153
11/16/80

(1)

Feasibility of Burning Refuse-Derived Fuel in Institutional-Size Oil-Fired Boilers

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

Under Contract No. AC01-76CS201617

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Available from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price:	Printed Copy:	\$7.00
	Microfiche:	\$4.00

Feasibility of Burning Refuse-Derived Fuel in Institutional-Size Oil-Fired Boilers

Final Report
October 1980

Prepared by:
National Center for Resource Recovery, Inc.
Washington, D.C. 20036
Under Contract No. AC01-76CS201617

Prepared for:
U.S. Department of Energy
Assistant Secretary for Conservation and Solar Energy
Office of Buildings and Community Systems
Washington D.C. 20585

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ABSTRACT

This study investigates the feasibility of retrofitting existing oil-fired boilers of institutional size, approximately 3.63 to 36.3 Mg steam/h (8,000 to 80,000 lbs steam/h) for co-firing with refuse-derived fuel (RDF). Relevant quantities describing mixtures of oil and RDF and combustion products for various levels of excess air are computed. Savings to be realized from the use of RDF are derived under several assumptions and allowable costs for a retrofit are estimated. An extensive survey of manufacturers of burners, boilers and combustion systems showed that no hardware of proven design is yet available for such retrofit. Approaches with significant promises are outlined: the slagging burner, and a dry ash double vortex burner for low heat input from RDF. These two systems, and an evaluation of a small separate RDF dedicated combustor in support of the oil-fired boiler, are recommended as topics for future study.

CONTENTS

Abstract.....	i
Figures.....	iv
Tables.....	v
 1. Objectives, Approach and Conclusions.....	 1
Objectives.....	1
Approach.....	2
Conclusions.....	3
 2. RDF and Oil Combustion Parameters.....	 6
Introduction.....	6
Fuels characterization.....	7
Selected oil.....	7
Selected RDF.....	8
Mixture of oil and RDF.....	9
Mass of ash generated.....	10
Oil savings.....	13
Mass flow rates.....	13
Comments.....	16
Excess air and combustion products.....	16
 3. Allowable Investment for Co-firing Retrofit.....	 21
Introduction.....	21
Fuel savings from the use of RDF.....	21
Allowable capital cost.....	27
Comments.....	34
 4. Oil Burners: Features and Retrofit Aspects.....	 35
General.....	35
Packaged boilers.....	35
Oil burners.....	36
Cell burners	37
Circular burners.....	37
Cyclone burners	38
Implications on retrofits for RDF co-firing...	39
Comments.....	41
 5. Survey of Manufacturers for Scope and Cost of Retrofit.....	 42
Introduction.....	42
Survey procedure.....	42

Survey: Main results.....	43
Detailed review of manufacturers' responses.....	46
Technical features of a possible solution.....	51
Preliminary discussions with potential users.....	57
Conclusion.....	60
 6. Future Solutions and Recommendations.....	 61
Cyclonic type, slagging (or "wet-ash") burner for RDF and oil.....	 61
Double vortex, dry ash burner, at low RDF energy input, in a boiler retrofitted for wood and agricultural waste burning.....	 62
Auxiliary, separate unit (fluidized bed combustor) in the loop of the main boiler.....	 63
 References.....	 65
 Appendices	
A1. Composition of product gases vs. RDF input heat and excess air.....	 67
A2. Partial list of manufacturing companies presently or potentially interested in RDF-oil co-firing in small boilers.....	 70

FIGURES

<u>Number</u>		<u>Page</u>
2-1	Higher heating value of mixture vs. percent RDF, by weight and heat.....	11
2-2	Ash produced for 10.55 GJ/h (10^7 Btu/h) gross input vs. RDF contribution by weight (f) or heat (b).....	12
2-3	Oil savings and weight of mixture vs. percent RDF (equal heat input).....	14
2-4	Weight flow rates for 10.55 GJ/h (10^7 Btu/h) input vs. percent RDF.....	15
2-5	Adiabatic combustion temperature vs. RDF percent of heat input and excess air (EA).....	20
3-1	Ideal fuel savings vs. unit size for various percentages of heat input from RDF, b.....	24
3-2	Ideal fuel savings vs. unit size, for various percentages of heat input from RDF, b.....	25
3-3	Yearly savings in fuel costs vs. energy output/hour, for various percentages of heat input from RDF, b (co-firing combustion efficiency = 0.89). ..	29
3-4	Yearly savings in fuel costs vs. energy output/hour, for various percentages of heat input from RDF, b (co-firing combustion efficiency = 0.88). ..	30
3-5	Yearly savings in fuel costs vs. energy output/hour, for various percentages of heat input from RDF, b (co-firing combustion efficiency = 0.85). ..	31
3-6	Allowable capital cost vs. yearly savings in fuel costs.....	33

TABLES

<u>Number</u>		<u>Page</u>
2-1	Composition and amount of product gases vs. RDF heat input and excess air.....	18
3-1	Yearly savings for 105.5 GH/h (10^8 Btu/h heat input.....	23
3-2	Savings for 95 GJ/h (0.9 M Btu/h) output.....	28

CHAPTER 1. OBJECTIVES, APPROACH AND CONCLUSIONS

Objectives

The purpose of the present investigation is to evaluate the feasibility of burning a form of refuse-derived fuel, or RDF, as a supplemental fuel in relatively small oil-fired boilers, typically in the 3.63 to 36.3 Mg steam/h (8,000 to 80,000 lb steam/h) range.

Refuse-derived fuel is obtained by a variety of methods used to extract a mostly combustible fraction from municipal solid waste. It is produced in a variety of physical forms, loose or as "fluff," as a dewatered slurry, densified as pellets or briquettes, or as a fine powder similar to pulverized coal (1,2).

Oil-fired boilers in the range considered, 10.55 to 105.5 GJ/h (10^7 to 10^8 Btu/h) for a boiler efficiency of 80%, are mostly packaged units (3), with high heat release per unit volume, and with minimal provisions (if any) for bottom or fly ash collection and removal. Often installed in large office complexes, military bases, hospitals, universities, they are said to be of "institutional size."

In assessing the feasibility of retrofitting this type of boiler to accommodate some contribution of energy from RDF, a number of technical questions need to be addressed. Which presently-manufactured equipment could accommodate a retrofit for RDF co-firing? In which shape and size should the RDF be fed into the boiler, and by which method? How would the ash be handled in and

out of the combustion chamber? Finally, if an acceptable solution can be developed, which types of pollution control devices would assure compliance with applicable standards?

It is also of interest to define, from the predicted fuel savings resulting from such a retrofit, a range of allowable investments to purchase, install and operate the added equipment. Among other factors, the latter should be a function of boiler size and contribution (by heat) from RDF as the substitute for fuel oil.

If warranted, this investigation also proposed to include the design and costing of an experimental plan to demonstrate co-firing of RDF and oil at a cooperating heating plant of institutional size.

Approach

In the first phase of this work, information was obtained from the literature on oil-fired boilers and some earlier assessments of oil and RDF co-firing for utility-sized boilers. What might be considered a typical refuse-derived fuel, of known elemental composition and calorific value, was used to compute combustion properties for various levels of excess air and ratios of RDF to oil.

Potential fuel savings were determined for various levels of contribution from RDF (by heat) as a function of the size of the installation. Allowance was made for an estimated decrease in combustion efficiency. Capital investments allowable for a retrofit were derived.

A survey of equipment manufacturers was conducted by mail, phone or visits. It aimed at determining whether experienced burner designers viewed RDF and oil co-firing in their units as achievable with off-the-shelf hardware, after some sizable modifications, or more within the realm of long-term research and development ventures.

Simultaneously, a few installations were considered as potential candidates for a retrofit experiment, and discussions about a possible joint project were held with some heating plant operators.

Conclusions from these surveys and our in-house evaluations were analyzed and resulted in a number of recommendations.

Conclusions

From this feasibility study, the following conclusions could be drawn:

- retrofitting of oil boilers to allow some degree of co-firing with RDF in institutional-size boilers is not presently achievable with proven, off-the-shelf hardware
- at present prices of oil, any future retrofit should be for larger units and accommodate an energy input from RDF of no less than 10% at the design point. For example, to break even, the annualized cost of retrofit of a 36.3 Mg of steam/h (80,000 lb steam/h)

boiler, working at rated load, for 10% heat input from RDF and a 2 point drop in combustion efficiency (from 0.90, for oil only, to 0.88) should not exceed \$96,000 if the fuel is free or \$17,000 if the fuel costs \$1.42/GH (\$1.50M Btu)

- there exist three promising approaches to the problem, which either warrant further experimentation or are in the developmental stage
 - the use of a slagging burner, in which the RDF ash is collected prior to the tube enclosure
 - the use of a "wood waste" type of vortex burner, at moderate heat input (10%) from RDF, in a boiler normally retrofitted to accommodate as much as 100% of a 2% ash fuel (such as wood waste)
 - the use of a separate unit, of the fluidized bed type, to generate pressurized water or low pressure steam.

Our recommendations are:

- Additional research, both experimental and theoretical, should be carried out on the mechanics and thermodynamics of combustion, heat transfer and ash deposition in slagging burners for the

co-firing of oil and properly sized RDF. As a related question, methods for the size reduction of RDF to sizes (1 mm or less) should be investigated more systematically.

- . As the technology of vortex burners (non-slugging) might allow -- substitution of moderate amounts of RDF to lower ash waste fuels, so as to keep the total weight of ash generated constant -- should be attempted in a boiler already retrofitted for the use of wood wastes.
- . Co-generation with RDF in a dedicated fluidized bed combustor should be monitored at a heating plant of institutional size.

CHAPTER 2. RDF AND OIL COMBUSTION PARAMETERS

Introduction

In this section, the main combustion parameters (flue gas composition, higher heating value, temperature of combustion) for various mixtures of oil and RDF are examined in a global sense, i.e., without delving into the particular mechanism, such as vortex mixing, slurry mixing, etc., by which the two fuels are mixed first and then co-fired. Obviously, the latter aspects are of extreme importance in effecting a stable, efficient combustion.

After characterizing the fuels to be co-fired, i.e., oil and RDF, the following cases are considered:

- stoichiometric combustion of oil and a given percentage, f (by weight), or b (by energy) of a specified RDF
- combustion of the same mixtures with "EA" percent of excess air.

In all of the above, the quantities considered are:

- amount of ash produced
- composition and amount of flue gases
- adiabatic temperature of combustion
- combustion temperatures allowing for expected thermal losses.

Fuels Characterization

Without loss of generality, an industrial fuel (oil #6) is selected for the analysis. Similarly, a typical composition for a refuse-derived fuel, such as was made available to us from an analysis of six samples in the beginning of the study, is assumed for the purpose of computation.

Selected Oil

The selected fuel oil has a composition typical of a #6 grade for carbon, sulfur and hydrogen (4). Ash was taken as 0.4% by weight. The composition is as follows:

FUEL OIL, GRADE #6

Higher heating value (HHV): 42.56 MJ/kg (18,300 Btu/lb)

Specific gravity: 0.97 (8.1 lb/gallon)

Ultimate analysis

Percent, wt.

S 2.3

H 9.7

C 85.6

N₂, O₂ 2.0*

Ash 0.4

100.0

*Taken to be O₂ in calculations

It is found, using a standard method such as outlined by Corey (5), that the stoichiometric dry air required for the combustion of 1 kg of fuel is 13.29 kg of dry air/kg of fuel, or 13.39 kg of standard air/kg of fuel. Standard air is defined as air containing 1.3% moisture, by dry weight (6).

The volume and weight percentages of the products from stoichiometric combustion are given in Appendix A1.

Thus, per kg of fuel burned, 14.38 kg of combustion gases and 0.004 kg of ash are produced if the combustion is stoichiometric.

Selected RDF

The selected refuse-derived fuel has properties measured in an analysis of six samples performed by an independent laboratory.

The average properties were as follows (7):

Composition, typical RDF

<u>Ultimate</u>		<u>Ultimate</u>		<u>Proximate</u>	
Dry Basis		As received		As received	
C	0.4767	C	0.3603	Moisture	0.2442
H	0.0571	H**	0.0703	Ash	0.1342
N	0.0082	N	0.0062	Volatile	0.5425
O*	0.2804	O**	0.4218	Fixed C†	<u>0.0791</u>
Ash	<u>0.1776</u>	S	0.0072		
		Ash	<u>0.1342</u>		
TOTAL	1.0000	TOTAL	1.0000	TOTAL	1.0000

*by difference; includes S, Cl

**with hydrogen and oxygen present in 24.42% moisture

† by difference

Higher heating value: 13.52 MJ/kg (5811 Btu/lb), as received
17.88 MJ/kg (7689 Btu/lb), dry basis

As above, the stoichiometric standard air required for the combustion of the fuel is computed to be 4.83 kg air/kg fuel. The composition of combustion products is given in Appendix A1.

Per kg of RDF, 5.70 kg of combustion gases and 0.134 kg of ash are produced at zero excess air.

Mixture of Oil and RDF

Let f_{RDF} be the mass fraction of RDF in one unit mass of mixture of RDF and oil

$$f_{\text{RDF}} = \frac{\text{mass of RDF}}{\text{mass of mixture}}$$

Defining f_{OIL} in a similar way

$$f_{\text{OIL}} = 1 - f_{\text{RDF}}$$

Below, the higher heating value of such a mixture is examined as well as the amount of ash, oil savings and mass flow rates of each component for a fixed energy input in the boiler.

Higher heating value

The higher heating value of the mixture $(\text{HHV})_{\text{MIXT}}$ is expressed as a function of the heating values $(\text{HHV})_{\text{OIL}}$ and $(\text{HHV})_{\text{RDF}}$ of the components by

$$\begin{aligned} \text{HHV}_{\text{MIXT}} &= (\text{HHV})_{\text{OIL}} (1 - f_{\text{RDF}}) + (\text{HHV})_{\text{RDF}} f_{\text{RDF}} \\ &= \text{HHV}_{\text{OIL}} \left[1 - f_{\text{RDF}} \left(1 - \frac{(\text{HHV})_{\text{RDF}}}{(\text{HHV})_{\text{OIL}}} \right) \right] \end{aligned} \quad (2.2.3)$$

In particular, for the above values:

$$(\text{HHV})_{\text{OIL}} = 42.56 \text{ MJ/kg (18,300 Btu/lb)}$$

$$(\text{HHV})_{\text{RDF}} = 13.52 \text{ MJ/kg (5811 Btu/lb)}$$

$$\text{HHV}_{\text{MIXT}} = 42.56 [1 - 0.6825 f_{\text{RDF}}] \quad (\text{MJ/kg})$$

This quantity is plotted vs. the RDF content by weight of the mixture in Fig. 2-1. It is seen that for $f_{\text{RDF}} = 0.259$, corresponding to a heat input of 10% from RDF by weight of the mixture, the HHV_{MIXT} has been reduced from 42.56 MJ/kg (18,300 Btu/lb) (oil only) to 35.04 MJ/kg (15,063 Btu/lb)

Mass of Ash Generated (fixed energy input)

As compared to RDF, oil has a low ash content, on the order of 0.5% maximum for grade #6. Standard oil-fired boilers are not normally equipped to handle the much larger masses of ash from even a moderate heat input from RDF.

Assume that the energy input into the combustor is fixed at E_{tot} . For varying proportions of RDF to the total mass of the mixture, f_{RDF} , the mass of mixture for given E_{tot} , in MJ,

$$m_{\text{MIXT}} = \frac{E_{\text{tot}}}{\text{HHV}_{\text{MIXT}}}$$

and the mass of ash produced, m_{ASH} , is expressed as

$$m_{\text{ASH}} = E_{\text{tot}} \frac{0.004 (1 - f_{\text{RDF}}) + 0.1342 f_{\text{RDF}}}{42.56 (1 - 0.6825 f_{\text{RDF}})} \quad (\text{kg})$$

if oil ash is 0.4% by weight and RDF ash 13.42% in the respective fuels. As an example, the mass of ash/h for a 10,550 MJ/h (10^7 Btu/h) input (3,629 kg/h or 8,000 lb steam/h) is plotted in Fig. 2-2 as

HIGHER HEATING VALUE,

(10^3
Btu/lb)

FIG. 2-1. HIGHER HEATING VALUE OF MIXTURE
VS. PERCENT RDF, BY WEIGHT AND HEAT

(lb/h) kg/h

Note: For 105,500 MJ/h (10^8 Btu/h) gross input, multiply vertical scale readings by 10.

FIG 2-2. ASH PRODUCED FOR 10.55 GJ/h (10^7 Btu/h) GROSS INPUT VS. RDF CONTRIBUTION BY WEIGHT (f) OR HEAT (b)

a function of the percentage of RDF in the mixture. It is seen that even for this smallest size in the range considered, the amount of ash to be dealt with is quite significant, increasing markedly, from 0.99 kg/h (2.2 lb/h) for oil only, to 11.38 kg/h (25.06 lb/h) for a 10% by heat input from RDF.

Oil Savings

For a given energy input, E_{tot} , the percentage of oil saved, compared to burning oil alone, and provided the efficiency of combustion remains the same, is equal to

$$S_{\text{OIL}} = 100 \times \left[1 - \frac{1 - f_{\text{RDF}}}{1 - 0.6825 f_{\text{RDF}}} \right] \text{ (percent)}$$

and is plotted as a function of f_{RDF} in Fig. 2-3. At a 25.9% (by weight) contribution from RDF, oil savings are exactly 10%. On the same figure, the ratio between the mass of the mixture and the mass of oil for the same energy input, is also plotted vs. f_{RDF} .

Mass Flow Rates

Fig. 2-4 shows a breakdown between the mass flow rates of oil and RDF, and the total mass flow rate of mixture, for a 10.55 GJ/h (10^7 Btu/h) heat input. The applicable formulae are, per unit time,

$$\dot{m}_{\text{mixt}} = \frac{\dot{E}_{\text{tot}}}{\text{HHV}_{\text{oil}} (1 - 0.6825 f_{\text{RDF}})}$$

$$\dot{m}_{\text{oil}} = (1 - f_{\text{RDF}}) \dot{m}_{\text{MIXT}}$$

$$\dot{m}_{\text{RDF}} = f_{\text{RDF}} \dot{m}_{\text{MIXT}}$$

FUEL OIL #6 @
18,300 Btu/lb

I: OIL SAVINGS, PERCENT, COMPARED TO FUEL #6 INPUT ONLY

II: RATIO OF MIXTURE INPUT WEIGHT TO FUEL #6 INPUT WEIGHT

FIG. 2-3. OIL SAVINGS AND WEIGHT OF MIXTURE VS. PERCENT RDF
(EQUAL HEAT INPUT)

FIG. 2-4. WEIGHT FLOW RATES FOR 10.55 GJ/h (10^7 Btu/h) INPUT VS. PERCENT RDF

Comments

Due to the ratio of 1/3.15 in heating values between RDF and oil, oil savings will only be "significant" (10%)* at contributions by mass in the mixture, from RDF, of about 26%. At this ratio of RDF to oil, the ash produced by the combustion of the same mass of mixture will be increased approximately 11.5 times. If the same energy input is maintained, the amount of ash is multiplied approximately 14 times, since the mass of fuel is increased 21.5%.

At this stage, it can be speculated that the amount of ash produced would be the limiting factor in a retrofit, even for very small contributions by heat from RDF. The maximum contribution by heat input from RDF would result from a compromise between ash produced and oil savings sufficiently important to justify the retrofit. This is confirmed in Chapters 4 and 5.

Excess Air and Combustion Products

Excess air

Let EA be the excess air, defined (in percent) as the amount of air used in excess of what is strictly needed for the stoichiometric combustion of the mixture. Thus

$$EA = 100 \times \frac{\text{air used} - \text{stoichiometric air}}{\text{stoichiometric air}} \%$$

With the above notations, (S.A.)_x designating the stoichiometric air of "x":

*This level of "significance" is somewhat arbitrary, but is thought to be larger than incremental savings in an already energy efficient system.

$$EA = 100 \times \left[\frac{\text{air used}}{f_{RDF} (S.A.)_{RDF} + f_{OIL} (S.A.)_{OIL}} - 1 \right]$$

Efficient oil burners operate with as little as 2.5 to 7% excess air (8). A more common range for well adjusted multi-fuel burners is in the 10% to 20% range (9). The excess air required for efficient co-firing of oil and RDF mixtures will obviously depend on the combustor, size of feed, and other equipment-specific parameters.

In their study of emissions which might result from co-firing of oil and RDF in utility boilers, Galeski and Schrag (10) estimated a likely value of the excess air which might be required for stable, satisfactory combustion. They pointed out that "there is evidence that excess air may need to be higher when firing refuse with oil than when firing oil alone. The reason for this is corrosion and deposition of molten ash on the tube surfaces. Also, in water-wall incinerators, the excess air rises to levels well in excess of 70% to alleviate corrosion problems. The authors stated that in firing oil with RDF in utility-sized boilers, reasonable values to be anticipated for the excess air might be 15% for a percentage heat input of RDF of 10% ($b = 10\%$), and 25% if the percentage is 20% ($b = 20\%$).

Products of combustion

For three values of the excess air: $EA = 0\%$, 10% and 20% , and three values of RDF heat input (0% , 5% , 10%), Table 2-1 gives the computed amounts of flue gases for 1 kg of mixture as the

TABLE 2-1. COMPOSITION AND AMOUNT OF PRODUCT GASES
VS. RDF HEAT INPUT AND EXCESS AIR
(b = energy contribution from RDF, percent)

b	HHV _{MIXT} MJ/kg (Btu/lb)	Mass of Mixture/ Mass of Oil Only*	Equivalent mol. wt. (product gases)	Ash, kg/kg mixt.
EA = 0%				
b = 0%	42.56 (18,300)	1.000	29.35	0.004
kg product gases/ kg mixture = 14.38				
b = 5%	38.43 (16,524)	1.1075	29.26	0.022
kg product gases/ kg mixture = 13.15				
b = 10%	35.04 (15,063)	1.215	29.17	0.038
kg product gases/ kg mixture = 12.13				
EA = 10%				
b = 0%	42.56 (18,300)	1.000	29.30	0.004
kg product gases/ kg mixture = 15.72				
b = 5%	38.43 (16,524)	1.1075	29.21	0.022
kg product gases/ kg mixture = 14.36				
b = 10%	35.04 (15,063)	1.215	29.14	0.038
kg product gases/ kg mixture = 13.25				
EA = 20%				
b = 0%	42.56 (18,300)	1.000	29.26	0.004
kg product gases/ kg mixture = 17.06				
b = 5%	38.43 (16,524)	1.1075	22.18	0.022
kg product gases/ kg mixture = 15.58				
b = 10%	35.04 (15,063)	1.215	29.11	0.038
kg product gases/ kg mixture = 14.37				

input into the boiler. Compositions are given in Appendix A1. Factors by which the mass of the mixture has to be increased, compared to the case of firing oil only, in order to maintain the same heat input into the boiler, are indicated in the third column. In Fig. 2-5, the adiabatic combustion temperatures were computed using the specific heats at mid-range, for the above values of EA, as a function of the percentage, b , of heat input from RDF. As expected, the combustion temperatures decrease with b for constant excess air. From these, the actual combustion temperatures can be computed after making allowance for thermal losses.

For the same heat input, for a 10% contribution from RDF ($b = 10\%$) and an assumed excess air of 20%, the mass of flue gases produced, compared to firing oil only (with an excess air of 10%) increases by a factor of approximately 11% (values from Table 2-1):

$$\frac{14.37}{15.72} \times 1.215 = 1.111$$

Note that this figure will depend on the fuels used and particularly on the RDF moisture content.

FIG. 2-5 ADIABATIC COMBUSTION TEMPERATURE VS. RDF PERCENT OF HEAT INPUT AND EXCESS AIR (EA)

CHAPTER 3. ALLOWABLE INVESTMENT FOR CO-FIRING RETROFIT

Introduction

If a technical approach to co-firing RDF and oil in institutional-sized boilers can be found, its cost of implementation should be no higher than the savings in oil costs resulting from the substitution of RDF.

We now proceed to examine the likely savings from RDF in lieu of oil, under various assumptions regarding

- the percentage of input (by heat) from RDF
- the decrease in combustion efficiency caused by the use of RDF
- the price of RDF as a supplemental fuel
- the load factor of the boiler (referred to its design rating)

From these, estimates of the maximum allowable investment for the retrofit are derived, corresponding to the break-even case.

Fuel Savings from the Use of RDF

No reduction in combustion efficiency ("Ideal" case)

As an ideal, it is assumed that the combustion efficiency, η_c , does not change with the substitution of RDF for oil. Thus, an input energy E_{tot} , whether from oil only or from oil and RDF, for a percentage of RDF (by heat)

$$b = 100 \times \frac{E_{\text{from RDF}}}{E_{\text{tot}}}$$

of the total, will result in the same energy in the combustion gases, $\eta_c E_{tot}$.

The price of RDF, P_{RDF} , is another parameter which can take the values, in \$/GJ (\$/M Btu): of 0, 0.47, 0.95, 1.42 (0, 0.50, 1.00 and 1.50), delivered. These values are thought to represent a realistic range, between disposal at zero cost of the fuel and an upper limit representative of coal prices for small industrial users (11).

The boiler load factor, k_L , is defined as the ratio of the average load $\bar{\ell}$ (in kg steam/h) to the nominal load ℓ_o , or with t in hours:

$$k_L = \frac{1}{8760} \frac{1}{\ell_o} \int_0^{8760} \ell(t) dt$$

Values of $k_L = 1, 0.5, 0.25$ are used for the graphs which follow.

The price of oil, P_{OIL} , in \$/GJ, is taken at an end of 1978 value of \$0.106/ ℓ (\$0.40/gallon) or \$2.56/GJ (\$2.70/M Btu).

Let S be the yearly savings in fuel oil costs (in \$/year) and $\dot{E}$ the desired input energy per hour at rated load (J/h)

$$S = \dot{E} \times 8760 \times 10^{-9} (P_{OIL} - P_{RDF}) k_L \frac{b}{100}$$

This relation is represented in the graph of Fig. 3-1 and 3-2 and tabulated in Table 3-1 giving the yearly savings for a 105.5 GJ/h (10^8 Btu/h) input (36.3 Mg/h or 80,000 lb of steam at 80% efficiency), a range of prices for RDF and contributions by heat from RDF of 2%, 5% and 10%. For example, at the high end of the range (105.5 GJ/h or 10^8 Btu/h), the yearly savings from a 10% energy input from RDF, would be \$236,520 at full load, and \$59,130

TABLE 3-1. YEARLY SAVINGS FOR 105.5 GJ/h (10^8 Btu/h) HEAT INPUT

Percentage (by heat) from RDF	RDF Price, \$/GJ (\$/M Btu)	Yearly Savings (Full load, $k_L = 1$)
2%	\$0.00 (\$0.00)	\$ 47,304
	\$0.42 (\$0.50)	\$ 38,544
	\$0.95 (\$1.00)	\$ 29,784
	\$1.42 (\$1.50)	\$ 21,024
5%	\$0.00 (\$0.00)	\$118,260
	\$0.42 (\$0.50)	\$ 96,360
	\$0.95 (\$1.00)	\$ 74,460
	\$1.42 (\$1.50)	\$ 52,560
10%	\$0.00 (\$0.00)	\$236,520
	\$0.47 (\$0.50)	\$192,720
	\$0.95 (\$1.00)	\$148,920
	\$1.42 (\$1.50)	\$105,120

Assumptions:

105.5 GJ/h (10^8 Btu/h) heat input.

(36.3 Mg/h or 80,000 lb of steam @ 80% boiler efficiency)

No loss in combustion efficiency

$$k_L = 0.25 \quad k_L = 0.5 \quad k_L = 1$$

ASSUMED: RDF IS FREE. COMBUSTION EFFICIENCY UNCHANGED
OIL AT 42.56 MJ/kg, \$0.50/GALLON

FIG. 3-1. IDEAL FUEL SAVINGS VS. UNIT SIZE FOR
VARIOUS PERCENTAGES OF HEAT INPUT
FROM RDF (b)

$k_L=0.25$ $k_L=0.5$ $k_L=1$

ASSUMED: COMBUSTION EFFICIENCY UNCHANGED
OIL AT 42.56 MJ/kg, \$0.40/gallon

FIG 3-2. IDEAL FUEL SAVINGS VS. UNIT SIZE,
FOR VARIOUS PERCENTAGES OF HEAT
INPUT FROM RDF, b.

at quarter load on the average over the year, if the fuel is free. At the low end (10.55 GJ/h or 10^7 Btu/h), these figures would proportionally be reduced to \$23,652 and \$5,913, respectively.

It is readily apparent that, even in the most favorable combination of free fuel and no loss in combustion efficiency, the amount of savings which can be realized will limit retrofits to relatively low cost modifications on the larger units of the ranges being investigated.

Savings when the combustion efficiency is reduced

Realistically, a reduction in combustion efficiency should accompany the use of RDF as a supplemental fuel in oil firing. In previous work (12-14) it is stated that for utility-size oil-fired boilers using a 20% heat input from MSW, major losses in efficiency could be categorized as from:

- heating of additional excess air, 1%
- incomplete fuel combustion, 2%
- heating of additional fuel moisture (25% moisture in MSW), 4%
- increased dry gas losses due to increased flue gas volume, 1%

On this basis, a realistic estimate for $b = 10\%$ heat input from RDF might be 2 to 4 points in efficiency drop, from a 90% combustion efficiency for oil only.

Figures 3-3, 3-4 and 3-5, and Table 3-2 give the reduced yearly savings to be expected, for the same set of parameters as before, when the combustion efficiency is reduced from $\eta_c = 0.90$ (oil only) to 0.89, 0.88, 0.85, i.e., 1, 2 or 5 points of efficiency. In the calculation, a net output of 95 GJ/h (0.9×10^8 Btu/h) is assumed throughout, corresponding to an energy input of 105.5 GJ/h (10^8 Btu/h) at $\eta_c = 0.9$. For other values of η_c , the gross input will be correspondingly increased so as to maintain an output of 95 GJ/h (0.9×10^8 Btu/h) from the combustor.

With the same notations as above, applicable expressions are, for a net output $\dot{E}_{out}$ (J/h)

$$S = 8760 \times 10^{-9} \times k_L \left\{ - \frac{\dot{E}_{out}}{\eta_c} [b P_{RDF} + (1 - b) P_{OIL}] + \dot{E}_{out} P_{OIL} / 0.9 \right\}$$

From these figures, it appears that the potential savings resulting from the use of RDF are very sensitive to the decrease in combustion efficiency. A drop in combustion efficiency of 2 points practically precludes the use of RDF for less than 5% by heat input; a drop of 5 points would require a low priced RDF, at \$0.47/GJ (\$0.50/M Btu) or less, and a high contribution from RDF (8% or more).

Allowable Capital Cost

The allowable capital cost (A.C.C.) for the retrofit can be estimated from the yearly savings, S, computed as above. The

TABLE 3-2. SAVINGS FOR 95 GJ/h (0.9 M Btu/h) OUTPUT
(REDUCED COMBUSTION EFFICIENCY)

Percentage (by heat) from RDF	RDF price, \$/GJ (\$/M Btu)		1 point drop: $\eta_c = 0.89$	2 point drop: $\eta_c = 0.88$	5 point drop: $\eta_c = 0.85$
			Yearly Savings, Full Load ($k_L = 1$)	Yearly Savings Full Load ($k_L = 1$)	Yearly Savings Full Load ($k_L = 1$)
2%	\$0.00	(\$0.00)	\$21,260	-	-
	\$0.47	(\$0.50)	\$12,402	-	-
	\$0.95	(\$1.00)	\$ 3,543	-	-
	\$1.42	(\$1.50)	-	-	-
5%	\$0.00	(\$0.00)	\$ 93,013	\$ 67,193	-
	\$0.47	(\$0.50)	\$ 70,867	\$ 44,795	-
	\$0.95	(\$1.00)	\$ 48,721	\$ 22,398	-
	\$1.42	(\$1.50)	\$ 26,575	-	-
10%	\$0.00	(\$0.00)	\$212,602	\$188,141	\$111,304
	\$0.47	(\$0.50)	\$168,310	\$143,345	\$ 64,927
	\$0.95	(\$1.00)	\$124,018	\$ 98,550	\$ 18,550
	\$1.42	(\$1.50)	\$ 79,725	\$ 53,755	-

$$k_L = 0.25 \quad k_L = 0.5 \quad k_L = 1.0$$

CO-FIRING COMBUSTION EFFICIENCY = 0.89

FIG. 3-3. YEARLY SAVINGS IN FUEL COSTS VS. ENERGY OUTPUT/HOUR, FOR VARIOUS PERCENTAGES OF HEAT INPUT FROM RDF, b

CO-FIRING COMBUSTION EFFICIENCY = 0.88

FIG. 3-4 YEARLY SAVINGS IN FUEL COSTS VS. ENERGY OUTPUT/HOUR, FOR VARIOUS PERCENTAGES OF HEAT INPUT FROM RDF, b.

$$k_L = 0.25 \quad k_L = 0.5 \quad k_L = 1.0$$

CO-FIRING COMBUSTION EFFICIENCY = 0.85

FIG. 3-5. YEARLY SAVINGS IN FUEL COSTS VS. ENERGY OUTPUT/HOUR, FOR VARIOUS PERCENTAGES OF HEAT INPUT FROM RDF, b

following cost factors are used, following in the A.D. Little study on converted boiler systems to fire solid waste (15):

- yearly capital amortization, 8% for ten years: 0.149
 - yearly maintenance cost: 0.020
 - yearly power costs: 0.002
- 0.171

Labor costs are estimated at 2,000 hours @ \$7/h, with a 70% overhead (20% labor, 50% administrative) for a total of \$23,800. Thus

$$A.C.. = \frac{S - 23,800}{.171} \quad (3-6)$$

which is plotted vs. the yearly savings, S, in Figure 3-6.

Savings of less than \$23,800 would entail a loss.

If, for example, the energy output is 95 GJ/h (0.9×10^8 Btu/h) (full load) and the combustion efficiency is 0.89 (1 point drop), no retrofit can be justified regardless of the price of RDF with a 2% heat input from RDF. For a 5% input, the allowable capital cost at breakeven would be \$405,000 if the fuel is free, and only \$16,200 if RDF is priced at \$1.42/GJ (\$1.50/M Btu). Finally, for a 10% by energy input from RDF, these figures would be \$1,104,100 and \$327,050.

If we look now at the case where the combustion efficiency drops 5 points, from 0.9 to 0.85, due to the use of RDF, the allowable capital cost decreases markedly. Even for a 10% by energy input from RDF, it is only \$511,720 if the fuel is free, and already negative for RDF at \$0.95/GJ (\$1.00/M Btu).

FIG. 3-6 ALLOWABLE CAPITAL COST VS.
YEARLY SAVINGS IN FUEL COSTS.

Comments

The above discussion stresses some of the main points in assessing "how much of a retrofit" makes economic sense in attempting to substitute RDF for oil in institutional-sized boilers. Due to fixed costs, large units (in the 10.55 to 105.5 GJ/h (10^7 to 10^8 Btu/h) range) are the more likely candidates, and more so if they operate at full load for most of the time. Heat inputs from RDF should be in the 8 to 10% range, or higher, if the high ash production rates can be accommodated. Also, RDF should be available, delivered, at a price of \$0.95/GJ (1.00/M Btu) or less.

CHAPTER 4. OIL BURNERS: FEATURES AND RETROFIT ASPECTS

General

In this chapter, some of the main features of oil-fired boilers and burners are reviewed, and various technical aspects of possible retrofits of such equipment are discussed. This should place in perspective, and help to understand the manufacturers' views and reservations, as they are reported in Chapter 5.

Packaged Boilers

Whereas field-erected boilers are shipped in segments or separate parts, package boilers are assembled at the manufacturer's plant. It is only required that they be anchored on the foundation and connected to the peripherals.

A reasonable upper limit for packaged boilers size is 136 Mg steam/h (300,000 lbs steam/h). Installed costs per lb of steam are said to be about three times lower for packaged boilers than for field-erected ones (16).

Two designs are used: fire-tube and water-tube. In the fire-tube, the hot combustion gases flow inside the tubes of a boiler. In the water-tube, water flows through tubes immersed in the stream of hot gases.

In fire-tube boilers, the combustion of the fuel oil takes place in a chamber or furnace located in the lower part of the assembly. From there, the combustion gases, in a forced or induced draft, make a first pass in a central, large circular chamber, followed by one (two-pass), two (three-pass) or up to three (four-pass) additional passes through fire tubes before exiting to the

stack. The optimum economical size is around 12.7 Mg/h (28,000 lbs/h).

Water-tube boilers have a steam drum located on top of the furnace and either two mud drums at the bottom, connected to the steam drum by tubes forming "walls" ("A" type); or only one mud drum and tube "wall" on one side ("D" type). The A type is sometimes equipped with a water tube "floor" and "back wall" (on the side opposite to the burner). It is furnished in capacities of up to 136 Mg/h (300,000 lbs/h).

In order to improve the overall efficiency of these units, the sensible heat in the stack gases, at about 316°C (600°F), can be recovered by economizers or air heaters of the recuperative or regenerative type.

Since the ash present in the fuel oil (particularly heavy oil) may foul or corrode the surface of the tubes, soot blowers might be needed as a method of ash removal from the surfaces to be cleaned. Normally, no other ash removal equipment is provided (except for fly ash).

Oil Burners

It is fairly common practice that with the package boiler, the fuel burning assembly comes as a completely integrated unit, manufactured by the boiler maker or a specialized company. Many of these have multi-fuel capability, and can fire oil, natural gas and possibly selected solid fuels.

The main types of burners are the cell, circular register, and cyclone types. They normally are located in the vertical walls of the furnace. Their design is obviously very much determined

to meet requirements of simplicity, reliability, minimum space, and ease of operation at fractions of the rated load while maintaining stable and complete combustion throughout the range.

Cell Burners

These burners are especially suited for the combustion of natural gas, due to the good stability they provide even under combustion air flow variations (17). Oil is injected in the center through an impeller which creates rotation and mixing of the fuel. The central part is surrounded by a circle of gas spuds equipped with flame retainers which stabilize ignition at reduced loads. The (secondary) combustion air is introduced through an annulus of registers, adjustable through a common central linkage.

Cell burners have ratings of up to 552 GJ/h (495 M Btu/h). The injection of solid fuels (principally pulverized coal) takes place in an annular region between the core (where oil would be atomized) and the outer annulus of gas spuds. Simultaneous injection of coal and oil might lead to coking on the pulverized-coal element and is not recommended.

At full load, air injection velocities at the secondary air ports are in the range from 20 m/sec (4000 FPM) for unheated air to 30 m/sec (6000 FPM) for preheated air at 316°C (600°F).

Circular Burners

The circular burner has a central, fuel-carrying rod connected to a diffuser core and impeller. The oil is atomized at the end, and the impeller provides a gyration to the fuel and surrounding air. Secondary air enters through the air register doors (louver-like) centered around the fuel tube. The throat

section surrounding the flame ignition zone is often made of refractory material with studded water tubes connected to the outer side. The capability of a circular burner is up to 174 GJ/h (165 M Btu/h). Velocities at the secondary air registers are again from 20 m/sec (4000 FPM) to 30 m/sec (6000 FPM).

Cyclone Burners

The cyclone burner is based on the idea that the high temperatures needed for complete combustion could be maintained in a chamber separate from the main boiler furnace where cooling of the combustion gases will occur. It was designed to accommodate coal of lower ranks, and allows the use of coals of ash content of up to 25% (dry basis).

The burner has the form of a horizontal cylinder, refractory-lined and water cooled. It comprises a smaller radial burner, and a main barrel or cyclonic chamber. At the center of the radial burner, a small amount of "tertiary" air is introduced (5%). The oil burner can be located along the axis of this burner. If crushed coal is used, it is introduced tangentially in the second part of the radial burner, together with tangential primary air (about 20%). The coal or solid fuel acquires a whirling motion. In the adjacent cyclonic chamber, secondary air enters tangentially and further centrifuges the solid particles to the wall. They are held to the wall on a bed of molten slag, where combustion is completed. Oil also can be injected in the secondary air stream, and the burner can be left in place if coal is fired.

Heat release rates reach 16.73 to 29.74 GJ/m³, h (800,000 Btu/ft³, h), combustion temperatures 1649°C (3000°F),

and the low absorption rates at the wall explain how the temperatures needed to keep the slag molten (2600°F or lower) can be maintained. The liquid slag continuously flows from the chamber into the boiler furnace, where it is tapped, solidified and disposed of.

Note that most of the ash from coal is retained in the molten bed, thus fly ash emissions will be much lower than for other solid fuel burners.

Implications on Retrofits for RDF Co-firing

The characteristics of oil-fired (or multi-fuel) burners and boilers discussed above have direct implications in several aspects of retrofitting for cofiring with RDF, namely: fuel injection, excess air, and ash collection.

Fuel injection: As a solid fuel, RDF would be most conveniently fired as pulverized coal in cell or circular burners (70 to 85% less than 200 mesh, or 74 microns). Injection velocities would be in the 15 m/s to 25 m/s (3000 FPM to 5000 FPM) range.

Another possibility explored with manufacturers was to inject suitably sized RDF with the secondary air flowing through the registers surrounding the fuel conveying rod, as is the case for some wood or other organic waste burners or the vortex type (see Chapter 5).

Cyclone burners would appear to be ideally suited to the injection of RDF through the secondary injection port, or in powdered form through the pulverized coal feed port on top of the radial burner.

Excess air: Experimental evidence is rather scanty on the amount of excess air needed to sustain the combustion of RDF and oil in various proportions (18). It is well known that cell and circular burners, properly adjusted, will operate with less than 10% excess air and as low as 5% when using only oil. Multi-fuel burners operate with excess air of 10 to 20%. Cyclone furnaces operating on crushed coal require 10 to 15% excess air. Based on the excess air requirements for cellulosic type of fuels in vortex burners with a feed size of about 1 mm ($\approx$ 20 mesh), the required excess air at moderate heat inputs from RDF is estimated to lie in the 10% to 15% range.

Ash collection: Except for the use of soot blowers, oil-fired boilers in the range of sizes investigated are not designed to accommodate large amounts of bottom ash, such as the ten-fold (or more) increase to be expected for the same output energy. However, cyclone burners, or variations thereof, can be used as oil burners and simultaneously fire a solid fuel of high ash content (such as RDF) since the ash will be collected as a liquid slag prior to the boiler tubes enclosure.

Fusion temperatures of RDF ash at Ames, Iowa (19) were in the range of 1127°C to 1249°C (2060°F to 2280°F). No information is available on the viscosity of such ash at these temperatures. Note that for coal the " T_{250} "-criterion is used, the temperature at which the fuel ash has a viscosity of 250 poises. At this viscosity, slag will "just flow" on a horizontal surface (20).

The distribution of ash is typically 80% fly ash, 20% bottom ash for pulverized coal, dry-ash furnaces; 50% fly ash,

50% bottom ash for PC slag-top furnaces; and 20% fly ash, 80% retained ash (tapped) in cyclone furnaces.

For mixtures of oil and RDF, Galeski and Schrag (21) computed the split between fly ash and bottom ash in oil/RDF cofiring utility-sized boilers, using an assumption based on test results at the Saint Louis Union Electric facility (with shredded MSW and coal). Namely, with increasing MSW heat input, there is no apparent net increase in flue gas grain loading. The amount of ash reporting to fly ash, 16%, was found to agree favorably with the average value they found for waterwall incinerators, i.e., 13% (21).

In estimating emissions, there is obviously a need to know the feed particle size-distribution, the type and geometry of burner and combustor used for the retrofit, as well as the existing or additional pollution control devices used to clean the flue gas.

Comments

The three main "touchstones" of technical feasibility for the proposed retrofit are identified as: RDF feeding and sizing, excess air necessary, and ash generation, collection and removal.

CHAPTER 5. SURVEY OF MANUFACTURERS FOR SCOPE AND COST OF RETROFIT

Introduction

To assess the practical feasibility to retrofit an institutional-size, oil-fired boiler for co-firing with RDF in the immediate future, a survey of manufacturers of burners and/or boilers was conducted. These consultations were mostly by mail or phone, but several visits and technical meetings with engineering personnel took place.

Survey Procedure

The manufacturers surveyed were drawn from the latest list of "Active Member Companies and Plants" of the American Boiler Manufacturers Association (ABMA); a recent list (1977) published by Pollution Engineering Magazine of selected manufacturers of "waste incinerators"; and the THOMAS register. A total of 42 companies were contacted.

Our inquiry was basically worded as follows: "Do you presently have available, or could you readily engineer, for an oil-fired boiler in the 10 M Btu to 100 M Btu per hour range, a retrofit arrangement to allow the co-firing of oil and RDF? The percentage of the energy contribution due to RDF is not expected to be much below 10%. The percentage of ash, on a dry basis, is expected to range 15 to 25%. Moisture is estimated at 20 to 25%. The higher heating value of the RDF ranges 12.8 to 14.0 MJ/kg (5500 to 6000 Btu/lb). Sizing can be assumed to be as per your technical requirements."

Of the 42 companies contacted, two-thirds expressed limited interest and later declined to pursue the matter. One-third chose to discuss, send literature and/or correspond. Among those who declined, the largest fraction did not manufacture burners themselves but purchased them from other companies with whom we had technical discussions. A smaller number only dealt with much larger, utility-size burners and boilers. Two companies responded after a short period of technical analysis that they had no solution available.

Of the 14 companies initially interested: 10 sent letters and technical literature concerning their products; two failed to send the information promised; one was working on a prototype in the 10^8 Btu/h range, but was not willing to part with data at this time; one was most helpful in verbally analyzing for us the reasons for limiting the size of cyclone burners significantly above the 10^8 Btu/h upper limit of this study.

A further breakdown on the basis of size of manufactured equipment is (for the 14 companies responding):

- "Small" (up to 100,000 lb/h): 8
- "Small" and "large" (more than 100,000 lb/h): 2
- "Large" (more than 100,000 lb/h): 4

Survey: Main Results

Before proceeding to report and analyze in detail the teachings from this survey, it might be of interest to summarize what we were told.

First, not a single one of the respondents considered that the retrofit was possible with only minor modifications to existing, off-the-shelf hardware. In many cases, modifications, if at all possible, were viewed as "major" and "expensive," probably exceeding in cost and certainly in complexity the purchase of a separate, RDF dedicated combustor. These modifications would pertain mostly to: the solid fuel sizing, feeding and injection equipment; the removal of bottom and fly ash; the steam tubes location and spacing, for protection against corrosion and abrasion; and the air-pollution control equipment. Even with these changes, there would be no guarantee of success or economical advantage. In essence, the reactions were mostly negative and provided little encouragement.

Second, in those cases described below where a technical solution could be seen, it was apparent that the time-frame involved was much larger than a few months. What was required was at least the scaling down and factory testing of some proprietary burner designs, or a major redesign of existing equipment of the appropriate scale but normally burning fuels of much lower ash content than RDF. In any event, we are faced here with an applied (or even theoretical) research and development effort which many of the smaller firms did not seem to be willing to fund on their own. The larger manufacturers, obviously, tend to give priority to bigger units, with proprietary methods to process the solid fuel and co-fire it.

Third, a medium-to-long term development of "co-firing" schemes for smaller units would proceed along one of three routes:

- The use of slagging burner, in which the solid fuel of high ash content is injected in a cylindrical chamber along a vortex of horizontal axis. The solid fuel and ash particles centrifuge to the wall on a liquid bed of molten slag where combustion is completed. The walls of the chamber are refractory-lined, water cooled, and the hot combustion gases contain little residual ash when they enter the boiler furnace volume.
- The use of a modified, double vortex-type non-slagging burner, as is presently used for combustion of forest and agricultural wastes of low ash content (2% or less). The solution here would be based on the use of the supplemental RDF fuel (having an ash content of, say 20%), for only 10% by heat in the co-firing scheme. Given a proper sizing of the feed product and the appropriate gas flow pattern, all of the ash would fly. The amount of ash to be dealt with then should not exceed that present when burning 100% of a solid waste fuel of similar heating value having only 2% ash.

- Finally, as a "misnomer", co-firing with oil could be replaced by "co-generation" in a separate, RDF dedicated unit, used to generate low pressure steam or preheat the feedwater.

The manufacturers' responses are now discussed in detail, broadly dividing the units between "large" (L), "small" (S) or both (L/S).

Detailed Review of Manufacturers' Responses

For obvious reasons, it is not possible to identify the manufacturers by name in each specific case. However, the reader might wish to refer to a partial list, in Appendix A2, of companies having an interest in the co-firing of oil and RDF in institutional-size boilers. No claim is made that the list is comprehensive and no endorsement is implied.

Manufacturer "M₁" (L)

For the problem at hand, this manufacturer essentially would suggest a cyclone furnace (see Chapter 4). They have had extensive experience in the co-firing of oil and crushed coal in this type of furnace. The smallest unit, installed at a university, is a 77.2 Mg/h steam (170,000 lb steam/h) boiler. The next smallest one, rated at 158.9 Mg/h (350,000 lb/h), was sold to a utility company. Higher heat releases, flexibility in accommodating coals of high ash content (up to 25%, dry basis), low excess air, low size-reduction power requirements are among

the main advantages. A drawback is the formation of nitrous oxides due to the high flame temperatures using coal, in excess of 1649°C (3000°F). However, this might not be a significant problem if a fuel of lower heating value, such as RDF, is used. Another limiting factor is the high power requirements for conveying of the fuel and the generation of the vortex, 4.98 to 9.96 kPa (20 to 40 in.W.G.) pressure drop, instead of 0.50 to 2.49 kPa (2 to 10 in.W.G.) for pulverized coal units. This results in setting a lower limit, significantly above 45.4 Mg steam/h (100,000 lb steam/h), for the range of application of cyclone furnaces. As far as could be determined, this company has no plans at present to develop smaller cyclone burners, or cyclone burners specifically studied for the combustion of RDF.

Manufacturer "M₂" (L/S)

This company is a manufacturer of combustion systems, with or without heat recovery. Recovery is affected in a variety of ways, including thermal fluid or hot water as the heat conveying medium. The company also designs and manufactures burners, burner assemblies and other peripheral equipment. A low excess air burner of the register type, normally using fuel oil or gas, operates at 2 to 5% excess air. It is based on a double vortex configuration -- one is created by the blades of the secondary air register, the other by the impeller in the diffuser core surrounding the top of the fuel injection rod.

However, this was not the configuration or device recommended. It turns out that the company is presently working on the advanced design and prototypes of a slagging burner to co-fire oil or gas and a processed, proprietary form of RDF in pulverized form, or high ash coals. The feed would be sized, typically, for pulverized sub-bituminous coal, at 90 % less than 0.1 mm (140 mesh). The main targets of the effort are the utilities, but scale-down is said to be possible, to allow retrofitting onto existing institutional-size boilers. There was a definite expression of interest on the part of the company to cooperate. Mention was made that a 3.17 GJ/h (3 M Btu/h) burner used at their test facility might be made available for industrial experimentation, subject to future negotiations.

Although an experimental venture of this kind would certainly be of high technological value, it is not thought to be within the scope of a retrofit and burn scheme, but rather well advanced research and development in using a proprietary device. Furthermore, proper functioning might have been predicated upon using a form of RDF processed by a proprietary method, about which little is known, from a technological or cost viewpoint. The possibility, however, is to be kept in mind if a suitable framework of funding and disclosure could be worked out.

Manufacturer "M₃" (S)

This company manufactures package burners for gas and oil-fired units, for firing rates of up to 56.8 Mg steam/h (125,000 lb steam/h) for a single burner. Single air registers are used

in units to 18.2 Mg steam/h (40,000 lb steam/h), dual registers on larger units. Excess air is normally 15% for oil, 10% for gas. In the dual circular register burners, flame shaping is effected by a small, uni-directional register and a large, multi-directional register. Oil and gas are often used in combination.

This supplier also routinely manufactures packaged steam boilers of up to 45.4 Mg steam/h (100,000 lb steam/h) capacity.

They have three main lines of boilers: one is basically the water tube type, with capacities in the 3.4 Mg to 45.4 Mg/h (7,500 to 100,000 lb/h) range, and design pressures from 1.38 to 5.17 MPa (200 to 750 psig). It is normally used for gas and liquid fuels only. Another line has a section with two waterwalls, one upper drum and one lower drum, and ratings in the 2.27 to 18.14 Mg steam/h (5,000 to 40,000 lb steam/h) range. The third one is for larger capacities (not packaged). The last two lines were designed for capability with gaseous, liquid or solid fuels (stoker fed or pulverized).

Initially, this manufacturer expressed interest in considering a retrofit on one of their 17.24 Mg/h (38,000 lb/h) boilers installed at a military facility in the Washington, D.C. metropolitan area.

To assess the feasibility of such a retrofit, this company requested specific information regarding feeding and sizing of the solid fuels, the ash fusion temperature of RDF, and the ash viscosity of RDF at combustion temperatures.

Fusion, hemispherical and softening and initial deformation temperatures reported by J. C. Even et al. (19) were given to the supplier. Costs to reduce the size of RDF to the millimeter or fraction of a millimeter range are not readily available, due to the fibrous nature of the material. Some estimates made by grinding equipment manufacturers we consulted then might add as much as \$22/Mg (\$20/ton) processed. An offer was made by one of the suppliers to run grinding costs on RDF, at a fee deductible in case of purchase of their equipment.

A technical evaluation was made over a period of several weeks by this manufacturer, receiving the information we provided to them on the refuse-derived fuel. In final analysis, they resolved that they could not supply a burner for RDF and oil co-firing. This vendor declined to do further work on this project, but might cooperate in an experiment on one of their boilers equipped with some other vendor's burner.

Manufacturer "M₄" (S)

Manufacturer M₄ designs, engineers and fabricates combustion systems, burners and packaged control systems using standard fuels (gas, oil) or wood wastes, bagasse fines, rice hulls, or other finely ground organic fibers.

The design of their waste fuel burner is based on effecting turbulent mixing between two counter-rotating concentric streams, or vortices having a horizontal axis. The resulting flame is said to be compact, with beneficial results in boiler applications.

The finely ground solid fuels are fed through a scroll at the interface between the two vortices, entering this zone at low velocity. Combustion originates back in the throat of the burner. Complete combustion is effected in suspension, and air pollution is minimized.

Sizing of the solid fuels is in the 1.6 to 0.4 mm (1/16 to 1/64 inch) range. This is normally effected by a combination of hogger, dryer (if needed), grinder and dust collectors.

No special provisions exist for settling ash. It is claimed that proper sizing of the fuel will result in having all ash particles reporting to fly ash. A normal upper limit for the ash content of waste fuels handled is approximately 2%.

We provided Manufacturer M₄ with data pertaining to the variety of RDF produced by NCRR and used at Hagerstown, Md., in two boilers rated at 22.68 to 31.75 Mg steam/h (50,000 to 70,000 lb steam/h) of the stoker-fired type.

After further correspondence and telephone conversations, one of the chief engineers of the company outlined the elements of a medium-term solution, subject to more research work and measurements on a few critical points. The technical features are summarized below.

Technical features of a possible solution

Burner: The burner to be used would be based on their exclusive dual vortex design, with injection of the solids fines in the turbulent mixing zone between the two vortex annuli. The concept is well proven on conventional package boilers, using as

fuels hydrogen, natural gas, fuel oil, pitch tar, wood waste, straw, fruit pits, leaves, bagasse, etc.

Boiler design: If the ash initial deformation temperature is in the range 1032°C to 1154°C, mean 1106°C (1890°F to 2109°F, mean 2023°F) and the fusion temperature in the range 1127°C to 1249°C, mean 1177°C (2060°F to 2280°F, mean 2150°F), the boiler furnace outlet temperature might need to be maintained at or below 1010°C (1850°F), approximately, to avoid excessive ash buildup on convection tube surfaces. The boiler will also have to be fitted with properly sized soot blowers so as to keep the convection section free of ash and soot accumulation.

Solid fuel sizing: A 0.4 to 0.5 mm (0.016 to 0.020 inch) maximum size would be acceptable for most package boilers, i.e., if the space heat release rates are lower than 1.86 GJ/m³, h (20,000 Btu/cft, h). It is possible that particles of up to 1 mm could be fed if the release rate does not exceed 0.74 GJ/m³, h (20,000 Btu/cft, h).

Ash production and particulate collection: Our suggestion to fire only a portion of the boiler load with RDF (no more than 10% by heat, for example) was thought to have some merit, in that the total mass of ash resulting from the co-firing of oil and a 20% ash RDF would be no more than that from the combustion of a similar solid waste with a 2% ash content. In this case, depending on the local standards, pollution codes could be met with a simple mechanical collector.

Points of special interest: Some points were thought to deserve special attention.

There exists a possibility that an eutectic might form, with a low melting point, between the #6 fuel oil ash and the RDF ash. This was found not to be of concern for coal and oil mixtures. A test for RDF and oil ash should be done to check for the existence of such an eutectic.

Abrasion of the registers by RDF might be a problem. In that case, the manufacturer would recommend a design similar to the one they presently use for pulverized coal. The scroll assembly is fitted with a special ceramic lining.

Safety features should be included to prevent undesirable shut-off of the boiler. When the solid fuel feeding system no longer operates properly, the full load should be automatically switched onto the fossil fuel (oil or gas).

Boiler design: in most cases, the boiler would have to be modified to increase the residence time in the furnace. Residence time should be about three seconds.

In conclusion, it was the opinion of this manufacturer that real possibilities existed here to develop a design compatible with a retrofit of an oil-fired boiler, with heat exchange surfaces modified, equipped with soot blowers, and abrasion resistant scroll assembly. However, experimentation on oil and ash mixtures, sizing of the feed and abrasion of the registers ought to precede any full-scale industrial trials.

Manufacturer "M₅" (L/S)

This company could not readily supply a retrofit burner for our purpose. However, through a patented process, they process a variety of biomass products, such as rice and peanut hulls,

tree bark, wheat straw, wood, manure, peat, as well as "municipal refuse" and "sewage sludge." Fuel can be produced in the form of small cylindrical pellets (about 9.55 mm (3/8") dia. x 3.2 mm (1/8") length)

The burner developed by the company is of the cyclonic type, with hot ash removal. Injection of the finely ground solids is on the side of the vortex injection air ports opposite to the hot gases exit section. The clean hot gases go to a hot cyclone for additional particles collection before use.

The customer list does not contain any installation using municipal solid waste, but a number of references for sawdust, alfalfa, sander dust, bagasse, etc. are included.

The system sells as a package for use with their own "refined" fuels.

Manufacturer "M₆"

In this case too, this manufacturer did not have available equipment for the proposed retrofit, but they expressed interest in a possible test firing of the 454 kg (1,000 lb) sample as part of a series of tests they are presently conducting on a new developmental boiler.

Their present line covers steam generation systems in the range of 0.32 to 31.75 Mg steam/h (700 to 70,000 lb steam/h), at pressures up to 2068 kPa (300 psi). Fuels used are gas, oil and solids. The increase in fuel costs and environmental constraints has induced them to develop a multi-fuel (oil, gas, coal) fluidized bed combustor which can use any of these fuels separately or in combination. A prototype is being tested.

The projected capacity, per unit, should range from a low of 1.50 to 18.14 Mg/h (3,300 to 40,000 lb/h). Design pressures will be up to 1724 kPa (250 psi). The combustor will be a multi-cell fluidized bed packaged unit, using coal (including high ash and high sulfur coals), gas, oil and waste materials. Turndown ratios will be at least 3 to 1, possibly as much as 6 to 1.

Ash removal will be automatic, from the chamber into a hopper, so as to maintain a constant bed level.

Combustion efficiency should be in excess of 90%, with fuel to steam efficiency of 76% (coal), 80% (gas) and 83% (oil).

Such a system might be used as a separate, RDF dedicated unit, "co-generating" rather than "co-firing."

Manufacturer "M₇"

This company manufactures and engineers burners and combustion systems, with heat rates in the 6.33 GJ/h to 47.48 GJ/h (6 M Btu/h to 45 M Btu/h) range. The burner system uses a variety of wood residues for industrial processes, such as veneer dryers, dry kilns, dryers and package boilers.

The burner is of the cyclonic, dry-ash type. Air is injected tangentially, as is the pneumatically conveyed solid fuel. The combustion chamber is refractory lined, with one end closed. The other end has a constricted section, refractory-lined, through which the gases exhaust.

A variation of this design, using a slagging mode, with slag top and ash quenching, was used to some extent in the past but

is no longer marketed. Apparently, some difficulties were experienced in liquefying wood ash at temperatures below 1371°C (2500°F) and refractory life was thereby reduced. The manufacturer agreed with us that RDF ash, fusing at 1177°C (2150°F), probably would not be as much of a problem.

The presently available dry-ash system uses mostly fuels with a low ash content, typically around 0.5%, and never higher than 2%. Feed size specified for "thick" veneer, for example, is from 2.5 mm (1/10 inch) to 4.2 mm (1/6 inch). A "nominal" size might be 3.2 mm (1/8 inch), typically.

Although the manufacturer acknowledged that there might be a sizable potential market in developing this cyclonic burner for solid fuels of high ash content, such as RDF, they have no immediate plans or funding available to develop the slagging feature. They expressed an interest in keeping in touch should this situation change in the future.

Manufacturer "Mg"

The company manufactures vertical axis cyclonic furnaces which they say are suitable for the combustion of RDF. The flue gases can be used for steam generation. The system would thus be a separate unit, not a retrofit "kit" for oil and RDF in an existing institutional boiler.

Others

A number of quotes and descriptive literature were received from manufacturers of fluidized combustion systems. These vendors

proposed that the RDF in fact be burned in a separate, dedicated unit, to preheat the boiler feedwater or raise steam, and provide a fraction of the energy load. The ratings of these units ranged from 5.28 GJ/h to 82.29 GJ/h (5 M Btu/h to 78 M Btu/h), a typical "mean" value being 15.83 GJ/h (15 M Btu/h).

This alternative is not within the scope of the present investigation, but is mentioned as another possible approach to using RDF as an auxiliary fuel.

Preliminary Discussions with Potential Users

It became increasingly apparent, in the course of our investigation, that the hardware to retrofit an oil-fired boiler of institutional size for co-firing RDF is still to be designed. We had to limit our discussions with potential users, both in number and in scope.

Papermill, New Jersey. Early in this work, we contacted a paper manufacturer operating mills in various parts of the country. Our organization maintains close contacts with this company, and they were agreeable to discuss a possible retrofit in one of their New Jersey plants. That particular plant has four boilers (plus one package type boiler). The four boilers are rated at 226.8 Mg steam/h (500,000 lb steam/h), and are used on the average at 136.1 Mg steam/h (300,000 lb steam/h), total load.

The units were retrofits from coal to oil. During their coal-burning past, they were equipped with Riley stokers and an ash sluicing circuit. The steam pressure is either 2578 kPa (400

psi) and 324°C (615°F) or 3867 kPa (600 psi) and 399°C (750°F).

It was hoped that these might be ideal candidates for a retrofit experiment. Unfortunately, and this is likely to occur quite often, all devices having to do with coal feeding and ash handling were disassembled and removed when retrofitting for oil. They were sold or otherwise disposed of. Furthermore, the physical space they occupied is taken by other hardware. The boilers presently are fueled with low-sulfur oil, with no pollution control devices required. The company engineering management thought that even if it were immediately possible with proven hardware, the costs of a retrofit would be unrealistically high. Furthermore, all of these boilers are operational, and the company would take no risks that could impede production.

Military base, Washington, D.C. area. As described under Manufacturer "M₃", a 17.2 Mg/h (38,000 lb/h) package oil-fired boiler in use at a military base in the Washington, D.C. metropolitan area had been located at the suggestion of the boiler system vendor. However, after reviewing the characteristics of the RDF, the company stated that their line of business could not handle the retrofit. A retrofit of their boiler would have to wait for the development of a specially designed burner, by others.

Applied Physics Laboratory, Johns Hopkins University, Laurel, MD. Preliminary discussions were held at the National Center for Resource Recovery and at the Applied Physics Laboratory with some of the scientific staff and boiler operators. The purpose of

this investigation was explained and a technical presentation was made by NCRR engineers in March, 1978. Seven staff members from APL were in attendance.

Two oil-fired units at their facility were discussed and inspected. One is using #2 fuel oil at a 178 l/h (47 gallon/h) rate, to generate 544 kg/h (1200 lb/h) of 1724 kPa (250 psi) steam. The heat release is approximately 6.96 GJ/h (6.6 M Btu/h). It is a facility boiler in continuous use, and possibly difficult to use for the trials and errors of an experimental program. The other is an oil heater used to heat an accumulator matrix rated at approximately 1.37 GJ/h (1.3 M Btu/h) and used when needed, about three days a week.

After inspecting the boiler site, it was concluded that there was little or no space for a solid fuel feeding system. Fitting an ash collection system between the burner wall and the building concrete wall also appeared impractical.

Interest was expressed by our contacts at APL in cooperating with us in research efforts to

- define or get a better grasp of the mechanics and thermodynamics of swirling and/or wet wall burners for the co-firing of RDF and oil
- test models or prototypes of such a device, using their existing combustion cells and testing facilities.

The laboratory is very well equipped for experiments in developing advanced combustion and heat transfer systems. It has extensive air, steam, electrical, heating supply systems and specially

instrumented test cells where combustors can be tested and data acquired for processing in an elaborate control and data processing system.

Conclusion

As stated earlier, after detailed consultations with experienced equipment manufacturers, it appeared unfeasible at the present time to assemble from existing, proven components or systems an off-the-shelf or slightly modified "retrofit kit" that could be used to allow co-firing of RDF and oil in institutional-size boilers.

However, the paths leading to some answer to the problem appeared quite clearly. They are: the development of slagging burners, the use of dry-ash double vortex burners in retrofitted boilers and the operation of a "side" RDF dedicated combustor of simple design.

Especially on the two first approaches, much more research and development, technological or theoretical, is needed before proven hardware becomes readily available for a retrofit experiment.

CHAPTER 6. FUTURE SOLUTIONS AND RECOMMENDATIONS

This chapter is a summary of three approaches which hold the best promise of success in retrofitting an institutional size boiler 10.55 to 105.5 GJ/h (10 to 100 M Btu/h) for cofiring of oil with RDF.

Cyclonic type, slagging (or "wet-ash") burner for RDF and oil.

As is clear from the discussions of the previous chapters, the prevalent concern expressed by manufacturers and potential users alike is with the manyfold increase in ash production, even at an RDF input by heat not exceeding 10%; its subsequent deposition on tube surfaces; and the erosive effects of increased fly ash.

The use of a slagging burner, for example, of the type mentioned above (Manufacturer M₂), presently at the prototype stage, would alleviate most of these potential problems. Combustion and ash capture take place in a chamber separate from the boiler furnace. Indications are that the amount of fly ash (4% of total ash in one example, using sub-bituminous coal) is drastically reduced, and that particulates, NO_x and SO₂ emissions are low. Furthermore, these units can be designed throughout the size range of interest 10.55 to 105.5 GJ/h (10 to 100 M Btu/h). Developmental work is in progress on various aspects of the design and in the area of materials.

It is recommended that the problem of feed sizing for a typical shredded, air classified refuse-derived fuel to be used in a slagging burner be investigated as regards requirements for good

operation of the burner. For ignition, the smallest dimension of the fuel particles is of significance; constraints on feed sizing of "flakes" or "fibers" of paper or plastics might be less strict than for spherical or bulky particles, such as pulverized coal.

It is also recommended that theoretical and experimental effort be spent on the fundamentals of combustion of RDF and liquid fuels in a wet-ash cyclonic combustor. A recent article (21) notes such current interest in swirl burners "confined in furnaces and enclosures of small area ratio." The objective is to better understand combustion systems of restricted size and smaller pressure drop, and to provide furnace design for the stabilized combustion of low calorific value fuels.

Double vortex, dry ash burner, at low RDF energy input, in a boiler retrofitted for wood and agricultural waste burning.

The elements of this solution were outlined above (Manufacturer M_4). It includes limiting the heat input from RDF to a level such that the total mass of ash produced is no more than that produced by the combustion of a wood waste having a 2% ash content. For example, the heat input from RDF should not exceed 10%, or its mass input 25%, if its ash content is 20% and it is cofired with an ash-free oil. Also, the solution requires modifying the boiler surfaces and residence time so that the combustion gases temperature is kept below the minimum ash softening temperature of RDF of about 1032°C (1890°F); and feed sizing at approximately 0.5 mm (0.020 inch) for space heat releases of 1.86 GJ/m³, h (50,000 Btu/ft³, h), and possibly as high as 1 mm (0.039 inch) for 0.74 GJ/m³, h

(20,000 Btu/cft, h). Soot blowers will be needed. It is recommended that investigations be conducted on equipment and processes for the size-reduction of RDF from fluff dimensions to those required by the burner specifications. Also, measurements and qualitative observations should be made on laboratory and industrial units, specially designed or modified for RDF, of the combustion characteristics and stability (efficiency, ash despoits, fly ash particle size distribution). Also, after proper operation under laboratory conditions has been obtained, a retrofit should be made on an industrial boiler already modified to allow 100% heat input (at a fraction of the rated load) from low ash waste "fines" (2% maximum) such as from wood, rice hulls, wheat straw, etc. The ash generated for the selected heat input from RDF should not exceed the total amount generated when firing the waste fuels having a 2% ash content.

Auxiliary, separate unit (fluidized bed combustor) in the loop of the main boiler

This approach is not "cofiring," but rather generation side-by-side of hot water or steam by the oil-fired boiler and a dedicated RDF burning unit.

The capacities of fluidized bed combustors for RDF, as mentioned above in Section 5, span the range of interest, 10.55 GJ/h to 105.5 GH/h (10 M Btu/h to 100 M Btu/h).

It is claimed that simple mechanical collectors will often suffice to meet pollution regulations. Hot water or steam generation would be through a heat recovery boiler of standard design.

It is recommended that the operation of an auxiliary fluidized bed combustor using RDF to provide a fraction of the load (as

preheated feedwater or steam) of an oil-fired boiler of institutional size be monitored over a period of several weeks. Besides studying the operational characteristics and stability of the combustor using RDF, the coupled system oil-fired boiler/RDF-fired combustor should be investigated for thermal and combustion efficiency and response to load variations for various energy splits between the two fuels.

References

- (1) H. Alter, J. Arnold, "Preparation of Densified Refuse-Derived Fuel on a Pilot Scale," Proc. of the Sixth Mineral Waste Utilization Symposium, sponsored by U.S. Bureau of Mines and IITRI, Chicago, IL, May 2-3, 1978, pp. 171-177.
- (2) M. L. Renard, "Refuse-Derived Fuel and Densified Refuse-Derived Fuel," Research Monograph RM 77-2, National Center for Resource Recovery, Washington, D.C., June, 1978, 67 p.
- (3) M. A. Buffington, "How to select package boilers," Chem. Engrg., 82, 23, Oct. 27, 1975, pp. 98-106.
- (4) Babcock and Wilcox (Co.), Steam, its generation and use, Rev. 38th Edition, New York, NY, 1975, p. 5-18.
- (5) R. E. Grey (Ed.), Principles and Practices of Incineration, Wiley Interscience, New York, 1969, pp. 16-24.
- (6) Op. cit, Ref. (4), p. 6-4.
- (7) L. Hearn, "Observations Regarding Preliminary RDF-3 Samples," Williams Bros. Process Services, Inc. Tests dated 8/26/77, 8/30/77, 9/5/77.
- (8) Op. cit, Ref. (4), pp. 7-6, 7-7.
- (9) Op. cit, Ref. (4), p. 6-10.
- (10) J. B. Galeski, M. P. Schrag, "Performance of Emission Control Devices on Boilers Firing Municipal Solid Waste and Oil," Report EPA-600/2-76-209, Midwest Research Institute, Kansas City, MO., July, 1976, pp. 24-26.

References (continued)

- (11) P. Muehlberg, "Assessment of Economic Viability of the d-RDF System Concept," Final Report, EPA Contract 68-03-2568/7002, Dow Chemical, Freeport, 1978, p. 55.
- (12) Op. cit, Ref. (10), p. 24
- (13) D. E. Fiscus, P. G. Gorman, J. D. Kilgroe, "Bottom Ash Generation in a Coal-Fired Power Plant when Refuse-Derived Supplementary Fuel is Used," ASME Solid Waste Processing Conference, Boston, MA, May 23-26, 1976.
- (14) T. R. Blackwood, W. H. Hedley, "Efficiencies in Power Generation," EPA 650/2-74-021, March, 1974.
- (15) Study of the Feasibility of Federal Procurement of Fuels Produced from Solid Waste, EPA Report SW-123C, Arthur D. Little, Inc., Cambridge, MA, July, 1975, p. 3.19.
- (16) Op. cit, Ref. (3), p. 99.
- (17) Op. cit, Ref. (4), p. 7-5.
- (18) Op. cit, Ref. (10), p. 26.
- (19) J. C. Even, S. K. Adams, P. Gheresus, A. W. Joensen, J. L. Hall, D. E. Fiscus, C. A. Romine, "Evaluation of the Ames Solid Waste Recovery System, Part I", EPA 600/2-77-205, Cincinnati, U.S. Environmental Protection Agency, 1977, p. 43.
- (20) Op. cit, Ref. (4), p. 10-3.
- (21) N. Syred, K. R. Dahman, "Effect of High Levels of Confinement Upon the Aerodynamics of Swirl Burners," AIAA Journal of Energy, 2, 1, January-February, 1978, p. 8.

APPENDIX A1

COMPOSITION OF PRODUCT GASES VS. RDF INPUT HEAT AND EXCESS AIR

<u>EA (PERCENT EXCESS AIR)</u>	<u>PERCENT HEAT INPUT FROM RDF</u>	<u>COMPONENT</u>	<u>WEIGHT FRACTION, PERCENT</u>	<u>VOLUME FRACTION, PERCENT</u>
0	0	CO ₂	21.81	14.54
		H ₂ O	7.22	11.77
		SO ₂	0.32	0.15
		N ₂	70.65	73.54
		O ₂	-	-
	5	CO ₂	22.01	14.63
		H ₂ O	7.91	12.85
		SO ₂	0.31	0.14
		N ₂	69.77	72.38
		O ₂	-	-
	10	CO ₂	22.17	14.69
		H ₂ O	8.49	13.75
		SO ₂	0.30	0.14
		N ₂	69.04	71.42
		O ₂	-	-
10	0	CO ₂	19.96	13.29
		H ₂ O	6.72	10.93
		SO ₂	0.29	0.13
		N ₂	71.09	73.87
		O ₂	1.94	1.78

APPENDIX A1 (continued)

<u>EA (PERCENT EXCESS AIR)</u>	<u>PERCENT HEAT INPUT FROM RDF</u>	<u>COMPONENT</u>	<u>WEIGHT FRACTION, PERCENT</u>	<u>VOLUME FRACTION, PERCENT</u>
10	5	CO ₂	20.14	13.37
		H ₂ O	7.35	11.92
		SO ₂	0.28	0.13
		N ₂	70.29	72.81
		O ₂	1.94	1.77
	10	CO ₂	20.29	13.43
		H ₂ O	7.88	12.74
		SO ₂	0.27	0.12
		N ₂	69.62	71.94
		O ₂	1.94	1.77
20	0	CO ₂	18.39	12.23
		H ₂ O	6.29	10.22
		SO ₂	0.27	0.12
		N ₂	71.46	74.15
		O ₂	3.59	3.28
	5	CO ₂	18.58	12.32
		H ₂ O	6.88	11.14
		SO ₂	0.26	0.12
		N ₂	70.72	73.17
		O ₂	3.56	3.25
	10	CO ₂	18.72	12.38
		H ₂ O	7.37	11.91
		SO ₂	0.25	0.11
		N ₂	70.10	72.36
		O ₂	3.56	3.24
		68		

APPENDIX A1 (continued)

PRODUCT GASES FROM STOICHIOMETRIC COMBUSTION OF RDF (EXAMPLE)

EXCESS AIR: EA = 0

<u>COMPONENT</u>	<u>WEIGHT FRACTION, PERCENT</u>	<u>VOLUME FRACTION, PERCENT</u>
CO ₂	23.19	15.11
H ₂ O	12.11	19.28
SO ₂	0.25	0.10
N ₂	64.45	65.51
O ₂	0.00	0.00

Appendix A2: PARTIAL LIST OF MANUFACTURING COMPANIES
PRESENTLY OR POTENTIALLY INTERESTED
IN RDF-OIL CO-FIRING IN SMALL BOILERS

The companies are listed in alphabetical order, from information available at the date of writing. No claims are made that the list is comprehensive. No endorsement is implied.

- 1) AFB Contractors Inc., 261 Arthur Rd., Martinez, CA 94553
- 2) Babcock & Wilcox Co., 20 S. Van Buren Ave., Barberton, OH 44203
- 3) CEA, Inc., 61 Taylor Reed Pl., Stamford, CT 06906
- 4) Coen Co., 1510 Rollins Rd., Burlingame, CA 94010
- 5) Copeland Systems Co., 708 Enterprise Drive, Oak Brook, IL 60521
- 6) Eclipse Inc., Combustion Div., 1100 Buchanan St., Rockford, IL 61103
- 7) Energex Ltd., P.O. Box 4170, Portland, OR 97208
- 8) The Engineer Co., P. O. Box 39, S. Plainfield, NJ 07080
- 9) Guaranty Performance Co., P. O. Box 748, Independence, KA 67301
- 10) Johnston Boiler Co., Pine St., Ferrysburg, MI 49409
- 11) E. Keeler Co., 238 W. St., Williamsport, PA 17701
- 12) Peabody-Gordon Piatt Inc., P. O. Box 650, Winfield, KA 67156
- 13) TR Systems Inc., 1330 Blue Hills Ave., Bloomfield, CT 06002
- 14) York-Shipley Inc., P. O. Box 349, York, PA 17405

**United States
Department of Energy
Washington, D.C. 20585**

THIRD — CLASS MAIL
POSTAGE & FEES PAID
U.S. DEPT. OF ENERGY

PERMIT NO. G 20

THIRD CLASS MAIL

Official Business
Penalty for Private Use, \$300