Processed Engineered Fuels Derived From Paper and Plastics -- Techno-Economic Factors and Regulatory Issues in a Competitive Market

Michael M. Fisher, Ph.D.
Director of Technology
American Plastics Council, Inc.
1801 K Street, NW, Suite 701-L
Washington, DC 20006

Oscar O. Ohlsson
1014 Thunderbird Lane
Naperville, IL 60563

Arun Singhania
Amoco Chemical Company
4500 McGinnis Ferry Road
Alpharetta, GA 30202

José Sosa, Ph.D.
FINA Oil and Chemical Company
Box 1200
Deer Park, TX 77536

INTRODUCTION

Plastics have gained a prominent position in modern society because their unique properties, cost-performance and versatility. They contribute to almost every aspect of modern life including transportation, recreation, medicine, packaging, appliances, furniture, textiles and building and construction. The diverse properties of plastics allow them to play a major role in providing solutions for technical progress as well as solutions for everyday life.

Plastics also make a significant contribution to effective resource management and conservation, reducing our use of natural resources and helping to minimize waste. By choosing plastics, manufacturers, designers, distributors and retailers in every sector have been able to respond to the challenge of preventing excess use of resources and, at the same time, bring increasingly sophisticated products to the market. Resource conservation seeks to maximize efficiency and minimize waste from a product's manufacture, use and disposal. It involves more than managing and minimizing waste, however; it also includes taking advantage of effective life-cycle resource management at local and global levels. There are many ways that plastics contribute to effective resource management. From manufacture to use, to recovery, to waste management, plastics help conserve resources. Not only are plastics energy efficient, but they often create less waste than other materials. They can be recovered, recycled and safely landfilled.

Plastics play an important role as a potential source of energy. Since they are manufactured from oil and natural gas, plastics can be viewed as "diverted" energy that is reclaimed in an energy recovery process. Recovering energy from post-consumer plastics is important for two reasons. First, plastics contain the highest energy value of any component of the municipal solid waste stream. Second, practical, technical and economic barriers limit the sensible reuse and recycling options of any material. By committing high-energy materials like plastics to land disposal, a significant energy resource is lost.

One objective of the American Plastics Council (APC) is to explore and extend the benefits of plastics that are not currently being realized and utilized. An important goal is to help ensure that all economic and environmentally responsible recovery options are available for plastics. By providing information about the environmental and economic impacts, positive and negative, of each municipal solid waste management and resource recovery option, we can make more informed decisions and achieve the goal of effective resource conservation.

This paper reviews the energy recovery option for post-use plastics. It discusses plastics' role in modern waste-to-energy (WTE) systems and then reviews some recent work exploring the use of plastics as alternative fuels. The emphasis is on solid fuels, often referred to as process engineered fuel or PEF. The liquefaction and gasification of plastics offers additional opportunities for resource recovery, but this subject is only briefly discussed in this paper.

OVERVIEW

Figure 1 summarizes three basic options for the recovery of energy from post-use plastics. They are municipal solid waste combustion or waste-to-energy; process engineered fuel (PEF) derived from plastics or combinations of plastics and paper; and liquid or gaseous fuels derived from the liquefaction or gasification of post-use plastics. The end product from all three processes is useful energy. The first option can be categorized as commercial and mature, the second as commercial and embryonic, especially with regard to the use of plastics; and the third as developmental. On the basis of these three options and the expanding need for energy worldwide, energy recovery from post-use plastics is expected to grow as a significant component of integrated resource management.

WASTE-TO-ENERGY (MUNICIPAL WASTE COMBUSTION)

According to the most recent U.S. EPA report on municipal solid waste titled *Characterization of Municipal Solid Waste in The United States: 1995 Update,* [1] plastics make up 9.5 percent by weight (19.8 million tons) of municipal solid waste. On this basis, plastics contribute almost 30% to the fuel value of MSW. In combination with the non-recycled paper content of MSW, the combined contribution is more than 50% of the fuel value (Figure 2).

The same EPA study found that in the United States, 20% of MSW, after recycling and composting, is combusted--essentially all with energy recovery. The 20% figure is not often cited. The more common convention in the United States is to report the percentage for a given disposal or recovery technology applied to the total of all MSW generated. On this basis, the percent of MSW combusted is about 15.5% according to both EPA and Integrated Waste Services Association (IWSA) data.[2] It is often unclear on which basis European and Japanese data are being presented. Nevertheless, many countries such as Denmark, Switzerland, and Japan, and some regions of the United States, presently recover the energy from over 50% of generated MSW. Table 1 summarizes information from the Integrated Waste Services Association (Washington, DC) on municipal waste combustion, which confirms that more than 97% of MSW combustion in the United States involves energy recovery.

A recent modeling study suggests that there is significant potential for further growth of the waste-to-energy industry in metropolitan areas across the United States under the assumption that the minimum viable resource recovery plant throughput is 400 tons per day of MSW. [3] This was essentially a hypothetical landfill diversion study. The study indicated that up to 76% of the U.S. population could effectively be served by modern mass burn technology compared to about 16% today. With 76% of the population served, approximately 58% of generated MSW would be managed in waste-to-energy facilities. In practice, of course, marketplace economics are often the controlling factor as to which waste management option is used.

The same study examined certain economic assumptions which could impact the viability of WTE in the future. Figure 3 shows a theoretical relationship between the calculated tipping fee which would need to be charged by a newly constructed WTE plant to break-even as a function of electricity sales price (effectively revenue). For comparison, Figure 3 also shows the range of average regional landfill tipping fees across the U.S. According to the assumptions of this model, relatively high electricity sales revenues are needed for WTE costs to be competitive with average landfill tipping fees. It is important to note, however, that this model is for new plants and assumes that all of the ash would be landfilled as an expense, rather than beneficially used.

As noted above, plastics provide an important fuel source for the waste-to-energy process. Indeed, in the U.S. today, roughly one out of every five pounds of post-use plastics are used for energy recovery in modern waste-to-energy plants. A recent study in Würzburg, Germany involving a mass burn municipal waste combustor equipped with baghouse and carbon injection demonstrated that mixed plastics in the MSW stream improve burn-out of gases and solid residue without adversely affecting ash or emissions. [4] As plastic loadings were increased during the tests, CO and SO_2 emissions were reduced. In addition, higher polymer content, including specific addition of polyvinyl chloride, did not result in an increase in dioxins and furans. This finding supports the general conclusion of a recent ASME study that dioxin emissions from modern waste-to-energy plants do not correlate statistically with the quantity of chlorine in the feed. [5] In fact, both the findings of the Würzburg study and the International Ash Working Group Report [6] indicate that modern waste-to-energy plants are a net destroyer of dioxins.

Today, waste-to-energy technology is playing an important role in utilizing the energy content of plastics and other polymeric materials, and there are additional opportunities for the future. Recently, APC completed a study to assess the energy recovery option for automotive shredder residue, the byproduct of the automobile shredding operation. [7] The energy content of ASR ranges from about 4000 to 11,000 Btu/lb depending on the degree of processing. The study looked at mass burn technology, RDF, industrial boilers, cement kilns, and emerging gasification technologies, and concluded that co-firing ASR with MSW in a modern mass burn waste-to-energy plant offered the most practical means to capture the inherent energy of this material.

PROCESS ENGINEERED FUEL

Basic Definition

Process engineered fuel (PEF) can be defined as a processed solid fuel, made from segregated plastic and paper, derived from industrial, commercial, and residential sources, for use by utilities and industry.[8] The term paper is used broadly to refer to a wide variety of non-recyclable paper, boxboard, corrugated, and other cellulosic-based feedstocks. Plastic feedstocks can be in rigid, foam, or film form. Figure 4 shows the sourcing options, fuel processing step, and markets for PEF. PEF can be produced and marketed in both densified and fluff forms.

The term Process Engineered Fuel has not yet gained wide acceptance in Europe. The terms Packaging Derived Fuel (PDF) and Plastics Packaging Derived Fuel (PPDF) have been proposed[9] but not broadly accepted. "Alternative fuel" is considered an appropriate generic term. In practice, PEF feedstocks often go beyond packaging-derived materials. When derived from post-use materials or from industrial, agricultural, or forest based products, or related industrial process streams, e.g., certain biofuels, these fuels all fall under the broad category of renewable fuels. The production and use of PEF is often referred to as fuel recovery rather than energy recovery.

Process engineered fuel should not be confused with Refuse Derived Fuel (RDF). A recent paper proposed a classification system to differentiate PEF, RDF, and MSW based on certain fuel properties.[10] A basic distinction can be made on the basis of higher heating value with a lower limit of 6500 Btu/lb suggested for PEF (Table 2). This comparison is useful, but the definition of PEF provided above suggests that only in certain cases would PEF feedstocks be related to MSW or RDF. PEF should be viewed as a manufactured fuel not a waste. Definitions and terminology related to PEF are further discussed in the section on Regulatory Issues.

Production of PEF

Very little has been published concerning the manufacture of process engineered fuels. Beyond a few captive operations within the paper and forest products industry, there are probably fewer than twenty commercial PEF producers manufacturing a true PEF product operating in the U.S. today. World-wide, the total production of PEF is believed to be less than 2 million tons. APC believes that advances in technology could expand the use of PEF significantly.

The production of PEF requires specialized equipment and reliable quality control procedures. A representative PEF plant might include the following processing steps:

Specified Feedstock Acquisition→Feedstock QC→First Stage Size Reduction→
Separation/Blending→Second Stage Size Reduction→Separation/Blending→
Densification (optional)→Product QC

Densified forms of PEF are produced by either a cubing or a pelletizing operation using size reduced feedstocks. Moisture content is an important variable. Table 3 compares representative properties of pellets, cubes, and non-densified PEF. The authors believe that proper size reduction is one of the most critical factors when incorporating higher loadings of plastics. Much more work needs to be done to optimize fuel pellets and cubes containing high levels, i.e., greater than 10% by volume of plastics. Heated dies are being explored to facilitate the incorporation of higher loadings of plastics while maintaining good structural integrity of the densified fuel and associated handling properties.

PEF Economics

The overall economics of PEF are highly case-specific and very dependent of feedstock acquisition costs, disposal avoidance costs, and markets. Reference 10 provides a good introduction to PEF economics. An often overlooked factor is the ability of PEF to compete with other alternative fuels, not just coal, on a dollars per million Btu delivered basis. All other things being equal, PEF becomes more competitive as its Btu value increases, i.e., plastics content, increases. For a densified PEF of 7500 Btu per pound, a value of approximately $0.80 per million Btu is representative. At this price, PEF can be competitive with many other alternative fuels including agricultural waste and hog fuel. Any complete financial study must also include the cost to retrofit an industrial or utility boiler to handle PEF in either densified or non-densified form.

One PEF scenario that has been studied at some length is the addition of a PEF production capability to a mixed waste processing facility. [11] A key variable is avoided disposal cost. Capital costs start at about 0.75 million dollars to add densified PEF production capacity to typical mixed waste processing facilities depending on the amount of infrastructure already available such as a building to house the system and the throughput of the facility. Figure 5 shows the relationship between net PEF revenues (fob PEF market) and net savings to the mixed waste processing facility for recovering targeted materials as PEF as compared to landfill disposing of the same materials. The analysis shows that the production of PEF can be cost-effective in some regions of the U.S. In the final analysis, the PEF industry will need to grow and broaden its base of operation before real world economics can be identified and reliably analyzed.

Characterization of PEF

Beginning in late 1995, APC began to characterize samples of commercial and developmental PEFs and to compare their fuel properties with fossil fuels and other alternative fuels. The database presently consists of seventeen samples and continues to grow. Residential, commercial, and industrial feedstocks are included among the samples tested. Representative higher heating value (HHV), chlorine, nitrogen, and sulfur data for a number of samples in the database are shown in Figures 6-9. HHVs ranged from about 5000 Btu/lb to over 15000 Btu/lb. In general, most of the samples easily meet the criteria for PEF presented in Table 2. Sulfur content was consistently low, and over 90 percent of the samples had a chlorine content below 0.5%. The complete database includes ultimate, proximate, ash fusion temperature, ash mineral content, trace metals (17) and TCLP analyses. A detailed report on these findings is being prepared.

PEF Test Burns

Published information on the performance of PEF in industrial and utility boilers is limited. Test burns of densified PEF co-fired with coal in a spreader stoker traveling grate system at Argonne National Laboratories has been reported by Ohlsson. [12] Blends of densified PEF with coal up to 50 percent based on Btu content were investigated. In these experiments the PEF was sourced from a residential and commercial mixed waste processing facility and involved special processing including the addition of lime as a binding agent. The PEF averaged about 7500 Btu/lb. The results showed a reduction in flue gas SO_2, NO_x and CO_2 when PEF was substituted for high sulfur coal. The same paper reported favorable results co-firing a similar paper derived fuel with coal at the Otter Tail pulverized coal boiler. However, the Btu value of the fuel used at Otter Tail was reported to be only 6400 Btu per pound and therefore does not meet the definition for PEF used in this paper. PEF and RDF did not negatively affect ash quality in any of these tests.

Recently, Doraiswamy, et al., [13] reported results from the co-firing of a secondary fiber/plastics recycled paper mill reject stream with coal. This process stream had a heating value above 10,000 Btu/lb and on this basis would be considered PEF. The reject stream contained about 40% plastic on a dry basis. The tests showed no adverse affects on emissions or ash quality co-firing 10% rejects with coal. Economics looked favorable and the co-firing of this type of PEF at other mills and industrial sites can be expected to grow.

Except for some recent Finnish studies reported by Martin Frankenhaeuser, [14] very little has been published on the co-firing of process engineered fuels in fluidized bed systems. Last year, a two day trial burn of densified PEF derived from commercial paper and plastic feedstocks was completed using the fluidized bed boiler at the Idaho National Engineering Laboratory. The boiler has a maximum rated capacity of 67,500 lb steam/hr.

Fuel characterization data for the coal and PEF is shown in Table 4. This was a true PEF with a HHV of 7,449 Btu/lb. The test program measured emissions of trace metals, particulate matter, hydrochloric acid (HCl) and gaseous species (for NO_x, SO_2, $C0_2$, O_2) while firing three different PEF pellet to coal rations (10%:90%, 20%:80%, 25%:75%) in the boiler. Baseline emissions of the species listed above were also measured while firing only coal in the boiler. The coal was relatively low in sulfur (0.37%) and had a higher heating value of 12,600 Btu/lb. Boiler performance was uncompromised at all pellet feed ratios and emissions profiles held essentially constant even at the highest PEF to coal ratio. Preliminary emissions data for $C0_2$, NO_x, and SO_2 are shown in Table 5. A complete report of this test burn will be available later this summer. The role of PEF containing sufficient quantities of plastics and the effect of such plastics in achieving HHVs in excess of 10,000 Btu/lb needs to be more thoroughly documented.

In the Fall of 1995, APC completed a bibliography of published information on refuse derived fuels and process engineered fuels including test-burn reports.[15] The bibliography is available from APC in hard copy and disk format.

Regulatory Issues

Regulatory Issues were prominent on the agenda during the recent Pellet Fuel Conference held in Washington, DC.[16] Regulations, laws, and policies can act as drivers or barriers to the use of PEF as a supplemental fuel. Regulatory issues affecting the use of PEF are briefly discussed below and fall into four categories.

- Definitions and terminology
- Fuel standards and quality assurance
- Air emissions standards
- Ash management

PEF Definitions and Terminology. The concept of PEF is relatively new, so federal and state regulations generally do not contain a definition for PEF. Regulators may be inclined to interchangeably use the terms "PEF" and "RDF", but the general consensus of the industry is that PEF is higher quality and more homogeneous fuel than RDF, as noted earlier. In order to minimize barriers to the growth of PEF use, it is important that PEF be considered a resource by regulators rather than a waste, in order to avoid the generally more stringent regulations associated with waste management as compared to resource management. Earlier, this issue also had to be addressed by the traditional recycling industry in order for it to grow to its current level.

PEF can also be considered an indigenous and renewable fuel because it is generally composed of post-use paper and plastics. Clearly defining PEF as a renewable fuel would further the industry by allowing PEF to qualify for incentives or mandates established to encourage the use of renewable fuels in the United States, as well as further its perception as a valuable energy resource. This issue is developing as an important consideration during the electricity deregulation discussions underway at both the state and federal levels.

Some states offer recycling (or waste diversion) credit for materials that are diverted from disposal through PEF systems, thus acknowledging their role in resource conservation. For example, Florida and Maine provide recycling credit to local governments for combustion of PEF in existing boilers. It is interesting to note that recycling credit in Florida cannot be obtained for combustion of the same materials in traditional WTE facilities.

PEF Standards and Quality Assurance. Also because the concept of PEF is still relatively new in the United States, standards and quality assurance measures for PEF have not yet been developed, although some efforts to start this process are underway. An effort to develop similar standards is currently active in Europe for recovered fuel. Ideally, the development of such specifications in the United States would potentially:

- Minimize the stringency of regulations imposed on PEF production and use (such as reducing expensive air emissions and ash testing requirements often imposed by regulators on boiler operators wanting to co-fire alternative fuels with other conventional fuels) or possibly exempt PEF from some regulations;
- Simplify permitting procedures and requirements associated with the production and use of PEF and make them comparable to those for conventional fuels; and
- Facilitate the perception and definition of PEF as a resource and renewable fuel.

The development of standards and quality assurance for PEF must address both producer and user responsibilities and specific sampling and testing protocols. A classification system based on key properties is a possibility.

Air Standards. Under the Clean Air Act, up to 30 percent by weight of MSW can be co-combusted with other fuels without triggering municipal waste combustor (MWC) regulations. It is probable that PEF, with one or more source separated types of post-consumer materials such as paper, would fall under the 30 percent restriction. However, PEF made from industrial scrap that has not been commingled with MSW may not fall under the same percentage restriction. At the state level, additional restrictions are sometimes placed on the amount of PEF that can be co-fired before triggering MWC regulations. For example, Washington state has a limit on the use of PEF that supersedes and is more stringent than the 30 percent exemption in the Clean Air Act.

Regulations that govern WTE facilities, or MWC regulations, are generally more stringent for certain pollutants (such as organics and trace metals) than regulations for boilers fired with conventional fuels. Therefore, it is possible that co-firing PEF in existing boilers will be less stringently regulated than combusting MSW in WTE facilities. However, regulatory consequences could result from co-firing PEF depending on the emissions consequences. Testing will most likely be required to determine the impact of co-firing PEF on emissions unless strict PEF standards and quality assurance measures are developed.

Co-firing of PEF with conventional fuels, particularly coal, can have positive affects on air emissions. Most notably, co-firing of PEF with coal offers a potentially more cost-effective means to achieve compliance with the federal Acid Rain Program of the 1990 Clean Air Act Amendments than through installation of scrubbers or other capital-intensive alternative compliance strategies.

Anticipated regulatory changes could affect the way and the amount of PEF used by industrial combustion facilities. It is anticipated that relevant definitions and regulations will be thoroughly revisited as part of the Industrial Combustor Coordinated Rulemaking Process underway at the U.S. Environmental Protection Agency. The uncertainty regarding environmental regulation of PEF use can be a barrier to the development of the PEF industry. Some state-level restrictions on the amount that can be co-fired before triggering MWC regulation can also be barriers, as well as costs for ongoing required testing can be prohibitive to the use of PEF. However, potential positive effects on air emissions are helping to drive the industry.

Ash Management. The regulation of ash resulting from the co-firing of PEF with conventional fuels is not clear. Currently, ash from combustion of coal is treated as a "Bevill waste" and need not be tested for hazardous characteristics. Bevill waste can be fired with up to 50 percent of other types of fuels and not be subject to Subtitle C regulation. However, the Clean Air Act exemption of 30 percent does not clearly exempt the resulting ash from MWC ash regulations which includes testing requirements for hazardous characteristics. Also, it is not clear if ash from boilers co-firing PEF from residential sources is exempt from Subtitle D regulations and there is no clear guidance on the federal level regarding how ash from a facility co-firing PEF derived from industrial feedstocks should be regulated. Federal legislation or regulatory clarification of these issues could improve the use of PEF.

States generally have the primary responsibility for regulating the management of ash from facilities co-firing PEF although general guidance is typically provided from the federal government such as that discussed above. Typically states require ash from facilities co-firing MSW with any type of conventional fuels in amounts greater than 30 percent of the total fuel to be regulated the same as ash from MWC's. Ash from co-firing PEF derived from industrial feedstocks with coal at levels greater than 50 percent must generally be tested for hazardous characteristics. Regulations for management of ash from co-firing wood waste with PEF derived from industrial sources at any percentage must be completely determined at the state level since no specific federal regulations address this issue.

In general, competition in the fuel and energy industries is increasing as a result of in place and planned deregulation of the electric utility industry. Increased competition is resulting in a reassessment of alternative fuels. PEF, on the basis of overall environmental performance and economics, has the potential to be the alternative fuel of choice in many situations.

REFERENCES

1. *Characterization of Municipal Solid Waste in the United States: 1995 Update*, EPA530-R-96-001, March 1996.

2. *The 1996 IWSA Municipal Waste Combustion Directory of the United States Facilities*, Integrated Waste Services Association, Washington, DC, 1996.

3. *PEF Economic/Business Viability Analyses Report*, R.W. Beck & Associates, (APC report) January 1997.

4. F. Mark, *Energy Recovery Through Co-Combustion of Mixed Plastics Waste and Municipal Solid Waste*, APME Technical Paper, Brussels, June 1994.

5. *The Relationship Between Chlorine in Waste Streams and Dioxin Emissions from Waste Combustor Stacks*, ASME Research Report, CRTD-Vol. 36, 1995.

6. *An International Perspective on Characterisation and Management of Residues from Municipal Solid Waste Incineration--Summary Report*, The International Ash Working Group, July 1995.

7. *Energy Recovery from Automotive Shredder Residue--Summary Report,* Roy F. Weston, Inc., May 1995.

8. G. Sutherland and L. Tomczyk, *Pellet Fuels*, Proceedings of The International Conference on Solid Waste Management, Thermal Treatment & Waste-to-Energy Technology, Air & Waste Management Association, Washington, DC, 1995, pp 135-146.

9. *A Fuel for the Future: Energy from Plastics Waste*, Association of Plastics Manufacturing in Europe, Brussels, Belgium.

10. L. Tomczyk, *Engineered Fuel: Renewable Fuel of the Future?* Solid Waste Technologies, January/February: 25 (1977).

11. *Processed Engineered Fuel Economic Case Study,* R. W. Beck & Associates, (APC report) June 1996.

12. O. Ohlsson, *Development and Evaluation of Lime Enhanced Refuse-Derived Fuel (RDF) Pellets,* Proceedings of The International Conference on Solid Waste Management, Thermal Treatment & Waste-to-Energy Technology, Air & Waste Management Association, Washington, DC, 1995, pp 124-134.

13. J. Doraiswamy, N. Sell, J. Norman, G. Massey, K. Nelson, and M. Doshi, Use of Secondary-Fiber Rejects as Fuel for a Coal-Fired Stoker Boiler, TAPPI Journal, 79(3), 199 (1996).

14. M. Frankenhaeuser, H. Manninen, I. Kojo, J. Ruuskanen, T. Vartiainen, R. Vesterinen, and J. Virkki, *Organic Emissions from Co-Combustion of Mixed Plastics with Coal in a Bubbling Fluidized Bed Boiler*, Chemosphere, Vol. 27, Nos. 1-3, pp 309-316, (1993).

15. *Annotated Bibliography of Refuse Derived Fuel (RDF) References and Densified Refuse Derived Fuel (dRDF) Pellet Test Firings,* Argonne National Laboratory, November 1995.

16. *Proceedings, Pellet Fuels Conference, November 16-17, 1995*, Washington, DC.

Table 1. Municipal Waste Combustion Industry Profile (1995)

	Number	Annual Operating Capacity (MM tons)
Mass Burn Facilities	70	22.6
RDF Combustion Facilities	23	7.9
Modular Facilities	21	0.8
Incinerators (without energy recovery)	21	0.9
States with Facilities	34	
Communities Served	1688	
Population Served (million)	41.2	
Total Capacity		32.2
Percentage of MSW Processed	15.4	

Source: Adapted from The 1996 IWSA Municipal Waste Combustion Directory

Table 2. Comparative Properties of Characteristics of PEF, RDF, and MSW

			Dry Basis		
Type of Fuel	**Moisture (% by wt)**	**HHV (Btu/lb)**	**Ash Content (% by wt)**	**Sulfur Content (% by wt)**	**Chlorine Content (% by wt)**
MSW, unprocessed	15-50	4,500-5,500	18-30	0.10-0.50	0.10-1.00
RDF	3-35	5,500-6,500	8-25	0.10-0.50	0.10-1.00
PEF	3-20	6,500-16,000	2-15	0.02-0.20	0.03-0.50
Bituminous Coal	2-20	11,000-14,500	3-16	0.50-4.7	0.01-0.90

Table 3. Comparison of Pelletizing and Cubing Technologies

Criteria	**Pellets**	**Cubes**	**Non-densified**
Size Reduction Required	1/4” to 3/4” max size	3/4” to 3-1/2 (1-1/2” nominal)	1/4” - 2”
Final Bulk Density	35-45 lbs/cu ft	20-33 lbs/cu ft	2-12 lbs/cu ft
Final Product Diameter	1/4” to 3/4”	1” to 1-1/4”	N/A
Cooling Required After Densification	Yes	No	N/A
Throughput	2-4 tons per hour	6-8 tons per hour	> 5 tons per hour

Table 4. Fuel Characterization - INEL Test Burn

Fuel Type	C (%)	H (%)	O (%)	N (%)	S (%)	HHV (Btu/lb)
Coal	73.33	4.78	10.75	1.20	0.37	12,582
PEF	43.31	5.74	35.40	0.32	0.18	7,449

Table 5. INEL emissions data.

Coal/PEF Ratio	100%/0%	90%/10%	80%/20%	75%/25%
CO_2, %	9.58	9.60	9.57	9.00
NO_x, ppm @ 7% O_2	239	210	197	212
SO_2, ppm @ 7% O_2	29	34	43	45

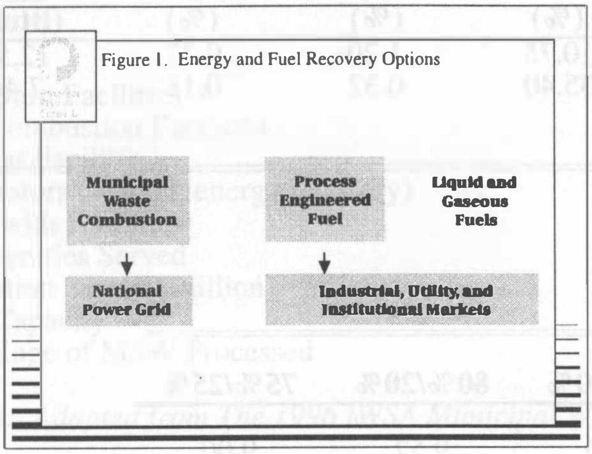
Figure 1. Energy and Fuel Recovery Options

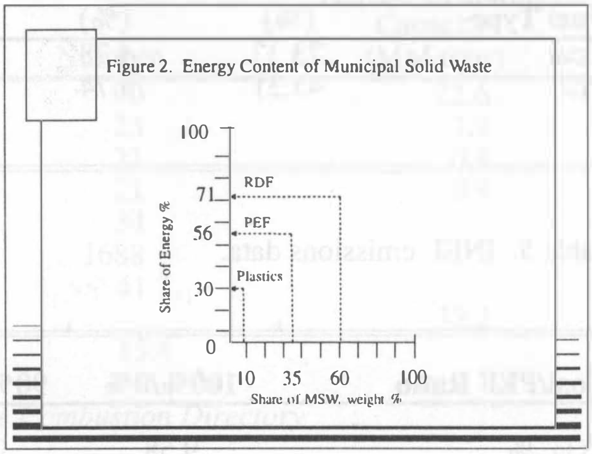
Figure 2. Energy Content of Municipal Solid Waste

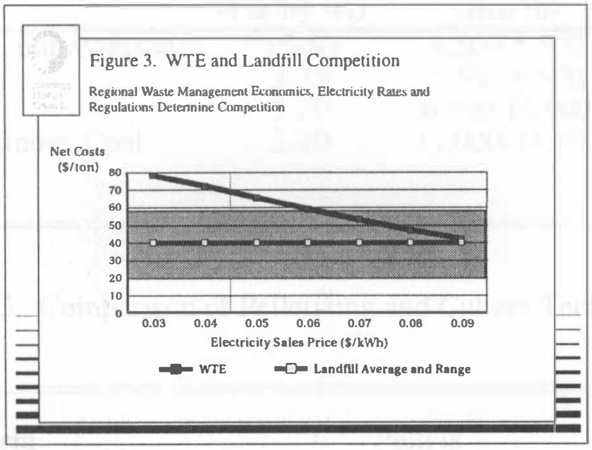
Figure 3. WTE and Landfill Competition

Regional Waste Management Economics, Electricity Rates and Regulations Determine Competition

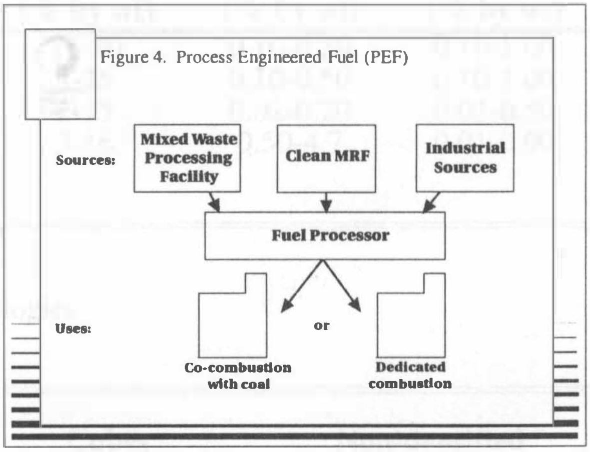
Figure 4. Process Engineered Fuel (PEF)

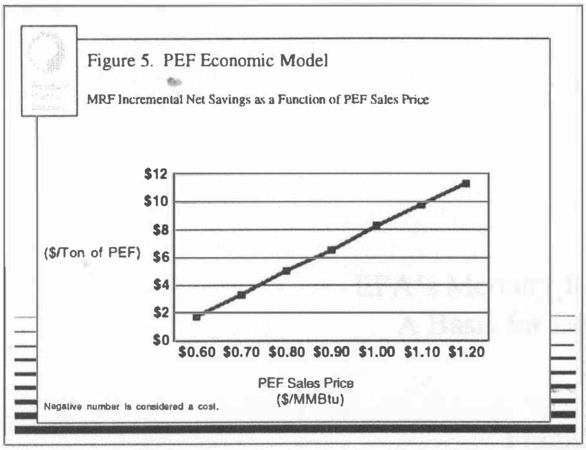

Figure 5. PEF Economic Model

MRF Incremental Net Savings as a Function of PEF Sales Price

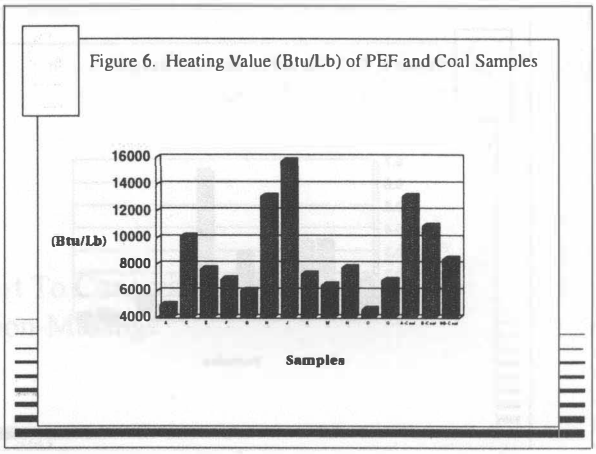

Figure 6. Heating Value (Btu/Lb) of PEF and Coal Samples

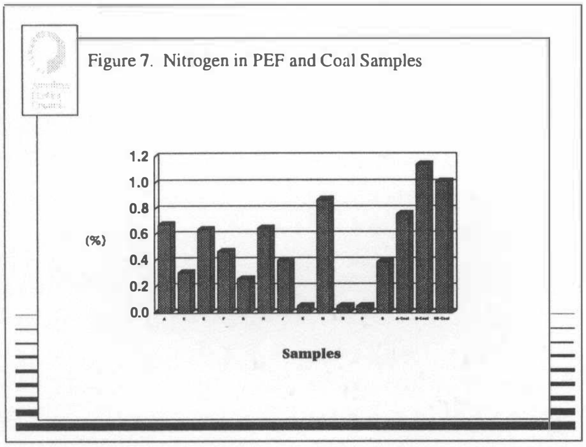

Figure 7. Nitrogen in PEF and Coal Samples

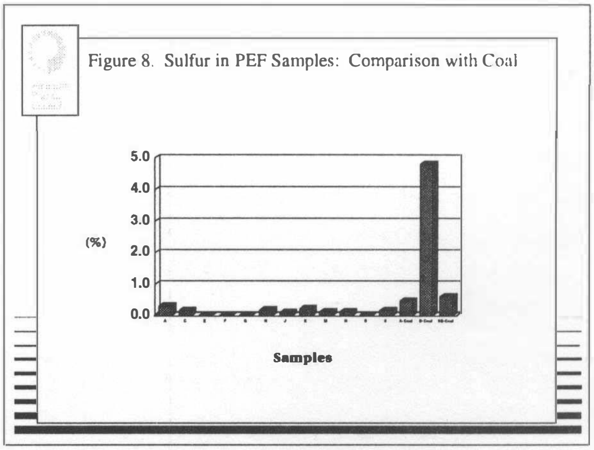

Figure 8. Sulfur in PEF Samples: Comparison with Coal

Figure 9. Chlorine in PEF and Coal Samples