Chapter 4

Evaluation of Processing Options

The Working Group considered the full range of technologies proposed for processing solid wastes. It evaluated seven – one a mechanical process (autoclave with mechanical processing), three biological process (aerobic composting, anaerobic digestion, and bioreactor landfills), and three thermal processes (waste-to-energy, gasification, and plasma arc conversion). It also investigated several other processes, but rejected them without undertaking a thorough evaluation.[1]

It is important to note, however, that within a process, the systems proposed by specific vendors can differ substantially from one another. Indeed, the variation among different vendors relying on the same process can be as great as the variation among different processes. One high variation is in the pre-processing stage (how inappropriate or recyclable materials are removed and how the remaining materials are prepared for processing) and the extent to which these operations are integrated with the rest of the process. It appears as if vendors with more experience in commercially processing MSW are more aware of the importance of the pre-processing stage for successful operation, and, therefore, are likely to have paid more attention to integrating it into their system. Similar observations can be made about the environmental controls incorporated into the processes.

However, it is also true that there can be significant differences between the operations of the processing systems themselves. These differences result in some vendors asserting that they are sufficiently different from competitors proposing the same process that they should not be lumped together, and there may well be some validity to such claims. This variation significantly complicated the Working Group's efforts to evaluate the technological processes, for the rating of a process might differ significantly from one vendor to another, and the particular vendor making a presentation to the Working Group understandably had a large influence on our perceptions of the suitability of the technology that vendor represented. We have attempted to compensate for any undue influence by reviewing other evaluations of the systems offered by other vendors.[2]

Two notes about the economic evaluations included here. The first is that the cost estimates do not, as indicated in Chapter 3, include the cost of land acquisition, site preparation, oversight by DSWA, or, in some cases, the cost of a containment building. Thus the tipping fee required to cover all these additional costs could well be $20 to $40 higher than the estimated "break-even" net costs calculated for the various processes. The second is that the Working Group made substantial efforts to develop consistent cost estimates from all the other evaluations as well as from the information presented directly to it. As a result, the economic evaluations presented here include substantial discussion about

[1] These processes, and the reasons for rejecting them, are described briefly in Appendix E.
[2] See Appendix C for a listing of the primary multi-process evaluations the Working Group used.

the variations in these estimates. In spite of these efforts, many of these cost and revenue estimates are very uncertain.

Autoclave With Mechanical Processing

Several vendors offer systems that autoclave the wastes as one step in the process. The autoclave subjects the wastes to high temperature (usually with superheated steam) under high pressure for a sufficient length of time to kill all the bacteria and pathogens that might be in the waste. Some vendors then separate out the paper pulp for recycling as a raw material for paper manufacturers.[3]

The process reviewed by the Working Group is somewhat different and is only provided by one company.[4] It involves several steps. After minimal pre-processing, the wastes are shredded and ferrous metals are removed by magnets.[5] These partially processed wastes are then fed to an autoclave to kill any pathogens. Non-ferrous metals are removed after the wastes leave the autoclave and the waste stream passes through a grinder to produce an end product – called "fluff" – which, as the name implies, is a light, dry downy material.[6] The fluff is relatively homogeneous and has a high organics content, although it also contains all the glass and plastics (and other non-organic materials not removed by the ferrous and non-ferrous metal separators) that were in the original waste stream.[7] The company has demonstrated that the fluff can be successfully used to improve the fertility of barren soils, and is experimenting with its use as a raw material for extruded composite timber.

The company has had one commercial facility in successful operation for several years processing residential wastes, but has not demonstrated the effectiveness of the system in processing municipal solid wastes. Other installations are reportedly underway or pending.

Readiness and Reliability

Autoclaving is a proven technology for the destruction of infectious agents such as bacteria and viruses, although it has not been used extensively to decontaminate MSW. The concept of mechanically shredding and grinding the wastes to produce a homogeneous fluff product is, as far as the Working Group is aware, unique to this system.

The technology has only been in use for a few years processing residential solid waste at a rate of 50 tons per day. Because it has not been used to process MSW, and has not demonstrated its reliability over a 5-year period, it rates relatively low in terms of readiness in term of meeting Delaware's needs.

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[3] Tests have apparently indicated that the separated pulp is of suitable quality to be used in the production of paperboard and cardboard. However, the economics of the system substantially depends upon a paper manufacturing plant being readily accessible to the facility, a condition that does not exist in Delaware (personal communication from Gary Hater).

[4] The company is called WastAway Services and is a subsidiary of the Bouldin Corporation, located in McMinniville, Tennessee, a long established manufacture of machinery for the horticultural industry.

[5] The pre-processing would involve removing materials that are too bulky or otherwise unsuitable for the shredder.

[6] The moisture in the waste as well as the steam added in the autoclave flash evaporates from the material when it exits from the high temperature and pressure of the autoclave.

[7] These materials are apparently ground so fine that they are not visibly detectable in the end product.

In terms of reliability, the vendor reports that the process has demonstrated a run time of 80 percent. This was for a relatively new facility, and more mechanical problems would be expected as the machinery ages. However, the fact that multiple units operating in parallel would be required for a large facility would increase the reliability of the system, for it could continue to operate even though one or two processing lines were down for repair. The standard system is designed to process 120 tons per day utilizing two lines in parallel. Thus a 1000 ton per day facility would require 8 units incorporating 16 processing lines.

The technology appears reliable for rendering a solid waste mass free of biological agents of concern. However the technology does not result in a significant overall reduction of the solid waste mass. Thus, the success of this technology depends on an accessible and profitable market for the treated material. Should markets not be available on a reliable long-term basis, excessive storage requirements and alternative, and potentially expensive, handling and disposition of the materials will affect the long-term viability of this technology.

This technology is novel and, in time, may have a role in MSW management, but the Working Group concludes that it is not currently ready to address Delaware's needs.

Inputs and Pre-Processing

The autoclave/mechanical processing system reviewed by the Working Group has been operated with unsorted residential wastes, and the vendor believes that it will be able to handle municipal solid wastes as well. It cannot process sewage sludge (at least without substantial pre-processing and modifications to the system) or tires, and, like most systems, bulky goods such as appliances have to be removed from the waste stream before it enters the process. The system is also not established to handle yard wastes, although it seems unlikely that some of these wastes mixed in with the rest of the wastes would seriously disrupt the process.

In terms of other inputs, this process requires water (40 gallons per ton of waste) to be converted into steam for the autoclave, natural gas to heat the water (35 therms per ton of waste), and electricity to operate the equipment.

One possible concern is small dense items that are overlooked during the removal of the bulky items. These could cause damage to the mechanical processors. Items of this sort containing iron and steel might be removed by the magnetic separator that removes ferrous metals for recycling before the wastes enter the autoclave. However, non-ferrous metals are not removed until the end of the process, and there seems to be no provision for removing ceramics, stones, and other such items that could damage the mechanical equipment. Another concern, which could affect the marketability of the fluff as a soil amendment, is hazardous substances included in the waste stream. If such substances are contained in steel cans, they would likely be removed early in the process. If contained in plastic or other containers, they would be ground up and mixed with the other wastes. This contamination would likely limit the use of the product as a soil amendment.

The process incorporates automatic controls that adjust the rate of feed depending upon the density of the feedstock. Apparently, it is not otherwise sensitive to normal variations in the content of the waste stream.

Because the system is built on a modular basis, long-term increases in the quantity of the wastes can be easily handled (as long as there is sufficient room and the site has been appropriately laid out to accommodate expansion) by installing additional processing lines; decreases by shutting down a line. Short term variations would most likely be addressed by slowing the lines (for decreases) or by the temporary accumulation of wastes on the tipping floor (for increases).

Public Health, Environmental, and Worker Safety Risks

Public Health Risks

The public health risks associated with the autoclave/mechanical processing system appear to be low. The mechanical processing element is enclosed, and the autoclave part of the process, which is carried out inside a closed vessel, kills the bacteria and other microorganisms in the wastes. However, if batteries or other hazardous substances are not first removed from the waste stream, they would be incorporated into the fluff produced by the system, and could generate public health risks depending upon how the fluff is used. For instance, using fluff containing hazardous substances as a soil amendment could create a risk of heavy metals and/or persistent organic compounds entering the soil. If the land was used for food crops, these contaminants could enter the food chain.[8]

With respect to air pollutants, there have apparently been no measurements of potential air emissions such as volatile organic compounds. Given that the autoclave process heats the waste to a relatively high temperature and pressure and then releases the wastes to atmospheric conditions, most of the volatile organic compounds would be expected to be released as air emissions, and the system does not appear to incorporate any controls to prevent the release of these compounds to the atmosphere. Once released, such compounds contribute to the formation of ozone (smog), which is already an air pollution problem, causing adverse health effects, in Delaware.

Environmental Risks

The environmental risks associated with this system appear to be low as long as the types of materials processed do not include hazardous substances. Nothing in the process reduces the toxicity associated with chemical hazards in the incoming waste stream. The

[8] To protect against these risks of future public exposure, some type of future land use control would be required to ensure that the contamination does not become another externality. The only way to try to internalize this externality would be to establish a robust form of land use control like a fully funded restrictive covenant that would run with the land or, in the case of nursery soil, run with the individual potted plant. This type of tracking and control scheme seems like it would be impractical and ineffective, and therefore the failure could lead to unacceptable public exposures to hazardous contaminants.

manufacturer claims that any incoming chemicals would be mixed relatively thoroughly with the rest of the waste materials thereby reducing their concentration and lowering the risk to anyone exposed. But this dilution effect could also result in the risks being spread more broadly, depending upon how the fluff resulting from the process is used. The issue of how the fluff would be used creates a major uncertainty about the environmental risks associated with the process.

Environmental risks, particularly odor and contaminated storm water runoff, could also result if the fluff is stored for extended periods, particularly if it is stored outside. Although the fluff is probably relatively inert when it exits the process, it still contains substantial amounts of biomass and would be expected to begin to compost, possibly anaerobically, if stored for some time in humid conditions.

The net impact of this process on greenhouse gas emissions depends very much on what use is made of the fluff. If the fluff is sequestered by manufacturing it into durable composite timber, there would be no emissions of methane and very few emissions of CO_2, resulting in a much lower impact than a normal landfill. If the fluff were used as a soil amendment, it would be converted to CO_2, and the impact would be larger, although it would still less than a normal landfill because there would still be no methane emissions.[9]

The water consumption associated with the operation of such a unit is approximately 40 gallons per ton of waste processed. Approximately 8 gallons of waste water per ton is discharged. This waste water is likely to be heavy in COD and dissolved contaminants, and would have to be treated before discharge. The remainder of the water is presumably evaporated.[10]

Worker Safety Issues

The system reviewed by the Working Group appears to be largely mechanized, involving very limited direct interaction between workers and the waste stream.[11] Thus this process itself appears to create few worker safety concerns. Preprocessing by hand to remove recyclable materials, hazardous substances, and other unsuitable items before the waste is processed in the facility would be beneficial for public health and the environment, but it creates more of a risk for the plant workers who do the sorting.

Energy Balance

This process consumes about 2000 BTUs per pound of waste processed. About 85% of this energy is in the form of natural gas to heat the water for the autoclave (35 therms per ton

[9] The impact of methane on climate change is estimated to be about 20 times higher than the impact of an equivalent amount of CO2 (Ref: Alison Smith et al. "Waste Management Options and Climate Change, Final report to the European Commission, DG Environment, 2001, p. 16.

[10] If the waste feed has a moisture content of 45% and the end product has a moisture content of 25%, approximately 80 gallons of water per ton of waste would have to be evaporated, including the boiler feed water that is not discharged.

[11] Some interaction might be involved in removing items from the waste stream that are too large to process, but this is a characteristic of all the waste processing systems.

of waste) and the rest is electricity for running the equipment (90 kwh per ton of waste).[12] The "fluff" produced by the process is not an energy source if used as a soil amendment or timber replacement. The company, however, is also investigating the possibility of using the fluff as a feedstock for a gasification facility, claiming a heat value of 9000 BTUs per pound.[13] This potential use, however, would involve additional energy inputs and costs, and the Working Group did not assess the energy balance of the process if its products were used as a fuel source for another process. Therefore, the energy balance is taken as being zero – this process is a net consumer of energy.

Materials Balance

In the units processing residential solid wastes, about 2% of the incoming material is eliminated in the pre-processing step as a residue requiring landfill. The process converts 86% of the feedstock into "fluff", and minor quantities of ferrous and non-ferrous metals are recovered using mechanical separation. There is no other residue left at the end of the process aside from the fluff.

As indicated earlier, the readiness of the technology for commercial application at the levels of capacity to meet Delaware's needs is highly questionable. Nevertheless, the ability of the autoclave technology to recover 86% of the RSW feedstock makes it an excellent candidate for ongoing scrutiny and future consideration if viable uses are demonstrated for the product, and if it demonstrates an ability to efficiently process MSW.

Economics

Because there is only one vendor for the autoclave/mechanical processing system reviewed by the Working Group, and this vendor was not reviewed in any of the other evaluations available, the cost estimates are based solely on the information this vendor provided the Working Group.

Processing Costs: The vendor estimated that a 500 ton per day facility would require an investment of $20 million, and a 1000 ton per day facility twice that amount. It is not clear whether these estimates include the cost of a building to enclose the facility.

The estimates provided by the vendor make it one of the less capital intensive processes the Working Group reviewed (depending upon the cost of constructing an enclosure building). The investment required per annual ton of capacity would be about $130 to $150. However, the low investment cost is partially offset by a shorter estimated life for a facility – 15 years compared to 20 to 25 years for other types of facilities. The shorter life expectancy seems reasonable given the stress this system presumably places on the mechanical processing equipment it employs.

[12] Ref: Letter from Robert Brown, Bouldin Corporation, to Edwin H. Clark, II, letter sent by email on February 2, 2006.
[13] Ibid.

The vendor estimates that operation and maintenance costs are $69 a ton. This presumably is based on the vendor's experience in processing residential solid wastes, and could be higher for a facility processing MSW.

Combining the annualized capital costs and the operating costs gives a total cost of approximately $85 per ton of waste processed.

Revenues and Net Costs: The major uncertainty with this process is what value the product has. It is high in organic content, and the vendor has demonstrated that it can be used as a soil enhancer for infertile lands. The vendor has also demonstrated the feasibility of using the material to manufacture extruded composite timbers, although the high level of organics in the product raises questions about the long-term durability of these products[14]. Finally, the vendor has suggested that it would provide a valuable feedstock for a waste-to-energy or gasification facility, and estimates that the substance has an energy value of 9000 BTUs per pound.[15]

It is not clear what market, if any, would exist for the fluff in any of these uses in Delaware. Therefore, we have been unable to assign any value to the products of this system.

If there were no revenues from the sale of the fluff product, the net costs would be at least $85 per ton. They would be significantly higher if the facility had to pay for the disposal of the fluff.

Legal and Policy Issues

The mechanical processing component of any autoclave/mechanical processing facility would appear to qualify as a "Resource Recovery Facility" for purposes of DNREC's "Regulations Governing Solid Waste." Accordingly, any applicant would need to submit an application to DNREC pursuant to Section 4, subpart D of these regulations. Such an application would include an environmental assessment, including the requirement to mitigate any potential environmental impacts.[16] Additionally, the facility would have to meet the Operation and Maintenance Standards set forth in Section 9, Subpart D of the regulations. Prior to construction of any new facility, the applicant would need to submit an application to DNREC pursuant to Section 4, subpart D of those regulations. That permitting process would involve the imposition of various operation controls, set forth in section 9, subpart D of the regulations. Local land use controls to minimize offsite impacts such as odor and noise nuisances would also be addressed through this process, and in addition would be addressed through local government review.

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[14] The extruding process apparently also requires the addition of plastic materials to the fluff in order to form a solid coating on the timbers. This might not be necessary if the MSW feedstock contained a higher plastics content than residential solid wastes. On the other hand, an effective recycling program that removed plastics from the waste stream would inhibit this use.

[15] Because of the uniformity in both size and content of the fluff, as well as its low moisture content, it would probably be superior to unprocessed MSW as a fuel for these processes.

[16] *See* Regulations Governing Solid Waste, 4.D.1.h.

The ultimate end-use of the autoclaved material may raise legal issues, depending upon the use of the material. Any application of the material to land, as fluff or otherwise, could raise liability concerns, as there is a possibility of minor levels of contaminants in the fluff.

Aerobic Composting

There is a wide variation in the processes incorporating aerobic processing. Traditionally, composting operations have predominately used windrows on open ground for the composting process. These must be turned periodically to maintain aerobic conditions. Otherwise, they can generate substantial odors. In addition to concerns about odors, these operations also require a substantial amount of land – hundreds of acres for a facility handling wastes from a metropolitan area. These two factors limit this approach to rural areas with low cost land. Rapid City, North Dakota is reported to be using such an approach.[17]

Because these factors do not pertain to most of Delaware, the Working Group did not consider such an open composting process. Instead, we focused on in-vessel composting systems. In this approach, the majority of the composting takes place within a contained vessel in which the waste is agitated and carefully monitored to ensure that the moisture and oxygen are maintained at appropriate levels to promote rapid composting and prevent the system from going anaerobic.[18] Off gasses (predominately carbon dioxide) from the composting process are collected and usually cleaned with a bio-filter. The temperatures within the composter reach sufficient levels to kill the bacteria and pathogens in the waste.

The vessels used to process the wastes are either long inclined tunnels that are continually in rotation, or stationary units that use other mechanisms for agitating the wastes and moving them through the process. Although most of the processing occurs within these vessels, the compost still needs to be “cured” for several weeks. These curing piles must continue to be agitated and monitored to prevent them from going anaerobic.

Composting only breaks down the organic component of the wastes. The other components – plastics, metals, glass, etc. – are unaffected by the process. Thus, unless the system includes some process for their removal, the end product has few uses, except possibly as a feedstock for a thermal process that produces electricity.[19] If it is adequately screened and otherwise processed, it can be used to improve the fertility of soils in gardens, horticultural operations, and on farms.

17 See Nora Goldstein, “Rapid City Closes The Loop On MSW Management” BioCycle November 2003, Vol. 44, No. 11, p. 34.

18 Anaerobic conditions will occur when the aerobic bacteria have consumed all of the available oxygen. When this occurs, anaerobic bacteria begin converting the organic materials into malodorous gasses such as hydrogen sulfide.

19 One of the vendors making a presentation to the Working Group emphasized the advantages of using a composting process to reduce the moisture content of the waste and improve its net energy value as refuse derived fuel.

Readiness and Reliability

The Working Group evaluated two in-vessel aerobic MSW composting technologies. One uses a rotating kiln and the other uses a horizontal tunnel. Both approaches appear to be simple in design and operation. Rotating kilns are standard technology and in use in many industries and have been demonstrated to process MSW on a small to medium scale with minimal problems. The horizontal chamber vessel is a proprietary product that diminishes its attractiveness to meet the condition of being equipment readily available in the market place. Its hardiness has been demonstrated only on a food waste stream.

Most of the units in operation are relatively small, processing 100 to 200 tons per day. At least one of these facilities is said to have been in successful operation of over ten years.[20] The vendor reports that the systems are down for maintenance or as a result of process upsets only 5 percent of the time (two to three weeks a year). Because a large processing facility would be comprised of modular units operating in parallel, its reliability would be higher. Taking one or two units out of operation for maintenance would not affect the operation of the other units. The reliability of the technology is proven for organic fraction waste reduction; provided there has been adequate solid waste separation of non-organic wastes to the extent possible prior to treatment. However, a large residual is generated from the process that needs to be further managed. Further, the reliability of both compost technologies to divert MSW is dependent on an accessible and profitable market for the compost material. Should markets not be available on a reliable long-term basis, excessive storage requirements - an alternative, and potentially expensive, handling of disposition of the materials will affect the long-term reliability of this technology.

Inputs and Pre-Processing

In-vessel composters can accept the full range of residential or municipal solid wastes, although they only digest the organic materials. Generally, the more the feedstock fed into the composter is free of plastics, metals, and other non-digestible materials, the more valuable the compost that emerges. Thus, the amount of pre-processing that is required depends upon how the end product will be used. Compost from MSW that has received little pre-processing is good for little more than landfill cover or as a fuel for a mass burn or other thermal processing facility.[21]

Aerobic composters typically cannot process sewage sludge effectively unless it has been pre-processed to reduce the moisture content.[22] Nor can they process tires. And, of course, bulky items like appliances need to be removed ahead of time.

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[20] This facility apparently processes MSW and operates 12 hours a day.

[21] One of the vendors making a presentation to the Working Group emphasized this use of the system. But even here, the vendor included a substantial pre-processing stage to remove recyclable and undesirable materials.

[22] However, facility that has recently begun operating in Delaware County, NY is designed to process about 20 tons of sewage sludge (biosolids) a day along with a 100 tons of MSW.

In terms of other inputs, the system requires a little water to maintain the proper moisture content in the wastes while they are being processed, and electricity to operate the equipment.

The capacity of the system can be expanded by installing additional processing lines. If the facility has been laid out to accommodate expansion, additional vessels can be added to handle increased waste flows. Similarly, vessels can be shut down if waste flows decrease.

Variations in the composition of the wastes are unlikely to cause upsets, particularly in the tunnel vessels, because the wastes are well mixed in the process. The moisture content of the wastes being processed is carefully monitored while processing is occurring so that moisture can be added to maintain optimum composting conditions. The problems resulting from an excessively moist feedstock are more difficult to deal with, although increased air can be drawn through the vessels to promote evaporation.

Public Health, Environmental, and Worker Safety Risks

Public Health Risks

The in-vessel composting process is unlikely to generate any new hazards or to significantly concentrate hazardous materials in the residual waste stream. However, it also does little to reduce these hazards. Metals and many stable chemical compounds will go through the system unmodified. One system reviewed by the Working Group incorporates processes for removing metals and some other items from the waste stream both before and after processing occurs. However, if hazardous chemicals are disbursed through the waste stream, the in-vessel composting process does nothing to remove them. If compost containing heavy metals and persistent organics were to be used as a soil amendment, these contaminants could enter the soil. If the land was used for food crops, these contaminants could enter the food chain. Like most waste management technologies, effective control of inputs and outputs can reduce these risks. If hazardous materials are not eliminated from the MSW feedstock the use of the compost, and possibly the land on which the compost is applied, may have to be restricted.

The processes operate at a sufficient temperature for a sufficient period of time to kill pathogens in the waste stream. The composting process takes place in an enclosed vessel that is carefully monitored for temperature and moisture content.

Problems can occur with odor and the waste pile heating up if the materials are stored too long before processing, for instance, if there is an extended breakdown of the system. But this is true of any solid waste processing system. Materials exiting the compost vessel also have to be “cured” for several weeks and odor problems can occur if this is not done properly.

Environmental Risks

Composting operations in Southern California are reported to release a mass of volatile organic compounds almost as large as that released from the oil refineries in the region.[23] Such releases contribute to air pollution problems that can have adverse public health effects. Most of the Southern California releases presumably come from open air composting efforts. The two in-vessel composting systems reviewed by the Working Group use bio-filters to control releases of air pollutants from the facility.[24] These filters apparently work well if properly maintained.[25]

The bio-filters are designed to remove non-chlorinated volatile organic compounds if they are maintained with a slightly elevated pH. They do not remove chlorinated volatile organics because this requires an acidic environment. The chlorinated compounds present more of a health risk, but their volume in solid wastes is usually very limited, particularly if there is an effective program for diverting household and commercial hazardous compounds from the waste stream, prior to the in-vessel composting process.

A study for the European Union Environmental Directorate estimates that the net impact of composting on greenhouse gas emissions would be slightly positive (that is, it would result in a net reduction in the release of these gases to the atmosphere) and much better than a normal landfill: a reduction of 10 kg of CO_2 equivalent per ton of waste compared to a net increase of 328 kg CO_2 per ton.

Depending upon the initial moisture content of the waste stream, in-vessel composters may consume small amounts of water to maintain optimal processing conditions. They typically do not discharge any waste water. The moisture in the waste is evaporated by the heat generated as the waste composts and is drawn off by fans and discharged through the biofilter.[26]

Worker Safety Issues

The extent of risks to worker safety depend primarily upon how mechanized the processing system is. One system reviewed by the Working Group was highly mechanized and appeared to provide no significant worker safety issues. Another involved substantial

[23] See press release from South Coast Air Quality Management District, "Air Pollution Controls Proposed for Compost Facilities" April 5, 2002.

[24] A bio-filter is a layer of woodchips or mulch through which the air withdrawn from the composting unit and facility passes before being released to the environment. Bacteria in the bio-filter decompose many of the contaminants in the air stream. Others are adsorbed onto the bio-filter materials.

[25] *Klause Fricke et al, "Comparison of selected aerobic and anaerobic procedures for MSW treatment", (Waste Management, Volume 25, Issue 8, October 2005, Pages 799-810). Fricke et al. concludes that optimized biofilters can reduce total organ carbon emissions by 50%-70% although they do not remove methane. Nevertheless, odor emissions are much lower than the strict German limitations.*

[26] About 50 gallons of water per ton of waste would be evaporated. Much of this would likely condense in the biofilter, helping to maintain its functionality. See also, Fricke et al, op cit, p. 306.

hand picking from the waste stream and would appear to generate increased worker safety issues.

Handling of compost can also result in contamination of the air breathed by the workers due to inhalable dust, VOC's, and levels of bacteria in the vicinity. The most significant species of concern regarding waste management facilities are gram negative bacteria, aspergillus, and penicillium.[27] All of these exposures can be monitored and controlled with relatively simple protective measures and worker monitoring, and these potential exposures should not be a significant deterrent to safe and sustainable operations.

Energy Balance

An in-vessel composting system requires relatively little energy to operate (an open air system depending upon windrows even less). We estimate that the electrical consumption to operate the machinery, lights, etc to be equivalent to approximately 150 BTUs per pound of waste. However, the system does not produce any usable energy,

One vendor making a presentation to the Working Group did emphasize the idea of using the composting process to prepare a low moisture "biomass derived" fuel. In this process, the heat naturally generated in the composting process (i.e. no external energy is required) was used to evaporate the moisture in the waste, reducing the moisture content to approximately 20 percent.[28] Even though this process involved removing the highest energy components of the waste stream, the plastics, for recycling before the organic materials were composted, the vendor claimed a heat value of 5000 to 7000 BTUs per pound for the compost.[29]

As in the case of the Autoclave/mechanical processing system, no consideration was given to using the system's product as a fuel source for another system. As a result, the energy balance of this system is also zero. Whether or not it makes sense to use "biomass derived" fuel for a mass burn or other electrical generating system is more a question of economics than energy balance.

Materials Balance

The composting technology demonstrated the lowest overall recovery of products – ranging between 30% and 65%.

The material balances for the two systems reviewed by the Working Group support the emphasis of the types of composts being generated. In the case of the "bioreactor", only

[27] Crook and Swan, 2001 reported in UK DEFRA "Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes" p. 36.

[28] Russell Blades "Green Energy and Recycling (GEAR) Facilities: A Potential Solution to Delaware's MSW Problem" a paper prepared for the Delaware Solid Waste Management Technical Working Group, January 2006.

[29] Ref: *Ibid.* It is, of course, true that, as discussed under materials balance, only 65% of the waste stream entering the process emerges as composted organics. Thus the 5000 to 7000 BTUs per pound of output is equivalent to 3,200 to 4,500 BTUs per pound of wastes processed.

30% of the commingled feedstocks were recovered in the form of compost product along with minor quantities of ferrous and non-ferrous metals. Almost 47% of the feedstocks were converted to carbon dioxide and water vapor. This still resulted in a total system residue of 22.7% requiring landfilling. The pre-processing of the feedstocks generated less than 2% residue.

The system focused on producing RDF had an overall recovery of 65% of the MSW in the form of bio-fuel and minor quantities of metals, glass and plastics. However, this process incorporated significant pre-processing of the MSW feedstock, resulting in this step generating 25% landfill residue. The objective of generating a high carbon content bio-fuel compost accounts for the higher overall recovery of this system.

Marketing compost in general is challenging. The primary market outlets are in agricultural and horticultural applications, and both generally require high quality compost free of contaminants and foreign matter, which would involve additional pre and post processing of the waste materials. However, an aggressive marketing effort could result in the sale of the compost product(s).

Economics

The cost estimates depend primarily upon the information provided to the Working Group by the two vendors proposing in-vessel composting systems.[30] Fortunately, both vendors provided relatively complete information based on their experience in commercial applications. However, there is a wide difference in estimated costs between the two vendors. This may be because one vendor was proposing the use of a composting system to dry and prepare MSW as a feedstock for a waste-to-energy or gasification facility, whereas the other (and more expensive vendor) was proposing a complete composting system for processing the waste stream.

Processing Costs: The capital costs for an in-vessel aerobic composting system are relatively low, estimated to be 5 to 11 million dollars for a 100 TPD facility, 18 to 30 million for a 500 TPD facility, and 30 to 60 million for a 1000 TPD facility. In terms of capital cost per annual ton capacity, the costs for one vendor ranged from $100 for a 1000 TPD facility to $ 170 for a 100 TPD facility. The corresponding costs for the other vendor ranged from $190 for the largest facility to $366 for the smallest.

The operation and maintenance costs also varied between vendors, ranging from $8 to $10 per ton processed for one vendor, and $23 to $48 per ton processed for the other.[31]

The total cost per ton processed ranged from about $20 to $26 for the one vendor, and $ 40 to over $ 80 for the other. In both cases, the higher per ton costs were associated with the smaller facilities.

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[30] None of the other multi-process evaluations included aerobic composting systems.
[31] In both cases the higher per ton costs were associated with the smaller facility.

Revenues and Net Costs: High quality compost sold in bulk has a value of about $15 per ton. Whether there is a market in Delaware at this price for the type of compost produced by these systems is unclear. Composting facilities that have developed good markets for their products often have to process the composted material after it leaves the facility to remove plastics and other undesirable components and reduce it to a relatively uniform size.

Because of the uncertainties about the marketability of the product produced by composting facilities, we have reduced the value per ton to $5 in estimating the net costs per ton. For a facility with a capacity of 500 to 1000 tons per day, the net costs would be $20 to $50. If the lack of market for the material resulted in its having to be disposed of in a landfill, the required net costs would be twice as high. These costs are consistent with European experience where composting is much more common than it is in the United States.[32]

Legal and Policy Issues

An in-vessel aerobic composting facility would appear to qualify as a "Resource Recovery Facility" for purposes of DNREC's "Regulations Governing Solid Waste." According would need to submit an application to DNREC pursuant to Section 4, subpart D of these regulations. Such an application would include an environmental assessment, including the requirement to mitigate any potential environmental impacts.[33] Additionally, the facility would have to meet the Operation and Maintenance Standards set forth in Section 9, Subpart D of the regulations. Local land use controls would also apply to minimize offsite impacts such as odor and noise nuisances.

Because the facility generates air emissions, and includes emissions control devices, it would need to comply with 7 Del. C., Chapter 60 and the Regulations Governing the Control of Air Pollutants.

The ultimate end-use of the composted material may raise legal issues, depending upon the use of the material. Any application of the material to land could raise liability concerns, as there is a possibility of minor levels of contaminants in the compost.

[32] Ref: Ecotec Research and Consulting, "Costs for Municipal Waste Management in the EU: Final Report to Directorate General Environment, European Commission, 2002
[33] *See* Regulations Governing Solid Waste, 4.D.1.h.

Anaerobic Digestion

The anaerobic digestion process is similar to the aerobic composting process in that it relies on natural bacteria to decompose the wastes. The difference is that the anaerobic process intentionally takes place in an environment with no oxygen. With anaerobic digestion, the gasses produced contain methane and can be used as a low-grade natural gas synfuel. More decomposition occurs than in an aerobic process, although the non-organic materials such as plastics, glass and metals are similarly unaffected. All anaerobic processes occur within closed vessels and the off gasses are collected and cleaned.[34] The recovered gas contains 2% to 4% higher methane concentration, fewer contaminants, and less oxygen than that normally recovered from landfills. Lastly, the gas from in-vessel system typically contains no siloxanes and thus is easier to use as liquefied natural gas.

A number of anaerobic process facilities have been constructed in Europe during the past decade, although the technology is just beginning to be considered in the United States.[35] The major differences between the anaerobic processes being proposed is how "wet" they are and how they handle recyclable and other materials that the bacteria do not digest. The particular process presented to the Working Group was an extremely wet process that uses a water bath at the front end to separate the waste materials by density, and prepare the organic materials for the series of ensuing digestion chambers.

Wet anaerobic processes produce a waste water stream. This is created by the moisture content of the wastes and any water added during the process. Most of the other processes reviewed rely on evaporation to handle excess moisture.

The final residue from an anaerobic process has limited use. If sufficiently processed it can be used as a soil amendment like compost although it has a lower organic component. The relative lack of organic component also makes it less desirable as refuse derived fuel.

Readiness and Reliability

The anaerobic digestion process is becoming very popular in Europe with the installed capacity increasing at a rate of about 20 percent a year. One major vendor, Valorga, began its first commercial plant processing about 200 tons per day of residential solid waste in 1987. Most of these plants, however, process source separated waste streams comprised of yard trimmings and food wastes, or include substantial pre-processing to separate out the digestible component of the waste stream. Some more recent installations are handling MSW.

The development of anaerobic digestion facilities for MSW in the United States is just beginning, with Palm Desert, California recently having selected this process. Nevertheless, the extensive experience in Europe would suggest that this is a technology that is relatively

[34] If there is no market for the synfuels produced by this process, they can, of course, be flared off.
[35] After an extensive review, Palm Desert, California selected an anaerobic process for its new solid waste processing facility (ref: Hater *et al.*, "Conversion Facility Chosen for Palm Desert, California, BioCycle, July 2005, Vol. 46, No. 7, p. 63)

ready for small or medium sized facilities, particularly if they include a process for separating out the non-organic materials that cannot be processed by the system. The Valorga technology, for example, which is an in-vessel operation that is fully enclosed, has 4 plants with capacity of over 100,000 tons/year and one at 185,000 tons/year.

Although some of the earlier plants apparently suffered frequent upsets, improvements in design and operating procedures seem to have largely eliminated these problems, particularly if there is adequate solid waste separation of non-organic wastes prior to treatment. The fact that a large facility would be comprised of multiple units operating in parallel would also increase reliability as in the other processes using a modular approach. The size of the modules would be about 200 tons per day.

One uncertainty pertains to the amount of residual materials and what use can be made of these materials. Twenty to thirty percent of the organic wastes are left over at the end of this process. They have high water content and can be malodorous.[36] They need to be dewatered, and can be aerobically cured to produce nutrient rich compost. However, odor control seems to be a major issue in handling these materials, and the problem of marketing the materials successfully could be even greater than it is for aerobically composted wastes.

Inputs and Pre-Processing

Like aerobic composters, this system can accept residential or municipal wastes as a feedstock although the digestion system only processes the organic materials. Unlike aerobic composters, however, this system can also readily accept sewage sludge. It cannot accept tires, appliances or other bulky items.

High-density non-digestible materials such as sand, rocks, ceramics, and metals can cause problems in the circulators and other equipment used to manage the wastes flowing through an anaerobic digestion system when they sink to the bottom of the digestion tanks.[37] Floatable materials such as many plastics can also cause problems. Thus many anaerobic processes include a pre-processing step to remove these materials along with other recyclables.

In terms of other inputs, water may be needed at the time of initial startup, and electricity to operate the equipment. However, there is no continuous need for water, because even wet systems can recirculate sufficient water within the process.

These are biological systems and, therefore, upsets can be caused by variations in the wastes being processed. Here again, the wet systems appear to be less prone to this problem because substantial mixing of the wastes occurs within the system. One particular concern is maintaining the carbon/nitrogen ratio that is required for these systems to operate

[36] See Karena Ostrem, “Greening Wastes: Anaerobic Digestion for Treating the Organic Fraction of Municipal Solid Wastes” Department of Earth and Environmental Engineering, Columbia University, May, 2004, p.13.
[37] One purpose of the water bath incorporated as the first step in the particular process presented to the Working Group was to allow these times of materials to sink to the bottom and be removed from the waste stream.

efficiently. The amount of nitrogen in MSW may not be high enough to maintain the necessary ratio. However, if this is the case, nitrogen fertilizer or, in Delaware's case, chicken manure can be added to provide the required nitrogen.

Parallel processing lines can be installed to respond to long-term increases in the quantity of the wastes to be processed. Opportunities for such expansion, if anticipated, should be incorporated in the initial design and layout of the facility.

Public Health, Environmental, and Worker Safety Risks

Public Health Risks

Anaerobic digestion systems operate within a totally enclosed system, with all gasses emitted by the process collected for subsequent use as a low-grade syngas or as a feedstock for chemical processes. Thus there are no direct air releases from the system. Like other biological processes, anaerobic digestion also does not generate hazardous pollutants. However, it also has limited ability to break down hazardous compounds in the waste stream. [38]

The process operates at sufficient temperature to kill pathogens in the wastes, and is carefully monitored for temperature, oxygen and moisture content.

The residuals ("digestate") remaining after processing are likely to contain most of the hazardous compounds mixed in with the feedstock. Thus the use of the digestate may have to be restricted.[39] However, if the feedstock for the process is not the full MSW waste stream, but a source separated stream containing primarily food wastes and yard wastes, the digestate may be used for soil enhancement without restrictions.

If the syngas generated by the anaerobic digestion process is used as a fuel source, the facility using it would need to be sampled regularly to ensure no hazardous contaminants are present, as well as complying with requirements for control of other emissions.[40]

As with any process, odors can result at the input side if the refuse is not expeditiously fed into the process.[41] The residuals at the end of the process can also generate odors if not

[38] UK DEFRA "Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes" p. 54.
[39] For the anaerobic digestion process presented to the Working Group, the vendor recommended using these materials as landfill cover.
[40] The facility may be able to purchase offsets, however, given the positive energy balance from clean combustion of methane which can replace the coal used in most of Delaware's electrical generating facilities.
[41] ArrowBio, who presented their technology to the Working Group, immerses the waste in a water bath immediately, which they say eliminates the odor of the waste material in the receiving area.

thoroughly digested.[42] Enclosing the system in a building with slightly negative air pressure so that no process air is allowed to escape from the building can control these problems.[43]

Environmental Risks

Combustion of biogas is expected to require air pollution controls. Standard air emission treatment systems should be adequate to treat the discharge from this combustion process.

Anaerobic digestion processes generate some waste water, with BOD and COD the primary treatment concerns.[44]

The study conducted for the European Union on the impact of waste management practices on climate change estimates that anaerobic digestion would have a larger net reduction in the release of greenhouse gases than composting - about 33 kg of CO_2 per ton of waste processed. If the methane is used to replace coal to generate electricity, the reduction would be much greater - probably in the range of 250 kg of CO_2 per ton.

Worker Safety Issues

This is generally a highly mechanized process that takes place within enclosed vessels. Thus the workers have little exposure to the wastes or the process, minimizing worker safety concerns. However, if there is a pre-processing step involving hand picking of undesirable and recyclable materials from the waste stream, there would be some risks.

Energy Balance

The anaerobic digesting process does convert solid waste into a readily usable form of energy – a gas that contains up to 75 percent methane (on a volumetric basis) at a rate of about 450 to 1500 BTUs per pound of waste. An estimated 90 to 170 BTUs pr pound are required to operate the system.

If the gas produced by the system is used to fire a traditional electrical generating facility, the net result is an electrical output equivalent to 60 to 260 BTUs of energy per pound of waste. Assuming that the waste itself has an energy content of 5000 BTUs per pound, this results in an energy balance of up to 10 percent – that is the electrical energy produced is up to almost 10 percent of the amount of energy (including the energy embodied in the wastes) consumed.

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[42] Shefali Verma, "Anaerobic Digestion of Biodegradable Organics in Municipal Solid Wastes", Department of Earth and Environmental Engineering, Columbia University, May 2002.
[43] The Working Group was impressed by a photograph of an anaerobic digestion facility in Europe which was located adjacent to a Burger King restaurant, giving the strong implication that odors were not an issue.
[44] Fricke et al, op cit. estimate that the amount of waste water discharged ranges from 100 to 170 liters of water per Mg of waste processed (equivalent to 24 to 41 gallons per US ton).

Materials Balance

The anaerobic digestion of MSW has an overall recovery rate of about 72%. Some minor pre-processing of the MSW feedstock is necessary, resulting in 2% residue requiring landfill. There are essentially two major products generated by the anaerobic digestion technology. They are biogas and digestate, which, if not contaminated, can be used as a compost. The biogas accounts for about 46% of the total products recovered and the digestate about 29%. The remaining recovered products consist primarily of plastics (18%) with the balance (7%) being metals and glass. The total system residue requiring landfilling is about 22%.

Economics

A number of cost estimates for anaerobic digesters are available, but the results of these analyses vary widely, even for the same vendor. The reason for these variations is not clear.[45]

Processing Costs: Estimated capital costs range up to $90 million for a 1000 TPD facility. For a 100 TPD facility the capital costs generally range from $ 10 million to $25 million. In terms of the capital cost per annual ton of capacity, one evaluation has the costs ranging from $300 to $800, while other evaluations have the costs ranging from $100 to $ 500 for similarly sized facilities.

Operation and maintenance costs also range widely, with estimates ranging from a low of $12 to a high exceeding $100 per ton of waste processed. However, the vendor associated with the lowest costs informed the Working Group that these estimates were incorrect, and that a more accurate O&M cost estimate would be $22 to $32 per ton. We assume that a reasonable expected O&M rate would be $25 to $50 per ton of waste processed.

With these assumptions, the total cost ranges from $45 to over $100 per ton processed.[46]

Revenues and Net Costs: The estimated revenues from anaerobic digestion systems vary much less than the estimated costs, generally falling between $ 15 and $25 per ton of waste processed. About half of these revenues are associated with using the methane gas the

[45] Cost estimates can vary significantly if additional sorting and pre-processing is required, if the vendor is supplying the capital instead of the municipality, if the supplier is paying royalties to investors. It is also true that waste streams in the US are different from site to site, largely because the level of recycling is variable from state to state while the Europeans are all moving towards a common goal. However, these factors would not be adequate to explain the wide differences in the estimated cost for the same size facility provided by the same vendor is two similar situations in the United States.

[46] There is substantial disagreement about the high end of this range as well. For one vendor proposing a 100,000 ton per year, one evaluation estimates the total cost to be about $124 per ton while another estimates the total costs for the same unit to be $67 per ton. The results for another vendor, however are just the opposite: the first evaluation estimating a total cost of $87 per ton while the second evaluation estimates a cost of $173 for the same size unit.

systems produce to generate electricity. The rest result from selling the recovered materials and compost produced by the system.

Although the various evaluations show a much larger variation, it is likely that the estimated net costs would fall in the range of $25 to $ 75 per ton.

Legal and Policy Issues

An anaerobic digestion facility would appear to qualify as a "Resource Recovery Facility" for purposes of DNREC's "Regulations Governing Solid Waste." According would need to submit an application to DNREC pursuant to Section 4, subpart D of these regulations. Such an application would include an environmental assessment, including the requirement to mitigate any potential environmental impacts.[47] Additionally, the facility would have to meet the Operation and Maintenance Standards set forth in Section 9, Subpart D of the regulations. Local land use controls would also apply to minimize offsite impacts such as odor and noise nuisances.

Because an anaerobic digestion facility may generate air emissions in connection with the combustion and flaring of biogas, the combustion facility would need to comply with 7 Del. C., Chapter 60 and the Regulations Governing the Control of Air Pollutants.

Anaerobic digestion facilities also generate waste water streams, and a permit would be required in connection with the waste water.

[47] *See* Regulations Governing Solid Waste, 4.D.1.h.

Bioreactor Landfills

The final biological process reviewed by the Working Group is the bioreactor landfill. This is a relatively new approach to landfill management. A conventional landfill is typically designed and managed to discourage natural biological decomposition.[48] Aerobic and anaerobic decomposition does occur, but at a relatively slow rate.[49]

Bioreactor landfills, in contrast, although they look like and are operated much like a conventional landfill, are designed and managed so as to promote the natural decomposition process. They include a leachate management system that recirculates the leachate to the top of the landfill in order to promote biological activity and a more extensive gas collection system to handle the increased volume of gas produced. Since much of the gas produced and collected is methane, it can be used as a low-grade synfuel if a potential user is located in proximity to the landfill. Otherwise it is flared off.

In addition to producing a potentially more marketable product, bioreactor landfills have the advantage of essentially increasing the capacity of a given amount of land to accept solid waste disposal, and are likely to reduce the amount of uncontrolled releases of gas since most of these releases occur while the landfill is in operation and are, therefore, more carefully managed.[50] It is also projected that bioreactor landfills will have a shorter methane generation cycle and a shorter post-closure care period.

Readiness and Reliability

The theory and practice of the bioreactor landfill has been under consideration for a number of decades, though EPA and state regulatory agencies have only permitted the recirculation of leachate generated by the receiving landfill for the past decade. EPA still considers the bioreactor landfill in the demonstration stage of development and not shelf-item technology. Two designs approaches are being implemented, 1) retrofitting an existing landfill to be a bioreactor landfill, and 2) the design of the recirculation system as part of an original design for a new cell or landfill.

The technology is currently ready for implementation from a technical perspective with new landfills to promote and acceleration of the decomposition and stabilization of the in-place solid waste mass within a given footprint. DSWA has successfully demonstrated the theory of recirculation of leachate at the central and southern sanitary landfills. However, the technical and administrative challenges with this relatively new technology could make

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48 Some observers say that conventional landfills become *de facto* bioreactors because the caps are never as effective at keeping rainwater out as they are designed to be.

49 The anaerobic decomposition is, of course, the source of most of the odors associated with landfills.

50 The added capacity results from the fact that the landfill operator can utilize the space created by the more rapid decomposition of the wastes in the landfill while it is still in operation. The fact that many commercial operations have shifted to bioreactor management is one explanation why the available landfill capacity has recently increased in the United States (See New York Times, "Rumors of a Shortage of Dump Space Were Greatly Exaggerated", Aug 12, 2005, available at http://www.nytimes.com/2005/08/12/business/12trash.html?ex=1143522000&en=9d42f22f3c94552b&ei=5070.)

retrofitting of existing landfills difficult. Although the technology has proven reliable in field applications with sanitary landfills designed as bioreactors, it remains in the demonstration and development stage for existing landfills.

The reliability of the process, if operated properly, is expected to be high. The major problem is to ensure that the landfill gas is collected efficiently. Otherwise, serious odor problems can arise. The leachate collection system also has to be robust to prevent leaks, clogs, and overflows. Neither of these problems, of course, affects the ability of the landfill to accept solid wastes, only its ability to operate as designed and prevent undesirable environmental releases.

Inputs and Pre-Processing

Like traditional landfills, bioreactor landfills will not accept bulky goods or tires unless they are shredded or crushed. They can, however, accept sewage sludge at a rate of up to 20 percent of the wastes disposed of. Stabilized sewage sludge can also be used for final cover but, as has been demonstrated at the Cherry Island facility, is not suitable for use as daily cover.[51]

Otherwise, there is little to distinguish a bioreactor landfill from a conventional landfill with respect to inputs and pre-processing requirements. In both cases, there are few limitations.

In terms of other inputs, landfills require gas or diesel oil as fuel for their placement and compaction equipment, and electricity to operate the leachate and gas collection systems along with lights, etc.

Public Health, Environmental, and Worker Safety Risks

Public Health Risks

The human health risks resulting from properly operated bioreactor landfills would appear to be no greater, and probably less, than those created by traditional landfills. The primary short term risk would be from air pollutants such as methane released from the landfill as decomposition occurs. Because bioreactor landfills accelerate this process, generating gas at a faster rate, collection is more cost-effective and, accordingly, more attention is given to collecting this gas, resulting in reduced releases to the environment. On the other hand, because the rate of gas generation is higher, if any releases do occur as a result of faults in or breakdown of the gas collection system, the amount of gas released during the period the problem exists would probably be greater than would be released from a traditional landfill during an equivalent period.

[51] In some cases, bioreactors are managed in such a manner that they initially operate in an aerobic phase before shifting over to the anaerobic stage where the methane is produced. In this type of operation, mixing in sewage sludge would be inadvisable.

The other risk is from landfill leachate contaminating the ground or surface waters. All modern landfills are designed with an "impermeable" barrier below the landfill and a leachate collection system.[52] However, such barriers deteriorate over time, and the leachate collection systems may not be maintained well after the landfill is closed. In this respect there is little reason to expect such risks resulting from a bioreactor landfill to be significantly different from those resulting from more traditional landfills.

Odor control from a bioreactor landfill may be more effective than a traditional landfill because of the greater attention to methane capture as discussed above.

As with any landfill, after closure a bioreactor landfill can become a community liability if there is no careful plan for safe reuse. A long-term stewardship plan after the landfill is closed can help ensure the site is not inadvertently exhumed or built on in a way that results in safety or property damage issues from subsidence or results in harmful exposures to hazardous constituents.

Environmental Risks

The environmental risks resulting from landfills are the same as the public health risks – primarily releases to the air and the water. The environmental benefits (or lack thereof) resulting from bioreactor landfills compared to traditional landfills would be the same as the public health benefits. Bioreactor landfills should result in lower releases to the air over the long-term, but releases to ground or surface waters should not be significantly different.

Bioreactor landfills would likely result in much lower releases of greenhouse gases than traditional landfills because the gas would be more efficiently collected. The advantages of a bioreactor would be particularly significant if the collected gases were used to generate electricity that would otherwise be generated by coal fired power plants. However, there would inevitably be some gases released, making bioreactor landfills probably less advantageous by this measure than anaerobic digestion, which involves decomposition and gas collection under a more controlled environment.[53]

Although bioreactor landfills involve the application of water to the wastes to accelerate their decomposition, most of this water is obtained from landfill leachate. During extended dry spells, some make-up water may be required. During periods of heavy rainfall, there may be excess leachate generated, and it may be necessary to treat and discharge the leachate to a sanitary sewer system or a package treatment system.

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[52] The Pigeon Point and Cherry Island Landfills in northern Delaware, having been originally placed in operation many years ago, have impermeable barriers beneath them composed of the dredge fill at the site, not a HDPE liner system as in modern landfill designs.

[53] One estimate is that the maximum efficiency of the gas collection system is about 90%. See Barlaz et al., Comparing Recycling, Composting and Landfills, Biocycle, September 2003, p. 62.

Worker Safety Issues

The worker safety issues should generally be no greater at a bioreactor landfill than they are at a traditional landfill. These issues are primarily associated with the handling of mechanized equipment and the exposure of workers to gaseous emissions from the wastes.

Energy Balance

The bioreactor landfill consumes energy in three ways: a) the fuel consumed by the equipment distributing and compacting the wastes and daily cover, b) the leachate recirculation system, and 3) the gas collection system if this system is maintained under a slight negative pressure to improve collection efficiency. Since landfills are typically located in remote areas, there may also be increased energy consumption associated with hauling the wastes a longer distance. However, because the Working Group's purview did not include siting issues, this source of consumption has not been considered in estimating the energy balance. The estimated energy consumption for the three items that were considered is 200 BTUs per pound of waste.

The energy content of the gas generated by the landfill depends upon the operating conditions and the phase of operation. Some operating procedures call for the landfill to be operated for some period of time in an aerobic mode in which case there is no usable gas produced. When operated in an anaerobic mode, gas production is estimated to be as high as 1600 BTUs per pound of waste.[54] This waste is typically of lower quality (containing about 50 percent methane by volume) than that generated by an anaerobic digester, which operates under more carefully controlled conditions.

The gas collection systems for landfills, of course, are not completely effective. Their maximum effectiveness is estimated to be about 90%.[55] Assuming that over the life of the collection efforts the average collection efficiency is 75%, the average usable energy output is 1200 BTUs per pound of waste. If this is used to generate electricity in a normal electrical generating station, the resulting output would be about 240 BTUs per pound of waste. This would result in an energy balance of approximately 5 percent.

Except for the limited capacity left at Cherry Island, no bioreactor landfill sited in Delaware is likely to be located close enough to an electrical generating station to allow it to use the gas generated by the facility. Thus the electrical generating potential would probably be limited to reciprocating engines linked to a generator.[56] In this case, the efficiency of the generating system would be somewhat less than that assumed, resulting in a

[54] The rate of methane production starts low, increases to a maximum rate after about 20 years of operation, and then decreases again as the waste is digested. Ref: Barlaz *et al.*, "Comparing Recycling, Composting and Landfills" BioCycle, October 2003, p. 53.
[55] See Barlaz et al., Comparing Recycling, Composting and Landfills, BioCycle, September 2003, p. 62.
[56] California is also experimenting with using "micro-turbines" to generate electricity form landfill gasses.

lower energy balance. However, over 200 landfill gas-to-energy projects in the United States are producing electric power in this manner.[57]

Materials Balance

Since the bioreactor is a landfill, it does not divert any materials from a landfill, so this is not a relevant criterion for this technological process.

Economics

Landfill costs depend substantially upon site-specific conditions such as the price of land and the amount and type of site preparation that is required. All these factors were outside the purview of the Working Group. Therefore, instead of estimating the total cost of an a bioreactor landfill, the Working Group limited itself to estimating the additional costs that would be involved in operating a bioreactor landfill compared to a traditional landfill at the same location. None of the available evaluations undertaken by other organizations include cost estimates for alternative types of landfills.[58] Thus the incremental cost estimates presented here are based upon the personal knowledge and experience of some of the Working Group members, as well as the information provided to the Working Group by a vendor who operates a number of traditional and bioreactor landfills.

Processing Costs: Bioreactor landfills require some additional capital investment compared to a traditional landfill. The increased investment is primarily for a better leachate collection, pumping, and distribution system, a more efficient and larger capacity gas collection system, and a more extensive monitoring system. Operating costs are also somewhat higher while the landfill is in operation. These increased costs are associated with leachate and gas management, more extensive monitoring, and more careful supervision of operations. The total increase in costs, including annualized capital and O&M costs, is estimated to be from $1.0 to $1.6 per ton of waste disposed of (the larger the landfill, the lower the costs on a per ton basis).

These costs, however, are largely or completely offset by cost savings associated with a bioreactor landfill and the additional revenues the landfill generates. The cost savings result from decreased monitoring and maintenance costs after the landfill is closed because most of the decomposition will have occurred during the operation period.[59]

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[57] Communication from Roger Green, Waste Management, January 6, 2006.

[58] However, a study conducted for the State of California does thoroughly investigate the alternative technologies that can be used to construct and operate landfills. See Geosyntec Consultants, Inc., Landfill Facility Compliance Study Task 7 Report – Study of Emerging Technologies in Waste Management for MSW landfills, December 2003.

[59] There is another potential future capital cost saving associated with bioreactor landfills. As a result of the accelerated waste digestion occurring in the landfill, the landfill's capacity is filled up more slowly than is the case with a traditional landfill, postponing the need to develop a new landfill to handle the waste stream. Because a new landfill is likely to be significantly more expensive than an existing landfill, postponing this future capital expenditure has some significant potential economic advantages. However, these were not taken into account in the cost estimates included here.

Revenues and Net Costs: Because bioreactor landfills produce gas at a higher rate than traditional landfills, it is likely to be more economic to collect this gas and transport it to a user such as an electrical generating station, allowing the landfill to generate revenue in addition to the tipping fee. However, the prospect for such revenue depends upon the location of the landfill and the nearby availability of potential customers for the gas. If the gas cannot be sold or converted to electricity with an on-site unit, it has to be flared off without generating any revenue.[60] Because the Working Group did not consider siting factors, no credit is given for potential revenues from gas sales.

If there are any revenues from gas sales, the bioreactor landfill could well be less expensive than a conventional landfill in terms of the net costs per ton disposed of.

Legal and Policy Issues

A bioreactor landfill would qualify as a sanitary landfill for purposes of DNREC's "Regulations Governing Solid Waste." Accordingly, any new facility under consideration would need to submit an application to DNREC pursuant to Section 4, subpart B of DNREC's "Regulations Governing Solid Waste." Such an application would include an environmental assessment, including the requirement to mitigate any potential environmental impacts.[61] Additionally, the facility would have to meet the Operation and Maintenance Standards set forth in Section 5, Subpart I of the regulations. Local land use controls would also apply to minimize offsite impacts such as odor and noise nuisances.

Because the facility generates air emissions, and includes emissions control devices, it would need to comply with 7 Del. C., Chapter 60 and the Regulations Governing the Control of Air Pollutants.

Local land use controls would likely impose significant restraints on any bioreactor landfill, or any kind of landfill, located in New Castle County. The amount of land required for such a use, and the need for buffer space separating the use from nearby land uses, render very few usable sites as realistic alternatives for a landfill use.

[60] California is experimenting with the installation of "micro-turbines" on landfills located remotely from an electrical generating station. See California Energy Commission, California Distributed Energy Resources, Installations, Lopez Canyon Landfill, (http://www.energy.ca.gov/distgen/installations/lopez_canyon.html).
[61] *See* Regulations Governing Solid Waste, 4.B.1.f.

Waste-to-Energy

The first of the thermal processes the Working Group reviewed was the modern waste-to-energy facility. This is a process that uses a mass burn approach to combust the waste and then uses the heat generated by this combustion to produce the steam used in a steam powered electrical generating facility. Waste-to-energy facilities have been used to process MSW for many years, although none has been constructed during the past decade in the United States.[62]

Very little pre-processing of the wastes is required for these facilities, and they have demonstrated a high degree of reliability. However, the residues left over from the mass burn process have no use and must be disposed of in a landfill. In the past, these facilities were a major source of air pollution. However, pollution control requirements imposed by EPA have significantly reduced their emissions. One concern with waste-to-energy processes, as with any thermal process, is that subjecting waste materials containing chlorine compounds to high heat can generate dioxins and furans, which are highly toxic substances.[63] High heat can also vaporize mercury, lead, and other toxic metals.[64] This makes the quality and proper operation and maintenance of pollution control equipment particularly important for processes relying on heat to process the wastes. Current air emission data appear to be much better than what is perceived by the general public.

Readiness and Reliability

Over 16% of the MSW generated in the U.S. is processed through mass burn and refuse derived fuel (RDF) waste-to-energy plants.[65] There are 89 such facilities currently operating in the United States, and the amount of waste they process has increased at a rate of about 1.5% per year.[66]

Mass burn technology receives and burns MSW as is delivered by collection vehicles. The basic technology (the grate system) for mass burn plants is European in origin, although the boiler systems are standard technology available from American manufacturers. The RDF technology is an American developed technology and uses much of the same processing equipment that can be used in material recovery facilities (MRF) and compost systems that require front-end processing. Given the amount of experience with waste-to-energy facilities in the United States, this technology has to receive a high rating for readiness. Only a conventional landfill can claim a higher rating. However, there are only a few vendors currently offering this type of technology in the United States.

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[62] See Kiser and Zannes, The 2004 IWSA Directory of Waste-to-Energy Plants, Integrated Waste Services Association, 2004.
[63] The National Academy of Sciences established a committee of experts to undertake a comprehensive review of the toxicology of dioxins and furans. This committee's report is expected to be released at the end of May 2006.
[64] On the other hand the heat can destroy toxic compounds that are unaffected by other processes.
[65] EPA's Municipal Solid Waste Factbook.
[66] The 2004 IWSA Directory of Waste-to-Energy Plants, Integrated Waste Services Association, and EPA's Municipal Solid Waste Factbook.

The technology currently available has also been demonstrated to be reliable on a continuing basis over the past 20 years in plants that receive and process in excess of 1000 TPD of MSW. Down time is typically less than 10 percent. Waste-to-energy facilities, however, are not typically built in parallel modular units, and, therefore, do not normally have the ability to continue in operation if one part of the system suffers an upset or is down for maintenance or repairs.

Inputs and Pre-Processing

Waste-to-energy facilities have clearly demonstrated their capacity to handle a wide rage of MSW. Typically appliances and very bulky items are removed from the waste stream on the tipping floor, and modern waste-to-energy facilities involve a mixing stage to make the feedstock more homogeneous. They can accept sewage sludge, but only if it has been pre-processed to significantly reduce the moisture content. They, like other thermal process, can accept tires, but in limited quantities because of their high BTU content. Otherwise, very little pre-processing is required.

However, prior processing or the waste stream through a mixed-waste materials recovery facility or otherwise removing non-combustible components can generate additional revenues, increase the efficiency of the process, and reduce the amount of residual left over at the end of the process.[67] How plastics should be handled is often a question. They have a high heat value, so including them in the materials fed to the combustion chamber will increase the energy output of the facility. However, they can also be a significant source of the chlorine required to create some of the air pollutants – particularly dioxins and furans – generated by the facility.

In terms of inputs, the main requirement is cooling water for the electrical generating component of the system. Other inputs are boiler feed makeup water and fuel electricity to operate the equipment.

Waste-to-energy facilities demonstrate significant economies of scale. Therefore, they are initially sized to handle the entire waste flow, and expansion is difficult. Adding a small parallel processing line is not likely to be economically viable.

Public Health, Environmental, and Worker Safety Risks

Public Health Risks

Under past practices, the incineration of solid wastes has created significant public health concerns, particularly because air emissions often included dioxins, furans, acid gases, heavy metals such as mercury and lead, and other toxic substances. Among some

[67] It is worth noting that some of the northern European countries having the highest recycling rates are also making extensive use of waste-to-energy facilities.

elements of the general public and the scientific community these concerns remain unabated.[68]

Since the 1980s when Delaware's waste incinerator operated, significant improvements have occurred in both technical control to limit air pollution and the regulatory requirements to ensure effective controls are used. Nonetheless, significant issues remain, compared to other technologies. One outstanding issue is the control of and health effects from dioxins.[69] During normal operating conditions modern controls effectively limit the release of dioxins and other hazardous emissions. However, it is less clear whether these controls operate with such effectiveness during start-up, shut-down, and upset conditions.

The emissions from modern waste incinerators are substantially lower than a decade ago because of the adoption of improved combustion processes and controls (e.g. better gas-phase mixing, higher combustion temperatures, and lower particulate matter loading), and compliance with current EPA pollution control regulations.[70] The EPA regulations have brought about major retrofitting of all American MSW combustion plants. These regulations not only address emissions, but also operating and monitoring procedures. They impose emission restrictions on products of combustion such as particulates, acid gasses, heavy metals, dioxins, furans, mercury, chlorinated hydrocarbon compounds, etc. Ash is also now regulated and must be tested to determine if the material is a hazardous waste. As a result of facilities installing the improved combustion processes and pollution control systems, emissions, on a national basis, have been reduced significantly as indicated in Table 4.1. For instance, this table shows that, over a 10-year period, mercury emissions have been reduced 92 percent and releases of dioxins have dropped 99 percent. At the same time, the amount of waste processed by these facilities has increased over 12 percent.[71]

Currently, municipal waste combustors only contribute to 1 percent of the national emissions of dioxins, as opposed to 63% in 1987. In contrast, backyard burning contributes to 57% of the current national dioxin emissions.[72] While these data provide a broad overview of the improvements in waste incinerators, they may not be reassuring to a community immediately downwind from such a facility.

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68 See for instance, Jeremy Thompson and Honor Anthony, "The Health Effects of Waste Incinerators", 4th Report of the British Society for Ecological Medicine, December 2005.

69 Dioxins (and di-benzo-furans, a similar substance) are a series of chlorinated compounds that are thought to be extremely hazardous (the National Academy of Sciences is in the process of completing a comprehensive revive of the available information concerning the risks that these chemicals pose). These substances can occur in very low concentrations in waste streams, and are generated when wastes are burned at temperatures up to 1,800 ºF. They are largely destroyed at combustion temperatures exceeding 1800 ºF. (See National Research Council, Committee on Health Effects of Waste Incineration, *Waste Incineration and Public Health*, National Academy Press, Washington, DC, 2000, p. 55).

70 The new EPA Municipal Waste Combustor Rule was put into effect on December 19, 1995, and all large facilities were required to meet the new standards by December 19, 2000.

71 EPA's Municipal Solid Waste Factbook

72 USEPA Inventory of Sources of Dioxin-Like Compounds in the US for 1987 and 1995 and http://www.trifacts.org/quantified_sources/quantified_sources.php.

Table 4.1
Nationwide Emissions from Municipal Waste Combustors

Pollutant	1990 Emissions (tons per year)	2000 Emissions (tons per year)	Percent Emission Reduction Achieved
Dioxin (g/yr, TEQ)[73]	4,260	13.9	99 +
Cadmium	4.75	0.52	89
Lead	52.1	8.12	84
Mercury	45.2	3.68	92
Particulate Matter	6,930	1,070	85
HCl	46,900	3,080	93
SO_2	30,700	5,620	82
NOx	56,400	50,700	10

Source: EPA "National Emission Trends for Large Municipal Waste Combustion Units (Years 1990-2005), Docket A-90-45, Item VIII-B-7

The National Academy of Sciences convened an expert committee to study health risks from waste incineration, which issued its report - *Waste Incineration and Public Health* - in 2000, concluding:

> with current technology, waste incinerations can be designed and operated to produce nearly complete combustion of the combustible portion of waste and the emit low amounts of pollutants of concern under normal operating condition. In addition, using well-trained employees can help ensure that an incinerator is operated to its maximal combustion efficiency and that the emissions-control devices are operated optimally for pollutant capture or neutralization. However, for all types of incinerators, there is a need to be alert to off-normal (upset) conditions that might result in short-term emissions greater than those usually represented by typical operating conditions or by national averages. Such upset conditions usually occur during incinerator startup or shutdown or when the composition of the waste being burned changes sharply. Upset conditions can

[73] The dioxin emissions are presented on a g/yr, toxic equivalent quantity (TEQ) basis; all other emission reductions are expressed in tons per year (TPY). TEQ dioxin emissions are based on 1989 NATO Toxic Equivalency Factors.

> be caused by malfunctioning equipment, operator error, poor management of the incinerator process, or inadequate maintenance.[74]

Several of the qualifiers in this report are worth noting: One, an incinerator should use current technology, not compromise on effective design or omit needed air pollution controls. Two, the low emissions potential depends upon whether the waste incinerator is in fact designed and operated properly. Three, waste-to-energy facilities do not destroy toxic metals and radionuclides, and may convert them to a form (vapor or small particles) that are more difficult to control. Four, proper operations resulting in low emissions depend on "well-trained employees" operating the facility 24 hours a day.[75] Five, "normal" operating conditions can be upset by the normal variability in the MSW waste stream.

The NAS committee further expressed concern that monitoring data from these facilities do not typically include information pertaining to start-up, shut down, or upset conditions. The Working Group is concerned that this lack of information has apparently not been rectified since the NAS report was prepared.[76]

Hence, the question is not simply whether waste incineration can be done safely. It can be done safely if a number of preconditions are met. The question to be addressed is will waste incineration be done safely on a sustained basis. The critical issues here are related to how much money the state is willing to invest in an adequate design, installation and operation of the system, and how robust and independent the regulatory oversight system will be to ensure long-term protection of public health and the environment with adequate transparency to regulators and the public. Box 4.1 lists a series of recommendations made by Del-EASI for siting and operating waste-to-energy facilities to reduce their potential public health and public nuisance impacts.

Two European epidemiological studies attempted to identify adverse health effects associated with waste incineration facilities.[77] One concluded that

> exposure to air pollution can bring forward death in patients with severe pre-existing disease although the degree of life-shortening is typically on the order of a few weeks at most per individual. However, there is currently little convincing evidence that ambient levels of air pollution cause adverse health effects in healthy people.[78]

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74 National Research Council, *Waste Incineration and Public Health*, National Academy Press, Washington, DC, 2000, at page 3.

75 It is worth noting in this regard that there is no clear and rigorous international qualification system for operator certification and fail-safe system for incinerators as there is for other critical industrial system like chemical operators, sewage treatment plant operators, and nuclear power plants operators.

76 Oral response to question by Richard Stone during presentation to the Working Group on January 10th, 2006.

77 UK DEFRA "Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes" p. 208.

78 UK DEFRA "Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes" p. 139. This study concluded that the most likely outcome determined from epidemiological studies was that there would be one additional respiratory hospital admission every 5 years

Box 4.1

Del-EASI's Suggested Elements for a Successful Waste-to-Energy Operation

1. Site the plant away from inhabited area, preferable close to a power station and/or an existing landfill and/or near a commercial facility that could utilize steam, either as it is supplied by the WTE plant or as a feedstock for high-pressure steam.
2. Reduce the visual impact. A waste incinerator is a prominent feature in any landscape. However, there have been many designs that result in visually unobtrusive, yet impressive landmarks. Also install soundproofing into the walls, thereby creating an operating facility that is neater looking less smelly and less noisy than a landfill operation.
3. Enclose all operating areas, especially the waste collection facility, to prevent noxious odors from escaping into the environment. Negative pressure in the truck unloading area is necessary to achieve this.
4. Provide easy access for trucks delivering waste.
5. If possible, collect industrial waste with high caloric value (especially organic wastes from hospitality establishments: restaurants, fast-food, hotels, school and hospital cafeterias) and combine with "normal" municipal wastes. This is especially beneficial if one separates and removes recyclable "thermal value" materials, such as paper.
6. Provide for large enough waste collection bins at the plant to provide for greater homogenization of feedstock. Many current plants have a holding bin with a 3-day to one-week capacity.
7. Eliminate large, non-burnable objects by
   - removing metallic objects
   - reducing (hammer-milling) to small enough size.
8. Use high enough temperature (degree to depend on the eventual design) in the burning to get rid of odor and harmful by-products of incineration, especially the array of toxic dioxins.
9. Consider using water-cooled grates in the burner to allow higher burn-chamber temperatures in the kiln.
10. Reduce the need for "virgin" water for the operation by reclaiming used water from the cooling towers and scrubbers (with sufficient purification that may be necessary anyhow for the legal release of wastewater into the environment.).
11. Install catalytic beds to destroy traces of dioxins, furans and NO_R.
12. Remove (if step 7.a was not involved) metallic residue from the ashes. Zinc has been successfully and economically recovered from ashes where the wastes contained unusually large amounts of batteries.
13. Remove (leach out) heavy metals from the ashes, to be able to deposit the "clean" ashes in a regular landfill
14. Provide for a separate "toxic" landfill for all residues that cannot be shipped to a regular landfill
15. Partially dry any sludge-type residues intended for a landfill, to reduce the volume and weight of the material to be transported

.Source: Technical Advisory Office, Municipal Solid Waste Processes Assessment of Alternative Technologies

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from an individual incineration facility and one death every 100 years, both of which would be undetectable by any practical means. (p. 208).

The second study investigated health effects surrounding a modern incinerator in Spain. It found no difference in the levels of exposure to toxic substances (based on the analysis of blood samples) in residents living near the incinerator and those living further away. The conclusion from both studies and other investigations was that even studies based on the older generation of incinerators, which produced many more emissions than modern incinerators, have not shown clear indications of the presence or absence of health effects, even though some of the individual studies reviewed concluded that incineration has a negative effect on public health.[79]

Other public health risks are associated with the residue left over from the combustion process. This residue may contain elevated levels of hazardous constituents, such as heavy metals. However, most studies have shown that ash from municipal waste combustors is not a hazardous waste as defined in RCRA. Removing heavy metal contamination from the waste stream will help minimize the levels of heavy metals in the ash. Most (87%) of this ash is currently used as daily landfill cover, with the rest primarily used in road construction in preparing sub-bases.[80]

Environmental Risks

Most of the environmental risks from waste-to-energy facilities are related to or essentially the same as the public health risks.

In addition, a waste-to-energy facility is a large consumer of water used for cooling – an estimated 500,000 gallons per day is evaporated in the cooling towers of a typical 1,000 TPD facility[81]. Air cooling could be substituted for water cooling, but the facility would operate at a much lower efficiency if this were done, particularly during hot summer months when electrical demand is typically highest. No process water is required, and no wastewater discharges are expected.

A waste-to-energy facility has some significant indirect environmental benefits since the electrical energy it produces substitutes for electricity that would otherwise be produced from some other fuel source, eliminating the environmental costs associated with the extraction, transportation, and processing of the displaced fuel. Analyses of these indirect effects estimate that a 1,100,000 to per year facility would result in a net energy savings of 2.8×10^6 million BTUs per year (equivalent to about 820 million kwh of electricity or 483,000 barrels of crude oil). Life cycle analysis data concerning air and water emissions for both a waste-to-energy facility and truck transfer to a landfill 300 miles away are shown in Table 4.2.[82]

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[79] UK DEFRA "Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes" p. 140-141, 174-181

[80] The 2004 IWSA Directory of Waste-to-Energy Plants, Integrated Waste Services Association

[81] Estimate provided by Wheelabrator in their presentation to the Working Group on January 10, 2006.

[82] Three hundred miles, of course, would only apply to Delaware if the landfill option involved shipping the wastes to a landfill in, for instance, southern Virginia or western Pennsylvania.

Table 4.2
Life Cycle Analysis Comparison
Of a Waste-to-Energy Facility and a Landfill
Processing 1.1 Million tons of MSW per year

Parameter	Units	Waste-to-Energy	Landfill - Truck Transfer
Energy Consumption	MBTU	-2,851,765	765,809
Air Emissions			
Total Particulate Matter	Lb	-352,827	112,538
Nitrogen Oxides	Lb	-65,727	1,405,191
Sulfur Oxides	Lb	-2,714,649	-418,703
Carbon Monoxide	Lb	-389,960	1,618,060
Carbon Dioxide Biomass	Lb	551,582,197	484,449,329
Carbon Dioxide Fossil	Lb	-315,046,603	14,085,026
Hydrocarbons (non-methane)	Lb	-303,551	281,782
Lead	Lb	50	-6
Ammonia	Lb	9,331	-1,910
Methane	Lb	-569,259	13,339,090
Hydrochloric Acid	Lb	4,160	10,575
Water Emissions			
Dissolved Solids	Lb	-1,636,153	-235,935
Suspended Solids	Lb	-162,668	-34,554
BOD	Lb	-1,861	254,187
COD	Lb	-1,506	705,249
Oil	Lb	20,308	186,090
Sulfuric Acid	Lb	-1,807	-414
Iron	Lb	-9,457	-2,229
Ammonia	Lb	-598	8,160
Cadmium	Lb	-73	-12
Phosphate	Lb	-878	-155
Chromium	Lb	-73	-11
Zinc	Lb	-26	-3

Source: Life Cycle Study of Waste Management Options for Long Island, New York. Prepared by Keith Weitz at RTI International; provided by Wheelabrator Technologies

Worker Safety Issues

The operations of modern waste-to-energy facilities are highly mechanized with the waste being handled with conveyor facilities or mechanical equipment. Thus they would appear to create no unusual worker safety concerns. However, studies have shown that workers at municipal solid waste combustors are at a much higher risk for adverse health effects than the surrounding community.[83]

[83] National Academy of Science, Waste Incineration and Public Health – p. 168.

Energy Balance

The waste-to-energy facility is the only option evaluated that converts the energy embodied in the waste stream directly to heat for generating electricity rather than converting this energy into an intermediate energy source that is then used to generate heat.

Some small amount of energy is consumed in preparing the waste stream for processing in a waste-to-energy facility, but this is fairly minor.[84] Otherwise, this process consumes very little energy.

The amount of heat energy produced by the process depends upon the composition of the waste, the combustion efficiency of the process, and the moisture content of the waste. Modern waste-to-energy facilities usually have a closely controlled and high efficiency combustion process. Heating and evaporating moisture consumes about 1000 BTUs per pound of water. Thus, with 100 percent combustion efficiency, if the waste has an energy value of 5000 BTUs per pound and a moisture content of 40 percent, about 8 percent of the energy content of the waste is used in evaporating the moisture. At a more realistic combustion efficiency, it is reasonable to expect that the net energy value of the heat produced will be about 3100 BTUs per pound of waste. An aggressive recycling program that removed a large proportion of the plastics in the MSW feed stream would reduce the energy content of the waste. However, programs that removed yard trimmings, glass, metals, and food wastes would increase the net energy value.

Given the efficiency of the standard electrical generating station, the net result of this combustion will be about 900 BTUs per pound of waste, giving the process an energy balance of 18% to 20%.

Materials Balance

Modern waste-to-energy facilities have an overall recovery of 74 to over 90 percent of the incoming wastes depending upon how much the wastes have been processed prior to being burned. Most of the material is converted to electricity, with minor quantities of ferrous and non-ferrous metals. The technology employs combustion using 100% excess air resulting in large quantities of flue gas containing low concentrations of regulated air pollutants.

The residuals left over (bottom ash and materials captured by the pollution control devices) can sometimes be used for beneficial purposes such as daily cover for landfills and constructing sub bases for roads. However, if sufficiently contaminated, they may need to be disposed of in specially designed landfills.

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[84] If the facility includes a materials recovery facility (MRF), the energy consumption for preparing the waste stream would increase some. However, this is true of any process that incorporated a MRF, and this energy consumption is more appropriately associated with the operation of the MRF than with the operation of the conversion process. Therefore, it has been ignored in all of the evaluations.

Economics

The economics of waste-to-energy facilities are pretty clear since a number of these facilities are in operation, and the technologies well established. Air pollution requirements are a major cost element for such facilities. However, all of the cost estimates available to the Working Group were for facilities located in non-attainment areas, and, therefore, should be applicable to a facility located in Delaware.[85]

Processing Costs: A waste-to-energy facility having a capacity of about 1000 tons per day requires an investment of about $180 million, and even smaller facilities appear to cost in the range of $450 to $ 550 per ton of annual capacity, which is equivalent to a capital cost of $40 to $60 per ton of waste processed.[86]

Operation and Maintenance costs range from $30 to $45 per ton, giving a total cost of $85 to $90 per ton of waste processed.[87]

Revenues and Net Costs: The primary revenues produced by waste-to-energy facilities result from the electricity they generate. These amount to approximately $30 per ton of waste processed, although these estimates may be somewhat low given that energy process are rising. Other evaluations also indicate a value of $2 to $5 per ton of waste processed for other products such as metals, hydrogen chloride, and gypsum.

The resulting net cost is in the range of $50 to $75.

Legal and Policy Issues

S.B. 280, "An Act to Amend Title 7 of the Delaware Code Relating to Incinerators," prohibits the construction of incinerators outside of an industrial zoned area, and also within any area that is within 3 miles of a school, church or residence. Although no formal study has been undertaken of the matter, the restrictions imposed by S.B. 280 on any future waste-to-energy facility in the state appear to render the siting of such a facility all but impossible.[88] Thus, the statute would have to be amended prior to any waste-to-energy facility being constructed.

Were such an amendment to occur, any such facility would still need to obtain a variety of permits prior to operation. The most important such permit would be under the Clean Air Act. In the 1990 Clean Air Act Amendments, Congress enacted Section 129, which

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[85] The major air pollution control requirements are, as indicated above, the MACT emission control requirements imposed by EPA in 1995. Because Delaware is in a non-attainment area, such a facility might also have to acquire offsets, but the cost of these offsets has not been included in these cost estimates because they tend to be very site specific.

[86] Although the Working Group received cost estimates for a 100 TPD facility, this is too small for a commercial waste-to-energy and, therefore, the costs of such a facility are not reflected in this assessment.

[87] European costs appear to be 10% to 15% higher (ref: Eunomia Research and Consulting, "Costs for Municipal Waste Management in the EU: Final Report to Directorate General Economic, European Commission" (circa 2002).

[88] *See* McCabe, *Municipal Solid Waste Landfill Capacity in Delaware* at 56.

required EPA to issue New Source Performance Standards (NSPS) and other requirements under Section 111 of the Clean Air Act for different categories of new and existing "solid waste incineration units".[89]

Under Section 129, the NSPS and emissions standards adopted for solid waste combustion units must reflect the maximum available control technology (MACT). This means that EPA standards under CAA Section 129 must "reflect the maximum degree of reduction in emissions of [the listed] pollutants … that the Administrator, taking into consideration the cost of achieving such emissions reductions, and any non-air quality health and environmental impacts and energy requirements, determines is achievable for new or existing units in each category …." [90]

Accordingly, any solid waste incineration unit proposed to be located in Delaware would have to undergo the NSPS process applicable to the particular category of unit proposed, as established by the EPA under Section 129 and 111 of the Clean Air Act.

In addition to air permits, any facility proposed would qualify as a "Resource Recovery Facility" for purposes of DNREC's "Regulations Governing Solid Waste," and accordingly, the applicant would need to submit an application to DNREC pursuant to Section 4, subpart D of these regulations. Such an application would include an environmental assessment, including the requirement to mitigate any potential environmental impacts.[91] Additionally, the facility would have to meet the Operation and Maintenance Standards set forth in Section 9, Subpart D of the regulations.

Local land use controls would also apply to minimize offsite impacts such as odor and noise nuisances and thus prior to construction of any new facility, the applicant would need to submit an application to DNREC pursuant to Section 4, subpart D of those regulations. That permitting process would involve the imposition of various operation controls, set forth in section 9, subpart D of the regulations. Localized noise and odor nuisances would be addressed through this process, and in addition would be addressed through local land use controls.

Given all these legal requirements, the development time to have a waste-to-energy facility up and operating would be at least 8-10 years. This is longer than the time required for most of the other processes reviewed. The actual plant construction time is 2 to 3 years.

Gasification

Gasification is a process that subjects the wastes to high temperatures with limited oxygen inside a closed reaction vessel. The high heat breaks down the waste compounds and generates a gas synfuel containing hydrogen, carbon monoxide, methane, lighter hydrocarbons, and carbon dioxide. This synfuel can be used to generate heat for an electrical generating facility or other manufacturing process, or as a raw material for

[89] See 42 U.S.C. § 7429.
[90] 42 U.S.C. § 7429(a)(2).
[91] *See* Regulations Governing Solid Waste, 4.D.1.h.

chemical processes. Gasification operates at a higher temperature (1300 degrees Fahrenheit or higher) than waste-to-energy facilities and at pressures from 1 to 5 atmospheres. This temperature range is higher than that in which dioxins and furans are formed.

Versions of the gasification process have been in use for over a century to convert coal into synthetic gas.[92] The modern attempt to commercially apply this technology to the processing of solid wastes began about a decade ago in Europe. A 2004 survey found 39 facilities processing MSW in Europe and Japan.[93] However, it is not clear how economically viable these facilities are. One built in Italy to demonstrate the process was closed down after a few years, and a second built in Germany is also reported shut down because of a contract dispute. However, others seem to be operating on a continuous basis

The wastes are processed through the facility relatively quickly, and the only solid residuals remaining cool to an inert, glasslike product that the vendor claims can be ground up and used for sandblasting. The high heat vaporizes heavy metals such as mercury, lead, and zinc, but, in the process reviewed by the Working Group, the first step in cleaning the syngas generated by the facility is a quick quench which precipitates these compounds. The materials recovered from the quick quench can be sold to non-ferrous smelters as a high-grade ore.

There is vendor for this process in the United States representing the company that developed the ThermoSelect process (which actually includes a brief pyrolysis stage as a first step) that has been used in the many of the European and Japanese facilities. Other US vendors are not known to have built any commercial facilities processing MSW.

Readiness and Reliability

There are currently no gasification plants in the U.S. or Canada using MSW as a feedstock that can demonstrate that the technology is ready for on-line shelf-item performance. Most of the MSW gasification facilities are located in Japan, where solid waste disposal costs are very high, and most of these began operation after the year 2000.[94] Seven facilities are processing over 400 tons per day. Very few companies offer this technology for MSW.

Because of the present limited history, it is unlikely that many vendors could meet reasonable requirements for constructing a facility in Delaware. However, evaluations of alternative MSW processing technologies undertaken for the City of Los Angeles and Los Angeles County rated gasification as their highest or one of their highest choices.

Little is known about the reliability of these systems. Some of the European experience raises questions in this regard, and it has not been possible to obtain information about the

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92 A century ago most of the street lights in eastern cities burned “coal gas”.
93 Hackett *et al., op. cit.*
94 Hackett *et al., op cit*, p. 44.

reliability of the systems operating in Japan. However, the fact that these facilities continue to be constructed in Asia suggests that their experience has been reasonably positive.[95]

Inputs and Pre-Processing

Gasification facilities are able to handle the full range of MSW as well as other types of wastes susceptible to treatment by high temperatures. Sewage sludge needs to be preprocessed to reduce the moisture content to 20 to 25 percent. Appliances and bulky items need to be shredded before entering the process. It may also be prudent to cut up tires into small chunks before feeding them into the reactors. Otherwise, this is a process that is apparently very robust with respect to the waste stream.

Similarly, the system can handle variations within the waste stream without significant problems. The main issue here is the heat content of the feedstock. If the heat content exceeds 6000 BTUs per pound, the rate of feed has to be decreased. Monitors within the ThermoSelect system make these adjustments automatically.

The other major process inputs are natural gas to startup and moderate the process (1,270 cubic feet per ton of waste), diesel oil to assist in the ignition of the synthesis gas in the engine generators (about 2.2 gallons per ton of waste) as well as to operate waste moving equipment, electricity to operate the other equipment, and cooling water (about 875 gallons per ton of waste processed) for the electrical generating component of the process.[96]

At present, the optimal ThermoSelect reactor size is 386 tons per day. Thus a 1000 ton per day facility would have 3 reactors. Small variations in waste flows can be handled by the reactors, which can operate within a range of 50% to 110% of their design capacity.[97] Additional reactors can be added to respond to increased waste flows, although given the optimal capacity of each reactor, such expansion is not as easy as it is with systems employing smaller capacity modules. Again, it is best if this possibility is incorporated in the original design.

Public Health, Environmental, and Worker Safety Risks

Public Health Risks

Gasification is another thermal processing system and, therefore, might be thought to have the potential for generating public health risks similar to more traditional thermal processing systems (e.g. waste-to-energy). However, there are three characteristics of the gasification system which should eliminate some of these risks.

One is that the gasification occurs within a contained facility with no direct releases to the ambient air. A second is that gasification occurs at temperatures in the range of 1200 to

[95] For instance, a 1,600 ton per day gasification facility is being built in Kuala Lumpur, Malaysia. (Ref Hackett *et al, op. cit*., p. 45.

[96] Presentation to the Working Group by Frank Campbell, Interstate Waste Technologies, January 10, 2006.

[97] *Ibid.*

2000 degrees centigrade, temperatures higher than those that result in the formation of dioxins and furans. A third is that the start-up and shut down periods are significantly shorter - usually less than 15 minutes - than waste-to-energy facilities so that any releases during these periods would be of shorter duration than for mass burn units.

The ThermoSelect gasification system reviewed by the Working Group also incorporates a sophisticated pollution control system to process the gasses produced by the system.[98] A key element in this system is a "quick quench" process that uses a water spray to cool the gasses generated from a temperature of about 1200 degrees centigrade to less than 95 degrees centigrade immediately after the gas leaves the facility. This quenching operation precipitates the volatized metals such as zinc, mercury, and lead that are generated by the gasification process, removes entrained particulates, and allegedly cools the gases quickly enough to prevent the formation of dioxin and similar compounds. Other steps in the gas cleaning process include acid scrubbing, dust removal, desulphurization, and fine dust removal.

This gas cleaning train should result in a synthetic fuel that can be burned in an electrical generating facility or otherwise used without creating any greater public health risks than are associated with the use of natural gas. Indeed, the synthetic gas may well be cleaner than natural gas.

The solid residuals resulting from the unit are in two forms. One is the melt from the gasification unit itself which cools to an inert vitrified solid, and, therefore, should pose no significant public health risk. The other residuals are those collected in the gas cleaning process. The precipitant from the quencher has a sufficiently high metal content that it is a valuable raw material for metallurgical operations and therefore need not be disposed of in a manner that could threaten public health. Similarly the wastes resulting from the desulphurization process can be used as an industrial raw material. Potential uses or disposal requirements from the other air cleaning wastes are less clean, but these are expected to be very limited in volume.

A well-designed and operated gasification facility should not cause odor or noise problems. There could be a stigma, however, associated with living near such a facility because the lay public may consider it the same as a traditional mass burn water wall incinerator.

Environmental Risks

The environmental risks associated with a gasification unit would appear to be highly coincident with the public health risks. The water consumption associated with the operation of a gasification facility is minimal. ThermoSelect states that their units have no process water discharges.

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[98] The ThermoSelect system is the only gasification system that has commercially developed to any significant extent.

A gasification facility would also be expected to generate significant indirect environmental benefits. Some of these, like those resulting from waste-to-energy facilities, would result from the substitution of this source of energy for energy that would otherwise be generated using other fuel sources. No analyses estimating these indirect environmental benefits have been conducted for the gasification process, but extrapolating from those conducted for waste-to-energy facilities would suggest that the benefits would be similar to those shown in Table 4.2 in the waste-to-energy analysis.

Gasification would appear to have a more positive impact on the release of greenhouse gases than waste-to-energy facilities because a significant portion of the gas is in the form of hydrogen, which releases no greenhouse gases when it is combusted. A study undertaken for the European Union concludes that the impacts would be about the same as a waste-to-energy facility. However, this conclusion appears to be based upon an assumption that these facilities "provide virtually identical greenhouse gas fluxes" as a mass burn facility. This suggests that they did not take into account the cleaner burning fuel that these facilities produce. Thus, we conclude that a gasification facility should have a more positive impact on the release of greenhouse gases than either waste-to-energy or anaerobic digestion facilities.

The other indirect benefit would result from the reprocessing of the metal precipitate from the gas cleaning system. These indirect benefits are much more difficult to estimate, but the environmental costs of mineral extraction and the smelting and other processing of metal ores is significant.

Worker Safety Issues

The ThermoSelect process appears to be highly mechanized and involve very little direct interaction between workers and the waste stream. Therefore, it is expected that there would be no significant worker safety issues associated with this process.

Energy Balance

Gasification produces a gas that is a combination of hydrogen (H_2), carbon monoxide (CO) and Carbon dioxide (CO_2). The carbon dioxide, of course, has no energy value, but the hydrogen and carbon monoxide do. Information presented to the Working Group indicates that the three gasses are produced in approximately equal parts (by volume). This results in an energy value of approximately 4000 BTUs per pound of waste processed.

The gasification process requires energy input in the form of natural gas to initiate the gasification process, and electricity to move the wastes through the process. The information provided to the Working Group indicated that indicates that these inputs total slightly over 900 BTUs per pound of waste processed.

The process of converting these gasses into electricity in a traditional electrical generating facility results in the equivalent of 1150 BTUs of electricity being produced per pound of waste. Dividing this by the total energy inputs (including an assumed 5000 BTUs per pound of waste processed) results in an energy balance of about 20 percent. The review of alternative processing technologies undertaken for the City of Los Angeles concludes that gasification is the process having the highest energy efficiency – producing a net of up to 900 kilowatt hours of electricity per ton of waste processed.[99]

Materials Balance

The information presented to the Working Group indicated that gasification has an overall recovery of over 99 percent using MSW as the feedstock. The major product is a synthesis gas (syngas) and a minor quantity of ferrous and other metals is produced. The vendor claims that under normal conditions, there are no residuals that have to be disposed of in a landfill.

Economics

Although no commercial MSW gasification facilities have been built in the United States, several prospective vendors submitted proposals including cost estimates to the City of New York, the City of Los Angeles, and the county of Los Angeles. In these submissions, the cost estimates varied substantially although the revenue estimates were relatively consistent. In general, the factors influencing the cost estimates appeared to be the size of the facility (the larger the proposed facility, the lower the unit costs), and the experience of the vendor (or with the technology the vendor was proposing to use) with those having more experience generally estimating higher unit costs.

Processing Costs: The capital costs for a gasification facility are high, but demonstrate substantial economies of scale. A 300 TPD facility would probably cost at least 75 to 100 million dollars, a 1000 TPD facility 160 to 200 million dollars. The capital cost per ton of annual capacity thus ranges from $750 to $1000 for smaller units, down to $500 to $750 for the larger facilities.

Operation and maintenance costs are estimated to range from $50 to $100 per ton of waste processed, with the higher costs generally associated with smaller facilities. Some of the vendors submitting proposals to other evaluators estimated much lower O&M costs, but these estimates are suspect because of the vendor's lack of experience in operating such a facility.

The total costs per ton of waste processed are estimated to range from $110 to $200, with the lower range of costs associated with the larger facilities. Again, some vendors estimated lower processing costs, but these vendors generally had limited or no experience actually building and operating such facilities.

Revenues and Net Costs: The revenue estimates were generally in the range of $ 25 to $ 60 per ton of waste processed. Approximately 90% of the revenues are, in most cases,

[99] URS Corporation, "Summary Report: Evaluation of Alternative Solid Waste Processing Technologies" prepared for the City of Los Angeles Department of Public Works, September, 2005, p.20.

projected to come from the sale of electricity.[100] The other ten percent of the projected revenues are associated with recyclables collected from the system or the sale of the vitrified solid residuals as grinding or sand blasting media, a much less certain source of revenue.

The estimates of the tipping fee required for a gasification facility to break even cover a substantial range – from about $50 per ton of waste processed to as much as $200 per ton, with the lower fees generally being associated with the larger facilities. The cost information presented to the Working Group was at the low end of this range.

Legal and Policy Issues

A gasification facility would qualify as a "Resource Recovery Facility" for purposes of DNREC's "Regulations Governing Solid Waste." Accordingly, any such facility would need to submit an application to DNREC pursuant to Section 4, subpart D of these regulations. Such an application would include an environmental assessment, including the requirement to mitigate any potential environmental impacts.[101] Additionally, the facility would have to meet the Operation and Maintenance Standards set forth in Section 9, Subpart D of the regulations. Local land use controls would also apply to minimize offsite impacts such as odor and noise nuisances.

Because the gasification facility itself is totally enclosed and releases no air emissions, it would probably not require a permit under the federal and state clean air acts. However, the electrical generating units associated with the facility well might require such a permit. It is likely, however, that this permitting process would be more straightforward than that for a waste-to-energy facility.

However, a major regulatory obstacle to such a facility exists in the state, in that S.B. 280 may be interpreted as applying to gasification. The bill, as enacted, defines incineration as including "any structure or facility operated for the combustion (oxidation) of solid waste, even if the by-products of the operation include useful products such as steam and electricity." [102] In the absence of a legislative clarification, whether or not the gasification process fits within that definition is likely to be a subject of controversy and litigation. It is worth noting that an early version of S.B. 280, specifically identified gasification as being encompassed within the concept of incineration. Later versions of the bill, including the version ultimately enacted, removed any explicit identification of gasification as being included and focused the definition of incineration as "combustion (oxidation)." Gasification is not combustion in the sense the term is normally used, but does involve some oxidation.

Because of this ambiguity, it is quite possible that any effort to build a gasification facility would be subject to a court challenge, which could significantly delay the

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[100] However, it is not clear that the cost estimates include the costs of building and operating an electrical generating facility to use the gas produced by the gasification facility. If not, the revenues would be substantially overstated.
[101] *See* Regulations Governing Solid Waste, 4.D.1.h.
[102] 7 *Del. C.* § 6002(10).

development of the facility unless the law were amended to explicitly exclude such a facility from its definition of incineration.

Plasma Arc

Plasma arc technologies generate their heat by shooting high energy electrical arcs (equivalent to small lightning bolts) inside a chamber. In some of these processes, the arc is shot from an electrode at the top of an enclosed chamber into the waste materials. An alternative approach uses a plasma arc between an external anode and cathode to heat gasses circulated through the processing chamber to very high temperatures. The electrical discharge ionizes the gas it passes through creating plasma, which can reach temperatures of 7,000 degrees Fahrenheit, and the wastes reach temperatures in the range of 3,000 degrees. This extreme heat breaks down the organic and hydrocarbon molecules that comprise most of the waste into their atomic components – carbon, hydrogen, oxygen, etc. These components then react to form gasses – predominately carbon monoxide, carbon dioxide, and hydrogen (H_2). The system has a very high destruction efficiency. Inorganic materials are either volatilized by the high heat or form an inert lava-like fluid which is released from the bottom of the chamber. The synfuel gasses produced by the process can be used to fuel electrical generating facilities or chemical processes. Like the gasification process, the gasses have to cleaned before they are used.

Plasma arcs have been used in industrial processes for over a century, and for the destruction of chemical weapons and biological materials for several years. However, the application to MSW processing is limited primarily to a couple of relatively small plants in Japan.[103]

There are several vendors offering plasma arc MSW processing facilities. The largest of these, and the only one to have experience with commercial installations, is the Westinghouse Company.

Readiness and Reliability

Although used in other applications for many years, this technology has no history of processing MSW at a scale that would be significantly help Delaware. Attempting to scale up from the current sized demonstration units to a commercial sized facility that would be suitable for Delaware would not be consistent with good engineering practice. The technology's unique characteristics do offer consideration for some troublesome solid wastes such as chemical, medical and electronic wastes, but these are not the focus of the Working Group's evaluations. There are limited vendors for this technology, which would suggest that in a competitive bidding process, few responses would be received – also reducing the readiness rating. A study recently undertaken for the City of Honolulu also questioned the readiness of this technology.[104]

[103] Another 300+ tons per day plant is reported to being in startup in Rome. (Ref., R.W Beck, Inc, report prepared for City of Honolulu, Review of Plasma Arc Gasification and Vitrification Technology for Waste Disposal, January 23, 2003, available at http://www.opala.org/TechStudies/plasma.html.

[104] R.W.Beck, Inc., "City of Honolulu: Review of Plasma Arc Gasification and Vitrification Technology for Waste Disposal" January 23, 2003.

With respect to reliability, no performance data were available although the vendor making a presentation to the Working Group asserted, on the basis of experience with a demonstration facility, that the units are very reliable and would not be expected to experience more than one upset a year which would take the unit out of production for one or two days. In a large facility, several modules would most likely be operating in parallel, so that even if one were taken out of service, the others could keep operating. .

Although the Working Group rates the readiness of this technology relatively low, it does show some significant promise and its development should be followed closely.

Inputs and Pre-Processing

Plasma Arc facilities are said to be able to handle even a wider range of wastes than gasification facilities. Indeed, most of the facilities currently in operation are processing waste streams such as military ordinance and waste-to-energy slag that cannot be processed by other types of facilities.[105] The pre-processing requirements are probably very similar to those described for the gasification facility. The Working Group received no information indicating whether or not the heat content of the wastes was a factor affecting the processing rate. As with any thermal process, dewatering sludge before feeding it to the process increases efficiency.

The major input for a plasma arc facility is the electricity required to operate the arc (approximately 527 kwh per ton of waste processed).[106] Additional fuel and electricity is required to operate the equipment, and cooling water for any associated electrical generating facility.

Plasma arc reactors, as currently being proposed, are somewhat smaller than the reactors proposed for the gasification process – having a capacity of about 200 tons per day.[107] Thus a 1000 ton per day facility would require 5 reactors. The capacity can be increased to respond to increased waste flows by installing additional reactors. During periods of reduced waste flow, reactors can be shut down.

Public Health, Environmental, and Worker Safety Risks

Public Health Risks

The plasma arc conversion process would, like the gasification process, occur within a contained unit with no direct environmental releases. The temperature within the unit is even higher than that within a gasification unit and, therefore, should not result in the formation of dioxins or related hazardous substances. The time required for start-up and

[105] See R.W.Beck, Inc, "City of Honolulu Review of Plasma Arc Gasification and Vitrification Technology for Waste Disposal", January 23, 2003.
[106] This is for the process presented to the Working Group.
[107] Of course, this is much larger than any of the plasma arc reactors that have yet been built to process MSW, and whether they can process at this rate reliably remains to be seen.

shut down is reportedly shorter than that required for gasification units, and should be another factor reducing releases that could create public health risks.

The higher temperatures within the plasma arc unit make the volatilization of certain metals and other potentially hazardous substances a major concern. Presumably, the gases produced could be cleaned in a manner similar to that adopted by the ThermoSelect gasification process. Unfortunately, the vendor briefing the Working Group on the plasma arc process was unable to provide any detailed description of the proposed gas cleaning process, so this remains a theoretical possibility.

The melt from the plasma arc process is, like the gasification process, an inert vitrified material presenting apparently little public health risk, regardless of how it is disposed of.[108] The residuals from whatever gas cleaning process is employed would be expected to create the same opportunities and risks as those from the gasification process.

A well-designed and operated plasma arc unit would not cause substantial odor or noise issues. There could be a stigma, however, associated with living near such a facility because the lay public may consider it the same as a traditional mass burn water wall incinerator.

Environmental Risks

The environmental risks resulting from the plasma arc process would be expected to be substantially coincident with the public health risks. The Working Group was presented with no information on these risks.

A plasma arc unit would apparently require little process or cooling water, but no information was presented to the Working Group regarding these requirements, or about any waste water discharges.

The indirect environmental benefits associated with the plasma arc process would be expected to be similar to those associated with the gasification process, at least in terms of the indirect benefits resulting from the production of synthetic gas. The vendor presenting this technology to the Working Group claimed that a high proportion of the synthetic gas produced by a plasma arc facility is in the form of hydrogen.[109] If this is true, these indirect benefits could be particularly significant assuming that the hydrogen could be separated from the other components of the syngas.[110] The hydrogen could then be used as a source of energy without any negative environmental effects, including the production of greenhouse gases. The conversion of hydrogen into other forms of energy results only in the formation of pure water. There are no other releases. Therefore, if the information provided about the

[108] This might not be true if the material were finely ground up and released to the environment, for instance by being used as a material in sand blasting. Not only would the dust particles create potential respiratory problems, but contaminates in the material might increase these risks.
[109] However, as discussed below under energy balance, the accuracy of this claim is uncertain.
[110] The vendor making the presentation of the plasma arc process to the Working Group said that they had developed a filter that would separate the hydrogen gas from the rest of the syngas.

composition of the synthetic gas is correct, the plasma arc process would, by this measure, probably be the most advantageous of the processes evaluated.

Worker Safety Issues

The Working Group was presented with insufficient information regarding how a plasma arc facility would operate and thus was unable to determine whether there would be any significant worker safety issues. It is probably reasonable to expect that such facilities would be highly mechanized, minimizing such risks.

Energy Balance

The vendor making a presentation to the Working Group claims that the gasses produced in this process are particularly high in hydrogen (45%) and carbon monoxide (45%), giving them a very high energy value. However, from a chemical engineering perspective, it is not clear why this should be the case. Furthermore, tests run by Westinghouse at a pilot facility processing MSW showed a very different gas composition: 5%-15% Hydrogen, 15%-30% CO, 40%-60% nitrogen, 10%-20% carbon dioxide, and 0.5%-2% methane.[111]

The assumptions about the composition of the gas obviously have a significant effect on the energy balance of the process. If we accept the vendor's claims, we estimate that gas plasma would have an energy balance of about 21 percent, assuming that the gas is used to generate electricity in a conventional steam-electric power station. Using the gas with a lower energy value would reduce this balance.

Materials Balance

The plasma arc technology converts virtually 100 percent of the wastes into useful products. The major product is a synthesis gas (syngas) and only minor quantities of ferrous and non-ferrous metals are produced.

Economics

The cost estimates for a plasma arc conversion processes provided to the Working Group were incomplete and sketchy, and only two other evaluations included estimated costs for such a facility. This may not be surprising since no vendor has any significant experience in building and operating commercial MSW facilities using this technology. The lack of information again emphasizes the high degree of uncertainty associated with this process.

Processing Costs: The capital costs for such a facility are very uncertain. The vendor providing information to the Working Group estimated that a 100 TPD facility would require an investment of $30 million. However, it was not clear what in addition to the plasma arc furnace was included in this estimate. This is equivalent to approximately $1000 per ton per year capacity. The other evaluators received estimates ranging from one-tenth this value (for much larger facilities) to fifty percent higher. It seems unlikely that the

111 Power Point briefing on Westinghouse Plasma System Technologies provided to DSWA.

investment required to build a plasma arc facility would be any less than that required for a gasification facility, and it could well be higher.

Even less information was available about the operation and maintenance costs. The estimates presented ranged from $20 up to $160 per ton of waste processed. Again, it is unclear why a plasma arc facility should operate at a lower cost than a gasification facility.

Given these wide cost ranges, the total cost of a plasma arc facility would probably exceed $ 100 per ton, and could well be in the range of $200 per ton.

Revenues and Net Costs: The revenue estimates were even sketchier and appear to vary more than the cost estimates. The vendor providing information to the Working Group had apparently submitted a proposal to New York City to construct a 2000 TPD facility claiming that it would generate a net profit of about $15 per ton of waste processed. This appears to imply revenues in the range of $100 per ton. Apparently these high revenue estimates are based on the value of the hydrogen in the gaseous product, although there was no information provided the Working Group on what values were used for calculating these revenues.

If all the gas produced were used to generate electricity, the revenues might be somewhat higher than those estimated for gasification as a result of the apparently higher percentage of hydrogen in the gas.

Given all these uncertainties, it is not surprising that estimates of the tipping fee required for a plasma arc facility to break-even ranged from zero (or even a minus $15) up to almost $200 per ton of waste processed.

Legal and Policy Issues

A gas plasma conversion facility would qualify as a "Resource Recovery Facility" for purposes of DNREC's "Regulations Governing Solid Waste." Accordingly, any such facility would need to submit an application to DNREC pursuant to Section 4, subpart D of these regulations. Such an application would include an environmental assessment, including the requirement to mitigate any potential environmental impacts.[112] Additionally, the facility would have to meet the Operation and Maintenance Standards set forth in Section 9, Subpart D of the regulations. Local land use controls would also apply to minimize offsite impacts such as odor and noise nuisances.

As with gasification, gas plasma processing units emit no air emissions, and, therefore, would probably not require an air pollution control permit. However, the gas produced by the unit is used to generate electricity, the electrical generating facility would need a permit.

However, a major regulator obstacle to such a facility exists in the state, in that S.B. 280 may be also interpreted as applying to gas plasma conversion. The bill as enacted defines incineration as including "any structure or facility operated for the combustion (oxidation)

[112] *See* Regulations Governing Solid Waste, 4.D.1.h.

of solid waste, even if the by-products of the operation include useful products such as steam and electricity."[113] In the absence of a legislative clarification, whether or not the gas plasma conversion process fits within that definition is likely to be a subject of controversy and litigation.

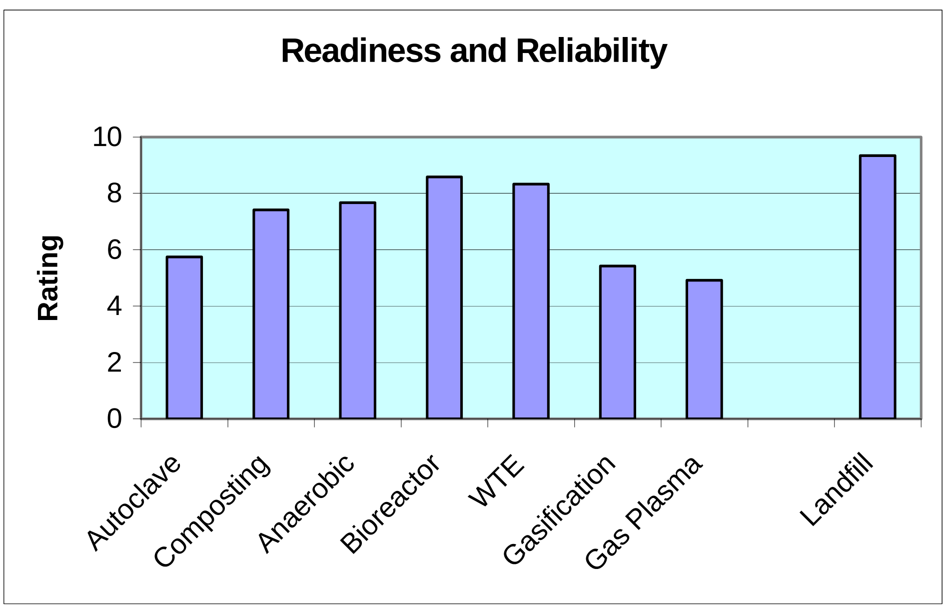
[113] 7 *Del. C.* § 6002(10).

Conclusions

Based on these evaluations, the members of the Working Group assigned a summary rating on a scale of zero (very unfavorable) to ten (very good) to each of the technologies for each of the seven evaluation criteria. These ratings integrated, admittedly subjectively, all of the various factors considered in the evaluations. As indicated in Chapter 3, these ratings are not on a mathematical scale. For instance, a rating of 8, although significantly better, is not necessarily twice as good as a rating of 4. Nor can the ratings be added together to provide a summary score. Nevertheless, we believe they provide a useful qualitative summary of our evaluations. We also included a summary rating for the conventional landfill to provide a point of comparison.

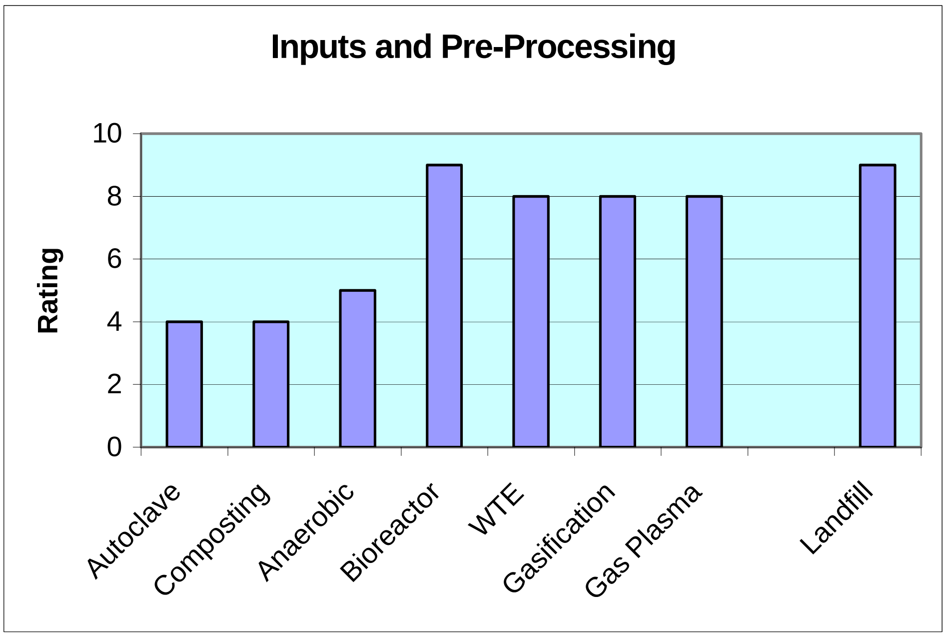
Readiness and Reliability

As indicated in the chart below, the technologies with the highest rating with respect to readiness and reliability are conventional landfills, bioreactor landfills, and waste-to-energy. These are the only technologies that have already been employed in a large number of commercial units in operation over a sufficient length of time to have clearly demonstrated their commercial viability and reliability. The biological processes, followed by the autoclave/mechanical process, rate slightly lower. The other thermal processes rate lowest.



Inputs and Pre-Processing

None of the processes is able to handle all of the waste streams considered, at least without some pre-processing. As indicated in the chart below, conventional landfills and bioreactor landfills are rated highest on this criterion as well. These facilities require little preprocessing and separation of the wastes before disposal. The thermal processes, waste-to-energy, gasification, and plasma arc, rate a little lower because they too accept most wastes with limited pre-processing. Sewage sludge, for instance, needs to be dewatered before being fed into thermal facilities. Anaerobic digestion is rated somewhat lower because it only processes organic wastes. Depending upon the particular anaerobic system, materials not subject to bacterial digestion can be fed into the process (as long as they are not too large) but will emerge unprocessed. The autoclave and aerobic composting processes are rated lowest because they also have limitations on what materials they can process and because potentially substantial additional pre-processing is required to remove undesirable materials from MSW if the end product is to find widespread use as a soil conditioner.

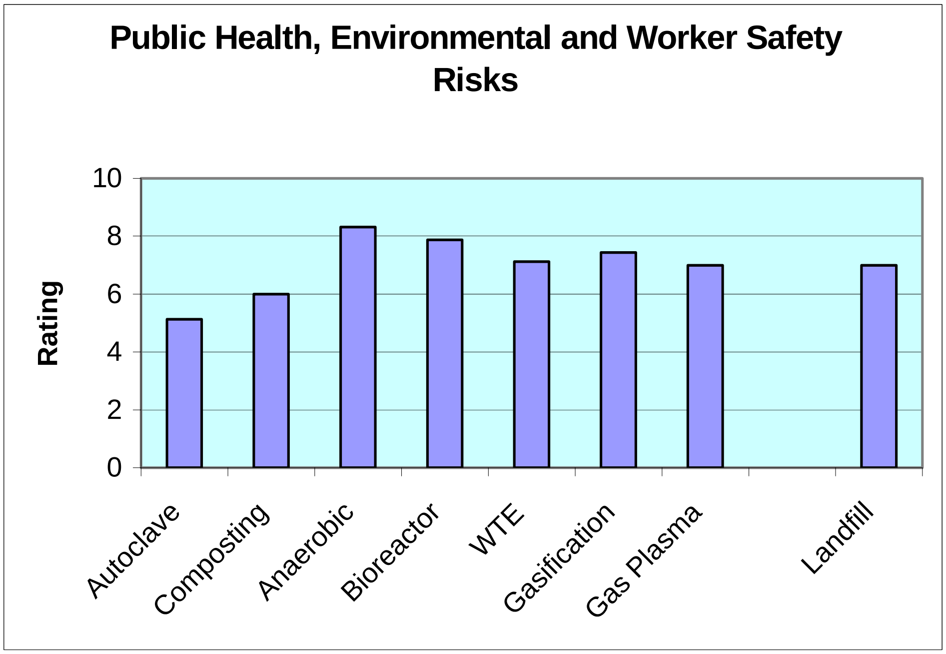


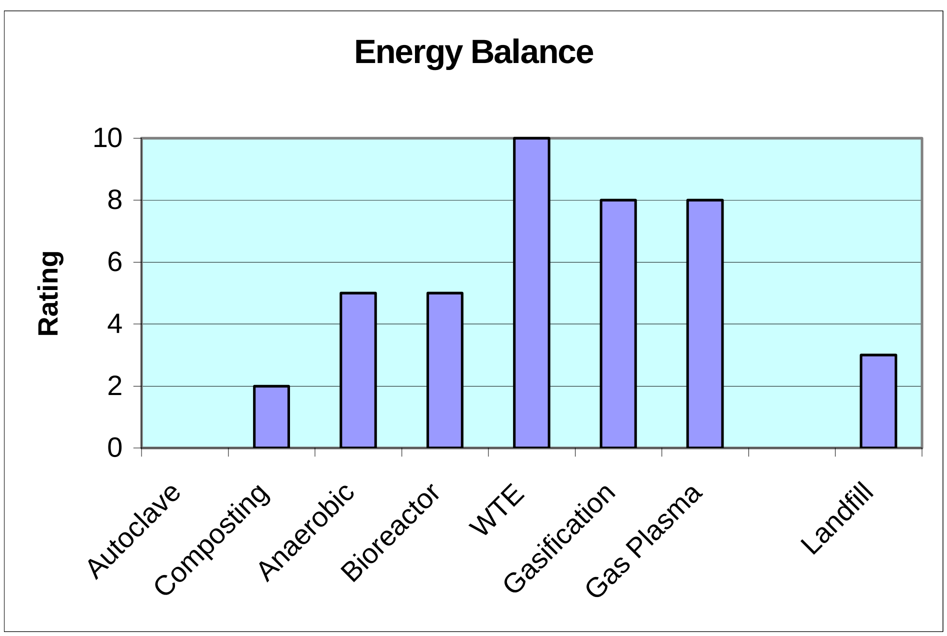
Public Health, Environmental, and Worker Safety Risks

None of the processes rate badly according to this criterion, and environmental releases from all the processed are expected to fall under, and in many cases well under, emission limitations in both the United States and Europe. The anaerobic digester is rated highest because it generates no hazardous substances and the process is totally enclosed preventing the release of obnoxious gasses. The bioreactor landfill is close behind for similar reasons.[114]

The thermal technologies (waste-to-energy, gasification, and gas plasma) are rated next because advanced pollution control systems have demonstrated their ability to capture and remove any hazardous substances these systems generate. Autoclave/mechanical and aerobic composting are rated lowest because, unless there is substantial pre-processing of

[114] The Bioreactor landfill, of course, is not totally enclosed, but it is designed, constructed, and operated so as to maximize the collection of the gasses it generates.


Public Health, Environmental and Worker Safety Risks
Rating
10
8
6
4
2
0
Autoclave
Composting
Anaerobic
Bioreactor
WTE
Gasification
Gas Plasma
Landfill


Energy Balance
Rating
10
8
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Autoclave
Composting
Anaerobic
Bioreactor
WTE
Gasification
Gas Plasma
Landfill

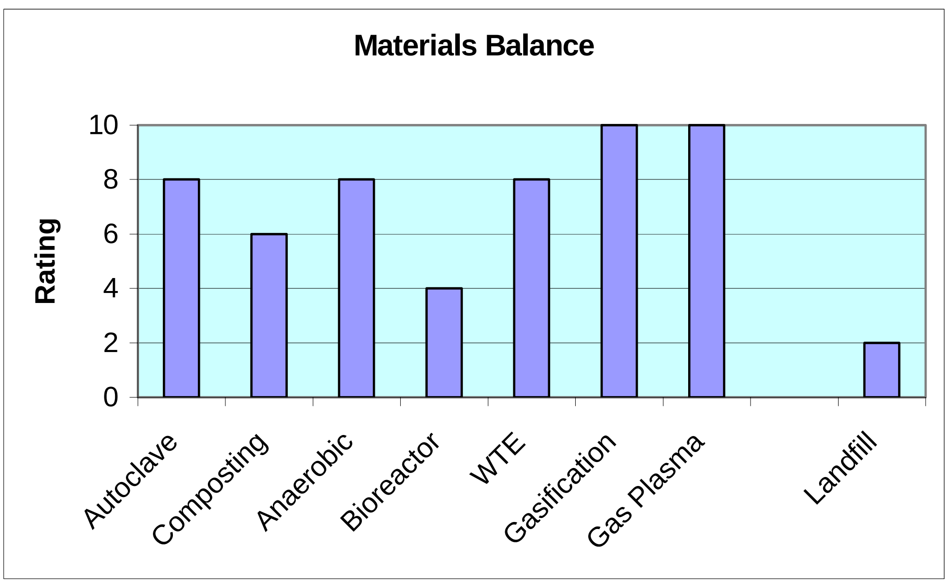
the waste materials, the use of their product as a soil conditioner could release hazardous substances to the environment.

Energy Balance

With respect to the energy balance, the waste-to-energy process rates highest because it generates the highest net amount of useable energy. The other thermal processes also demonstrate a high net energy balance. The products of the anaerobic digestion process and the bioreactor landfill can also be used to generate electricity, although their net energy balance is lower than the thermal process. The aerobic composting process does not generate such a product but consumes a limited amount of energy in the process.[115] The autoclave/mechanical process also does not generate such a product and, in addition, consumes substantial amounts of energy in processing the wastes.

Materials Balance

By this criterion, the gasification and plasma arc processes rate highest because they have the lowest residual rates. Anaerobic digestion and autoclave/mechanical processing are close behind. The landfill alternatives, by definition, are not processes that reduce the amount of waste materials that has to be landfilled.

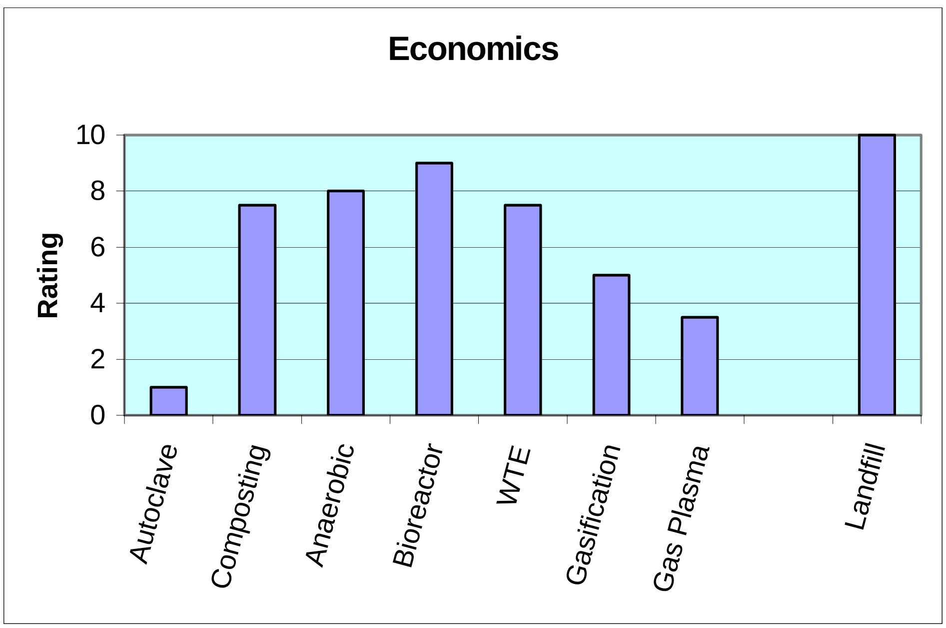


[115] The products of both the aerobic composting process and the autoclave process could be used as refuse-derived-fuel for a mass burn facility or as a feedstock for the gasification or plasma arc energy producing processes. However, the benefits of processing the wastes through the autoclave or composting processes before feeding them to a thermal process were not clear to the Working Group.

Economics

In terms of net cost per ton of material disposed of, it is hard to beat the conventional landfill in areas with reasonable land prices (not necessarily a condition that applies in Delaware). Anaerobic digestion, aerobic composting, and waste-to-energy are rated slightly lower. The cost of anaerobic digestion appears to be lower than the cost of some of the other processes and it generates a valuable product. The cost of aerobic composting appears to be even lower, but the value of its product is limited unless substantial pre-processing occurs (which would increase its cost). Waste-to-energy is relatively expensive, but it produces a valuable product. Increases in electricity prices would increase the ratings for waste-to-energy and anaerobic digestion relative to aerobic composting. The ratings for gasification and gas plasma reflect the expected higher costs for these processes as well as substantial uncertainty about what these costs would actually be. Here again, the ratings for these processes would be improved by increased energy prices.

The autoclave/mechanical processing option rates lowest because it is expensive to operate and there is no demonstrated value for the end product in Delaware.



Legal and Policy Issues

The permitting process for any new MSW processing or disposal facility is likely to raise several legal and policy issues. This is particularly true for thermal processes, and for any facilities located in Delaware's coastal zone. The biological processes (composting and anaerobic digestion) and autoclave/mechanical process are expected to raise the fewest difficulties. A waste-to-energy facility is expected to raise the most, primarily because of the perceived public opposition to this process and the fact that current Delaware legislation restricting the siting of incinerators would most likely have to be amended or repealed by the

General Assembly before such a facility could be built in the state. The rankings for both gasification and gas plasma would fall substantially if they were also found to fall under the restrictions of this legislation. Given the extent of development that is occurring in Delaware, finding an adequate site for a new landfill would probably also be difficult.