# CLEAN FUELS FROM MUNICIPAL SOLID WASTE FOR TRANSPORTATION IN NEW YORK CITY AND OTHER MAJOR METROPOLITAN AREAS

Eric D. Larson
Ernst Worrell
Jeffrey S. Chen*

PU/CEES Report No. 293

January 1996

*Center for Energy and Environmental Studies*
*School of Engineering and Applied Science*
*Princeton University, Princeton, NJ*

Prepared with financial support from The New York Power Authority, The Energy Foundation, The Merck Fund, The W. Alton Jones Foundation, The Geraldine R. Dodge Foundation, and The Research Institute for Innovative Technology for the Earth.

---

* Present address: Thermo Fibertek, Inc., 35 Sword St., Auburn, Mass., 01501.

*Table of Contents*

## Executive Summary

This report is based on a detailed study by Princeton University's Center for Energy and Environmental Studies assessing the technical, economic, and environmental feasibility of producing clean transportation fuels from municipal solid waste (MSW). The primary purpose of this report is to communicate the implications of Princeton's technical findings to policy makers in major metropolitan areas of the US, taking New York City as an illustration.

Increasing volumes of MSW pose increasing disposal problems in New York City and other major urban centers. Costs for landfilling in New York are high and rising as the Fresh Kills landfill approaches capacity. The primary alternative disposal option--incineration--is politically contentious and will be difficult, if not impossible, to implement. Composting and anaerobic digestion are suitable options for only a very limited portion of the waste stream. The production of clean transportation fuels from MSW is a promising alternative disposal option that has not received much attention from waste management and other decision makers.

Methanol or hydrogen fuel can be produced from MSW via gasification followed by additional gas processing. An attractive feature of such systems is that elimination of essentially all air pollutant emissions is intrinsic to the process: stringent gas clean up steps are required immediately following the gasification step to protect downstream catalysts from poisoning. Current and future air emissions standards should be easily met.

Using MSW-derived methanol or hydrogen as transportation fuels can help address other problems as well, including deteriorating urban air quality due to vehicle pollution and heavy dependence of the transport sector on imported petroleum. Furthermore, MSW contains largely renewably-produced material, so its use for transport energy would reduce net emissions of $CO_2$ to the atmosphere, assuming it displaces fossil fuels.

While hydrogen and methanol can be used to fuel internal combustion engines, their use in fuel cell vehicles (FCVs) may be considerably more attractive both economically and environmentally. The commercialization of fuel cell vehicles is being aggressively pursued in the US through the *Partnership for a New Generation of Vehicles*, a joint initiative of the US automobile industry and the federal government announced in September 1993. Commercialization efforts are also ongoing in Europe. Fuel cell vehicles are projected to have on-the-road performance comparable to IC engine vehicles, but with double or triple the fuel economy and zero or near-zero tailpipe emissions. Buses are initial targets for commercial applications. The City of Chicago has announced its commitment to purchase and put into service

in 1996 three hydrogen/fuel cell buses. If these trials are successful, Chicago will consider converting its 2,000 public bus fleet to fuel cell power. Similar trials are under discussion for other cities, including Washington DC, Los Angeles, a suburb of San Diego, and Vancouver (British Columbia). Commercial introduction of passenger FCVs is likely to follow buses within a few years.

Coupled with FCVs, MSW is a potentially major transportation energy resource for New York City and other metropolitan areas. Because of the high fuel economy of FCVs, methanol derived via gasification from the present total MSW generated in New York City could provide the fuel for over 30% of all car and light-duty truck vehicle-miles in New York City. Conversion efficiencies would be higher with hydrogen--over 40% of all vehicle-miles could be provided from MSW in this case. As for the New York City bus fleet, less than 25% of the City's MSW supply would be sufficient to produce the methanol or hydrogen needed to fuel the entire 3800 bus fleet.

Estimated breakeven tipping fees required for hydrogen or methanol from MSW to compete with the estimated cost of producing these fuels from natural gas today are $47 to $81/raw ton MSW for hydrogen and $58 to $94/raw ton MSW for methanol (in 1991$), depending on the gasification technology considered. For comparison, the present average tipping fees at the Fresh Kills, New York City landfill is $67/ton (1991$). The tipping fee in Philadelphia is about $70/ton. New Jersey has some of the nations highest tipping fees, including $110/ton in Newark and $108/ton in Mercer County (Princeton's home). Because of the high efficiencies and expected longer lifetimes for FCVs, total lifecycle costs per vehicle-mile could very well be lower than for comparable internal combustion engine vehicles (at present US gasoline prices) with tipping fees lower than the breakeven estimates noted above. Some quantitative results are presented in this report for buses and passenger cars.

All unit processes required for fuels production from MSW other than gasification are commercially well established. Pilot-scale development work has been done on MSW gasification, and several commercial orders have been placed (in Europe) for one manufacturer's gasifier design, where the gas will fuel an internal combustion engine electricity generating unit. Additional research, development, and demonstration efforts are needed to bring clean fuels production from MSW to commercial reality. Three major follow-on actions to this report are recommended.

*To help catalyze the commercial development of fuels production technology, additional pilot-scale and subsequent commercial-scale demonstrations are needed for MSW gasifiers alone*

*and coupled with downstream fuels production systems.* Demonstrations should include comprehensive emissions measurements (air, liquid, solids), especially for dioxins. Special focus on indirectly-heated gasifiers appears warranted based on the preliminary economic assessment in this report, but it would be useful to encourage competitive development efforts among alternative gasifier developers. In this regard, it should be noted that the one MSW gasifier design that is now being offered commercially has undergone extensive (and successful) pilot-scale emissions and operational testing. Detailed total-system engineering design efforts are needed to refine the preliminary cost estimates presented here and to improve understanding of unit level operations.

*With reference to a specific metropolitan area (e.g. New York City), the potential role for fuels production from MSW should be evaluated within the context of alternative integrated waste management strategies.* This should include assessing alternative technological strategies, including fuels production, composting, anaerobic digestion, recycling, electricity production via incineration (primarily for reference, as future construction of incinerators seems unlikely in many major metropolitan areas), and any other potentially important options. Technology readiness, lifecycle costs, lifecycle environmental impacts, infrastructure requirements and other factors should be evaluated. This evaluation would also require a detailed assessment to be carried out of the waste stream of interest to determine potential quantities and qualities of feedstocks available for gasification versus other waste management options.

*The state of advancement of technology for fuels production from MSW and for utilization of these fuels in fuel cell buses, taken together with the prospective benefits of using these technologies, are such that planning for major bus demonstration projects can be initiated.* The City of Chicago has announced plans to demonstrate hydrogen buses in its public fleet beginning in 1996. Similar trials are under discussion for other cities. Hydrogen from natural gas will be used to fuel such early trials. Building on the experience in Chicago and elsewhere, New York City and other metropolitan areas could begin detailed analysis and planning for conversion of some or all of their public bus fleets to fuel cell power, with fuels made from MSW.

## 1. Introduction

New York City faces a major environmental challenge in dealing with growing volumes of municipal solid waste (MSW). New Yorkers generate an estimated 17,000 tons daily [Rockwell, 1994], most of which is not recycled and disposal costs for which are rising steadily. By some estimates, the Fresh Kills Landfill is expected to reach capacity by the turn of the century, and federal legislation has been proposed that could significantly reduce options for New York to transport waste out of state [Connor, 1995]. While recycling will help reduce waste volumes, reaching the target recycle rate of 25% by 1996 will still leave significant quantities for disposal.

The production and use of methanol or hydrogen transportation fuels from MSW--the subject of this report--is a waste management option that has not received serious recent attention. The idea of producing methanol from MSW did receive some attention from developers in the 1970s, when oil prices were high, but once oil prices fell, development work stopped, because methanol from MSW would have been more costly than gasoline, and the environmental benefits of methanol over gasoline in internal combustion engine vehicles were marginal. The potential environmental benefits of converting MSW to methanol instead of incinerating it were not sufficiently well understood to motivate continued work on the methanol option.

Five factors have fundamentally changed the outlook for clean transportation fuels from MSW: *(i)* landfill space is in considerably shorter supply; *(ii)* tipping fees have increased substantially, thereby improving the prospective economics of using MSW as an energy feedstock; *(iii)* public opposition to new incinerators for waste disposal/energy production has effectively eliminated this as a future option, at least for New York City; *(iv)* there is now clear empirical evidence that environmental benefits of fuels production from MSW would be substantial compared to incineration; and *(v)* stimulated by state and federal transportation policy initiatives, major advances in vehicle technology are occurring that will lead to clear environmental benefits for methanol or hydrogen fuel vehicles, while maintaining cost competitiveness with gasoline vehicles, even with low oil prices.

The last of these factors is a critical, relatively recent development. To address deteriorating air quality, the states of New York and Massachussetts, following the lead of California, are now requiring that zero emission vehicles (ZEVs) constitute 2% of new car

sales by 1998, ramping up to 10% by 2003. A coalition of 10 other Northeast states and the District of Columbia are considering adopting similar requirements. In light of serious pollution problems in megacities of the world like Mexico City and Sao Paulo [UNEP/WHO, 1992], such policies are likely to become widespread.

The battery-powered electric vehicle is the only commercially available technology that can meet the near-term ZEV mandate. However, a more attractive vehicle option from many perspectives is the fuel cell vehicle (FCV). Like a battery, a fuel cell converts chemical energy directly into electricity. Unlike a battery, the chemical energy is continuously supplied in the form of hydrogen or a hydrogen carrier like methanol. No combustion is involved in the operation of the fuel cell, and the only significant compound emitted to the atmosphere is water vapor that results from the reaction of hydrogen and oxygen.

In addition to their attractive environmental performance, FCVs will have double to triple the fuel economy of comparable-duty internal combustion engine vehicles (ICEVs) due to the high efficiency of fuel-to-electricity conversion in a fuel cell. Thus, the fuel cost to the consumer per mile of vehicle use should be competitive with that for a gasoline-ICEV even if gasoline prices are relatively low and FCV fuel prices are relatively high.

The commercialization of fuel cell vehicles is being aggressively pursued in the US through the *Partnership for a New Generation of Vehicles*, a joint initiative of the Big-3 US automobile companies and the federal government announced in September 1993 with the aim of developing within a decade production-ready prototypes of low polluting cars with triple the fuel economy of today's gasoline ICEVs, without sacrificing performance. Commercialization efforts are also ongoing in Europe. Most of the efforts today are focussed on the development of FCVs that would use proton exchange membrane (PEM) fuel cells [Williams, 1994]. Based on projected performance and costs for PEM FCVs, even when using relatively high cost fuels like hydrogen or methanol, the total lifecycle cost per mile driven is projected to be competitive with that for gasoline ICEVs at the present world oil price, as discussed later in this report.

The largest future market for FCVs will be passenger cars, but the FCV will first be widely introduced in buses and trucks, because storage volumes for fuel cell fuels, which have considerably lower volumetric energy densities than gasoline, are less constrained. Also, the cost per horsepower for a bus engine is higher than that for a passenger car power plant,

which provides an easier target for fuel cells. Furthermore, buses operate more frequently at lower engine loads.[2] This provides a fuel efficiency boost for the fuel cell bus, because efficiency increases with decreasing load for a fuel cell [Kartha and Grimes, 1994], while it drops with decreasing load for a diesel engine. Several commercially-oriented demonstration projects of fuel cell buses are well underway in the US, Canada and Europe, and rapid advances are being made. Ballard Power Systems, Inc. of Vancouver, Canada, introduced a prototype PEM fuel cell bus in 1993, followed by a second generation unit in 1995. They plan to offer commercial sales by the beginning of 1998. H-Power, another company has announced intentions to have a fuel cell bus on commercial offer in 1997 [Hoffman, 1995]. The City of Chicago will put three hydrogen-fueled commercial prototype Ballard buses into service in 1996 [Chicago, 1995]. If this demonstration is successful, Chicago will consider converting all 2000 of its public buses to fuel cell power. Similar trials will also begin soon in Washington DC and Sacramento, California, and are under discussion for several other cities.

If fuel cell buses were to be commercially available by 1998, New York City would have a near-term option for significantly improving air quality by introducing them into the city's 3800-bus fleet. Such an initiative would also help catalyze the wider commercial introduction of FCVs. Fuels for a fuel cell bus fleet could initially be provided from existing sources of hydrogen or methanol (as is planned for the three-bus demonstration in Chicago), while the technologies for deriving these fuels from MSW are brought to commercialization and the needed infrastructure for fuel production and delivery is put in place.

The subsequent four sections of this report draw on the results of a technical, economic, and environmental assessment of methanol and hydrogen production from MSW carried out at Princeton University's Center for Energy and Environmental Studies [Chen, 1995]. The report concludes with a set of recommendations for catalyzing the development of MSW into a major transportation energy resource for urban areas like New York City.

## 2. Technology for Fuels Production from MSW

The production of methanol or hydrogen from MSW involves a series of chemical and physical reaction steps. Details will vary with specific technologies. Figure 1 shows the

[2] The average bus travel speed in Manhattan is 3.6 miles per hour [Pellegrin, 1995].

basic process blocks. With the exception of the gasifier, a facility producing methanol or hydrogen from MSW would utilize unit operations commonly found in many chemical refining and synthesis processes today. In fact, downstream of the gasifier the chemical reactors and other gas processing equipment are the same as those used in producing methanol or hydrogen from natural gas--the principal feedstock for production of these fuels today. The overlap in process technologies between existing commercial methanol and hydrogen production and those needed for production from MSW facilitates understanding and quantifying the technical performance that can be expected in the latter.

*Feed preparation*

For the production of methanol or hydrogen, MSW would first undergo processing to prepare it for gasification. One gasifier design that is now being offered commercially by Thermoselect, Inc. (see next sub-section) accepts raw, unprocessed MSW. All other proposed MSW gasifier designs require the removal of non-combustible elements, followed by sizing and mixing of the remaining components into a refuse-derived fuel (RDF). RDF can be produced as fluff, briquettes, or pellets. The relatively uniform particle size, bulk density, heating value, ash and moisture content of the RDF product facilitates the design and operation of the subsequent gasification step, although approximately 4% of the energy contained in the raw MSW is lost in the conversion to RDF. Commercial RDF facilities are operating today in North America and in Europe to produce boiler fuel.

*Gasification*

Gasification refers to the conversion of a solid feedstock (by heating) into a gas suitable for combustion or for thermochemical processing into a desired product. The key components in gasifier product gases include hydrogen ($H_2$), carbon monoxide (CO), carbon dioxide ($CO_2$), methane ($CH_4$), and higher hydrocarbons. Unlike combustion, gasification occurs in an oxygen-starved atmosphere--some gasifier designs eliminate altogether any direct contact between the feedstock and air or oxygen. Because of the reduced oxidant/feed ratio compared to combustion, the volumes of product gas from a gasifier are 1/3 to 1/5 of those from a combustor (or incinerator) using the same feedstock. This significantly reduces the required capacity (and hence cost) of any gas cleanup equipment needed downstream of the

reactor. Also, some data suggest that the oxygen-deficient environment helps inhibit the formation of dioxins and furans, which require oxygen to form (see Section 4).

Gasification is widely used with coal. Some woody-biomass gasifiers are also operating commercially in applications where the product gas is directly burned in a boiler or kiln. A number of pilot-scale MSW gasifier designs have been tested over the past couple of decades. Currently, there are two commercially operating MSW gasification plants in the world, both in Italy,[3] and several additional units have been ordered.

Gasifiers can be classified according to the way heat is supplied to drive the reactions. In directly-heated (or partial-oxidation) gasifiers, some of the feedstock is burned in air or oxygen. Oxygen is preferred for synthesis gas production to minimize nitrogen dilution and product gas volumes, but cost savings from smaller reactor volumes will be offset to some extent by the cost of producing oxygen. Partial oxidation is the basic principle behind all coal gasifiers, because it can achieve the high temperatures needed for efficient gasification of coal, a relatively unreactive feedstock. Alternatively, heat can be provided indirectly via some heat exchange mechanism. Such indirectly-heated gasifiers are suitable only for high reactivity feedstocks like biomass or MSW, because indirect heating is not able to support reaction temperatures as high as with partial oxidation. The use of indirect heating makes possible the production of a gas undiluted by nitrogen without the use of costly oxygen.

Three MSW gasifier designs assessed in detail by Chen [1995] are included in the assessment here for fuels production. One of these--the Thermoselect gasifier--is an oxygen-blown partial-oxidation unit. A prototype commercial plant of this design is operating in Italy, where it fuels an internal combustion engine-generator set, and orders have been placed for several fully commercial units for the same power generation application. The other two--the Battelle Columbus Laboratory (BCL) and MTCI gasifiers--are indirectly-heated gasifier designs that have undergone limited pilot-scale testing with MSW feed. Table 1 gives some details of the expected performance of these three gasifiers to augment the following more general description of the units.

Thermoselect gasifier. Thermoselect is a Swiss company that has developed a gasifier

[3] The largest of these is found in Greve, Italy. It is an air-blown gasifier built by TPS (Sweden) and the gas is fed to a gas engine and a clinker kiln (for cement production). It is not discussed further in this report because it is not suitable for fuels production: as an air-blown gasifier, it produces a synthesis gas diluted with nitrogen. The other gasifier in Italy is of the Thermoselect design discussed later in this report.

that operates at about atmospheric pressure and is designed to use minimally pre-processed MSW.[4] To deal with the non-homogeneous nature of raw MSW, the design (Fig. 2) includes a first-stage reaction chamber in which the MSW is subjected to mechanical pressure and temperatures of about 1100°F for approximately two hours. This chamber dries the MSW and drives the volatile carbon, hydrogen and oxygen (which account for more than half the mass of the raw feedstock) into vapor form (termed pyrolysis vapors) and densifies the remaining carbon and inorganic materials. The vapors and solids pass into the gasification chamber, where they are entrained in a flow of oxygen in the lower section of the reactor. Some of the solid carbon burns, raising the chamber temperature in excess of 3600°F. Residence times of the gas phase in the upper section of this chamber are measured in seconds. Solid carbon that is not burned readily gasifies at the temperatures in the reactor. The inorganics melt, flow slowly through the oxygen-rich section of the chamber (insuring complete oxidation of the inorganic materials), and into a quench-water bath where they solidify into mineral-oxide aggregates and metal-oxide pellets. The product gas from the reactor contains little methane and no higher hydrocarbons, which is a key distinguishing feature compared to the other gasifiers considered here. The first commercial-scale Thermoselect gasifier, with a capacity of approximately 110 tons per day of raw MSW, has been operating at a site in Fondotoce, Italy, since 1993. Three commercial facilities are currently are various stages of permitting in Europe, and two additional facilities are under negotiation. Extensive air and solid effluent emissions measurements have been carried out at the Fondotoce unit (see Section 4).

BCL gasifier. The BCL gasifier design involves a set of two coupled atmospheric-pressure fluidized beds (Fig. 3). The design resembles that of fluid catalytic crackers commonly used in petrochemical refining. RDF is fed to the first bed, wherein pyrolysis (devolatilization) of the biomass occurs at an operating temperature near 1500°F. The residual char (fixed carbon) is transferred to the second bed where it burns to heat sand that is circulated back to the first bed to provide the heat to drive the devolatilization. Ash is removed from the combustor. Steam and/or recycled product gas are used to fluidize the first bed. A pilot-scale (13 tons/day) BCL gasifier has operated for a total of more than 20,000 hours. Most of this testing effort has focussed on woody biomass, and construction has begun on a 200 dry ton/day wood gasifier in Vermont [Moon, 1995]. Some pilot-plant tests

[4] One feedstock tested in the prototype Thermoselect gasifier in Italy was half of a Fiat automobile.

have been carried out with RDF fuel and provide the basis for the performance estimates in Table 1.

MTCI gasifier. MTCI is a small US company developing an indirectly-heated gasifier that uses an advanced heat exchanger design fixed inside an atmospheric-pressure fluidized-bed to provide heat for gasification (Fig. 4). (A US license for the MTCI design is held by Stone and Webster Engineering.) Some product gas is burned to provide the heat to the heat exchanger. Steam and/or some recycled product gas is used for fluidization. Reaction temperatures are low (about 1300°F) due to the indirect heating. Development of the MTCI technology has been focussed on black liquor as a feedstock, the lignin-rich byproduct of cellulose extraction during chemical pulp production for paper making. A pilot-scale MTCI black liquor gasifier (53 tons/day capacity) has operated since 1992 in Erode, India, and a 100 ton/day demonstration unit has recently completed testing at a pulp mill in New Bern, North Carolina. Also, a pilot-scale pulp-mill sludge gasifier with a capacity of 26 tons/day has been test operated at a paper mill in Ontario, California. A 120 ton/day unit fed with residues from a sugar mill distillery is to begin full operation in Pennadam, India this year. Some small-scale pilot tests have been carried out with RDF fuel, and the New York Power Authority is currently discussing with Stone and Webster Engineering the possibility of demonstrating gasification of urban waste wood for fuels production at a site in New York City [Kapner, 1995].

*Gas cleanup*

After gasification, trace contaminants in the product gas must be removed to prevent poisoning of catalyst beds in downstream reactors. This inherent requirement of the downstream processing helps insure that fuels production from MSW has low external environmental impacts. Key contaminants of concern are sulfur, particulates, heavy metals, and tars and oils that form during gasification.

A typical cleanup process might first involve particulate removal with a cyclone, a simple device that separates particulates from the gas on the basis of density differences. The gas stream would then be quenched in a wet scrubber to remove smaller particles, heavy metals, and any tars and oils that are present. If needed, the concentration of halide gases (e.g., HCL and HF) can be further reduced by injection of an alkaline solution in the wet

scrubber. If the particulate concentration is still too high following the scrubber, a fabric filter or electrostatic precipitator could be used. Sulfur (primarily from rubber in the MSW feed) leaves the gasifier largely as hydrogen sulfide ($H_2S$) and passes the scrubber. Commercial systems are available for removing $H_2S$ from gases at the low temperatures that would be found following a scrubber and for converting it into elemental sulfur, a marketable material.

*Balance of process*

After gas cleanup, the individual unit processes to convert the gas into methanol or hydrogen (Fig. 1) are the same as those used commercially to convert natural gas into these fuels. The processing begins with reforming methane ($CH_4$) and other hydrocarbons, if these are present in the gas. These are converted to carbon monoxide (CO) and hydrogen ($H_2$) by reacting the gas in steam over a catalyst at around 1650°F. (If the gas contains no hydrocarbons, as with the Thermoselect gasifier, no reformer is needed.) The ratio of $H_2$ to CO in the gas is next adjusted in one or more "shift" reactors to the level required for final processing. The water-gas shift reaction ($CO + H_2O <=> H_2 + CO_2$) allows CO to be converted into $H_2$ on a one-to-one basis.

For methanol production (see Fig. 1), a single shift reactor operating at 840 to 1020°F produces a volumetric $H_2$:CO ratio of about 2. Following the shift, the gas passes through a solvent process (e.g., Union Carbides' Selexol) that dissolves $CO_2$ and water out of the gas. With essentially only CO and $H_2$ remaining, the gas stream is compressed and fed to a methanol synthesis reactor (e.g. an ICI low-pressure synthesis unit), wherein CO and $H_2$ combine over a catalyst at about 480°F to form a methanol solution, from which methanol is extracted by a final distillation.

For hydrogen production (see Fig. 1), two shift reactors in series (the first operating at about 840°F and the second at about 450°F) convert as much of the gas as possible to $H_2$. The gas then undergoes pressure swing adsorption (PSA), whereby gases are separated by exploiting the ability of specially designed porous materials to selectively adsorb specific molecules at high pressure and desorb them at low pressure. A first PSA bed would adsorb $CO_2$ and $H_2O$, and a second would adsorb all remaining components except $H_2$. Up to 97% of the $H_2$ fed to a PSA can be recovered as final product with greater than 99.999% purity.

The $H_2$ would then be compressed for storage or pipeline transmission.

*Energy efficiency of fuels production from MSW*

Detailed process modeling was carried out by Chen [1995] to estimate the energy efficiency of methanol and hydrogen production from MSW using each of the three gasifier designs discussed above. An industry-standard chemical process simulation software package, ASPEN PLUS, was used for the analysis. Raw MSW was the assumed feedstock in each case. The two indirectly-heated gasifiers require an RDF feed, so it was assumed that RDF production was integrated into these facilities. Mass and energy balances around each of the gasifiers were obtained through a review of published literature and discussions with the respective gasifier developers (Table 1). Reactor operating conditions downstream of the gasifier (temperatures, pressures, steam-to-gas ratios, etc.) were selected so as to simulate prevailing industrial practice. For methanol and hydrogen production, as with many chemical processes, waste heat recovery is important to maximize energy efficiency. To include waste heat recovery in the simulations, pinch analysis was used to match process streams needing heating with those needing cooling to the fullest practical extent feasible. In all results reported here, all of the process heating needs can be met by heat exchange from other, hotter process streams. Waste heat remaining after this matching is assumed to be used to raise steam for expansion through a steam turbine to produce electricity for use in the process, or for sale when there is excess power. Shortfalls in on-site electricity supply are assumed to be provided from external sources, the energy requirements for which are accounted for in the analysis.

Following the above approach, Chen [1995] developed detailed energy and mass balances for methanol and hydrogen from MSW using each of the three gasifiers discussed earlier. In each case, the capacity of the conversion facility was assumed to be 1155 dry tons per day of MSW. Because of differences in moisture contents of feedstocks used in tests on which the performance estimates are based (Table 1), the "as-received" quanitity of MSW ranges among the three different gasifiers from 1395 to 1494 tons daily, which is within a capacity range that is typical for recently built mass burn incinerators in the U.S. Table 2 summarizes the results of the simulations, with overall energy performance expressed in terms of an energy ratio (ER) and a thermal efficiency (TE).

The ER is defined as the energy contained in the product fuel divided by the energy in the raw MSW input.[5] In subsequent cost analysis (Section 5), the ER determines the feedstock cost per unit of product. The ER is consistently about ten percentage points higher for hydrogen than for methanol.[6] The Thermoselect gasifier design provides the highest energy ratio for either methanol or hydrogen production. This is due largely to the fact that no energy-consuming reformer is required with the Thermoselect design.

The TE is defined as the energy in the product fuel divided by all primary energy required as inputs to the process. Thus the TE takes account of external energy inputs and measures whether the total energy balance for fuels production from MSW is positive. The TE is positive in all cases, with TEs for hydrogen production higher than for methanol. For either fuel alone, the TE is roughly the same regardless of the gasifier design used--about 50% for methanol and approaching 60% for hydrogen. The indirectly-heated gasifiers (BCL and MTCI) fare well against the Thermoselect design in terms of TE, though they have considerably lower ERs. The BCL and MTCI designs have considerably more waste heat available to raise steam for on-site electricity production, which improves the TE relative to the Thermoselect design. With the BCL design, some electricity would actually be exported. The Thermoselect case has less waste heat available and requires oxygen. Electricity demand for oxygen production amounts to 30% of total electricity used at the facility.

## 3. Potential for MSW to Meet New York City Transportation Fuel Demands

The energy balance results discussed above provide a basis for a preliminary estimate of the potential for New York City's waste streams to be used to meet New York City's transportation fuel demands. The total quantity of non-recycleable waste available in New York City is estimated to be nearly 3 million tons per annum (Table 3), with a total energy content of 25 trillion Btu. Assuming an energy ratio for methanol or hydrogen production as with the BCL gasifier, 49% and 58%, respectively (Table 2), the total potential methanol or

---

[5] The energy contents of all MSW, methanol, hydrogen, natural gas, gasoline, diesel, and other energy carriers discussed in this report are given in terms of higher heating values.

[6] This is largely explained by the fact that some of the energy in the feed gas to the methanol synthesis step is converted to heat, rather than to methanol. The thermodynamic processes in hydrogen production are similar to those in methanol production, except that there is no energy release in hydrogen production analogous to that in the methanol synthesis step.

hydrogen fuel production from non-recyclable waste in New York City is 12.4 trillion Btu/year of methanol (190 million gallons per year) or 14.7 trillion Btu/year of hydrogen (44 billion scf/year). While these numbers are modest compared to present gasoline use in New York City for light-duty vehicles (estimated for 1991 to be 950 million gallons,[7] or 120 trillion Btu), if the methanol or hydrogen were used in fuel cell vehicles, these fuel quantities could meet a substantial share of New York City's transportation fuel needs because of the high expected efficiency of fuel cell vehicles.

A fuel cell passenger car that would operate on methanol (hydrogen) is estimated to have a gasoline-equivalent fuel economy 2.4 (2.8) times that for comparable-duty gasoline vehicles.[8] Thus, if all of the estimated 19 billion vehicle-miles (v-m) driven in New York City annually [DOT, 1992] were driven by methanol (hydrogen) FCVs, the potential volumes of these fuels produced from MSW would be sufficient to drive 32% (44%) of these vehicle-miles.

Fuel cell buses will be introduced commercially sooner than light-duty vehicles, as discussed earlier. Thus, the New York City public bus fleet might be an attractive initial target for conversion to fuel cell power, with fuel derived from MSW. The total revenue miles traveled by public buses in New York City in 1994, excluding empty trips such as returning to the garage, is estimated at about 90 million bus-miles [DOT, 1995]. The total amount of fuel needed to meet this travel demand using a fleet of fuel cell buses is an estimated 2.7 trillion Btu with methanol or 2.3 trillion Btu with hydrogen.[9] Converting 23% of New York's available non-recyclable MSW (Table 3) to methanol or 16% to hydrogen would be sufficient to provide these quantities of fuel. One production facility of the scale described in Table 2 would be sufficient to produce the required quantities of fuel.

---

[7] The total estimated 1991 light-duty vehicle-miles (v-m) driven in New York City was 19 billion v-m [DOT, 1992]. Assuming an average fuel economy of 20 miles per gallon gives 950 million gallons of fuel.

[8] A year-2000 version of the Ford Taurus gasoline IC engine vehicle is projected to get 25.8 miles to the gallon, as reported by Ogden, et al. [1994] based on detailed vehicle modeling by DeLuchi [1992] and unpublished updates thereof. The gasoline-equivalent fuel economies ($mpg_{ge}$) for comparable-duty methanol and hydrogen fuel cell vehicles are estimated to be 61.5 $mpg_{ge}$ and 71.6 $mpg_{ge}$, respectively [Ogden et al., 1994]. (The gasoline-equivalent fuel economy is the miles per MBtu fuel economy of the FCV times the higher heating value of gasoline, 0.125 MBtu per gallon.)

[9] This assumes an average energy requirement of 29,500 Btu/mile for a methanol (30-foot phosphoric-acid) fuel cell bus (2.2 miles per gallon of methanol) [Fisher, 1995] or 25,340 Btu/mile for a hydrogen (40-foot PEM) fuel cell bus (75 scf/mile) on a typical intracity bus drive cycle [Howard, 1995].

## 4. Environmental Aspects of Fuels from MSW and Their Use in Fuel Cell Vehicles

A major motivation for examining transportation fuels production from MSW and use in fuel cell vehicles is an expected environmental benefit relative to conventional MSW disposal and conventional vehicle transportation options.

*Environmental aspects of fuels production*

Before reviewing specific emissions characteristics of methanol and hydrogen production from MSW, a qualitative discussion of environmental performance is useful. MSW incineration provides a well understood benchmark in this discussion.

Gasification, the process at the heart of methanol or hydrogen production from MSW, produces 1/5th to 1/3rd the product gas volumes of an incinerator. This is due to an intrinsic characteristic of gasification--reaction in an oxidant-deprived environment--and to the fact that gasifiers of interest either use oxygen as the oxidant or are indirectly heated, so that product gases are not diluted with nitrogen. In contrast, incinerators operate with a greater-than-stoichiometric amount of air as the oxidant. The smaller gas volumes from a gasifier simplify gas cleanup: smaller (lower-cost) cleanup equipment can be used, and the elimination of nitrogen dilution means that contaminants to be removed would be more concentrated in the gas (and thus probably more easily removed). Also, some data suggest that gasification will produce few toxic polychlorinated aromatic compounds (dioxins and furans) because oxygen is needed for precursor compounds to form.

Unlike incineration, where the combustion products are vented directly to the atmosphere after cleanup, fuels production requires that the gasifier product gases be cleaned and then processed through a series of downstream reactors. The catalysts used in these reactors have a very low tolerance for contaminants--concentrations must be much lower than those reflected in public-health based emissions regulations. For example, 0.5 ppm of sulfur (as $H_2S$ from a gasifier) will poison the nickel-based catalyst used in a reformer. Thus, air emissions from a MSW-to-fuels production facility will be extremely low because catalytic reactors in the process could not be operated successfully otherwise. For comparison, some state regulations allow concentrations of 30 to 50 ppm $SO_2$ (or 90% removal) in MSW incinerator flue gases [Bechtel Group, 1992]. This discussion has not addressed liquid or solid effluents, which must also be considered. However, liquid and solid effluents are

considerably easier to deal with than gaseous emissions (as discussed below).

Considerably more empirical data are needed than are presently available to confirm the above qualitative analysis. However, detailed empirical emissions data on all effluent streams for one gasifier (the Thermoselect unit) and more-limited data for the indirectly-heated gasifiers support the above analysis, as discussed below.

Emissions to air. Air emissions during methanol or hydrogen production are limited to products of combustion from the combustor portions of each gasifier and from the reformer furnace.

With the Thermoselect gasifier, a portion of the cleaned gasifier product gas is burned in air to heat the first-stage reaction chamber (see Fig. 2). This is the only potential source of air emissions during fuels production, since no reformer would be used with this system. The gas cleanup system would be designed in part to minimize flue gas emissions from the first-stage combustor. (Stringent gas cleanup is also required to protect catalyst beds downstream of the gasifier from being poisoned during conversion of the gas to the desired fuel.)

The highly-respected German technology testing agency (RWTUV) in the state of Nordrhein-Westfalen carried out comprehensive measurements of contaminants in *all* effluents from the Thermoselect demonstration plant in Italy during random visits to the facility (Central Department, 1994) and also conducted two engineering tear down assessments to examine the condition of the reactor. Table 4 shows the RWTUV measurements for contaminants in the flue gas from the combustor associated with the first-stage reaction chamber. Also shown are proposed post-1997 US and present European limits for incinerator flue gases. All measured concentrations of contaminants in the Thermoselect flue gas are far below the US and European specifications. Importantly, the toxicity-equivalent emissions of dioxin/furan are two orders of magnitude lower than the US and European guidelines.[10] Furthermore, it can be noted that the Thermoselect system would generate considerably fewer contaminants than suggested by Table 4, because of the lower total volume of flue gases that would be produced per unit of MSW during fuels production compared to incineration.

[10] Thermoselect technology developers claim that the lack of oxygen combined with the high temperatures (up to 3600°F) in the gasifier prevent dioxin formation and that subsequent shock cooling of the product gas (from 2200°F to less than 200°F) in the absence of oxygen prevents de-novo synthesis of dioxins and furans.

With the indirectly-heated MTCI gasifier, cleaned product gas would be used to fire both the combustor section in the gasifier and the reformer furnace. No empirical data are available regarding gas quality after cleaning, but it is reasonable to assume that a gas quality comparable to that achieved in the Thermoselect tests (Table 4) can be achieved with gas from an MTCI gasifier, especially because the MTCI gasifier uses a more predictable feedstock, RDF, which facilitates stable operation. On the other hand, because the MTCI gasifier operates at a much lower temperature than the Thermoselect unit, different species of chemical contaminants may be present in the product gas, and empirical measurements are needed to verify that these can be dealt with adequately by the cleanup system.

With the BCL gasifier, cleaned product gas would be used to fire the reformer furnace. As with the MTCI gasifier, it is reasonable to assume (though must be verified empirically) that the product gas can be cleaned to the same extent as with the Thermoselect gasifier. An additional concern is flue gases from combustion of the RDF char used to supply heat to the gasification reactor (see Fig. 3). Neither the contaminants in the char nor in the flue gases have been measured, but with proper operation of the gasifier few if any volatile contaminants should remain in the char. In any case, the volume of flue gas to be cleaned would be about 1/5th the volume of flue gases from a mass-burn incinerator with the same MSW throughput. The requisite gas cleanup system would be proportionally smaller.

Emissions of nitrogen oxides ($NO_x$) are a potential concern with any combustion system. However, for combustors burning medium energy content gases (as produced by the gasifiers considered here) the formation of $NO_x$ from dissociation of atmospheric nitrogen (thermal $NO_x$) is less of a concern than with high energy content gases (like natural gas), because flame temperatures are lower.

Liquid and solid effluents. The low emissions of contaminants to the air with gasifier-based fuels production from MSW suggests that contaminant concentrations in liquid and solid effluents should be examined carefully.

Data on liquid effluents are available only for the BCL gasifier (limited data) and Thermoselect gasifier (detailed data). In test operation of RDF gasification in a pilot-scale BCL unit, combustor flue gases were cleaned using a spray tower, and a simple water quench was used with the product fuel gas. The waste waters were treated through a simple settling

chamber, sand filter, and charcoal filter. After treatment, the concentration of contaminants in the waste water were below those specified in the EPA Safe Drinking Water Act standards [Paisley, 1989]. Comprehensive emissions data (solid, liquid, and gaseous) that would allow a more careful assessment were not collected during the tests, but the results of the waste water tests suggest that pollutants in liquid effluents will be minimal from fuels production based on the BCL gasifier.

Detailed and comprehensive effluent-stream measurements were made on the pilot-plant Thermoselect gasifier. The high exit gas temperature of this gasifier (2200°F) suggests that many species of pollutants that might not be volatilized in lower-temperature gasification processes would be present in the raw product gas (especially metals--Table 5) and would end up in liquid effluents from the cleaning plant. At the pilot plant, the Thermoselect product gas is first shock quenched with water to below 200°F, then successively scrubbed in acid and alkaline washes, passed through a sulfur removal unit, and finally passed through an activated charcoal filter. A final fabric filter removes particulates picked up from the charcoal filter. All waste waters are processed through a treatment system, and water quality measurements were made before and after treatment. Levels of chlorine and other contaminants in the raw gas were found to be high, as expected. However, their chemical forms were such that after a more-or-less conventional water treatment process the water quality was such that it could be discharged to sewer under Germany's "Basic Administrative Wastewater Regulations,[11]" except for excessive iron, lead, and nitrite concentrations. Additional provisions in water treatment would be needed to deal with these.

Data on the solid effluents are available for the MTCI gasifier (limited) and Thermoselect gasifier (detailed). Ash or slag produced during gasification are the primary solid wastes. Additional residues may be generated during gas cleaning or waste water treatment. The principal concern with solid wastes is toxicity. Ash resulting from the gasification of RDF in the MTCI gasifier has been tested for toxicity using EPA's toxicity characteristics leachate procedure (TCLP). Since none of the metals in the ash were found in concentrations above the soluble threshold limit concentration (STLC) (Table 6), this ash would not be classified as hazardous. No corresponding measurements were made on other solid waste streams associated with the MTCI gasifier. The high temperatures in the

[11] Translated from the German "Rahmenabwasserverwaltungsvorschriften."

Thermoselect gasifier lead to melting of the ash. The molten ash is quenched to form a glassy granulate (at a rate of about 460 lb/dry ton of MSW). Tests on granulate samples and on the minimal amount of leachate from the granulate show that neither would be classified as hazardous under either U.S. or German regulations. The granulate might be suitable as construction material (e.g. for road fill or concrete production). If the hydraulic and physical quality of the granulates are comparable to slags used in blast furnaces, selling the granulate might generate additional income of about $4/ton MSW, assuming 1989 market prices for blast furnace slag [Owens, 1991]. The much smaller volumes of residues from gas cleaning (estimated for the Thermoselect gasifier to be 37 lb/dry ton dry MSW) would require proper disposal.

Dioxins. There is widespread public concern over emissions of toxic polychlorinated dibenzo-dioxins and -furans (PCDDs/PCDFs), a large class of chemicals often simply called dioxins. A concensus is growing that dioxins are among the most toxic human-made substances known, having carcinogenic and even more harmful non-carcinogenic effects (e.g. damage to the reproductive system) [Hileman, 1993].

MSW incinerators presently account for the vast majority of dioxins entering the environment [Thomas and Spiro, 1994], and are a primary reason for public opposition to incineration. The chemical pathways leading to dioxin formation are not fully understood. The theory gaining increasingly wider acceptance, however, is that it occurs on combustion fly ash, which acts as a catalyst for dioxin formation reactions involving precursor compounds: polyaromatic hydrocarbons (PAH's), polychlorinated biphenyls (PCB's), and chloride donors. Oxygen is also required. It has been proposed, therefore, that the rate of dioxin formation is determined by the relative concentrations of fly ash, oxygen, precursors, and temperature. Incinerator flue gases typically have a concentration of about 10% oxygen, which is sufficient for dioxin formation. Dioxin precursors form during combustion, but are destroyed if exposed to temperatures above 1500°F for about one second. "Cold spots" in an incinerator would allow precursors to survive to form dioxin on fly ash at temperatures between 400°F and 750°F.

With gasification, the availability of fly ash may not be very different than in incinerator flue gases. However, the oxygen concentration is essentially zero. The very low

dioxin emissions associated with the Thermoselect gasifier (Table 4) may be explained by a combination of factors: high temperatures (2200-3600°F) help destroy precursors, the absence of oxygen inhibits dioxin and precursor formation reactions, and shock-cooling of the product gas (from 2200°F to below 200°F) minimizes the residence time at the temperatures (400°F-750°F) that promote dioxin formation. Dioxin emissions data are not available for the indirectly-heated BCL and MTCI gasifiers. Reactor temperatures are too low to destroy dioxin precursors, but the oxygen-starved nature of the reactions may substantially inhibit the formation of dioxin precursors. This conjecture must be assessed empirically.

*Environmental aspects of using MSW-derived fuels in vehicles*

Dramatic reductions in both local and global pollutants would result if methanol or hydrogen from MSW were used in fuel cell vehicles (FCVs) to replace internal combustion engine vehicles (ICEVs) operating on gasoline or diesel fuel.

Emissions of criteria pollutants (carbon monoxide, nitrogen oxides, sulfur oxides, particulate matter, and volatile organic compounds) would be completely eliminated from a hydrogen/FCV and would be reduced by close to 100% with a methanol/FCV.[12] Table 7 shows some measured results for hydrogen and methanol fuel cell buses compared to the 1998 Federal emission standards for heavy duty ICEVs. Additionally, other toxic tailpipe emissions (benzene, formaldehyde, acetaldehyde, and 1,3-butadiene) would also be eliminated.[13]

Net emissions of carbon dioxide, the major contributor to the global greenhouse effect, would be reduced very significantly per mile driven if MSW-derived fuels were used with FCVs. For example, it is estimated that replacing diesel-fueled IC engine buses with methanol or hydrogen fuel cell buses would result in reduced net emissions of carbon to the atmosphere ranging from 34-54% or 59-68%, respectively (Table 8). If MSW were a fully renewable resource, the emissions reductions would be essentially 100%. However, only

[12] There would be very minor emissions with a methanol/FCV due to the need to convert the methanol into hydrogen on-board the vehicle. (The fuel cell requires essentially pure hydrogen.) The fuel conversion process (reforming) would have some emissions associated with it.

[13] Some of these toxic pollutants would increase if the fuels were used in an ICEV instead. For example, a methanol powered ICEV would have increased emissions of formaldehyde and possibly benzene compared to a gasoline ICEV [Ogden et al., 1994].

some of the components in MSW can be considered to be renewably produced. These include paper, wood, food, and yard wastes. In total, renewably produced materials account for approximately two-thirds of all carbon in an average MSW stream in the U.S. These renewable components provide a photosynthetic credit against carbon emissions (see lower section of Table 8), because carbon is taken up during regrowth of the plant matter from which these components are derived.[14]

## 5. Economics

The estimated costs of MSW-derived fuels are examined here per unit of product and per mile of vehicle transport service provided. Total estimated lifecycle costs per mile of driving are also estimated.

*Production costs of fuels from MSW*

Capital and operating cost estimates[15] for future, commercially-mature plants for fuels production from MSW using each of the three gasifiers discussed in Section 2 have been assembled from a variety of sources, including equipment vendors, A&E firms, and published studies (Table 9). There is some uncertainty in the capital cost estimates due to the pre-commercial nature of the systems being considered, but the three gasifier designs probably encompass the range of likely capital costs for MSW-to-fuels systems. Costs are highest for the Thermoselect gasifier. These estimates are well grounded, since they are based on costs for the commercial prototype system operating in Italy. However, there is likely scope for cost reductions in successive generations of the design of this system, as with most new process technology, and the cost estimates exclude revenues that would likely be generated from the sale of byproduct materials (iron, sulfur, slag, etc.) that are readily recovered with this design. There is greater uncertainty (perhaps $\pm$ 25% in the capital cost) estimates for the

[14] Additionally, some or most (depending on the gasification technology and fuel being produced) of the $CO_2$ generated during fuels production could be recovered for long-term sequestering, e.g. in depleted natural gas wells [Hendricks, 1994], which would lead to lower positive (or possibly negative) lifecycle $CO_2$ emissions associated with fuels production. Alternatively, the $CO_2$ might also be used for other purposes; byproduct $CO_2$ from ammonia production today is shipped in large quantities worldwide for use in soft drink production, urea synthesis, $CO_2$ fertilization in greenhouses, and other uses.

[15] These and all other costs discussed in this report are expressed in constant 1991 dollars. U.S. GDP deflators [Council of Economic Advisors, 1995] have been used to convert other-year dollars to 1991 dollars.

BCL and MTCI gasifiers due to the more limited commercial design efforts behind the cost estimates, but these designs (especially the BCL design) appear to offer lower cost routes to fuels production from MSW. In economic comparisons made in this section of the report costs for systems using the BCL gasifier are considered low-end estimates and those for systems using the Thermoselect design are considered high-end cost estimates.

The cost estimates in Table 9 are for plant capacities of 1155 tons (dry basis) of daily MSW input, corresponding to a raw (wet) MSW input ranging from 1400-1500 tons per day (see Table 2). This is in the characteristic size range for new mass burn incinerators in the U.S. Total costs are shown as a function of the tipping fee, *tf* (in $/wet ton delivered), in units of $ per wet ton of MSW processed, $ per million Btu of product, and $ per unit volume of product. For a given gasifier, the cost is a linear function of the tipping fee. To provide some perspective on the cost estimates in Table 2, two comparisons are helpful.

One comparison is between the production costs estimated here and those estimated when the feedstock is natural gas, the predominant source for methanol and hydrogen today. For illustration, consider methanol. With the same capital charge and discount rates as assumed in Table 9, the cost of producing methanol from natural gas at the 1994 average industrial gas price in the U.S. ($2.9/MBtu [EIA, 1995b]), would be about $7.9/MBtu ($0.52/gallon).[16] For the cost range spanned by the three gasification systems considered here, a minimum tipping fee ranging from $58 to $94/ton would be needed to better this production cost (Fig. 5). For comparison, the average tipping fee at the Fresh Kills, New York City landfill today is $67/ton [Bekoweis, 1995]. The tipping fee in Philadelphia is about $70/ton [EPA, 1994]. New Jersey has some still higher fees, including $110/ton in Newark [EPA, 1994] and $108/ton in Mercer Co. (home of Princeton) [Planning Section, 1995]. For the low-end cost estimates in Fig. 5, MSW-derived methanol at any of these locations would be less costly than making methanol from natural gas at the 1994 average U.S. price of gas. The relative economics of methanol from MSW versus natural gas can be expected to improve further in the future, because natural gas prices are forecast to rise. The U.S. Department of Energy projects the price of natural gas to industrial users to be

[16] The cost of methanol production is estimated by Williams et al., (1995) as a function of $P_{ng}$, the $/MBtu price of natural gas: $/MBtu = 3.83 + 1.42·$P_{ng}$ or $/gal = 0.249 + 0.092·$P_{ng}$. Also, the cost of hydrogen production is estimated to be $/MBtu = 2.74 + 1.115·$P_{ng}$ or $/kscf = 0.926 + 0.377·$P_{ng}$.

$3.6/MBtu in 2005 and $4.0/MBtu in 2010 [EIA, 1995a]. If tipping fees at Fresh Kills and elsewhere also rise in the future, which seems likely, the economics of fuels from MSW would improve still further.

Methanol prices are historically subject to substantial fluctuations as market demands and/or industry production capacities change. For example, the U.S. wholesale price of methanol (FOB producer) during the period from 1984 to 1992 varied from $8.9/MBtu to $5.4/MBtu, or 58-35 cents/gal [ITC, 1994]. Since natural gas prices did not fluctuate in parallel with methanol prices, low methanol-price years were very well loss-making years for methanol producers. For example, in 1990 the average industrial natural gas price was $3.1/MBtu [EIA, 1995b], at which methanol would cost about $8.2/MBtu to produce (see footnote 16). In contrast, the 1990 average U.S. wholesale price of methanol was only $5.8/MBtu (nearly the lowest methanol price since 1985). It is notable that with the present tipping fee at Fresh Kills, methanol from MSW (using the low-end cost estimates) could be profitably sold for $5.6/MBtu (Fig. 5).

A second comparison is between the cost of MSW conversion to methanol or hydrogen and MSW conversion to electricity in a mass burn incinerator, the only commercially established energy option for MSW disposal in the US today. Assuming that the product derived from MSW (methanol, hydrogen, or electricity) were sold at prices equal to the cost of producing these products from natural gas (the least expensive source for generating these energy carriers today), then the required breakeven tipping fee would be higher for electricity production than for fuels production, if the low-end cost estimates in Table 9 are realized.

In particular, at the average 1994 gas price to electric utilties ($2.1/MBtu [EIA, 1995b]), a new combined cycle would generate electricity at the busbar for about 3.5 ¢/kWh. (Most new utility electric generation being installed today is natural gas fired combined cycle capacity.) With a mass burn incinerator, a tipping fee of about $65/ton (approximately today's tipping fee at Fresh Kills, New York City) would be required to compete (Fig. 6). The required fee might fall to $55/ton by 2010, if forecasted increases in natural gas prices materialize, and there are no further advancements in combined cycle technology. Methanol and hydrogen from MSW using the BCL gasifier would require tipping fees of $59/ton and $49/ton, respectively, to compete with the cost of methanol and hydrogen from natural gas at the average 1994 industrial gas price (Fig. 6).

*Total vehicle lifecycle cost comparisons*

Regardless of the feedstock from which methanol or hydrogen might be derived, the fuel cost per vehicle-mile of transport service provided by a methanol or hydrogen fueled FCV would be substantially lower than the cost per mile with an internal combustion (IC) engine vehicle burning petroleum-derived fuel, and total lifecycle costs (including capital, maintenance, and fuel) are likely to be comparable or lower under many conditions. Cost comparisons are described here for passenger vehicles and intracity buses.

Buses. As noted in Section 1 (Introduction) of this report, fuel cell propelled buses are likely to be introduced commercially before passenger vehicles. Forty-foot, wheelchair-equipped hydrogen/PEM fuel cell buses are expected to achieve fuel consumption levels of 60 to 90 standard cubic feet of hydrogen per mile, or 4.4-6.6 mpg diesel-equivalent ($mpg_{de}$)[17] [Howard, 1995]. For comparison, the average fuel economy for comparable IC engine buses in New York City today is 3.2 mpg diesel [Pellegrin, 1995].[18] Fig. 7 shows the estimated range in fuel cost per mile for a hydrogen-from-MSW bus as a function of the tipping fee, assuming a fuel economy of 5.5 $mpg_{de}$. At the low end of hydrogen production costs (with the BCL gasifier), a tipping fee under \$60/ton would be sufficient to match the fuel cost-per-mile for a diesel engine bus, when the diesel price is 72 ¢/gal, the average 1993 price in the New England census region (excluding 41 ¢/gal in state and federal taxes). For the pre-tax diesel price projected for 2010 in this region (96 ¢/gallon) [EIA, 1995a], a tipping fee as low as \$45/ton would be competitive. At the upper end of hydrogen production costs (with the Thermoselect gasifier), a tipping fee approaching \$100/ton would be needed to match the diesel fuel cost when diesel sells for 72 ¢/gal. A \$77/ton fee would be needed when diesel sells for 96 ¢/gal.

Because fuel costs are a small part of the total per-mile lifecycle cost of owning and operating a bus, a comparison of total lifecycle costs of a diesel engine and PEM fuel cell bus is important. Assuming a tipping fee equal to the present Fresh Kills Landfill fee (\$67/ton), the estimated total lifecycle cost per mile for a fuel cell bus is comparable to that for a diesel

---

[17] The mpg diesel-equivalent is calculated as the higher heating value of diesel fuel (138,690 Btu/gallon) divided by the Btu/mile consumption of hydrogen. (One standard cubic foot of hydrogen has a higher heating value energy content of about 338 Btu.)

[18] In Manhattan Borough, where buses move especially slowly--3.6 mph average--average fuel economy is 2.6 mpg.

engine bus (excluding all taxes), assuming the projected 2010 pre-tax price for diesel fuel and hydrogen production using the BCL gasifier (Table 10, "low"). The fuel cell bus is 5-10% more costly assuming the hydrogen production cost using the Thermoselect gasifier (Table 10, "high"). These calculation assume per-mile maintenance costs for the fuel cell bus would be the same as they are for an IC engine bus. Maintenance costs for a fuel cell bus are not known with any certainty today, but this assumption is probably conservative because the fuel cell bus has fewer moving parts subject to wear, vibrates less, and operates at lower average temperatures. Fig. 8 shows the effect on lifecycle cost if the per-mile maintenance cost for the fuel cell bus were two-thirds of that for the diesel engine bus.

Fig. 8 also highlights the important contribution of the bus purchase price. Because capital is a large fraction of the per-mile lifecycle cost (Table 10), the discount rate assumed in amortizing the purchase price of the bus has a significant impact on the total per-mile cost. Results are shown for real (inflation-excluded) discount rates of 5% and 10%. With the lower discount rate, the attractiveness of the fuel cell bus relative to the diesel engine bus increases (breakeven tipping fees are lower). Since intracity bus service is typically a public service, with public funds expended to purchase buses, the 5% discount rate may be the more appropriate one to use in this comparison. Even with the 10% discount rate, however, the fuel cell bus would be competitive with the diesel engine bus (assuming year-2010 pre-tax diesel price) for tipping fees from $65/ton to $105/ton (depending on the assumed hydrogen production cost), if fuel cell buses were, indeed, to have lower maintenance costs (Fig. 8).

Cars. Consider a passenger car with capacity and performance comparable to a year-2000 version of the Ford Taurus. Such a gasoline IC engine vehicle is projected to have a fuel economy of 25.8 miles per gallon [Ogden et al., 1994]. A comparable methanol/fuel cell version is projected to have a fuel economy 2.4 times this level (61.5 mpg of gasoline equivalent--$mpg_{ge}$), and a comparable hydrogen/fuel cell version would have 2.8 times the fuel economy (71.6 $mpg_{ge}$). Taking account of production, distribution, and filling-station costs, Fig. 9 shows an estimated range in fuel cost per mile to a consumer for the fuel cell versions of this vehicle using fuels produced from MSW. For comparison, the fuel cost per mile for the IC engine version of the vehicle burning reformulated gasoline is shown for the 1994 average world oil price and for the oil price projected by the US Department of Energy for

2010. With a tipping fee of $67/ton, the cost per mile for using methanol and hydrogen would range from 2 to 3.1 ¢/mile and 1.4 to 2.2 ¢/mile, respectively. These consumer costs would be 1.5 to 3 ¢/mile lower than the cost per mile for a gasoline ICEV using reformulated gasoline from oil at the project 2010 world oil price (Fig. 9). The low fuel costs per mile for using methanol or hydrogen contribute to lower estimated total per-mile lifecycle costs to consumers for buying and operating fuel cell vehicles compared to gasoline ICEVs (Fig. 10).

## 6. Conclusions and Recommendations

Conversion of MSW into clean transportation fuels is a promising advanced technology option for dealing with the growing waste disposal problem in large urban areas. The attractive features of this option include: very low pollutant emissions inherent in the conversion process, prospectively competitive economics at prevailing tipping fees, and production of fuels suitable for use in zero emission fuel cell vehicles.

Emissions from gasification, which is at the heart of MSW conversion to methanol or hydrogen, have been demonstrated to be very low. Additional data are needed to draw final conclusions, but data that have been generated from MSW gasification (detailed data on all effluent streams for the Thermoselect gasifier and partial data for the indirectly-heated gasifiers) lend confidence in the conclusion that environmental benefits would be large with gasification-based fuels production compared to incineration.

A preliminary evaluation of the economics of methanol or hydrogen production from MSW indicates that at tipping fees prevailing in New York City today, fuels production at a commercial facility is prospectively competitive with production of these fuels from natural gas at the prevailing average natural gas price to industry in the US. Furthermore, in the case of methanol, the production cost from MSW would be competitive even with a wholesale methanol price close to the lowest yearly average value recorded in the US during the past decade.

Fuel cell vehicles (FCVs) are under intensive development in the US and Europe as a replacement for internal combustion engine vehicles. Fuel cell vehicles require hydrogen or a hydrogen carrier like methanol as fuel. Fuel cell vehicles would have zero (with hydrogen) or near-zero (with methanol) tailpipe emission of criteria pollutants. Because of the high efficiency of FCVs, the fuel cost per vehicle-mile will be low, even if costs per gallon for the

fuel (hydrogen or methanol) are relatively high. The first commercial fuel cell vehicles will be intracity buses that are expected to be offered for commercial service beginning in 1998. Private passenger FCVs are expected to be available in the first decade of the next century.

The above conclusions are based on a preliminary assessment of the performance and cost of three gasification-based fuels conversion systems and of fuel cell vehicles. One of the gasifiers considered in this report is commercially ready, and development of the other two is ongoing. Unit operations downstream of the gasifier are widely used commercially in the chemical process industries. Given the pre-commercial nature of the data used here, uncertainties are inherent in this assessment. Nevertheless, the findings here are very encouraging, and several recommendations can be offered aimed at developing MSW fuels production technology towards commercialization and, ultimately, at implementing MSW-powered vehicle transportation systems in New York City and other major metropolitan areas.

*To help catalyze the commercial development of fuels production technology, additional pilot-scale and subsequent commercial-scale demonstrations are needed for MSW gasifiers alone and coupled with downstream fuels production systems.* Demonstrations should include comprehensive emissions measurements (air, liquid, solids), especially for dioxins. Special focus on indirectly-heated gasifiers appears warranted based on the preliminary economic assessment in this report, but it would be useful to encourage competitive development efforts among alternative gasifier developers. In this regard, it should be noted that the one MSW gasifier design that is now being offered commercially has undergone extensive (and successful) pilot-scale emissions and operational testing. Detailed total-system engineering design efforts are needed to refine the preliminary cost estimates presented here and to improve understanding of unit level operations. Preliminary engineering design evaluations of potential longer-term cost reductions, e.g. once-through methanol synthesis reactors, would also be useful.

*With reference to a specific metropolitan area (e.g. New York City), the potential role for fuels production from MSW should be evaluated within the context of alternative integrated waste management strategies.* This should include assessing alternative technological strategies, including fuels production, composting, anaerobic digestion, recycling, electricity production via incineration (primarily for reference, as future construction of incinerators seems unlikely in many major metropolitan areas), and any other

potentially important options. Technology readiness, lifecycle costs, lifecycle environmental impacts, infrastructure requirements and other factors should be evaluated. This evaluation would require a detailed assessment to be carried out of the waste stream of interest to determine potential quantities and qualities of feedstocks available for gasification versus other waste management options.

*The state of advancement of technology for fuels production from MSW and for utilization of these fuels in fuel cell buses, taken together with the prospective benefits of using these technologies, are such that planning for major bus demonstration projects can be initiated.* The City of Chicago has announced plans to demonstrate hydrogen buses in its public fleet beginning in 1996. Similar trials are under discussion for other cities. Hydrogen from natural gas will be used to fuel such early trials. Building on the experience in Chicago and elsewhere, New York City and other metropolitan areas could begin detailed analysis and planning for conversion of some or all of their public bus fleets to fuel cell power, with fuels made from MSW.

Table 1: Performance estimates for three MSW gasifiers based on pilot-scale testing [Chen, 1995].

| Gasifier → | BCL | | MTCI | | Thermoselect | |
|---|---|---|---|---|---|---|
| Bed design | fast fluidized | | circulating fluidized | | pyrolysis oven + entrained flow | |
| Feed to gasifier | RDF | | RDF | | MSW | |
| Moisture (weight %) | 22.5 | | 17.0 | | 20.0 | |
| Ash (weight %) | 9.1 | | 12.7 | | 25.5 | |
| Heat content per dry ton (MBtu, higher heat value) | 15.6 | | 15.1 | | 12.9 | |
| Composition (weight %, moisture and ash free) | | | | | | |
| C | 50.0 | | 47.0 | | 55.6 | |
| H | 6.4 | | 7.6 | | 6.5 | |
| O | 43.0 | | 43.8 | | 36.9 | |
| N | 0.4 | | 0.8 | | 1.0 | |
| S | 0.15 | | 0.87 | | n.a. | |
| Cl | 0.00 | | 0.01 | | n.a. | |
| Other inputs to gasifier | | | | | | |
| Steam (lb/dry lb feed) | 0.31 | | 1.00 | | 0.00 | |
| Oxygen (lb/dry lb feed) | 0.00 | | 0.00 | | 0.41 | |
| Cold gas efficiency (%) | 79.1 | | 84.8 | | 87.9 | |
| Carbon conversion eff. (%) | 63.2 | | 70.8 | | 96.0 | |
| Product gas | | | | | | |
| Exit temperature (°F) | 1,479 | | 1,450 | | 2,192 | |
| Composition (volume %) | *Wet* | *Dry* | *Wet* | *Dry* | *Wet* | *Dry* |
| $H_2O$ | 61.2 | --- | 52.4 | --- | 20.0 | --- |
| $H_2$ | 7.2 | 18.6 | 22.3 | 46.8 | 32.6 | 40.8 |
| CO | 16.2 | 41.8 | 6.8 | 14.3 | 33.9 | 42.4 |
| $CO_2$ | 4.2 | 10.8 | 11.8 | 24.8 | 11.9 | 14.9 |
| $CH_4$ | 6.5 | 16.8 | 3.9 | 8.2 | 0.0 | 0.0 |
| $C_{2+}$ ... | 4.3 | 11.1 | 2.7 | 5.7 | 0.0 | 0.0 |
| N | 0.4 | 0.01 | 0.0 | 0.0 | 1.6 | 2.0 |
| Yield (kmol/dry ton feed) | 67.4 | | 108.7 | | 69.4 | |
| Energy content (higher heat value) | | | | | | |
| MBtu/ton wet gas | 9.22 | | 8.62 | | 8.79 | |
| Btu/scf dry gas | 571 | | 408 | | 285 | |

Table 2. Overall energy balances for methanol and hydrogen production from MSW [Chen, 1995].

| Gasifier → | BCL | MTCI | T.S. | BCL | MTCI | T.S. |
|---|---|---|---|---|---|---|
| | HYDROGEN | | | METHANOL | | |
| **MSW feed capacity to plant** | | | | | | |
| As received (short tons per day) | 1392 | 1490 | 1444 | 1392 | 1490 | 1444 |
| Dry (short tons per day) | 1155 | 1155 | 1155 | 1155 | 1155 | 1155 |
| Million Btu per hour | 650 | 628 | 622 | 650 | 628 | 622 |
| **RDF feed capacity to gasifier** | | | | | | |
| As fed (tons per day) | 1157 | 1239 | n.a. | 1157 | 1239 | n.a. |
| Dry (tons per day) | 960 | 960 | n.a. | 960 | 960 | n.a. |
| Million Btu per hour | 624 | 603 | n.a. | 624 | 603 | n.a. |
| **Hydrogen output capacity** | | | | | | |
| Million Btu per hour | 378.8 | 405.2 | 467.5 | | | |
| Million std. cubic feet per day | 26.9 | 28.8 | 33.2 | | | |
| **Methanol output capacity** | | | | | | |
| Million Btu per hour | | | | 317.5 | 350.7 | 401.0 |
| Thousand gallons per day | | | | 117.6 | 129.9 | 148.5 |
| **Electricity balance (MW)** | | | | | | |
| Required by process | 13.0 | 16.2 | 26.2 | 16.3 | 19.8 | 27.3 |
| Produced from waste heat[a] | 14.8 | 8.4 | 7.0 | 17.5 | 11.0 | 9.8 |
| Purchased[b] | -1.8 | 7.8 | 19.2 | -1.2 | 8.8 | 17.5 |
| **Overall Energy Performance** | | | | | | |
| **Energy ratio[c]** | 0.58 | 0.65 | 0.75 | 0.49 | 0.56 | 0.64 |
| **Thermal efficiency[d]** | 0.60 | 0.58 | 0.59 | 0.50 | 0.49 | 0.51 |

(a) Electricity is generated in a steam turbine, with the steam raised using waste heat.

(b) For facilities using the BCL gasifier, there would be a net surplus of electricity that could be sold.

(c) The Energy Ratio is defined as the higher heating value (HHV) energy content of the fuel produced divided by the HHV energy content of the raw MSW feed to the plant.

(d) The thermal efficiency (TE) is defined as the HHV energy content of the fuel produced divided by the HHV of all energy inputs, including the raw MSW feed and the primary energy that would be needed to generate the purchased electricity. For the latter, for consistency, it is assumed that the electricity would be generated in a gasifier/gas turbine combined cycle using MSW as the gasifier feedstock.

Table 3. Estimated quantity of annual wastes potentially available in New York City for energy use.

| | Million short tons per year[a] |
|---|---|
| **Organics collected by Department of Sanitation[b]** | |
| The Bronx | 0.055 |
| Brooklyn | 0.229 |
| Manhattan | 0.017 |
| Queens | 0.189 |
| Staten Island | 0.040 |
| **Organics collected by private collectors[b]** | |
| The Bronx | 0.058 |
| Brooklyn | 0.138 |
| Manhattan | 0.394 |
| Queens | 0.165 |
| Staten Island | 0.029 |
| **Urban wood waste[c]** | 1.455 |
| **Non-recyclable plastics[d]** | 0.186 |
| **TOTAL NON-RECYCLED WASTE STREAM** | 2.95 |

(a) The "as-received" moisture content of the w ;te streams included here vary considerably with geography and season. An across-the-board average of 25% is probably not unreasonable [Chen, 1995]. Similarly, the heat contents of different materials differs considerably. An across-the-board average of 8.6 MBtu/ton (as-received) is a reasonable estimate.

(b) As estimated by LaValva [1994]. Included in the figures for each borough are food wastes, yard wastes, unrecyclable and soiled paper products, and other miscellaneous compostable materials such as diapers.

(c) This is an estimate made for the Department of Sanitation by Atlantis [1990]. It includes 1.36 million tons of "dry urban wood" (construction scrap, demolition debris, and crates and pallets), 0.05 million tons/yr of "green wood" (from tree trimmings and land clearings), and 0.045 million tons of "special use wood" (treated wood such as rail ties, telephone poles, and pilings).

(d) This is our estimate assuming that an average of 7% of the waste stream is plastics--the estimated U.S. average [Chen, 1995], half of which is recyclable, and a total waste stream of 5.3 million tons per year (which is based on an estimated total waste stream of 17,000 tons per day [Rockwell, 1994] and 312 collection days per year).

Table 4. Measured contaminants in flue gas from combustion of cleaned Thermoselect gasifier product gas, with comparisons to U.S. and European MSW incinerator flue gas emission limits. (n.a. = not available).

| *Contaminant* [a] | Combustion of Thermoselect product gas (measurements)[b] | Incinerators | |
|---|---|---|---|
| | | US guidelines[c] | European limits[c] |
| In mg/Nm$^3$ | | | |
| Particulates | 3 | 15 | 14 |
| Cadmium (Cd) | 0.004 | 0.01 | n.a. |
| Cadmium (Cd) + Thallium (Tl) | < 0.006 | n.a. | 0.07 |
| Mercury (Hg) | 0.015 | 0.08 | 0.07 |
| Lead (Pb) | 0.012 | 0.1 | n.a. |
| ΣPb, As, Sb, Cr, Co, Cu, Mn, Ni, V, Sn | < 0.04 | n.a. | 0.7 |
| Sulfur dioxide ($SO_2$) | < 3 | 88 | 70 |
| Hyd. chloride (HCl) | < 0.3 | 41 | 14 |
| Hyd. flouride (HF) | < 0.14 | n.a. | 1.4 |
| Total PCDD/PCDF (dioxins/furans) in Toxicity Equivalents[d] (ng/Nm$^3$) | 0.0017 | 0.2 | 0.14 |

(a) Units are milligrams (mg) or nanograms (ng) per normal cubic meter. Normal conditions are 0°C and 1 atmosphere pressure.

(b) These are the average of measurements (adjusted to 7% oxygen) taken on three separate days at the Fondotoce, Italy gasifier [Central Department, 1994]. The measurement point is the flue gas stream leaving the combustor in which heat for the pyrolysis chamber is generated by burning cleaned product gas. Product gas cleanup includes shock cooling through direct contact with water to below 200°F immediately following the gasifier, followed multi-stage alkaline washing, and a final filtering through activated charcoal.

(c) The US guidelines are proposed new source performance standards for Municipal Waste Combustors constructed after Sept. 22, 1997 (Federal Register, Vol. 59, No. 181, Sept. 20, 1994), as cited by Central Department [1995]. The European limits are from the Council Directive 94/67/EC, Dec. 16, 1994 on the incineration of hazardous wastes (Official Journal of the European Community, No. L 365/34 of 31.12.94), as cited by Central Department [1995]. Both the US and European numbers are referenced to 7% oxygen.

(d) PCDD and PCDF are polychlorinated dibenzo-*p*-dioxin and polychlorinated dibenzofuran, respectively. These compounds are commonly called dioxins and furans, respectively. The measure of toxicity equivalents takes into account the fact that different permutations of PCDD and PCDF have different levels of toxicity. The toxicity equivalents shown here are based on NATO toxicity equivalency factors.

Table 5. Melting and boiling temperatures of some metals found in MSW [CRC, 1972].

| Metal | Chemical symbol | Melting temperature (°C) | Boiling temperature (°C) |
|---|---|---|---|
| Mercury | Hg | -39 | 357 |
| Arsenic | As | -- | 613 |
| Potassium | K | 63 | 759 |
| Cadmium | Cd | 321 | 767 |
| Sodium | Na | 98 | 883 |
| Zinc | Zn | 420 | 907 |
| Magnesium | Mg | 650 | 1090 |
| Calcium | Ca | 842 | 1484 |
| Lead | Pb | 328 | 1749 |
| Aluminum | Al | 660 | 2519 |
| Copper | Cu | 1085 | 2562 |
| Tin | Sn | 232 | 2602 |
| Chromium | Cr | 1907 | 2671 |
| Iron | Fe | 1538 | 2861 |
| Nickel | Ni | 1455 | 2913 |

Table 6. Results of toxicity tests on ash from RDF gasification with the MTCI gasifier [MTCI, 1990]. The tests followed the EPA's toxicity characteristics leachate procedure (TCLP). If the concentration of any of the metals is above the soluble threshold limit concentration (STLC), the ash is classified as hazardous. (n.d. = none detected)

| Metal | Chemical symbol | Measurement detection limit (mg/lit) | TCLP result (mg/lit) | STLC (mg/lit) |
|---|---|---|---|---|
| Arsenic | As | 0.0125 | n.d. | 5.0 |
| Barium | Ba | 0.1 | 1.3 | 100.0 |
| Cadmium | Cd | 0.1 | n.d. | 1.0 |
| Chromium | Cr | 0.1 | n.d. | 5.0 |
| Lead | Pb | 0.1 | n.d. | 5.0 |
| Mercury | Hg | 0.0025 | n.d. | 0.2 |
| Selenium | Se | 0.0125 | 0.021 | 1.0 |
| Silver | Au | 0.1 | n.d. | 5.0 |

Table 7. Measured tailpipe emissions (in grams per brake horsepower-hour) from hydrogen and methanol powered fuel cell buses compared to the 1998 Federal emission standards for heavy-duty internal combustion engine vehicles. The methanol bus estimates are from Georgetown [1993]. The hydrogen fuel cell bus emissions estimates are from Steinbugler [1995].

| | 1998 Federal standards for heavy-duty internal combustion vehicles | Hydrogen fuel cell bus | Methanol fuel cell bus |
|---|---|---|---|
| Carbon monoxide (CO) | 15.5 | 0 | ≈ 0.2 |
| Nitrogen oxides ($NO_x$) | 4.0 | < 0.002 | 0.15 |
| Volatile organics (VOCs) | 1.3 | 0 | ≈ 0 |
| Particulates | 0.05 | 0 | 0 |

Table 8. Lifecycle carbon emissions from methanol or hydrogen production from MSW and use in fuel cell buses compared to emissions from diesel-fueled internal combustion engine buses.

| | Methanol | | | Hydrogen | | |
|---|---|---|---|---|---|---|
| Gasifier → | BCL | MTCI | T.S. | BCL | MTCI | T.S. |
| **Lifecycle carbon emissions (lbs C per bus-mile)** | | | | | | |
| Fuel cell bus[a] | 1.24 | 0.86 | 0.98 | 0.78 | 0.61 | 0.62 |
| Diesel IC engine bus[b] | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 |
| **Percentage reduction w/fuel cell bus** | 34% | 54% | 48% | 59% | 68% | 67% |
| **Carbon balances for fuels production from MSW (tons C per dry ton MSW arriving at the plant gate)[c]** | | | | | | |
| Released to atm. during fuel production[d] | 0.25 | 0.19 | 0.24 | 0.37 | 0.33 | 0.39 |
| Released during fuel use in vehicle | 0.13 | 0.14 | 0.16 | 0 | 0 | 0 |
| Photosynthetic credit[e] | - 0.25 | - 0.23 | - 0.27 | - 0.25 | - 0.23 | - 0.27 |
| **Total net lifecycle carbon emissions** | 0.13 | 0.10 | 0.13 | 0.12 | 0.10 | 0.11 |

(a) The net carbon emissions associated with hydrogen or methanol production from MSW are detailed in the lower section of this table. It is estimated that a hydrogen/fuel cell bus of comparable duty to the diesel bus described in note *(b)* would require 25,340 Btu/mile of hydrogen fuel (for a PEM fuel cell bus on a typical intracity bus cycle [Howard, 1995]). A comparable methanol/fuel cell bus is estimated to require 29,500 Btu/mile (for a phosphoric-acid fuel cell bus [Fisher, 1995]. The rates of methanol and hydrogen production per ton of MSW are detailed in Table 2.

(b) The assumed fuel requirement for a diesel bus is 43,340 Btu/mile (3.2 mpg), the average for New York City [Pellegrin, 1995], and the carbon content of diesel fuel is assumed to be 0.0217 tons per million Btu. Carbon emissions associated with crude oil recovery from the earth, transport to refinery, and refining to diesel are not included in this comparison. Assuming these emissions would be comparable to those associated with gasoline production [Williams et al., 1995], adding them here would increase the total emissions per bus-mile by about 20%.

(c) The BCL and MTCI gasifiers use RDF, while the Thermoselect gasifier uses raw MSW. For the BCL and MTCI gasifiers, the yield of RDF is 0.83 dry tons per dry ton of MSW arriving at the plant gate. The 17% of the original dry MSW mass that is lost in this conversion is assumed to contain negligible carbon.

(d) The primary carbon releases are $CO_2$ emissions from the combustion sections of each of the three gasifiers and (for methanol production) from the Selexol acid gas removal system and (for hydrogen production) from the steam reformer furnace.

(e) Assuming that two-thirds of the carbon in MSW is accounted for by renewably-generated materials.

Table 9. Capital and operating cost estimates (in 1991$) for methanol and hydrogen production from MSW for plant capacities of 1155 dry tons per day MSW at the plant gate.[a]

| | Methanol | | | Hydrogen | | |
|---|---|---|---|---|---|---|
| Gasifier → | BCL | MTCI | T.S. | BCL | MTCI | T.S. |
| **Installed costs ($/dry ton MSW/yr capacity)** | **545.3** | **612.3** | **738.7** | **460.3** | **504.3** | **625.5** |
| Feed pre-processing | 109.1 | 109.1 | 0.0 | 109.1 | 109.1 | 0.0 |
| Gasifier | 19.2 | 51.8 | 162.2 | 19.2 | 51.8 | 162.2 |
| Gas cooling and cleaning | 22.8 | 22.8 | 81.7 | 22.8 | 22.8 | 81.7 |
| Oxygen plant | 0.0 | 0.0 | 46.4 | 0.0 | 0.0 | 46.4 |
| Reformer | 49.4 | 61.1 | 23.1 | 49.4 | 55.8 | 25.0 |
| $CO_2$ removal-MeOH or shift reactor-$H_2$ | 18.7 | 24.9 | 28.8 | 6.97 | 8.03 | 5.35 |
| Methanol synthesis or PSA & gas comp | 49.7 | 53.1 | 58.1 | 16.9 | 17.5 | 19.7 |
| Waste-heat cogeneration plant | 53.6 | 40.0 | 37.4 | 48.4 | 33.9 | 30.3 |
| Balance of plant | 81.0 | 90.7 | 109.4 | 68.2 | 74.7 | 92.7 |
| Contingencies | 81.0 | 90.7 | 109.4 | 68.2 | 74.7 | 92.7 |
| Owner's fees, costs, profits | 40.5 | 45.4 | 54.7 | 34.1 | 37.4 | 46.3 |
| Startup costs | 20.2 | 22.7 | 27.4 | 17.1 | 18.7 | 23.2 |
| **Working cap, land ($/dry tMSW/yr capacity)** | **43.4** | **48.3** | **57.7** | **37.0** | **40.3** | **49.3** |
| **Operating Costs** | | | | | | |
| **Fixed ($/dry ton MSW capacity)** | **28.3** | **30.7** | **30.6** | **25.1** | **26.7** | **26.4** |
| RDF plant | 10.1 | 10.1 | 0.0 | 10.1 | 10.1 | 0.0 |
| Other | 18.1 | 20.6 | 30.6 | 15.0 | 16.6 | 26.4 |
| **Variable ($ per MBtu of production)** | | | | | | |
| Feed (*tf* = tipping fee, $/wet ton MSW[b]) | -0.20·*tf* | -0.17·*tf* | -0.15·*tf* | -0.17·*tf* | -0.14·*tf* | -0.13·*tf* |
| Other[c] | 0.18 | 1.63 | 2.28 | 0.06 | 1.28 | 2.14 |
| **Total Levelized Cost[d] (with *tf* = tipping fee in $/wet ton MSW[b])** | | | | | | |
| $/wet ton MSW processed | 100-*tf* | 128-*tf* | 147-*tf* | 85-*tf* | 107-*tf* | 128-*tf* |
| $ per MBtu of production | 19.6 - 0.20·*tf* | 21.3 - 0.17·*tf* | 22.1 - 0.15·*tf* | 14.0 - 0.17·*tf* | 15.4 - 0.14·*tf* | 16.5 - 0.13·*tf* |
| $/gallon MeOH or $/1000 scf $H_2$ | 1.27 - 0.013·*tf* | 1.38 - 0.011·*tf* | 1.43 - 0.010·*tf* | 4.73 - 0.011·*tf* | 5.22 - 0.009·*tf* | 5.59 - 0.008·*tf* |

(a) Totals may not add due to rounding. See Chen [1995] for details.

(b) Assuming an average moisture content of 22.5% for wet MSW with the BCL systems, 17% with the MTCI systems, and 20% with the Thermoselect systems.

(c) Includes catalysts, chemicals, and (see Table 2) some purchased electricity, except in the cases with the BCL gasifier. The latter includes some credit for the sale of electricity generated (in excess of on-site needs) from process waste heat.

(d) Assumes a 15.1% capital charge rate, based on average financial parameters for major U.S. corporations from 1984-1988 (9.91% real RoR on equity, 6.2% real RoR on debt, a 30% debt fraction, 44% corporate income tax), a 1.5%/yr insurance rate, and a 25 year plant life. For land and working capital, the annual capital charge rate is 9.91%, the corporate discount rate.

Table 10. Cost comparison for New York City of 40-foot, wheelchair-equipped diesel engine and fuel cell buses.

| | Diesel Engine Bus | | Fuel Cell Bus | |
|---|---|---|---|---|
| Fuel economy (mpg diesel-equivalent)[a] | 3.2 | | 5.5 | |
| Lifetime (years)[b] | 12 | | 18 | |
| Annual mileage (miles)[c] | 25,000 | | 25,000 | |
| Lifetime mileage (miles)[d] | 300,000 | | 450,000 | |
| Purchase price (1991$)[e] | 217,000 | | 297,000 | |
| Fuel price on vehicle, excl. taxes (1991$/MBtu) (*tf* = tipping fee in $ per raw ton MSW) | in 1993:[f] 5.19<br>in 2010:[f] 6.92 | | low:[g] 19.2-0.17·*tf*<br>high:[g] 21.7-0.13·*tf* | |
| Maintenance costs (1991$)[h] | | | | |
| Annual inspections ($/yr) | 1,500 | | Levelized annual O&M cost (see below) assumed to be the same as for diesel engine bus.[i] | |
| Year-3 and year-9 upgrade ($ per upgrade) | 8,700 | | | |
| Year-6 major overhaul ($ per overhaul) | 41,700 | | | |
| | Discount Rate | | | |
| **Levelized costs (thousand $/year)** | 5% | 10% | 5% | 10% |
| Capital | 24.5 | 31.8 | 25.4 | 36.3 |
| Maintenance | 6.5 | 6.5 | 6.5 | 6.5 |
| Fuel (with *tf* = $67/ton MSW) | 1993: 5.6<br>2010: 7.5 | 5.6<br>7.5 | low: 4.9<br>high: 8.2 | 4.9<br>8.2 |
| TOTAL | 1993: 36.6<br>2010: 38.5 | 43.9<br>45.8 | low: 36.9<br>high: 40.1 | 47.7<br>50.9 |
| **Levelized costs ($/mile)** | | | | |
| Capital | 0.98 | 1.27 | 1.02 | 1.45 |
| Maintenance | 0.26 | 0.26 | 0.26 | 0.26 |
| Fuel (with *tf* = $67/ton MSW) | 1993: 0.23<br>2010: 0.30 | 0.23<br>0.30 | low: 0.20<br>high: 0.33 | 0.20<br>0.33 |
| TOTAL | 1993: 1.46<br>2010: 1.54 | 1.76<br>1.83 | low: 1.48<br>high: 1.61 | 1.91<br>2.04 |

(a) The diesel engine bus fuel economy is the current New York City average [Pellegrin, 1995]. (The average for the Borough of Manhattan is 2.6 mpg, due to the slow average bus speed in Manhattan--3.6 mph.) The fuel economy for the fuel cell bus is 75 scf $H_2$/mile (5.5 mpg-diesel equivalent), the average of the range 60-90 estimated by Howard [1995] for a Ballard hydrogen/PEM fuel cell bus on an intracity drive cycle.

(b) The assumed bus lifetimes of 12 years for the diesel and 18 years for the fuel cell correspond to the replacement schedule authorized by the Federal Transit Authority (FTA) for diesel and electric-trolley buses, respectively. The FTA provides funds to cities for the purchase of public buses. See next two notes.

(c) The average annual travel distance per bus in New York City is 25,000 miles [Pellegrin, 1995]. In cities where average bus speeds are higher, the average annual bus travel is probably closer to 42,000 miles. See next note.

(d) The Federal Transit Authority, which provides funds to urban transit authorities for purchase of buses, authorizes bus retirement after 12 years operation, over which time it is assumed that an average of 500,000 miles would be traveled. The FTA standard for electric trolley buses is 18 years/750,000 miles. These standards imply an average annual mileage of 41,700 miles. The New York City average is 25,000 miles, because bus speeds there are slower than the average for U.S. urban areas. For 12 and 18 year lifetimes, total bus miles in New York City are 300,000 and 450,000, respectively. Assuming 500,000 and 750,000 miles instead would not significantly change the tipping fees at which the lifecycle cost per mile for the fuel cell bus would compete with that for the diesel engine bus.

(e) The capital cost for the diesel bus, $216,900 (or $237,000 in 1995$), is based on a recently contracted price for diesel buses by the New York City Transit Authority [Pellegrin, 1995]. The capital cost for the fuel cell bus, $297,400 (or $325,000 in 1995$), is an estimate for mass production of a commercially mature hydrogen/PEM fuel cell bus from Ballard [Howard, 1995]. The market entry price for the fuel cell bus (production of about 100 units) is estimated to be $500,000 to $600,000 [Howard, 1995].

(f) These are diesel fuel prices in the New England census region, excluding 41¢/gal of state and federal taxes. In 1993, this price was 96 ¢/gal. It is projected to reach 96¢/gal in 2010 by the Department of Energy [EIA, 1995].

(g) The hydrogen price includes the production cost (Table 9, which assumes a discount rate of 9.91%) plus $5.17/MBtu [Williams et al, 1995] for distribution and filling station costs. The "low" fuel cost is with the BCL gasifier. The "high" fuel cost is with the Thermoselect gasifier.

(h) For the diesel bus, these are O&M costs based on the standard maintenance schedule, procedures, and replacement parts of the New York City Transit Authority [Smith, 1995], assuming (in 1991$) a cost of $36.6/person-hour (which includes administrative and other overhead and indirect costs), and maintenance consisting of monthly inspections (41 person-hours/year and negligible parts costs), a suspension system and body upgrade after 3 years (112 p-h and $5000 in parts), a major overhaul of the transmission and engine after 6 years (140 p-h and $40000 in parts), and a suspension and body upgrade after 9 years (112 p-h and $5000 in parts).

(i) Estimates of the O&M costs for the fuel cell bus are not available. However, they are likely to be lower than for a diesel engine bus because of fewer moving parts, lower operating temperatures, and less vibration. Fig. 8 examines the impact on cost of assuming lower O&M costs for the fuel cell bus.

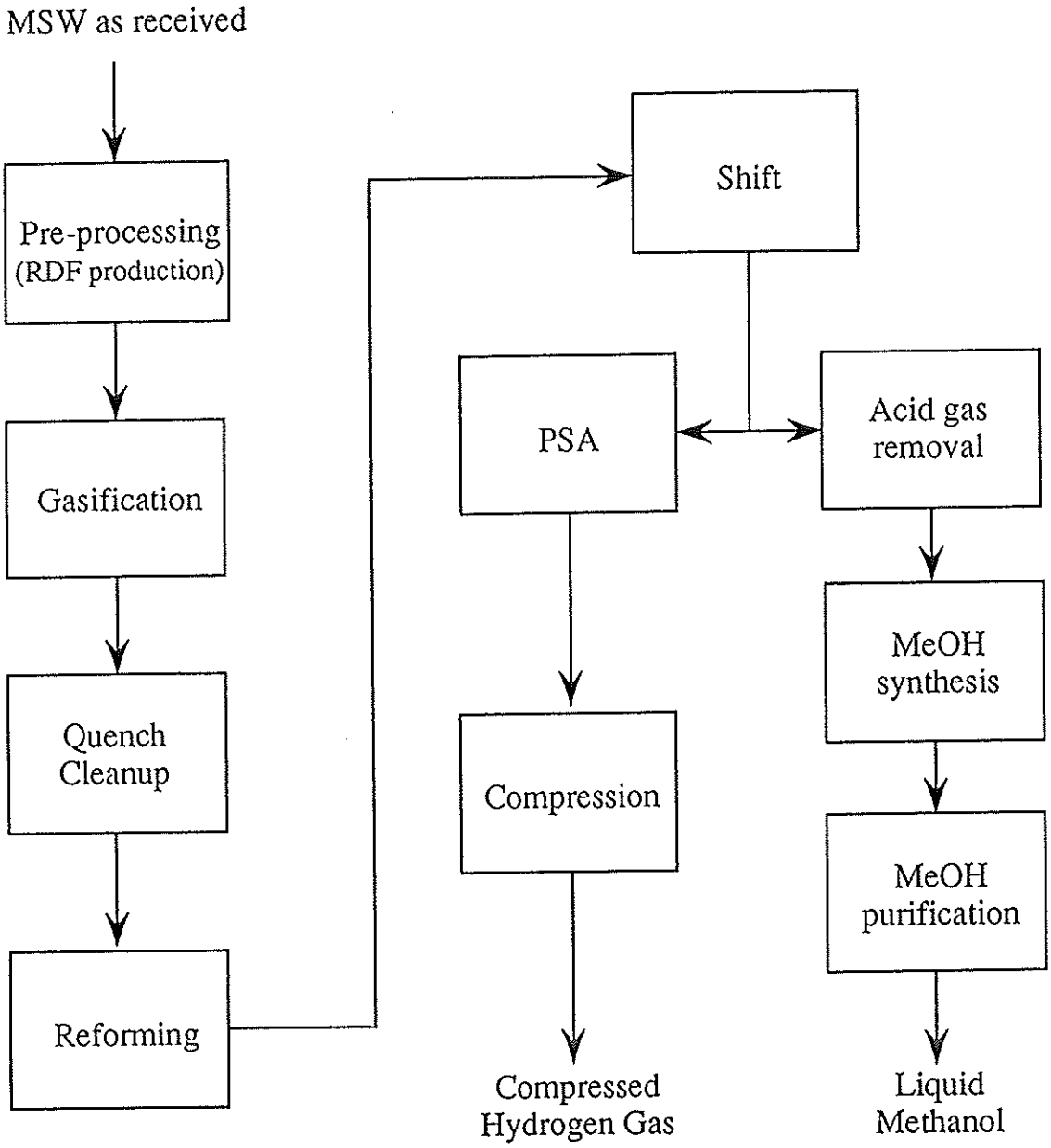


Fig. 1. Process steps in the production of methanol or hydrogn from municipal solid waste. With some gasifier designs not all steps shown are required. For example, with the Thermoselect gasifier (discussed under gasification), preprocessing and reforming are not used. All operations downstream of gasification are widely used in chemical process industries today.

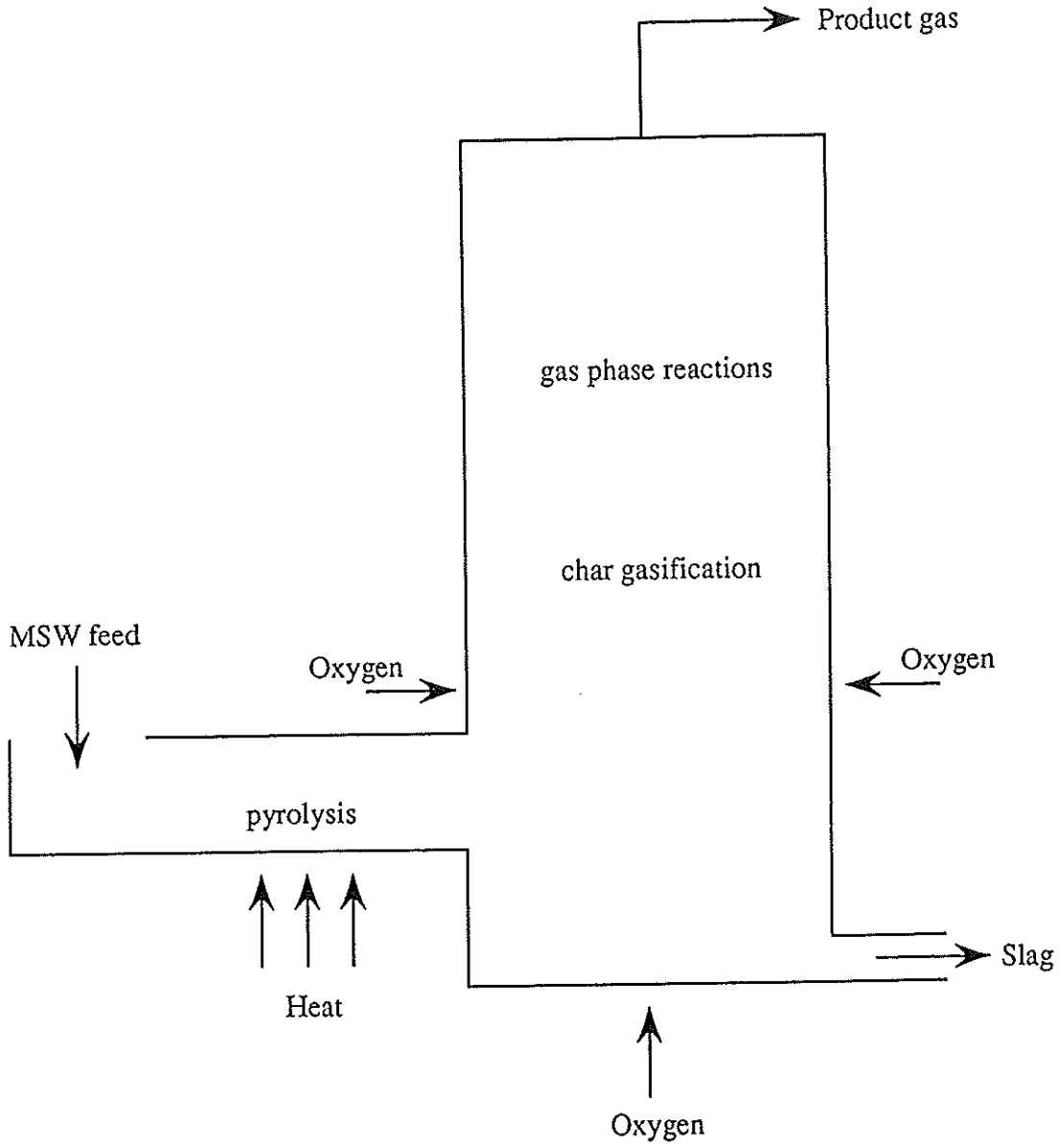


Fig. 2. **Schematic of the directly-heated Thermoselect gasifier design.** Raw MSW is compacted while being heated in the pyrolysis (devolatilization) chamber. Heat is provided by burning some cleaned product gas. The resulting char and gaseous compounds react with a sub-stoichiometric amount of oxygen in a second chamber designed as an entrained bed. The high reaction temperature leads to a product gas with low levels of methane and higher hydrocarbons, as well as to melting of the ash, which is removed as a vitrified slag. Oxygen is used in the second chamber (rather than air) because of the high temperatures that must be reached.

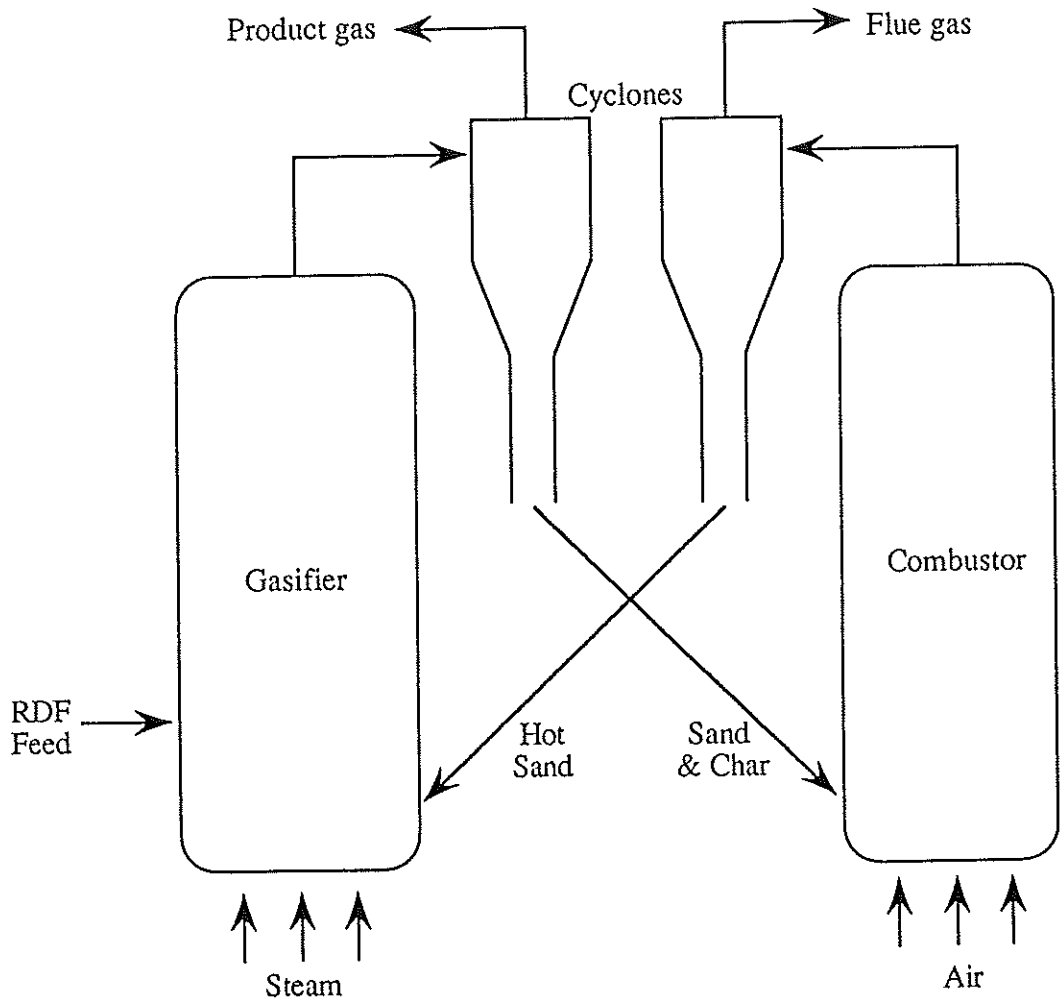


Fig. 3. **Schematic of the indirectly-heated Battelle Columbus Laboratory (BCL) gasifier design.** The BCL design requires a feed of refuse derived fuel (RDF), rather than raw MSW. The design of this system is similar to that of fluid catalytic crackers used in petrochemical refining. The RDF enters the entrained-bed gasifier chamber, where it mixes with steam and hot sand as it travels through the reactor. The RDF devolatilizes in the gasifier. The resulting gaseous products are separated from the residue char and the sand in a cyclone. The solids travel to a second entrained-bed reactor, the combustor, where the char is burned in air to reheat the sand. The heated sand is separated from the flue gases and returned to the gasifier.

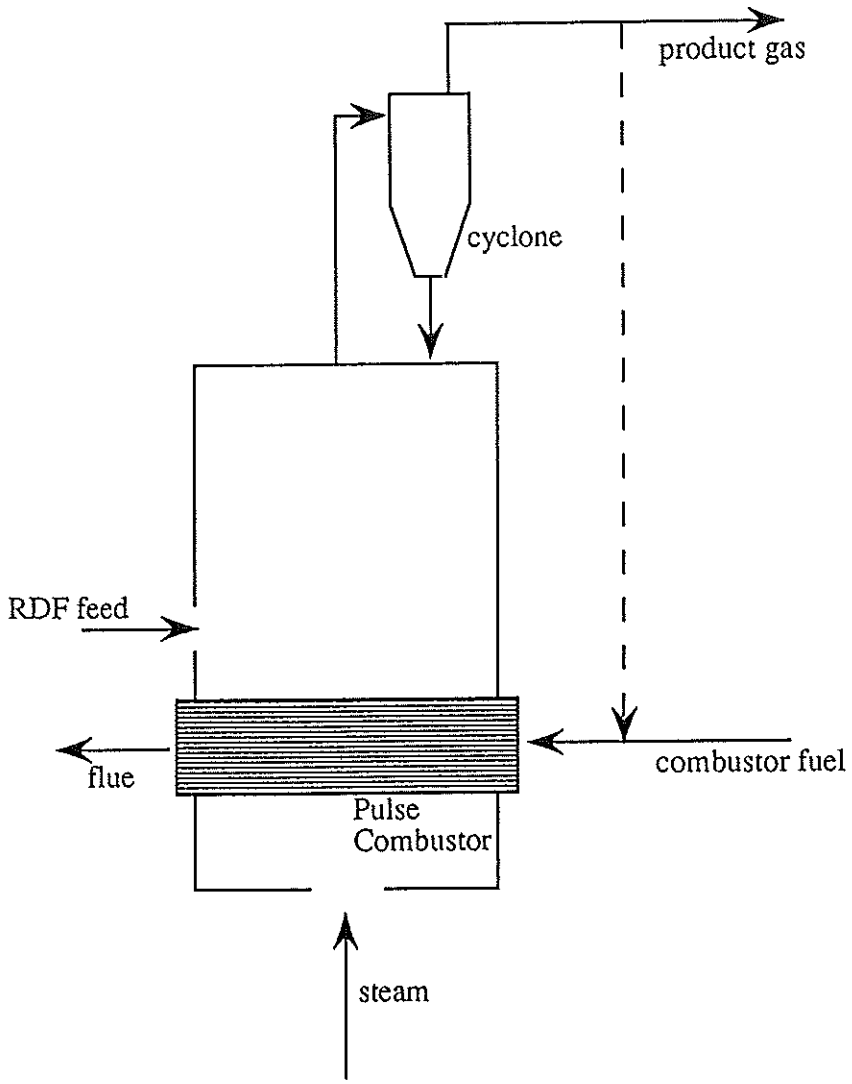


Fig. 4. **Schematic of the indirectly-heated MTCI gasifier design.** The MTCI design requires a feed of refuse derived fuel. The RDF is gasified in a fluidized-bed where steam is the fluidizing agent. Heat is provided through a heat exchanger by burning some of the product gas. The combustor/heat exchanger uses pulse combustion, the turbulent nature of which leads to substantially higher heat transfer rates than can be achieved with a conventional gas-to-gas heat exchanger.

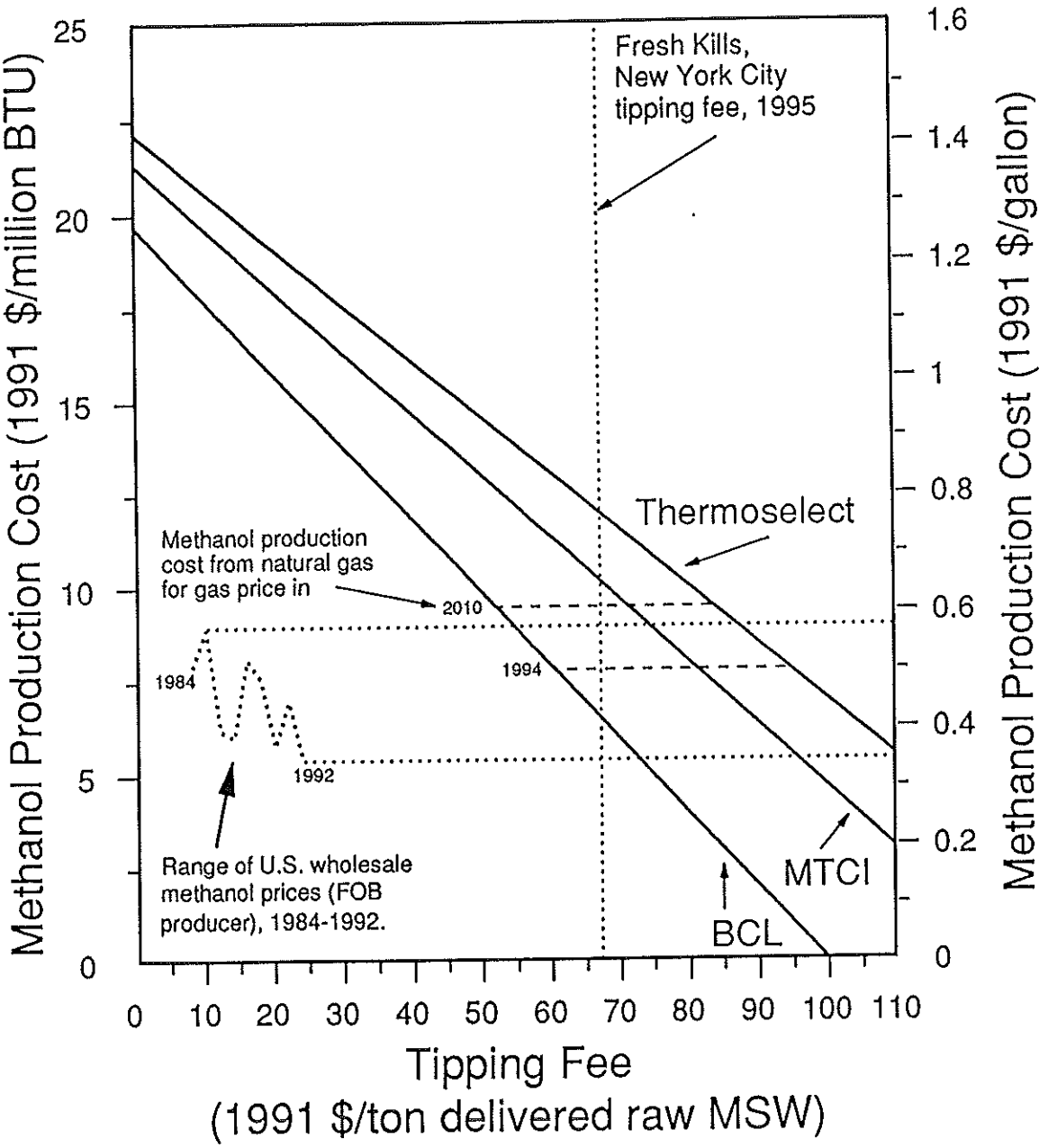


Fig. 5. **Estimated levelized costs of methanol production from MSW as a function of the tipping fee for production systems using three different gasifiers.** Details of the cost estimates are given in Table 9. Shown for comparison are the 1995 tipping fees at the Fresh Kills landfill in New York City [Bekoweis, 1995]. (Tipping fees in Philadelphia and Newark, NJ, are about $70/ton and $110/ton, respectively [EPA, 1994].) Also shown are estimated costs of producing methanol from natural gas (see footnote 16), assuming industrial-sector prices of natural gas in 1994 ($2.9/MBtu [EIA, 1995b] and as forecast for 2010 by the Department of Energy in their reference case ($4.0/MBtu [EIA, 1995a]). Also indicated is the range in wholesale methanol prices in the US from 1984 to 1992 (ITC, 1994).

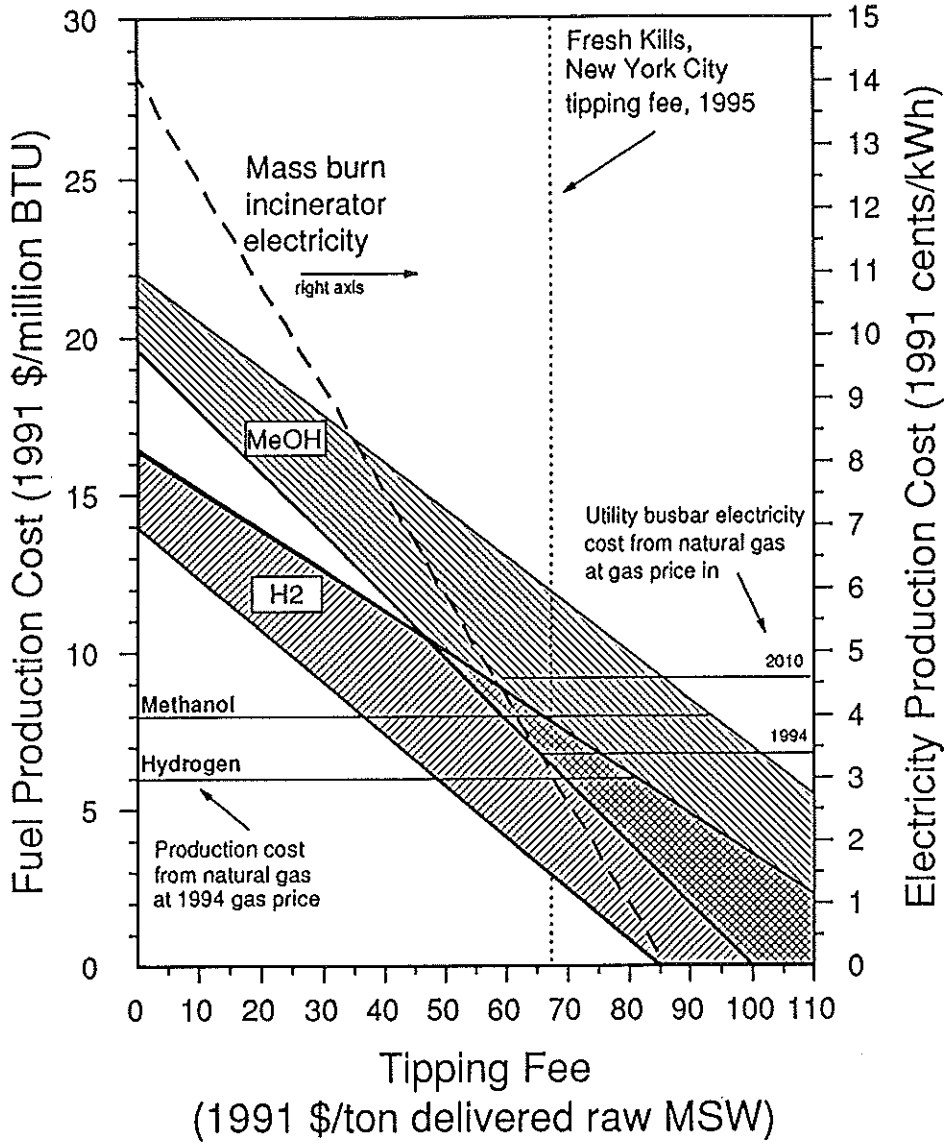


**Fig. 6. Comparison of tipping fees required for fuels production from MSW and for electricity generation from MSW in a mass burn incinerator to compete with alternative sources of fuels and electricity.**

The cost ranges for hydrogen and for methanol from MSW correspond to costs with the BCL gasifier (lower edge of range) and with the Thermoselect gasifier (upper edge of range). The costs of producing methanol and hydrogen from natural gas (see footnote 16) assume average US industrial-sector prices of natural gas in 1994 ($2.9/MBtu [EIA, 1995b]). All fuels production costs and the mass burn incinerator costs assume private financing (see Table 9, note *d*). All electricity production costs are from EPRI [1993] and assume a 75% capacity factor. Utility financing is assumed for the coal and natural gas plants. MSW for mass burn is assumed to contain 10.3 MBtu/raw ton.

| | MSW Mass Burn | Subcritical pulv. coal with FGD | Natural gas combined cycle |
|---|---|---|---|
| Installed capacity ($MW_e$) | 40 | 300 | 120 |
| Installed capital cost (1991$/$kW_e$) | 4,482. | 1,552. | 698. |
| Fixed O&M cost (1991$/$kW_e$-yr) | 129. | 45.0 | 33.2 |
| Variable O&M (1991 mills/kWh) | 18.3 | 5.8 | 0.77 |
| Heat rate (Btu/kWh) | 16,870 | 9,891. | 8140. |
| Capital charge rate | 0.151 | 0.117 | 0.111 |
| 1994 avg. US utility fuel price (1991$/MBtu) [EIA, 1995b] | | 1.26 | 2.08 |
| 2010 forecast utility fuel price (1991$/MBtu) [EIA, 1995a] | | 1.43 | 3.55 |

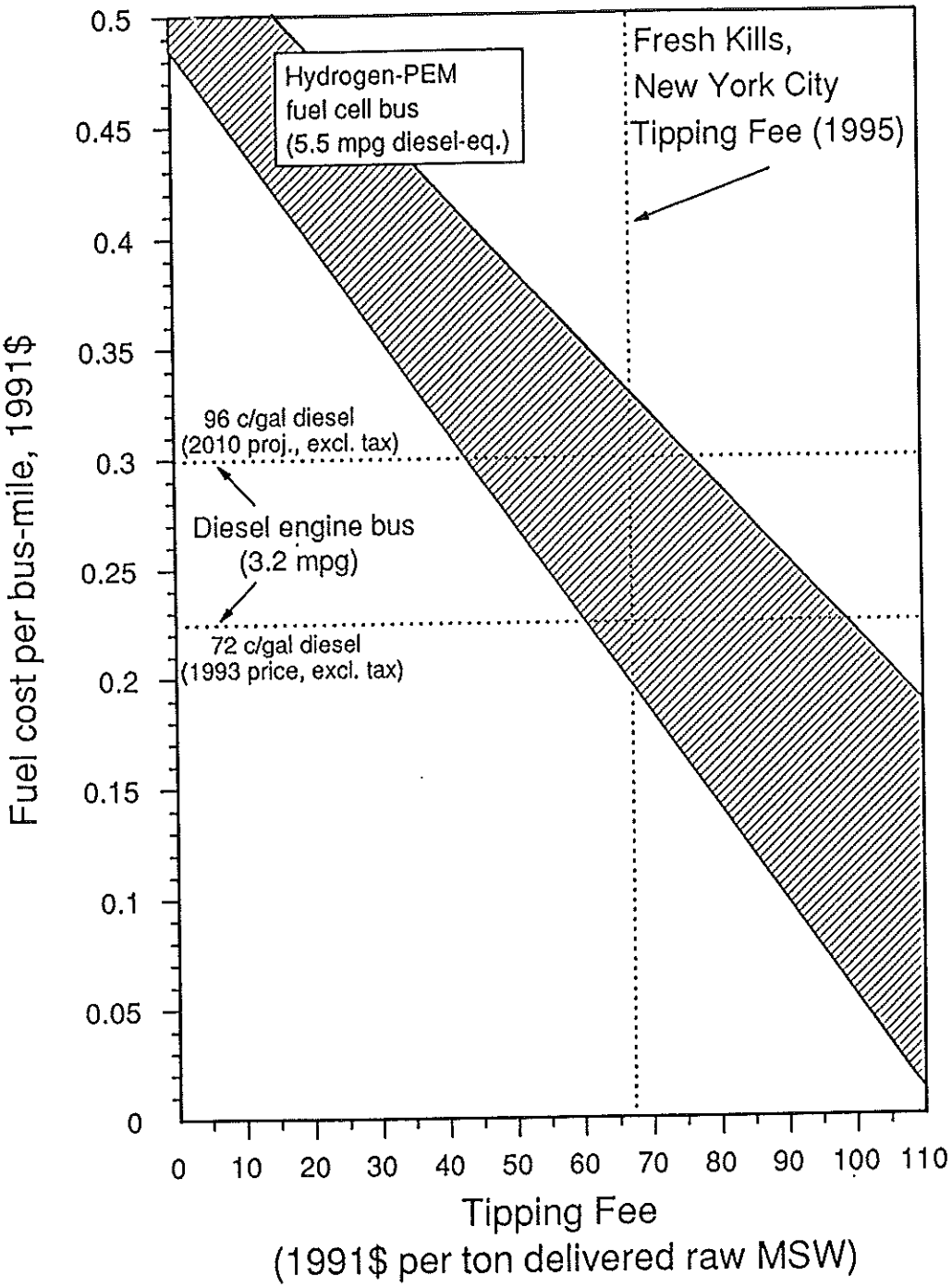


Fig. 7. Estimated range in fuel costs per mile for a 40-foot PEM fuel cell bus operating on hydrogen produced from MSW, with comparisons to fuel costs per mile for diesel engine buses for two diesel fuel prices. The cost range for hydrogen from MSW corresponds to costs with the BCL gasifier (lower edge of range) and with the Thermoselect gasifier (upper edge of range). (Table 10 has detailed assumptions.)

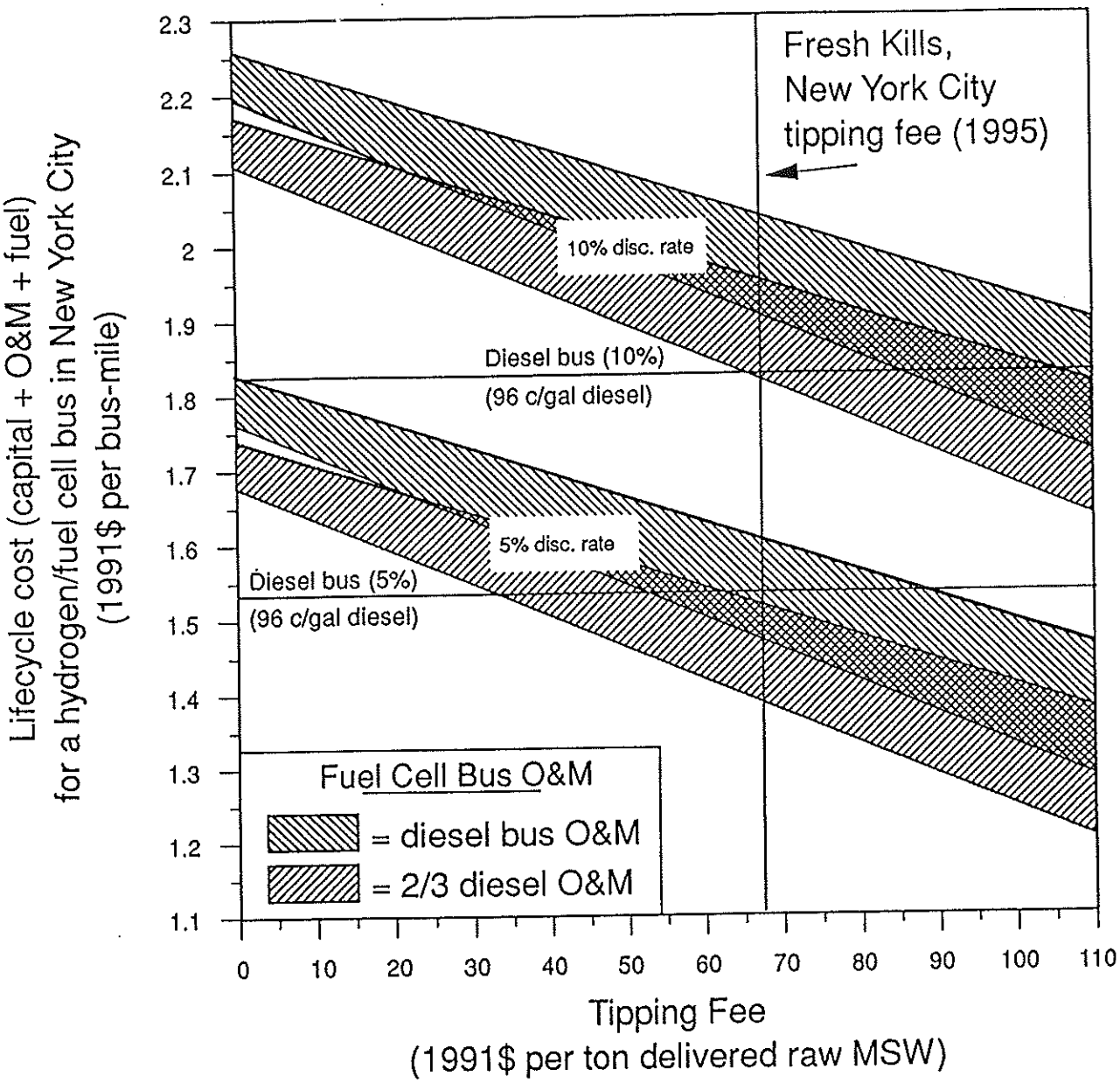


Fig. 8. **Estimated total lifecycle cost per mile (excluding taxes) of buying and operating a 40-foot, wheelchair equipped hydrogen/PEM fuel cell bus in New York City with hydrogen made from MSW and for discount rates of 10% and 5%.** The cost range for the hydrogen buses correspond to hydrogen production with the BCL gasifier (lower edge of range) and with the Thermoselect gasifier (upper edge of range). For comparison, total lifecycle costs per mile (excluding taxes) for comparable diesel IC engine buses are shown, with diesel fuel at $6.9/MBtu (96 ¢/gal), the projected price (excluding 41 ¢/gal state plus federal taxes) in the New England census region in 2010 [EIA, 1995a]. At each discount rate, the upper shaded region assumes that levelized annual O&M costs are the same for a fuel cell bus as estimated for a diesel bus today. The lower range assumes the O&M cost is two-thirds of the diesel O&M cost. Table 10 has detailed assumptions.

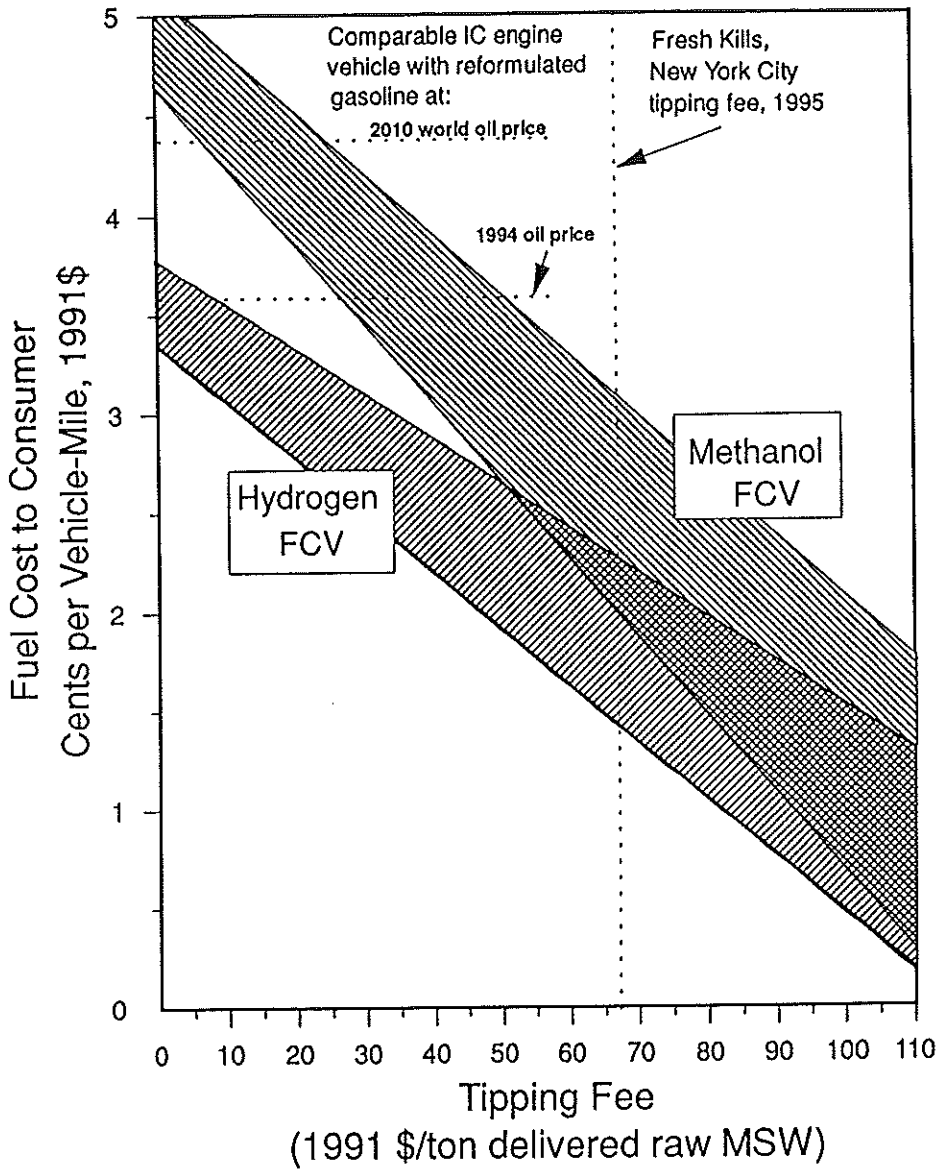


Fig. 9. **Estimated fuel costs to consumer for driving a fuel cell powered passenger vehicle comparable to a year-2000 version of the Ford Taurus.** The IC engine version of this vehicle would have a fuel economy of 25.8 mpg when operating on reformulated gasoline, as in Ogden et al., 1994 (based on detailed vehicle modeling in DeLuchi [1992] and unpublished updates thereof). The fuel cell versions of this vehicle, which would be powered by proton exchange membrane (PEM) fuel cells operating on either hydrogen or methanol, are estimated to have gasoline-equivalent fuel economies of 71.6 $mpg_{ge}$ or 61.5 $mpg_{ge}$, respectively. (The gasoline-equivalent fuel economy in miles per $gallon_{ge}$ is calculated as the miles per MBtu fuel economy of the methanol or hydrogen FCV in combined city and highway driving, multiplied by 0.125 MBtu/gallon-gasoline.) The range in methanol and hydrogen costs shown include the production cost with the BCL gasifier (lower edge of shaded ranges) or the Thermoselect gasifier (upper edge of shaded ranges) plus estimated distribution and filling station costs of $3.27/MBtu for methanol and $5.17/MBtu for hydrogen (Williams et al., 1995). Costs shown for reformulated gasoline include production costs from oil at the 1994 world oil price ($14.5/barrel [EIA, 1995b]) and at the reference price forecast for 2010 ($23/barrel [EIA, 1995a]) by the Dept. of Energy. The production cost per gallon for reformulated gasoline as a function of the world oil price, $P_{wo}$ (in $/barrel), is estimated to be $0.9 \cdot P_{wo}/42 + 0.25 + 0.15$, where 0.9 is the fraction of a gallon of gasoline derived from crude oil, 42 is the number of gallons per barrel, $0.25 is the estimated cost of refining standard gasoline, and $0.15 is the additional cost for refining reformulated gasoline [DeLuchi, 1992]. The distribution and filling station costs for gasoline are assumed to total 21 ¢/gallon, or $1.69/MBtu [Williams et al., 1995].

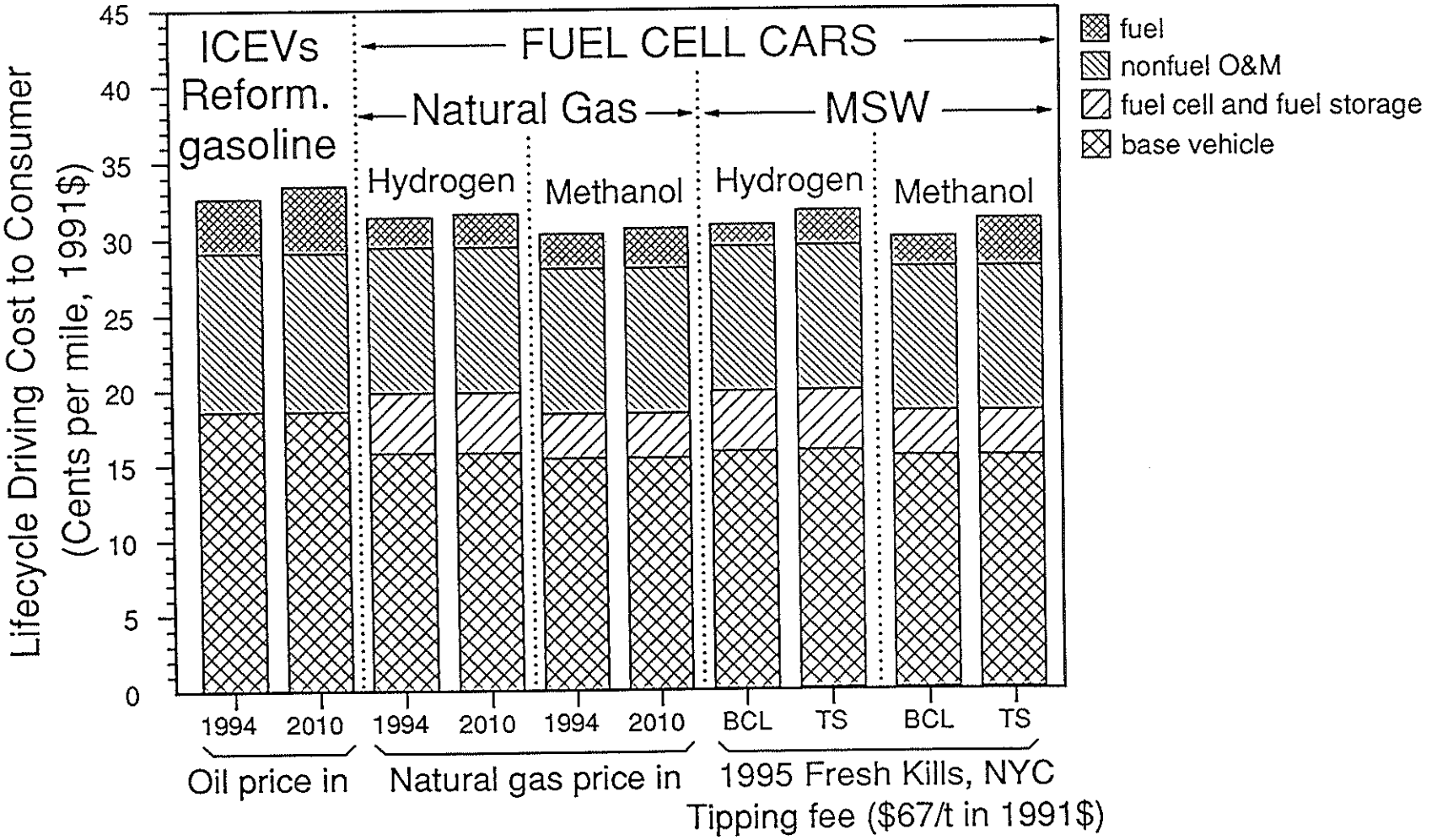


Fig. 10. **Estimated total lifecycle cost to consumer of owning and operating a passenger car comparable to a year-2000 version of the Ford Taurus.** Results are shown for an IC engine version of this vehicle using reformulated gasoline (see Fig. 9 caption for assumed gasoline prices) and PEM fuel cell versions of this vehicle using methanol or hydrogen derived from natural gas or MSW. Assumed end-user prices for hydrogen and methanol from natural gas (including distribution and filling station costs) are based on average industrial sector natural gas prices in 1994 and as forecast for 2010 (see Fig. 5 caption). The cost of the MSW-derived fuels assume a tipping fee of $67/ton and use of the BCL gasifier (BCL) and the Thermoselect gasifier (TS). The non-fuel cost components for each case are as reported by Ogden, et al. [1994], based on detailed vehicle and cost modeling by DeLuchi [1992, and unpublished updates thereof].

## References


Atlantis, Inc., "Sources and Disposition of New York City Wood Waste," a report to the Marketing Unit, Recycling Programs and Planning Division, Dept. of Sanitation, New York City, 28 August 1990.

Bechtel Group, *Waste-to-Energy Permitting Sourcebook*, TR-100716, Electric Power Research Institute, Palo Alto, CA, 1992.

P. Bekoweis (R&D, Dept. of Sanitation, New York City), personal communication, August 1995.

Central Department, Prevention of Air Pollution, Emissions, "Report on Measurements in the Synthesis Gas, the Waste-Gas Downstream the Gas Engine and Degassing Duct Heating System and Sampling and Analysis of Product and Material Specimens for Evaluation of the Thermoselect Process," Institute for Environmental Protection, Chemistry and Biology (RWTUV), Essen, Germany, Oct. 21, 1994.

Central Department, Prevention of Air Pollution, Emissions, "Comment on the Limitation of Emissions in the USA and in the FRG: Comparison taking the emission levels determined at the Thermoselect plant," Institute for Environmental Protection, Chemistry and Biology (RWTUV), Essen, Germany, April 11, 1995.

J.S. Chen, *The Production of Methanol and Hydrogen Fuels from Municipal Solid Waste*, Report 289, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, March 1995.

Chicago Dept. of Environment, "World's First Commercial Hydrogen Fuel-Cell Bus Unveiled in Chicago," press release, Chicago, Sept. 11, 1995.

J. Connor, "Senate Passes Bill To Aid Muni Bonds Tied to Trash Flow," *Wall Street Journal*, May 17, 1995.

Council of Economic Advisors, *Economic Indicators*, USGPO, Washington, DC 1995.

CRC, *Handbook of Chemistry and Physics*, 53rd ed., Weast (ed.), The Chemical Rubber Co., Cleveland, 1972.

M.A. DeLuchi, *Hydrogen Fuel Cell Vehicles*, UCD-ITS-RR-92-14, Institute of Transportation Studies, University of California, Davis, September 1992.

DOT, (Dept. of Transportation), *Annual Travel Monitor Report*, State of New York, Albany, NY, 1992.

DOT (Dept. of Transportation), Transit Division, State of New York, Albany, NY, personal communication, Aug. 1995.

EIA (Energy Information Admin.), *Annual Energy Outlook 1995, with Projections to 2010*, DOE/EIA-0383 (95), USGPO, January 1995a.

EIA (Energy Information Admin.), *Monthly Energy Review*, DOE/EIA-0035 (95/7), USGPO, July 1995b.

EPA (Environmental Protection Agency), *Waste Prevention, Recycling, and Composting Options: Lessons from 30 Communities*, EPA530-R-92-015, USEPA, Washington, DC, Feb. 1994.

EPRI (Electric Power Research Institute), *Technical Assessment Guide (TAG™)*, Vol.1: Rev.7, (TR-102275-V1R7), EPRI, Palo Alto, CA, 1993.

J.K. Fisher, "Description and Test Results of the 30 foot PAFC Transit Bus," prepared for *TOPTEC Conference on Fuel Cells for Transportatopm*, Santa Fe, NM, March 28-29, 1995.

Georgetown, "Fuel Cell Bus," brochure, Georgetown University, Washington, DC, 1993.

J. Hahn, C. Nagge, P. Ponlot, B. Bahor, and D. Sussman (Ogden Martin Systems), "Control by Using Automatic Combustion with Dry Scrubber/Fabric Filtration (DS/FF)," *Chemosphere*, 25 (1-2), pp. 153-156, 1992.

C.A. Hendricks, *Carbon Dioxide Removal from Coal-Fired Power Plants*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994.

B. Hileman, "Dioxin Toxicity Research: Studies Show Cancer, Reproductive Risks," *Chemical and Engineering News*, Sept. 5, 1993.

P. Hoffman, "H Power to Roll Out Commercial Fuel Cell Busses Next Summer, Seeks ZEV Certificate," *Hydrogen and Fuel Cell Letter*, X(9), Sept. 1995.

P. Howard, (Vice President, Programs, Ballard, North Vancouver, BC), personal communication, Oct. 1995.

International Trade Commission, *Synthetic Organic Chemicals: U.S. Production and Sales*, Annual reports, US International Trade Commission, Washington, DC, 1985-1994.

M. Kapner (R&D Division, New York Power Authority, New York City), personal communication, Oct. 1995.

S. Kartha and P. Grimes, "Fuel Cells: Energy Conversion for the Next Century," *Physics Today*, November 1994, pp. 54-61.

R. LaValva (Dept. of Sanitation, New York City), personal communication to Mark Kapner (New York Power Authority), 18 April 1994.

S. Moon, "A Big Leap Forward for Biomass Gasification," *Biologue*, 3(13), 1995, pp. 4-11.

MTCI, *Testing of an Advanced Thermochemical Conversion Reactor System*, PNL-7245, Pacific Northwest Laboratory, Richland, WA, 1990.

K. Lützke and K.-H. Wehde, *Test Report on the Main Product and Material Flows in the Thermoselect Process*, RWTÜV (commissioned by Thermoselect S.r.l.), Essen Germany, March 9, 1993.

J.M. Ogden, E.D. Larson, and M.A. Delucchi, *A Technical and Economic Assessment of Renewable Transportation Fuels and Technologies*, US Congress, Office of Tech. Assessment, Wash. D.C., May 27, 1994.

J.F. Owens, "Slag-Iron and Steel," in *Minerals Yearbook 1989*, Bureau of Mines, US Dept. of the Interior, USGPO, Washington, DC, 1991.

M.A. Paisley, K.S. Creamer, T.L. Tewksbury, and D.R. Taylor, *Gasification of Refuse Derived Fuel in the Battelle High Throughput Gasification System*, PNL-6998, Pacific Northwest Laboratory, Richland, Wash., 1989.

V. Pellegrin (Chief Officer, Research and Development, New York City Transit Authority, Brooklyn), personal communication, Oct. 1995.

Planning Section, Mercer County Improvement Authority, Trenton, New Jersey, personal communcation, 29 Sept. 1995.

F. Rockwell, "New York City Recycling Update," *BioCycle*, June 1994, pp. 65-67.

J. Riegel and D.J. Runyon (Thermoselect), "Energy and Raw Material Recovery Through Thermal Chemical Transformation in a Closed-Loop System," presented at Third Int'l. Conf. and Seminar on Municipal Waste Combustion, March 31, 1993.

J. Smith (Ass't. Chief Maintenance Officer, New York City Transit Auth., Brooklyn), personal communication, Oct. 1995.

M. Steinbugler (Mechanical and Aerospace Engineering Dept., Princeton University), personal communication, Aug. 1995.

P.M. Sullivan, W.H. Hallenbeck, and G.R. Brenniman, *Municipal Solid Waste Combustion: Waste-to-Energy Technologies, Regulations, and Modern Facilities in USEPA Region V*, School of Public Health, Univ. of Illinois at Chicago, August 1993.

V.M. Thomas and T.G. Spiro, *An Estimation of Dioxin Emissions in the United States*, PU/CEES Rpt. 285, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, December 1994.

UNEP/WHO (United Nations Environment Program/World Health Organization), *Urban Air Pollution in the Megacities of the World*, Blackwell Publishers, Oxford, 1992.

R.H. Williams, "Fuel Cells and Their Fuels for Cars," *Technology Review*, April 1994.

R.H. Williams, E.D. Larson, R.E. Katofsky, and J. Chen, *Methanol and Hydrogen from Biomass for Transportation, with Comparisons to Methanol and Hydrogen from Natural Gas and Coal*, Report 292, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, July 1995.