ENERGY RECOVERY FROM SOLID WASTE:

LOOKING THROUGH A DARK FURNACE SLOWLY*

by

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Introduction

An allegory:

Washington: The Energy Recovery and Dispersal Agency today announced the discovery of vast new reserves of fuel. This one source is equivalent to about 2 percent of the nation's requirements, a significantly large amount for a single find. Also, unlike other fuels (except possibly from the breeder reactor), the new one is self-perpetuating. It is derived from the waste and discards of society.

ERDA's companion government group, the Environmental Proportionment Administration, cautioned the new energy source may be dangerous to the environment. A spokesman said emissions from the combustion contained unknown compounds which are likely to be dirty and toxic. Besides, the fuel contains bacteria which are known to reproduce. In reply, ERDA countered that many components of the new fuel were chemically less complex than the carcinogens and mutagens which can be derived from petroleum sources and that the ash from the new fuel was less radioactive than ash from coal. The two agencies agreed that a new research program was needed to investigate the origins and chemical reactions of waste. Each pointed out that such programs fell into their recent charge from Congress.

On hearing the announcement, five congressional committees claimed the new fuel discovery fell within the province of their committee. One Senator, who did not wish to be identified, said, "I have long been conducting wastefuel investigations." Informed sources said that prompt Congressional action can be expected.

At the same time, a spokesman for the National Legion of Cities claimed that mineral and fuel rights belonged to the cities, that federal aid was necessary to protect and develop these rights, and cities would not permit idle speculators to clean up.

*"For now we see through a glass, darkly, but then face to face; now I know in part; but then shall I know..." (Corinthians, 1:13.)

"No profiteering at the expense of our waste-generating taxpayers," said the spokesman. "We want to work with the private sector to the maximum extent possible and be assured of no risks."

ERDA and EPA are formulating new studies and expect 150 million tons of the new fuel to be ready for exploitation within "two or three decades." Asked if this is realistic, a Washington expert displayed cautious optimism, saying, "This is a lot of garbage."

I hope the allegory, with its silly exaggerations, illustrates in part why the furnace is dark and energy recovery from wastes proceeds slowly.

The supply of energy world-wide is finite, at least in the absence of economical fusion. It is likely that many small and even diverse sources of fuel will be used to supply our aggregate needs. Waste has been, and will continue to be a source of fuel. Yet, at the present rate of implementation of energy recovery projects, it was predicted that just the amount of solid waste generated in the urban areas today would not all be processed for resource recovery until after 1992 (1).

Implementation of new energy projects is retarded by confusion, complexity and uncertainty; whereas much may originate from non-technical or institutional sources, some originates from scientists and engineers. Two examples will illustrate this and, hopefully, stimulate new research. The examples are not in the allegory but are the confusion, complexity and uncertainty of trying to define the efficiency and cost of resource recovery systems, two essential factors in choosing--or not--energy recovery from wastes.

Efficiency

Efficiency is a term too loosely applied to resource recovery systems even though unambiguously defined by the laws of thermodynamics. For example, Table 1 lists values of the "efficiency" of various resource recovery systems given by two authors (2,3)--who agree in only some cases. Also, some seven different values of "efficiency," with seven different names, were identified in the literature for one system (4).

In an attempt to overcome the ambiguities and be thermodynamically rigorous, a method of computing the efficiency of open, non-cyclic steady-state systems, where the product is not work, was proposed by Bailie and Doner (4). The method sums the enthalpy of all streams flowing across the system boundaries into the system, less the enthalpies of all streams flowing out, less the energy flows which are not associated with mass. As in any thermodynamic computation, the standard state of reactants and products and system boundaries must be defined.

The method of Bailie and Doner must be used with caution to define the final product. The efficiency of producing what? For example, processes being compared may use solid waste directly to produce power or may convert the waste to some other fuel by mechanical, chemical or biological means and the new fuel used to produce power. Such processes are not directly comparable; conversion will itself use energy.

A mass of fuel M of enthalpy ΔH may be upgraded to a new fuel of mass M' and enthalpy $\Delta H'$. By upgrade is meant $\Delta H < \Delta H'$ and the law of conservation of mass-energy dictates $M\ \Delta H > M'\ \Delta H'$. Because of the inequality, one definition of the conversion equivalence of a new fuel was given as $M'\ \Delta H'$ (5) and the conversion efficiency to produce the new fuel might be $M'\ \Delta H'/M\ \Delta H$.

More rigorously, the method of Bailie and Doner (4) was used to attempt the computation of the conversion efficiency of three resource recovery processes (6). The results are listed in Table 2 along with the final product of the conversion. Two of the three values listed do not agree with the "efficiencies" listed in Table 1. The values in Table 2 are presented with the caveat that the computations are based on generalized--not detailed--designs and little information about actual mass and energy balances.

The conversion efficiency does not necessarily relate to the final product of resource recovery. Solid waste--whether or not converted to new solid, liquid or gaseous form--may be used as a supplement to or substitute for fossil fuel. In a given application, the new form of fuel may deliver the same, more or less net energy per unit input than the fuel it is replacing. Thus, the substitution equivalence was defined as the amount of fuel in the new form that must be used to replace the conventional fuel in a specific application (5). It is the substitution equivalence, or what is herein termed the substitution efficiency, that should be the basis for choice of energy recovery systems.

Two recent analyses of energy recovery systems in effect computed the conversion efficiency (and one the substitution efficiency) without using the terms. Lewis (7), from consideration of the mass and heat balances of four systems, computed the ratio of mass of waste per mass of steam. This ratio may be used to compute the conversion efficiency of waste to steam as:

$$\text{CONVERSION EFFICIENCY} = 1 \Big/ \frac{\text{mass of waste}}{\text{mass of steam}} \times \frac{\text{enthalpy of waste}}{\text{enthalpy of steam}}$$

The enthalpy of the waste was, as used by Lewis, a heat of combustion of 11.0 MJ/kg (4750 Btu/lb). In all of his systems but one, the enthalpy of the steam was 2.8 MJ/kg (1200 Btu/lb), the value used to compute the results shown in Table 3.

Hecklinger (8) tabulated the energy requirements for processing, generating steam and converting this steam to electricity for six types of resource recovery systems. The need for external fuel (not in all cases) and the temperature and pressure of the steam from the different processes (hence differences in efficiency of electricity production) were taken into account. These data were used to compute the conversion efficiency of converting raw waste to solid (RDF), liquid or gaseous fuel and the conversion efficiency when these fuels are used to generate steam. The results for five of the systems are listed in Table 4, along with the computed substitution efficiency for the systems to produce electricity.

The computations based on Lewis (7) and on Hecklinger (8) may not be directly comparable and certainly do not agree, emphasizing the point of Table 1. The data of Hecklinger illustrate the differences in conversion and substitution efficiencies and that relative rankings of systems can change, depending on which efficiency term is used.

The issue of process efficiency is complex, remains confused, and municipal managers, or their consultants who have to choose an energy recovery system, remain uncertain.

<u>The Cost of Resource Recovery</u>

The cost of an energy recovery system may be represented somewhat unconventionally as the sum of three categories of cost:

- design and construction
- reliability
- uncertainty

The first category is straightforward. Reliability confuses issues of: Does the process work as represented? Will it operate day to day? Should equipment be redundant and is redundancy equivalent to reliability?

Sometimes municipal planners have sought recovery plants which will operate with the reliability needed for disposal. The public health responsibility and the inability of energy recovery plants to accept all kinds of solid waste or recover all components of the waste, require that a landfill be operated. High reliability for a processing plant will be cost increasing. (Indeed, plants intended to produce and deliver steam on demand include auxiliary fossil-fueled boilers.) The incremental cost of an additional few percent reliability must be balanced against the marginal, or discounted cost of the alternative landfill.

Another element of reliability is the tnedency--or perhaps even the requirement--to over-design those plants which are based on relatively new technology. The lack of operating experience must be compensated for by oversizing, contingency piping, etc., all of which raise the cost. Thus, the first purchasers of new processes will always pay a premium for lack of experience, a premium which may dissuade them from becoming the first purchasers.

Uncertainty combines doubts of whether a process works at all with the conflicting view of asking for an up-to-date system which is not likely to be early and embarrassingly obsolete. The public sector decision makers seek "proven technology," whatever that may mean. One school of thought appears to be that pilot scale demonstration proves technology; another that the existence of a large number of plants proves technology. Ordinarily, I would subscribe to the second school, but in the case of energy recovery from solid waste, cannot at this time.

It is reported that there are now approximately 70 steam-generating incinerators operating in Europe, designed to process 49,000 metric tons (54,300 U. S. tons) per day of waste, and 8 in the United States, designed to process 5,500 metric tons (6,100 U. S. tons) per day of waste (9). Some believe this "proves" the technology of this form of energy recovery. However, disposal costs and recovery objectives in Europe are generally different in the U. S., confusing the translation of "proven," and the record of consistent operation of steam-generating incinerators in the U. S. is poor. For example, of the 8 plants listed (9), only one or two consistently sell steam. (I dismiss as unnecessary the various excuses and stories which seem to accompany almost every plant. Indeed, a sort of folk-lore has built up around most of these plants as to why they are as they are.) Also, technical issues of capacity, corrosion, slagging, air pollution and so forth, are still debated at technical meetings, including this one. Thus, I submit the technology - and hence the associated costs - are unproven.

Proven technology or not, there has to be some basis for estimating the cost of energy recovery projects for the guidance of the public sector decision makers and their consultants. In providing such guidance, it is obvious that the capital costs of a plant to produce refuse-derived fuel for burning in an existing boiler will always be less than any competitive process which requires a new boiler. Also, it will always be less than the cost of any competitive process which converts the refuse-derived fuel to a gas or liquid.

Other generalizations and guidance are not as simple. Costs are usually reported in the form of past records of bids and construction costs, expressed in the now familiar units of dollars per daily ton of capacity. For purposes of review and comparison, Table 5 lists some recently reported costs in such units. The general lack of consistency in these data contribute to the complexity, confusion and uncertainty of energy recovery from solid waste.

The reported costs of processes must be viewed keeping in mind the final product or recovery. The more expensive plants are generally those which produce oil, gas or steam, products which are likely to command a higher selling price than solid fuels. However, the selling price has to produce a revenue to retire the higher capital debt (and higher operating costs, if so). For example, the difference in capital cost to produce solid RDF to burn in an existing boiler or to produce steam (or oil or gas) is approximately $15 million for 900 metric tons (1,000 U. S. tons) per day plant, judging from Table 5 (all figures for U. S. tons SI conversion factors are provided). The amortization of this difference at 10 percent interest over a 10-year period amounts to $8.63 per input metric ton ($7.83 per input U. S. ton) of waste and over a 20-year period (if the plants can be expected to last that long), to $6.40 per input metric ton ($5.81 per input U. S. ton) of waste. At the present time, it is problematical if the revenue difference (net of operating costs) between solid fuel and other energy forms will be this high and so justify the higher investment.

The capital cost expressed in dollars per daily ton of capacity fails to communicate two significant aspects affecting the final cost of energy recovery. One aspect is the number of operating hours, or operating capacity per hour; the other is the substitution efficiency.

An example of the first criticism is the reported cost of the plant in Ames, Iowa. It is an approximate 181 metric tons (200 U. S. tons) per day plant, reported to cost $5.6 million, with perhaps an additional $0.5 million for unanticipated start-up costs. This computes to $33,600 per daily metric ton ($30,500 per daily U. S. ton) capacity, a seemingly exorbitant figure compared to the reported costs of other energy recovery plants. However, this 181 metric tons (200 U. S. tons) per day plant was designed to process 45 metric tons (50 U. S. tons) per hour. Thus, if the plant operated for longer than 4 hours per day, say 8 or even 16 hours per day, the cost per daily ton plummets. The concept of daily ton capacity becomes meaningless.

I suggest that the unit cost of energy recovery plants be normalized to dollars per hourly ton capacity, as a means of lessening the confusion over costs.

The second criticism is that a normalized cost of a process should somehow reflect technical factors, such as differences in substitution efficiency. One way of doing this would be to construct a parameter something like investment per hour ton of capacity divided by the substitution efficiency. If so, certain processes (such as solid RDF) would become a bigger "bargin," and so forth, judging from the few figures in Table 4.

Seemingly, technical factors such as substitution efficiency should have a role in choosing or recommending an energy recovery process. In a survey of eight reports by different consultant groups, this was found not to be the case. Rather, the authors ranked or recommended energy recovery systems solely on the basis of operating and capital costs (14). Table 6 lists the final consensus rank, combining the eight reports. Statistical analysis of the rank correlation showed it to be highly significant (14). Table 6 is shown to emphasize two important points about the confusion, complexity and uncertainty of energy recovery systems.

The first point is that consultant reports recommend on the basis of cost, not technical factors, perhaps because the latter are not well known. The second point: The observation that the consultant reports agree is interpreted that they used the same data bases for their analyses (probably vendor estimates). Thus, the warning must be posted for all concerned that the data are not likely independent and so neither are the conclusions. Table 6 (or another like it) is meaningless as a decision basis for resource recovery.

Conclusions

The efficiency and cost of resource recovery systems have been used as examples to illustrate the confusion, complexity and uncertainty surrounding this field. Undoubtedly, there are others. However, it is believed that these two factors, plus the market specifications for the final energy product, are the three most important factors in choosing an energy recovery process. If a least two of the three are confused, how then are decisions to be made?

The rate of implementation of resource recovery is likely to be determined by the number of plants built and operating. That is, cities are more likely to implement recovery when and after other cities have done so. At least the few data now available are consistent with this model (1).

If energy recovery from solid wastes is to become the normal and usual alternative to burying, and a contribution to the energy needs of our society, the bases for technical and cost decision making must be strengthened and broadened. The confusion, complexity and uncertainty must be lessened. Research programs must be directed to these specific needs.

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TABLE 1

Energy Recovery Efficiencies

System	Reported Efficiency, % Ref. 2	Ref. 3
Waterwall incinerator	67	57
Solid RDF	66	70
Pyrolysis to Oil ("Oxy")	37	37
Pyrolysis to Gas ("Purox")	62	63
Anaerobic digestion to CH_4	25	42
Pyrolysis to Gas ("Torrax")	45	65

TABLE 2

Conversion Efficiencies of Resource Recovery Processes (6)

System	Conversion Efficiency, %
Mechanical processing to Solid Refuse-Derived Fuel and materials recovery	79
Pyrolysis to gas "Purox" process	73
Anaerobic Digestion to 95/5 CH_4/CO_2	43

Notes: Calculations for waste of 8.4 MJ/kg (3600 Btu/lb).
Mass and materials balances from systems' designers.

TABLE 3

Conversion Efficiency According to Lewis (7)

Waste to Steam*

System	Conversion Efficiency, %
Conventional incineration 982°C, 125% excess air	71.6
Indirectly heated pyrolysis process with combustion at 20% excess air	65.6
Gasification with 0.1 kg O_2 added per kg of waste; combustion at 20% excess O_2	72.4
Directly heated, oil-fired pyrolysis process; 100% excess air	51.1

*Temperature and pressure of the steam are not reported.

TABLE 4

Conversion and Substitution Efficiencies Reported by Hecklinger (8)

System	Conversion Efficiencies, %[a]		Substitution Efficiencies, %[a]
	To Fuel	To Steam	To Produce Electricity
Raw refuse incineration combustion at 100% excess air	b	60.5[c]	21.0
RDF, combustion at 30% excess air	85.2	54.0[d]	23.0
Pyrolysis to liquid fuel "Oxy" process combustion at 10% excess air	52.8	32.5[d]	13.8
Pyrolysis to gas "Purox" process combustion at 15% excess air	77.7	51.6[d]	21.9
Anaerobic digestion to 95/5, CH_4/CO_2 combustion at 5% excess air	41.7	22.8[d]	9.9

[a]Based on waste of 10.5 MJ/kg (4500 Btu/lb).

[b]Undefined.

[c]Steam at 4.50 MPa(650 psi), 470°C(875°F). Turbine heat rate 2.86(9750 Btu/KWH).

[d]Steam at 12.4 MPa(1800 psi), 540°C(1000°F). Turbine heat rate 3.4(10,000 Btu/KWH).

TABLE 5

Reported Costs of Resource Recovery Processes

Process or System and City	Capital Cost $000/Daily U.S. Ton Capacity	Reference
Waterwall incineration	30.8	2
Nashville, TN	25.7, 34.7	10, 11
Saugus, MA	25.0, 31.7	10, 12
Wet-Processing, Black Clawson	13.5	2
Hempstead, NY	27.5, 35.5	10, 11
Monsanto, Landgard	21.5	
Baltimore, MD	16.0, 29.0	10, 11
"Oxy" Pyrolysis to Oil	21.9 (est. for 1000 tpd)	2
San Diego Co., CA	72.0 (act. for 200 tpd)	11
Union Carbide "Purox"	22.9 (1000 tpd)	2
State of CA est. for San Diego	44.0 (1000 tpd)	11
RDF Solid Fuel (all 1000 tpd or greater)	10.4	2
Chicago, IL	16.0, 18.0	10, 11
Milwaukee, WI	17.0, 15.0	10, 11
Ames, IA (200 tpd)	28.0, 30.5	10, 11
Monroe Co., NY	12.5, 14.0, 16.1	10, 11
Akron, OH (includes boiler) (600 tpd)	18.0, 28.0	10, 11
Albany, NY (includes boiler)	10.0	10
Bridgeport, CN	16.0	10
Washington, DC (650 tpd)	14.8	11, 13

Conversion Factors: (Cost/U.S. Ton) = 1.102 (Cost/metric ton)
(U.S. ton/day) ≡ 0.9072 (metric ton/day)

TABLE 6

Consensus Ranking of Resource Recovery Systems
in Consultant Reports (14)

Ranking By Cost			Ranking By Cost		
Ranking	No. of Times Considered	System	Ranking	No. of Times Considered	System
1.0	(34)	Shredded Fuel	.94	(34)	Shredded Fuel
.75	(12)	Slagging Incinerator	.69	(13)	Slagging Incinerator
.67	(32)	Union Carbide "Purox"	.67	(30)	Union Carbide "Purox"
.62	(34)	"Oxy" pyrolysis	.59	(22)	CPU - 400
.54	(28)	Monsanto Landgard	.36	(28)	Monsanto Landgard
.41	(24)	CPU - 400	.35	(34)	"Oxy" pyrolysis
.26	(19)	Black-Clawson	.33	(12)	Incineration-Prepared
.24	(21)	Incineration-Prepared	.29	(14)	Black-Clawson
.10	(31)	Incineration-Raw	.14	(28)	Incineration-Raw