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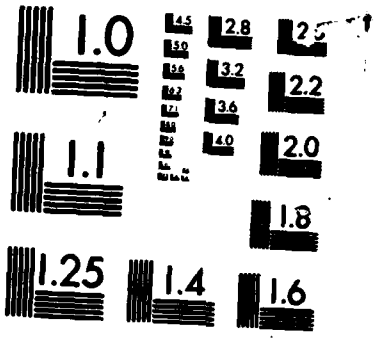

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Refuse-Derived Fuels in U.S. Air Force Heating and Power Systems

DR. ALFRED W. JOENSEN

IOWA STATE UNIVERSITY
AMES, IOWA 50011

JANUARY 1986

FINAL REPORT

JUNE 1982 - FEBRUARY 1985

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This investigation was conducted to document and review all data associated with densified refuse-derived fuel (dRDF)--its preparation and properties, storage and handling, boiler cofiring efficiency and environmental emissions, potential boiler metal wastage, and any other experiences associated with the use of this fuel.

The results of this investigation provide the basis for the development of an optimum dRDF fuel specification. These results identify performance characteristics and operating problems of the existing dRDF fuel pellet and contain an economic feasibility assessment of using this fuel.

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PREFACE

This report was prepared by the Iowa State University College of Engineering, Ames, Iowa 50011 under contract number F08635-82-K-0351, for the Air Force Engineering and Services Center (HQ AFESC/RDCS) Tyndall AFB FL, 32403.

This report summarizes work done between 1 Jun 1982 and 28 Feb 1985. The HQ AFESC Project Officer for this effort was Captain Paul C. Vitucci. This work unifies earlier, more diverse, technical data and analyses on refuse-derived fuel (RDF) combustion into a single comprehensive technical report. It examines low-and high-boiler-load environmental emissions, storage, handling, combustion efficiency and overall boiler performance. The report recommends criteria and specifications for cofiring RDF and coal based on the overall data and analyses. It also provides an economic assessment of this technology.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public including foreign nationals.

This report has been reviewed and is approved for publication.

Paul C Vitucci
PAUL C. VITUCCI, Capt, USAF
Project Officer

Robert E. Boyer
ROBERT E. BOYER, Col, USAF
Director, Engineering and Services Laboratory

Everett L. Mabry
EVERETT L. MABRY, Lt Col, USAF
Chief, Engineering Research Division

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SECTION I

INTRODUCTION

A. OBJECTIVE

This investigation was conducted to document and review all data associated with densified refuse-derived fuel (dRDF)--its preparation and properties, storage and handling, boiler cofiring efficiency and environmental emissions, potential boiler metal wastage, and any other experiences associated with the use of this fuel.

The results of this investigation will provide the basis for the development of an optimum dRDF fuel specification, quantify any performance changes and operating problems, identify future research needs, and, finally, after completion of a life-cycle cost study, examine the economic feasibility of using this fuel.

The U.S. Air Force is committed to an energy program that will provide independence from use of foreign oil. This objective includes:

- Institution of energy management and conservation practices,
- Complete reliance on domestic energy resources, and
- Greater utilization of renewable energy fuel feedstock.

B. BACKGROUND

Fuel supply requirements for steam generators at U.S. Air Force bases can be satisfied by utilization of coal, along with solid waste, processed refuse-derived fuel, or other biomass in new or converted existing boilers. Air Force Facility Energy Goals call for providing 20 percent of facility energy from renewable sources by the year 2000. For heating and power systems, the optimum engineering application would be a flexible multi-fuel-fired boiler at any base facility. This would be possible only after existing steam generators undergo major modification, modernization, or replacement.

The strategies available to reduce foreign oil consumption and to provide for facility steam heating requirements include:

- Cofiring of coal and dRDF in industrial boilers,
- Burning of MSW in controlled-air or modular incinerator units with heat recovery,
- Cofiring of coal and RDF in heating and power systems,

- Cofiring of coal and wood or MSW in boilers, and

- Mass burning of MSW with heat recovery in boilers.

The first two strategies listed above represent possible short-term goals, while the remaining alternatives are long-term goal objectives.

In addition to these conservation objectives, another new strategy has been established by the Department of Defense. The U.S. Air Force is now required to develop a program that will ensure a high degree of energy security at its facilities so that the assigned mission can be completed.

The Air Force Engineering and Services Laboratory has completed a Research and Development program that included the cofiring of coal and densified refuse-derived fuel at Wright-Patterson Air Force Base. In addition, other support studies were instituted to provide a broader data base for possible implementation of this technology.

Because of the location and operational mode of U.S. Air Force facilities, the use of dRDF, rather than fluff refuse-derived fuel (RDF), with coal in existing or new stoker boilers appeared more viable. Although large metropolitan areas possess the greatest potential for the economical production of RDF, not enough boilers are available to use this fuel.

Thus, the early motivation for pelletizing processed municipal solid waste was the anticipated increase in benefits--fuel storage, handling, and firing. The potential benefits were:

- A reduction in storage space and transportation costs because of an increase in bulk density,

- A reduction in odor and dust,

- An improvement in handling and fuel feed because of improved free-flowing characteristics, and

- Increased fuel properties.

SECTION II

dRDF RESEARCH CHRONOLOGY

A. INTRODUCTION

The original application of waste-to-energy systems involved the cofiring of fluff refuse-derived fuel (RDF) in utility-type pulverized coal-fired steam generators. The attractiveness of this technology was that existing boilers could be retrofitted to accommodate the pneumatic injection of the RDF, thereby, requiring a minimum capital expenditure.

Another potential market for used RDF became apparent when it was found that approximately 50 percent of 42,000 industrial and institutional boilers used coal. Thus, the coal-fired stoker boiler became especially attractive for implementation of refuse cofiring technology. Because of storage and fuel-feed requirements, an RDF product with properties similar to coal appeared more desirable and was the motivation for densification of fluff RDF.

In response to this possibility, the Municipal Environmental Research Laboratory (MERL) of the EPA, Cincinnati, Ohio, initiated a research program to evaluate the technical, environmental, and economic aspects of producing and burning densified refused-derived fuels (dRDF).

The U.S. Air Force research, development, test and evaluation (RDT&E) program in solid waste resource recovery is managed through Headquarters Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base, Florida, 32043.

The National Center for Resource Recovery (NCRR), Washington, D.C., (EPA-sponsored) began a research effort on the preparation and properties for densification of RDF and conceptual studies on systems that might be used in small communities. The results of this program are described in Reference 1. NCRR pellets were produced at their Equipment Test and Evaluation Facility (ETEF) located at the District of Columbia Solid Waste Reduction Center Number 1. ETEF was operational from 1974 through June 1979. About 300 tons of dRDF were produced in fall 1976 and spring 1977. After completion of some process line changes, 1,100 tons were made from fall 1977 through fall 1978. These pellets were used for the Maryland Correctional Institute and Erie, Pennsylvania, tests, respectively (discussed below). The potential for using Washington, D.C., office waste for dRDF was also investigated by NCRR, and 96 tons of these pellets were produced from December 1978 through March 1979. Here, spray water was injected at the primary and secondary shredder inlets to increase the feedstock moisture to the 15-20 percent range considered necessary for good pelletization.

Teledyne National Corporation, in the construction and operation of its Cockeysville, Maryland, resource recovery facility, also produced dRDF as part of a program to optimize refuse fuel production. In further discussion, reference to these fuel sources will be identified as the NCRR (N) or Teledyne (T) pellets.

B. BOILER TESTS

Major boiler thermal and environmental emission performance associated with dRDF-coal cofiring was evaluated in four major tests programs.

An EPA Phase I test series was conducted on two small institutional units at the Maryland Correctional Institute (MCI) Boiler House near Hagerston, Maryland, from December 1976 through May 1977. Complete results are reported in Reference 2. Two Erie City Iron Works rated at 150 psig, saturated vapor, at 75,000 lb/hr and 60,000 lb/hr were tested. Approximately 285 tons of NCRR pellets were cofired up to 230 hours of operation for steam loads of 30-55 percent at coal:dRDF volumetric ratios of 1:2.

The EPA Phase II test program was conducted in a large industrial spreader-stoker boiler at the General Electric Company power plant at Erie, Pennsylvania, from March 1979 through May. The Unit Babcock and Wilcox boiler rated at 675 psig/825° F and 150,000 lb/hr was tested at steam loads from 40 percent to 97 percent. About 1,702 tons of pellets were fired at coal:dRDF volumetric ratios of 1:1, 1:2, and 1:4 with the predominant ratio 1:2. In addition, the testing involved five different coals and both NCRR and Teledyne pellets. Complete test data are given in a two-volume report (References 3 and 4).

An EPA-USAF cofunded test program for boiler thermal and environmental performance was conducted on Boiler 3 at the Wright-Patterson AFB (WPAFB), Dayton, Ohio, Building 1240 (and identified as WPAFB Building 1240) hot water heating plant. This evaluation, using Teledyne pellets, was made during April 1981 and May with eight dRDF-only and three baseline coal-only tests being conducted. A Babcock and Wilcox Company hot water heating boiler, rated at 100 by 10^6 Btu/hr output (582,000 lb/hr of hot water, temperature rise of 165° F at 275 psig) was tested at a nominal heating load of 30 percent. Complete test results are reported in Reference 5.

A second USAF-sponsored cofiring test was conducted on Boiler 4 at the WPAFB Building 770 heating plant during February 22-26, 1982, using Teledyne dRDF. A Keeler Company boiler, rated at 400 psig, saturated vapor, and 150,000 lbs/hr was operated at coal-only, dRDF-only, and 1:1 volumetric ratio (a 3 by 3 test matrix). Test data are given in Reference 6.

In addition, as part of the USAF RDT&E program administered by AFESC, a contract was initiated with Teledyne to furnish approximately

18,480 tons of dRDF from May 1979 through August 1981. The pellets were to be burned at WPAFB at Building 1240 in a 1:1 volumetric coal-dRDF ratio. Test analysis of the pellets will be discussed in Section III.

A General Services Administration (GSA)-sponsored boiler test was conducted at the GSA Arlington, Virginia, heating plant on March 20-23, 1979. NCRR pellets made from Washington, D.C., office waste were tested in a Riley Stoker Company multiple-retort ram underfeed stoker boiler. This unit was rated at 125 psig, saturated vapor, and a steam flow of 70,000 lbs/hr. The boiler was fired at coal:dRDF volumetric ratios of 1:0, 4:1, and 2:3 at steam loads of 40-62 percent and burned 96 tons of pellets. A detailed description of the dRDF production, boiler tests, and economic analysis is given in Reference 7.

C. SUPPORTING dRDF RESEARCH

Additional research projects to characterize the dRDF fuel, and implement various phases of cofiring technology were completed by various agencies involved in waste-to-energy programs. The scope of this effort is given below in a listing of the agencies and the corresponding report titles issued. It should be noted that summary papers based on these efforts were also published elsewhere and are listed in the references.

- U.S. Air Force Engineering and Services Center (AFESC), Tyndall AFB, Florida.
    - Production and Use of Densified Refuse-Derived Fuel (dRDF) in Military Central Heating and Power Plants, March 1980 (Reference 8).
    - Technology Evaluation for Densified Refuse-Derived Fuel Specification and Acquisition. March 1981 (Reference 9).
    - Investigations of Engineering and Design Considerations in Selecting Conveyors for Densified Refuse-Derived Fuel (dRDF) and dRDF Coal Mixtures. August 1981 (Reference 10).
    - Advanced Bioenergy Systems for Air Force Installations. October 1981 (Reference 11).
    - Performance Analysis of Cofiring Densified Refuse Derived Fuel in a Military Boiler. December 1981 (Reference 12).
    - Management Impact Assessment of Refuse-Derived Fuel Implementation at Wright-Patterson AFB. March 1982 (Reference 13).

- U.S. Navy Facilities Engineering Command (NAVFAC), 200 Stovall Street, Alexandria, Virginia.

    - Design Concept for Densified Refuse-Derived Fuel Production and Handling Systems in Military-Scale Applications. August 1970 (Reference 14).

    - Naval Facility Energy Conversion Plants as Resource Recovery System Components. January 1980 (Reference 15).

    - Waste Fuel Utilization in Existing Boilers on U.S. Naval Bases. January 1980 (Reference 16).

    - Densified Refuse-Derived Fuel Characteristics, Test Methods, and Specifications for Medium Capacity Boiler Facilities. September 1981 (Reference 17).

- Municipal Environmental Research Laboratory (MERL), Environmental Protection Agency, Cincinnati, Ohio.

    - A Pneumatic Conveying Test Rig for Municipal Solid Waste Fractions (Reference 18).

    - Considerations in Selecting Conveyors for Solid Waste Applications (Reference 19).

    - Fundamental Considerations for Preparing Densified Refuse Derived Fuel (Reference 20).

- U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL), P.O. Box 4005, Champaign, Illinois.

    - Control and Disposal of Byproducts of Refuse-Derived Fuel Production and Use. March 1979 (Reference 21).

    - A Literature Review of Military Scale Production, Handling, Energy, Energy Recovery and Byproduct Disposal of Refuse-Derived Fuel. June 1979 (Reference 22).

    - Densified Biomass as an Alternative Army Heating and Power Plant Fuel. March 1980 (Reference 23).

    - Physical Characteristics of Densified Refuse-Derived Fuel and Their Impact on Flow Properties. May 1982 (Reference 24).

- National Center for Resource Recovery, Washington, D.C.

    - Proposed Draft Document for GSA Office Waste Removal and Procurement of a Densified Refuse-Derived Fuel

for Use as a Supplemental Fuel in GSA-Operated Boilers (Reference 25).

The remainder of this report discusses both summary results and areas that need further investigation.

SECTION III

dRDF FUEL PROPERTY CHARACTERIZATION

A. INTRODUCTION

In general, refuse-derifed fuel (RDF) implies a solid fuel that results from the processing of municipal solid waste (MSW) owing to the use of a combination of various mechanical (and/or chemical) operations. Thus, the physical, mechanical, and combustible characteristics of the MSW may be greatly enhanced through processing. The various unit processes used in producing RDF include:

- Size reduction or shredding,
- Magnetic separation,
- Screening (trommels, or disc screens or vibrating screens), and
- Air classification (air density separation).

The ultimate objective is to produce a fuel with a high heating value (HHV) from the heterogeneous mixture of combustibles in MSW which includes various forms of paper, cardboard, wood, and plastic film.

Previously, RDF was identified as three forms dependent on the amount of processing that was involved. These categories were:

- Coarse RDF,
- Fluff RDF, and
- Densified RDF (dRDF).

Densified refuse-derived fuel is RDF that has been exposed to further mechanical compaction such as extrusion or rolling to produce pellets, cubettes, or briquettes.

Recently, all forms of refuse-derived fuels have been further categorized as a result of the efforts of the ASTM Committee E-38 on Resource Recovery. This classification is shown in Table 1. Approved ASTM standards for the analyses of fluff RDF or RDF-3 are listed in Appendix A. Some proposed standards for analysis of dRDF or RDF-5 are listed in Appendix B. As discussed in Section II, fluff RDF was the first-generation fuel produced in waste-to-energy systems. The potential market for use in cofiring in coal stoker industrial or institutional boilers led to further development of pellet or dRDF.

TABLE 1. ASTM CLASSIFICATION OF REFUSE-DERIVED FUELS (E-38).

RDF-1: Municipal solid waste (MSW) used as a fuel in as-discarded form.

RDF-2: Wastes processed to coarse particle size with or without ferrous metal operation.

RDF-3: MSW that has been processed to remove metal, glass, and other inorganics. This material has a particle size such that 95 percent weight passes through a 2-inch square mesh screen.

RDF-4: Combustible waste processed into powder form, 95 percent weight passing through 10-mesh screening.

RDF-5: Combustible waste densified (compressed) into the form of pellets, slugs, cubettes, or briquettes.

RDF-6: Combustible waste processed into liquid fuel.

RDF-7: Combustible waste processed into gaseous fuel.

B. dRDF PROPERTIES

The major properties of dRDF that were of initial interest were those associated with the handling and combustion of the pellets. These were grouped as:

- Moisture, ash (dry basis), bulk density, and fines,
- Ultimate and proximate analysis.

Briefly, the ultimate (or elemental) analysis is used for combustion calculations and determination of boiler efficiency. The proximate analysis (volatile matter, mineral ash, fixed carbon, and moisture) has been used for furnace geometry evaluators. High moisture increases heat losses and reduces boiler efficiency. The composition (i.e., paper, wood, plastics, cardboard, organics (grass), etc.) is not normally described, although the quantity of this material in the source feedstock ultimately affects the amount of processing and the final pellet quality.

Detailed discussions of these properties are given in References 1, 9, and 17, which were published at the NCRR Equipment Test and Evaluation Facility (ETEF). A very good summary of dRDF properties is also given in Reference 26.

The pellet fines content is a measure of the fuel integrity. Integrity, in turn, may be defined as the ability to sustain its original fines content and bulk density during fuel transport, storage and reclaim, and ultimate injection or feed into a boiler. Pellet deterioration because of water absorption in open storage or disintegration upon repeated mechanical handling results in reduced flow out of bins and the generation of dust (undesirable). Based on the additional experience gained in the various boiler tests, a property classification known as bulk flow of solids has become extremely important. Achieving and maintaining high bulk density is important since all fuel mixing for cofiring is done on a coal-dRDF volumetric ratio, usually 1:1 or 1:2. The higher the bulk density, the more dRDF consumed per unit of fuel although the mixture heating value decreases.

Pellet integrity or fines content has not only been affected by repeated fuel handling but also by outside storage weathering. To reduce outside storage effects, silo storage has been used. The bulk solid flow properties exert an influence, especially where bin filling increases dRDF compaction and, possibly, its unconfined yield strength. The initial discussion of suitable dRDF flow properties (References 9, 17, and 24) includes items such as angle of repose, angle of maximum inclination, angle of slide, and maximum surcharge. These parameters may be suitable in certain storage or conveyor applications, but more suitable bulk flow properties are being specified, as discussed in Section X.

C. PELLET PRODUCTION

The two major facilities involved with pellet production were NCRR (in operation between fall 1976 and spring 1979) and the Teledyne Cockeysville, Maryland, plant. Washington, D.C., MSW was the feedstock for the NCRR dRDF, and Baltimore suburban residential waste was the source of MSW for the Teledyne pellets. The NCRR process line initially consisted of shred, air classify, screen, shred, and densify.

After a production run of 300 tons, the vibratory screen was positioned before the air classifier, apparently to remove more fines and ash. The NCRR pellets were not dried before pelletization or cooled or subjected to fines screening afterwards. The test for fines was an adaptation of ASTM D3038-75 in which the pellets were dropped 6 feet onto a steel plate.

The Teledyne process line consisted of shred, magnetic separation, air classification, trommel screening, and density. No postcooling or postscreening was utilized.

The NCRR dRDF production and boiler test schedule arrangements resulted in storing the pellets outside from September 1977 through September 1978. Temperature measurements in the pile and pellet integrity tests were conducted and are discussed in Reference 1. After 10 months of storage, smoldering seams of pellets were encountered and temperatures became high enough to ignite the polyethylene covers and tire restraints. Smoldering seams were encountered on four more occasions.

D. dRDF PROPERTY TEST DATA

An initial comparison of NCRR and Teledyne dRDF properties as reported in Reference 9 is shown in Table 2. The WPAFB initial dRDF fuel specification was

- Heating value, Btu/lb, dry $\geq$ 6500
- Ash content, percent, dry $\leq$ 15
- Moisture content, percent, AR[1] $\leq$ 20
- Bulk density, lb/ft^3 $\geq$ 35
- Fines, < 3/8 in., percent, AR $\leq$ 5

[1] AR = As received.

TABLE 2. dRDF PROPERTY COMPARISON.

	NCRR[a]	NCRR[b]	NCRR[b]	NCRR[c]	NCRR[d] post-storage	Teledyne[d] national poststorage	NCRR[e]
Diameter, inches	0.5	0.5	1.0	0.5	0.5	0.5	0.5
Length, inches	0.70	0.63	--	0.79	--	--	--
Bulk density, AR[f]	38.73	35.92	26.99	42.92	33.61	32.61	26.5
Fines content, %, AR	N/A	14.9[g]	9.6[g]	2.6[h]	46.7[g]	27.9[g]	23.0[g]
Moisture content, %, AR	19.1	22.9	22.8	21.5	29.0	31.4	12.67
Ash content, %, dry	26.6	23.4	22.8	9.6	30.7	13.8	27.18
Higher heating value, Btu/lb, dry	N/A	7,480.6	--	7,738.6	6,749.8	8,125.5	6,517.46
No. of samples	> 69	> 15	> 10	> 10	4	13	> 4

[a]Process flow scheme A. Screening after air classification.

[b]Process flow scheme B. Screening prior to air classification.

[c]Pellets produced from office waste.

[d]Erie boiler tests.

[e]Maryland Correctional Institution boiler tests.

[f]As received.

[g]Less than 3/8 inch.

[h]Less than 1/4 inch.

The NCRR drop/shatter (integrity) test data are shown in Table 3. Long-term outside storage was used to increase the potential for disintegration into fines. The long-term storage effects on NCRR pellets are listed in Table 4.

The amount of pellet deterioration at Erie after further outside storage of 2 to 5 months is shown in Tables 5 and 6. The as-shipped pellets did not meet the "less than 5 percent weight passing a 3/8-inch screen" criteria.

A listing of the dRDF fuel properties for the MCI, Erie, and WPAFB boiler tests is shown in Table 7. The higher heating value (dry basis) and ash content (dry) for the Teledyne (T) pellet meets the USAF specification. However, only the WPAFB moisture content is less than the 20 percent allowable. The Erie pellets had been stored outside, and the analysis was based on the as-fired condition.

The WPAFB dRDF firing test program from July 1979 to August 1981 included the analysis of as-received pellets, and the test data covering the period July 1980 through August 1981 are shown in Table 8. The heating value, percent dry ash, and moisture content all satisfy the original fuel specification values. The bulk density criteria of "35 lb/ft^3" on the average is only satisfied in November 1980 data. The fines content never meets the "less than 5 percent passing 3/8 inch" criteria.

E. EUROPEAN dRDF RESEARCH

The Warren Spring Laboratory (WSL), supported by the United Kingdom Department of Industry, engaged in research for extensive resource recovery including paper, metals, glass, and dRDF. Air-classified light material passed through a knife mill and was then pelletized. The WSL research resulted in the construction of two facilities known as the Doncaster (South Yorkshire) and the Byker (Tyne and Wear, Northumberland) plants.

The Doncaster flowsheet includes lights passing through a knife mill for further size reduction, a drier, the pelletizer, and, finally, the pellets are both cooled and screened. The Byker plant originally did not include any drying prior to pelletization but did have postcooling and postscreening. The production of low quality 4,000-5,200 Btu/lb pellets resulted in the use of a low-moisture, higher-paper content feedstock. In addition, the process line was modified to include glass fines screening prior to secondary shredding and drying prior to densification. Pellets with a heating value of 6,025 Btu/lb, as received, were anticipated.

The Buhler-Miag pelletizing (press) process has been incorporated in the Eastbourne refuse pulverization plant (East Sussex County). Here again, the air-classified light material is knife-cut to reduce

TABLE 3. NCRR dRDF DROP/SHATTER (INTEGRITY) TEST DATA[a].

Sample	Description	Percent moisture	Fines %	Mean length inches
A	As produced	11.0	9.8	0.563
	2 drops		10.0	0.561
B	As produced	21.0	11.5	0.453
	2 drops		12.0	0.408
C	Storage yard	15.0	17.9	0.405
	2 drops		22.1	0.367
	4 drops		24.2	0.370
	10 drops		25.6	0.378
D	Storage yard	34.0	N/A	0.272
	2 drops			0.235
	10 drops			0.215

[a]One-half inch diameter pellets.

TABLE 4. NCRR STORAGE EFFECTS ON dRDF PROPERTIES.

	As-produced			After storage		
	$\bar{x}$[a]	σ[b]	n[c]	$\bar{x}$	σ	n
Moisture, %, AR[d]	22.9	8.2	40	43.9	39.2	27
-3.8 in. fines, %, AR	14.9	7.10	15	28.1	24.9	27
Bulk density, lb/ft^3	35.9	4.78	49	25.6	3.5	28
Ash, %, DW[e]	23.4	4.1	55	23.4	1.80	13
Mean length, in.	0.626	0.100	15	0.386	0.049	19

[a]Property average.

[b]Standard deviation.

[c]Number of samples.

[d]As-received basis.

[e]Dry basis.

TABLE 5. ERIE BOILER TEST FUEL FINES CONCENTRATION (% > 3.8 INCH), AS FIRED.

Fuel mixture	No. of samples	Coal		dRDF	
		X[a]	S[b]	X	S
A/O	5	79.5	7.7	--	--
B/N	4	42.3	10.8	46.5	7.6
C/T	7	51.1	7.3	27.9	13.6
D/T	5	48.4	13.5	28.0	4.1
E/O	4	62.0	2.9	--	--

[a]Property average.

[b]Standard deviation.

TABLE 6. ERIE dRDF AS-SHIPPED AND AS-FIRED PROPERTIES.

	NCRR			Teledyne		
	As-shipped average	As-fired Min.	As-fired Max.	As-shipped average	As-fired Min.	As-fired Max.
Moisture, %	17.0	18.0	29.5	16.0	14.0	33.7
Bulk density, lb/ft^3	38.0	31.0	35.0	35.0	29.0	37.0
Fines, % > 3.8 inch	12.0	39.0	54.0	[a]	10.0	48.0

[a]Not measured.

TABLE 7. SUMMARY SITE AVERAGE dRDF PROPERTIES, AS RECEIVED.

	MCI average, N[a]				WPAFB, T[b]		Erie, PA	
	Dec.	Mar.	May	Overall	Bldg. 770	Bldg. 1240[c]	N	T
Proximate, %								
Fixed carbon	10.10	8.89	9.76	9.61	N/A	N/A	11.42	9.97
Volatile matter	56.54	54.08	49.27	52.72	N/A	N/A	42.33	55.26
Ash	19.97	24.47	28.75	25.00	N/A	N/A	23.85	10.50
Free moisture	13.40	12.62	12.22	12.67	N/A	N/A	22.33	23.88
Ultimate								
Carbon	39.27	34.17	31.36	33.61	44.26	40.80	31.54	34.79
Hydrogen	4.73	3.93	4.01	4.10	6.05	5.16	3.57	4.64
Nitrogen	0.31	0.34	0.75	0.54	0.35	0.31	0.46	0.28
Chlorine	0.36	0.39	0.31	0.35	N/A	N/A	0.24	0.29
Sulfur	0.17	0.23	0.24	0.22	0.13	0.19	0.33	0.18
Ash	16.95	24.42	28.68	25.31	8.31	8.94	23.85	10.50
Oxygen	27.50	23.93	22.37	23.75	29.14	33.06	17.63	25.04
Moisture	10.72	12.62	12.22	12.67	11.76	11.57	22.33	23.88
Higher heating value (HHV), Btu/lb	6667	5534	5266	5692	7585	7189	5247	6183

[a]NCRR.

[b]Teledyne.

[c]Corrected.

TABLE 8. WPAFB TELEDYNE dRDF ANALYSES.

	7/80	8/80	9/80	10/80	11/80	1/81	2/81	3/81	4/81	7/81	8/81	Average
HHV,[a] Btu/lb, dry												
X	8519	6586	7566	7781	8163	8364	8283	8686	8887	8173	8672	8321
S	748	919	450	631	702	331	596	498	1329	438	1480	840
Ash, %, dry												
X	16.28	20.1	10.3	12.5	13.6	12.4	13.5	11.1	7.58	16.5	12.9	13.5
S	4.65	2.7	2.0	5.2	2.0	2.4	2.4	2.5	6.3	2.9	3.2	3.7
Moisture, %, AR[b]												
X	15.75	18.3	13.2	12.0	11.1	9.7	14.9	12.9	12.1	9.3	8.7	12.6
S	8.21	4.6	2.4	2.1	3.0	1.8	3.1	3.8	1.9	1.5	5.9	4.6
Bulk density, lb/ft^3												
X	26.28	34.6	24.9	32.3	44.3	34.3	30.5	30.7	33.3	30.0	31.4	32.1
S	6.47	3.9	1.7	6.5	5.1	2.2	2.7	3.8	1.5	1.3	3.6	6.1
Fines, %, AR												
X	11.44	13.3	13.0	17.6	6.6	7.2	9.6	11.0	6.0	5.2	5.6	9.1
S	6.92	8.4	1.7	14.4	5.2	4.9	4.2	5.1	7.1	2.9	3.6	6.6
No. of samples	12	3	3	6	10	12	14	14	4	10	11	99

[a]Higher heating value.

[b]As received.

size, dried, cooled, and screened. The screened fines are reintroduced at the pellet mill inlet. Specific burning tests of these pellets indicated a heating value of 7,316 Btu/lb, ash contents of 13-18 percent, and moisture contents of 8-15 percent.

These plants are mentioned only because of the process flow line includes drying prior to pelletization to reduce the moisture content to the desired range of 15-20 percent. In addition, postpellet mill cooling and screening is also used.

F. CONCLUSIONS

Based on the dRDF property characterization data available from research performed on the NCRR and Teledyne pellets, the NCRR ash content was relatively high and Teledyne pellets possessed excellent properties. Recently, some properties have been developed as part of the preparation of "Utility Guidelines for Cofiring of RDF."[1] A comparison of the WPAFB Teledyne analysis, the latest WPAFB fuel specification, and the proposed EPRI[2] RDF I and RDF II properties are shown in Table 9. The WPAFB criteria appear to be within normal dRDF processing capability, except for fines and bulk density.

The dRDF pellets have appeared to disintegrate with time in storage and mechanical handling. The drop/shatter test does not appear to be truly indicative of this behavior of pellet degradation. Postpellet cooling may not prevent disintegration into more fines. The Argonne National Laboratory is sponsoring a research program on the use of binders in dRDF. The results of this study may provide a better description of a fuel specification.

Finally, the problems with bunker (and unloading hopper) bridging and/or ratholing indicate more research effort is required in bunker flow behavior before a commitment to a 10-year operation of dRDF cofiring. Continued or repeated intervals with reduced bunker dRDF outflow is unacceptable because of both decreased boiler load and operational manpower.

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[1] Private communication with Midwest Research Institute, Kansas City, Missouri.

[2] Electric Power Research Institute.

TABLE 9. dRDF PROPERTY COMPARISON.

	WPAFB teledyne	WPAFB specification	EPRI RDF I	EPRI RDF II
HHV,[a] Btu/lb, dry				
X	8321	7500	8125	7763
S	848	--	--	--
Ash, %, dry				
X	13.5	15	12.0	15.8
S	3.7	--	--	--
Moisture, %, AR[b]				
X	12.6	16	20.0	24.0
S	4.6	--	--	--
Bulk density, lb/ft^3				
X	32.1	30.0	--	--
S	6.1	--	--	--
Fines, %, AR				
X	9.1	--	--	--
S	6.6	--	--	--
No. of samples	99	--	--	--

[a]Higher heating value.

[b]As received.

SECTION IV

BOILER EFFICIENCY

A. INTRODUCTION

Steam generator (or boiler) efficiency is a measure of the effectiveness of the conversion of the available fuel chemical energy into heat energy absorbed by the working fluid.

Boiler efficiency, η_β is defined[1] as

$$\text{Efficiency, percent} = \frac{\text{heat absorbed by the working fluid}}{\text{heat in fuel + heat credits}} \times 100$$

and can be calculated by the ASME Input-Output Method (Direct Method) or the Heat Loss Method.

In the Input-Output Method,

$$\text{Efficiency} = \frac{(\text{lbs/hr } H_2O)(\text{enthalpy increase, Btu/lb})}{(\text{lbs/hr fuel})(\text{higher heating value})} \times 100, \text{ percent}$$

In the Heat Loss Method,

$$\text{Efficiency} = 100 \text{ percent} - (\text{sum of all heat losses, percent})$$

It has been the standard practice of boiler manufacturers to guarantee their performance on the basis of the ASME-abbreviated efficiency test. In this case, only the major heat losses are considered and no heat credits are allowed.

The major heat losses (percent)[2] are

- Loss due to dry gas (L_G')
- Loss due to moisture in fuel (L_{mf})
- Loss due to H_2O from combustion of H_2 in fuel (L_H)
- Loss due to combustible in refuse (L_{HC})

---

[1] ASME PTC 4.1, 1964.

[2] Heat losses can be expressed either as Btu/lb fuel or on a percent basis, where the loss has been divided by the fuel heating value. For convenience, percent will be used.

- Loss due to radiation (L_β)[1]
- Manufacturer's allowance for unaccountable losses - 1.5 percent[2]

Total heat loss = sum of major heat losses.

Use of the input-output method requires the metering of either the feedwater flow into the unit or the steam leaving the boiler and usually has resulted in widely varying numerical values. It is not accepted as a valid procedure by boiler manufacturers in verifying that contract guarantee has been achieved. One reason for the variation is associated with the flowmeter flow constant. The instrument manufacturer simplifies the chart or integrator readout as

$$\text{lb/hr} = \text{constant} \times (\text{meter differential pressure})^{1/2}$$

The instrument constant contains the various flow loss correction coefficients and the fluid density. The normal practice is to calculate the constants on an arbitrarily selected maximum design flow and temperature (for density). Thus, at lower loads, reading discrepancies may exist as given by

$$\dot{m}_{actual} = \dot{m}_{chart} \times \left(\frac{\text{actual density}}{\text{design density}}\right)^{1/2} .$$

These discrepancies were noted in the MCI and Erie tests.

The specific calculation steps to determine the ASME heat loss components are given in Table 10. The ASME dry gas heat loss procedure for L_G' requires the calculation of the pounds of dry gas per pound of fuel, W_G', by using the fuel Orsat (volumetric) analysis and both the carbon and sulfur in the fuel. This is known as a carbon balance.

The test protocol used in MCI, Erie, and WPAFB for boiler efficiency calculation was developed for military heating plants and is reported in Reference 27. Essentially, the flow rates are measured then using the fuel analyses converted to a dry basis, a mass balance is used to calculate the flow rates of each species in the dry flue gas leaving, namely, CO_2, SO_2, O_2, and N_2. The oxygen leaving is determined by using the Orsat readings in the short-form ASM excess air calculation to find the excess oxygen and nitrogen above stoichometric air requirements. This involves an oxygen balance not involved in the ASM procedure for dry gas weight determination. When cofiring, if a fuel mixture analysis

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[1]Determined from ABMA standard radiation loss chart given in ASME PTC 4.1, 1964.

[2]Specified in most boiler guarantee specification sheets.

TABLE 10. CALCULATION OF MAJOR HEAT LOSSES FOR BOILER EFFICIENCY.

Total Heat Losses are $L_G' + L_{mf} + L_H + L_{HC} + L_B$ + Unaccountable Loss (1.5%)[a]

- L_G' = Heat loss due to heat in dry flue gas, %

$$= \frac{W_G' \times C_{p_G}' \times (T_g - T_{ra})}{HHV} \times 100$$

where W_G' = lbs dry flue gas per lb as fired fuel

$$= \frac{44.01(CO_2) + 32.00(O_2) + 28.02(N_2)}{12.01(CO_2 + CO)} \left[C_b + \frac{12.01}{32.07} S\right]$$

CO_2, O_2, CO are percent by volume of measured dry flue gas

N_2 = 100 minus the sum of the measured flue gases

C_b = pounds of carbon burned per pound of fuel

S = pounds of sulfur in the fuel per pound of fuel

C_{p_G}' = average specific heat of the dry flue gas

T_G = flue gas temperature leaving the economizer (or leaving the air heater if used)

T_{ra} = reference inlet air temperature (either at forced draft fan outlet or air heater inlet if used)

HHV = higher heating value of as-fired fuel, Btu/lb.

- L_{mf} = Heat loss due to moisture in the as-fired fuel

$$= \frac{m_f \left[h_g - h_{R_W}\right]}{HHV} \times 100$$

[a]Usually specified in most boiler efficiency guarantee contracts.

TABLE 10. CALCULATION OF MAJOR HEAT LOSSES FOR BOILER EFFICIENCY (CONCLUDED).

where m_f = pounded free moisture in the fuel per pound of as-fired fuel

h_g = enthalpy of water vapor at partial pressure (usually p = 1 1/2 psia) and exit flue gas temperature, T_g, from steam tables

h_{RW} = enthalpy of saturated liquid at reference temperature, T_{RA}.

- L_H = Heat loss due to moisture from combustion of hydrogen in as-fired fuel

$$= \frac{8.936 \times H \left[h_g - h_{R_W}\right]}{HHV} \times 100$$

where H = pounds of hydrogen in fuel, exclusive of moisture, per pound of as-fired fuel

- L_{HC} = Heat loss due to unburned carbon in total dry refuse per pound of as-fired fuel, percent

$$= \left(\frac{\text{lbs total refuse}}{\text{lb fuel}}\right)\left(\frac{\text{\% combustible}}{HHV}\right) 14500, \text{ percent}$$

$$\text{or } \frac{(C_H)\ 14500}{HHV} \times 100$$

where C_H = pounds of unburned carbon per pound as-fired fuel

- L_B = Loss due to surface radiation and convection, percent

  from ABMA Radiation Loss Chart (ASME PTC 4.1)

- Manufacturer's allowance for unaccountable losses,[a] percent

[a]Usually specified in most boiler efficiency guarantee contracts.

can be obtained, the dry gas heat loss can be determined very simply. If only separate coal and dRDF flow rates are available, then the average fuel analysis must be calculated and then used for the dry gas loss. The short-form excess air calculation does not account for nitrogen in the fuel or unburned carbon which can lead to some discrepancies. This can be seen by calculating the excess air using what is known as the ASME Appendix 9 carbon-nitrogen balance. In summary, it is recommended that the test protocol given in Reference 27 be reevaluated in terms of more adherence to the dry gas loss calculation.

B. MCI BOILER TESTS

The Maryland Correctional Institute (MCI) evaluation tests were performed on two boilers from December 1976 through May 1977 (Reference 2). Only four boiler efficiency tests were made, and these were run on the 60,000 lb/hr Unit 2. The reported thermal performance is shown in Table 11. The average efficiency of the two cofire tests (at different volumetric fuel ratios) was 53.8 percent at an average steam load of 31.5 percent. The average efficiency for the two coal-only baseline tests was 57.4 percent at an average steam load of 18 percent. Unusually high unburned combustible losses were experienced, as shown in Table 11, and a comparison can also be made with predicted performance. The fuel analyses for these tests are shown in Appendix C, Tables C-1 and C-2. The test report indicated that grate clinkering was experienced, and the combustion air was biased to more undergrate air. This may have resulted in much more unburned carry over into the collector.

C. ERIE BOILER TESTS

The Babcock and Wilcox boiler cofiring tests at Erie, Pennsylvania, were conducted from March 1979 through May and are documented in a two-volume report (References 3,4). The tests used fine coals and pellets from both NCRR and Teledyne; see Table 12. The original report graphically displayed a plot of boiler efficiency versus steam load. A straight-line fit of the before and after coal-only tests were made.. Similarly a straight-line fit of all the dRDF tests were made that included coal-dRDF volumetric ratios of 1:1, 1:2 and 1:4. The predominant ratio was 1:2. Wide scatter in the above data was noted, and the average drop in boiler efficiency was given as 2.5 percent (percentage points). Review of the testing procedure also included the examination of the efficiency calculation protocol procedures (Reference 27) described above.

It was noted that two tests per day were conducted. The afternoon boiler efficiency calculation was based on fuel flow rates determined from a midday bunker refill and another full refill the following morning. In the interim, load changes were made late in the day after completion of the afternoon emissions testing. It seemed prudent to retabulate only the morning calculated heat-loss data and arrange the values in

TABLE 11. MCI BOILER EFFICIENCY.[a] UNIT NO. [b]2.

	Test conditions				Predicted performance	
Blend; coal:dRDF	1:0	1:1	1:2	0:1	1:0	1:0
Test date	5-4-77	5-13-77	5-11-77	5-14-77	--	--
Load, %	17	33.0	30.0	19.0	17.0	33.0
Heat losses, %						
• Dry gas	17.9	13.7	17.8	19.4	12.41	10.85
• Moisture from fuel and hydrogen	4.1	6.0	6.6	12.1	4.02	4.01
• Unburned combustible	18.3	25.3	16.6	3.0	0.8	1.0
• Radiation	3.7	1.8	1.8	3.7	3.66	1.83
• Unaccountable and manuf. allow.	1.5	1.5	1.5	1.5	1.50	1.50
Total losses, %	45.5	48.3	44.1	39.7	22.73	19.54
Boiler efficiency, %	54.5	51.7	55.9	60.3	77.27	80.45
• Excess air, %	104	82	55.9	60.3	96.5	57.1
• Air inlet temperature, °F	68	78	70	78	80	80
• Exit flue gas temperature, °F	457	501	512	472	432	454

[a]ASME heat loss method.

[b]Unit No. 2 rated at 150 psig (saturated vapor), 60,000 lb/hr.

TABLE 12. ERIE BOILER EFFICIENCY PERFORMANCE DATA--1:2 VOLUME MIX.[a]

Fuel mixture[b]	Test date	Boiler load %	Excess air %	Major heat losses, %						Boiler[d] efficiency %	Exit gas temperature °F
				Radiation	Bottom ash	Fly ash	Dry gas	Wet gas	Total[c]		
A/O	3/6	41.9	106	0.87	0.98	0.82	12.68	4.82	20.15	79.9	395
	3/5	49.7	95	0.99	1.74	1.43	12.19	4.80	21.19	78.8	400
	3/7	76.4	86	0.59	1.81	0.56	12.0	5.07	20.04	79.9	410
	3/9	93.8	64	0.43	1.51	0.94	10.93	5.30	19.11	80.9	420
	3/8	96.5	42	0.45	1.65	0.77	9.90	5.14	17.91	82.1	435
B/N	3/13	66.1	47	0.54	2.36	0.56	10.11	6.56	20.13	79.9	425
	3/14	66.5	90	0.55	2.13	1.02	13.16	7.46	24.32	75.7	430
	3/15	75.9	86	0.53	4.57	1.03	12.87	6.50	25.49	74.5	430
	3/16	81.1	53	0.46	4.11	0.39	10.79	7.05	22.81	77.2	435
C/T	4/23	55.1	136	0.59	1.71	0.39	15.08	8.30	26.62	73.4	410
	4/18	75.9	54	0.49	1.68	0.88	10.77	8.44	22.27	78.8	415
	4/20	80.3	54	0.69	1.55	1.23	10.26	8.22	21.93	78.1	420
	4/24	80.4	68	0.45	1.79	0.74	11.63	8.42	23.36	76.6	435
	4/19	86.7	65	0.49	3.35	1.22	10.78	8.40	24.25	75.8	445
D/T	5/9	83.4	54	0.45	1.34	0.46	10.68	7.20	20.13	79.9	440
	5/10	85.9	84	0.47	0.81	1.03	12.69	6.89	21.87	78.1	440
	5/8	95.0	70	0.59	1.59	0.64	11.43	7.16	21.41	78.6	430
E/O	5/15	72.3	55	0.80	0.39	1.51	10.43	4.55	21.27	78.7	425
	5/14	76.1	108	0.92	0.84	1.32	13.48	4.78	21.32	78.7	415
	5/16	92.1	65	0.45	1.15	2.17	12.02	4.54	20.33	78.7	455
	5/17	93.3	49	0.46	1.01	2.04	12.39	4.58	20.48	79.5	445
	5/18	96.1	64	0.46	1.04	1.51	11.00	4.61	19.35	80.7	425
E/O	5/11	94.6	47	0.40	0.15	0.46	10.16	7.97	19.41	80.6	440

[a]Morning test data extracted and plotted in increasing steam load sequence.

[b]Coal source/dRDF source.

[c]Does not contain manufacturer's allowance for unaccountable losses.

[d]Based on reported values.

order of increasing steam load. The tabulation is shown only for the 1:2 fuel ratio in Table 12. The effect of cofiring on boiler efficiency can be seen. The boiler design data are given in Table 13. In addition, running a coal-only test after cofiring can lead to a lower boiler efficiency owing to higher exit gas temperature because of furnace slagging, as shown in Figure 1. A straight-line curve fit for the combined coal-only test data (from Table 12) resulted in

$$\text{Efficiency, percent} = 77.58 + (0.02935)(\text{percent steam load}).$$

All the Teledyne cofiring data (for coals C and D) were subjected to a straight-line curve fit and resulted in

$$\text{Efficiency, percent} = 67.83 + (0.1193)(\text{percent steam load}).$$

At 80 percent steam load, the coal-only and the combined Teledyne pellet cofiring efficiencies are 79.93 percent and 77.37 percent for a difference of 2.56 percentage points as shown in Figure 2. Average coal properties for the Erie test are shown in Appendix C, Table C-3.

D. WPAFB BUILDING 1240 TESTS

The Building 1240 tests were conducted during April 1981 and May on Boiler 3, and the test data are reported in Reference 5. Again, the boiler efficiency calculation procedure followed the protocol reviewed in the discussion above. Because of the successful energy conservation practices, the hot water available heat load was only about 30 percent of the design load of 100 by 10^6 Btu/hr; see Table 14.

Further examination of the test report revealed inconsistencies in the tabulated fuel ultimate analyses. Communication with the report author resulted in the correct fuel analyses, and these are given in Appendix C, Tables C-4 and C-5. The author also indicated that the calculated boiler efficiency would be off and the average of the tabulated fuel properties were used, on a dry basis, for each individual mass balance (on a rate basis) calculation necessary to find the boiler efficiency.

To fully determine the impact of firing coal versus firing only dRDF as was done at Building 1240, the boiler efficiencies were recalculated using the standard ASM heat loss method and the corrected fuel properties. The fuel design data are shown in Table 15. The results for each dRDF and coal test are shown in Tables 16 and 17. A comparison of the average values of coal and dRDF with design values are shown in Table 18. The design performance is for a 100 percent load while the test data are for a boiler load of about 30 percent. The dry gas loss is high because of the excess air--169 percent for coal and 160 percent for dRDF. Thus, a decrease of 3.44 percentage points in efficiency was experienced in going from coal-only to dRDF firing.

TABLE 13. ERIE BOILER DESIGN DATA--BABCOCK AND WILCOX STERLING BOILER.

Design steam flow	150,000 lb/hr
Steam pressure	675 psig
Steam temperature	825° F
Economizer inlet water temperature	225° F
Economizer exit flue gas temperature	400° F
Excess air, boiler exit	33%
Rated boiler efficiency	84.5%
Fuel flow rate	17,400 lb/hr
Flue gas flow rate	240,000 lb/hr
Furnace volume	7,860 ft^3
Furnace heat-release rate	27,900 ft^3/hr-ft^3
Grate area	376 ft^2

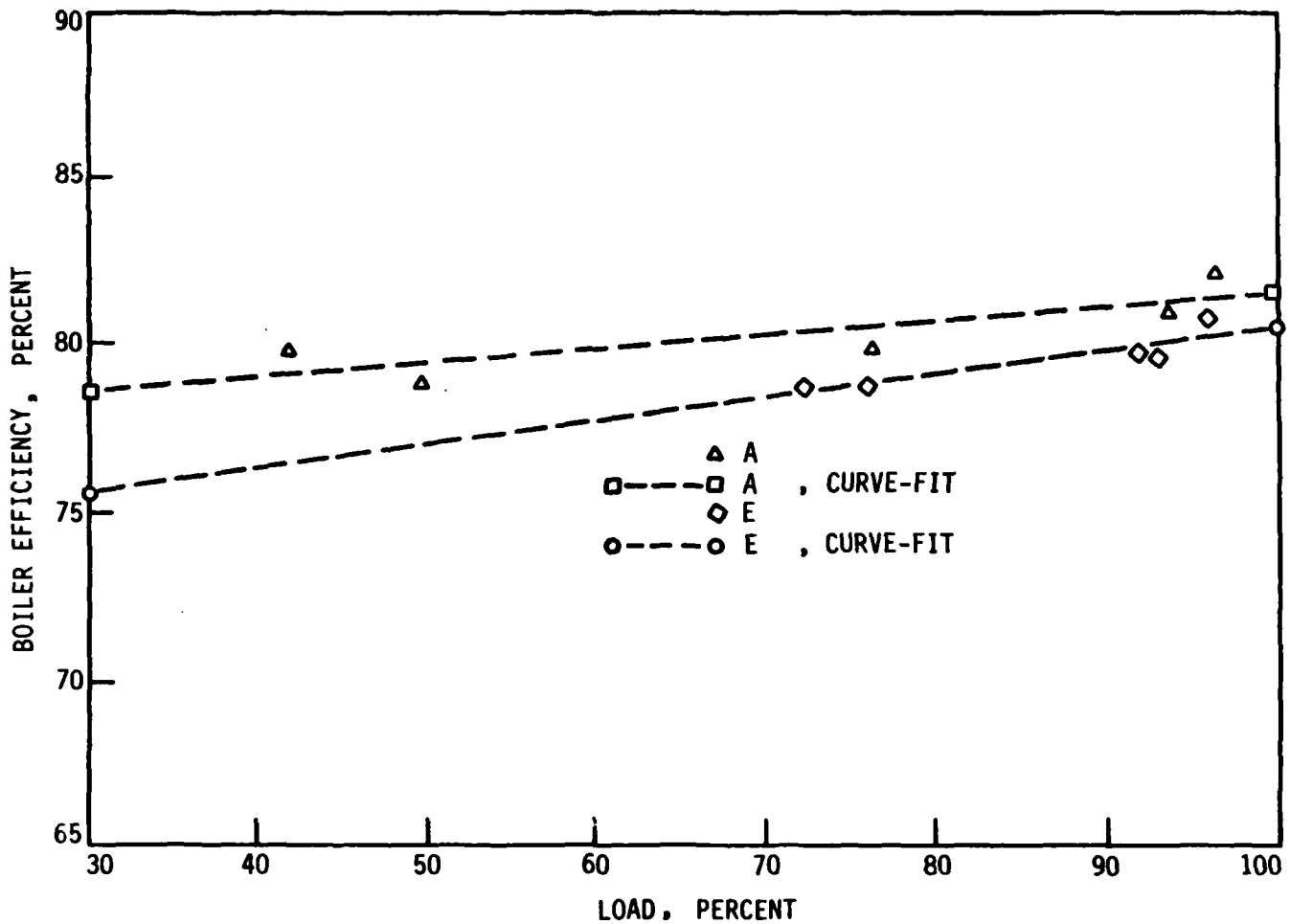

Figure 1. Erie Boiler Efficiency, Coal-only Tests.

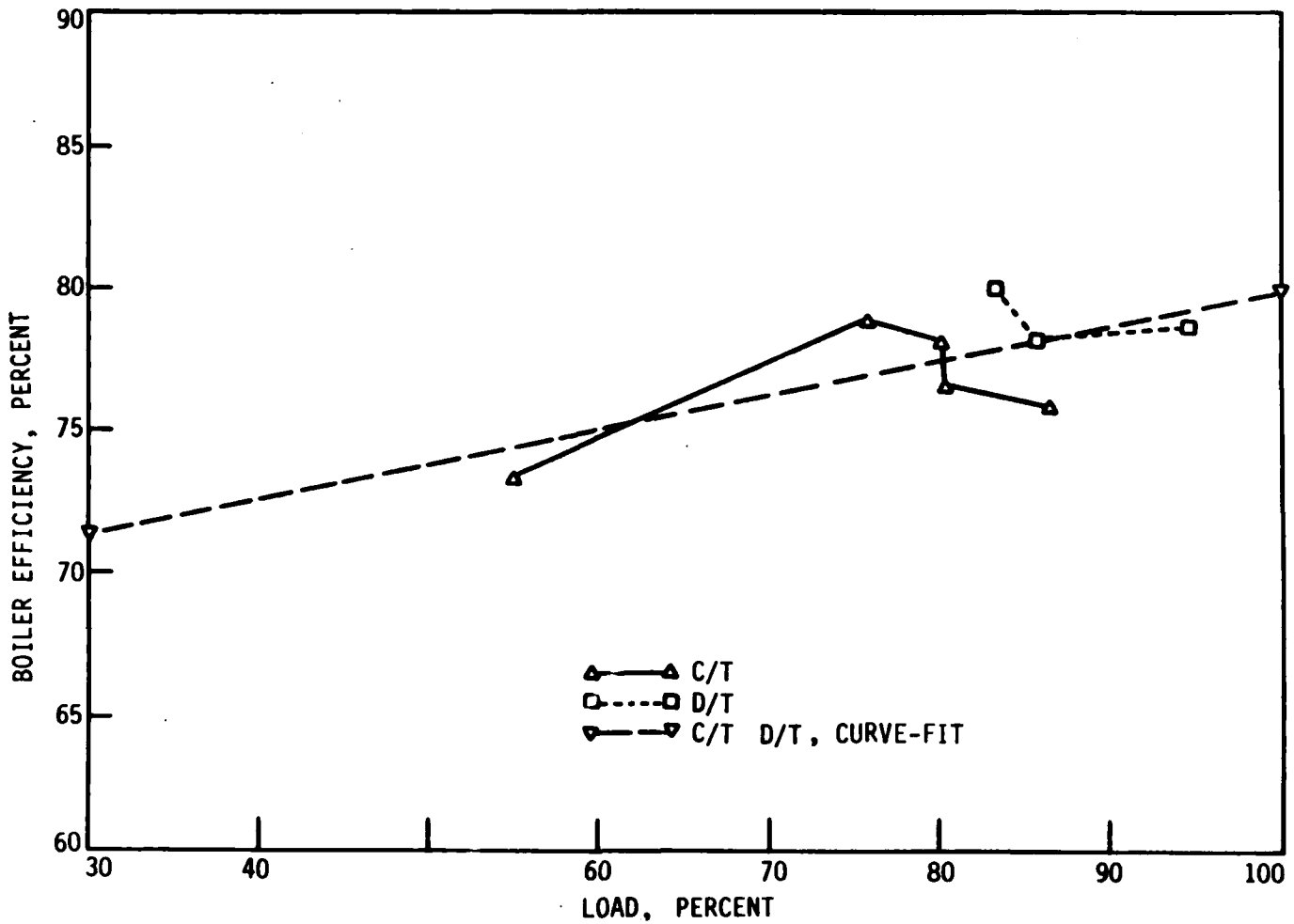

Figure 2. Erie Boiler Efficiency, Cofiring Teledyne Pellets.

TABLE 14. BUILDING 1240 BOILER 3 PREDICTED THERMAL PERFORMANCE.

High-temperature hot water (HTHW) flow	582,000 lb/hr
H_2O temperature entering	250° F
H_2O temperature leaving	414° F
H_2O pressure at boiler outlet	275 psig
H_2O pressure drop	20 psi
Heat output (into H_2O)	100×10^6 Btu/hr
Flue gas	
Flow rate leaving boiler	122,000 lb/hr
Temperature leaving boiler	524° F
Temperature leaving air heater	381° F
Draft loss, inches H_2O	6.4
Combustion air	
Flow rate leaving air heater	105,000 lb/hr
Temperature entering air heater	70° F
Temperature leaving air heater	245° F
Draft loss, inches H_2O	5.1
Heat losses, %	
Dry gas	7.5
H_2 and H_2O in fuel	4.2
Moisture in air	0.2
Unburned combustible	1.1
Radiation	0.7
Unaccountable and manuf. allowance	1.5
	15.3
Predicted boiler efficiency (heat loss method)	84.7
Excess air leaving boiler	28%

TABLE 15. BUILDING 1240 BOILER 3 DESIGN DATA.

Design specification

Waterwall heating surface	1150 ft^2
Boiler heating surface	8850 ft^2
Furnace volume	3270 ft^3
Net grate surface area	187 ft^2

Recommended fuel specification

Proximate Analysis, %		Ultimate Analysis, %, As Received	
Fixed carbon	54.4	Carbon	75.5
Volatile matter	33.7	Hydrogen	5.0
Moisture	2.4	Sulfur	0.9
Ash	8.5	Nitrogen	1.3
	100.0	Ash	8.5
		Moisture	2.4
		Oxygen	6.4
			100.0

Higher heating value = 13,450 Btu/lb

Grate heat release rate = 631,357 Btu/hr-ft^2

Furnace volume heat release rate = 36,105 Btu/hr-ft^3

TABLE 16. BUILDING 1240 HEAT LOSSES AND BOILER EFFICIENCY--REVISED CALCULATIONS.[a]

	dRDF									
	R-1	R-2	R-3	R-4	R-5	R-6	R-7[b]	R-8	Average	Std. dev.
Load, %	36.0	18.00	32.75	26.00	24.00	32.00	32.50	34.75	29.50	6.2
Heat loss, %[c]										
Dry gas	11.15	10.60	10.82	10.85	11.28	11.16	13.04	11.83	11.34	0.78
H_2O (from fuel)	9.13	8.89	9.64	9.02	9.26	9.03	10.61	9.4	9.37	0.55
Combustible	0.92	0.94	0.69	0.25	0.35	0.51	0.62	0.47	0.59	0.25
Radiation and convection	1.40	2.60	1.60	1.80	2.05	1.60	1.60	1.40	1.76	0.4
Unaccountable and manuf. allowance[d]	1.50	1.50	1.50	1.50	1.50	1.5	1.5	1.5	1.5	0.0
Loss total	24.10	24.53	24.25	23.42	24.44	23.80	27.37	24.60	24.56	1.20
Boiler efficiency	75.9	75.47	75.75	76.58	75.56	76.2	72.63	75.40	75.44	1.20

[a]New calculations based on revised ultimate analysis.

[b]Refuse fuel had higher heating value of 6,304 Btu/lb.

[c]Based on original Orsat reported as 6.9 percent CO_2, 13.0 percent O_2.

[d]Not included in original report.

TABLE 17. BUILDING 1240 HEAT LOSSES AND BOILER EFFICIENCY--REVISED CALCULATIONS.[a]

	Coal				
	C-1	C-2	C-3	Average	Std. dev.
Load, %	32.75	30.0	31.5	31.4	1.4
Heat loss, %[b]					
Dry gas	13.29	12.05	12.02	12.45	0.72
H_2O from fuel	4.82	4.29	4.19	4.43	0.34
Combustible	1.19	1.20	0.95	1.11	0.14
Radiation and convection	1.60	1.65	1.62	1.62	0.03
Unaccountable and manuf. allowance[c]	1.50	1.50	1.5	1.5	0
Loss total	22.40	20.69	20.28	21.12	1.12
Boiler efficiency	77.60	79.31	79.72	78.88	1.12

[a]Calculation based on revised ultimate analysis.

[b]Based on original Orsat reported as 6.5 percent CO_2, 13.2 percent O_2.

[c]Not included in original report.

TABLE 18. COMPARISON OF BUILDING 1240 HEAT LOSSES AND BOILER EFFICIENCY.

	Design	Coal	dRDF
Load, %	100.00	31.40	29.50
Heat loss, %			
Dry gas	7.6	12.45	11.34
H_2O from fuel	4.4	4.43	9.37
Combustibles	1.1	1.11	0.59
Radiation and convection	0.7	1.62	1.76
Unaccountable and manuf. allowance	1.5	1.50	1.50
Loss total	15.3	21.12	24.56
Boiler efficiency, %	84.7	78.88	75.44
Excess air, %	28.0	169.0	160.0

E. BUILDING 770 BOILER EFFICIENCY

The boiler efficiency tests for dRDF cofiring evaluation were performed February 22-26, 1982, and the resulting data along with environmental emission data have been reported (Reference 6). Boiler efficiency was calculated as

$$\text{Efficiency} = \frac{\text{Heat input into } H_2O \text{ (Btu/hr)}}{\text{Fuel heat input + credits (Btu/hr)}} \times 100$$

With regard to the net heat input into water, the following observations are noted. The feedwater temperature actually used to find the liquid enthalpy was based on the condensate return and should have been based on the feedwater temperature of 220° F entering the boiler.

Steam flow values were obtained from charts (with one division equal to 2,500 pounds). In addition, the test steam pressure was given as 388 psia instead of 414.2 psia (400 psig). This requires an instrument meter correction of

$$\dot{m}_{actual}/\dot{m}_{chart} = 0.971$$

Because of difficulty with the fuel-weighing scales, the fuel heat input was calculated using

$$Q_f(10^6 \text{ Btu/hr}) = \frac{(Q_{SD})60}{(F)\left(\frac{20.9}{20.9 - \text{percent } O_2}\right)}$$

where

Q_f = fuel heat input

Q_{SD} = dry stack flue gas volumetric flow rate, DSCFM

F[1] = fuel emission factor, theoretical or stoichometric volume of dry flue gas at standard conditions produced from fuel combustion

= stoichmetric DSCFM/10^6 Btu

$\left(\frac{20.9}{20.9 - \text{percent } O_2}\right)$ = excess air correction for measured flue gas oxygen content, percent O_2(dry volume basis)

[1]See 10 CFR 60; Subpart D for further discussion.

The calculation of heat credits included fan horsepower energy and erroneously calculated energy content for the inlet combustion air moisture. These heat credits are not used in the abbreviated efficiency calculation and can be disregarded.

The use of the fuel emission factor, F, for fuel heat input calculations resulted from EPA procedures used in particulate emission testing when it became impossible to measure fuel flow rates. This fuel emission factor, F, can have a 4-percent error (because of no allowance for unburned carbon), making its real value lower. Thus, the calculated value can make the particulate emissions higher (or on the conservative side) but would make the fuel heat input values lower (and increase boiler efficiency). Recalculated efficiencies using only the F factor heat input (disregarding heat credits), the corrected steam flow, and feedwater enthalpy are given in Table 19. The results are the reverse of those normally expected. Normally, coal-only boiler efficiencies should be higher, even after some furnace wall slagging, which would raise the flue gas exit temperatures. The design boiler performance was obtained from the manufacturer and is shown in Table 20. The predicted full-load boiler efficiency is 81.8 percent at 25 percent excess air using an air heater. Unfortunately, no flue gas temperatures were recorded at the air heater outlet so no heat loss efficiency could be made.

The concern and possible error in use of flue gas DSCFM measurements, F values, and Orsat values can be seen in reexamining the data from the ESP acceptance tests on the Building 1240 Unit 3 (Reference 28). A comparison of the fuel heat input values (10^6 Btu/hr) revealed the following:

- 71.9, based on measured coal flow and fuel heating value
- 71.5, based on F factor and ESP inlet flue gas DSCFM
- 57.0, based on F factor and ESP exit flue gas DSCFM.

A further concern for using the F factor and flue gas DSCFM can be seen by a comparing these data with fuel flow heat input for the Building 1240 test data shown in Table 21. Because of the variation, this method should not be used in a boiler efficiency determination.

F. GSA BOILER TEST

The results of GSA boiler tests taken March 20-23, 1979, are shown in Table 22. The boiler, a ram-type underfeed stoker, is found in small numbers throughout the country.

A listing of early cofiring tests is given in Table 23. Because the experimental fuel is no longer available, no further discussion seems in order.

TABLE 19. BUILDING 770 WPAFB BOILER EFFICIENCY DATA--REVISED.

Fuel	Nominal steam load %	Heat input[a] 10^6 Btu/hr	Heat output[b] into H_2O 10^6 Btu/hr	Boiler efficiency %	Excess air %
Coal/RDF 40% weight					
$\bar{x}$[c]	76.5	142.7	116.64	81.47	58.3
s[d]	7.6	16.6	11.57	1.58	0.6
RDF 100%					
$\bar{x}$	64.5	131.4	98.33	74.9	88.3
s	3.1	6.3	4.70	0.7	5.9
Coal 100%					
$\bar{x}$	97.6	201.6	148.92	73.9	44.3
s	2.6	9.05	3.98	1.8	12.0

[a]Based on fuel emission factor and no heat credits.

[b]Steam flowmeter correction (for H_2O density = 0.971 and inlet feedwater at 220° F).

[c]Average.

[d]Standard deviation.

TABLE 20. BUILDING 770 KEELER BOILER UNIT 4 DESIGN DATA.

- General Design Data

Steam flow		150,000 lb/hr
Flue gas temperature:	Boiler exit	650° F
	Air heater exit	450° F
Excess air:	Boiler exit	25%
	Air heater exit	30%

Fuel: (reconstructed) ultimate analysis, %

C	70.5
H	4.5
H_2O	10.0
Ash	10.0
O	5.0
	100.0

Heating value	12,500 Btu/lb
Fuel flow rate	14,920
Grate heat release rate	722,830 Btu/hr-ft^2
Grate area	258 ft^2
Flue gas weight flow	193,020 lb/hr

- Heat Losses, %

	Full Load
Dry gas	8.71
H_2O from air	0.21
H_2O in fuel	4.98
Unburned combustible	2.30
Radiation	0.50
Manufacturer's allowance	1.50
	18.20

- Efficiency, % 81.8

TABLE 21. BUILDING 1240 COMPARISON OF HEAT INPUT BY USE OF FUEL DATA AND THE F FACTOR METHOD.

Test	Nominal load %	Fuel heat input[a] 10^6 Btu/hr	Flue gas[b] volume flow DSCFM	F Factor[c]	O_2[d] %	Heat input[e] F method 10^6 Btu/hr
3-30-81 (R-5)	24.00	30.15	17,564	9364.3	13.0	42.54
3-31-81 (R-6)	32.50	39.29	22,966 18,524	9067.1	13.0	57.44 46.33
4-2-81 (R-8)	34.75	39.31	30,336	9263.4	13.0	74.27
4-6-81 (C-1)	32.75	37.30	20,550 15,690	11,277	13.2	40.28 30.76
4-8-81 (C-3)	31.50	36.26	18,047 13,557	9679.0	13.2	41.22 30.96

[a]Based on revised fuel analysis and fuel firing rate.

[b]From Building 1240 stack emission tests.

[c]Calculated from revised fuel analysis.

[d]Reported average values.

[e]Heat input = (DSCFM)(60)/(F-Factor)(20.9/20.9-% O_2) × 10^6, Btu/hr.

TABLE 22. GSA BOILER EFFICIENCY TESTS (1979).[a]

- Boiler Design Data

Steam flow	70,000 lb/hr
Pressure	125 psig, saturated

- Manufacturer: Riley Stoker multiple-retort inclined ram underfeed (8 rams)

Grate heat release rate	455,000 Btu/hr-ft^2
Furnace volume	3,700 ft

- Thermal Performance

Test date	3/20	3/21	3/22
Fuel mixture, coal:dRDF	1:0	4:1	2:3
Steam flow, % load	62.9	40.1	42.9
Excess air, %	133.5	133.4	284
Exit flue gas temperature, °F	621	591	571
Air reference temperature, °F	71	70	70
Inlet water temperature, °F	225	225	225
Heat losses, %			
Dry gas	23.50	20.23	41.76
Moisture in fuel	0.17	0.65	1.52
H_2O from H_2	4.19	4.34	5.29
Combustible	3.99	4.89	1.09
Radiation	--	--	--
Manufacturer's allowance	--	--	--
Total, %	31.85	30.15	50.52
Average fuel heating value, Btu/lb	13,662	12,443	10,220

[a]Excess air fluctuations from 140 percent to 660 percent because of inoperative forced draft fan control.

TABLE 23. CHRONOLOGICAL SUMMARY OF PREVIOUS COFIRING TESTS.

	Location of test	Test sponsor	dRDF manufacturer	Date of test	Type of dRDF	Volume blend Coal:dRDF	Fired (tons)	Test duration (hours)
1.	Municipal Power Plant, Fort Wayne, IN	National Recycling Center		1972	cubette 1 1/2" × 1 1/2" × 2"	3:1	40	--
2.	Eugene Water & Electric Board	Sandwall International, Inc.	Vista	1974	3/8" pellets	--	21	1.5
3.	Sunbury Steam Electric Station, Pennsylvania Power & Light		Elo & Rhodes	1975	5/8" pellets	--	80	48
4.	Municipal Power Plant Piqua, OH	Black-Clawson Fibreclaim, Inc.		1975	3/8" pellets	1:1	22	7
5.	Building 770 Wright-Patterson AFB	Air Force Black-Clawson Fibreclaim, Inc.		1975	3/8" pellets	1:1 1:2	40	34 6
6.	Chanute AFB	U.S. Army CERL	Vista	1975	1 1/8" pellets	1:1 & 0:1	150	--
7.	Stockertown, PA	Hercules Cement	Vista	1975	1 1/8" & 5/8" pellets	--	201	168
8.	Univ. of Wisconsin Oshkosh, WI	Wisconsin Solid Waste Recycling Authority	Vista	1976	1 1/8" pellets	1:1, 1:3, & 0:1	21	--
9.	Appleton Division	Wisconsin Solid Waste Recycling Authority	Grumman	1976	3/4" pellets	--	40	8
10.	Menasha Paperboard Mill	Wisconsin Solid Waste Recycling Authority	Grumman	1976	3/4" pellets	3:2	21	--
11.	Waupun, WI	Wisconsin Solid Waste Recycling Authority		1976	3/4" pellets	20%, 30%, and 40% by heating value	21	--
12.	Green Bay, WI	Ft. Howard Paper	Grumman	1976	3/4" pellets	1:3 and 1:2		--
13.	Psychiatric Center, Marcy, NY	New York State Energy and Development Authority	Teledyne	1980	--	1:1, 1:2, 2:1, 3:1	50	--

In conclusion, the test protocol for boiler efficiency calculation should be reviewed to allow for the use of the more common ASME heat loss procedure. In addition, the use of the fuel emission factor for heat input and steam flow for heat output calculation may result in discrepancies. Further study on the precision of data should be made before the results can be considered reliable.

SECTION V

PARTICULATE COLLECTION EFFICIENCY

A. INTRODUCTION

As the change is made from coal-only to dRDF cofiring or to dRDF-only firing, one concern is the change in the particulate removal efficiency. Because of the stricter limits on stack emissions, many stoker installations now use high-efficiency electrostatic precipitator (ESP) collection devices. The nominal efficiency is expressed in terms of the sample Deutsch equation where efficiency is given as

$$\eta = 100 \left[1 - \text{esp} \; -\left(W \times \frac{A}{Q} \right) \right], \text{ percent}$$

where

w = Migration velocity, ft/min (also called the Deutsch drift velocity)

A = Collection surface area, ft^2 (positively charged ground electrode)

Q = Actual wet flue gas volumetric flow rate, ACFM.

For dRDF cofiring, normally higher moisture content, higher excess air operation, and higher exit temperatures occur and, thus, the actual volume flow rate of the wet flue gas increases, lowering ESP efficiency. ESP operation imposes high DC voltage on the negative electrode and results in a corona discharge or ionization of gases. The fly ash or dust becomes negatively charged and is attracted to the collection plate. A resultant buildup of a fly ash layer occurs on the collection plates. The electrons on the dust move to the plate, and the resistance to this current flow is expressed by the fly ash resistivity, ρ, (ohm-cm). For typical bituminous coals, resistivities are in the range of 1×10^{10} ohm-cm. When the resistivity increases, the voltage drop across the dust layer increases, reducing the voltage available for inducing the corona discharge. Thus, less fly ash particle charging occurs, and this reduces the movement (because of polarity attraction) toward the collection plates. The other effect occurs when the fly ash contains unburned carbon, which will induce short circuiting, reducing the collection efficiency. Thus, the measurement of fly ash resistivity, either in situ or by ASME PTC 28, gives some indication of possible changes in performance.

B. MCI TESTS

The MCI heating plant boiler uses a mechanical collector for particulate removal. An attempt to characterize the impact of cofiring was made with a portable ESP test unit. Continued short circuiting of the charging electrode was experienced, and the data were considered unreliable. Fly ash resistivity was measured by use of a Wahlco® probe. The test results are listed in Table 24.

It is interesting to note the increase of resistivity from 10^7 ohm-cm for coal-only firing to 1.71 by 10^{12} ohm-cm for 1:2 volumetric ratio cofiring Erie tests.

Results of ESP efficiency tests conducted at nominal high loads for the various coals and pellets are listed in Table 25. The results vary for the firing of Coal A only and for the Coal B/NCRR pellet. The 1:1 and 1:4 volumetric ratio for the D/T coal pellet cofiring also decreased. The average efficiencies (based on a 1:2 ratio) were C/T, 98.6 percent; D/T, 94.0 percent; and E/O, 95.6 percent. The corresponding power usage (KVA) was 38.5, 36.7, and 25.5. Thus, an increase in ESP power consumption for cofiring occurred, based on the use of Coal E. This behavior is similar to the ESP power consumption experienced at WPAFB Building 1240 where the kW use was coal-only, 24.6 kW; dRDF-only, 42.0 kW. Fly ash sizing distribution parameters, based on the Roslin-Rammler distribution, are shown in Table 26. The fly ash resistivity data for four tests are shown in Table 27.

C. WPAFB TESTS

The ESP efficiencies and resistivities for the Building 1240 and 770 tests are shown in Table 28. The efficiencies seemed to increase very slightly for dRDF firing, compared to coal-only firing. This trend was similar to the Erie C/T test verses firing of Coal E only (see Table 25). No ESP power measurements were made at Building 770. Table 29 lists the particulate sizing at the inlet and outlet of the ESP. The largest decrease in inlet size occurred for dRDF-only firing. The calculated value for the Deutsch drift velocity, w, (ft/min) for the dRDF and coal tests were listed as 717.11 and 823.43. These seemed high, and the values were recalculated as 25.02 ft/min for dRDF and 23.96 ft/min, based on a 30,000 ACFM and a collection area of 4,680 ft^2. These values are in the range of drift velocities normally expected, i.e., 20 ft/min to 40 ft/min.

D. SUMMARY

The results of fly ash resistivity tests completed on ESP hopper ash by ASME PTC 28 were generally lower than the <u>in situ</u> measurement values at MCI.

TABLE 24. MCI FLY ASH RESISTIVITY DATA.

	No. of samples	Blend ratio	Boiler no.	Steam load %	Resistivity ohm-cm	Flue gas temp, °F	Excess air %
	2	1:0	2				
Average				40.0	$<10^7$	509.5	104
Standard deviation				0	0	0.707	0
Average	1	1:0	1	40.0	$<10^7$	395	72
	3	1:1	1				
Average				43.3	8×10^9	427.3	83.3
Standard deviation				0.6	3.5×10^9	3.8	16.2
	4	1:1	2				
Average				34.0	1.65×10^{12}	512.8	125.0
Standard deviation				2.8	1.77×10^{12}	5.1	11.8
	2	0:1	2				
Average				26.5	1×10^{12}	471.5	119.5
Standard deviation				0.7	0	2.1	19.1

TABLE 25. ERIE ELECTROSTATIC PRECIPITATOR PERFORMANCE.[a]

Fuel mixture	No. of samples	Steam load		Efficiency, %		Power consumption	
		X^b	S^c	X	S	X^{KVA}	S
A/O	4	95.4	1.2	72.7	19.5	40.3	1.4
B/N	3	80.9	0.5	49.6	43.7	39.9	1.3
C/T	7	85.9	5.8	98.6	0.42	38.5	5.6
D/T	3	--	--	94.0	5.6	36.7	2.4
	1[d]	99.5	--	87.7	--	36.7	--
	2[e]	93.4	1.7	77.1	15.8	40.5	0.8
E/O	6	94.4	1.6	95.6	0.4	25.5	1.7

[a]Coal-dRDF volumetric ratio 1:2 unless otherwise noted.

[b]Average.

[c]Standard deviation.

[d]Volumetric mixture ratio 1:1.

[e]Volumetric mixture ratio 1:4.

TABLE 26. ERIE ESP INLET FLY ASH SIZING.[a]

Fuel mixture	No. of samples	D_{67},[b] μm		M[c]	
		X	S	X	S
A/O	4	58.3	32.2	0.62	0.14
B/N	3	27.7	15.9	0.62	0.07
C/T	7	34.6	27.9	0.71	0.08
D/T	3	73.3	12.3	0.67	0.19
	1[d]	80.0	--	0.75	--
	2[e]	66.0	2.8	0.55	0.11
E/O	6	47.2	29.8	0.74	0.05

[a]Sizing based on Roslin-Rammler sizing distribution and corresponds to ESP efficiency tests.

[b]Characteristic diameter, 63 percent less than this value.

[c]Rosin-Rammler exponent-characteristic of size distribution.

[d]Volumetric mixture ratio 1:1.

[e]Volumetric mixture ratio 1:4.

TABLE 27. ERIE FLY ASH RESISTIVITY MEASUREMENTS.[a]

Test date	Fuel mixture	Resistivity[b] ohm-cm	Unburned combustibles %
5/8	D/T	1.56×10^6	25.6
5/9	D/T	1.05×10^8	20.7
5/16	E/O	2.09×10^4	39.7
5/18	E/O	4.36×10^4	33.6

[a]Boiler at full load.

[b]ASME PTC 28/Note minimum range value is 10^7 ohm-cm.

TABLE 28. WPAFB ELECTROSTATIC PRECIPITATOR PERFORMANCE.

	Efficiency %	Resistivity[a] ohm-cm	Power KW
Building 1240			
Coal	97.62	5.49×10^3	24.63
dRDF	97.98	2.7×10^5	41.96
Building 770			
Coal	97.00	4.6×10^7	N/A
Coal-dRDF	97.00	4.7×10^7	N/A
dRDF	97.40	4.9×10^7	N/A

[a]ASME PTC 28.

TABLE 29. BUILDING 770 PARTICULATE SIZING CHARACTERIZATION.

Fuel	Boiler load %	ESP inlet[a] DG μM	ESP inlet[a] σ_G μM	ESP outlet DG μM	ESP outlet σ_G μM
Coal-dRDF	73.7	42.5	19.77	2.15	4.89
	83.3	14.5	21.64	0.63	4.74
dRDF	68.67	4.25	22.97	2.15	4.00
	63.33	1.8	10.59	1.9	5.07
Coal	101.33	20.5	8.20	3.4	3.47
	96.67	13.3	6.65	3.10	4.59

[a]For log normal distribution.

DG = Geometric mean diameter.

σ_G = Geometric standard deviation.

SECTION VI

BOILER CORROSION POTENTIAL

A. INTRODUCTION

In the continued development of the waste-to-energy technology the specific application of cofiring processed refuse-derived fuels (i.e., fluff RDF or pellets, dRDF) with coal, one area of concern is the potential for boiler corrosion. This possible boiler tube metal waste could be caused by the presence of chlorine, Cl_2, in the RDF.

This concern arose from corrosion associated with burning MSW in mass-burner or water-wall incinerators. This fireside corrosion appears to result from the combined reaction of certain constituents in the liquid-phase mineral ash (and in the flue gas) that have been deposited on the boiler tube metal.

B. EARLY STUDIES

A major research effort to investigate the mechanism of corrosion in incinerators was initiated by Battelle Memorial Institute, and test results reported (Reference 29) were based on the use of corrosion probes inserted into the furnace region as well as additional laboratory studies. The inserted test probes were formed from a repeated group of various metal coupons that had been water-cooled to maintain various metal temperatures. This allowed for the study of corrosion reaction at various metal temperatures. These analyses of the tube metal coupons and the accompanying ash deposits attributed the metal attack to the chlorine, which was originally in the MSW, with the final formation of iron chloride, FeCl. Apparently hydrochloric acid, HCl is formed in the liquid ash deposits and reacts directly with the tube if the metal temperature is above 600° F. If the tube temperature is below 600° F, the HCl first reacts with O_2 to form Cl_2 which then attacks the metal to form FeCl.

The presence of iron sulfide in the deposit layer implied that sulfur may have contributed to corrosion, involving what is known as "coal-type corrosion." Here the coal sulfur led to the formation of alkali pyrosulfates in the waterwall liquid ash deposit where metal temperatures ranged between 750° F and 900° F (Reference 30). Likewise, coal sulfur led to the formation of alkali iron trisulfates in boiler superheater sections where metal temperatures were in the general range of 1050° F to 1300° F. Because of appropriate boiler heat transfer design and use of various tube alloys, coal sulfur type corrosion has been used.

Further studies by Battelle involved the seeding of MSW with sulfur (Reference 31). Test results indicated that, as more sulfur was

added, the measured chlorine concentration in the ash deposits decreased with a corresponding reduction in metal wastage.

The proposed rationale is that the vaporized metal chlorides from the fuel mineral ash react in the gas phase with the increased sulfur oxides to form HCl and Cl_2. Thus, the chlorine reaction is occurring in the gas phase and is carried out with the flue gas.

This neutralization of the chlorine behavior was examined further using corrosion probes inserted in a coal-dRDF cofired stoker boiler installation at Columbus, Ohio, (Reference 32). For an 8-hour test period, the tests indicated that the metal wastage rates for mass burning was an order of magnitude higher than that for coal or coal-RDF cofiring (with RDF up 42 percent by Btu).

Further tests of 700 hours in duration at the same boiler installation (Reference 33) indicated that the metal wastage rates of firing fluff RDF and high sulfur coal were 5-10 times less than that of burning only MSW.

Excellent summaries of the series corrosion studies mentioned above are reported in References 34-36. A more complete discussion of the proposed chemical reactions resulting from the above research are given in Appendix D.

C. dRDF COFIRING CORROSION TESTS

Corrosion studies performed during the Maryland Correctional Institute Power Plant cofiring tests involved the exposure of eight clamp-on test specimens. These test coupon shields, attached to the rear waterwall tubes 5 feet above the grate fuel bed, were exposed to the complete spectrum of cofiring fuel ratios: 1:0, 1:1, 1:2, 1:1, then 0:1, 100 percent pellets, and finally 1:0, coal-only for a total of 478 hours of exposure. Normal wastage (less than 5 mils/ year) was experienced on seven coupons while one specimen, 1018 carbon steel, had 2,700 mils/year. This test coupon was at the rear wall location where high slagging occurred, apparently because of a poorly operating distributor rotor.

The corrosion tests performed at Erie involved analysis of collected waterwall ash deposits for corrosion potential. The procedure involved analyzing the deposit samples for ash chemistry, melting temperatures using differential thermal analysis and thermogravimetric analysis, and surface morphology using a scanning electron microscope. As a result of these ash deposit studies, the conclusion was reached that there was no concern for possible corrosion.

No corrosion studies were performed at the WPAFB tests.

In conclusion, coal-dRDF cofiring stoker operation with excess air values between 40 percent and 100 percent appears to result in an environment that minimizes metal wastage. Air leakage up through the side walls of the grate air seal would provide an oxidizing atmosphere to reduce corrosion if waterwall ash buildup occurs.

SECTION VII

AIR EMISSION EVALUATION STANDARDS FOR SOLID FOSSIL FUEL-FIRED STEAM GENERATORS

A. BACKGROUND

Air emissions from five boilers have been measured where densified refuse-derived fuel (dRDF) was cofired with coal. Two of these boilers were at Wright-Patterson Air Force Base (WPAFB); one was located at the General Electric (GE) plant, Erie, Pennsylvania, and two were located at the Maryland Correctional Institute (MCI), Hagerstown, Maryland. During tests at these locations, a variety of pollutants were measured to ascertain the effect (i.e., increase or decrease) on emissions because of cofiring dRDF. In addition to merely stating the increase or decrease of a given pollutant, it is necessary to compare the change to air emission standards. For example, a large increase in a given pollutant may not be significant if the emission is below the air emission standard for that pollutant.

Emissions from steam generators (boilers) can be addressed from the viewpoint of criteria pollutants for which federal air quality standards have been promulgated and state regulations subsequently enacted. However, the list of criteria pollutants is relatively short and does not cover all of the emission species measured during the five boiler tests. Threshold limit values (TLVs), which are the maximum safe exposure values for workers, are listed for many of the pollutants not covered by criteria pollutant standards. TLVs values may be used for comparison purposes when examining emission species not covered by published air quality standards. Another category in common use in environmental discussions is priority pollutants, but this has no application to air emissions from solid fossil fuel-fired steam generators. Following is a discussion of criteria pollutants, threshold limit values, priority pollutants, and the developed comparison standards for the pollutants measured during the boiler tests.

B. CRITERIA POLLUTANTS

1. New Source Performance Standards

Fossil fuel-fired boilers are governed by the federal Environmental Protection Agency (EPA) New Source Performance Standards (NSPS) listed in the Code of Federal Regulations (CFR). The specific section is 40 CFR Part 60, Subpart D, "Standards of Performance for Fossil Fuel-Fired Steam Generators." Present regulations apply to boilers larger than 250 by 10^6 Btu/hr heat input. Regulations have been proposed but not yet promulgated for units larger than 100 by 10^6 Btu/hr. The most rigorous NSPS (Table 30) are for boilers larger than 250 by 10^6 Btu/hr constructed after September 18, 1978. For Air Force

TABLE 30. FEDERAL EPA NEW SOURCE PERFORMANCE STANDARDS FOR SOLID FOSSIL FUEL-FIRED STEAM GENERATORS.

Pollutant	Condition	Maximum allowable emission	
		$lb/10^6$ Btu	ng/J
Boilers rated over 250×10^6 Btu/hr heat input constructed after August 17, 1971			
Particulates		0.10	43
SO_2		1.20	520
NO_x	All solid fuels other than lignite	0.70	300
NO_x	Lignite in a slab tap furnace[a]	0.80	340
Boilers rated over 250×10^6 Btu/hr heat input constructed after September 18, 1978			
Particulates		0.03	13[b]
SO_2		1.20	520[c]
NO_x	Sub-bituminous coal	0.50	210
NO_x	Anthracite, bituminous and lignite coal, and other solid fuels	0.60	260
NO_x	Lignite in a slag tap furnace[a]	0.80	340
Proposed (April 23, 1982) for boilers rated over 100×10^6 Btu/hr heat input[d]			
Particulates	Boiler with no wet scrubber	0.05	22
Particulates	Boiler equipped with wet scrubber	0.10	43
SO_2		no regulation	
NO_x	All solid fuels except pulverized coal	0.60	260
NO_x	Pulverized coal	0.70	300

[a]Lignite from North Dakota, South Dakota, and Montana burned in a cyclone furnace.

[b]In addition to 0.03 $lb/10^6$ Btu, the stack emission can be no more than 10 percent of the ash in the coal.

[c]In addition to 1.20 $lb/10^6$ Btu, the stack emission can be no more than 10 percent of the sulfur in the coal (30 percent if emission less than 0.60 $lb/10^6$ Btu).

[d]Proposed rule not yet promulgated.

base boilers (stoker-fired units burning bituminous coal) the NSPS most restrictive values are

Pollutant	Allowable emission $lb/10^6$ Btu heat input
Particulates	0.03
SO_2	1.20
NO_x	0.60

2. Boiler Size

The size of the five boilers where dRDF was cofired are

Location	Maximum rated heat input, 10^6 Btu/hr
WPAFB--Building 770	100
WPAFB--Building 1240	100
GE--Erie, Pennsylvania	205
MCI--Hagerstown, Maryland	
Boiler 1	87
Boiler 2	67

Boiler sizes at WPAFB are based on the manufacturer's 10^6 Btu/hr rating. The sizes at Erie and Hagerstown are calculated from the manufacturer's lb/hr rated fuel consumption and coal-heating value.

The five boilers listed above are not covered by existing NSPS, and only one would be covered by the proposed regulations. However boilers at U.S. Air Force bases are expected to be within a 40×10^6 Btu/hr to 300×10^6 Btu/hr size range. Therefore, it is possible that Air Force base boilers could exist within the size ranges covered by NSPS, and these can be used as a comparative value in evaluating air emissions from test studies.

3. State Regulations

Some states regulate pollutant concentration in the exhaust gas (i.e., lb/ft^3). In these cases, boiler design performance must be known to convert the regulation into $lb/10^6$ Btu heat input. In the case of sulfur, some states restrict the percentage of sulfur in the fuel instead of specifying a maximum allowable emission regulation. However, the majority of states do have total particulate, SO_2 and NO_x regulations specifying the maximum allowable emission in terms of

$lb/10^6$ Btu. Review of the state air pollution codes indicates that no state currently has a particulate or NO_x regulation more restrictive than the most restrictive federal NSPS. State regulations generally use the 250×10^6 Btu/hr limitation whenever a distinction is made based on size.

Five states do have SO_2 regulations more restrictive than the federal NSPS. These state regulations (Table 31) range from 0.2 $lb/10^6$ Btu to 1.1 $lb/10^6$ Btu. As expected, state regulations are very specific: often have different allowable emissions for different regions within the state, have provisions for variances, and may have regulations for a specific plant location, etc. A complete and detailed evaluation of all state air pollution codes is beyond the scope of this study. The purpose of this discussion is to show that the states are not more restrictive than NSPS for particulates and NO_x, but the states can be more restrictive for SO_2. Further, this situation highlights the fact that federal EPA NSPS should not be taken as the measure for compliance for a specific boiler at a specific location.

4. Ambient Air Quality Standards

Atmospheric levels of pollutants are governed by national ambient air quality standards (NAAQS) established by the federal EPA. These are published in the Code of Federal Regulations (40 CFR Part 60, Subpart D) and include both primary and secondary ambient air quality standards for particulates, SO_2, NO_x, Pb, O_3, and total hydrocarbons (THC) (Table 32). Primary standards are set to protect the public health. Secondary standards, which are different only for particulates and SO_2, are set to protect the public welfare.

For the six NAAQS pollutants, particulates, SO_2, and NO_x are regulated by NSPS. Ozone was not measured during the five boiler tests. However, lead and total hydrocarbons were measured during the boiler tests, and NAAQS can be used as a comparison for these two emissions.

5. Hazardous Air Pollutants

The federal Environmental Protection Agency has established standards for the following hazardous air pollutants:

- Asbestos
- Beryllium
- Mercury
- Vinyl chloride (includes polyvinyl chloride and ethylene dichloride)

The maximum allowable emissions are contained in the Code of Federal Regulations (40 CFR Part 60, Subparts A through F). Asbestos and vinyl

TABLE 31. STATE SO_2 STANDARDS MORE RESTRICTIVE THAN FEDERAL EPA NSPS STANDARDS FOR SOLID FUEL-FIRED STEAM GENERATORS.

State	Maximum allowable emission lb/10^6 Btu	Rule applies to sizes larger than 10^6 Btu/hr heat input	Rule applies to construction after
Wyoming	0.2	All sizes	Jan. 1, 1974
New Jersey	0.3[a]	250	No date specified
Nevada	0.4	250	May 16, 1980
Arizona	0.8	All sizes	May 30, 1974
Connecticut	1.1	250	No date specified

[a]If emissions are below this level, no restriction on % S in fuel, otherwise regulations specify maximum allowable fuel S content.

TABLE 32. FEDERAL EPA NATIONAL AMBIENT AIR QUALITY STANDARDS.

Pollutant	Primary standard			Secondary standard		
	Annual mean $\mu g/m^3$	Maximum 24 hr concentration $\mu g/m^3$	Maximum 3 hr concentration $\mu g/m^3$	Annual mean $\mu g/m^3$	Maximum 24 hr concentration $\mu g/m^3$	Maximum 3 hr concentration $\mu g/m^3$
Total particulates	75	260		60	150	
SO_2	80	365				1,300
NO_x	100			100		
Pb	1.5			1.5		
O_3	235[a]			235[a]		
THC[b]			160			160

[a]Based on maximum hourly average formula. See 40 CFR 60 Appendix H.

[b]Nonmethane total hydrocarbons.

chloride (including polyvinyl chloride and ethylene dichloride) were not measured during the boiler tests. The standard for mercury is a maximum allowable total weight in grams per day which is not useful in comparison to an emission measured in terms of $lb/10^6$ Btu or mg/m^3. The standard for beryllium is an average 30-day ambient air concentration of 0.01 mg/m^3. Therefore, this beryllium standard is included with the NAAQS for lead and total hydrocarbons.

C. THRESHOLD LIMIT VALUES

Threshold limit values (TLVs) exist for many noncriteria pollutants. The TLV reference is the maximum safe 8-hour exposure for workers. TLVs do not provide a ground-level concentration of each pollutant because such a calculation is site-specific based on the dilution factors for that site. The measured air emission elements and compounds with published TLVs for that element or compound are listed below.

D. PRIORITY POLLUTANTS

Priority pollutants are metals and chemical compounds thought to be indicators of industrial hazardous waste. Priority pollutants were originally used by EPA and others in evaluating waste waters for the presence of industrial pollution; but their use has been expanded to evaluation of samples from all media (air, water, solids, and biota). The priority pollutant list Table 33 contains 125 items.

At the present time, there are no existing or proposed priority pollutant regulations for air emissions from solid fossil fuel-fired steam generators. Thus, priority pollutants are not useful in assessing the importance of a specific level of a given emission from a boiler other than to note that a particular emission compound or metal is on the priority pollutant list.

E. MEASURED AIR EMISSIONS

Sixty-one different air emissions were measured at the five boiler locations. The objective of this study was to assess the effect of cofiring dRDF on emissions. This was done in part by comparing emissions to any existing standards. As the previous discussions have shown, there are three standards: NSPS, NAAQS, and TLVs. These standards were used on the basis of their applicability.

NSPS standards are most applicable because these have been specifically established for stationary point sources of fossil-fired steam generators. NAAQS and hazardous pollutant standards are also important because these are established EPA standards. Although TLVs do not represent an EPA standard, they are recognized standards that address health hazard potential.

TABLE 33. PRIORITY POLLUTANTS.

Metals	Acids	Polycyclic aromatic hydrocarbons
Arsenic	2-Nitrophenol	Acenaphthene
Antimony	4-Nitrophenol	Acenaphthylene
Beryllium	Pentachlorophenol	Anthracene
Cadmium	Phenol	Benz[a]anthracene
Chromium	Total phenol	Benzo[b]fluoranthene
Copper	2,4,5-Trichlorophenol	Benzo[k]fluoranthene
Lead	4-Chloro-3-methylphenol	Benzo[g,h,i]perylene
Nickel	2-Chlorophenol	Benzo[a]pyrene
Selenium	2,4-Dichlorophenol	Chrysene
Silver	2,4-Dimethylphenol	Dibenz[a,h]anthracene
Thallium	4,6-Dinitro-2-methylphenol	Fluoranthene
Zinc		Fluorene
Phthalates	**Bases**	Indeno[1,2,3cd]pyrene
Bis(2ethylhexyl)phthalate	Benzidine	Naphthalene
Butylbenzylphthalate	3,3-Dichlorobenzidine	Phenanthrene
Diethylphthalate		Pyrene
Dimethylphthalate		
Di-n-butylphthalate		
Di-n-octylphthalate		

TABLE 33. PRIORITY POLLUTANTS (CONTINUED).

Chloroalkyl Ethers	Chlorinated Hydrocarbons	Miscellaneous Neutrals
Bis(2-chloroethyl)ether	2-Chloronaphthalene	4-Bromophenyl phenyl ether
Bis(2-chloroethoxy)methane	1,2-Dichlorobenzene	4-Chlorophenyl phenyl ether
Bis(2-chloroisopropyl)ether	1,3-Dichlorobenzene	2,4-Dinitrotoluene
	1,4-Dichlorobenzene	N-Nitrosodi-n-propylamine
	Hexachlorobenzene	N-Nitrosodimethylamine
	Hexachloro-1,3-butadiene	2,6-Dinitrotoluene
	Hexachloroethane	Isophorone
	Hexachlorocyclopentadiene	Nitrobenzene
	1,2,4-Trichlorobenzene	N-Nitrosodiphenylamine
	PCB-1242	
	PCB-1221	
	PCB-1254	
	PCB-1232	
	PCB-1248	
	PCB-1260	
	PCB-1016	

TABLE 33. PRIORITY POLLUTANTS (CONCLUDED).

Pesticides	Other organics (continued)	Other organics (continued)
Endosulfan sulfate	Vinyl chloride	Bromoform
δ-BHC	Chloroethane	Tetrachloroethene
Chlordane	Dichloromethane	Toluene
Toxaphene	Trichlorofluoromethane	1,1,2,2-Tetrachloroethene
β-Endosulfan	1,2-Diphenylhydrazine	Chlorobenzene
α-BHC	1,1-Dichloroethene	Ethylbenzene
γ-BHC	1,1-Dichloroethane	Acrolein
β-BHC	trans-1,2-Dichloroethene	Acrylonitrile
Aldrin	Chloroform	Chloromethane
Heptachlor	1,2-Dichloroethane	Dichlorodifluoromethane
Heptachlor epoxide	1,1,1-Trichloroethane	Bromomethane
α-Endosulfan	Carbon tetrachloride	
Dieldrin	Bromodichloromethane	
4,4'-DDE	1,2-Dichloropropane	
4,4'-DDD	Benzene	
4,4'-DDT	trans-1,3-Dichloropropene	
Endrin	Trichloroethene	
	cis-1,3-Dichloropropene	
Other	Dibromochloromethane	
	1,1,2-Trichloroethane	
Cyanide	2-Chloroethylvinyl ether	

Determination of compliance with air pollution regulations was not the purpose of this study. Emission compliance involves boiler size, construction date, state regulations which may be site- or geographical-area-specific, and any local (i.e., county or city) regulations.

To determine which pollutant emission is affected most by cofiring, an index was calculated for those emissions where NSPS, NAAQS and hazardous pollutants, or TLVs apply. This will normalize the data for the various emission rates or concentrations per the various standards and allow the emissions to be ranked from highest to lowest index within each index category. The three indexes are

$$\text{NSPS Index} = \frac{\text{Pollutant Emission lb/}10^6\text{ Btu}}{\text{Most Restrictive NSPS lb/}10^6\text{ Btu}}$$

$$\text{NAAQS and Haz. Pol. Index} = \frac{\text{Pollutant Emission } \mu g/m^3}{\text{NAAQS or Haz. Pol. } \mu g/m^3}$$

$$\text{TLV Index} = \frac{\text{Pollutant Emission } mg/m^3}{\text{TLV } mg/m^3}$$

The most restrictive NSPS is used because it will cover any size of boiler that might be constructed in the future.

Thirty-one of the measured emissions have indexes that apply (Table 34). TLVs exist for measured values of the common stack gas of CO, the other stack gases of Cl, F, and formaldehyde, and all of the metals except strontium.

Beryllium has a TLV, but it is already covered by the hazardous pollutant standard. Lead has a TLV, but lead is covered by the NAAQS. The lead TLV is 0.15 mg/m^3 (150 $\mu g/m^3$) which is 100 times the NAAQS of 1.5 $\mu g/m^3$. The beryllium TLV is 0.002 mg/m^3 (2 $\mu g/m^3$) which is 200 times the hazardous pollutant standard of 0.01 $\mu g/m^3$. This points out the fact that NAAQS and TLVs are not directly comparable.

The above indexes are not directly comparable. As the example above demonstrates, standards intended for different purposes differ greatly. Also these indexes do not show compliance or lack thereof to state air pollution regulations. The indexes are only a method of comparing the various measured emissions to aid the assessment of cofiring dRDF.

Table 35 lists the measured emission for which there are no TLVs, NSPS, or NAAQS. TLVs are written for specific compounds and, thus, general categories such as organics and carbonyls do not have TLVs. TCDD and TCDF (dioxins and furans) and POMs are compounds of great

TABLE 34. CRITERIA POLLUTANT STANDARDS AND TLVs FOR MEASURED EMISSIONS.

NSPS		Most restrictive NSPS lb × 10^6 Btu heat input	Priority pollutant
Total particulates		0.03	
SO_2		1.20	
NO_x		0.60	
NAAQS and hazardous pollutants		**NAAQS and haz. pol. standard $\mu g/m^3$**	
Beryllium	Be	0.01	X
Lead	Pb	1.5	X
Total nonmethane hydrocarbons THC (maximum 3-hr concentration)		160	
TLVs stack gases		**TLVs mg/m^3**	
Carbon monoxide	CO	55	
Chlorine	Cl	3	
Fluorine	F	2	X
Formaldehyde	2HGHO	1.5	
Metals			
Aluminum	Al	10	
Antimony	Sb	0.5	X
Arsenic	As	0.2	X
Barium	Ba	0.5	
Boron	B	10 (as BO)	
Cadmium	Cd	0.05	X
Calcium	Ca	2 (as CaO)	
Chromium	Cr	0.05	X
Cobalt	Co	0.1	
Copper	Cu	0.2	X
Iron	Fe	5 (as Fe_2O_3)	
Magnesium	Mg	10 (as MgO)	
Manganese	Mn	1 (as MnO_3)	
Mercury	Hg	0.05	
Molybdenum	Mo	5	
Nickel	Ni	1	X
Silver	Ag	0.1	X
Tin	Sn	2	
Titanium	Ti	10	
Vanadium	V	0.05 (as V_2O_5)	
Zinc	Zn	5 (as ZnO)	X

TABLE 35. MEASURED EMISSIONS FOR WHICH NO PUBLISHED STANDARDS EXIST.

Dioxins and furans
Total tetrachlorodibenzo-p-dioxin (total TCDD)
2,3,7,8-Tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD)
Total tetrachlorodibenzo-furans (total TCDF)
2,3,7,8-Tetrachlorodibenzo-furans (2,3,7,8-TCDF)

Polycyclic organic material (POM)
Anthracene/Phenanthrene
Methyl anthracenes
Fluoranthene
Pyrene
Methyl Pyrene/Fluoranthene
Benzo(c)phenanthrene
Chrysene/Benz(a)anthracene
Methyl chrysenes
7,12-Dimethylbenz(a)anthracene
Benzo fluoranthenes
Benz(a)pyrene
Benz(e)pyrene
Perylene
Methyl Benzopyrene
3-Methyl Chloranthrene
Indeno(1,2,3,-cd)pyrene
Benzo(ghi)perylene
Dibenzo(a,h)anthracene
Dibenzo(c,x)carbazole
Dibenz(ai and ah)pyrenes
Coronene

Other hydrocarbon organics and metals
Hydrocarbons C_1-C_6
Total gaseous nonmethane organics
Carbonyls
Strontium Sr

concern, but at present no TLVs or other emission standards have been published. The items in Table 35 can be compared only on the basis of an increase or decrease because of dRDF cofiring.

In addition to the items in Tables 34 and 35, oxygen, carbon dioxide, and particle size were measured. Oxygen is, of course, an important stack gas measure as it applies to boiler performance and percent excess air, but it is not part of the pollutant emission study. A TLV of 9,000 mg/m^3 is published for carbon dioxide, but carbon dioxide is a normal product of combustion. The basic combustion process is carbon in the fuel reacting with oxygen to form carbon dioxide. Efficient combustion will result in maximum carbon dioxide production. Therefore, carbon dioxide, like oxygen, applies to boiler performance, but it is not part of the pollutant emission study. Particle size is important in evaluating air pollution control equipment needs and performance. A TLV applies to particle size only in the sense of the TLV for nuisance dust in the respirable range. However, once the metals in Table 34 are measured and comparisons are made on the basis of the TLV for these metals, then a comparison basis TLV for nuisance dust is a redundant analysis. Therefore, oxygen, carbon dioxide, and particle size will be included in the analysis only on the basis of increases or decreases because of cofiring.

SECTION VIII

ENVIRONMENTAL EMISSIONS

A. BACKGROUND

In this phase of the program, an assessment of the effects of cofiring dRDF on environmental quality was made based on several reports of investigations describing tests conducted at

- Maryland Correctional Institute (MCI) Power Plant near Hagerstown, Maryland
- Wright-Patterson AFB (WPAFB) Building 1240 Hot Water Heating Plant near Dayton, Ohio
- Wright-Patterson AFB (WPAFB) Building 770 Steam Heating Plant
- The General Electric Company Power House at Erie, Pennsylvania, (and identified as Erie, PA).

Blends of coal and dRDF were fired to generate steam or hot water under monitored conditions. The reports examined were References 2, 3, 4, 5, 6, and 37. The available data were summarized, missing or incomplete data were identified, and recommendations for further study were made.

B. SO_x, NO_x, PARTICULATES, CHLORIDES AND FLUORIDES

The data for SO_x, NO_x, particulate, chloride and fluoride commissions are summarized in Tables 36 through 39. In the tests conducted at the Maryland Correctional Institute (Reference 2), coal, dRDF, and 1:1 and 1:2 blends were burned under test conditions. As shown in Table 36, the NO_x emissions declined with an increase in substitution of dRDF for coal up to a blend of 1:2, coal:dRDF. The NO_x emission for dRDF alone was somewhat higher than that for coal. SO_x emissions declined uniformly with an increase in substitution of dRDF for coal, as would be expected from the low sulfur content of dRDF. The amounts of particulate effluent from the multiclone collectors were found to be less for the blends than for both coal and dRDF. Chloride emissions were found to increase uniformly with an increase in substitution of dRDF for coal, while fluoride emissions did not appear to change significantly.

The data for tests conducted at Wright-Patterson Air Force Base at Building 1240 (References 5 and 37) and Building 770 (Reference 6) are summarized in Tables 37 and 38. Here the observed emissions are reported as an index, which is the ratio of the observed value to the New Source Performance Standard (NSPS). For both installations, the

TABLE 36. NO_x, SO_x, PARTICULATE, CHLORIDE, AND FLUORIDE EMISSIONS FOR TESTS CONDUCTED AT MARYLAND CORRECTIONAL INSTITUTE (REFERENCE 2).

Pollutant	Coal:dRDF substitution, volume basis			
	1:0	1:1	1:2	0:1
NO_x (ppm)				
N[a]	16	6	3	2
High	577	387	273	489
Low	136	225	219	441
Avg.	312	306	238	465
SO_x (ppm)				
N[a]	24	12	7	2
High	5,946	1,809	994	303
Low	283	755	461	268
Avg.	1,700	1,199	820	289
Particulates (gr/scf)				
N[a]	22	11	6	2
High	0.588	0.441	0.320	0.356
Low	0.199	0.138	0.176	0.348
Avg.	0.306	0.229	0.235	0.352
Chlorides (ppm)				
N[a]	19	11	6	2
High	115	437	438	654
Low	14	58	198	610
Avg.	46	243	290	632
Fluorides (ppm)				
N[a]	19	9	6	2
High	46	27	14	9
Low	5	7	9	8
Avg.	13	20	12	9

[a]Number of observations.

TABLE 37. NO_x, SO_x, AND PARTICULATE EMISSION INDEXES FOR TESTS CONDUCTED AT BUILDING 1240 WRIGHT-PATTERSON AIR FORCE BASE (REFERENCE 5).

Pollutant	NSPS max. $lb/10^6$ Btu	Emission index[a]	
		dRDF	Coal
NO_x	0.6	0.75	1.10
SO_x	1.2	0.32	0.67
Particulates	0.03	0.63	0.77

[a]Ratio of reported emission to NSPS maximum.

TABLE 38. NO_x, SO_x, AND PARTICULATE EMISSION INDEXES FOR TESTS AT BUILDING 770 WRIGHT-PATTERSON AIR FORCE BASE (REFERENCE 6).

Pollutant	NSPS max. lb/10^6 Btu	Emission index[a]		
		dRDF/Coal	dRDF	Coal
NO_x	0.6	0.84	0.97	1.13
SO_x	1.2	0.71	0.31	0.77
Particulates	0.03	0.87	0.80	0.97

[a]Ratio of reported emission to NSPS maximum.

TABLE 39. NO_x, SO_x PARTICULATE, CHLORIDE, AND FLUORIDE EMISSION INDEXES[a] FOR TESTS CONDUCTED IN ERIE, PENNSYLVANIA, (REFERENCES 3,4).

Pollutant	NSPS max. $lb/10^6$ Btu	LTV ppm	dRDF substitution, wt %			
			0	35 to 45	49 to 52	65
NO_x	0.60					
N[b]			13	12	15	2
High			4.33	1.21	0.87	0.75
Low			0.92	0.33	0.57	0.57
Avg.			1.98	0.76	0.73	0.67
SO_x	1.20					
N[b]			19	12	13	2
High			4.41	5.45	1.99	0.88
Low			0.56	1.31	0.74	0.67
Avg.			2.91	3.13	1.34	0.77
Particulates	0.03					
N[b]			10	3	11	2
High			23.33	28.00	32.00	33.00
Low			4.33	4.67	1.00	10.00
Avg.			10.03	17.33	4.91	21.67
Chlorides		5				
N[b]		(as HCl)	10	4	13	1
High			25.81	20.21	48.06	
Low			12.93	0.94	23.42	
Avg.			18.49	7.98	32.62	29.91
Fluorides		3				
N[b]		(as HF)	10	4	11	2
High			0.43	1.00	2.33	1.10
Low			0.24	0.03	0.60	0.67
Avg.			0.36	0.37	1.56	0.88

[a]Index = ratio of observed emission level to NSPS or LTV.

[b]Number of observations.

NO_x emissions were slightly higher for coal than dRDF, attributable to the lower level of fuel bound nitrogen in dRDF. SO_x emissions were less for dRDF and blends than coal, as would be expected from the low sulfur content of dRDF. Both installations were equipped with electrostatic precipitators and met NSPS particulate emission rates; the emission rates were somewhat less for dRDF and blends than for coal. No data were reported for chloride and fluoride emissions.

The data for tests conducted in Erie, Pennsylvania, (References 3 and 4) are summarized in Table 39, with the observed emissions reported as an index. The NO_x emissions were found to decrease with an increase in substitution of dRDF for coal, and the SO_x emissions also decreased with an increase in fuel substitution level. At this installation, particulate emissions were somewhat less for a 50-weight percent blend of coal and dRDF, although on the average particulate emissions exceeded the NSPS. Both chloride and fluoride emissions increased with an increase in fuel substitution. Overall, with respect to NO_x, SO_x, and particulate emissions, there is no negative effect on environmental quality attributable to the cofiring of dRDF with coal.

C. TRACE ELEMENTS

Only one of the investigations (Reference 2) treated metal emissions in detail. In this investigation, two random samples each of dRDF and coal were analyzed for trace elements. The results of these analyses are summarized in Tables 40 and 41. From Table 40, the trace elements present in coal in amounts greater than 10 ppm were strontium, barium, zirconium, chromium, rubidium, manganese, nickel, vanadium, lithium, yttrium, boron, gallium, arsenic, molybdenum, scandium, cobalt, and cerium. In dRDF, the trace elements present in amounts greater than 10 ppm were manganese, zinc, cesium, lead, strontium, chromium, copper, nickel, tin, rubidium, boron, and neodymium. By comparison, the examined samples of dRDF contained significantly more zinc, lead, tin, and cesium. Certain metals, such as beryllium, osmium, platinum, and rhodium are toxic when present in water-soluble form; these water-soluble forms have time-weighted average threshold limit values of 2 μg/m or less, and, thus, may be of critical interest, although data for these trace metals are lacking.

The available data for trace metal emissions during testing at Maryland Correctional Institute are summarized in Table 42. Here the observed emissions are reported as indexes obtained by dividing the measured emission by the time-weighted average threshold limit value. The table shows that arsenic, manganese, nickel, tin, and antimony emissions were all less than the threshold limit values. Copper emissions increased with the level of substitution of dRDF for coal to a borderline value. Lead, vanadium, and cadmium emission exceeded the threshold limit values in all tests and increased with level of fuel substitution, while mercury, chromium, zinc, and silver emissions

TABLE 40. TRACE ELEMENTS PRESENT IN COAL IN MARYLAND CORRECTIONAL INSTITUTE TESTS, ppm (REFERENCE 2).

Element	Sample no. 1	Sample no. 2	Element	Sample no. 1	Sample no. 2
Strontium	300	690	Cadmium	<1	2
Barium	100	410	Praseodymium	1	5
Zirconium	100	280	Tungsten	<2	5
Chromium	100	88	Thorium	<1	17
Rubidium	100	33	Mercury	<5	<0.8
Manganese	100	22	Tin	<1	2
Nickel	100	19	Uranium	<1	8
Vanadium	40	97	Tantalum	<2	0
Lithium	50	54	Antimony	<2	<0.8
Yttrium	10	70	Tellurium	<1	0.8
Boron	30	23	Dysprosium	<1	0
Gallium	20	32	Erbium	<1	0
Arsenic	10	13	Europium	<0.6	1
Copper	10	13	Gadolinium	<1	2
Molybdenum	10	11	Holmium	<0.4	0
Scandium	10	14	Indium	<1	-
Fluorine	5	150	Iridium	<1	0
Zinc	5	16	Bismuth	<1	0
Cobalt	20	7	Lutecium	<0.4	0
Cerium	20	110	Gold	<2	0
Lanthanum	10	44	Palladium	<1	0
Niobium	5	11	Platinum	<2	0
Bromine	3	19	Osmium	<1	0
Neodymium	4	11	Rhenium	<1	0
Cesium	<3	3	Rhodium	<0.3	0
Iodine	1	5	Ruthenium	<1	0
Beryllium	1	4	Silver	<0.6	0
Hafnium	<2	9	Thallium	<1	0
Lead	<2	8	Thulium	<4	0
Selenium	<1	12	Terbium	<0.4	0.9
Germanium	<1	<5	Ytterbium	<1	0
Samarium	<1	7			

TABLE 41. TRACE ELEMENTS PRESENT IN dRDF IN MARYLAND CORRECTIONAL INSTITUTE TESTS, ppm (REFERENCE 2).

Element	Sample no. 1	Sample no. 2	Element	Sample no. 1	Sample no. 2
Manganese	500	>470	Erbium	<0.3	0.1
Zinc	500	300	Europium	<0.2	0.1
Cesium	200	330	Germanium	<0.3	0.1
Lead	500	170	Gadolinium	<0.3	0.1
Strontium	150	74	Holmium	<0.1	0.1
Chromium	40	260	Iodine	0.6	0.1
Zirconium	50	13	Mercury	<0.3	<0.1
Copper	30	41	Praseodymium	0.5	0.5
Nickel	20	15	Scandium	<1	0.7
Tin	20	8	Samarium	<0.3	0.4
Rubidium	20	3	Selenium	<0.5	0.4
Boron	20	<0.1	Terbium	<0.1	0.1
Fluorine	10	36	Thorium	0.1	0.7
Vanadium	10	8	Uranium	<0.1	0.5
Lithium	10	<0.1	Gold	<0.3	0
Neodymium	15	0.05	Hafnium	<0.3	0
Bromine	10	4	Indium	<0.6	-
Molybdenum	10	4	Iridium	<0.3	0
Cerium	10	3	Lutetium	<0.1	0
Arsenic	4	4	Osmium	<0.3	0
Gallium	2	4	Palladium	<0.2	0
Yttrium	2	1	Platinum	<0.3	0
Lanthanum	2	3	Rhenium	<0.3	0
Cobalt	1	2	Rhodium	<0.1	0
Niobium	1	2	Ruthenium	<0.2	0
Antimony	1	9	Tellurium	<0.2	0
Silver	1	0.4	Tantalum	<0.1	0
Beryllium	0.05	<0.1	Thallium	<0.1	0
Bismuth	0.2	0.1	Thulium	<0.1	0
Cadmium	<0.6	0.3	Tungsten	<0.3	0
Cesium	0.2	0.2	Ytterbium	<0.3	0
Dysprosium	<0.3	0.2			

TABLE 42. SUMMARY OF TRACE METAL EMISSIONS INDEXES[a] FOR TESTS CONDUCTED AT MARYLAND CORRECTIONAL INSTITUTE (REFERENCE 2).

		Coal:dRDF substitution, volume basis											
		1:0			1:1			1:2			0:1		
Metal	LTV_3 $\mu g/m^3$	High	Low	Avg.	High	Low	Avg.	High	Low	Avg.	High	Low	Avg.
Pb	150	2.22	0.86	1.53	44.37	16.95	27.37	81.93	30.91	52.92	80.31	52.39	66.35
Cd	50	0.18	0.04	0.09	1.79	0.99	1.51	7.22	2.34	4.53	6.06	4.62	5.34
As	200	1.58	0.40	0.89	3.36	0.13	0.50	0.69	0.17	0.43	0.25	0.25	0.25
Hg	50	0.22	0.06	0.13	0.53	0.22	0.35	0.31	0.14	0.24	1.82	1.97	1.89
Cr	50	2.22	0.20	0.90	0.80	0.60	0.70	1.30	0.90	1.00	1.70	1.50	1.60
Ni	1,000	1.05	0.14	0.41	0.45	0.25	0.34	0.88	0.17	0.46	0.33	0.26	0.29
Mn	1,000	0.07	0.01	0.04	0.08	0.03	0.06	0.14	0.09	0.11	0.30	0.25	0.28
Zn	5,000	0.23	0.04	0.12	1.35	0.90	1.17	2.67	0.87	1.69	1.97	1.24	1.61
Cu	200	0.37	0.14	0.25	0.54	0.41	0.45	0.79	0.22	0.54	1.04	0.99	1.02
Sn	2,000	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sb	500	0.29	0.07	0.15	0.11	0.09	0.10	0.21	0.09	0.15	0.22	0.21	0.21
Ag	10	1.23	0.36	0.76	1.35	0.41	0.93	2.87	0.89	1.82	3.06	2.89	2.97
Vn	50	2.94	0.15	1.53	1.12	0.82	1.01	1.78	0.46	1.19	2.18	2.06	2.12

[a]Index = ratio of observed emission level in $\mu g/m^3$ to LTV in $\mu g/m^3$.

exceeded the threshold limit values only when dRDF or blends of dRDF and coal were burned. At this installation, particulates were removed by multiclones, and particulate emissions exceeded NSPS. In contrast, tests at Wright-Patterson Air Force Base (Reference 5) showed no increase in lead or cadmium emission owing to burning of dRDF; this installation was equipped with electrostatic precipitators, and this aspect of performance was attributed to a high level of particulate removal.

The minerals present in the ash-forming constituents of dRDF and coal used in the Maryland Correctional Institute are shown in Tables 43 and 44. The composition of the coal ash is typical, with silica, alumina, and iron oxide being present in the greatest amounts. In dRDF, silica, lime, and alumina are present in the greatest amounts. In both materials, portions of the sulfur present in the unburned fuels is fixed in the ash as metal sulfates and, possibly, sulfo-aluminates. In addition to trace metals present in the undetermined fractions, appreciable amounts of sodium and potassium are present which may appear in leachates where such ash is used as landfill.

Samples of fly ash from the Maryland Correctional Institute tests were extracted with water by placing 19 to 23 mg of fly ash particulates in 15 ml of triple distilled water and subjecting the mixture to ultrasonic agitation for 2 hours. This procedure has been reported to quantitatively extract water solubles from inert materials. Analysis of the clear extract showed the presence of chloride ions, calcium, fluoride ions, lead, magnesium, manganese, nitrate ions, potassium, silicon, sodium, and sulfate ions in amounts greater than 1,000 μg/g of extract. Aluminum, barium, boron, cadmium, manganese, and phosphorus were present in amounts between 100 μg/g and 1,000 μg/g of extract, and beryllium, chromium, molybdenum, nickel, and strontium were present in amounts less than 100 μmg/g of sample. No other data on the water extraction of ash were found. Clearly, more information is needed on the effects of ash disposal methods on environmental quality.

D. TRACE HYDROCARBONS

Trace hydrocarbons are of interest because of their smog-forming potential. In two investigations (References 5 and 6), the amounts observed were below the detection limits of the test method used, and it was concluded that trace hydrocarbon emissions were of little significance at the facilities tested. In a third investigation (Reference 2), trace hydrocarbon emissions from dRDF did not differ from those of coal and decreased with increase in boiler load because of improved combustion. In the fourth investigation (Reference 3), the hydrocarbon emissions of dRDF did not differ from those of coal.

TABLE 43. ASH ANALYSIS OF dRDF USED IN MARYLAND CORRECTIONAL INSTITUTE TESTS (REFERENCE 2).

Constituent	Weight percent				
	1	2	3	4	5
Silica	55.52	64.29	63.06	63.58	64.31
Lime	10.75	10.08	10.54	7.82	10.87
Alumina	13.45	6.74	6.43	12.23	6.52
Ferric oxide	2.27	2.34	1.57	4.27	2.09
SO_3	6.03	1.49	3.60	0.93	5.08
Sodium oxide	6.82	9.60	9.69	5.81	7.08
Magnesia	1.14	1.77	1.71	1.54	1.51
Potassium oxide	1.30	0.60	0.65	1.22	0.86
Titania	0.66	0.55	0.56	0.73	0.79
Phosphorus pentoxide	0.87	0.67	0.73	0.58	0.64
Undetermined	1.19	1.87	1.46	1.29	0.25

TABLE 44. ASH ANALYSIS OF COAL USED IN MARYLAND CORRECTIONAL INSTITUTE TESTS (REFERENCE 2).

Constituent	Weight percent			
	1	2	3	4
Silica	35.43	52.05	62.23	57.00
Alumina	22.39	25.64	26.83	28.02
Ferric oxide	34.94	12.74	3.83	7.76
Lime	1.63	2.18	0.43	0.64
SO_3	1.23	1.66	0.02	0.62
Potassium oxide	0.99	1.87	2.52	2.12
Titania	0.56	0.70	0.89	0.91
Sodium oxide	0.25	0.47	0.27	0.34
Phosphorus pentoxide	0.48	0.41	0.30	0.35
Magnesia	0.28	0.36	1.19	1.10
Undetermined	1.82	1.95	1.49	1.14

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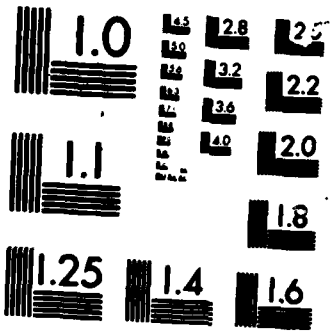


MICROCOPY RESOLUTION TEST CHART

E. TRACE ORGANIC COMPOUNDS

The trace organic compounds observed in tests at Maryland Correctional Institute are summarized in Table 45. The emission levels reported were well below the maximums recommended by the National Science Foundation. Emission of these compounds is not regulated at this time. Emission rate data for tetrachlorodibenzy-p-dioxin (TCDD) and tetrachlorodibenzo furans (TCDF) are shown in Table 46. No standards exist for these substances. From the data, it can be seen that in the tests, both coal and dRDF produced more TCDD and TCDF than as-received and trommeled refuse. Analysis of fly ash samples (Table 47) showed that fly ash from dRDF contained considerably more TCDD and TCDF than fly ash from coal. No other data for TCDD and TCDF were found, but more testing is needed to verify the findings in this investigation.

F. PLANT AMBIENT ENVIRONMENT DATA

Although all investigations discussed the transport, handling, and storage of dRDF, no data were reported for total and respirable dust concentrations.

G. CONCLUSIONS

A review of reports of investigations and the impact of the cofiring of dRDF and coal was made. NO_x, SO_x, and particulate emissions on environmental quality was not negative. Emissions of metals such a lead, cadmium, chromium, zinc, silver, and vanadium are greater with dRDF than coal, and chloride emissions are also greater with dRDF than coal. There is some evidence that particulate removal to at least NSPS would control metal emissions. Metals tend to concentrate in fly ash and may contaminate groundwaters if disposed of in landfills. There is also some evidence that both TCDD and TCDF are produced when dRDF and coal are burned; more testing is needed to verify and explore this aspect of dRDF combustion.

TABLE 45. TRACE ORGANICS OBSERVED IN TESTS AT MARYLAND CORRECTIONAL INSTITUTE, ppb (REFERENCE 2).

Component	1:1	1:2	1:0
Anthracene/Phenanthrene	0.0736	0.0516	0.0009
Methyl Anthracene	0.0126	0.0052	0.0003
Fluoranthene	0.0164	0.0064	0.0003
Pyrene	0.0039	0.0027	0.0018
Methyl Pyrene/Fluoranthene	0.0004	<0.0002	<0.0002
Benzophenanthrene	<0.0002	ND[a]	ND
Chrysene/Benzanthrancene	ND	ND	ND
Methyl Chrysene	ND	ND	ND
7,12 Dimethylbenzanthracene	ND	ND	ND
Benzofluoroanthene	ND	ND	ND
Benz(a)pyrene	ND	ND	ND
Benz(e)pyrene	ND	ND	ND
Perylene	ND	ND	ND
Methyl Benzopyrene	ND	ND	ND
3-Methyl Chloranthrene	ND	ND	ND
Indeno Pyrene	ND	ND	ND
Benzoperylene	ND	ND	ND
Dibenzoanthracene	ND	ND	ND
Dibenzocarbazole	ND	ND	ND
Dibenz Pyrenes	ND	ND	ND
Coronene	ND	ND	ND

[a]Not detected.

TABLE 46. EMISSION RATES OF TCDD AND TCDF IN TESTS CONDUCTED AT WRIGHT-PATTERSON AIR FORCE BASE (g/TON FUEL-FIRED BASIS) (REFERENCE 37).

Facility	Fuel burned	TCDD[a] Total	TCDD[a] Maximum 2,3,7,8	TCDF[b] Total	TCDF[b] Maximum 2,3,7,8
A	Trommeled refuse	1.1×10^{-4}	4.6×10^{-5}	c	c
	Trommeled refuse	1.4×10^{-5}	3.7×10^{-6}	1.8×10^{-4}	1.0×10^{-4}
	Average	6.2×10^{-5}	2.5×10^{-5}	c	c
	As-received refuse	1.5×10^{-5}	3.4×10^{-6}	9.4×10^{-5}	3.2×10^{-5}
	As-received refuse	1.6×10^{-5}	3.5×10^{-6}	1.9×10^{-4}	6.8×10^{-5}
	Average	1.6×10^{-5}	3.5×10^{-6}	1.4×10^{-4}	5.0×10^{-5}
B	As-received refuse and waste oil	5.1×10^{-5}	3.1×10^{-5}	5.4×10^{-4}	2.7×10^{-4}
	As-received refuse and waste oil	4.4×10^{-5}	1.3×10^{-5}	5.0×10^{-5}	2.2×10^{-5}
	As-received refuse and waste oil	2.8×10^{-5}	1.2×10^{-5}	1.2×10^{-4}	5.3×10^{-5}
	Average	4.1×10^{-5}	1.9×10^{-5}	2.4×10^{-4}	1.2×10^{-4}
C	dRDF	3.3×10^{-4}	1.0×10^{-4}	3.4×10^{-3}	1.2×10^{-3}
	Coal	6.3×10^{-4}	1.8×10^{-4}	5.3×10^{-3}	1.8×10^{-3}

[a]Tetrachlorodibenzo-p-dioxins.

[b]Tetrachlorodibenzo furans.

[c]Only one sample available.

TABLE 47. TRACE TCDD AND TCDF IN ELECTROSTATIC PRECIPITATOR ASH SAMPLES FROM TESTS CONDUCTED AT FACILITY C, WPAFB (REFERENCE 37).

Fuel burned	Total TCDD[a] (ppt)	Maximum 2,3,7,8-TCDD (ppt)	Total TCDF[b] (ppt)	Maximum 2,3,7,8-TCDF (ppt)
dRDF	7,300	2,000	154,100	42,700
Coal	600	200	12,300	4,300

[a]Tetrachlorodibenzo-p-dioxins.

[b]Tetrachlorodibenzo furans.

SECTION IX

MOISTURE CONTENT

A. BACKGROUND

1. Required Moisture Content for dRDF

Moisture is one of the variables affecting pellet quality. Animal feed has been pelletized from ground grains (mash) for more than 30 years, and the effect of moisture content is well known. Pellet mill manufacturer's recommended moisture content is 13-17 percent for animal feed mash prior to pelletizing. Since most such mashes are approximately 12-13 percent moisture, steam is often applied to the mash immediately before pelletizing. This adds moisture and heat, increases the surface temperature, and improves the adhesion properties of the mash.

While less experience is available for dRDF compared to animal feed, research (Reference 20) has shown that pellet density (lb/ft^3) increases with decreasing moisture content and that specific energy (hp-hr/ton) required to produce pellets decreases with increasing moisture content. Thus, with RDF feed to the pellet mill at low-moisture content, a high-density pellet can be produced but with high-pellet-mill power requirements; and at high-RDF-moisture content a low-density pellet is produced with low-pellet-mill power requirements. Concerning the appropriate range of moisture content, pellet mill manufacturers recommend that for paper, moisture content should be in the range of 15 percent to 20 percent. Pellets have been prepared over a wider moisture range by the National Center for Resource Recovery (NCRR) (Reference 1). Some RDF moisture is needed for pellet mill die lubrication and pellet cohesion, and NCRR found the minimum value to be approximately 12 percent. RDF moisture contents below 12 percent resulted in excessive die friction and power requirements. Also, NCRR found that RDF moisture content above 30 percent resulted in a loosely adhered pellet that was not durable and broke apart easily in handling. Thus, the upper and lower limits of RDF moisture content was found to be 12 percent and 30 percent, respectively. However, considering both equipment operation and pellet properties, NCRR recommended that the optimum RDF moisture content range from 15 percent to 20 percent, the same as the pellet mill manufacturer's recommendation for paper.

Average reported RDF moisture contents from several different producers range from 18 percent to 31 percent (Reference 38) with daily excursions as low as 2.3 percent and as high as 66 percent. The result is that, on the average, pellets can be produced from RDF because average moisture content is within or very close to the 12-30 percent range. However, daily occurrences can be expected with RDF moisture well outside the permissible range. The concern is that the average RDF moisture content of 18-31 percent tends to be higher than the recommended optimum

range of 15-20 percent moisture. Figure 3 graphically presents this situation, and demonstrates that RDF moisture content tends to be too high for best dRDF production.

2. Problem

Recommendations for the moisture content of RDF as an infeed into the dRDF pelleting process has been established by two sources: the pellet mill manufacturers and tests conducted by NCRR. These recommendations are

- Optimum--15-20 percent moisture
- Permissible--12-30 percent moisture.

From reported average and maximum and minimum data, RDF moisture content can be outside the recommended moisture ranges, and no current MSW processing practices are used to specifically reduce RDF moisture content. Because of the tendency of RDF moisture content to be too high for good dRDF production (Figure 3), an analysis of the suitability of RDF for production of dRDF pellets includes the following questions.

- What is the moisture content of MSW and how does it vary daily and seasonally?
- What is the relationship between RDF and MSW moisture content?
- Is there a seasonal variation in RDF moisture content and if so, which seasons are best for dRDF production?
- What is the daily RDF moisture content variation, and what is the potential, on a daily basis, of being within the permissible (12-30 percent) or optimum (15-20 percent) moisture content ranges recommended for dRDF production?
- The Baltimore, Maryland, RDF plant is the only location where dRDF has been produced commercially. The dRDF pellets fired at Wright-Patterson AFB were produced at Baltimore. Therefore, how does the RDF moisture content at Baltimore compare with other locations as well as to the recommended moisture content ranges?

Following is a discussion of what is known about MSW and RDF moisture content and the RDF produced at Baltimore from actual field measurements. From the standpoint of moisture content, an assessment is made of the potential for producing dRDF pellets.

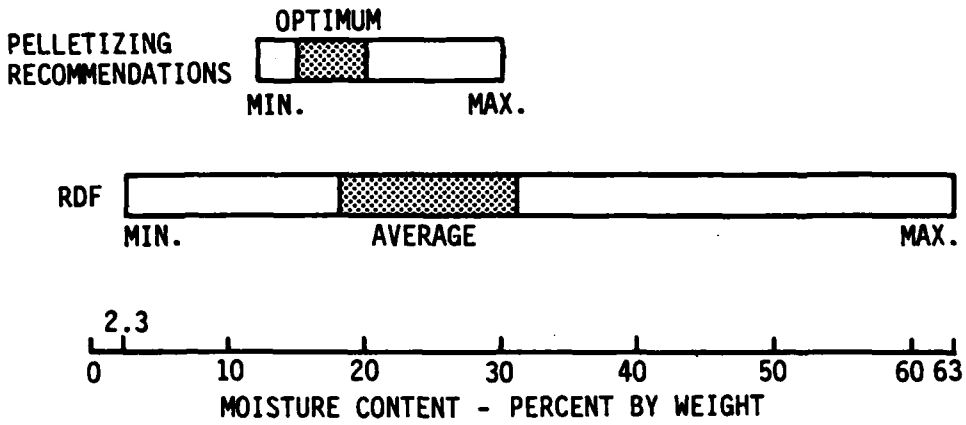


Figure 3. Comparison of RDF Moisture Content and Recommendations for dRDF Pelletizing.

B. MSW MOISTURE CONTENT

MSW moisture content is expected to vary from day to day because of composition and weather. Unfortunately, daily samples of MSW were analyzed over an approximate 1-year period, at only one location, St. Louis, Missouri, to verify this expectation.

The St. Louis MSW samples were collected after the shredder (Figure 4). During shredding, mechanical work is performed which increases MSW temperature and results in some moisture loss. From measurement of gaseous emissions from the shredder, it was estimated that 1.5 percent of the incoming MSW weight was lost as moisture loss in the shredding process. Therefore, the shredded MSW results reported at St. Louis are probably 1.5 percent lower than the unshredded MSW received at the RDF processing plant.

The St. Louis data cover the period of September 23, 1974, through September 5, 1975. For a variety of reasons the RDF plant did not operate every day. Also, from the last week of November through the third week of March, only weekly composite samples were analyzed and daily moisture content is not available. As a result, moisture content data are available for 97 different days with weekly averages reported for 38 different weeks dispersed through all the months except for June.

When the daily and weekly composite moisture data are shown as monthly averages (Figure 5) and as weekly averages (Figure 6) the results show, as expected, that MSW moisture content is higher in spring and summer than in fall and winter. While there is more variability in the weekly averages; the seasonal trend is well-represented by the weekly data.

There is, however, one major perturbation of the trend of MSW moisture with seasons of the year, and this is the large daily variability of MSW moisture content (Figure 7). These daily variations range from 7.7 percent to 40.1 percent moisture and partially mask the seasonal trends.

The significance of Figures 5, 6, and 7 is that the upper limit of 30 percent moisture content for dRDF production can be exceeded in spring and summer. Even during the lower moisture content periods of fall and winter, the 15-20 percent optimum range is seldom reached. In fact, the monthly averages never fall as low as 20 percent. Unless RDF moisture content is lower, the MSW data indicate potential problems in dRDF production because of high moisture content.

C. COMPARISON OF RDF AND MSW MOISTURE CONTENT

Regarding the question of how is RDF moisture content different from MSW moisture content, St. Louis is the only location reporting

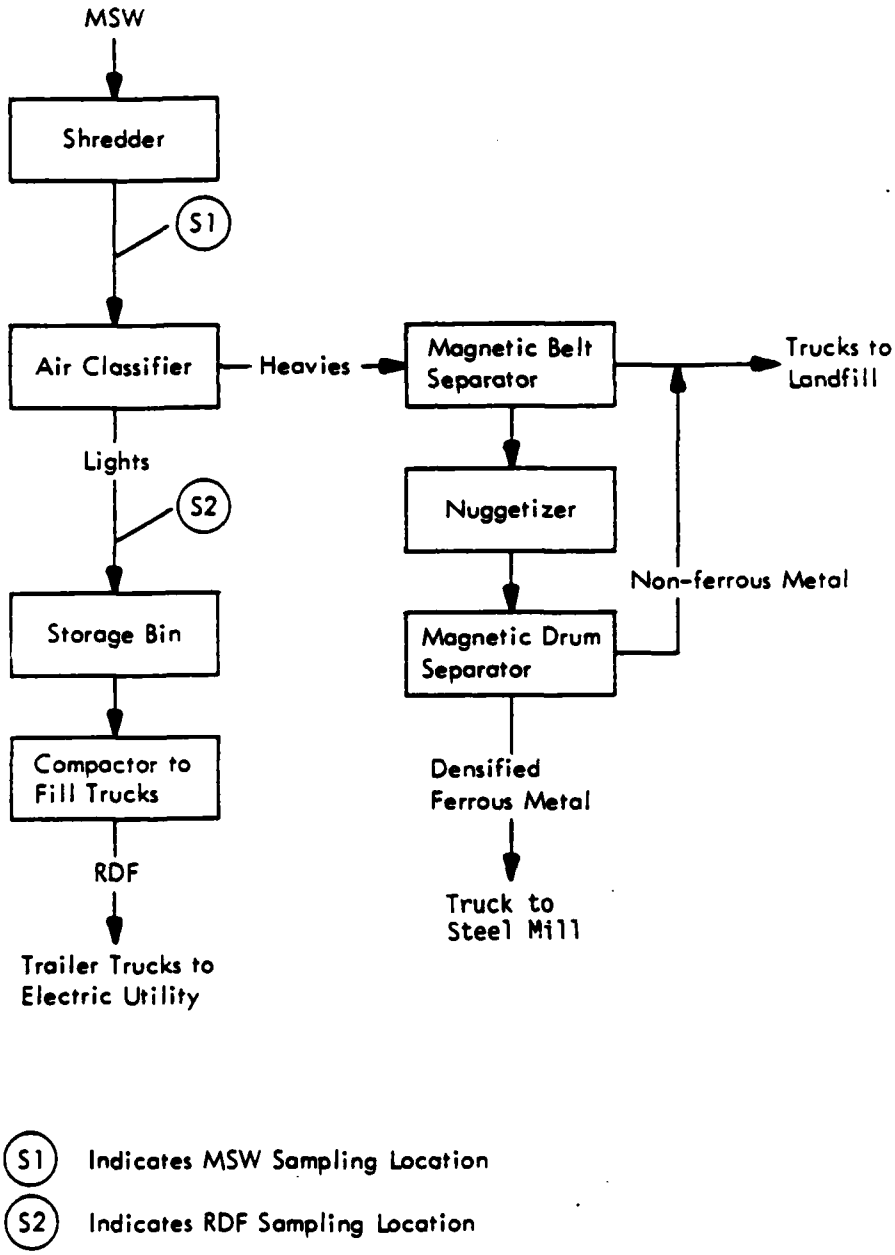


Figure 4. St. Louis, Missouri, RDF Plant Flow Diagram.

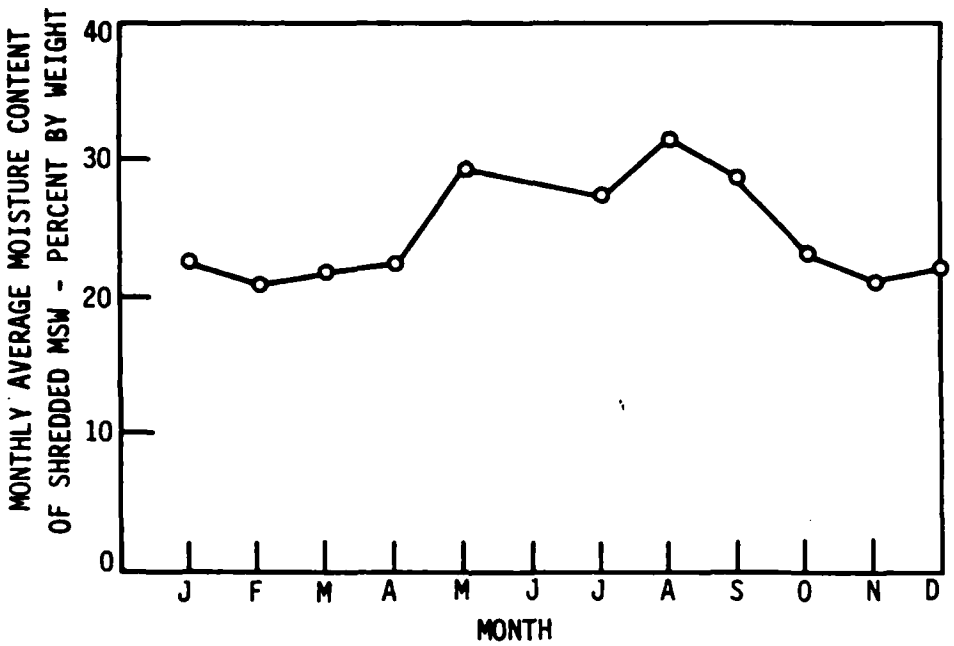


Figure 5. Monthly Average MSW Moisture Content at St. Louis.

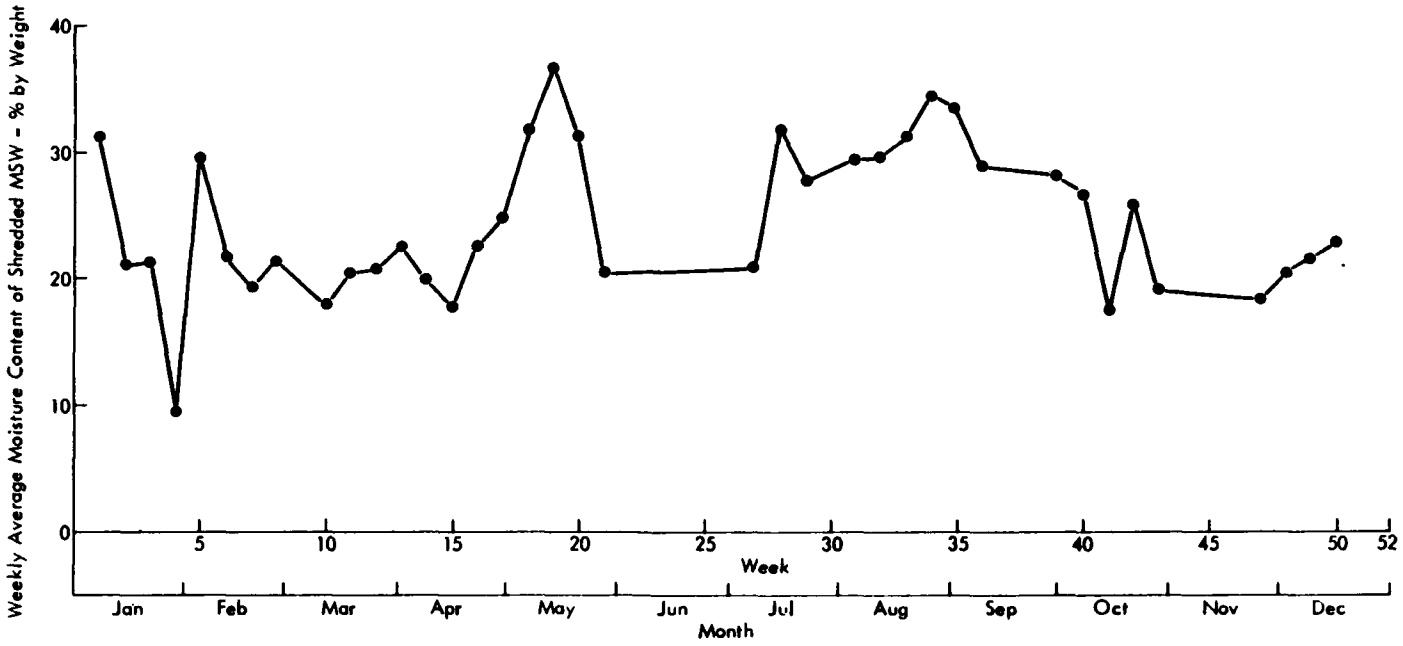


Figure 6. Weekly Average MSW Moisture Content at St. Louis.

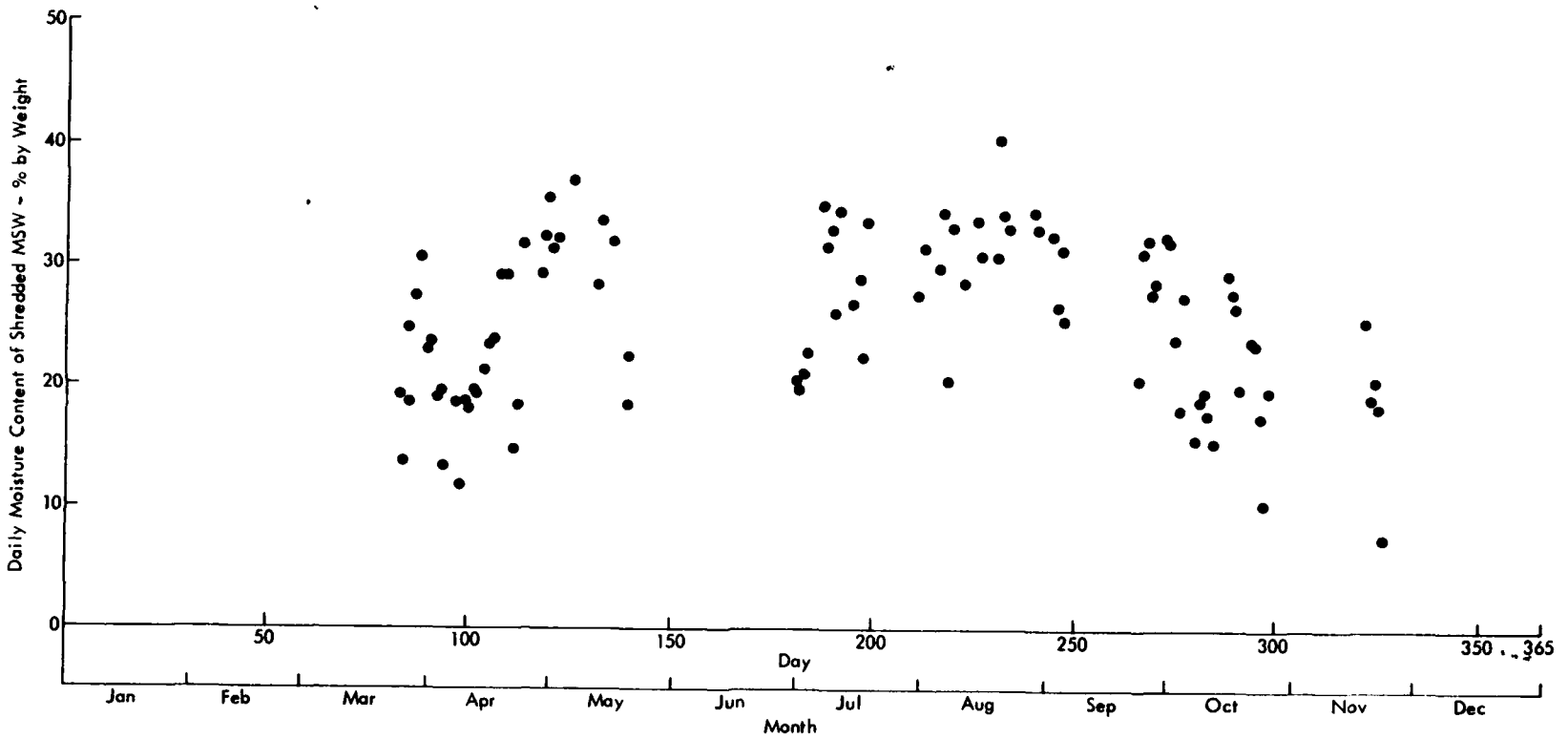


Figure 7. Daily MSW Moisture Content at St. Louis.

both MSW and RDF moisture content on a daily and weekly basis. Both MSW and RDF samples were taken on the same day (Figure 4). The comparison between the two (Figure 8) shows that on a weekly basis the RDF moisture content follows the same trend as the shredded MSW. An advantage of the MSW to RDF comparison at St. Louis is that, as Figure 4 shows, there are no processing operations between shredded MSW and RDF other than the air classifier, and the comparison is the effect of air classification on moisture content. The significance of Figure 8 is that while RDF in a particular week may be slightly higher or lower in moisture content than MSW, there are not, on a seasonal basis, items in the MSW that are removed by the air classifier that greatly changes moisture content.

Plotting of daily RDF moisture content produces a scatter diagram similar to Figure 7 for MSW; therefore, because of the high variability, it is not as useful as the weekly comparison in making comparisons.

The difference between St. Louis RDF and shredded MSW on a daily basis is shown in Figure 9. Some of the difference is due to unexplained variations in sampling and analysis, and some is due to the instantaneous variation in MSW moisture content. With two exceptions, the differences in daily moisture content falls within ±10 percent moisture. There are no seasonal trends in the difference. The only trend, supported by the weekly averages (Figure 7), shows that RDF tends to be higher in moisture content than MSW.

The reason for higher RDF moisture content is ferrous metal removal. An average 4.5 percent of the MSW was removed as ferrous metal having only an average 0.2 percent moisture content. This moisture is assumably due to waste material trapped on the surface of such items as steel cans. The average MSW moisture content was 25.3 percent. Removal of 4.5 percent of ferrous metal increases the remaining MSW moisture by 1.2 percent, as follows:

	MSW		MSW less ferrous	
	lb	%	lb	%
Moisture	25.3	25.3	25.3	26.5
Ferrous	4.5	4.5	0	0
Other dry materials	70.2	70.2	70.2	73.5
	100.0	100.0	95.5	100.0

The 0.2 percent moisture content of the recovered ferrous metal does not enter into the calculation because the effect is less than 0.1 (4.5 × 0.2 percent = 0.009).

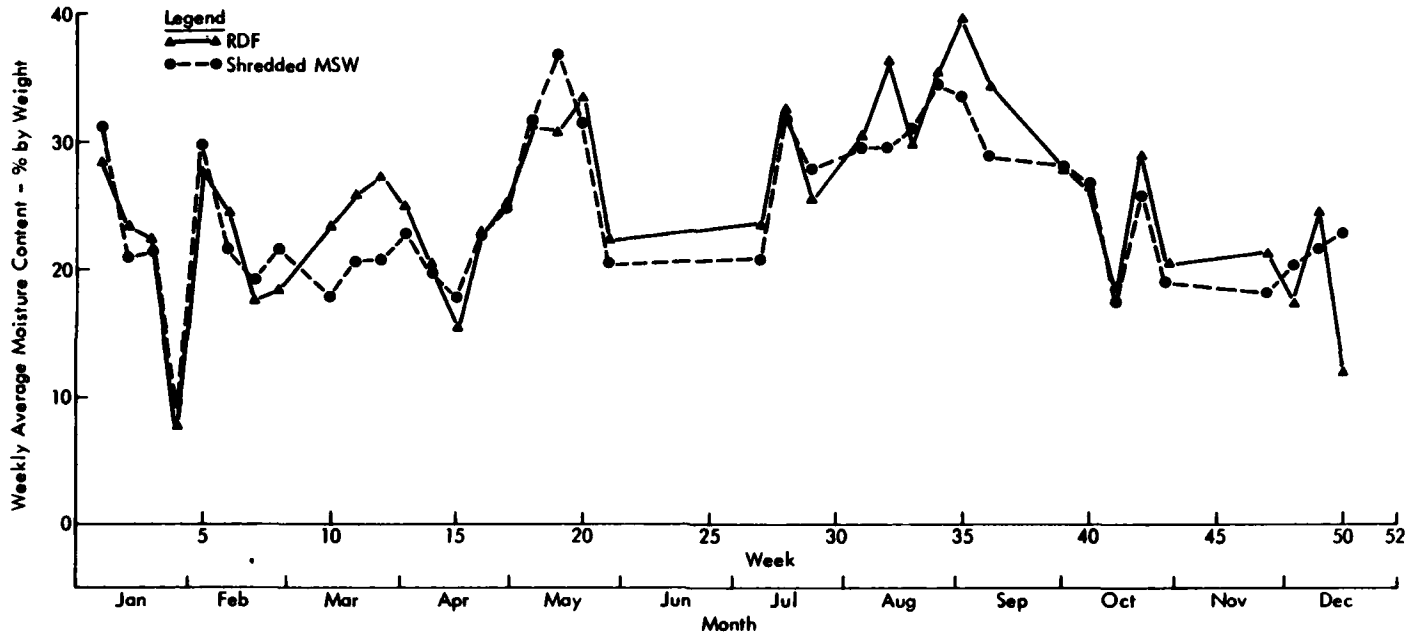


Figure 8. Comparison of the Moisture Content of RDF and MSW at St. Louis.

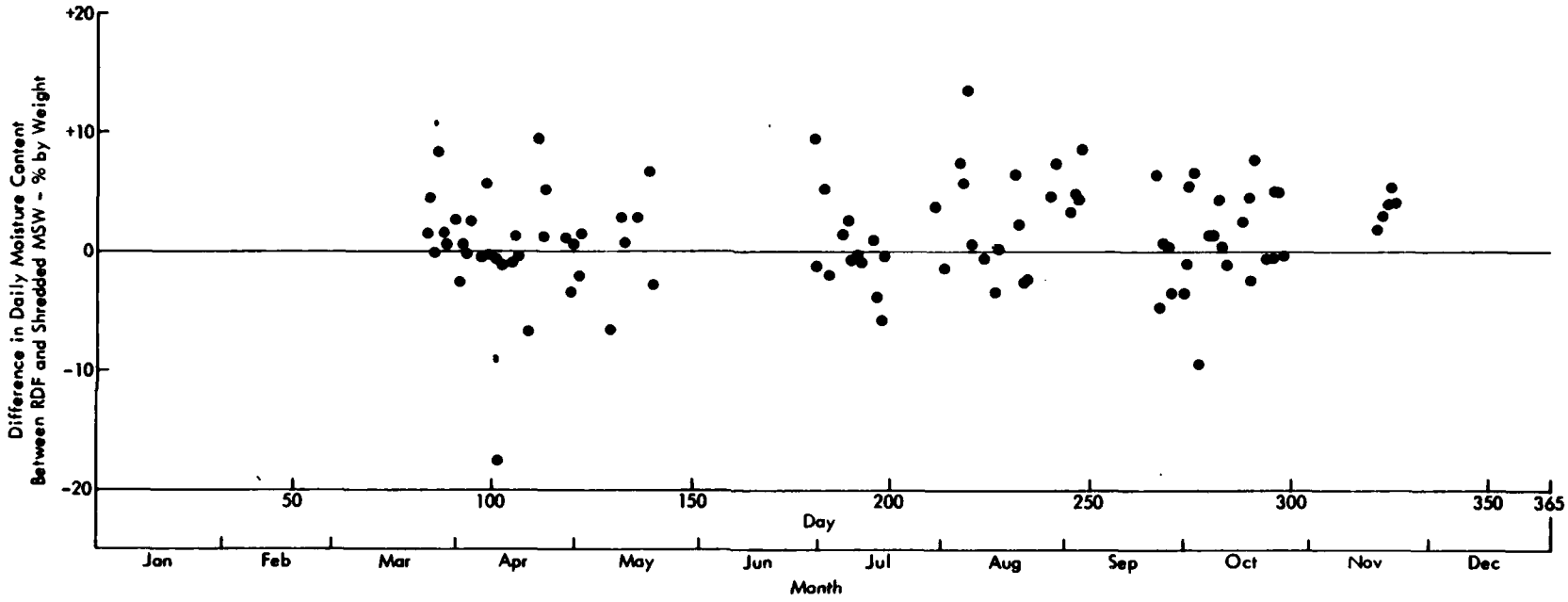


Figure 9. Difference in Moisture Content Between RDF and MSW at St. Louis.

The yearly average of 97 daily samples at St. Louis is:

	% Moisture
RDF	26.6
Shredded MSW	25.3
Difference	1.3

The 1.3 percent increase in RDF moisture content is approximately that predicted by the removal of ferrous metal. Obviously, removal of high-moisture heavy organics by the air classifier is balanced by the removal of low moisture materials such as glass and nonferrous metals. The results follow:

- RDF moisture content follows the same seasonal trends as MSW moisture content.

- Like MSW, RDF daily moisture content is highly variable and the difference between daily values of MSW and RDF moisture content is also quite variable. However, when expressed on a weekly average basis, RDF moisture closely follows the same weekly patterns as MSW moisture content.

- RDF moisture content tends to be higher than MSW. The yearly average RDF moisture content is 1.3 percentage points of moisture higher than MSW. This is almost entirely because of removal of ferrous metal, which is a dry material.

In summary, the yearly average data indicate that the St. Louis air classifier has no effect on moisture content because the yearly average moisture content increase in RDF after the air classifer can be explained by the removal of ferrous metal during air classification. However, weekly averages (Figure 8) and daily samples (Figure 9) show that while the trend is for higher moisture after the air classifier, on a weekly or daily basis the moisture may be lower and this cannot be explained by ferrous removal. This situation is an example of the problems in drawing conclusions from MSW and RDF sample data. Because of high variability, data other than yearly averages are often difficult to deal with. The important question still is, does an air classifier have an effect on RDF moisture content? Several references are available on air classification, but none directly address moisture content change. The major test report on air classifiers (Reference 40) has air-dried moisture data in an appendix, but it is beyond the scope of this project to convert these data into a before and after comparison. Fortunately, tests conducted at Ames, Iowa, can be used in conjunction with the St. Louis data to answer this question.

Unlike St. Louis, at Ames, ferrous metal removal was accomplished prior to the air classifier. The sequence of processing at Ames was shred, magnetic separation, secondary shred, and air-classify. Daily

samples before and after the air classifier were collected at Ames over a 1-year period (July 5, 1977, to July 13, 1978). These samples were composited weekly and analyzed. Unfortunately, the weekly data were not reported. However, the yearly mean and standard deviation were reported, and these can be used to determine if a significant difference exists between average RDF properties before and after an air classifier.

The test for whether a statistically significant difference exists between the average values was conducted using the usual test for the difference between two means as follows.

$$D = \bar{X}_2 - \bar{X}_1, \text{ where } \bar{X}_2 > \bar{X}_1 \qquad \sigma_D = \sqrt{\frac{\sigma_2^2}{n_2} + \frac{\sigma_1^2}{n_1}}$$

$\bar{X}$ = mean, σ = standard deviation, n = number of samples

Conclude no significant difference if $D \leq t_{n-1}\,\sigma_D$, t_{n-1} at 95 percent confidence coefficient.

The data for both Ames and St. Louis are as follows where $\bar{X}$ is the RDF percent moisture.

	Ames			St. Louis		
	$\bar{X}$	σ	n	$\bar{X}$	σ	n
Before air classifier	23.4	5.87	52	25.3	6.80	97
After air classifier	22.1	6.77	52	26.6	7.28	97
D	1.3			1.3		
$t_{n-1}\,\sigma_D$	2.5			2.0		
Significant difference	No			No		

It is interesting to note that, while the average Ames RDF moisture change is the same (D = 1.3) as St. Louis, it is the opposite direction of RDF after the air classifier being drier versus wetter at St. Louis. However, the statistical analysis shows no difference since a change of 1.3 percent moisture is not large enough to declare a significant difference. Therefore, the conclusion is that air classification has no effect on moisture content.

D. RDF MOISTURE CONTENT

1. RDF Moisture Content at Ames, Madison, Milwaukee, and St. Louis

RDF moisture content has been measured at several locations (Reference 38). Only five locations--Ames, Iowa (References 41 and 42); Baltimore, Maryland (References 43 and 44); Madison, Wisconsin (Reference 44); Milwaukee, Wisconsin (Reference 44); and St. Louis, Missouri (Reference 39)--have reported monthly, weekly, or daily RDF moisture content over extended periods of time. These data bases are as follows.

Daily	Weekly	Monthly
Ames, 1976	Ames, 1976	Ames, 1976
Baltimore, 1980	Baltimore, 1980/81	Baltimore, 1980
Madison, 1979	Madison, 1979	Madison, 1979/80/81
		Milwaukee, 1979/80
St. Louis, 1974/75	St. Louis, 1974/75	St. Louis, 1974/75

There is a larger data base for monthly averages than for weekly and daily RDF moisture contents. The Baltimore moisture contents were reported only over a brief time period in 1980 and 1981. However, the dRDF pellets used at Wright-Patterson AFB were produced at Baltimore, and the RDF moisture content at Baltimore is addressed in a separate section following this general discussion of RDF moisture content.

Figure 10 shows the processing flow diagrams for Ames, Madison, Milwaukee, and St. Louis up to the point where the RDF samples were taken. The flow diagram shows the processing arrangement during the time (year 1976) when daily RDF moisture content was reported. Only that part of the process affecting RDF is shown. The air classifier heavies processing at Ames, Milwaukee, and St. Louis is not included. Milwaukee, like St. Louis, has the air classifier immediately after the shredder, but then uses several stages of processing after the air classifier. Both Ames and Milwaukee utilize the air classifier as the last major processing step before samples of RDF are taken. In analyzing moisture results, the Ames RDF samples were taken at the discharge from the storage bin. The amount of elapsed time between when the samples were taken and when the RDF was produced is unknown, but it is estimated to be not more than 1 week. The Milwaukee samples were taken at the discharge of the truck receiving bin which was not used for storage, and the RDF sample date is representative of the RDF production date. The Ames plant installed a disc screen system after the time period when daily RDF moisture was measured.

Monthly average moisture content for Ames, Madison, Milwaukee, and St. Louis (Figure 11) shows that all locations except Ames exhibit the same trend in RDF moisture content that was found for St. Louis

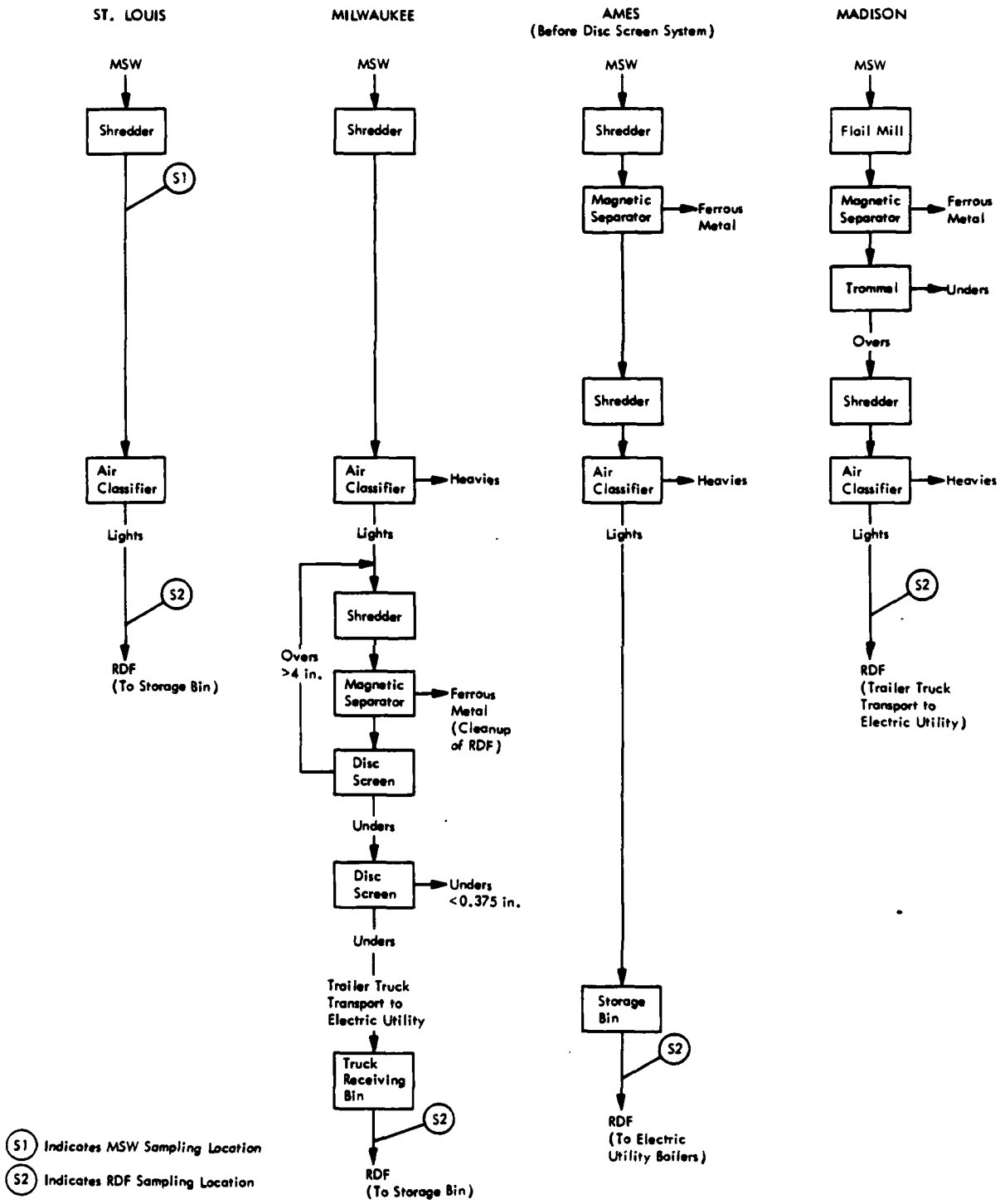


Figure 10. RDF Processing Plant Flow Diagrams.

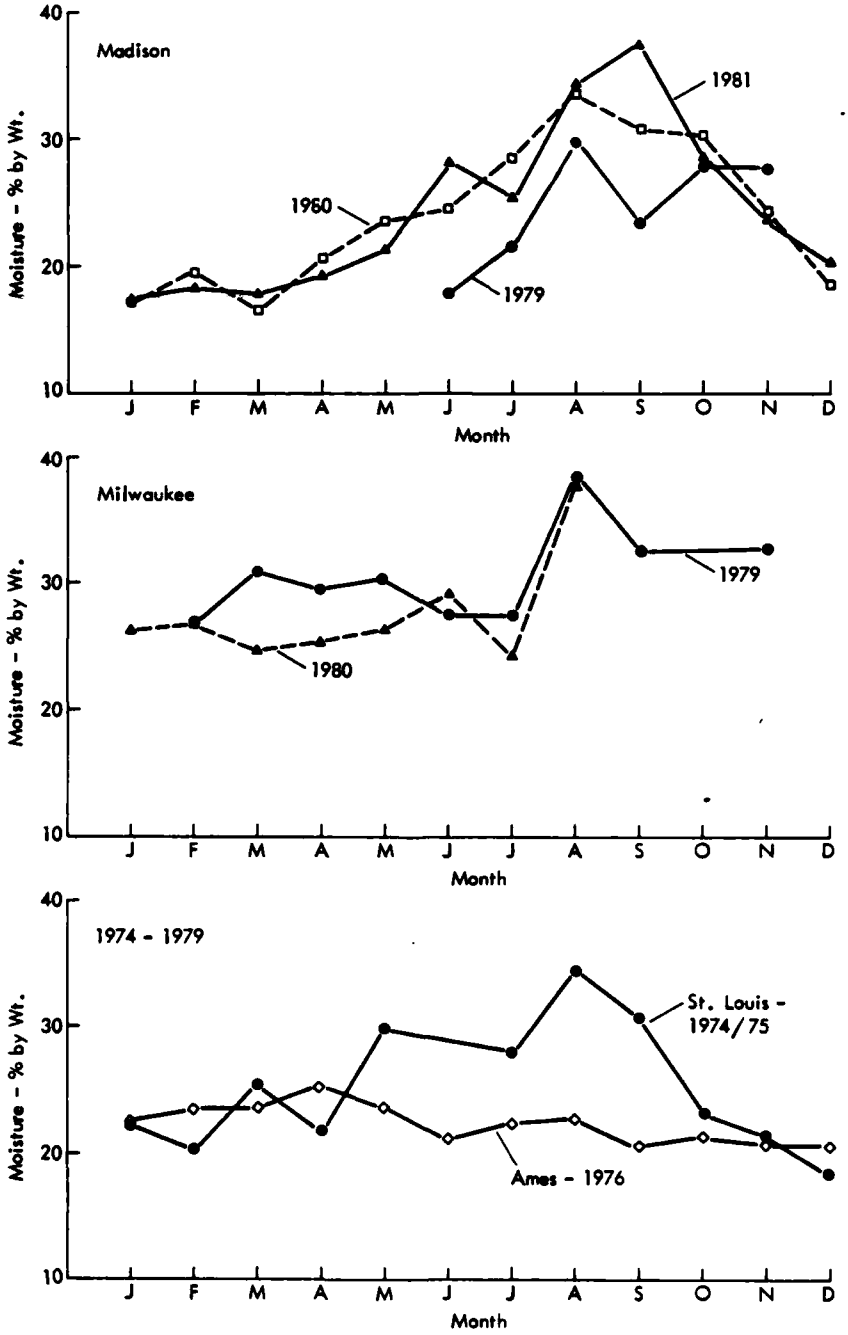


Figure 11. Monthly Average RDF Moisture Content.

MSW, which is that RDF moisture content is higher in spring and summer than in fall and winter. With the exception of Ames and Madison in 1981, moisture content peaks in August regardless of the year. The peak moisture content at Madison in 1981 was in September. The reason for Ames maintaining a more consistent monthly average RDF moisture content is unknown.

The significance of Figure 11 is twofold. First, with the exception of Ames, RDF moisture content clearly exceeds the 30 percent upper limit for dRDF production more often in August and September, and if a choice is possible, dRDF production should be avoided during these months. More important is the fact that RDF moisture content is almost always above 20 percent, the upper end of the optimum dRDF production range. This is shown in Figure 12 which is the Figure 11 data plotted all on one graph. The moisture scale is expanded to clearly show the differences between points. Regardless of year or location, monthly average RDF moisture content is seldom in the 15-20 percent optimum range, and, for all locations except Ames, the RDF moisture exceeds 30 percent--the maximum permissible--especially in August and September. Therefore, regardless of year and location, moisture contents are not present that would favor dRDF production.

2. RDF Moisture Content at Baltimore

RDF moisture content was measured during 40 days distributed through July, August, and September in 1980, and also during 3 days in October 1980, 3 days in January 1981, 2 days in May 1981, and 2 days in August 1981. This type of a data base lends itself best to a weekly comparison. Unfortunately, samples were not all taken at the same location. Figure 13 shows the Baltimore flow diagram and the RDF sampling locations. A comparison to the sampling locations used at other plants (Figure 10) shows the processing steps involved prior to each sampling location are unique to Baltimore.

Weekly average data from Baltimore are compared (Figure 14) to the weekly data available from the other plants tested (Ames, Madison, and St. Louis). Figure 14 shows that Baltimore, like the other locations, has peak moisture content in August, and the RDF moisture contents before and after the trommel are comparable to moistures reported at the other locations. The trommel does have a beneficial effect by decreasing moisture content. The lowest weekly average moisture content was measured after the secondary shredder which would be expected to have the lowest RDF moisture content because of moisture loss in the shredder.

Figure 14 shows two significant aspects. First, as shown above Ames, Madison, Milwaukee, and St. Louis all produce RDF with similar moisture contents. These four plants are all Midwest locations. Baltimore is an East Coast location in a different geographical area. However, Baltimore's RDF moisture content is not different from the range of moistures reported at the other cities with the exception

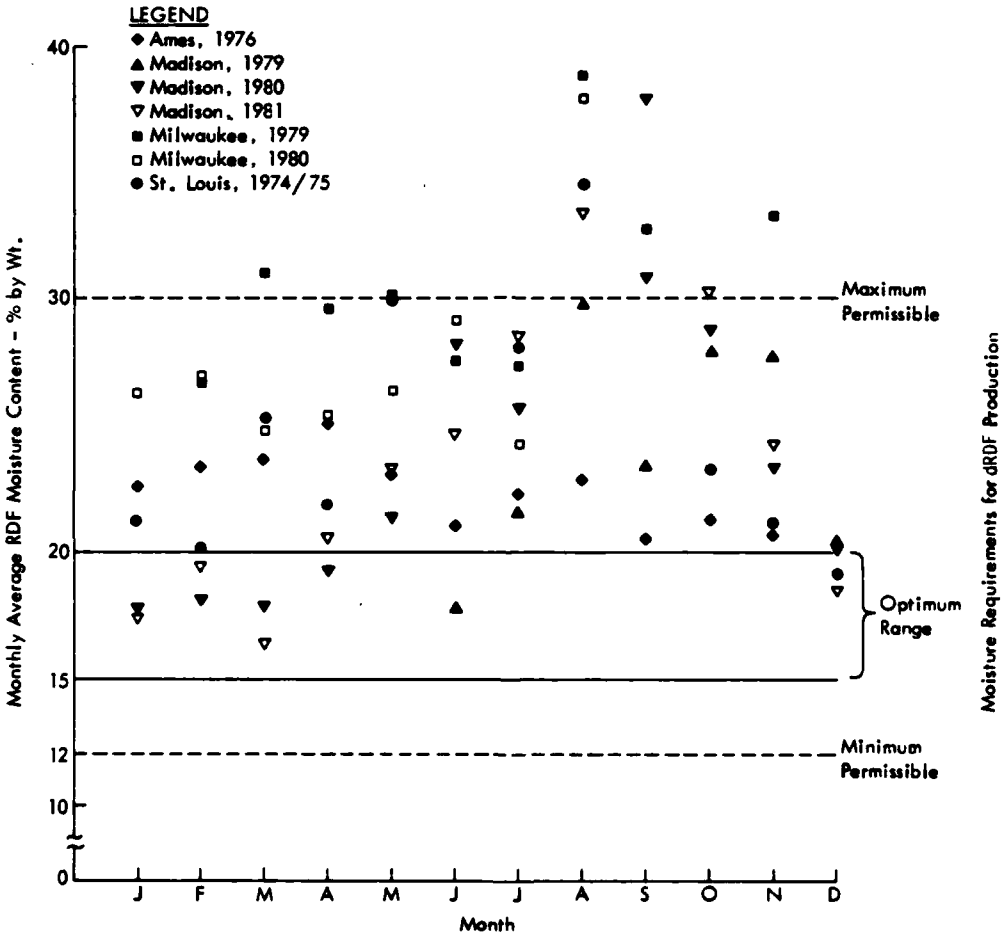


Figure 12. Monthly Average RDF Moisture Content Compared to Optimum Range for dRDF.

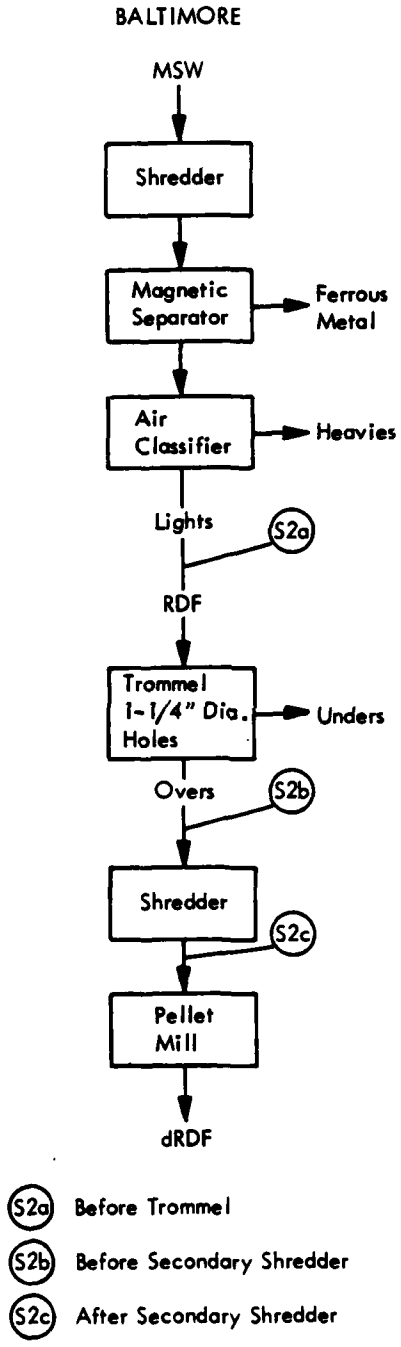


Figure 13. Baltimore Flow Diagram.

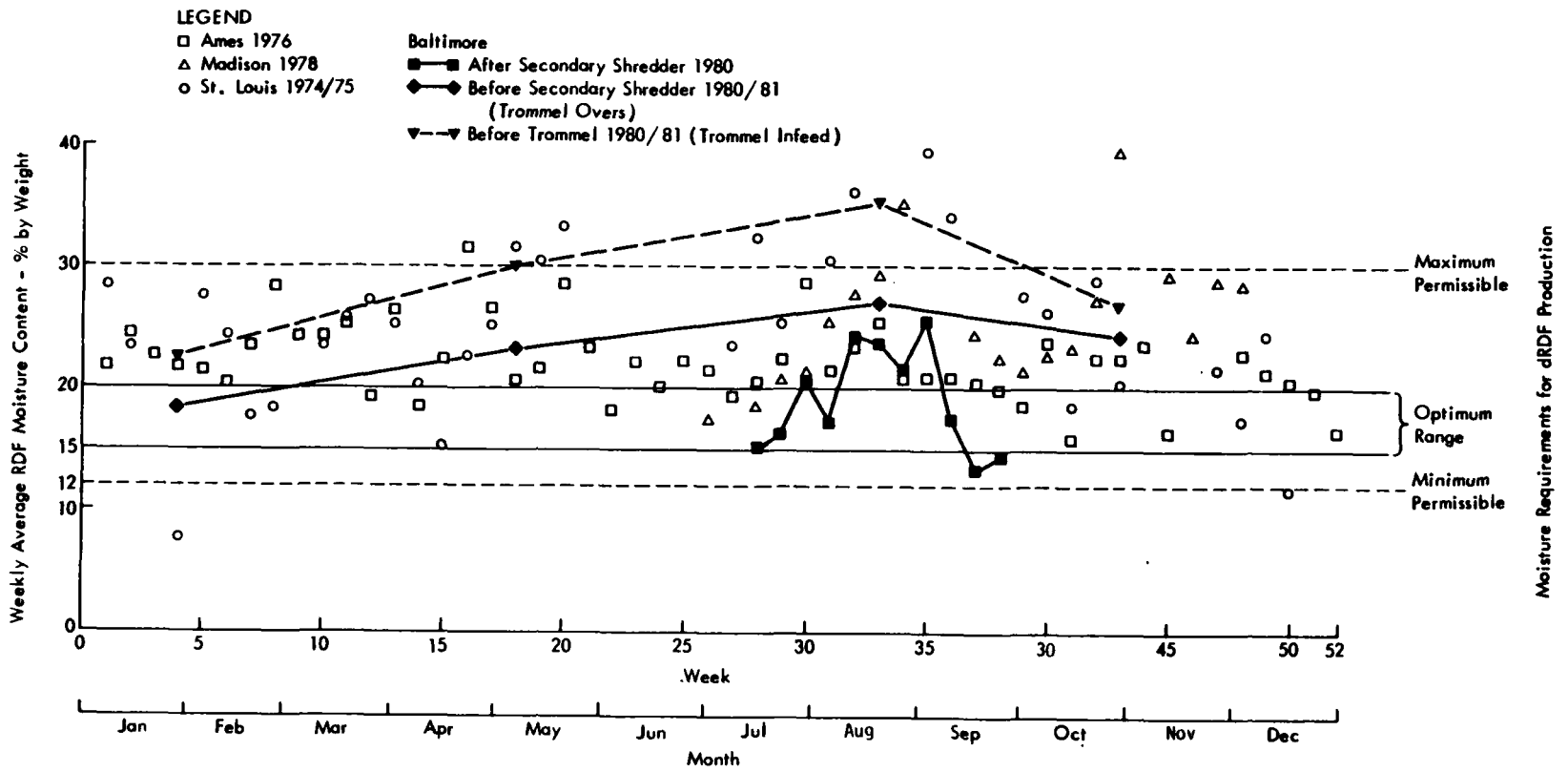


Figure 14. Comparison of Weekly Average RDF Moisture Content at Baltimore to Other Locations and Optimum Range for dRDF.

of samples taken after secondary shredding at Baltimore in July and September. The reason for this lower moisture content is unknown, as no other 1980 weekly averages are available for comparison. The August samples were taken in 1980 before the secondary shredder was installed.

The second significant aspect of Figure 14 is the conclusive demonstration that, regardless of the city, including Baltimore, and regardless of the season of the year, it is very difficult for moisture to be low enough to be within the 15-20 percent optimum RDF moisture content range for dRDF production. This conclusion was found in the preceding section, based on monthly averages (Figure 10). Considering the permissible range of 12-30 percent moisture content, RDF is never too dry with the exception of 1 week at St. Louis, but it can be too wet in spring and summer.

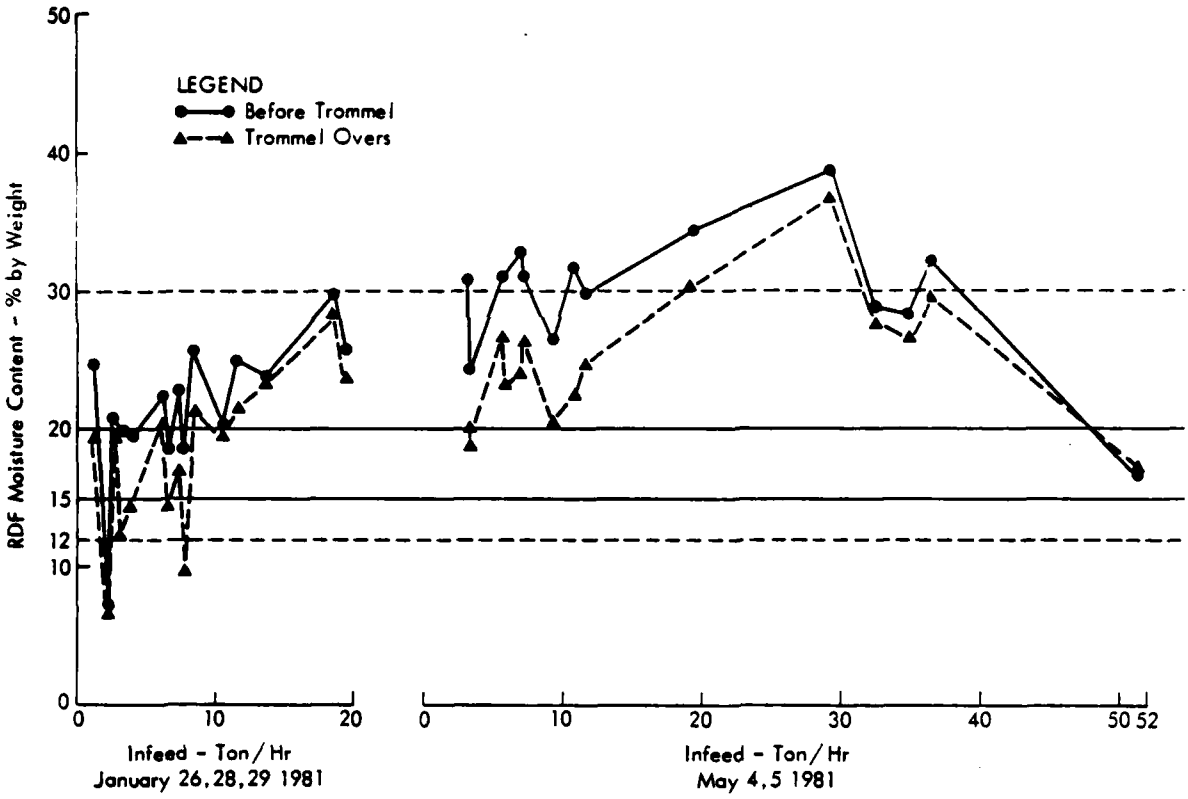
3. Effect of Trommel Screening on RDF Moisture Content

Figure 14 distinctly shows the effects of the trommel screen in lowering RDF moisture content at Baltimore. During October 1980 and January 1981, May, and August, a total of 60 tests (Reference 43) of the trommel (15 tests for each of the 4 months) were conducted at trommel infeed rates ranging from 1 ton/hour to 42 ton/hour. The purpose of these tests was to investigate trommel performance at various infeed rates and trommel rotational speed. Trommel rotational speed is not a significant variable because the interior of the trommel was fitted with lifter bars which tended to lift material to the same height before dropping regardless of rpm. Under normal operating conditions when dRDF pellets are being produced, the trommel was operated over a 6-15-ton/hour infeed rate range. This resulted in 23 of the total 60 tests being made over the normal trommel infeed rate range, and these data were used to calculate the weekly averages of samples collected before the trommel and before the secondary shredder in Figure 13.

Figure 15 shows the RDF moisture content before and after the trommel for all 60 tests. In every case except one, the trommel oversize (overs) had lower moisture content than the trommel infeed. Material smaller than 1-1/4 inch removed by the trommel was definitely higher in moisture content. There is a trend of the reduction in moisture content being less as infeed rate increases beyond 15 tons/hour, because as the infeed rate increases, the screening efficiency decreases, and at very high infeed rates, the trommel acts more as a conveyor than a screen.

However, even with the decrease in moisture content, Figure 15 clearly shows that it is difficult to consistently produce trommel overs in the optimum moisture content range even when the trommel is operated below a 15-ton/hour infeed rate.

Within the 6-ton/hour to 15-ton/hour infeed rate, the average RDF moisture reduction achieved by the trommel (Table 48) was 5.6 percent, which is certainly beneficial for dRDF production. However, this was



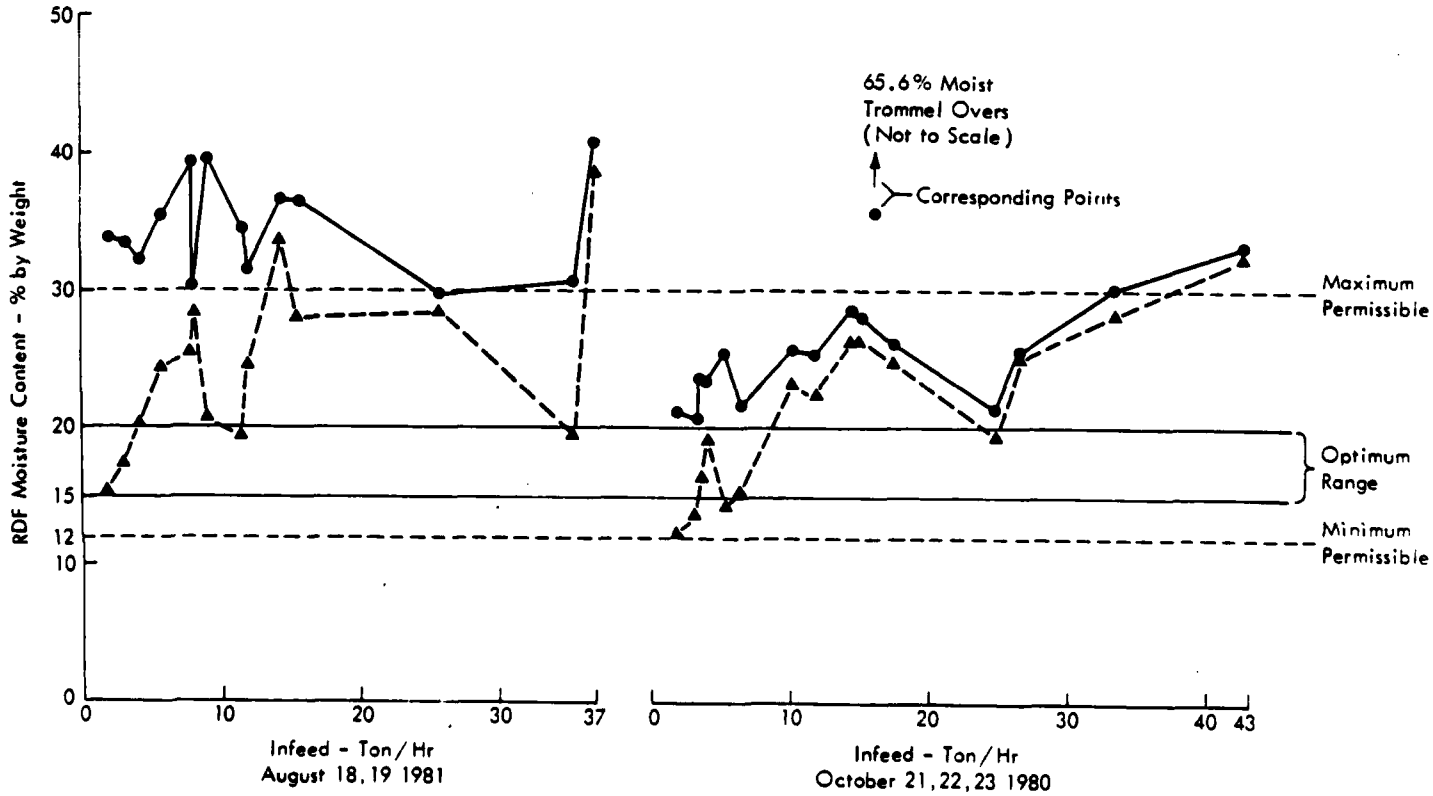


Figure 15. RDF Moisture Content Before and After Trommel at Baltimore.

TABLE 48. BALTIMORE TROMMEL SCREEN RESULTS.

Test day	Infeed (ton/hr)	Moisture--% by wt. rpm	Infeed	Overs	Reduction	Amount of infeed lost as undersize (% by wt.)
October 1980						
23	10.04	12	25.90	23.14	2.76	36.30
23	11.62	9	25.14	22.56	2.58	30.25
21	14.15	6	28.72	26.17	2.55	52.60
23	15.01	12	28.15	26.21	1.94	55.51
January 1981						
26	6.71	12	18.70	14.19	4.51	52.02
28	7.37	12	22.94	17.01	5.93	42.11
29	7.97	9	18.88	9.65	9.23	51.18
28	8.18	12	25.92	21.27	4.65	48.61
28	10.60	6	20.28	19.60	0.68	23.23
28	11.56	9	24.79	21.62	3.17	25.35
28	13.86	6	23.93	23.53	0.40	27.30
May 1981						
4	6.97	9	32.91	23.98	8.93	70.91
4	7.14	9	31.08	26.21	4.87	47.45
4	9.44	9	26.26	20.50	5.76	29.17
5	10.91	12	31.77	22.53	9.24	61.09
5	11.67	12	29.03	24.77	4.26	43.96
August 1981						
18	7.62	9	30.04	25.41	4.63	70.19
19	7.85	12	39.07	28.25	10.82	70.22
19	8.60	6	39.71	30.25	9.46	68.12
18	11.21	9	34.52	19.24	15.28	67.78
18	11.72	6	31.37	24.65	6.72	57.22
18	14.01	9	36.63	33.88	2.75	50.12
19	15.20	12	36.03	27.89	8.14	58.09
4-month avg.	10.41		28.77	23.15	5.62	49.53

achieved at the cost of removing an average 50 percent of the incoming RDF as trommel undersize. Material that passes the 1-1/4-inch round hole trommel openings may be higher in wet organics, and also the wetter materials may have higher density that would more readily fall through the trommel openings. However, removal of 50 percent of the RDF by trommeling applies only to a plant such as Baltimore. The main mission of the Baltimore facility is to shred MSW prior to landfilling. The volume of shredded MSW is much greater than the needs for dRDF. Therefore, 50 percent removal by a trommel screen is not a problem at Baltimore, but this would not necessarily be the case if dRDF production were to be maximized.

Figure 15 is a good example of the high daily variation that occurs. Each of the 15 tests for each month was conducted over only 2-3 days. The before-trommel sample was shredded MSW with ferrous metal removed that had been air-classified. The MSW moisture content therefore had not been modified except perhaps up to 1.5 percent moisture lost during shredding and up to 1.5 percent moisture increase because of ferrous metal removal. The air classifier would have little or no effect on moisture. The moisture range over these 2- to 3-day periods was

Month	No. of days	RDF % moisture before trommel: Maximum	RDF % moisture before trommel: Minimum	Range % moisture
October 1980	3	33.1	21.1	12.0
January 1981	3	29.7	7.2	22.5
May 1981	2	38.6	16.6	22.0
August 1981	2	40.7	29.8	10.9

The daily moisture range demonstrates the problem of drawing conclusions from daily samples, because the difference in moisture between two samples taken within 2-3 days can be higher than 20 percent moisture. This fact also points out the difficulty in dRDF production. The dRDF production process is sensitive to moisture content, and a potential variability of over 20 percent moisture is judged to have an adverse effect on pellet mill performance.

F. CONCLUSIONS

Steam injection, which heats the material to be pelletized and increases moisture content has been used with good success in the animal feed industry to improve the adhesion of the individual particles in the pellet. This process is not recommended for RDF because RDF moisture content is too high. Among five different plants, lowest moisture contents on a weekly average basis were found at Baltimore after the secondary shredder, but these were not consistently within

the optimum range of 15-20 percent moisture content. Therefore, if RDF is to be heated, methods that will not increase moisture content will be needed. Obviously, heating methods that would cause drying are preferred.

Moisture content of MSW is only slightly changed by processing. Removal of ferrous metal increases the moisture content of the remaining material because ferrous metal has a very low moisture content. For MSW in the range of 20-30 percent moisture, the approximate removal of the nominal 5 percent of the MSW weight as ferrous will increase the remaining material's moisture content approximately 1-1.5 percentage points of moisture. Shredding will decrease moisture content approximately 1.5 percentage points of moisture through moisture loss during the shredding process, although the data to support this conclusion are based on only a few environmental emission tests of one shredder at St. Louis. Air classification apparently has little or no effect on moisture content because the dry noncombustibles removed are offset by wet, heavy organics removed. The Baltimore trommel screen with 1 1/4-inch diameter holes had the greatest effect on moisture, reducing RDF moisture by an average 5.6 percent moisture percentage points. However, this was accomplished at the cost of discarding 50 percent of the RDF as trommel undersize.

In summary, the effects of RDF processing operations on moisture content are

Operation	Average or nominal % moisture change
• Shredding	-1.5
• Ferrous removal	+1 to 1.5
• Air classification	None
• Trommel	-5.6 (when discarding 50% of the infeed weight as undersize)

However, regardless of the processing steps used, RDF is, on the average, too high in moisture content for optimum dRDF production, and drying prior to pelletizing should be considered. Another possibility, instead of drying, is the use of very low moisture binder agents that would simultaneously reduce the moisture content of the total RDF plus binder agent mixture and increase the cohesive properties of the dRDF pellets.

SECTION X

FLOW OF BULK SOLIDS FROM FUEL STORAGE BINS

A. INTRODUCTION

Two major problems associated with the flow of dRDF (and perhaps coal) from fuel bunkers or silos are the possibility of no flow because of the formation of an arch or doming and the development of "ratholing" or "piping" in funnel flow bins, resulting in restricted flow.

Conical or wedge hoppers normally are designed to allow for flow of all solids without any stagnant regions during emptying. These mass flow bins contain a convergent hopper section at the bottom. Complete emptying will occur if the hopper bin half angle, θ, is steep or small and the wall friction (as specified by the wall friction angle ϕ') is also small. Thus, the formation of an arch or doming in the converging hopper should be avoided.

In funnel or core flow, as the solids move downward toward the bin outlet, a channel or a core is formed with stationary material remaining next to the bin wall. As the level drops, the material on the top may slew off with ultimate emptying. This results in a reduced fuel outflow feed rate and is, essentially, a first-in, last-out condition. In addition, further compaction or consolidation of the inert or "dead-stored" material may occur so that the channel narrows into a cylindrical core of material flow which is piping or ratholing.

In the Erie tests the shallow-slope dRDF ground-level truck unloading hoppers experienced pellet hang-up. Mixing of coal and dRDF was controlled both by the pellet hopper outflow reciprocating feeder speed giving a desired weight and the coal hopper unloading vibrating feeder speed giving a desired final test fuel ratio. Severe ratholing of the mixed fuel occurred in the bunker and air lances and rappers were used to prevent fuel hang-up. Mounted air blasters on the bunker sides were effective only when a low level existed in the bunker. Some bridging was also experienced in the distributor chute to the feeder.

During the MCI cofiring tests, a temporary fuel-handling system was constructed outside the building. Here, the coal and dRDF were stored separately (after truck filing) into two 8-yd^3 pyramid-bottom bins. Z-belt conveyors at the bin bottoms emptied the coal into a bucket elevator which, in turn, filled a weigh lorry that finally dumped in the boiler-spreader feed hopper. This temporary arrangement was utilized to prevent bridging in the regular coal square-sided concrete storage silo. Near the end of the tests in May, ratholing was experienced in these outside pyramidal bins, and this behavior was attributed to pellet fluting because of water absorption. Rodding was required.

During the WPAFB Building 1240 cofiring tests, funneling was experienced in the outside dRDF fuel silo, and ratholing occurred in the plant bunker where the dRDF was stored separately. An illustration of the funneling or piping is shown in Figure 16. Reported values of the funnel geometry had sides which were 10 feet high and diameters at the base from 2 feet to 8 feet in diameter (depending on the pile height).

As part of the dRDF Research and Development Program conducted by the Air Force Engineering and Services Laboratory (ESL), a "Bin and Feeder Design for Refuse Derived Fuel (RDF)" study (Reference 45) was performed for the U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, Illinois, as part of an interservice agreement. The study consisted of analyzing a fluff RDF and a dRDF sample for appropriate flow properties, then using these test results, recommending a 100-ton storage bin and a 2-ton/hr outflow rate feeder design. Both samples were NCRR-processed Washington, D.C., high-grade office waste.

The results normally given are

- Minimum outlet dimensions for 0-hour and 24-hour storage under gravity flow and overpressure effects including minimum diameters to prevent ratholing

- The bulk density and consolidating stress because of an effective consolidating head

- Maximum hopper slope angles for various conical, wedge hoppers, and wall friction angles, ϕ'.

The listed critical diameter necessary to prevent ratholing was given as 0.2-0.3 feet.

The WPAFB Building 1240 plant bunkers were of parabolic design (Figure 16) with a square outlet opening of 2 feet by 2 feet. The hopper angle at the bottom was 60° from the vertical, and outside the report listed the angle.

To fully understand the dRDF designated test properties and the computation procedure used to develop the suggested bin design values, a review of the testing firm's major reference was made (Reference 46). This effort seemed critical in view of the funneling, ratholing, and bridging experienced during all the dRDF tests. These flow problems were unacceptable since fuel flow is reduced with a corresponding drop in boiler load. In addition, extra manpower could be expended in clearing the obstruction.

The proposed bin design was based on an analysis procedure developed by Jenike and Johanson (Reference 46) which is based on appropriate continuum mechanics theory with corresponding developed methods for measuring certain flow properties. These flow properties

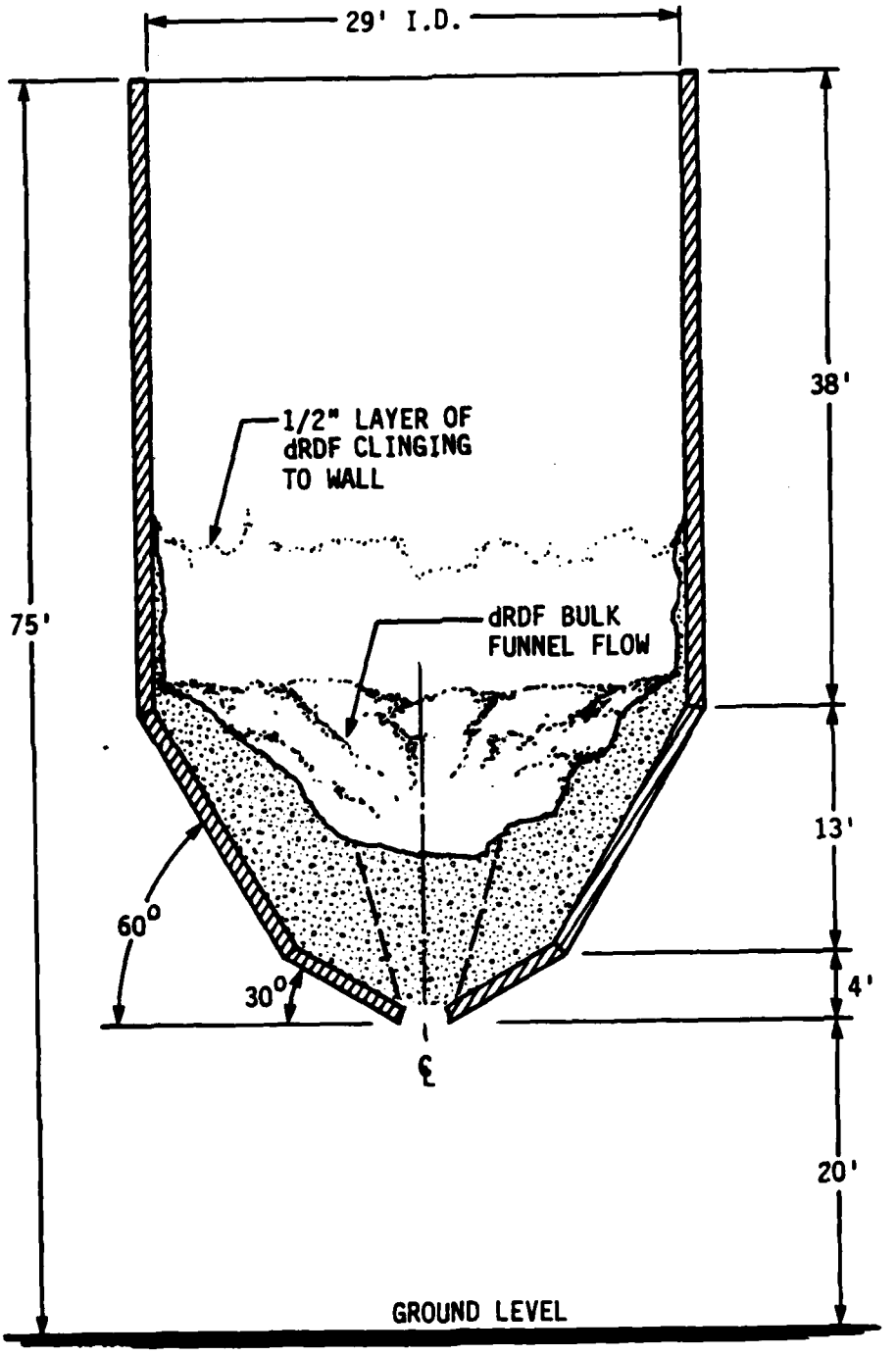


Figure 16. Building 1240 Storage Bin "Piping."

must be measured in the laboratory under the same conditions, i.e., temperature and moisture content that might exist in the storage bin. A further discussion of the shear test cell procedure used to determine properties is given in Appendix E.

B. SUMMARY OF NONBRIDGING DESIGN PROCEDURE

An effective consolidation head (or height) existing from the top of the material in the bin down to the hopper inlet, produces a corresponding consolidation pressure stress, σ_1, on the material. After the transition into the hopper, the consolidation pressure, σ_1, decreases and is independent of the developed head or weight of the material.

This stress, σ_1, produces a corresponding yield strength (or stress), f_c, which represents the stress at which the bulk solid would fail under an unconfined or uniaxial load (such as exists at the bottom of a formed hopper bridge). A shear cell test provides one value of f_c for one value of σ_1. Repeated stress tests result in a graphical plot of f_c versus σ_1 which is called the flow function, FF.

Arch stability, through the application of continuum mechanisms, is expressed in terms of a theoretical calculated stress, $\bar{\sigma}$, which is necessary to support an arch across the inwardly sloping sides of the hopper at the bottom of the bin. The flow criteria to prevent bridging are then

$$f_{cr} < \bar{\sigma}$$

That is, if $\bar{\sigma}_1$ is greater than the unconfined yield strength, f_c, the arch cannot sustain itself and gravity flow will result. Since at the hopper outlet, σ_1 and $\bar{\sigma}_1$ are straight lines passing through the origin, the flow factor, ff, was defined as

$$ff = \frac{\sigma_1}{\bar{\sigma}_1}$$

A typical stress distribution for a circular bin hopper is shown in Figure 17.

By appropriate continuum mechanics, the flow factor, ff, was calculated as a function of the hopper geometry, θ, and the bulk flow properties (measured and calculated from the shear test):

δ = effective internal angle of friction

ϕ' = the wall kinematic angle of friction were plotted as a series of working graphs.

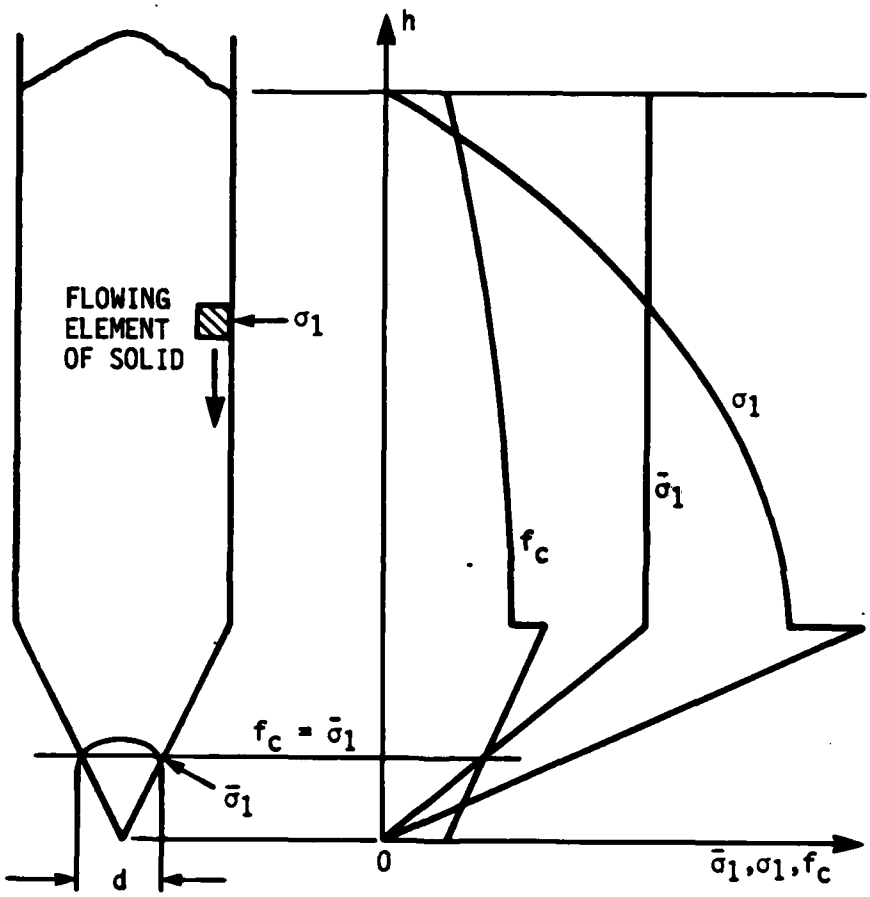


Figure 17. Typical Stress Distribution for σ_1, $\bar{\sigma}_1$ and f_c in a Circular Bin Hopper.

Thus, for a given δ, ϕ', and hopper angle θ_c (circular) or θ'_p (wedge), the flow factor, ff, can be extrapolated. Next, ff is plotted as $\bar{\sigma}_1 = \sigma_1/f_c$ on the yield strength (f_c) versus consolidation stress σ_1 graph that contains the flow function curve (f_c vs. σ_1) for the actual laboratory-tested material. The intersection point determines the critical value of unconfined yield strength (or stress) called f_{cr}. Then the minimum outlet dimension, d, to prevent bridging is determined by

$$d = \frac{H(\theta) \times f_{cr}}{\gamma}$$

where

$H(\theta)$ = nonarching function, analytically determined and given as a working curve

γ = consolidated density because of an effective head, h_e.

C. NONPIPING FLOW DESIGN

The calculation procedure necessary to determine the minimum outlet dimension, d, to prevent piping or ratholing again involves the graphical determination of the flow factor, ff.

The values of ff have been analytically determined again by use of continuum mechanics as a function of the laboratory-measured properties:

- the effective internal friction angle, δ (for the material)
- the internal friction angle, ϕ_t (of the material) for incipient flow.

A time-flow function, FF, curve of f_c vs. σ_1 is again determined from the laboratory shear cell test. Here, the bulk solid is first held under a consolidation stress for a time period, usually 24 hours.

As before, the flow factor, ff, is plotted as $\bar{\sigma}_1 = \sigma_1/ff$ on the same graph (f_c vs. σ_1) as the flow function, FF, curve. The intersection point gives the critical unconfined yield strength, f_{cr}.

Finally, the critical dimension to prevent ratholing is then calculated by

$$d = \frac{G(\phi_t) \times f_{cr}}{\gamma}$$

where

$G(\phi_t)$ = rathole function, theoretically calculated and given as a graphical plot

γ = consolidated density because of an effective head, h_e.

When the minimum dimension for nonpiping is calculated for square or circular hopper outlets, bridging will not occur.

In rectangular hopper outlets, the nonpiping dimension is the diagonal, while the nonbridging dimension is the minimum side and must be determined. A flow factor of 1.7 is assumed. This implies a time internal friction angle, ϕ_t. Next, the intersection of the ff curves with the flow function, FF, curve will give f_{cr}. Finally, the minimum dimension of the rectangle is found by

$$d_{min} = \frac{1.15\ \chi\ f_{cr}}{\gamma}$$

D. DISCUSSION OF SHEAR TEST CELL DATA

The shear test cell data and corresponding bin and feeder design are based on the tests of fluff RDF and dRDF produced from NCRR high-grade office waste. As stated earlier, this was done in an attempt to explain the Building 1240 ratholing experience. The minimum outlet dimensions necessary for mass flow by gravity and also needed to prevent ratholing are given, based on instantaneous and 24-hour storage shear cell test data. The results are shown in Table 49 and refer to bin geometry shown in Figures 18 and 19.

Recommended mass flow hopper slope angles (from the vertical axis) for various outlet dimensions for stainless steel 304-2B and Plasite 7122-type wall material are shown in Table 50.

Wall friction angles as measured from the slope angle of the instantaneous wall yield line were $\phi' = 11.5$ and $\phi' = 14.0$ for the above material. This implies that the oval width, B_p, should be 5 feet or the circular diameter, B_c, should be 10 feet. The parabolic shape bunker openings at 1240 are 2 feet by 2 feet. Hence the openings are not large enough, based on the wall friction angle. In addition, the slope angles (from the vertical) for oval hoppers should be 44.6° or 41.2°, respectively, for the material. The Building 1240 parabolic bunker hopper angles were 60° near the bottom.

The critical diameters to prevent ratholing were 0.2-0.3 feet for gravity flow and up to 0.7 feet for an impact pressure of 2.

TABLE 49. MINIMUM OUTLET DIMENSIONS FOR DEPENDABLE FLOW.

Storage time: 0.0 hrs[a]

A. Gravity flow

	BC[b]	BP[b]	BF[c]	Critical rathole diameters, DF,[d] at EH[e]	
	ft	ft	ft	2.5 ft	4.0 ft
Diameter:	0.0	0.0	0.0	0.2	0.3

B. Over-pressure effects

	BC	BP	BF	Critical rathole diameters, DF, at EH	
	ft	ft	ft	2.5 ft	4.0 ft
P-factor = 1.25[f]					
Diameter:	0.0	0.0	0.0	0.3	0.4
P-factor = 1.5					
Diameter:	0.0	0.0	0.0	0.3	0.5
P-factor = 2.0					
Diameter:	0.0	0.0	0.0	0.4	0.7

---

[a]Values are the same for tests based on 24-hour storage of dRDF under consolidation pressure.

[b]Minimum dimension for mass flow.
BC = conical hopper
BP = oval hopper

[c]Smaller dimension for funnel flow.

[d]Funnel flow large dimension.

[e]Consolidation head in feet.

[f]Over-pressure factor to bin filling.

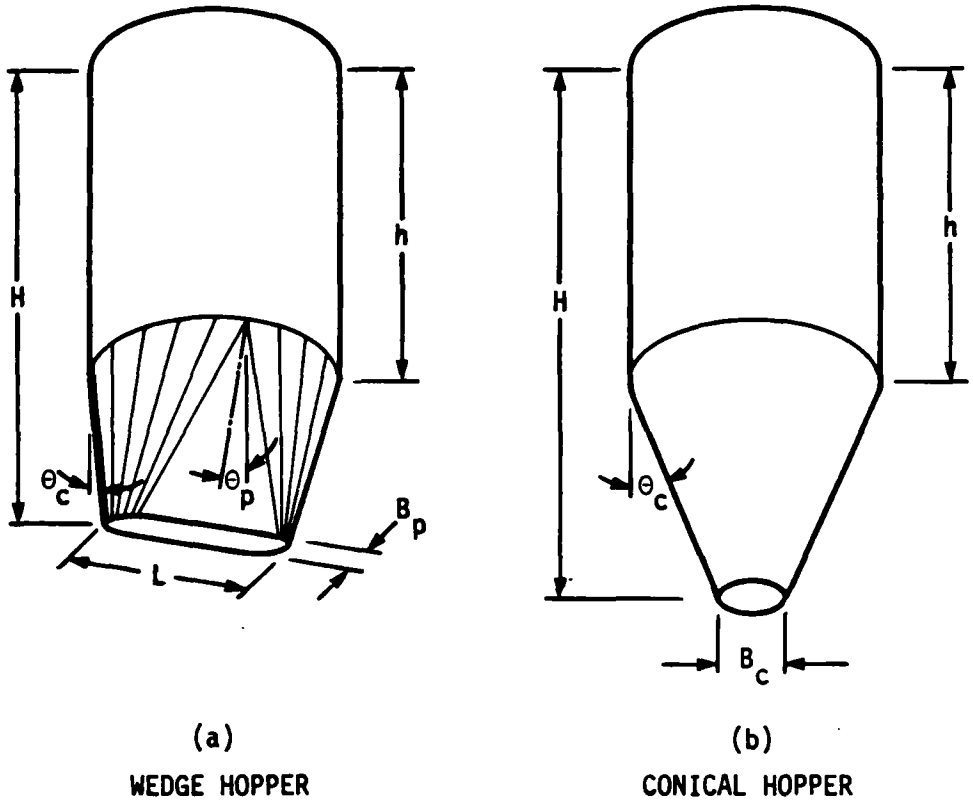


Figure 18. Mass Flow Hopper Bin Geometry.

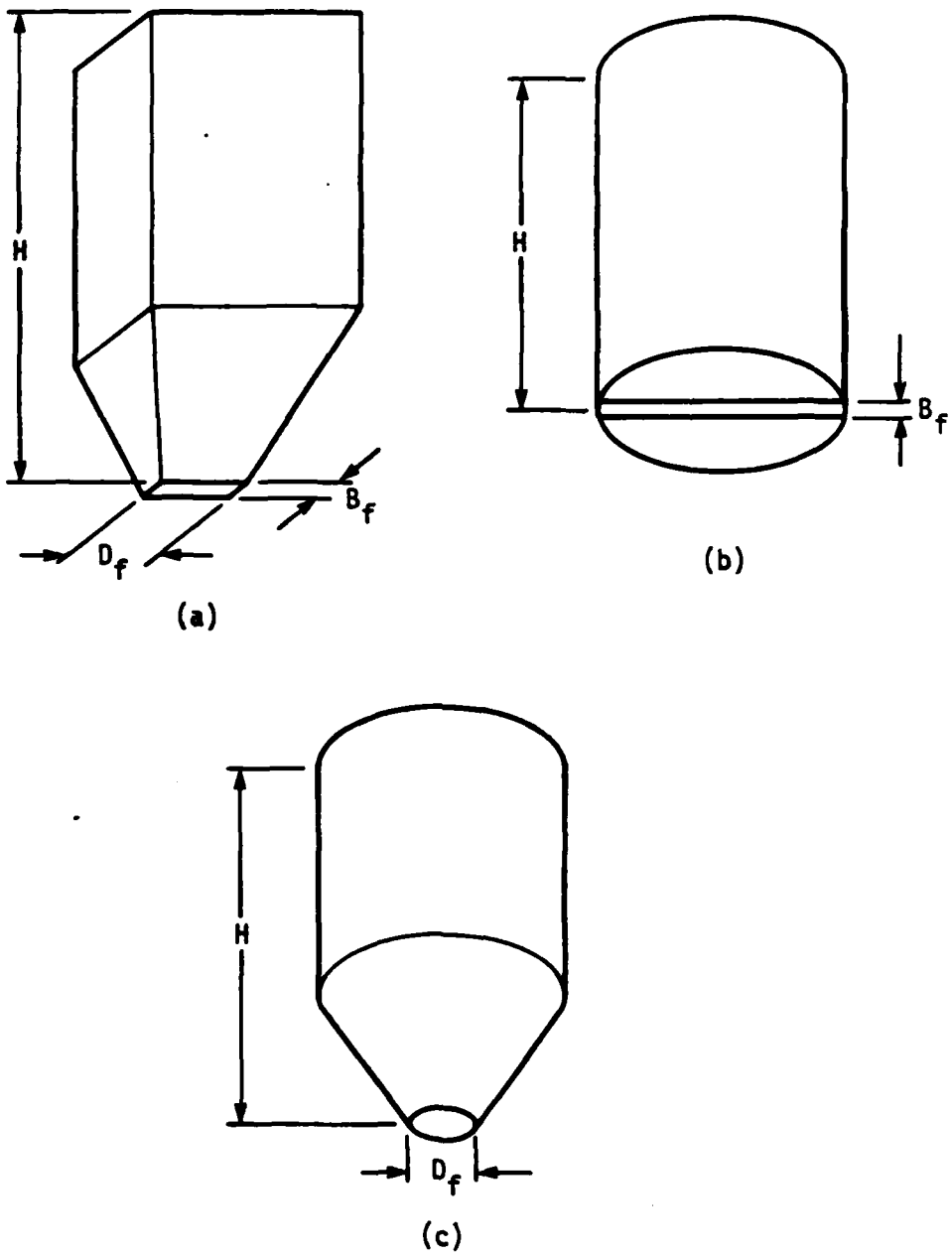


Figure 19. Funnel Flow Hopper Bin Geometry.

TABLE 50. RECOMMENDED MASS FLOW HOPPER SLOPE ANGLES.[a]

Stainless Steel 304-2B

Instantaneous Test

Hopper Slope Angle for Various Outlet Dimensions

Oval width	ft	0.25	0.50	1.00	2.00	4.00	5.00	13.71
Conical dia.	ft	0.50	1.00	2.00	4.00	8.00	10.00	27.42
Phi-prime[b]	deg	16.4	14.5	13.5	12.7	11.8	11.5	10.2
Theta-P	deg	38.1	40.6	42.0	43.1	44.2	44.6	45.0
Theta-C	deg	26.6	28.8	30.1	31.0	32.0	32.4	33.9

Plasite 7122 HAR

Instantaneous Test

Flow along walls is questionable for oval widths less than 0.29 foot and conical diameters less than 0.57 foot.

Hopper Slope Angle for Various Outlet Dimensions

Oval width	ft	0.25	0.50	1.00	2.00	4.00	5.00	13.68
Conical dia.	ft	0.50	1.00	2.00	4.00	8.00	10.00	27.35
Phi-prime	deg	37.5	24.0	18.1	15.5	14.3	14.1	13.5
Theta-P	deg	11.6	28.0	35.9	39.3	40.9	41.2	42.0
Theta-C	deg	0.7	17.7	24.6	27.7	29.1	29.4	30.1

[a]See Figures 18 and 19.

[b]ϕ' = wall friction angle.

Next an attempt was made to reevaluate the critical rathole diameter, D_f. Again the consolidation pressure is given by

$$\sigma = h_e \times \gamma$$

where

h_e = consolidation head, ft

γ = consolidated density given by

$$\gamma = (31.2)(\sigma_1/130)^{0.04105} \text{ (requires iteration)}$$

the consolidation head is calculated by the larger value of

$$h_e = \frac{R}{\mu k} \quad 1 - e^{-\mu k \frac{h}{R}} \qquad \text{(a)}$$

or

$$h_e = 2R \qquad \text{(b)}$$

where

R = hydraulic radius (cross-sectional area/wetted perimeter)

R = D/4, circular diameter, D

R = W/2, rectangular cylinder, width W

μ = wall coefficient of friction, tan ϕ'

k = ratio of horizontal to vertical pressures

h = height of vertical bin section.

The test report alludes that the above equations apply to pertinent sections of the bin. A bin normally consists of a vertical section plus the converging bottom hopper.

Using Building 1240 storage bin data, a sample calculation was made.

h = 20 ft ~ approximate fill height

$$R = \frac{A}{P} = \text{opening} = \frac{2 \times 2}{8} = 0.5$$

$k = 0.4$

$\mu = \tan 11.5° = 0.2035$

$$h_e = \frac{0.5}{(0.2035)(0.4)} \left[1 - e^{\frac{(-0.2035)(20)}{0.5}}\right] = 6.14 \text{ ft} \qquad \text{by (a)}$$

or

$$h_e = 2R = (2)\left[\frac{A}{P}\right] = (2)(0.5) = 1.0 \qquad \text{by (b)}$$

$h_e \approx 6.14$ ft will be used

then

$$\sigma_1 = (h_e)(\gamma) = (6.14)(35.01) = 214.96 \text{ lb/ft}^2$$

For verification of density,

$$\gamma = (31.2)\left(\frac{214.96}{13.0}\right)^{0.04105} = 35.01 \text{ lb/ft}^3$$

From the shear cell test graph of the flow function, FF,

$f_{cr} = 7$ psf

and

$$d_{min} = \frac{\dot{G}(\phi)f_{cr}}{\gamma} = \frac{(3.0)(7)}{35.01} = 0.60 \text{ ft}$$

This indicates the minimum dimension to prevent piping was 0.60 feet and does not agree with the bunker piping experienced for the hopper opening of 2 feet by 2 feet.

$$P = \frac{\omega\sqrt{2gh}}{gA\gamma B}(1 + m) \qquad \text{or } 1$$

using greatest value of P, the overpressure factor.

<u>Legend</u>

ω = mass flow rate into bin (lb/sec)

h = fall height, ft

m = long slotted outlet

$m = 1$ = for circular outlet

A = area of impact of falling stream of solid

γ = bulk density

B = outlet size or bin dimension in region of impact.

Based on test data reported for Building 1240, a sample calculation was made for P as

$$\omega = 1 \text{ ton}/15 \text{ min} = \frac{2000 \text{ lb}}{15 \times 60} = 2.222 \text{ lb/sec filling rate}$$

$h = 55'$ - height opening to outlet

$m = 0$

A = minimum door area = 2.2 = 4 sq ft

$\gamma = 33 \text{ lb/ft}^3$

B = 2 ft hopper opening

$$P = \frac{2.222 \sqrt{(2)(32.174)(55)}}{(32.174)(4)(33)(2)} = 0.0156$$

or

$$P = 0.015$$

and would be $P = (2)(0.0156) = 0.0311$ for an equivalent circular outlet.

Thus, $P = 1$ would be used and this implies no overfilling effect.

Since a 100-ton storage bin was specified, the impact of an arbitrary 50-ton/hour filling rate would be

$$W = 27.78 \text{ lb/sec filling rate}$$

or

$$P = 27.78/2.222 \times 0.0156 = 0.195$$

and no compaction because of filling is implied.

E. FURTHER EFFECTS OF FILLING

In May 1969, Johansen (Reference 47) updated bin flowability calculations to account for increased consolidation pressures because of filling with no material outflow.

For funnel flow hoppers, the calculation of the minimum diameter necessary to prevent ratholing involves the calculation of the flow factor, ff, a function of

ϕ = the internal friction angle

ϕ' = the wall friction angle

θ_p = the wall hopper angle (Building 1240).

For overfilling with no outflow, the flow factor is given as

$$ff = \frac{\sigma}{\bar{\sigma}_1} = G(\phi) \times F(\phi', \theta_p)$$

where

$G(\phi)$ = rathcling function (theoretically derived)

$F(\phi', \theta_p)$ = consolidating pressure factor.

For a combined hopper and vertical bin configuration, ff is a minimum of

$$ff = G(\phi) \times F$$

or

$$ff - \frac{h}{d} \times G(\phi)$$

where

h = distance from top of material in bin

d = diameter of rathole.

The flow factor, ff, would be then plotted as $\bar{\sigma}_1 = \sigma_1/ff$ on a graph of f_c vs. σ_1 in order to determine where $\bar{\sigma}_1 = \sigma_1 = f_{cr}$.

Using the dRDF shear test data and the bunker geometry, a sample calculation can be made.

$\phi_p = 60°$, wedge type hopper

$\phi' = 11.5°$, wall friction angle

$F(11.5, 60) = 10$, maximum value

$G(\phi) = G(35°) = 3.0$

such that $ff = G(\phi)\ F = 30$

Based on Building 1240 test observations

$10 \leq h < 17'$

$2 \leq d \leq 10'$

and by

$$ff = \left(\frac{h}{d}\right)^x G(\phi)$$

$$ff = \left(\frac{10}{2}\right)(3) = 15$$

$$ff = \left(\frac{17}{10}\right)(3) = 5.10$$

$$ff = \left(\frac{17}{2}\right)(3) = 25.5$$

Since the ff curve is plotted on the flow function, FF, diagramed as $\bar{\sigma}_1 = \sigma_1/ff$, higher values of ff would bring its line closer to the FF line. Should the ff line lie below the FF line, ratholing would always occur and perhaps no minimum diameter may exist.

The above simple analysis was performed using flow properties measured from a NCRR dRDF sample. No fuel analysis, including moisture or other characterization, was given.

The intent of this calculation was to demonstrate that it may be possible to develop a condition of continuous ratholing because of the combination of dRDF bulk flow properties, bunker filling, and the poor parabolic hopper angle.

It, therefore, seems appropriate to investigate this flow phenomena further prior to a long-term commitment of cofiring coal and dRDF.

SECTION XI

ECONOMIC ANALYSIS

A. INTRODUCTION

The decision to implement coal-dRDF firing is based on the potential benefit from the reduction of coal and other costs. In addition, an implied savings are associated with the need to provide energy security, including heating, if coal is not available.

The appropriate economic analyses to evaluate the potential of cofiring involve the use of life cycle costing (LCC) which allows for the time value of money. All current and future cash flows associated with an investment are converted or discounted to their present equivalent value.

"As used in energy conservation projects, LCC analysis evaluates net effect, over time, of reducing fuel costs in purchasing, installing, maintaining, operating, retiring and replacing energy-conserving features."[1] In the current analysis, the potential is replacing a nonrenewable fuel (coal) with the alternative dRDF (sometimes called a renewable fuel).

Under the Federal Energy Management Program, the savings-to-investment ratio, SIR, calculation procedure is required to prioritize available funding for energy conservation retrofit application.

Guidance for USAF implementation of the SIR analysis is given in USAF Engineering Technical Letter 82-4; Energy Conservation Investment Program (ECIP), and its attached Appendix, "Life Cycle Cost Analysis Summary."

The SIR analysis described is based on that required by "Title 10 Code of Federal Register, Part 436, Federal Energy Management and Planning Programs, Subpart A - Methodology and Procedures for Life Cycle Cost Analysis."

The basic approach used in the analysis work sheet involves the calculation of

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[1]NBS. U.S. Dept. of Commerce
Life Cycle Costing
NBS Building Science Series No. 113
National Bureau of Standards, U.S. Department of Commerce.

- Discounted annual energy savings (+) or costs (-)
- Discounted nonenergy annual savings (+) or costs (-)
- Discounted nonenergy nonrecurring savings (+) or costs (-).

This approach has been modified for use in evaluation of potential dRDF cofiring, and the new form is shown in Figure 20. It is assumed that prior knowledge exists in extracting the modified uniform present-worth factor, UPW*, the uniform present-worth factor, UPW, and the single present-worth factor, SPW, for a one-time future cost.

Review of all the past operational dRDF cofiring data involved mixing on a coal:dRDF volumetric basis because of arrangement of fuel bunkers and conveyors. The adverse impact of firing on 1:2 ratio at other sites and the tests at WPAFB Building 770 at 40 percent by weight suggests the use of a 1:1 volume ratio. This is approximately equal to 37.5 percent by weight for a coal density of 50 lb/ft^3 and a dRDF density of 30 lb/ft^3. Higher use of dRDF had resulted in a boiler efficiency drop of $3^{1/2}$ percentage points. Thus, a coal-only boiler efficiency of 80 percent and a cofiring efficiency of 77.5 percent was assumed. Based on the earlier test data, the impact of increase heat losses owing to moisture was not screened out because of the variation in excess air and boiler flue gas exit temperatures. Examination of the boiler logs revealed a daily average load output which was converted to an hourly output, MM (10^6)Btu/hr, for each month. A load distribution for the hourly average for each month was assumed, resulting in a yearly hourly average of 41.5 percent load (or 41.5 MM Btu/hr).

The parameters used in the base case are listed in Table 51. An interactive (tutoring) computer program written on VAX allows for calculation of the line items required in the SIR program. Except for volumetric ratios, only one set of assumed variables are accepted. A listing of the source program is given in Appendix F, and a sample run is given in Appendix G.

The results of the example calculation are given in Figure 21. No annual recurring labor costs for maintenance or operations were assumed. The results of a management impact assessment (Reference 13) imply 1-3 man-years of total labor plus possible project management time might be in order.

A 10-year use of cofiring results in an additional discounted costs of $1,123,302 (or -$1,123,302). These costs result because of the drop in boiler efficiency of $2^{1/2}$ points (considered conservative) and the high dRDF costs.

There is normally a variation in the dRDF moisture and also in the fuel density. A sensitivity analysis to show the change in tons/year

Coal-dRDF Cofiring Economic Analysis Summary
(Savings - Investment Ratio - SIR)

Location _____ Boiler Unit _____

Analysis Date _____ Economic Use _____

Prepared By _____ Date _____

1. Investment

A. Storage Bin/Silos, Conveyors Construction Cost	$_____	
B. Construction Supervision	$_____	
C. Miscellaneous Fuel Handling Equipment	$_____	
D. Salvage Value of Existing Equipment	$_____	
E. Total Investment		= $_____

2. Energy Savings (+)/Cost(-)

Item	($/Ton)	× (Tons/Year)	= Annual Savings	× Discount Factor (UPW*)	= Discounted Savings(+)/Cost(-)
A. Coal Usage	_____	(+)_____	(+)$_____	_____	$_____
B. dRDF Usage	_____	(-)_____	(-)$_____	_____	$_____
	($/kWhr)	(kWhr)			
C. ESP Power	_____	_____	(-)$_____	_____	$_____
D. Total					$_____ (a)

3. Non-Energy Savings(+)/Cost(-)

A. Annual Recurring (+/-)

Item	($/Year)	× Discount Factor (UPW)	= Discounted Savings(+)/Cost(-)
1. Ash Removal	(-)$_____	_____	$_____
2. Maintenance	(-)$_____	_____	$_____
3. Operations/Supervisor	(-)$_____	_____	$_____
4. Alternate Fuel Security[1]	(+)$_____	_____	$_____
5. Total			$_____ (b)

B. Non-Recurring Savings(+)/Cost(-)

Item[2]	Savings(+) Cost(-)/yr	× Year of Occurrence	× Discount Factor (SPW)	= Discounted Savings(+)/Cost(-)
(1) _____	$_____	_____	_____	$_____
(2) _____	$_____	_____	_____	$_____
(3) _____	$_____	_____	_____	$_____
Total				$_____ (c)

4. Total Discounted Savings(+)/Cost(-): (a) + (b) + (c) = $_____

5. Discounted Savings Investment Ratio (Item 4 ÷ Item 1) = _____

[1] Command-selected cost to insure mission objective completion in case of nonavailability of fossil fuel.

[2] These items can be labor or material costs for major maintenance overhauls performed in some multi-year basis.

Figure 20. Savings-Investment Ratio Calculation Form.

TABLE 51. ASSUMPTIONS FOR BASE CASE ECONOMIC ANALYSIS.

		Fuel	
		Coal (WPAFB Specification)	dRDF
Heating value, Btu/lb, dry		14,200	7,500
Moisture, %, AR[a]		5.0	15.0
Ash, %, dry		7.0	15.0
Density, lb/ft^3, AR		50.0	30.0
Boiler efficiency:	coal-only	80%	
	cofiring	77.5% (2 1/2 point drop)	

WPAFB Building 770, Unit No. 3, 100 MM Btu/hr rated output capacity.

Arbitrary boiler heating load variation; average load = 41.5 percent.

Cofiring coal:dRDF volumetric mixture ratio 1:1.

ESP power increase of 15 kW.

[a]As received.

Coal-dRDF Cofiring Economic Analysis Summary
(Savings - Investment Ratio - SIR)

Location WPAFB Building 770 | Boiler Unit No. 3

Analysis Date _____ | Economic Use _____

Prepared By Sample | Date _____

1. Investment

A. Storage Bin/Silos, Conveyors Construction Cost	$_____	
B. Construction Supervision	$_____	
C. Miscellaneous Fuel Handling Equipment	$_____	
D. Salvage Value of Existing Equipment	$_____	
E. Total Investment		= $_____

2. Energy Savings (+)/Cost(-)

Item	($/Ton)	× (Tons/Year)	= Annual Savings	× Discount Factor (UPW*)	= Discounted Savings(+)/Cost(-)	
A. Coal Usage	55	(+) 3302.7	(+)$ 181,651	11.2	$ 2,034,487	
B. dRDF Usage	34	(-) 8140.41	(-)$ 276,774	11.2	$ -3,099,869	
	($/kWhr)	(kWhr)				
C. ESP Power	0.039	131,400	(-)$ 5,125	8.5	$ -43,559	
D. Total					$ -1,108,941	(a)

3. Non-Energy Savings(+)/Cost(-)

A. Annual Recurring (+/-)

Item	($/Year)	× Discount Factor (UPW)	= Discounted Savings(+)/Cost(-)	
1. Ash Removal	(-)$ 2046	7.02	$ -14,361	
2. Maintenance	(-)$		$	
3. Operations/Supervisor	(-)$		$	
4. Alternate Fuel Security[1]	(+)$		$	
5. Total			$ -14,361	(b)

B. Non-Recurring Savings(+)/Cost(-)

Item[2]	Savings(+) Cost(-)/yr	× Year of Occurrence	× Discount Factor (SPW)	= Discounted Savings(+)/Cost(-)	
(1)	$			$	
(2)	$			$	
(3)	$			$	
Total				$ --	(c)

4. Total Discounted Savings(+)/Cost(-): (a) + (b) + (c) = $ -1,123,302

5. Discounted Savings Investment Ratio (Item 4 ÷ Item 1) = N/A

[1] Command-selected cost to insure mission objective completion in case of nonavailability of fossil fuel.

[2] These items can be labor or material costs for major maintenance overhauls performed in some multi-year basis.

Figure 21. Savings-Investment Ratio Example Calculation.

of coal saved and the tons/year of dRDF required for variation in as-received moisture from 10 percent to 20 percent and for dRDF densities of 30.0 lb/ft^3 and 27.5 lb/ft^3 are listed in Table 52. The corresponding change in only yearly fuel costs from a base value of -$95,123 is shown in Table 53. While the fuel specification is for the heating value and ash content on a dry basis, the density is on an as-received basis and the fuel is fired on an as-received basis. Thus, when converting the fuel heating to correct for as-received moisture, the resultant fuel Btu/lb will affect the tons of coal saved and the tons of dRDF.

There are also changes in the increased ash removal costs for changes in dRDF moisture and density. In addition, the impact of using a 12.5 percent ash (dry) dRDF compared to the base case is shown in Table 54. There would be a decrease in costs of $4,668 the first year or a decrease in discounted costs of $166,778.

It is interesting to note the required break-even dRDF cost required to offset the drop in boiler efficiency, ESP efficiency, and the increase in ash removal costs. Using the base case data shown in Figure 21, the requirement exists that the net discounted costs should be zero.[1] Therefore

$$\$2,034,487 - DCR - 43,559 - 14,361 = 0$$

where

DCR = new discounted costs of dRDF.

Solving,

$$DCR = \$1,976,576$$

and the yearly cost = DCR/UPW*

$$\text{or } \$1,976,576/11.2 = \$176,479.20$$

Finally the maximum dRDF cost per ton equals

$$\$176,479.20/8140.4 = \$21.68$$

This break-even cost does not include the effect of maintenance or operational labor. The effect of load changes and Btu fuel values are shown in Tables 55 and 56.

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[1]Based on coal costs of $55/ton.

TABLE 52. CHANGE IN FUEL USAGE FOR VARIATION IN dRDF MOISTURE AND DENSITY, ton/year.[a]

dRDF density lb/ft^3		As-received moisture, %				
		10.0	12.5	15.0	17.5	20.0
30.0	coal[b]	3476.8	3390.3	3202.7	3214.0	3124.1
	dRDF[c]	8036.0	8087.9	8140.4	8193.7	8247.6
27.5	coal	3214.0	3137.7	3048.3	2963.9	2878.5
	dRDF	7510.8	7556.1	7602.0	7648.4	7695.3

[a]Boiler load = 41.5%; coal-only boiler efficiency = 80%; co-firing boiler efficiency = 77.5%.

[b]Decrease in coal usage.

[c]dRDF usage.

TABLE 53. CHANGE IN YEARLY FUEL COSTS FOR VARIATION IN dRDF MOISTURE AND DENSITY.[a]

dRDF density lb/ft^3	As-received moisture, %				
	10.0	12.5	15.0	17.5	20.0
30.0	+13,122	+6,604	Base	-6,690	-13,468
27.5	+16,525	+10,455	+4,312	-1,907	-8,201

[a]Net fuel cost (coal and RDF) = -$95,123 for base case;
(+) = decrease in net fuel costs or savings ($);
(-) = increase in net fuel costs (less savings ($)).

TABLE 54. CHANGE IN ASH REMOVAL COSTS ($) FOR VARIATION IN AS-RECEIVED MOISTURE, dRDF DENSITY AND REFERENCE ASH CONTENT.[a]

Reference ash, %, dry	Density lb/ft^3	As-received moisture, %				
		10	12.5	15.0	17.5	20.0
15.0	30.0	-88	-45	Base	+45	91
	27.5	+45	+87	+129.3	+172	216
12.5	30.0	+364	+398	433	468	503
	27.5	+458	500	533	567	600

[a]Net incremental yearly ash removal costs = $2,046 (base costs) for 15 percent moisture and 15 percent ash, dry basis, 7,500 Btu/lb, dry basis reference fuel;
(+) = decrease in ash removal costs;
(-) = increase in ash removal costs.

TABLE 55. BOILER LOAD COST COMPARISON.[a]

Boiler load	Item	Unit	Annual savings	Discount factor	Discounted savings
30%	Coal	2383.7 T/yr[b]	$ 131,103	11.2[c]	$ 1,468,354
	dRDF	5875.2 T/yr	-199,757	11.2	-2,237,275
	ESP	131,400 kWhrs	- 5,125	8.5[d]	- 43,559
	Ash	590.6 T/yr	- 1,476	7.02[e]	- 10,364
	Total		$- 75,255		$- 822,844
41.51%	Coal	3302.7 T/yr	$ 181,651	11.2	$ 2,034,487
	RDF	8140.41 T/yr	-276,774	11.2	-3,099,869
	ESP	131,400 Kwhrs	- 5,125	8.5	- 43,559
	Ash	818.3 T/yr	- 2,046	7.02	- 14,361
	Total		$- 92,044		$-1,123,302
50%	Coal	3972.8 T/yr	$ 218,505	11.2	$ 2,447,257
	dRDF	9792 T/yr	-332,923	11.2	-3,728,792
	ESP	131,400 kWhrs	- 5,125	8.5	- 43,559
	Ash	984.3 T/yr	- 2,461	7.02	- 17,274
	Total		$-122,008		$-1,342,368

[a]Based on hot water heating boiler, 100 10^6 Btu/hr output; 10-year project life; discount = 7 percent; 1:1 volumetric firing ratio; coal $55/ton; dRDF $34/ton.

[b]T/yr = tons/year.

[c]UPW* for coal.

[d]UPW* for electricity, cost = $0.039/kWhr.

[e]UPW for nonenergy annual recurring costs.

TABLE 56. COST COMPARISON FOR TWO dRDF FUELS.[a]

Fuel	Item	Unit	Annual savings	Discount factor	Discounted savings
7500[b]	Coal	3302.7 T/yr[c]	$181,651	11.2[d]	$ 2,034,487
	RDF	8140.4 T/yr	-276,774	11.2	-3,099,869
	ESP	131,400 kWhrs	- 5,125	8.5[e]	- 43,559
	Ash	818.3 T/yr	- 2,046	7.02[f]	- 14,361
	Total		$-92,044		$-1,123,302
8000	Coal	3499.6 T/yr	$192,481	11.2	$ 2,155,782
	RDF	8022.3 T/yr	-272,757	11.2	-3,054,880
	ESP	131,400 kWhrs	- 5,125	8.5	- 43,559
	Ash		- 1,975	7.02	- 13,867
	Total		$-87,376		$- 956,524

[a]WPAFB Building 770, Unit 3, 100 10^6 Btu/hr rated output; 41.5% load.

[b]RDF fuels (a) 7,500 Btu/lb, dry; 15% moisture; 15% ash, dry
(b) 8,000 Btu/lb, dry; 15% moisture; 15% ash, dry.

[c]T/yr = tons/year.

[d]UPW* for coal.

[e]UPW* for electricity, cost = $0.039/kwhr.

[f]UPW for nonenergy annual recurring costs.

B. SUMMARY

Based on only the engineering aspects of cofiring dRDF, the analyses just performed indicate that it is not economically feasible to operate in this mode at this time. Additional costs would be annual recurring labor and some future costs.

However, a potential fuel credit is a yearly allowance that would be given for base energy security. The possible dRDF cofiring would increase the reliability that the base would be able to continue to perform its assigned mission of using primary fuel, if coal was not available. The coal would not be available because of a strike at the mine or a transportation strike. The dRDF does not lend itself to long-term storage--only perhaps 6 months at the most--therefore it can not be used as a backup fuel.

Finally, a sample break-even dRDF cost of $21.68/ton was calculated. At present, dRDF fuel costs charged by a production facility are based on its income being equal to cost plus profit. This income is from the fuel revenue and front-end tipping fees. Here the tipping fees are equal to those for landfilling the source MSW. This implies dRDF charges per ton will be high because of costs and the availability of an alternative disposal method, i.e., landfills. When, and only when, landfills are no longer allowed through legislation and user break-even fuel costs become one source of income (i.e., the only possible market), then the remaining income necessary for the dRDF producer to operate will come from increased tipping fees. Thus, the generator of the MSW will pay whatever is necessary for disposal. In this scenario, dRDF cofiring is more likely to be economical for U.S. Air Force implementation.

SECTION XII

CONCLUSIONS

A. INTRODUCTION

This section summarizes the results of the study of dRDF cofiring in stoker boilers with special emphasis on the potential implementation of USAF heating plant systems.

B. dRDF PROPERTIES

The potential exists for the dRDF supplier to provide a fuel with the capability to meet only the following specifications:

HHV = 7,500 Btu/lb, dry

Ash = 15 percent, dry

Moisture = 15 percent, as received

Bulk density = 30 lb/ft^2

At the present time, the dRDF pellet, in general, undergoes deterioration either because of outside storage weathering or through crushing by compaction in storage bunkers. The wide range of 18-31 percent of moisture found in MSW is higher than the 15-20 percent moisture recommended by the pellet mill manufacturers (see Section IX). The higher mositure, usually occurring in the summer, leads to the formation of a poor pellet which tends to degrade under handling and storage. It is recommended that further study be directed to determine the potential improvement resulting from prepelletization drying and postcooling and screening. In addition, the current research being conducted by Argonne National Laboratory on the use of binders for pellet enhancement should be monitored.

C. BOILER EFFICIENCY

The boiler efficiency decreases from $2^{1/2}$ to $3^{1/2}$ percentage points when cofiring dRDF. Test data from the Maryland Correctional Institute tests at low boiler load were influenced by high carbon losses and were not typical of those from the tests at Erie or WPAFB.

It is recommended that test protocol given in Reference 27 be reviewed for simplication in future calculations of boiler efficiency.

It is also suggested that, when boiler efficiency tests are included as part of a stack emissions evaluation, the use of the ASME

heat loss method be specified and the F emission calculation procedure not be allowed.

D. PARTICULATE COLLECTOR PERFORMANCE

There is no apparent difference in electrostatic precipitator performance when firing coal-only or when cofiring dRDF. The fly ash resistivity tends to increase when cofiring. Differences in numerical values were encountered when making ash in situ measurements compared to hopper ash being analyzed by the ASME PTC 28 method.

E. ENVIRONMENTAL EMISSIONS

The extensive evaluation of stack and ash emission data as discussed in Section VIII indicates the impact on the environment would not be negative with respect to NO_x, SO_x, and particulate emissions. Certain metal emissions do increase in cofiring.

F. BULK SOLID FLOW PROPERTIES

Continued difficulty with bunker bridging and/or ratholing has been experienced at all sites that cofired dRDF. Further studies should be implemented to better characterize the behavior of dRDF during bunker storage and outflow. The flow restriction will cause variation in boiler operation and require extra manpower to maintain continuous bunker outflow.

G. CORROSION

Based on published data, there is no indication that metal wastage would occur when cofiring dRDF. The presence of some sulfur in the coal and the low weight ratio of the dRDF implies that any chlorine present in the pellet would tend to react in the gaseous phase rather than in any molten ash deposits on the boiler water wall tube.

H. ECONOMIC EVALUATION

A savings-to-investment analysis technique now used for study of energy conservation modifications was adapted for use in evaluation of the potential for dRDF cofiring. Using the latest WPAFB coal price of $55/ton and quoted dRDF price of $34/ton, an analysis was made on one boiler (using a scenario discussed in detail in Section XI) with the following result. A decrease of 3,303 tons/year of coal used would result with burning 8,141 tons/year of dRDF (on a 1:1 volumetric mixture or 37.5 percent by weight of pellets). The total discounted increase in costs would be $1,123,302 for the 10-year study period

(Figure 21). Thus, it is recommended that dRDF not be used for base energy fuel security until an appropriate credit or savings be allowed.

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APPENDIX A

ASTM PUBLISHED STANDARDS FOR RDF-3 ANALYSIS

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ASTM PUBLISHED STANDARDS FOR RDF-3 ANALYSIS

E-771-81. Test method for gross calorific value of refuse-derifed fuel (RDF-3) by the bomb calorimeter.

E-775-81. Test method for total sulfur in the analysis sample of refuse-derived fuel.

E-776-81. Test method for forms of chlorine in refuse-derived fuel.

E-777-81. Test method for carbon and hydrogen in the analysis sample of refuse-derived fuel.

E-778-81. Test method for nitrogen in the analysis sample of refuse derived fuel.

E-790-81. Test method for residual moisture in refuse-derived fuel analysis sample.

E-791-81. Calculating refuse-derifed fuel analysis data from as-determined to different basis.

E-828-81. Designating the size of RDF-3 from its sieve analysis.

E-828-81. Preparing RDF-3 laboratory samples for analysis.

E-830-81. Test method for ash in the analysis samples of refuse-derived fuel (RDF-3).

E-856-82. Definition of terms relating to physical and chemical characteristics of refuse-derived fuels.

E-884-82. Practice for sampling airborne microorganisms at municipal solid waste processing facilities.

E-885-82. Analysis of metals in refuse-derived fuel (RDF) by atomic absorption spectrophotometry.

E-886-82. Dissolution of refuse-derived fuel-3 (RDF-3) ash samples for analysis of metals.

E-887-82. Test method for silica in refuse-derived fuel-3 (RDF-3) and RDF-3 ash.

E-889-82. Test method for composition or purity of a solid waste materials stream.

E-897-82. Test method for volatile matter in the analysis sample of refuse-derived fuel-3.

E-926-83. Method of preparing refuse-derived fuel-3 (RDF-3) samples for analysis of metals.

E-868-82. Conducting performance tests on mechanical conveying equipment used in resource recovery systems.

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APPENDIX B

PROPOSED STANDARDS FOR dRDF

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PROPOSED STANDARDS FOR dRDF

1. Proposed Standard Specification for Collecting and Dividing a Gross Sample of RDF-5.

   This method covers the sampling of RDF-5 for the purpose of measuring characteristics pertinent to the handling and storage of the fuel. The procedure is to collect by increments a gross sample representing one lot and divide this gross sample into sizes appropriate for subsequent testing.

2. Proposed Standard Method of Air-Drying RDF-5 for Further Analysis.

   This method covers the process of air-drying a gross or laboratory sample of RDF-5. The air dry loss is determined by establishing the weight loss of the sample when it is dried under specific controlled conditions. Air-drying may be performed on a drying floor or in a drying oven. The procedure selected depends on the sample size and equipment availability.

3. Proposed Standard Method for Measuring Bulk Density of RDF-5.

   This method determines the bulk density of RDF-5. Loose bulk density is determined by weighing a known volume of sample. Settled bulk density is determined by weighing a known volume of sample that has been mechanically settled or compacted.

4. Proposed Standard Method for Measuring Density of RDF-5.

   This method covers the determination of the density, or mass per unit volume, of RDF-5. The density of RDF-5 is found by determining the mass of a sample by direct measurement and the volume of a sample by measuring the amount of water displaced by the particle. Each particle to be tested is waterproofed by coating it with paraffin of a known density.

5. Proposed Standard Method for Measuring Total Moisture and Residual Moisture of RDF-5.

   This method covers the one-step measurement of total moisture in RDF-5. The method also covers the measurement of residual moisture in an air-dried sample of RDF-5. The total moisture content or residual moisture content is determined by establishing the weight loss of the RDF-5 laboratory sample when it is heated under controlled conditions.

6. Proposed Standard Method for Measuring Particle Size Distribution of RDF-5.

This method is used to determine the size distribution of a RDF-5 sample. Size is defined as the maximum length of the particle, where length is determined by the RDF-5 manufacturing process. That is, a pellet, cubette, or briquette all have a recognizable length.

7. Proposed Standard Method for Measuring Durablity of RDF-5.

This method covers the measurement of the relative durability of RDF-5 subjected to impact and abrasion. Durability may be used to rank different types of RDF-5 with regard to breakage during handling and storage.

8. Proposed Standard Method for Measuring Hydrophilia of RDF-5.

This method covers the evaluation of the absorbence of water by RDF-5. Water is sprayed onto a laboratory sample of RDF-5 under controlled conditions producing a weight gain that is dependent upon the relative absorbency of the RDF-5.

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APPENDIX C

BOILER FUEL TEST ANALYSES

TABLE C-1. MCI BOILER TEST FUEL ANALYSIS, AS FIRED.

Test blend, coal:dRDF	1:0	1:1	1:2	0:1
Test date	5-4-77	5-13-77	5-11-77	5-14-77
Proximate, analysis, %				
• Fixed carbon	54.23	38.38	29.09	8.96
• Volatile matter	22.55	31.68	38.26	48.59
• Ash	21.95	23.33	24.73	25.85
• Moisture	1.30	6.62	7.94	16.60
Ultimate analysis, %				
• Carbon	66.52	54.06	47.29	30.90
• Hydrogen	4.27	4.10	4.07	3.76
• Oxygen	3.38	9.83	14.19	21.78
• Nitrogen	1.33	1.06	0.90	0.55
• Sulfur	1.20	0.86	0.66	0.23
• Ash	21.95	23.33	24.73	25.85
• Moisture	1.30	6.62	7.94	16.60
Higher heating value, Btu/lb	11,706	8,988	8,382	5,103

TABLE C-2. MCI AVERAGE dRDF PROPERTIES, AS RECEIVED.

Analysis	Dec.	$\hat{S}$[a]	March	$\hat{S}$	May	$\hat{S}$	Overall avg.	$\hat{S}$
Proximate, %								
Moisture	13.40[b]	3.79	12.62	4.34	12.22	4.82	12.67	3.68
Ash	19.97	4.26	24.47	0.19	28.75	4.74	25.00	5.11
Volatile matter	56.54	4.74	54.08	5.32	49.27	8.43	52.72	6.60
Fixed carbon	10.10	3.31	8.89	1.17	9.76	1.15	9.61	1.66
Ultimate, %								
Carbon	39.27[c]		34.17	0.92	31.36	3.86	33.61	3.96
Hydrogen	4.73		3.93	0.90	4.01	0.89	4.10	0.76
Nitrogen	0.31		0.34	0.12	0.75	0.34	0.54	0.32
Chlorine	0.36		0.39	0.08	0.31	0.05	0.35	0.06
Sulfur	0.17		0.23	0.04	0.24	0.07	0.22	0.05
Ash	16.95		24.42	0.20	28.68	4.71	25.31	5.47
Oxygen	27.50		23.93	4.04	22.37	4.81	23.75	4.06
Moisture	10.72		12.62	4.34	12.22	4.82	12.67	3.68
Btu/lb	6667		5534	671.0	5266	672	5692	739
Fusion temp., °F								
Initial Def.	2018	88.	2040	67.0	2005	64.0	2057	62.0
Softening	2088	46.0	2103	70.0	2105	64.0	2099	55.0
Hemispherical	2175	--	2155	66.0	2125	64.0	2149	56.0
Fluid	2275	21.0	2215	34.0	2225	50.0	2233	40.0
Mineral, %								
P_2O_5	0.87		0.73	0.08	0.65	0.08	0.72	0.10
SiO_2	55.52		71.58	6.69	63.65	0.63	65.89	7.19
Fe_2O_3	2.27		2.89	1.09	2.64	1.43	2.69	1.15
Al_2O_3	13.45		4.43	1.68	8.39	3.32	7.42	4.01
TiO_2	0.66		0.99	0.40	0.69	0.12	0.82	0.29
Na_2O	6.82		5.66	4.08	7.53	1.98	6.63	2.78
K_2O	1.30		0.53	0.17	0.91	0.29	0.80	0.35
CaO	10.75		7.51	2.33	9.74	1.67	8.93	2.15
MgO	1.14		1.12	0.57	1.59	0.11	1.32	0.42
SO_3	6.03		1.22	0.24	3.2	2.10	2.76	2.14
Undetermined	1.19		1.87	--	1.00	0.66	1.21	0.60

[a]Standard deviation.

[b]Average of two analyses.

[c]Single analysis.

TABLE C-3. ERIE AVERAGE COAL PROPERTIES, AS RECEIVED.

Analysis	Coal A	Coal B	Coal C	Coal D	Coal E
Proximate, %					
Fixed carbon	44.78	43.78	49.03	51.26	51.85
Volatile matter	33.26	32.96	32.65	33.77	33.37
Ash	14.38	17.12	12.08	8.91	9.54
Free moisture	7.76	6.15	6.20	6.06	5.25
Ultimate, %					
H_2	4.39	4.27	4.68	4.53	4.62
C	63.18	61.21	66.90	68.69	70.89
N	0.98	0.96	1.13	1.19	1.18
S	3.83	6.36	2.06	1.63	1.98
Cl	0.13	0.13	0.15	0.11	0.16
O	5.35	3.81	6.73	8.89	6.38
Ash	14.38	17.12	12.08	8.91	9.54
Free moisture	7.76	6.15	6.20	6.06	5.25
Higher heating value, Btu/lb	11,368	11,142	11,725	12,040	12,347

TABLE C-4. BUILDING 1240 CORRECTED dRDF PROPERTIES, AS FIRED.

Date sample	3/2 R-1	3/3 R-2	3/4 R-3	3/5 R-4	3/30 R-5	3/31 R-6	4/1 R-7	4/2 R-8	Avg.	Std. dev.
Ultimate analysis, %										
C	40.16	40.57	39.03	41.21	41.60	41.85	41.02	40.96	40.80	0.89
H_2	4.93	5.17	5.06	4.95	5.25	5.52	5.21	5.17	5.16	0.19
O	32.55	32.95	32.56	33.16	32.77	33.51	33.77	33.21	33.06	0.44
N	0.33	0.38	0.25	0.32	0.21	0.29	0.37	0.31	0.31	0.06
S	0.23	0.16	0.36	0.11	0.23	0.17	0.07	0.19	0.19	0.09
Ash	9.28	9.39	8.87	7.77	9.20	9.33	8.80	8.91	8.94	0.53
Free moisture	12.50	11.42	13.85	12.50	10.72	9.42	10.76	11.42	11.57	1.36
Higher heating value, Btu/lb	7223	7549	7132	7305	7245	7593	6304	7164	7189	396

TABLE C-5. BUILDING 1240 CORRECTED COAL PROPERTIES, AS FIRED.

Sample	C-1[a]	C-2	C-3	Avg.	Std. dev.
Ultimate analysis, %					
C	81.63	74.30	74.12	76.68	4.28
H_2	5.30	4.81	4.78	4.96	0.29
O	0.71	7.86	8.69	5.75	4.39
N	1.72	1.56	1.50	1.59	0.11
S	0.54	0.76	0.65	0.65	0.11
Ash	5.02	5.26	5.73	5.34	0.36
Free moisture	5.08	5.47	4.53	5.03	0.47
Higher heating value, Btu/lb	12,805	13,187	13,161	13,051	213

[a]Coal sample identification.

TABLE C-6. BUILDING 770 AVERAGE FUEL PROPERTIES.

	100% Coal		100% dRDF		dRDF-Coal Mixture	
	Avg.	$\hat{S}$[a]	Avg.	$\hat{S}$	Avg.	$\hat{S}$
Moisture, %	6.73	0.21	11.76	0.37	8.51	1.05
Ash, %	4.96	0.41	8.31	1.19	6.59	2.46
Sulfur, %	0.70	0.03	0.13	0.02	0.60	0.10
Carbon, %	75.25	0.86	44.26	1.21	64.5	4.24
Hydrogen	5.08	0.02	6.05	0.36	5.18	0.06
Nitrogen	1.48	0.02	0.35	0.03	1.36	0.09
Oxygen	5.80	0.47	29.14	2.15	13.26	0.88
Higher heating value, Btu/lb	13,436	71	7,585	305	11,067	577
Ash softening temp., °F	2,753[b]	57	2,183[c]	163	2,353	164

[a]Standard deviation.

[b]Temperature greater than this value based on C-1 real sample.

[c]Temperature less than this value based on R-1 dRDF sample.

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APPENDIX D

BOILER TUBE WALL CORROSION MECHANISMS

APPENDIX D

BOILER TUBE WALL CORROSION MECHANISMS

The mechanism for chlorine corrosion as found in the Krause investigations was proposed as follows.

The alkali metals in the flue gas form alkali chlordies which then form a sulfate and releases HCl as

$$2KCl + SO_2 + \frac{1}{2} O_2 + H_2O \rightarrow K_2SO_4 + 2CHl$$

Then, the HCl attacks the metal as

$$2HCl + Fe \rightarrow FeCl_2 + H_2$$

This occurs in a liquid melt ash condition when the tube metal temperature is greater than 600° F. If the metal temperature is less than 600° F, the HCl forms chlorine as

$$2HCl + \frac{1}{2} O_2 \rightarrow H_2O + Cl_2$$

and then

$$Fe + Cl_2 \rightarrow FeCl_2$$

again in a liquid melt ash mode attack. If oxidizing (high O_2) conditions exist, another reaction continues the wastage cycle as

$$4FeCl_2 + 3O_2 \rightarrow 2Fe_2O_3 + 4Cl_2$$

The presence of iron sulfide, FeS, in the high concentration of iron chloride was assumed to occur from sulfur-type corrosion.

This sulfur corrosion was attributed to the intermediate formation of either alkali pyrosulfates, $K_2S_2O_7$, for low temperature corrosion or alkali iron trisulfates, $K_3Fe(SO_4)_3$, for high temperature metal wastage.

The results of the corrosion probe tests on RDF cofiring showed no iron chloride, $FeCl_2$, layer next to the metal surface only the presence of FeS. This confirmed the earlier response where burning MSW seeded with sulfur reduced the amount of chlorine (as $FeCl_2$) in the metal wall oxide layer.

A review of sulfur type corrosion previously experienced with straight coal firing was reviewed to ascertain the formation of FeS.

Reid (Reference 48) proposed that low-temperature (750-950° F) sulfur water-wall corrosion occurred as follows.

The metal alkalis deposited on the metal surfaces are converted to the alkali sulfates, Na_2SO_4 and K_2SO_4. These sulfates then react with SO_3 as follows

$$SO_2 + \frac{1}{2} O_2 \rightarrow SO_3$$

because of metal surface catalytic action and form the liquid melt deposit pyrosulfates $Na_2S_2O_7$ and $K_2S_2O_7$.

Next, these pyrosulfates react with the two forms of metal oxide film on the wall surface as

$$3Na_2S_2O_7 + Fe_2O_3 \rightarrow 3NaSO_4 + Fe_2(SO_4)_3$$

or

$$4Na_2S_2O_7 + Fe_3O_4 \rightarrow NaSO_4 + FeSO_4 + Fe_2(SO_4)$$

or as alternative reactions

$$3Na_2S_2O_7 + Fe_2O_3 \rightarrow 2Na\ Fe(SO_4)_3$$

$$2Na\ Fe(SO_4)_3 \rightarrow 3Na_2SO_4 + Fe_2O_3 + 3SO_3$$

Then the final wastage occurs as

$$3Fe + 2O_2 \rightarrow Fe_3O_4$$

This description of sulfur-type corrosion does not account for the iron sulfide, FeS, found in the metal layer by Battelle investigators.

Borio, Plumely, and Sylvestor (Reference 49) proposed a mechanism for high metal temperature (1050-1200° F) sulfur corrosion occurring in superheaters of pulverized coal-fired boilers.

Sulfur dioxide and trioxide are formed from the pyrites in coal as

$$2FeS_2 + 5\frac{1}{2} O_2 \rightarrow Fe_2O_3 + 4SO_2$$

$$SO_2 + \frac{1}{2} O_2 \rightarrow SO_3$$

Alkali oxides are formed in the furnace as

$$2Na + \frac{1}{2} O_2 \rightarrow Na_2O$$

$$2K + \frac{1}{2} O_2 \rightarrow K_2O$$

Next, these oxides react as

$$\begin{matrix} Na_2O & & Na_2SO_4 \\ \text{or} & + SO_3 & \text{or} \\ K_2O & & K_2SO_4 \end{matrix}$$

and this may occur in the tube ash deposits.

These alkali sulfates react with the iron oxide layer on the tube to form the alkali iron trisulfates:

$$\begin{matrix} 3 \; Na_2SO_4 & & & K_3Fe(SO_4)_3 \\ \text{or} & + Fe_2O_3 + 3SO_3 & \rightarrow 2 & \text{or} \\ K_2SO_4 & & & Na_3Fe(SO_4)_2 \end{matrix}$$

Hence, as the iron oxide scale is removed, more iron oxidizes. If the trisulfate is a liquid ash deposit, it may read directly with the iron as

$$\begin{matrix} 2 \; Na_2SO_4 & & & & \\ \text{or} & + Fe_2O_3 + 3SO_3 & \rightarrow & \frac{3}{2} FeS + \frac{3}{2} Fe_3O_4 + Fe_2O_3 \\ K_2SO_4 & & & \end{matrix}$$

$$\begin{matrix} & K_2SO_4 & \\ + 3 & \text{or} & + \frac{3}{2} O_2 \\ & Na_2SO_4 & \end{matrix}$$

Some of this latter SO_2 would form SO_3, and the reaction cycle of alkali sulfates to trisulfates would continue.

This mechanism does not result in the formation of iron sulfide found by Battelle.

In recapitualation, low-temperature coal sulfur corrosion was attributed to the intermediate formation of pyrosulfates and high-temperature coal sulfur corrosion was due to an intermediate reaction involving alkali iron trisulfates.

Vaughn, Krause, and Boyd (Reference 36) explain that the presence of iron sulfide in low-temperature sulfur corrosion is due to pyrosulfate reacting as follows

$$K_2S_2O_7 + 3Fe \rightarrow Fe_2O_3 + FeS + K_2SO_4$$

or

$$2KHSO_4 + 3Fe \rightarrow Fe_2O_3 + FeS + K_2SO_4 + H_2O$$

The appearance of iron sulfide, FeS, in the metal oxide-deposit interface of the high-temperature Battelle test probe coupons is attributed to the presence of the alkali iron trisulfate (the formation of which was discussed earlier) liquid melt deposit. Vaughn et al. indicates this final reaction as

$$4Ke_3Fe(SO_4)_3 + 12\ Fe \rightarrow 3FeS + 3Fe_3O_4 + 2Fe_2O_3 + 6K_2SO_4 + 3SO_2$$

A major conclusion of the Vaughn et al. or Battelle studies is the important fact that the higher sulfur content of the coal results in a higher amount of SO_2. This concentration would cause the chlorine in the RDF to react in the gaseous phase as

$$\text{Metal Chloride} + SO_2 + O_2 + H_2O \rightarrow \text{Metal Sulfate} + HCl \text{ or } Cl_2$$

The corrosive gases are carried out through the stack and would not react with the tube metal in the liquid melt wall deposits.

Another perspective on possible low-temperature tube-wall sulfur corrosion is given by French (Reference 50) as follows.

- Alkali metals to oxides as

$$4\ Na + O_2 \rightarrow 2Na_2O$$

$$4\ K + O_2 \rightarrow 2K_2O$$

- Formation of SO_3 by

$$S + O_2 \rightarrow SO_2$$

$$2SO_2 + O_2 \rightarrow 2SO_3$$

- Formation of pyrosulfates in metal wall liquid ash deposits as

$$Na_2O + 2SO_3 \rightarrow Na_2S_2O_7$$

$$K_2O + 2SO_3 \rightarrow K_2S_2O_7$$

- Carbon deposits in ash from unburned carbon or

$$2CO \rightarrow CO_2 + C$$

- Final tube wastage as

$$SO_3 + 3C + Fe \rightarrow FeS + 3CO$$

$$2SO_3 + 9C + Fe_2O_3 \rightarrow 2FeS + 9CO$$

The interesting implication here is the contribution of the carbon wall deposits.

In conclusion, the above chemical reactions explaining the various mechanisms for chlorine and chlorine-sulfur corrosions have been based on X-ray diffraction and chemical analysis of tube metal oxide layers and ash deposits. These analyses plus the corresponding temperature environment provided the only metallurgical reactions that were possible.

APPENDIX E

BULK SOLID SHEAR CELL TEST PROPERTIES

APPENDIX E

BULK SOLID SHEAR CELL TEST PROPERTIES

The Jenike and Johanson Shear Load Test Cell (Reference 46) is used to determine the necessary bulk solid flow properties used in their analysis procedure to determine bin geometry for nonbridging or nonratholing.

The bulk flow behavior is predicted on the existence of a solid limiting stress function or yield locus such that lower stresses will not result in failure or plastic flow of the solid. The position of this yield locus line (on a graphical plot of normal stress σ versus shearing stress) τ is a function of the compaction or consolidation of the solid.

Ideally, a bulk solid might be compressed or consolidated in a piston and cylinder device under a stress σ_1. This compacted material now has gained some compressive strength or stress, f_c, which may be measured. The solid core is removed from the piston and cylinder device and is compressively loaded to failure (under an unconfined condition), similar to a sample of concrete core being compressed to failure. The flow function, FF, curve relates the unconfined yield strength, f_c (psf), to the consolidation stress, σ_1, which a solid experiences at different levels in a silo or hopper. The flow function is dependent on moisture, temperature, and the time compressed under σ_1 before tested to failure.

The actual flow properties are determined by use of the Jenike-Johanson shear load cell tester as shown in Figure E-1. A review of the test procedure is necessary to understand the properties used in the bin design analysis.

A sample of the bulk solid is prepared by preconsolidated at a normal load V_V, lb as described in Reference 51. Then the material is consolidated (or compressed) to this load V_V and subjected to a shear load, S, lb, where failure or plastic flow occurs. The material has now been subjected to a combined stress σ_V, τ_V. Then a series of shear tests to failure are conducted where lower normal loads, V_n, have been applied. This results in a series of test points for the combined stresses σ_n, τ_n. In each lower shear test, the solid in the test cell is first compacted or preconsolidated to the original consolidation load, V_V, before being loaded to V_n and sheared to failure at τ_N.

The yield locus line, YL, the major consolidation pressure, σ_1, the kinematic or internal angle of friction, ϕ, and the unconfined yield strength, f_c, are then obtained as shown in Figure E-2. Each yield line has a Mohr circle drawn through its tangent point E which also goes through σ_V, τ_V. The Mohr circle intercepts the σ axis at a stress σ_1 which is the major consolidation pressure.

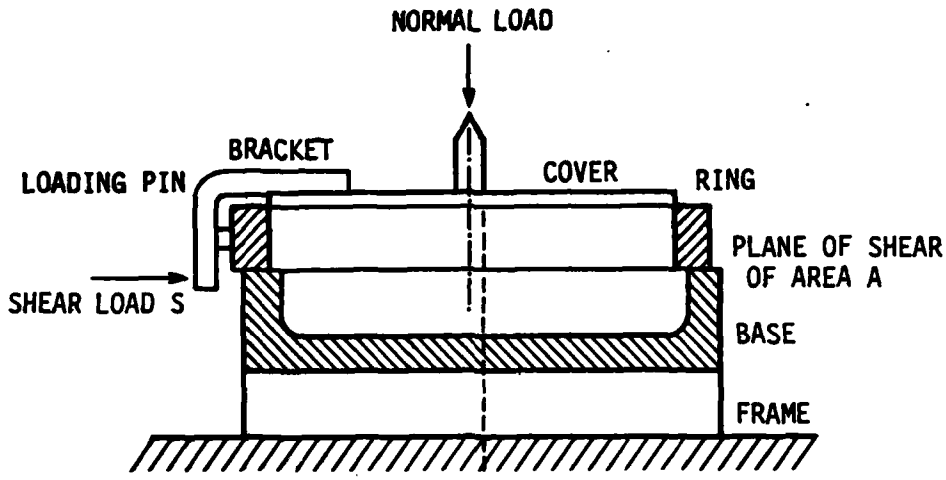
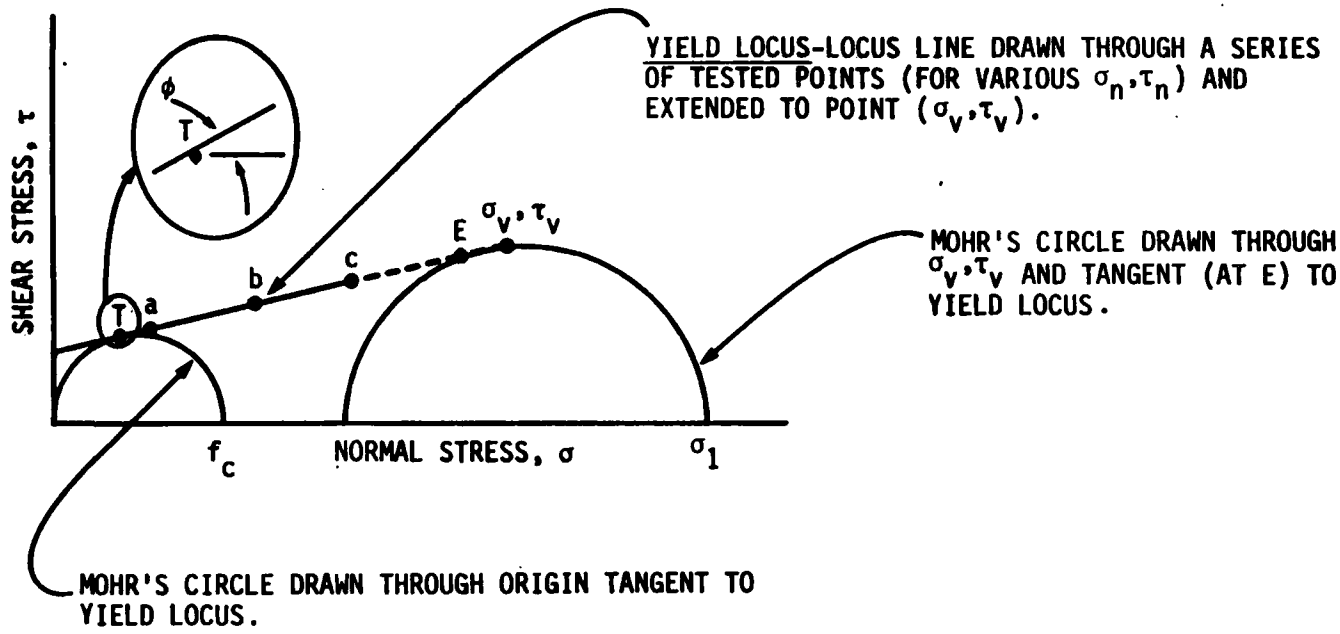


Figure E-1. Jenike and Johanson Shear Load Test Cell.



f_c = UNCONFINED YIELD STRENGTH (STRESS), INTERSECTION OF MOHR'S CIRCLE THROUGH ORIGIN WITH σ AXIS.

ϕ = KINEMATIC ANGLE OF FRICTION, ANGLE AT TANGENCY POINT OF MOHR'S CIRCLE WITH YIELD LOCUS.

σ_1 = MAJOR CONSOLIDATION PRESSURE, INTERSECTION OF MOHR'S CIRCLE WITH σ AXIS.

Figure E-2. Flow Property Determination from One Consolidation Pressure Shear Test (Cell).

If the shear tests are repeated for different values of consolidating force, V_V (or σ_V), a series of yield lines are obtained as shown in Figure E-3. A line is drawn from the origin tangent to each Mohr circle defining σ_1 for each yield line. This line is the effective yield locus line, EYL, and the corresponding tangent angle is δ, the effective angle of friction. This angle, δ, is used in the continuum analysis to aid in determining the nondoming condition.

Any bulk solid stored in a bin prior to emptying can also experience an increase in its strength because of consolidation under time. Thus, the time yield locus line, TYL, is also experimentally determined using the shear test cell. The material is first compressed under a consolidation force, $V = \sigma_1 A$ (where σ_1 was determined from the instantaneous test), for a specified time period, usually 24 hours. The shear test is then conducted to find the time yield locus line which gives f_{c_t} and ϕ_t, as shown in Figure E-4.

For determination of the minimum hopper diameter necessary to prevent bridging or doming, the wall angle of friction, ϕ' (or coefficient of wall friction, μ' = tangent ϕ'), is required. This angle is determined by again running the load cell through a series of normal and shear loads to determine σ_n, τ_n. In this case, a sample of the wall hopper material forms the cell base. The wall yield locus line is plotted through the series of σ_n, τ_n values. A straight line is now drawn to the point where this wall yield locus line intersects the Mohr circle that was drawn through the original normal force, V_v (and used to find the original value of σ_1). The tangent angle of this straight line is the wall friction angle, ϕ'.

In addition, the bulk density because of consolidation is also determined.

Further and extensive discussions of flow properties are given in References 52-56.

In summary, the data provided by the shear tests include

- FF = the flow function which relates the unconfined yield strength, f_c psf, to the consolidation pressure, σ_1 psf
- δ = the effective angle of internal friction
- ϕ = the internal angle of friction
- ϕ' = the wall friction angle
- ϕ_t = time internal friction angle (for incipient flow).

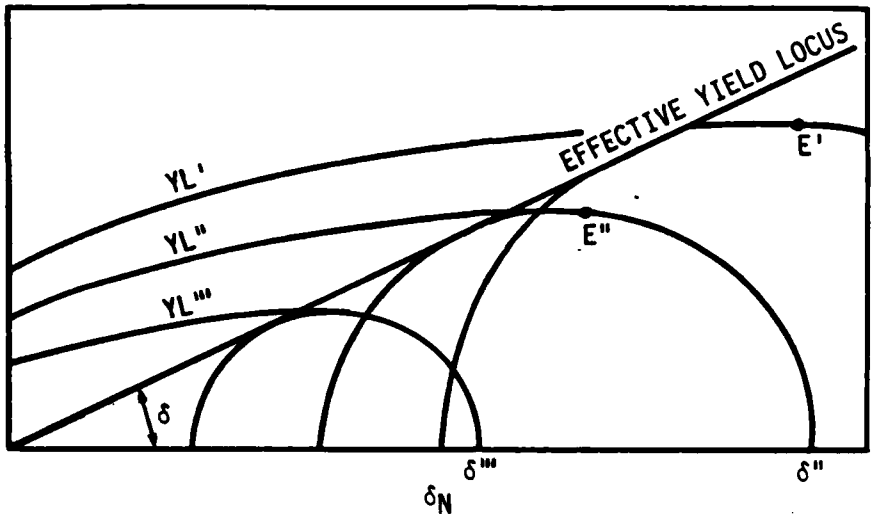


Figure E-3. Effective Yield Locus Line, EYL, and Effective Angle of Friction, δ.

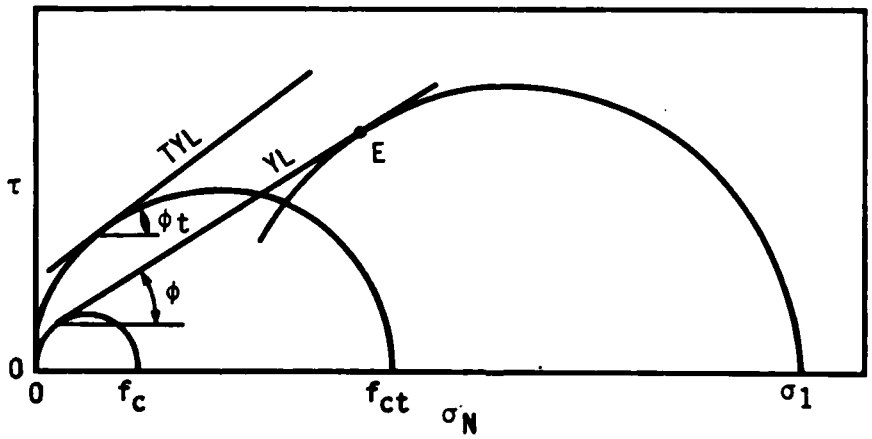


Figure E-4. Time Yield Locus Line, TYL, and Time Internal Angle of Friction, ϕ_t.

APPENDIX F

```
T ECOAL

*       CALCULATION OF COST SAVINGS FOR FUEL

        DIMENSION MO(12),QS(12),MS(12),QT(12),SAV(5),DSAV(5),NESAV(5)
        DIMENSION DNESAV(5),RNRSAV(5),DNRSAV(5)
        CHARACTER MO*9,ANSWER,FTYPE*12

        DATA (MO(I),I=1,12)/'JANUARY','FEBRUARY','MARCH','APRIL','MAY'
     :,'JUNE','JULY','AUGUST','SEPTEMBER','OCTOBER','NOVEMBER',
     :'DECEMBER'/

10      FORMAT (/)
20      FORMAT (//)
100     FORMAT (X,A,$)
200     FORMAT (X,A,A,A,$)
300     FORMAT (10X,A,F18.6)
301     FORMAT(10X,A)
400     FORMAT (X,A,I2,A,$)
401     FORMAT(X,A,I2,A,F20.2)
        PRINT 100,'THE PROJECT LIFE? '
        READ*,N
        PRINT 10
        PRINT100,'THE DISCOUNT RATE(%)?'
        READ*,RINTR
        RINTR=RINTR/100.0
        PRINT 10
        D=D/100.0
        PRINT 100,' UPW* FACTOR FOR COAL ?'
        READ*,UPWS
        PRINT 10
        PRINT 100,' THE UPW* FACTOR FOR ELECTRICITY ? '
        READ*,UPWSE
        PRINT 10
        PRINT 100,' THE UPW DISCOUNT FACTOR ?'
        READ*,UPW
        PRINT 10
        NUM1=3
        PRINT 10
        PRINT*,'DO YOU WANT TO USE EFFICIENCY POLYNOMIAL ?'
5       PRINT 100,'(ty ''Y'' or ''N'')  >  '
        READ '(A)',ANSWER
        PRINT 10

        IF (ANSWER.NE.'Y'.AND.ANSWER.NE.'y'.AND.ANSWER.NE.'N'.AND.
     :ANSWER.NE.'n')  GOTO 5
        IF (ANSWER.EQ.'Y'.OR.ANSWER.EQ.'y') THEN
           INDEX=1
        ELSE
           INDEX=0
          PRINT 100 'SUPPLY COAL ONLY BOILER EFFICIENCY(DECIMAL) '
```

```
      READ*,EFFC
      PRINT 10
   ENDIF

   PRINT*,'THE FORM OF DATA YOU WANT TO KEY-IN :'
   PRINT 10

   PRINT*,'        1) STEAM LOAD (LBS/HR)'

   PRINT 10

   PRINT*,'        2) HOT WATER HEAT LOAD (MMBTU/HR) '

   PRINT 10

   PRINT 100,'SUPPLY THE SERIAL NUMBER OF THE DESIRED METHOD  >'
   READ*,JINDEX
   PRINT 10
   IF(JINDEX.LT.1.OR.JINDEX.GT.2) THEN
      PRINT 100,'THE NUMBER SHOULD EITHER BE 1 OR 2   >  '
      READ*,JINDEX
      PRINT 10
   ENDIF
   IF (INDEX.EQ.1) THEN
      PRINT 100,'SUPPLY CONSTANTS (A,B,& C) FOR THE RIGHT
: EFFICIENCY POLYNOMIAL AND COAL ONLY OPTION   >  '
      READ*,A,B,C
      PRINT 10
   ENDIF

   SQT=0.0
   DO I=1,12
      IF(JINDEX.EQ.2) THEN
        PRINT 200,'SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF ',
:MO(I),' >  '
        READ*,QS(I)
        QS(I)=1000000*QS(I)
        PRINT 10
        IF (INDEX.EQ.1) THEN
           EFFC=A+B*QS(I)+C*(QS(I)**2)
           QT(I)=QS(I)/EFFC
        ELSE
           QT(I)=QS(I)
        ENDIF
      ELSE
       PRINT 200,'SUPPLY STEAM LOAD AND ENTHALPY CHANGE FOR ',
:MO(I),' >  '
        READ*,MS(I),DH
        PRINT 10
        QS(I)=MS(I)*DH
        IF (INDEX.EQ.1) THEN
           EFFC=A+B*MS(I)+C*(MS(I)**2)
           QT(I)=QS(I)/EFFC
        ELSE
           QT(I)=QS(I)
        ENDIF
      ENDIF
      SQT=SQT+QT(I)
   ENDDO
   AQT1=SQT/12.
   IF (INDEX.EQ.0) AQT1=AQT1/EFFC
   PRINT 100,'SUPPLY COAL HEATING VALUE  >  '
   READ*, HHVC
   PRINT 10
   WTC1=AQT1/HHVC
   WTC1Y=WTC1*8760/2000
```

```
      PRINT 100,'SUPPLY ASH CONTENT(%) OF COAL  >  '
      READ*, ASHC
      PRINT 10
      PRINT 100,'SUPPLY COST OF COAL ($/ton)  >  '
      READ*,PRICEC
      PRINT 10
      COSTC1=(WTC1*PRICEC*8760)/2000.

      WTASHC1=(WTC1*ASHC)/100.
      WTAS1Y=WTASHC1*8760/2000
      COSASHC1=(2.5*WTASHC1*8760)/2000.
      PRINT 300,'THE COAL ONLY FIRING RATE, TONS/YR = ',WTC1Y
      PRINT 300,'THE COAL ONLY FUEL COSTS/YR = $ ',COSTC1
      PRINT 300,'THE COAL ONLY ASH FLOW RATE, TONS/YR = ',WTAS1Y
      PRINT 300,'THE COAL ONLY ASH REMOVAL COSTS/YR = $ ',COSASHC1
      IRR=0
3000  PRINT 100,'SUPPLY COAL TO dRDF VOLUME RATIO (ty 1:1 as 1,1)
     : >  '
      READ*,VC,VR
      PRINT 10
      VM=VC+VR
      IF (VR.EQ.0) THEN
          IVR=0
          GOTO 1000
      ENDIF
      IF (IRR.GT.0.AND.IVR.EQ.1) GOTO 2000
         IVR=1
      PRINT 100,'SUPPLY dRDF HEATING VALUE (as received)  >  '
      READ*,HHVR
      PRINT 10
      PRINT 100,'SUPPLY ASH CONTENT OF dRDF (as received)  >  '
      READ*,ASHR
      PRINT 10
      PRINT 100,'SUPPLY COST OF dRDF ($/ton)  >  '
      READ*,PRICER
      PRINT 10
      PRINT 100,'SUPPLY dRDF DENSITY (as received)  >  '
      READ*,DR
      PRINT 10
      PRINT 100,'SUPPLY COAL DENSITY (lb/ft3)  >  '
      READ*,DC
      PRINT 10
      IF (INDEX.EQ.1) THEN
         PRINT 100,'SUPPLY CONSTANTS (A,B,& C) FOR THE RIGHT
    : EFFICIENCY POLYNOMIAL AND MIXED FUEL  >  '
      READ*,A,B,C
         PRINT 10
      ELSE
         PRINT 100,'SUPPLY BOILER EFFICIENCY FOR MIXED FUEL  >  '
         READ*,EFFM
         PRINT 10
         AQT=SQT/(12*EFFM)
      ENDIF
      PRINT*,'ELECTRICAL KW INCREASE FOR ESP = AMOUNT'
      PRINT 10
      PRINT 100,'SUPPLY INCREASE IN ESP KW USE >'
      PRINT 10
      READ*,AMOUNT
      AMOUNT=AMOUNT*8760
      PRINT 100,'COST OF ELECTRICAL ENERGY ($/KWHR) >'
      READ*,CELEC
      SAV(3)=-AMOUNT*CELEC
      DSAV(3)=SAV(3)*UPWSE
2000  IF (INDEX.EQ.1) THEN
         SQT=0.0
         DO I=1, 12
```

```
            IF (JINDEX.EQ.1) THEN
               EFFM=A+B*MS(I)+C*(MS(I)**2)
            ELSE
               EFFM=A+B*QS(I)+C*(QS(I)**2)
            ENDIF
            QT(I)=QS(I)/EFFM
            SQT=SQT+QT(I)
         ENDDO
         AQT=SQT/12.
      ENDIF
      RMM=(VC*DC)+(VR*DR)
      DM=RMM/(VM*1.0)
      RMFC=(VC*DC)/RMM
      RMFR=1-RMFC
      HHVM=(HHVC*RMFC)+(HHVR*RMFR)
      RHTFR=((RMFR*HHVR)/HHVM)*100.0
      PRDF=RMFR*100
      WTM=AQT/HHVM
      WTC=WTM*RMFC
      WTCY=WTC*8760/2000.0
      COSTC=(WTC*PRICEC*8760)/2000.0
      WTASHC=(WTC*ASHC)/100.0
      COSASHC=(2.5*WTASHC*8760)/2000.0
      WTR=WTM*RMFR
      WTRY=WTR*8760/2000
      COSTR=(WTR*PRICER*8760)/2000.0
      WTASHR=(WTR*ASHR)/100.0
      WINA=(WTASHC+WTASHR)-WTASHC1
      WINAY=WINA*8760/2000
      COSASHR=(2.5*WTASHR*8760)/2000.0
1000  SAV(1)=COSTC1-COSTC
      FTYPE='COAL'
      DSAV(1)=SAV(1)*UPWS
      SAV(2)=-COSTR
      FTYPE='dRDF'
      DSAV(2)=SAV(2)*UPWS
      DELASH=COSASHC1-(COSASHC+COSASHR)
      DASHC=DELASH*UPW
      PRINT 300,' DISCOUNTED EXTRA ASH COSTS FOR RDF VOLUME = $ ',
     :DASHC
      PRINT 20
      PRINT 300,'THE % OF dRDF IN FUEL MIXTURE (by weight) =',PRDF
      PRINT 20
      PRINT 300,'SAVINGS IN COAL COST = $',SAV(1)
      PRINT 20
      PRINT 300,'DISCOUNTED SAVINGS IN COAL COST = $',DSAV(1)
      PRINT 20
      PRINT 300,'SAVINGS IN dRDF COST = $',SAV(2)
      PRINT 20
      PRINT 300,'DISCOUNTED SAVINGS IN dRDF COST = $',DSAV(2)
      PRINT 20
      PRINT 300,'SAVINGS IN ASH REMOVAL COST = $',DELASH

      PRINT 20
      PRINT 300,'TONS/YEAR OF COAL USED DURING CO-FIRING=',WTCY
      PRINT 10
      PRINT 300,'TONS/YEAR OF RDF USED DURING CO_FIRING=',WTRY
      PRINT 10
      PRINT 300,'TONS/YEAR OF INCREASE IN ASH FLOW RATE=',WINAY
      PRINT 10
      PRINT 300,'SAVINGS IN ESP ELECTRICAL ENERGY = $ ',SAV(3)
      PRINT 10
      PRINT 300,'DISCOUNTED SAVINGS IN ESP ELECTRICAL ENERGY = $ ',
     :DSAV(3)
      PRINT 20
      TDSAV=0.0
```

```
      DO I=1,3
         TDSAV=TDSAV+DSAV(I)
      ENDDO
      PRINT*,'TOTAL ENERGY DISCOUNTED SAVINGS (+OR-) = $ ',TDSAV
      PRINT*,'DO YOU WANT TO RE-RUN FOR ANOTHER VOLUME RATIO ? '
25    PRINT 100,'(ty ''Y'' or ''N'')  > '
      READ '(A)',ANSWER
      PRINT 10
      IF (ANSWER.NE.'Y'.AND.ANSWER.NE.'y'.AND.ANSWER.NE.'N'.AND.
     :ANSWER.NE.'n')  GOTO 25
      IF (ANSWER.EQ.'Y'.OR.ANSWER.EQ.'y') THEN
         IRR=IRR+1
         GOTO 3000
      ENDIF


      PRINT*,'THE NUMBER OF NON-ENERGY ANNUAL RECURRING COSTS,
     : NESAV(I) INCLUDE:'
      PRINT*,'MAINTENANCE COSTS PER BOILER = NESAV(2) (-)'
      PRINT*,'OPERATIONS AND SUPERVISION = NESAV(3) (-)'
      PRINT*,'ALTERNATIVE FUEL SECURITY = NESAV(4) (+)'
      PRINT*,'WITH PROPER ALGEBRAIC SIGN'
      DO I=2,4
         PRINT 400,'NON-ENERGY ANNUAL COST SAVINGS IN ITEM ',I,'>'
         READ*,NESAV(I)
         DNESAV(I)=NESAV(I)*UPW
      ENDDO
      PRINT 300,'DISCOUNTED MAINTENANCE COST = $ ',DNESAV(2)
      PRINT 300,'DISCOUNTED OPERATIONS COST = $ ',DNESAV(3)
      PRINT 300,'DISCOUNTED FUEL SECURITY CREDIT = $ ',DNESAV(4)
      PRINT*,'THE NUMBER OF ONE TIME FUTURE COSTS=NRN'
      PRINT 10
      PRINT*,'THE YEAR OF EACH COST OCCURRENCE=IPNR'
      PRINT 10
      PRINT*,'THE AMOUNT OF EACH COST(+ OR -)= TEMP'
      PRINT 10
      PRINT 100,'SUPPLY THE NUMBER OF ONE TIME FUTURE COSTS > '
      READ*,NRN
      IF(NRN.EQ.0)GO TO 95
      PRINT 10
      TNRSAV=0.0
       TDNRSV=0.0
      DO I=1,NRN
         RNRSAV(I)=0.0
         DNRSAV(I)=0.0
         PRINT 400,'YEAR OF OCCURRENCE OF ITEM',I,' > '
         READ*,IPNR
         PRINT 10
         PRINT 400,' AMOUNT OF SAVINGS OR COST FOR ITEM',I,'>'
         READ*,TEMP
         PRINT 10
        SPW=1.0/((1.0+RINTR)**IPNR)
        DNRSAV(I)=TEMP*SPW
        TDNRSV=TDNRSV+DNRSAV(I)
        PRINT 401,'DISCOUNTED COSTS FOR ITEM',I,'=$',DNRSAV(I)
      ENDDO
95    CONTINUE
      PRINT 20
      PRINT 300,'TOTAL DISCOUNTED ONE TIME COSTS =$',TDNRSV
      PRINT 20
      PRINT 20
      END
*****************************************************************
$
```

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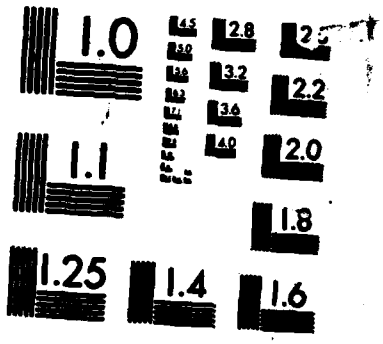

MICROCOPY RESOLUTION TEST CHART

APPENDIX G

```
$ RUN ECOAL
THE PROJECT LIFE? 10

THE DISCOUNT RATE(%)?7

 UPW* FACTOR FOR COAL ?11.2

 THE UPW* FACTOR FOR ELECTRICITY ? 8.5

 THE UPW DISCOUNT FACTOR ?7.02


DO YOU WANT TO USE EFFICIENCY POLYNOMIAL ?
(ty 'Y' or 'N')  >  N

SUPPLY COAL ONLY BOILER EFFICIENCY(DECIMAL).0.80

THE FORM OF DATA YOU WANT TO KEY-IN :

        1) STEAM LOAD (LBS/HR)

        2) HOT WATER HEAT LOAD (MMBTU/HR)

SUPPLY THE SERIAL NUMBER OF THE DESIRED METHOD  >2

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF JANUARY   >  65

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF FEBRUARY  >  60

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF MARCH     >  49

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF APRIL     >  34.4

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF MAY       >  34.4

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF JUNE      >  24

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF JULY      >  21

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF AUGUST    >  26
```

```
SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF SEPTEMBER >  26

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF OCTOBER   >  34

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF NOVEMBER  >  60

SUPPLY HEAT LOAD (MMBTU/HR) FOR MONTH OF DECEMBER  >  65

SUPPLY COAL HEATING VALUE  >  13490

SUPPLY ASH CONTENT(%) OF COAL  >  6.65

SUPPLY COST OF COAL ($/ton)  >  55

        THE COAL ONLY FIRING RATE, TONS/YR =        16870.089844
        THE COAL ONLY FUEL COSTS/YR = $       927855.000000
        THE COAL ONLY ASH FLOW RATE, TONS/YR =        1121.860840
        THE COAL ONLY ASH REMOVAL COSTS/YR = $        2804.652588
SUPPLY COAL TO dRDF VOLUME RATIO (ty 1:1 as 1,1)  >  1,1

SUPPLY dRDF HEATING VALUE (as received)  >  6375

SUPPLY ASH CONTENT OF dRDF (as received)  >  12.75

SUPPLY COST OF dRDF ($/ton)  >  34

SUPPLY dRDF DENSITY (as received)  >  30

SUPPLY COAL DENSITY (lb/ft3)  >  50

SUPPLY BOILER EFFICIENCY FOR MIXED FUEL  >  0.775

ELECTRICAL KW INCREASE FOR ESP = AMOUNT

SUPPLY INCREASE IN ESP KW USE >

15
COST OF ELECTRICAL ENERGY ($/KWHR) >0.039
         DISCOUNTED EXTRA ASH COSTS FOR RDF VOLUME = $      -14360.645508

        THE % OF dRDF IN FUEL MIXTURE (by weight) =        37.500000

        SAVINGS IN COAL COST = $     181650.625000
```

```
DISCOUNTED SAVINGS IN COAL COST = $    2034487.000000

SAVINGS IN dRDF COST = $    -276773.968750

DISCOUNTED SAVINGS IN dRDF COST = $   -3099868.500000

SAVINGS IN ASH REMOVAL COST = $      -2045.676025

TONS/YEAR OF COAL USED DURING CO-FIRING=      13567.352539

TONS/YEAR OF RDF USED DURING CO_FIRING=       8140.411621

TONS/YEAR OF INCREASE IN ASH FLOW RATE=        818.270447

SAVINGS IN ESP ELECTRICAL ENERGY = $       -5124.600098

DISCOUNTED SAVINGS IN ESP ELECTRICAL ENERGY = $      -43559.101563

TOTAL ENERGY DISCOUNTED SAVINGS (+OR-) = $   -1108941.
DO YOU WANT TO RE-RUN FOR ANOTHER VOLUME RATIO ?
(ty 'Y' or 'N')  > N

THE NUMBER OF NON-ENERGY ANNUAL RECURRING COSTS, NESAV(I) INCLUDE:
MAINTENANCE COSTS PER BOILER = NESAV(2) (-)
OPERATIONS AND SUPERVISION = NESAV(3) (-)
ALTERNATIVE FUEL SECURITY = NESAV(4) (+)
WITH PROPER ALGEBRAIC SIGN
NON-ENERGY ANNUAL COST SAVINGS IN ITEM  2>0
NON-ENERGY ANNUAL COST SAVINGS IN ITEM  3>0
NON-ENERGY ANNUAL COST SAVINGS IN ITEM  4>0
        DISCOUNTED MAINTENANCE COST = $          0.000000
        DISCOUNTED OPERATIONS COST = $          0.000000
        DISCOUNTED FUEL SECURITY CREDIT = $          0.000000
THE NUMBER OF ONE TIME FUTURE COSTS=NRN

THE YEAR OF EACH COST OCCURRENCE=IPNR

THE AMOUNT OF EACH COST(+ OR -)= TEMP

SUPPLY THE NUMBER OF ONE TIME FUTURE COSTS > 0

        TOTAL DISCOUNTED ONE TIME COSTS =$          0.000000
```

END
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DTIC