variations in RDF properties, particularly moisture content. There is some evidence that the moisture content of RDF may actually be advantageous in lime production. The presence of steam in the combustion products of a kiln has been reported to lower the temperature for calcination.⁵⁶ This phenomenon was reported for vertical kilns using wood fuel and it is unclear whether the same effect would be observed when using RDF in a rotary kiln.

As discussed earlier in this report, the interior walls of both cement kilns and lime kilns are coated with a layer

of deposits. This so-called "coating" layer insulates the shell of the kiln and also provides protection against abrasion of the refractory lining. The coating layer within a lime kiln differs in thickness and chemical composition from that in a cement kiln. Typically, lime kiln coatings are 1/2 inch thick while cement kiln coatings are up to 12 inches thick. Lime kiln coatings are primarily calcium oxide while cement kiln coatings are composed primarily of silicates. The differences in kiln coatings may affect the acceptability of RDF for use in the kiln. As discussed earlier, about 50% 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 toward 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.⁵⁷ 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.⁵² 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 nor has there been an analysis of the likelihood for RDF ash particles to be softened or melted on contact with kiln coatings.

Like kiln coatings, kiln products can also be affected by the incorporation of fuel ash. In cement manufacturing, it is an accepted practice to adjust the raw materials mixture to account for the addition of ash components to the clinker.

Again, as with kiln coatings, the ash components of RDF are generally compatible with the chemical composition of the clinker.

Many of the components of RDF ash are considered contaminants of lime. Thus, for example, silica, alumina and ferric oxide, three major components of RDF ash (and also of coal ash) are limited in the specifications for certain types of lime. There is little published information available on the incorporation of fuel ash into lime. This is true for coal ash as well as for RDF. Thus, it is difficult to estimate the effect of using RDF on the chemical composition of the lime product. Calculations such as those described earlier (in the discussion of research issues for the use of RDF in lime kilns) suggest that only a small percentage of RDF ash could be tolerated in lime for use in steel-making. The same could be said for coal ash, however, and yet there is some evidence that the use of coal does not appreciably increase silica levels in lime.⁵⁸ A key issue to be addressed is the extent to which RDF ash particles become incorporated into the lime rather than exiting the kiln entrained in the exhaust gas stream. Differences in softening temperatures of RDF vs. coal ash may result in differences in ash incorporation into the lime product but, again, these differences - if any - have neither been analyzed theoretically nor observed in actual trials.

One potential advantage in using RDF in lime manufacture is the low sulfur content of RDF relative to most coals. Sulfur levels in lime are limited by specification and are affected by the sulfur content of the kiln fuel. RDF may permit lowered sulfur levels in the lime or, alternatively, may enable a lime manufacturer to safely use cheap, high sulfur-content coal.

Because of the significant and growing size of the lime production market and because of the existence of several unanswered research questions, it is recommended that a study of the use of RDF in lime kilns be conducted. Such a study would include analysis, laboratory testing and an actual lime kiln trial. The objectives would be:

1. Estimate the effect of using RDF on the coating layer of the kiln and on the chemical composition of the product lime.
2. Demonstrate the successful firing of RDF into a lime kiln.
3. Determine by visual observation and chemical analysis, the effects of using RDF on the coating layer and the product lime characteristics during the lime kiln trial.
4. Determine the effect - if any - of using RDF on the air emissions from a lime plant.

The lime kiln study should be designed to take full advantage of the experience being gained in the cement plant

trials already completed or underway. This experience should be especially helpful as a guide to the storage, conveying, milling and feeding of RDF into the kiln.

Several factors should be considered when selecting a kiln site for the trial. Among lime industry plants, the most likely candidates for use of RDF are those plants using coal-fired rotary kilns. These kilns would be the ideal type for use in an RDF trial. There may also be an advantage in selecting an older kiln. Older kilns tend to be wider and less energy efficient than the newer, narrower ones. By increasing the effective distance from the flame zone to the kiln wall, the large diameter of the older kilns may reduce the chance that a softened ash particle would impact the coating layer or the lime product before being cooled and re-solidified.

There would be two distinct phases to the recommended lime kiln study. The first phase would be devoted primarily to analysis (including laboratory tests) of the potential effects of RDF use in a lime kiln. The second phase would be the actual trial.

During the first phase, an analysis of kiln conditions and RDF ash properties would be performed. Kiln conditions include gas flows, temperature profiles and heat release rates (per cubic meter of kiln space). The principal ash properties to be analyzed would be softening temperature and content of silica, alumina and iron oxide. Some information

on ash properties can be obtained from the literature but this should be supplemented by lab analyses of the RDF to be used in the kiln trial.

Based on kiln conditions and ash properties, estimates of the amount and location of ash deposition within the kiln could be made. These estimates would be used in anticipating any problems (ring formation, product chemistry, etc.) that might occur during the trials.

The trial itself would require modifying a lime kiln to fire RDF. This would include setting up a system for receiving, storing, conveying and perhaps processing the RDF for firing into the kiln. The processing might include equipment to break up bales of RDF, to reshred or at least re-fluff the fuel and to meter it into a pneumatic feeding duct. The configuration of the transport and feeding system could be designed along patterns used in cement kiln trials.

For credible results, the trial should be conducted for a minimum of one month's continuous (24 hr./day) firing of RDF. A reasonable approach would be to set a target of no less than 20% (calorific basis) and no more than 50% replacement of coal by RDF. A preliminary week or more of "shakedown" tests at varying fuel replacement levels would assist in removing "bugs" from the feeding system and could be useful in narrowing the range of fuel replacement levels to be tried during the month-long trial.

During the trial itself and also during a control period when no RDF is used, several types of information should be collected by measurement and by observation. Among the important conditions to measure are:

a) The chemical and physical properties of the RDF, the coal and the raw material (limestone or shell). Fuel samples (both RDF and coal) would be taken periodically and analyzed especially for particle size distribution, moisture content, calorific value and silica, alumina and iron content of the ash. Chemical composition data will be essential for determining mass balances within the kiln.

b) Time and amount of RDF (and other fuels) fed to the kiln. The amount of time that RDF is actually fed to the kiln is an indication of the reliability of the handling and feeding system.

c) Temperatures within the kiln. Variability over time would be of particular importance, especially when compared to similar data when using more conventional fuels such as coal.

d) The chemical and physical properties of the product lime. Samples of the lime would be analyzed for the content of calcium oxide, silica, alumina, iron oxide, and sulfur. The particle size distribution of the lime would be used as an indication of any sintering effect that may result from the incorporation of RDF into the lime.

e) Chemical analysis of samples of the kiln coating layer. These results will indicate the effects of deposition of ash particles onto the coating layer.

f) The emissions from the exhaust stack of the air pollution control equipment. Included among these tests should be analyses for combustion gases, determination of sulfur dioxide concentrations and measurement of total particulate concentrations. It might also be useful to analyze the collected particulates chemically to detect the effects of RDF ash.

Some aspects of kiln operations during RDF firing can be observed and recorded - even if not measured quantitatively. Included in this category would be observations on the flow characteristics of the fuel, the uniformity of the flame and the formation of rings within the kiln. The frequency of blockages in the feeding system or of ring formation in the kiln can be recorded along with the time and manpower necessary to clear the blockages or remove the rings.

By comparing the measurements and observations made during the RDF trials with similar data collected during the control period (i.e., when no RDF is used in the kiln), the effects of using RDF can be determined. Again, as outlined earlier, the overall objective is to determine whether RDF can be reliably fed to a lime kiln without significantly adverse changes in product quality, process control or air emissions.

Table 12 is offered as a first cut summary of the estimated costs for conducting the lime kiln trial. The table requires some explanation, especially the distinction between total costs and governmental costs. Implicit in the summary table is the sharing of costs and risks among the principals in the trial. Principals would include the federal government, the lime company and the resource recovery plant (i.e., the RDF producer). Given the economic interest of lime plants in finding inexpensive fuels and the economic interest of resource recovery plants in finding markets for RDF, it seems reasonable to expect at least some of the costs of a trial to be borne by the lime plant and the recovery facility. There are also, however, research interests in the lime kiln trial that extend beyond the economic interests of the fuel user and supplier and there are risks that neither party may be willing to assume without the intervention of a third party such as the federal government. There appears to be a legitimate and useful role for the federal government in providing funds to conduct the needed research, to offset some of the risks and to stimulate the commercial acceptance of RDF as a lime kiln fuel.

The actual allocation of costs among principals is impossible to determine a priori - or at least until a specific set of principals is identified. Rather than attempt to make too fine an allocation among principals, the summary table simply lists total costs and governmental costs. The formulae

Table 12: Estimated Costs for Lime Kiln Trial*

<u>Cost Category</u>	<u>Total Cost (\$)</u>	<u>Suggested Gov't Share (\$)</u>
Labor		
Manager (4 man-months @ \$10/hr)	6400	
Staff (9 man-months @ \$7.50/hr)	10,800	
Overhead (120%)	<u>20,640</u>	
	37,840	28,380
Laboratory Analyses		
Limestone and Lime (2 samples per day)	7500	
Coal, RDF	2000	
Air Sampling and Analysis	<u>17,000</u>	
	26,500	19,875
Fuel		
3500 tons RDF @ \$20/ton delivered	70,000	17,500
Equipment and Installation	200,000	100,000
Reimbursement for Losses		
Est. @ 1 day downtime; 500 tons @ \$40	20,000	
Est. @ 2 day off-spec lime; 1000 tons @ \$12	<u>12,000</u>	
	<u>32,000</u>	<u>32,000</u>
Subtotal	366,340	197,755
General and Administrative @ 10%	<u>36,634</u>	<u>19,776</u>
GRAND TOTAL	402,974	217,531

* See text for description of trial and explanation of costs.

used in determining governmental costs are admittedly arbitrary but the attempt here is simply to estimate costs in a reasonable fashion so as to give guidance for program planning. No claim can be made for the precision of the costs or of the apportionment formulae.

In compiling the estimates for Table 12, it was assumed that government would support 75% of the labor and laboratory analysis costs of the trial. These are costs that are outside the ordinary expenses of a lime or resource recovery plant and so it is assumed that the government would bear the major share of these costs. The government's share of the costs for RDF have been assumed to be 25% of the actual "market value" of the fuel. This 25% governmental share of fuel costs can be viewed as a subsidy to encourage the use of the fuel. The resource recovery plant may also subsidize the cost of the fuel by selling the RDF to the lime plant at a discount for the purposes of the trial. The total costs of purchasing and installing equipment at the lime plant to accommodate the RDF trial are estimated to be in the neighborhood of \$200,000. Among the several ways of lessening the budgetary impact of these costs are: the use of leased equipment, the use of equipment for more than one trial, and the negotiation of a buy-back arrangement with the fuel user. By the use of one or several of these cost-saving approaches, it is assumed that the governmental share of equipment costs can be limited to installation costs plus a portion of the equipment purchase

price - a factor of 50% is used to approximate the governmental share.

The final category of costs shown in Table 12 is "Reimbursement for Losses." This category can be viewed as insurance against the risks of unscheduled maintenance, downtime and defective lime that could result from the RDF trial. Although the trial is nominally scheduled to run for a full 28 day period, it is assumed that, if major problems are encountered in kiln operation or lime quality, the trial would simply be stopped thus providing an upper limit on the losses that could be incurred. For the purposes of estimating the losses that might need to be covered as a result of the trial, it was assumed that, at most, one full day of lost production could occur (e.g., due to the need to remove kiln rings) and two days of production of off-specification lime could result. Total costs for the day of downtime were estimated based on 500 tons of lime (one kiln) at \$40 per ton. Costs for the days of off-specification lime were estimated again based on 500 tons per day of lime but using \$12 per ton as the approximate price differential between steelmaking grades of lime and soil stabilization (i.e., less expensive) grades. The governmental share of loss reimbursement is assumed to be 100%.

Use of RDF in a Precalciner. Among the emerging technological trends in the cement industry is the use of precalcining

furnaces to calcine the raw materials before they enter the rotary kiln. It is estimated that within the next 15 years or so, 50% to 70% of all fuel used in cement plants will be used in precalcining furnaces.¹¹

As discussed earlier in this report, precalcining furnaces are designed to be fired with poorer quality, less expensive, fuels than those used in rotary kilns. Thus, precalciners appear to be good candidates for the use of RDF.

The objectives of a precalciner trial would be similar to the objectives of previous cement kiln trials, i.e., to determine whether RDF can be successfully fired into the furnace (in this case, a precalcining furnace) and whether the use of RDF will affect cement quality, plant operations or air emissions. As with the lime kiln trial discussed above, a month-long trial period preceded by a week or so of "shakedown" should provide a reasonable length of time for testing.

A major limiting factor in attempting to conduct an RDF trial in a precalcining furnace is the scarcity of such furnaces. There are only two precalcining units now known to be operating in the U. S. They are located in Mason City, Iowa (Lehigh Portland Cement Co.), and Ragland, Alabama (National Cement Company). Between these two cement plants, the closest to an operating resource recovery plant is the unit in Mason City, Iowa, which is 90 miles from the Ames,

Iowa plant. Several new precalcining units are expected to become operative in the next three years.

One possible alternative to the use of an existing precalciner would be the construction of a new precalcining furnace at an existing cement plant near a resource recovery facility. Costs for new precalcining furnaces are reported to be in excess of \$8 million, however, and thus this approach appears to be too expensive.^{59, 60} Of course, if a cement plant near a resource recovery facility were planning to install a precalciner anyway, there may be merit in federal support for the installation of equipment for firing RDF (perhaps this could be through offsets to oil conservation) but, at present, there are no cement plants (near recovery facilities) planning to install precalcining furnaces.

Assuming a suitable site can be found (e.g., the Mason City, Iowa cement plant), the trial would be conducted using RDF as most - if not all - of the fuel input to the precalciner. The reason for using RDF as a higher percentage of precalciner fuel than has been proposed for cement kilns is that precalciners use only 60% or so of the total fuel used in the cement plant. Therefore, to consume as much RDF as would be used in a rotary kiln where RDF provided 30% of the energy input would require RDF to be used as 50% of the input to a precalciner. Actually, total fuel consumption (per ton of clinker) is lower for plants with precalciners than for conventional rotary kiln plants,⁶⁷ further suggesting the

need to conduct tests using RDF as virtually all of the precalciner fuel.

The precalciner trial would be conducted for one full month of continuous operation, probably preceded by a week or so of "shakedown" testing. During the trial and shakedown period, the following conditions should be measured:

a) The chemical and physical properties of the RDF, the coal and the raw material mixture (limestone, clays, iron ore, etc.). Fuel samples (both RDF and coal) would be taken periodically and analyzed especially for particle size distribution, moisture content, calorific value and alkali content of the ash. Chemical composition data will be essential for determining mass balances within the cement plant.

b) Time and amount of RDF fed to the precalciner. The amount of time that RDF is actually fed to the furnace is an indication of the reliability of the handling and feeding system. The quantities of other fuels fed to the precalciner should also be monitored so as to measure total energy consumption within the furnace.

c) Temperatures within the precalciner. Variability over time would be of particular importance, especially when compared with similar data when using more conventional fuel, such as coal.

d) The chemical and physical properties of the product clinker. Samples of the clinker would be analyzed

for alkali and chloride content as well as for the major components of portland cement. Again, these data would be used for determining mass balances and for assessing the effects on cement chemistry of using RDF in the precalciner.

e) The physical properties of the clinker and the product cement should be tested both before and during RDF firing. Included among such tests would be the grindability of the clinker and the setting time and compressive strength (1, 3, 7 and 28 day) of the product cement.

f) The emissions from the exhaust stack of the air pollution control equipment. Included among these tests should be analysis of the combustion gases, determination of sulfur dioxide concentrations and measurement of total particulate concentrations. It would also be useful to analyze the collected particulates for chemical composition and size distribution to detect any effects of RDF ash. The sampling of collected particulates would be useful as an indication of whether the use of RDF in a precalciner would affect the ability of a cement manufacturer to recycle dusts.

Some aspects of operations during RDF firing can be observed and recorded - even if not measured analytically. Included in this category would be observations on the flow characteristics of the fuel, the uniformity of the flame and

the formation of deposits within the precalciner. The frequency of blockages in the feeding system or of excessive deposition of ash on the furnace lining can be recorded along with the time and manpower necessary to clear the blockages or remove the deposits.

By comparing the measurements and observations made during the RDF trials with similar data collected during the control period (i.e., when no RDF is used in the precalciner), the effects of using RDF can be determined. Again the overall objective is to determine whether RDF can be reliably fired into the precalciner without significant changes in the chemical or physical properties of the cement and without disruptive effects on process control or air emissions.

Estimates of the costs for conducting a precalciner trial (exclusive of capital costs for the precalciner itself) are shown in Table 13. The total cost of this trial is about that of the lime kiln trial discussed earlier in this report as is the approach used in estimating the costs. The principal cost difference between the lime kiln and precalciner trials would be the more extensive (and expensive) chemical and physical testing requirements for cement (in the precalciner trial) and the difference in risks between the two trials. It is assumed that there is equal risk of kiln downtime for the two trials but it is also assumed that there is less risk of adversely affecting product quality in the case of the cement (i.e., precalciner) trial than in the lime trial. This latter

Table 13: Estimated Costs for Precalciner Trial*

<u>Cost Category</u>	<u>Total Cost(\$)</u>	<u>Gov't Share(\$)</u>
Labor		
Manager (4 man-months @ \$10/hr)	6400	
Staff (9 man-months @ \$7.50/hr)	10,800	
Overhead (120%)	<u>20,640</u>	
	37,840	28,380
Laboratory Analyses		
Raw materials and cement (2/day)	15,000	
Coal, RDF	2000	
Air Sampling and Analysis	<u>17,000</u>	
	34,000	25,500
Fuel		
3500 tons RDF @ \$20/ton delivered	70,000	17,500
Equipment and Installation	200,000	100,000
Reimbursement for Losses		
1 day downtime; 500 tons @ \$55	27,500	
1 day of high alkali cement 1500 tons @ \$20	<u>30,000</u>	
	<u>57,500</u>	<u>57,500</u>
Subtotal	399,340	228,880
General and Administrative @10%	<u>39,934</u>	<u>22,888</u>
GRAND TOTAL	439,274	251,768

* See text for description of trial and explanation of costs.

assumption is based on the fact that, while successful cement kiln trials have been conducted in the past, no such trials using RDF at lime plants have been reported. Although there may be less risk of adversely affecting product quality in the precalciner trial, if product quality were affected (e.g., by increased alkali content of the cement) the loss per ton of product would be greater than losses during the lime trial. This is because the reported price of cement is higher than the price of lime and because the differential between the highest and lowest grades of cement is greater than the differential between the grades of lime. For cement, a differential of \$20 per ton was used in calculating the loss from production of off-specification clinker.

Use of RDF in an Extended Cement Kiln Trial. Despite the emergence of precalciners, most U. S. portland cement is produced in rotary kilns. As discussed in earlier sections of this report, there have been at least 13 cement plant trials conducted in rotary kilns, yet there are no U. S. cement plants currently using RDF on a regular basis. It is difficult to identify the exact reason why RDF has not been adopted more rapidly as a kiln fuel but conversations with cement industry officials suggest two factors. One is the limited availability of RDF; the other is a general lack of confidence in the results of short-terms trials. To date the longest U. S. trial has lasted only 3 to 5 days.

There are, of course, two (and perhaps, three) cement plant trials to be conducted in 1979 which will extend well beyond the periods of past trials. The Lehigh Valley Cement Co. trial in Union Bridge, Md. will last one full month; the Cement Lafarge trial in Woodstock, Ont. (already underway) will last one year; and the Gulf Coast Portland Cement Co. trial to be conducted near Houston, Texas, will last more than one week.

It is simply too early to know whether the trials to be conducted in 1979 will yield the data and experience necessary to develop confidence in RDF among cement plant operators. Some cement company officials report that it takes as long as 6 months of continuous operation even with conventional fuels such as coal to properly establish the correct mix of raw materials and kiln conditions for cement production.⁶²

In light of DOE interest in developing full-scale commercial markets for alternate fuels,⁶³ it may be decided that an extended RDF trial at a cement plant may be a reasonable way of establishing the reliability of RDF as a kiln fuel. If so, the trial should be conducted for at least one year of continuous operation, preferably at a modern coal-fired cement plant (e.g., one equipped with a suspension preheating system and bypass controls).

There are three types of long term issues that can be raised concerning the use of RDF in cement kilns. These are:

- 1) the long term performance of cements made in RDF-fired kilns;
- 2) the long term buildup of residuals in cements made in RDF-fired kilns;
- and 3) the long term effects on kiln operations.

The first of these issues does not require that RDF be used for a long time in a cement kiln. Rather, it requires that a long-term cement and/or concrete testing program be conducted on cements produced in RDF-fired kilns. The cement could be produced during a relatively short (one month or so) trial but the performance characteristics of the cement would be tested over a long period of time.

The second and third issues could both be addressed by a long-term RDF trial at a cement plant. During the trial, periodic sampling of raw materials, fuels, clinker and dusts should be conducted and analyses should be performed to determine the effects of using RDF on cement chemistry and characteristics of the entrained dusts. Also, monitoring of furnace temperatures, flame length, dust emissions and kiln coatings should be conducted in order to determine effects on kiln operation. The reliability of systems for receiving, storing, processing (at the cement plant) and feeding RDF should be evaluated.

It would be important not only to conduct the various tests but to analyze the results of these tests for changes

over time. This is especially true for the buildup of alkalies and chlorides in the cement product, for the formation of rings within the kiln and for any change in the efficiency of the air pollution control equipment. Each of these potential long term effects of using RDF have been mentioned as concerns by cement plant operators interviewed during the course of this study.

Costs for conducting an extended trial at a cement kiln are summarized in Table 14, again following the approach discussed in the description of the lime kiln and precalciner trials. It should be noted that the costs for conducting a one year trial at a cement kiln are not 12 times the costs for conducting a one month trial in a lime kiln or precalciner. Rather, the long-term trial costs are estimated to be approximately 3 times the costs of the shorter trials. The point is that the total costs need not increase in proportion to the lengthening of the trial period. Some costs, such as equipment purchase and installation, are essentially fixed and, although some equipment may have to be modified or improved to assure year-long performance, the added costs should be relatively small (a figure of \$50,000 has been used in Table 14). Other costs may be borne more heavily by the cement company and/or the recovery plant as the trial begins to resemble a part of their permanent operations. Examples of such costs would be labor for operation of the RDF receiving and feeding equipment and routine maintenance on this equipment. Sampling

Table 14: Estimated Costs for Extended
Cement Kiln Trial*

<u>Cost Category</u>	<u>Total Cost(\$)</u>	<u>Suggested Gov't Share (\$)</u>
Labor		
Manager, (15 man-months @ \$10/hr)	24,000	
Staff (18 man-months @\$7.50/hr)	21,600	
Overhead (120%)	<u>54,720</u>	
	100,320	75,240
Laboratory Analyses		
Raw Material and Cement	30,000	
Coal, RDF	5,000	
Air Sampling and Analysis	<u>30,000</u>	
	65,000	48,750
Fuel		
35,000 tons RDF @ \$20/ton delivered	700,000	175,000
Equipment and Installation	250,000	125,000
Reimbursement for Losses		
3 days downtime; 1500 tons @ \$55	82,500	
5 days high alkali cement; 2500 tons @ \$20	<u>50,000</u>	
	<u>132,500</u>	<u>132,500</u>
Subtotal	1,247,820	556,490
General and Administrative @ 10%	<u>124,782</u>	<u>55,649</u>
GRAND TOTAL	1,372,602	612,139

* See text for description of trial and explanation of costs.

and laboratory analyses could be conducted on a lesser frequency during the 1-year trial than during a 1-month trial - at least once the year-long trial had advanced beyond a week or so of "shakedown." Costs shown for reimbursement of losses are higher than those shown for the shorter trials but, again, the loss estimates reflect the fact that if the trial experiences severe problems it will simply end. Hence, there is an upper limit on the extent of losses due to kiln disruption or production of unsatisfactory clinker.

Concluding Remarks

The three potential research/demonstration projects discussed in this report are all directed toward resolving questions on the use of RDF as a fuel for producing construction materials. The projects differ, however, in the nature of the questions that need to be resolved.

In the case of the lime kiln trial, there are fundamental research questions to be addressed, such as the behavior of RDF ash particles in the heat release zone of the lime kiln. This trial can be considered an initial investigation of potential problems that might occur when using RDF to produce lime.

The precalciner trial includes some research issues (e.g., the degree to which furnace temperatures affect incorporation of RDF ash into the clinker) but, for the most

part, this trial is designed simply to demonstrate that RDF can be successfully fired in precalcining furnaces.

The extended trial in a conventional cement kiln would be directed almost exclusively toward accumulating experience and data on the use of RDF under commercial conditions. Put another way, this third proposed trial would not be designed to address any particular research issues, other than to note whether the long term use of RDF produces any effects that could not be anticipated based on the results of short-term trials.

In making these statements on the different types of issues addressed by the 3 proposed projects, no judgment is made concerning which type of issue is most important. Such judgements are to be made by the U. S. Department of Energy.

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