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Project Summary

NO_x Control Technologies Applicable to Municipal Waste Combustion

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Several technologies are available for reducing nitrogen oxide (NO_x) emissions from municipal waste combustors (MWCs), including combustion controls, natural gas injection (NGI), selective non-catalytic reduction (SNCR), and selective catalytic reduction (SCR). The full report documents the key design and operating parameters, commercial status, demonstrated performance, and cost of NGI, SNCR, and SCR, and identifies technology research and development needs associated with them.

Two NGI processes have been developed: (1) Methane de-NOX[SM] uses gas injection to inhibit NO_x formation and appears capable of reducing NO_x emissions from MWCs by approximately 60% and (2) reburning uses gas injection to create reducing conditions that convert NO_x formed in the primary combustion zone to molecular nitrogen. Because of the relatively high temperatures required for these NO_x-reduction reactions, it may be difficult to successfully apply reburning to modern mass-burn waterwall MWCs. Long-term emission reductions are 45-65% for SNCR and 80-90% for SCR. Operation of SNCR processes near the upper end of their performance range can result in unwanted emissions of ammonia or other by-product gases. An advanced version of SNCR using furnace pyrometry and additional process controls appears capable of achieving high NO_x reductions with less reagent than is needed for conventional SNCR. The combination of NGI and SNCR (advanced NGI) may be able to achieve overall NO_x reductions of 80-85%.

Comparing costs, SCR is the most capital intensive, followed by advanced SNCR and advanced NGI. Capital costs of NGI and conventional SNCR are comparable. In terms of tipping fee impact and cost effectiveness, conventional SNCR generally has the lowest costs of the evaluated technologies. For NGI, these costs depend on whether waste is diverted and tipping fee revenues are lost when applying this technology, along with the price of natural gas. Depending on the selected NGI scenario, the resulting tipping fee impacts and cost effectiveness values can be the highest of the evaluated technologies. After specific NGI scenarios, the next highest tipping fee impacts and cost effectiveness values are for SCR. These high costs result from high capital costs, as well as the cost of catalyst replacement and disposal.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Nitrogen oxides (NO_x) are of environmental significance because of their role as a criteria pollutant, acid gas, and ozone precursor. The current New Source Performance Standards (NSPS) for municipal waste combustors (MWCs) (40 CFR Part

60, Subpart Ea) limit NO_x emissions to a daily average of 180 parts per million (ppm) at 7% oxygen (O_2), dry basis.* By comparison, typical NO_x emissions from modern mass-burn waterwall (MB/WW) MWCs range from 220 to 320 ppm. To comply with the NSPS, most recently built MWCs have used a combination of combustion controls to limit NO_x formation and selective non-catalytic reduction (SNCR) to convert NO_x to molecular nitrogen (N_2). Because of pressure to achieve even lower emission levels, questions have been raised regarding the potential for advancements in NO_x control technologies. To respond to these questions, the U.S. Environmental Protection Agency's (EPA's) Air and Energy Engineering Research Laboratory and the Department of Energy's National Renewable Energy Laboratory initiated this assessment of three alternative NO_x control technologies: natural gas injection (NGI), SNCR, and selective catalytic reduction (SCR). The objectives of the assessment were to (1) document the key design and operating parameters, commercial status, demonstrated performance, and cost of each technology and (2) identify technology research and development needs.

The assessment of achievable NO_x emissions presented by the report is based on the average NO_x reduction potential of these technologies applied to "typical" MWCs. The assessment does not examine the potential severity or length of short-duration excursions in performance that can affect continuously achievable NO_x emission rates associated with short averaging periods. The assessment also does not consider potential limitations on technology performance that may result from combustor-specific design or operating restrictions.

NO_x Formation

The chemistry of NO_x formation is directly tied to reactions between nitrogen and O_2. To understand NO_x formation in an MWC, a basic understanding of combustor design and operation is useful. Combustion air systems in MB/WW MWCs include both undergrate (also called primary) air and overgrate (also called secondary or overfire) air. Undergrate air, supplied through plenums located under the firing grate, is forced through the grate to sequentially dry (evolve water), devolatilize (evolve volatile hydrocarbons), and burn out (oxidize nonvolatile hydrocarbons) the waste bed. The quantity of undergrate air is adjusted to minimize excess air during initial combustion of the waste while maximizing burnout of carbonaceous materials in the waste bed. Overgrate air, injected through air ports located above the grate, is used to provide turbulent mixing and destruction of hydrocarbons evolved from the waste bed. Overall excess air levels for a typical MB/WW MWC are approximately 80% (180% of stoichiometric [i.e., theoretical] air requirements), with undergrate air accounting for 60-70% of the total air. In addition to destruction of organics, one of the objectives of this "staged" combustion approach is to minimize NO_x formation.

NO_x is formed during combustion through two primary mechanisms: fuel NO_x formation and thermal NO_x formation. Fuel NO_x results from oxidation of organically bound N_2 present in the municipal solid waste (MSW) stream. Thermal NO_x results from oxidation of atmospheric N_2.

Fuel NO_x is formed within the flame zone through reaction of organically bound N_2 in MSW materials and O_2. Key variables determining the rate of fuel NO_x formation are the availability of O_2 within the flame zone, the amount of fuel-bound N_2, and the chemical structure of the N_2-containing material. Fuel NO_x reactions can occur at relatively low temperatures [<1,100°C (<2,000°F)]. Depending on the availability of O_2 in the flame, the N_2 compounds will react to form either N_2 or NO_x. When the availability of O_2 is low, N_2 is the predominant reaction product. If substantial O_2 is available, an increased fraction of the fuel-bound N_2 is converted to NO_x. Testing conducted in the 1970s and 1980s using coal showed that in O_2-rich, highly mixed systems approximately 50% of the fuel-bound N_2 can convert to NO_x; in O_2-starved staged-combustion systems, however, the rate of conversion decreases to near 5%. Other testing has shown that N_2 associated with volatile compounds is more readily converted to fuel NO_x than N_2 associated with nonvolatile materials. Still other research involving coal and oil combustion indicates that the extent of conversion is related to the amount of N_2 available, with the degree of conversion decreasing as the amount of fuel-bound N_2 increases.

Thermal NO_x is formed in high-temperature flame zones through reactions between N_2 and O_2 radicals. The key variables determining the rate of thermal NO_x formation are temperature, the availability of O_2 and N_2, and residence time. The key reactions resulting in thermal NO_x formation are

$$N_2 + O \rightleftarrows NO + N \qquad (1)$$

followed by

$$N + O_2 \rightleftarrows NO + O \qquad (2)$$

$$N + OH \rightleftarrows NO + H \qquad (3)$$

Because of the high activation energy required for Reaction (1), thermal NO_x formation does not become significant until flame temperatures reach 1,100°C (2,000°F). Kinetic calculations (assuming 30% excess air, average MSW properties, and residence time of 0.5 second) predict thermal NO_x concentrations of <10 ppm in MWCs. However, local flame temperatures may exceed 1,100°C and thermal NO_x concentrations may be greater than these calculated model results.

Examination of MWC operating conditions suggests that most of the NO_x emitted from MWCs (>80%) is attributable to fuel-bound N_2. Based on typical MSW N_2 contents of 0.3-0.7%, the expected NO_x emissions—assuming all of the fuel-bound N_2 is converted to NO_x—would be 1,000-2,500 ppm at 7% O_2. As noted earlier, however, actual emissions are generally between 220 and 320 ppm at 7% O_2, indicating that perhaps 10-30% of the fuel N_2 is converted to NO_x, with most of the remainder forming N_2.

A number of evaluations of MWC NO_x emissions data have attempted to define the role of N_2-containing materials in MSW (e.g., grass, leaves, wood, and food wastes) on NO_x emissions. The first of these evaluations was presented in 1987 and suggested that fluctuations in measured NO_x levels were attributable to seasonal fluctuations in MSW composition. This evaluation was based on NO_x compliance test data obtained from a number of MWCs in the U.S. and overseas at different times of the year, and concluded that the seasonal variations in measured NO_x concentrations might be the result of variations in the amount of yard waste in the MSW at different times of the year. A similar comparison of NO_x emission concentrations versus time of year for a number of U.S. MWCs compiled by EPA in 1989 to support the MWC NSPS did not show any significant relationship between NO_x concentration and time of year.

A more recent evaluation of NO_x continuous emission monitor data from 11 MWCs located in the northeast U.S. found no seasonal variations in NO_x concentrations. This evaluation compared monthly average NO_x data from the individual MWCs (covering 12-36 consecutive months of operation for each unit) with the estimated fraction of yard waste found in northeastern MSW during each of the four seasons. Monthly average NO_x concentrations from these units varied from

* Unless otherwise noted, all NO_x concentrations used in this summary are corrected to 7% O_2 and are on a dry basis.

140 to 310 ppm but did not show any consistent relationship between NO_x concentrations and the estimated percentage of yard waste.

Yet another evaluation compared NO_x concentrations measured during nine test runs conducted at the MB/WW MWC in Burnaby, British Columbia, to the amount of high-N_2 organics (grass, leaves, brush, stumps, wood, food waste, textiles, rubber, and footwear) in the MSW fired during each run. During these tests, high-N_2 organics accounted for 25-47% and yard waste accounted for 4-30% of the total waste stream. The estimated average N_2 content of the entire stream during each run ranged from 0.34 to 0.66%. NO_x concentrations in the flue gas during the runs varied from 261 to 304 ppm. Statistical analysis of the MSW and flue gas data from each run showed no relationship (at a screening 80% confidence level) between NO_x concentrations and MSW characteristics. The data suggest that, because of the staged-combustion design of the Burnaby MWC and other modern MB/WW MWCs, variations in NO_x emissions appear to be attributable to differences in combustor design and operation, rather than waste composition.

NO_x Control Technologies

NO_x control technologies can be divided into two subgroups: combustion controls and post-combustion controls. Combustion controls limit the formation of NO_x during the combustion process by reducing the availability of O_2 within the flame and lowering combustion zone temperatures. These technologies include staged combustion, low excess air, flue gas recirculation (FGR), and NGI. Staged combustion and low excess air reduce the flow of undergrate air in order to reduce O_2 availability in the combustion zone. Another option is FGR in which a portion of the combustor exhaust is returned to the combustion air supply to both lower combustion zone O_2 and suppress flame temperatures by reducing the ratio of O_2 to inerts [N_2 and carbon dioxide (CO_2)] in the combustion air system. One or more of these approaches are used by most modern MWCs. Test data for these techniques indicate that they can reduce NO_x concentrations by 10-30% compared to baseline levels from the same units. For NGI, two processes have been developed: (1) Methane de-NO_x℠ uses gas injection to inhibit NO_x formation and (2) reburning uses gas injection to create reducing conditions that convert NO_x formed in the primary combustion zone to N_2.

The most used post-combustion NO_x controls for MWCs include SNCR and SCR. SNCR reduces NO_x to N_2 without the use of catalysts. With SNCR, one or more reducing agents are injected into the upper furnace of the MWC to react with NO_x and form N_2. SNCR processes include Thermal DeNO_x™, which is based on ammonia (NH_3) injection, NO_xOUT™, which uses urea injection, and the addition of urea followed by methanol. Thermal DeNO_x and NO_xOUT have been used predominantly to date.

SCR is an add-on control technology that catalytically promotes the reaction between NH_3 and NO_x. SCR systems can use aqueous or anhydrous NH_3, with the primary differences being the size of the NH_3 vaporization system and the safety requirements.

Technical Approach

This assessment was conducted using information obtained from published literature and contacts with technology vendor and MWC industry personnel. For each technology, information was collected on the key process variables; commercial applications in Europe, Japan, and the U.S.; recent research and development activities; and costs. In addition to the current versions of NGI and SNCR, advanced concepts for the two technologies were examined, including advanced NGI (which combines conventional NGI and SNCR) and advanced SNCR (which employs additional process control equipment to enhance conventional SNCR performance). This information was then used to develop a series of computer-based spreadsheets designed to maintain basic material and energy balances for the technology and to calculate technology costs.

The output from these spreadsheets is presented in two formats. The first format is a table presenting capital costs, tipping fee impacts, and cost effectiveness levels** for each NO_x control technology as a function of MWC size and a second key technology variable. An example of this output, based on conventional SNCR, is shown in Table 1. For example, the estimated capital cost for SNCR operating at 60% NO_x reduction on a 400 ton per day (tpd) MWC is $1,980/tpd of capacity. For the same NO_x reduction level and MWC size, the tipping fee impact is estimated at approximately $1.50 per ton of MSW processed, and the cost effectiveness is approximately $1,270 per ton of NO_x removed from the flue gas.

The second output format is a graph showing the sensitivity of tipping fee impact and cost effectiveness to key process variables. An example of this output, also based on conventional SNCR, is presented in Figure 1. For example, the process variable having the greatest effect on cost is MWC size. Compared to the 400 tpd "reference" MWC, reducing plant size to 100 tpd increases the tipping fee impact from roughly $1.50 per ton of MSW to almost $4.00 per ton (shown on the left Y-axis), and increases the cost effectiveness value from $1,270 per ton of NO_x removed to $3,380 per ton (shown on the right Y-axis).

Technical Status of Evaluated Control Technologies

The technical status of each evaluated control technology is summarized in Table 2. As noted, two NGI processes have been developed. Methane de-NO_x uses gas injection to inhibit NO_x formation and appears capable of reducing NO_x emissions from MWCs by approximately 60%. The second approach, reburning, uses gas injection to create reducing conditions that convert NO_x formed in the primary combustion zone to N_2. Because of the relatively high temperatures required for these NO_x-reduction reactions, it may be difficult to successfully apply reburning to modern MB/WW MWCs. Short-duration tests of these processes have been conducted at MWCs in the U.S. and Europe. However, neither process has been adequately developed and demonstrated to be considered ready for commercial applications.

Both SNCR processes (Thermal DeNO_x and NO_xOUT) and SCR are considered to be commercially available. Long-term NO_x reductions are 45-65% for SNCR and 80-90% for SCR. Operation of these processes near the upper end of their performance range can result in unwanted emissions of unreacted NH_3 or other by-product gases. An advanced version of SNCR using furnace pyrometry and additional process controls has been tested on at least two MWCs and appears capable of achieving high NO_x reductions with less reagent than is needed for conventional

**Capital costs include purchased equipment costs, installation, engineering and home office expenses, and process and project contingencies. Tipping fee impact is calculated by dividing the technology's total annualized cost by the annual tonnage of MSW processed. Tipping fee impact is an incremental cost that indicates the potential cost of the technology on the MSW generator. However, it does not necessarily reflect the amount by which the plant's tip fee will increase as a result of applying the control technology. Cost effectiveness is calculated by dividing the technology's total annualized cost by the tonnage of reduced NO_x emissions and indicates the cost of the control relative to its environmental benefit.

Table 1. Model Plant Cost Estimates for Conventional SNCR [a]

	Total Capital Cost ($1000/TPD Capacity)			Tipping Fee Impact ($/ton MSW)			Cost Effectiveness ($/ton NO_x)		
NO_x Reduction (%)	45	60	65	45	60	65	45	60	65
100 TPD Mass Burn MWC	5.05	5.06	5.07	3.74	3.91	4.06	4,308	3,378	3,235
400 TPD Mass Burn MWC	1.97	1.98	2.00	1.30	1.47	1.62	1,496	1,268	1,289
750 TPD Mass Burn MWC	1.49	1.50	1.52	0.92	1.09	1.24	1,058	940	986

[a]$/ton can be converted to $/Mg by multiplying by 1.1.

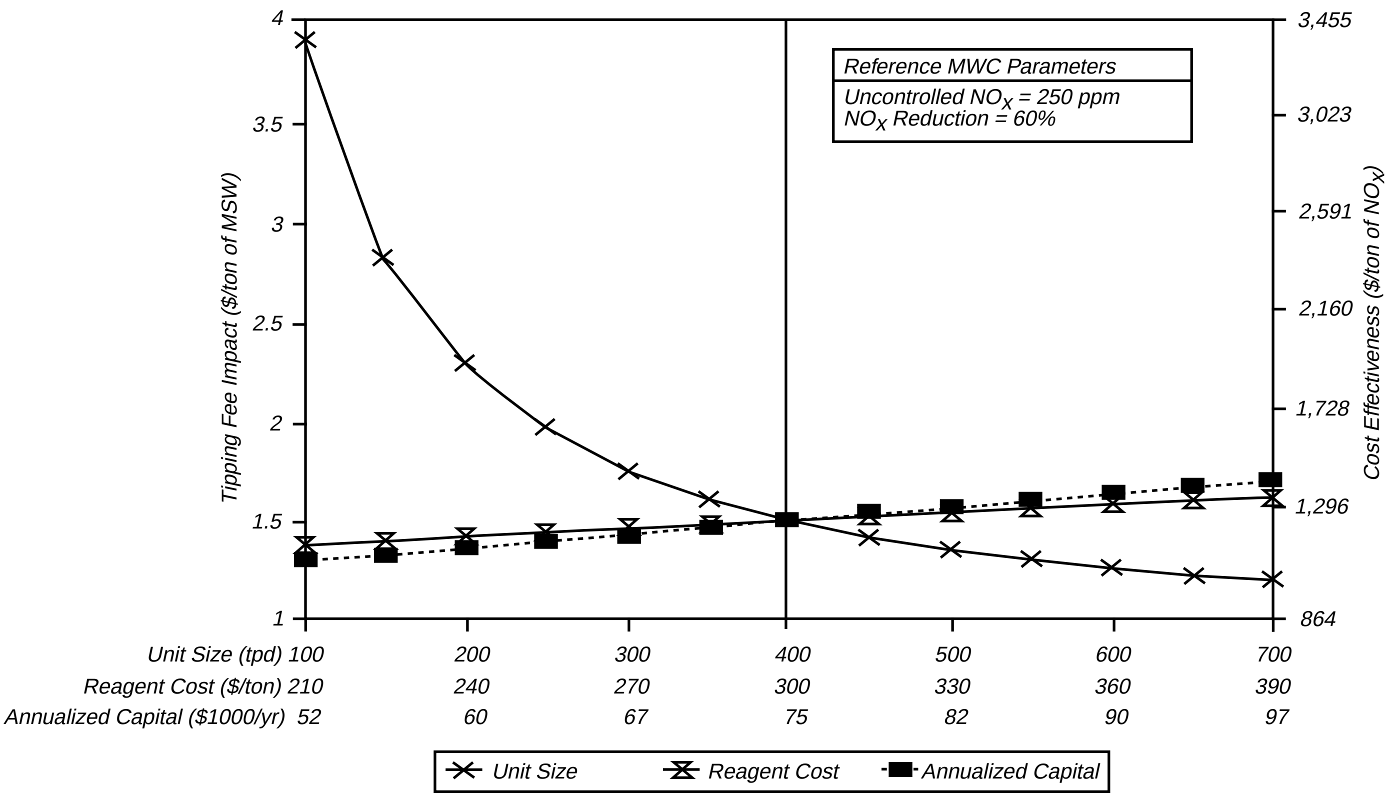

***Figure 1**. Effect of unit size, reagent cost, and annualized capital on tipping fee impact and cost effectiveness for conventional SNCR.*

SNCR. Combining NGI and SNCR to achieve an overall NO_x reduction of 80 - 85% may be feasible but will require testing to evaluate the interactions between the temperature and residence time requirements of each technology.

Comparative Costs of Evaluated Control Technologies

As part of this study, cost evaluations were conducted for several variations of NGI, SNCR, and SCR. For the evaluation of NGI, two scenarios were examined. The first scenario, referred to as NGI-100, assumes the MWC is firing MSW at 100% of its design heat input capacity. Therefore, under this scenario, the rate of waste fired must be reduced by an amount comparable to the heat input from natural gas. This results in a reduction of tipping fee revenues. The second scenario, referred to as NGI-85, assumes that the MWC is firing MSW at 85% of its design heat input capacity because of insufficient MSW flow or because the unit was designed with excess heat input capacity. In this case, natural gas can be used to reduce NO_x emissions without displacing any waste and, therefore, without a loss of tipping fee revenues. The average NO_x reduction assumed in both scenarios is 60%.

Four variations of SNCR technology were examined: (1) conventional SNCR, with an average NO_x reduction of 60%, (2) advanced SNCR, with an average NO_x reduction of 60% with lower reagent use compared to conventional SNCR, (3) a second advanced SNCR option with a NO_x reduction of 70% at a higher reagent feed rate, and (4) advanced NGI, which combines conventional NGI with conventional SNCR to achieve a NO_x reduction of 80%. The SCR evaluation focused on a cold-side system with a NO_x reduction level of

Table 2. Technical Overview of Evaluated NO_x Control Technologies

Technology	Commercial Status	NO_x Control Performance	Technical Issues
*NGI: Methane $deNO_x$^SM^*	*Tested on MWC in Olmsted County, Minnesota.*	*Testing achieved up to 60% NO_x reduction without increasing CO emissions.*	*Scaleup of technology to larger furnaces (> 100 tpd).*
NGI: Reburning	*Applied to fossil fuel boilers; use on MWCs limited to test program in Malmo, Sweden.*	*MWC testing encountered high CO levels when NO_x reductions exceeded 30 - 40%.*	*Reburn zone temperatures in MWCs may be too low for NO_x reduction reactions.*
SNCR: Thermal $DeNO_x$™	*Applied to six MWCs in U.S. plus others overseas.*	*Achieved short-term reductions of 45 - 75%, depending on NH_3 injection rate. Plume visible at higher reduction levels.*	*Impact of furnace temperature swings on NO_x and NH_3 emissions. Control of NH_3 slip and visible plume.*
SNCR: NO_xOUT™	*Applied to two MWCs in U.S. plus others overseas.*	*Comparable to NH_3 injection.*	*Similar to NH_3 injection. N_2O emissions also of concern.*
Advanced SNCR (improved process control)	*Tested at MWCs in Lancaster, Pennsylvania, and Munich, Germany.*	*Achieved 60 - 75% NO_x reduction with less reagent than is needed with conventional SNCR. Plume visible at higher reduction levels.*	*Demonstration of long-term performance capability. Additional process controls may benefit other combustor operations.*
Advanced NGI (conventional NGI plus SNCR)	*Concept only.*	*Potential for 80% reduction.*	*Interaction of temperature and residence time needs for each technology.*
SCR	*Installed at 20 MWC plants in Europe and Japan.*	*80 - 90% NO_x reduction.*	*Catalyst life in hot-side systems.*

80%. A limited evaluation of a hot-side SCR system was also conducted.

Costs for the different control technologies are compared in Figures 2, 3, and 4. Figure 2 presents the capital costs for each of the technologies. The advanced SNCR system with the 70% NO_x reduction and the hot-side SCR system are not represented, since only a limited analysis of these scenarios was conducted. As shown by the figure, the capital costs for each of the technologies increase with increasing unit size. SCR is the most capital intensive of the technologies, costing 4 to 5 times more than the next highest technology. Advanced SNCR and advanced NGI have the next highest capital costs, with both technologies estimated to cost $1 to 2 million per combustor. The capital costs associated with NGI and conventional SNCR are comparable, at less than $1 million per combustor.

The tipping fee impacts and cost effectiveness values presented in Figures 3 and 4, respectively, include both annualized capital costs and operating and maintenance costs. Conventional SNCR generally has the lowest costs of the technologies. NGI-100 has the highest tipping fee impacts for all but the 100 tpd MWC, for which SCR has slightly higher costs. Cost effectiveness values for NGI-100 are the highest for all combustor sizes. Both of the NGI-100 and NGI-85 scenarios result in an incremental cost increase; however, the revenue loss associated with diverting MSW when firing natural gas under NGI-100 results in much higher costs for this control technique. These revenues are not lost with the NGI-85 scenario, plus revenues are received under this scenario from sale of additional electrical production. The other key variable affecting both NGI scenarios is the price of natural gas. The average gas price used in these figures is $3.50/10^6Btu.

The high tipping fee impacts and cost effectiveness values with SCR result from the high capital costs for this technology, as well as from the cost of catalyst replacement and disposal. Advanced SNCR and advanced NGI have higher costs than NGI-85 applied to the small combustor size but are fairly similar when applied to the medium and large combustor sizes.

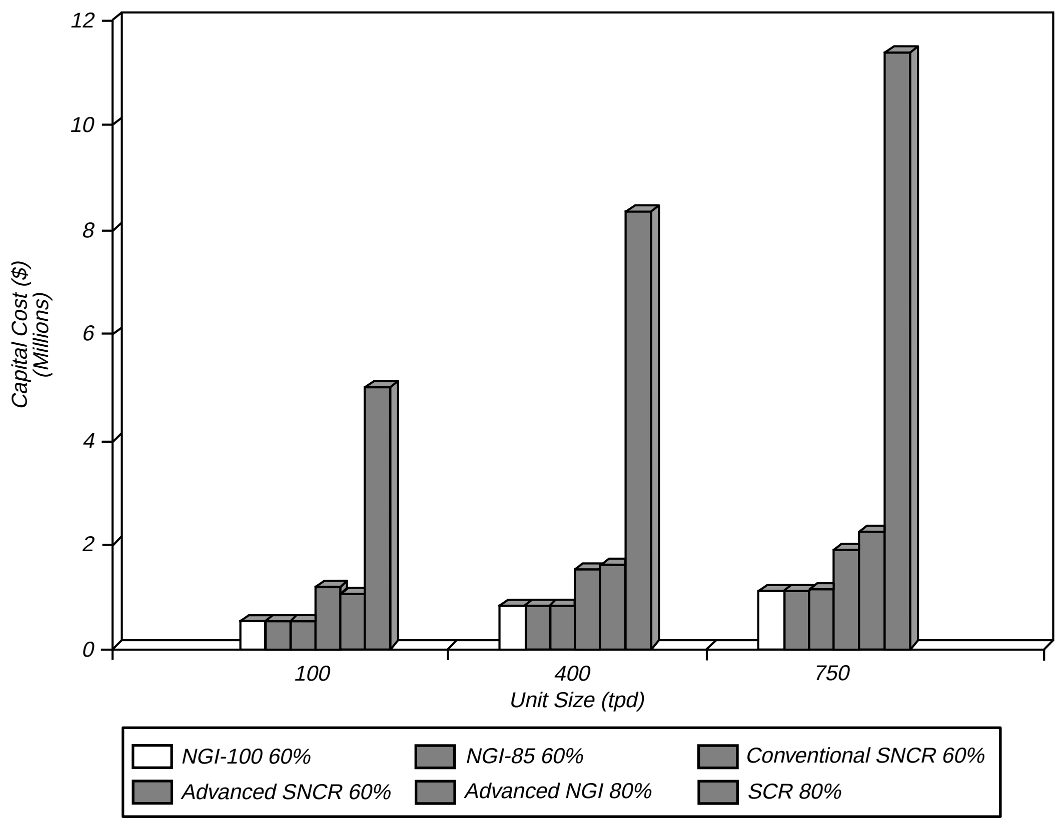

Figure 2. *Comparison of capital cost.*

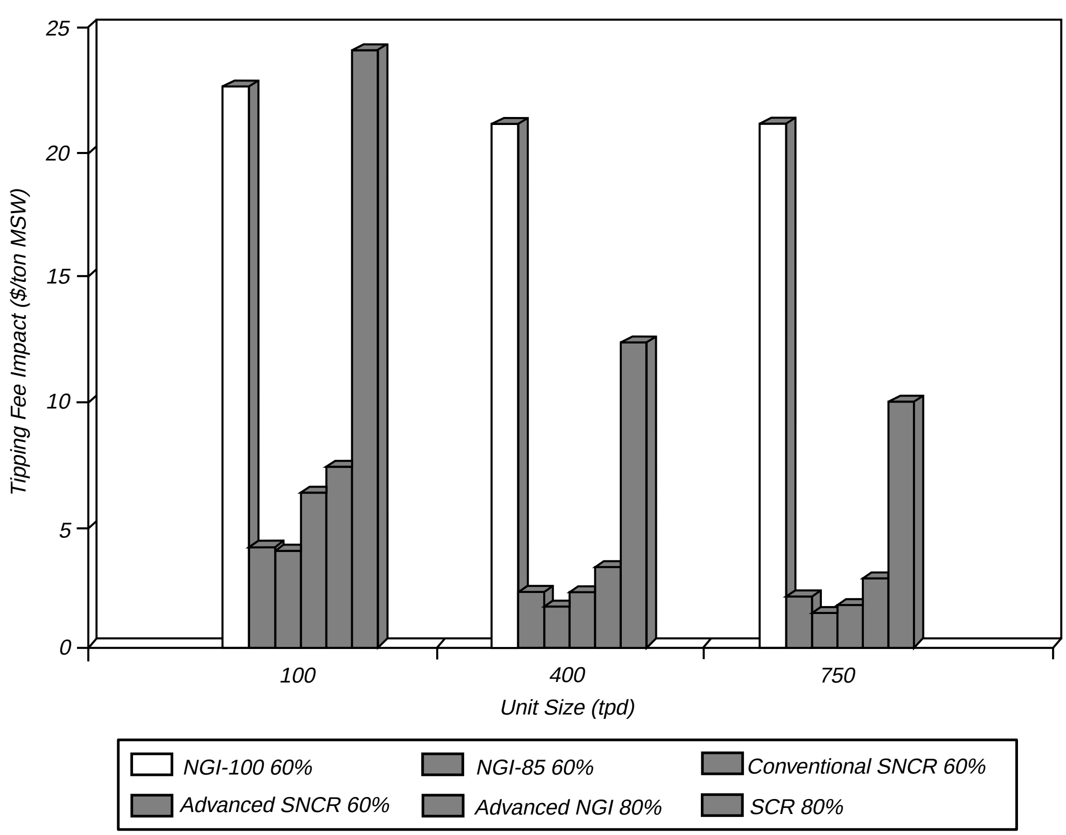

Figure 3. *Comparison of tipping fee impact.*

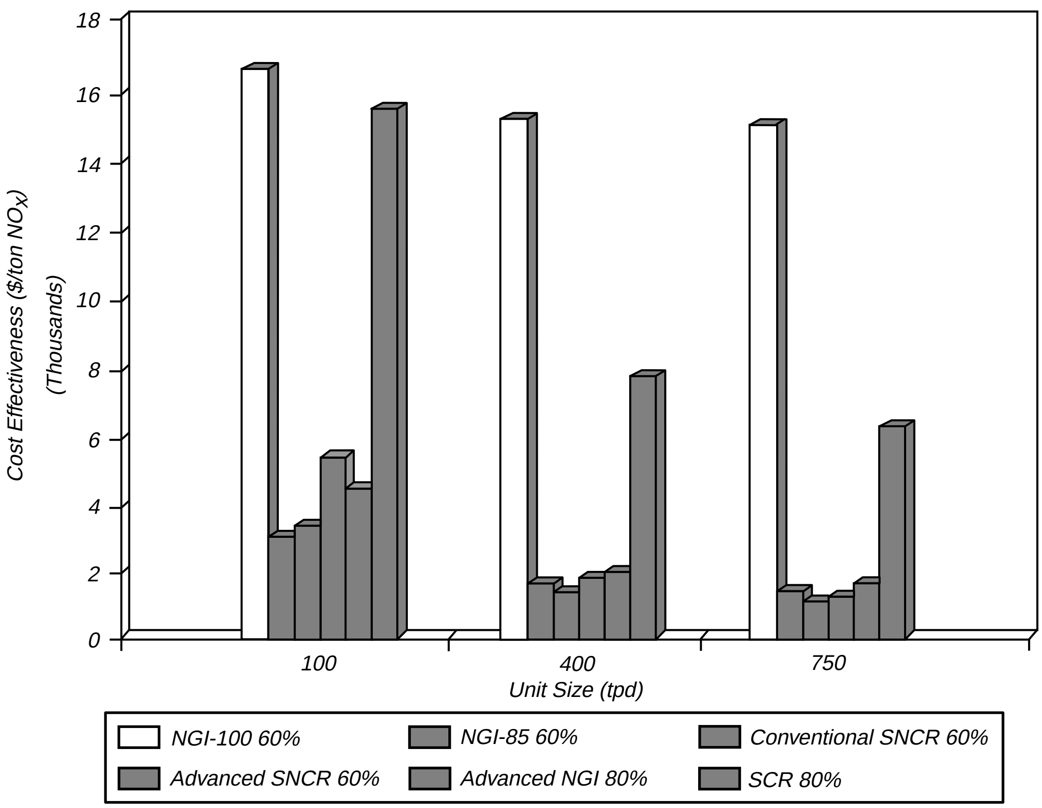

Figure 4. *Comparison of cost effectiveness.*

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The complete report, entitled "NO_x Control Technologies Applicable to Municipal Waste Combustion," (Order No. PB95-144358; Cost: $27.00, subject to change) will be available only from:
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