

Municipal Solid Waste Project

University of Oklahoma- CBME- ChE 4253 (Fall 2018)

Part 1-Preliminary Economic Assessment

Supplemental Narrative (Taken from an OU-CBME Capstone Class 2007 Report. Portion of it was extracted and adapted).

Current MSW disposal methods are landfilling and incineration. The alternative disposal method considered is pyrolysis (or gasification), in which the municipal solid waste undergoes thermal decomposition to produce partially combusted gas called synthesis gas (CO, H₂, CO₂, H₂O). This gas can be used as a feedstock to create several different chemical products.

Municipal Solid Waste in the United States

Municipal solid waste includes all waste items produced residentially and commercially. Residential waste includes waste from single family and multi-family dwellings and accounts for approximately 60% of the total MSW produced. Commercial waste includes waste produced from businesses and schools and accounts for approximately 40% of the MSW produced. In 2005, there was approximately 245.7 million tons of MSW produced in the U.S., the majority of which was landfilled. According to the Environmental Protection Agency approximately 133.3 million tons of MSW was landfilled in 2005. In addition, incineration with energy recovery disposed about 33.4 million tons of the total MSW. The remaining 79.0 million tons of waste produced was recovered for either recycling or composting. Table 1 shows a breakdown of the disposal methods for the MSW waste produced in 2005.¹

Activity	Amount (millions of tons)	% of Total
MSW Collected	245.7	100.0%
Recovery for Recycling	58.4	23.8%
Recovery for Composting	20.6	8.4%
Total Materials Recovery	79	32.1%
Combustion with Energy Recovery	33.4	13.6%
Discards to Landfill	133.3	54.3%

Table 1. 2005 MSW Breakdown

The composition of municipal solid waste is highly variable. It is typically composed of newspaper, product packaging, yard clippings, plastics, furniture, clothing, food scraps, glass, metals, appliances, and batteries.¹ The average composition of discarded municipal solid waste is shown in the pie chart in Figure 1.¹

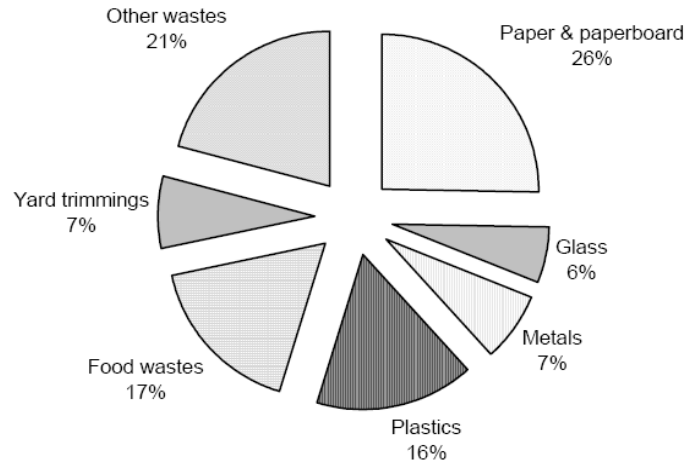


Figure 1. MSW Composition

The production of MSW has steadily increased over the last 45 years from 88 million tons in 1960 to 246 million tons in 2005. However, over the last 15 years, the amount of waste that has been recovered has also increased. Due to increased recycling rates, the amount of waste that has been landfilled and incinerated has remained approximately constant at 160 million tons/year. Figure 2 shows the generation and recycling trends in the U.S. from 1960 – 2005.¹

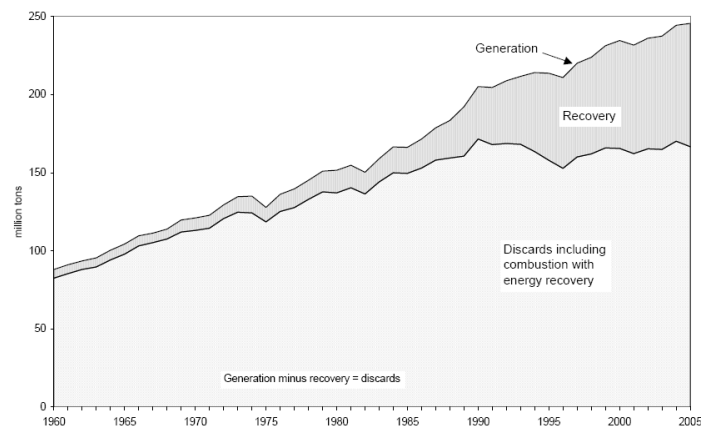


Figure 2. MSW Generation and Recycling Trends

Municipal Solid Waste Disposal Methods

Landfilling

Because it is typically inexpensive relative to other disposal methods, landfilling is the most common for municipal solid waste in the United States. Landfills are ideally designed so that the waste can be buried in the ground and isolated from the surrounding environment. However, when water comes in contact with the waste, a leachate is produced. Leachate can contain metal ions, chloride, sulfate, nitrate, and various organic acids.² If allowed to leak from the landfill site, these contaminants can infiltrate groundwater supplies. Newly built landfills use clay and synthetic liners to help isolate the waste and prevent leachate from polluting groundwater systems. Another consequence of landfilling is the production of landfill gas. Landfill gas consists of carbon dioxide and methane which are greenhouse gases. Significant efforts have been made at capturing landfill gas as a safety precaution and for energy usage. As shown in Figure 3, the number of landfills in the United States has been steadily decreasing.

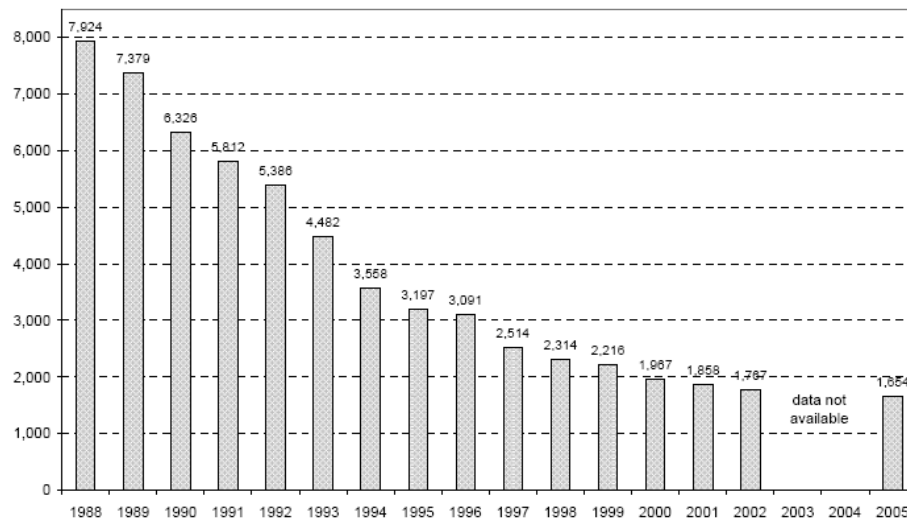


Figure 3. Number of Landfills in the U.S.¹

Since the number of landfills has been decreasing and the amount of waste being landfilled has stayed approximately constant over the last several years, the sizes of landfills that are still in use are becoming larger. Generally, land available for landfilling is not a problem; however, in some densely populated areas of the United States there are problems with insufficient availability of landfill space.¹ Figure 4 shows the number of landfills in 2005 by region in the U.S.

The northeast has approximately 8% of the operating landfills in the United States. This region of the United States is faced with the most critical problem of declining landfill space and therefore typically faces higher disposal costs than other locations. In some cities, where there is virtually no available landfill space, MSW must be exported out of city limits. In extreme cases, it is exported to other states. The cost of landfilling varies widely depending on location, but it can be as high as \$70/ton in some parts of New York City.

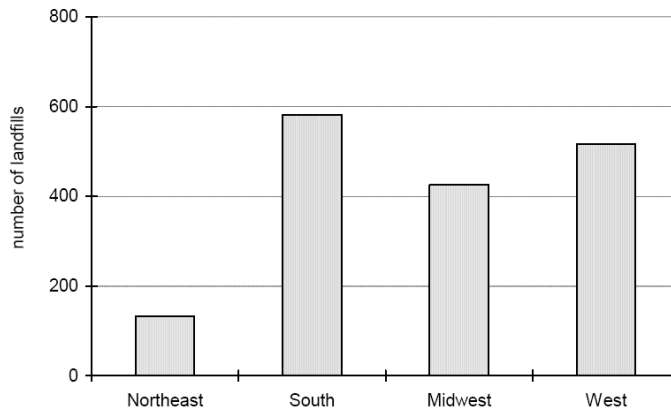


Figure 4. Number of Landfills by U.S. Region¹

Incineration

Incineration is a process that uses heat to directly combust municipal solid waste to produce gas and residual ash. The direct combustion of waste results in the production of dioxins, mercury, lead, sulfur dioxide, nitrogen oxides, carbon monoxide, and carbon dioxide, some of which are toxic. Most of the combustion facilities in the United States incorporate energy recovery to help offset some of the operating expenses.¹ Heat from the incinerators can be used to produce steam from water to generate electricity. The major benefit from incineration is the volume reduction of the waste. Incineration can reduce waste volume by up to 90% and total weight by 75%.³ In 2005, there were 88 operating waste-to-energy plants in the U.S. Approximately 44% of these facilities are located in the northeastern part of the United States. The northeast also has the highest capacity of waste incinerated per capita in the U.S.¹ Figure 5 shows the incinerator MSW capacity per capita for the four major regions in the U.S.

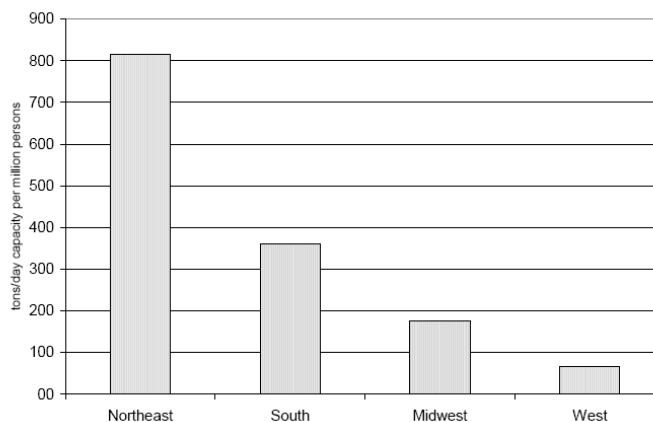


Figure 5. Incinerator MSW Capacity per capita in the U.S.¹

Pyrolysis/Gasification

An alternative method for managing solid waste is pyrolysis. Pyrolysis is the thermal decomposition of organic matter in the absence of oxygen. Gasification, a similar process, is the partial combustion of organic matter in a limited, or less than stoichiometric, amount of oxygen. The endothermic reactions involved in pyrolysis

require a heat source, but gasification is thermally self-sustaining. By allowing these reactions to occur simultaneously, the exothermic combustion reactions from gasification can generate heat for the pyrolytic reactions. The terms pyrolysis and gasification will be used interchangeably throughout this report.

Pyrolysis has a variety of benefits that set it apart from more conventional waste management methods: landfilling and incineration. One of the major products of pyrolysis is synthesis gas. Synthesis gas (syngas) is a gaseous mixture containing approximately 90% hydrogen, carbon monoxide and carbon dioxide. The other main components of syngas include methane, higher hydrocarbons and inerts. This syngas can be further processed to produce a variety of different products. Pyrolysis, as a waste management method, can be much more profitable due to the ability to produce a saleable end product from waste. Additionally, pyrolysis reduces the quantity and improves the quality of solid waste. This could remedy the problems associated with the lack of landfill space in many densely populated regions. Pyrolysis can comply with more stringent environmental regulations than incineration.

The Purox Pyrolysis system consists of three major sections: front-end processing, a pyrolysis reactor and gas cleaning. The front-end processing unit separates the heavy metal fraction and particulates from the organics and shreds the reactor feed. In the pyrolysis reactor, the solid waste feed is converted to synthesis gas. This gas is then purified, compressed and sent to another process system to be converted to the desired end-product.⁴

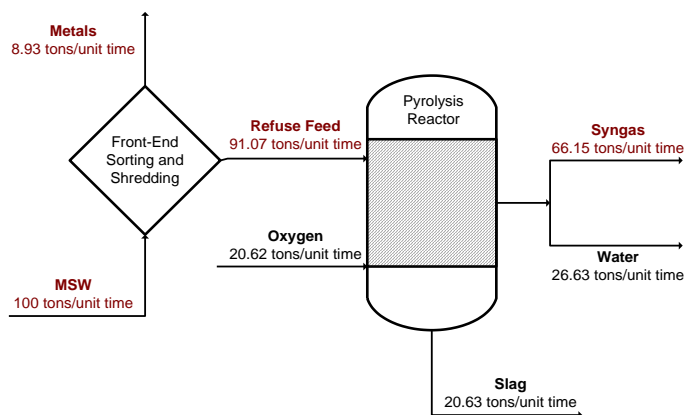


Figure 6. Pyrolysis Mass Balance

Front-End Processing

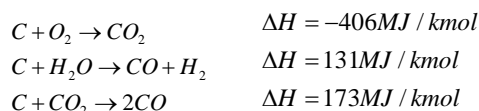
A front-end loader coordinates transportation of the solid waste from trucks to a conveyer. This conveyer feeds waste to a shredder that reduces the particle size to between 4 and 8 in.⁴ The waste is then fed to the top of an air classifier, where air is blown countercurrent to the waste stream.

The overhead stream is composed mostly of the less dense, organic fraction. This fraction flows to a cyclone separator to remove particulates. The air exits the top of the cyclone and is sent to a baghouse to be filtered and discharged to the atmosphere. The

organic portion of the cyclone is sent to a surge tank, where it is held until it can be fed to the pyrolysis reactor. The heavy fraction exits the air classifier through the bottom and is sent to a magnetic separator capable of removing 90% of the ferrous in the feed stream. The remaining heavy fraction goes to an Eddy Current Aluminum Separator that removes 66% of the aluminum in the solid waste feed. The remaining heavy fraction is combined with the light fraction in the surge bin to be fed to the pyrolysis reactor.⁴

Pyrolysis Reactor

The Union Carbide Corporation Purox gasifier is an ideal reactor system for conversion of municipal solid waste to synthetic gas due to its ability to process feed with varying composition. The separated solid waste enters the vertical shaft reactor through the top and flows downward. Purified oxygen from an air separation unit is fed to the bottom of the reactor.⁵ The solid waste is dried by the upward flowing gases at the top of the reactor and then pyrolyzed in the middle zone. The pyrolytic reactions, shown below, take place at temperatures above 1500°C. In the bottom portion of the reactor, the oxidative zone, combustion of the char from the upper zone produces the heat necessary for the endothermic pyrolytic reactions.⁶ The gas exiting the reactor is cooled by the incoming waste to between 93°C and 315°C.⁴



The synthesis gas leaving the reactor contains fly ash, water vapor and some oil mist, which must be removed downstream. The solid inorganic products accumulate at the bottom of the reactor and mix with water to form a black glassy aggregate. This aggregate can be used for construction purposes. A typical composition of the syngas product from the Purox pyrolysis system is shown below in Table 2. An exact syngas composition can not be defined due to the variability of the incoming refuse composition.

Typical Synthesis Gas Composition ⁴	
Component	Mole %, Dry Basis
H ₂	24
CO	40
CO ₂	24
CH ₄	5
C ₂ H ₂	0.7
C ₂ H ₄	2.1
C ₂ H ₆	0.3
Higher Hydrocarbons	2.35
Nitrogen	1
Argon	0.5
H ₂ S	0.05
Moisture Content	6

Table 2. Typical Synthesis Gas Composition

The syngas flows through a spraying water scrubber and then to an electrostatic precipitator which removes solid particulates and pyrolytic oils. These components can be recycled back to the reactor. The gas flows through an acid absorption column where salts are neutralized and also sent back to the reactor. Finally, water is removed from the syngas in a shell and tube vertical condenser.

TAKEN FROM WIKIPEDIA (https://en.wikipedia.org/wiki/Integrated_gasification_combined_cycle)

The plant is called *integrated* because (1) the syngas produced in the gasification section is used as fuel for the gas turbine in the combined cycle and (2) the steam produced by the syngas coolers in the gasification section is used by the steam turbine in the combined cycle. In this example the syngas produced is used as fuel in a gas turbine which produces electrical power. In a normal combined cycle, so-called "waste heat" from the gas turbine exhaust is used in a [Heat Recovery Steam Generator](#) (HRSG) to make steam for the steam turbine cycle. An IGCC plant improves the overall process efficiency by adding the higher-temperature steam produced by the gasification process to the steam turbine cycle. This steam is then used in steam turbines to produce additional electrical power. IGCC plants are advantageous in comparison to conventional coal power plants due to their high thermal efficiency, low non-carbon greenhouse gas emissions, and capability to process low grade coal. The disadvantages include higher capital and maintenance costs, and the amount of CO₂ released without pre-combustion capture."



Remember we use MSW, not coal, we use a scrubber to remove H₂S not a claus plant, so this information needs to be adapted. .

Power Generation Associated with MSW Incineration

Taken from https://www.eia.gov/energyexplained/?page=biomass_waste_to_energy#tab2

“The process of generating electricity in a mass-burn waste-to-energy plant has seven stages:

1. Waste is dumped from garbage trucks into a large pit.
2. A giant claw on a crane grabs waste and dumps it in a combustion chamber.
3. The waste (fuel) is burned, releasing heat.
4. The heat turns water into steam in a boiler.
5. The high-pressure steam turns the blades of a turbine generator to produce electricity.
6. An air pollution control system removes pollutants from the combustion gas before it is released through a smoke stack.
7. Ash is collected from the boiler and the air pollution control system”

A mass burn waste-to-energy plant

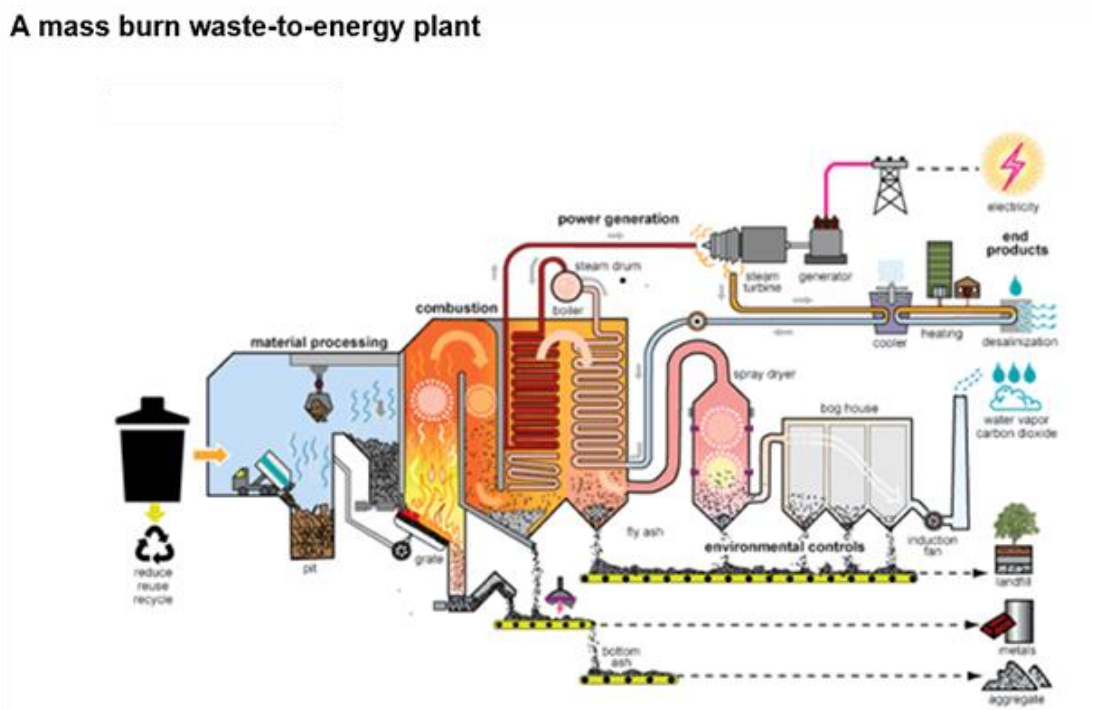


Figure 8. Waste to Energy plant

Visit the site to acquire more information.

Syngas to Chemicals

Synthesis gas can be used to produce many different chemicals and fuels. This is depicted in Figure 9.

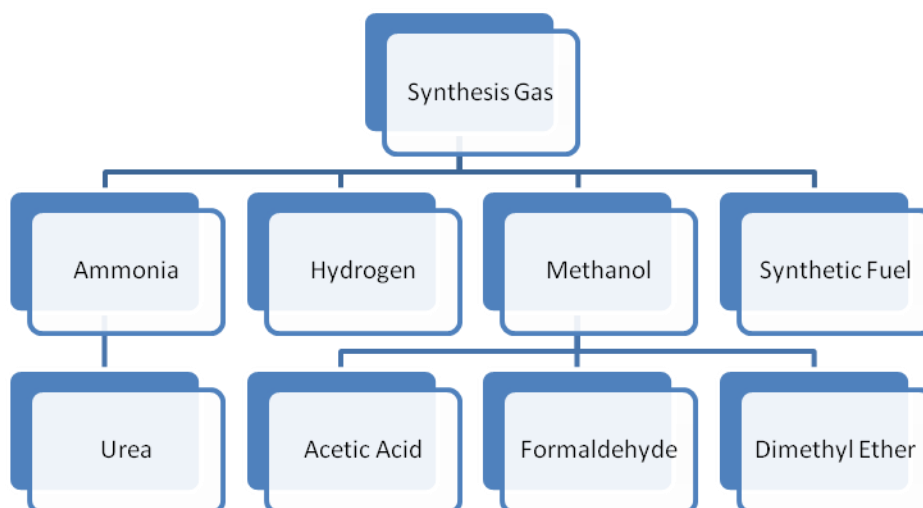
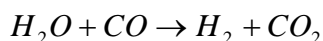


Figure 9. Potential Products

Hydrogen

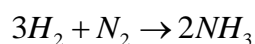
Hydrogen, a colorless, odorless gas, is frequently used for the processing of fossil fuels and to produce ammonia or methanol. Bulk production of hydrogen is usually accomplished by the steam reforming of natural gas. Hydrogen is one of the main components in synthetic gas produced from pyrolysis of municipal solid waste, constituting about 24% by volume of the gas. If hydrogen is the desired final product, the water-gas shift reaction would be used to convert the carbon monoxide to hydrogen and carbon dioxide:



Following water-gas shift, the synthetic gas would have to be further purified in order to produce saleable hydrogen. The total capital investment and operating cost to produce hydrogen from 1,500 tons/day MSW were estimated using information gathered from *The Encyclopedia of Chemical Technology*.⁸ These costs were found to be \$130,762,286 and \$3,268,073, respectively. The current price of hydrogen, \$0.08/m³, was estimated from this source as well.⁸ The annual production of hydrogen for a plant of this capacity would be 192,626,192 m³.

Ammonia

Ammonia is a colorless alkaline gas that possesses a characteristic, penetrating odor. It is one of the most largely produced inorganic chemicals. The largest market for ammonia is the fertilizer industry. The most common use of anhydrous ammonia is direct use as the nitrogen source in fertilizer. Another significant portion of ammonia use is in the manufacture of urea, another major fertilizer component. Ammonia is also used to produce nitric acid and ammonium nitrate. Ammonia is produced using the Haber-Bosch process:



This requires a hydrogen feed, typically coming from synthesis gas processed to increase hydrogen content and then purified (as described above for direct hydrogen production).

The total capital investment for a plant processing 1,500 tons/day of MSW, \$104,622,118, was estimated using information reported in the *Encyclopedia of Chemical Processing and Design*.⁹ The annual operating cost of this plant was estimated as \$6,916,562, using process information provided in the *Encyclopedia of Chemical Technology*.¹⁰ A plant of this capacity would produce 97,137 tons/year. The current price of ammonia, obtained from *ICIS Chemical Business Americas*, is \$275/ton.¹¹

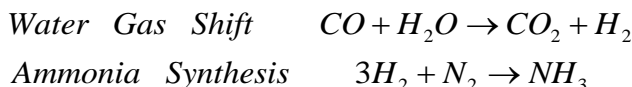
Urea

Urea is typically a solid produced as prills or granules, for use in fertilizers. It can also be used in plastics manufacturing and as a protein supplement in animal feeds. Urea is formed by reacting ammonia with carbon dioxide. The intermediate formed in this reaction is ammonium carbamate.



The total capital investment for a plant manufacturing urea from 1,500 tons/day MSW was estimated using information obtained from *Ullman's Encyclopedia of Industrial Chemistry*.¹² This cost was determined to be \$137,284,159. The annual operating cost was estimated to be \$9,006,088, which was based on process information provided in the *Encyclopedia of Chemical Processing and Design*.¹³ A plant capable of processing 1,500 tons/day of MSW would produce 171,418 tons/year of urea. The price of urea, \$223/ton, was found in *Chemical Market Reporter*.¹³

Urea is the product formed in the reaction of ammonia with carbon dioxide. Therefore, the first process unit for urea synthesis must produce ammonia and separate carbon dioxide from the synthesis gas. Ammonia production from synthesis gas requires two chemical reactions:¹⁰



A process flow diagram outlining the ammonia production unit is shown in Figure 10. This diagram shows a mole balance based on 100 tons/day MSW processed. This balance was scaled up for analysis of larger capacities.

The synthesis gas is first compressed after exiting the pyrolysis unit. The sulfur must then be removed because it will poison the catalyst used for ammonia synthesis downstream. This can be accomplished in a variety of ways. Due to the relatively small amount of sulfur that could be recovered in a sulfur production unit, a sulfur absorbent zinc oxide catalyst is used to remove the sulfur.¹⁰

The remaining synthesis gas is compressed again, and then fed to a two-stage adiabatic water-gas shift reactor. The water-gas shift reaction serves to remove carbon oxides capable of deactivating the ammonia synthesis catalyst, maximize hydrogen production for ammonia synthesis and maximizing carbon dioxide production necessary for urea

synthesis. The two-stage reactor consists of a high temperature converter and a low temperature converter. The majority of the carbon monoxide conversion occurs in the high temperature converter, and then the remaining portion reacts due to a more favorable equilibrium in the low temperature reactor.¹⁰

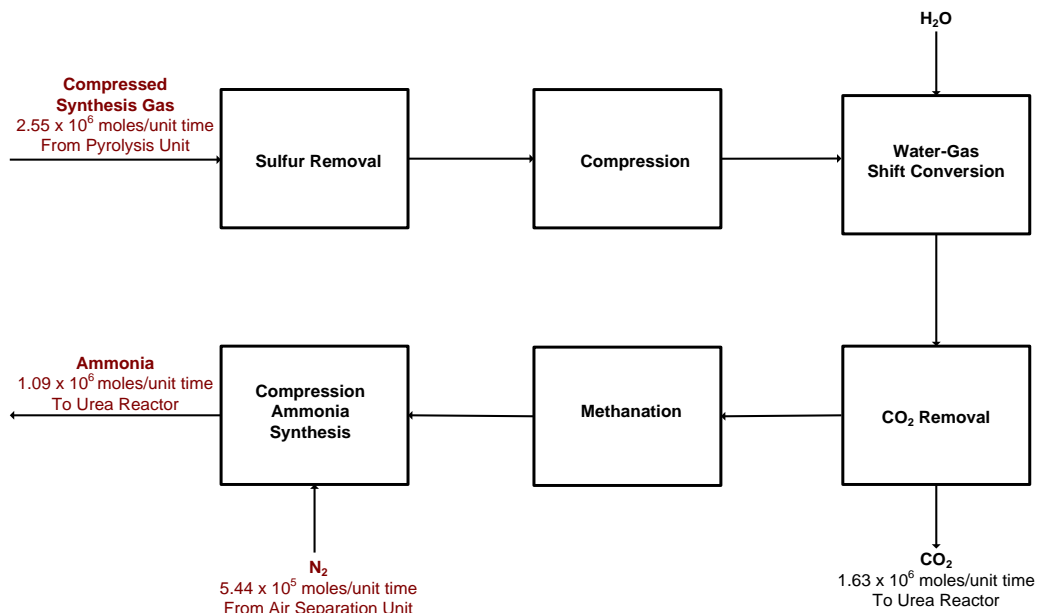


Figure 7. Ammonia Synthesis Mole Balance

In the next step, carbon dioxide is removed as a pure stream to be fed to the urea process unit. The solvent methyldiethylamine (MDEA) is used as the absorbent to remove carbon dioxide. This solvent requires very low regeneration energy due to weak CO₂-amine bonds.²⁷ The next process, methanation, removes any remaining carbon monoxide by reaction with water to form methane.¹⁰

Nitrogen is added to the purified hydrogen gas at a 3:1 molar ratio. This gas is compressed to reaction pressure, between 2100 and 2200 psi, and fed to the reactor. The reactor contains a catalyst produced mainly from magnetite that has been promoted using alkali such as aluminum, calcium or magnesium. The reactor bed must be cooled because of the exothermic nature of the synthesis reaction. The ammonia is recovered from the reactor by condensation at synthesis pressure. The un-reacted gases are recycled back into the reactor in order to achieve higher conversions due to equilibrium limitations.¹⁰ Using a total recycle process, as is typical in industry, virtually complete synthesis gas conversion is achieved.¹²

Ammonia and carbon dioxide are fed to the urea synthesis reactor at a 3.5:1 molar ratio. Therefore, only 19 mol% of the carbon dioxide produced from the pyrolysis and subsequent water gas shift reactions is used for urea synthesis. The remaining carbon dioxide must be emitted or sequestered.

The following reaction takes place, forming the desired product, urea, and ammonia carbamate as an intermediate:¹²



The reactor operates at a pressure of 2200 psi and temperatures between 185°C and 190°C to achieve high conversion and prevent corrosion resulting from production of the ammonia carbamate intermediate.¹²

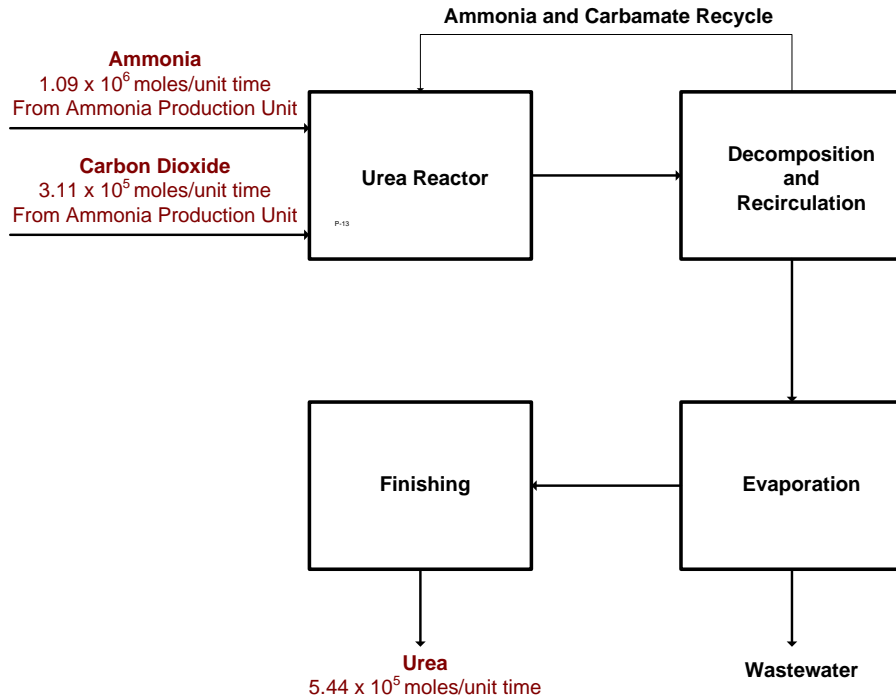


Figure 8. Urea Synthesis Mole Balance

The carbamate is then decomposed in three vessels. The first is at reaction pressure, the second decomposition stage is at 260 psi and the third is at 66 psi.¹² Ammonia and carbamate removed from the urea solution in these vessels are recycled back to the synthesis reactor to achieve virtually complete conversion of ammonia. The urea solution is then concentrated in an evaporator and proceeds to finishing, where the final prilled or granulated product is produced.

The urea market remained relatively constant from 1999-2005, varying from 11.4 million tons in 1999 to 11.6 million tons in 2005.¹¹ Figure 12 shows the U.S. urea demand from 1999-2005. The major driver for the urea market is the farming industry and therefore crop prices. Higher crop prices usually indicate that farmers are more likely to use more fertilizer in order to increase their crop yields. Approximately 41% of the urea sold is used on corn fields.¹¹ Corn is the major feedstock for ethanol production, which is being used as an alternate energy source. Corn plantings increased over 4% from 2003-2005. Several reports from the *Chemical Market Reporter* indicate that ethanol production will

increase due to the increased biofuel demand. This increase in ethanol production should result in an increase in fertilizer demand.¹³

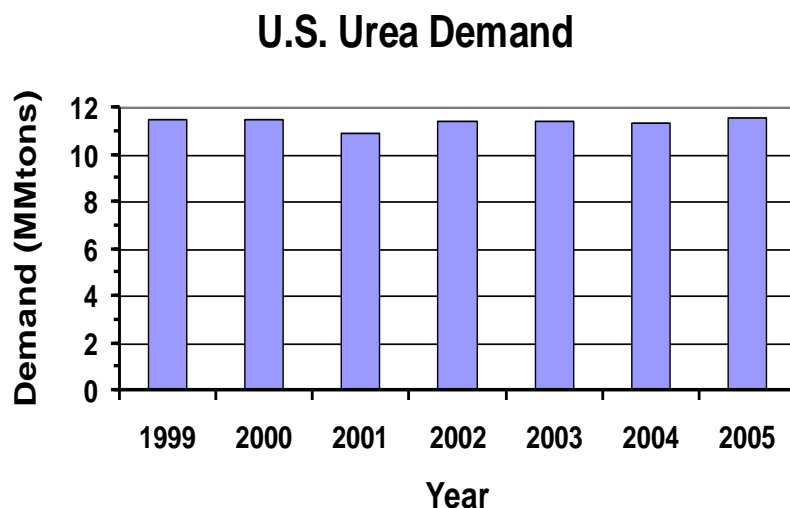
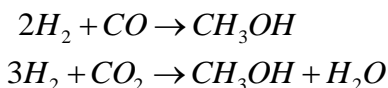


Figure 9. U.S. Urea Demand

Methanol

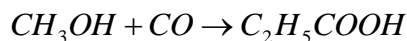
Methanol, the simplest alcohol, is a light, volatile chemical. It is typically used as an antifreeze, solvent, fuel, or as an intermediate in the production of other chemical products. Methanol is typically produced from synthesis gas. However, the synthesis gas is commonly formed from the methane in natural gas, by steam-methane reforming or partial oxidation. The chemical reactions to produce methanol from syngas are:



The conversion to methanol in these reactions is favorable at low temperatures and high pressures. The total capital investment and annual operating cost to produce methanol from 1,500 tons/day MSW, estimated from information found in *The Encyclopedia of Chemical Processing and Design*¹⁴, were determined to be \$82,317,331 and \$8,612,836, respectively. A plant of this capacity would produce 13,739,742 gal/year of methanol. The current price of methanol, \$1.015/gal, was reported on ICIS pricing.com.¹⁵

Acetic Acid

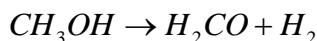
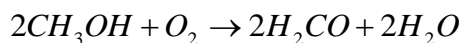
Acetic acid is a weak carboxylic acid used to produce vinyl acetate monomer and acetic anhydride. It is also an important component in vinegar and can be used as a solvent. The Monsanto process, commercialized in 1970, uses a rhodium-based catalyst to produce acetic acid from methanol by methanol carbonylation:



In the 1990's BP Chemicals developed the Cativa catalyst, capable of producing acetic acid from the same reaction, but doing so more efficiently and more environmentally friendly. This process is under license by BP, so the total capital investment and annual operating cost to produce acetic acid were estimated from a financial report for a Celanese acetic acid from methanol plant that uses the Monsanto process and the estimated cost of a methanol plant.¹⁶ These costs were found to be \$141,194,727 and \$34,751,576, respectively, for a plant processing 1,500 tons/day of MSW. A plant of this capacity would be capable of producing 170,202,384 lbs/year of acetic acid. The current price of acetic acid, \$0.310/lb, was reported on ICIS pricing.com.¹⁷

Formaldehyde

The simplest aldehyde, formaldehyde, is most often used to produce polymers and a wide variety of specialty chemicals. It is produced from the oxidation and dehydrogenation of methanol:



The catalyst used to produce formaldehyde is typically silver metal or mixture of an iron oxide with molybdenum and vanadium. From information in *The Encyclopedia of Chemical Processing and Design*, the total capital investment for a formaldehyde plant producing 85,115,364 lb/year of formaldehyde from 1,500 tons/day MSW was determined to be \$90,784,183.¹⁸ The annual operating cost for this facility would be \$11,406,889. The current price of formaldehyde, obtained from *Chemical Market Reporter*, and used for the economic analysis was \$0.21/lb.¹⁹

Dimethyl Ether

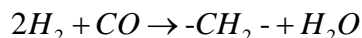
Dimethyl ether is a gaseous ether most commonly used as an aerosol spray propellant or a refrigerant. It is produced from methanol dehydration:



All sources of information regarding dimethyl ether manufacturing plants reported that these facilities are typically very small in scale, relative to the other potential products examined. The production rate of dimethyl ether from a plant processing 1,500 tons/day MSW would be 29,615 tons/year. A report prepared by Air Products and Chemicals, Inc., examining the market outlook for dimethyl ether, reported that the current dimethyl ether market is 143,000 tons/year.²⁰ Therefore, a plant processing 1,500 tons/day MSW would produce enough dimethyl ether to satisfy 21% of the current market. It was assumed that attempting to take over such a substantial portion of the current market, without a substantial increase in demand, would likely have an unfavorable affect on the already low price of \$0.06/lb.²¹ Therefore, the capital investment and operating cost to produce dimethyl ether were not researched and this potential product was assumed to be unprofitable.

Synthetic Fuel

Synthetic fuel can be produced by the Fischer-Tropsch process in which synthesis gas is reacted over an iron or cobalt catalyst to produce liquid hydrocarbons. The synthetic gas that is used to produce synthetic fuel is usually produced through the gasification of coal or steam reforming of natural gas. The reaction for Fischer-Tropsch synthesis is



The water gas shift reaction is used to make the synthesis gas have the ideal hydrogen to carbon monoxide ratio of 2:1. The Fischer-Tropsch process produces a wide range of liquid hydrocarbons and therefore further processing must be done before a final product is obtained. One of the most common products of synthetic fuel is diesel. Diesel that is produced from synthetic fuel is a high quality, low sulfur content diesel. It can be directly used as fuel source for diesel powered engines. Another product that is produced from synthetic fuel is naphtha. Naphtha can be used as a feedstock to produce higher octane gasoline or in the chemical industry as a chemical feedstock.

The total capital investment and operating costs to produce synthetic fuel from 1,500 tons/day MSW were estimated to be \$93,765,169 and \$5,207,041/year, respectively. These values were based on information from a Fischer-Tropsch design and economics paper written by members of the Bechtel Corporation and Syncrude Technology, Inc.²¹ It was estimated that approximately two-thirds of the syncrude could be refined into diesel, while the other third could be refined into naphtha. The price of diesel was estimated to be \$1.98/gal, which was the average 2006 diesel price reported by the United States Energy Information Administration.²¹ The price of naphtha was estimated to be \$1.63/gal, which was based on the August 2006 ICIS pricing report.²² The production rate for a plant of this capacity was 5,953,779 gal/year of diesel and 3,044,364 gal/year of naphtha.

Works Cited

1. United States Environmental Protection Agency. Municipal Solid Waste in the United States: 2005 Facts and Figures. Washington: GPO, 2006.
2. Wilson, David C. Waste Management: Planning, Evaluation, Technologies. New York: Oxford University Press, 1981.
3. "Solid Waste Combustion/Incineration." April 2006. United States Environmental Protection Agency. 14 March 2007.
http://www.epa.gov/garbage/landfill/sw_combst.ntm
4. Chatterjee, Anil K. "The Purox Process." Biomass Conversion Processes for Energy and Fuels. Ed. Samir S. Sofer and O. Zaborsky. New York: Plenum Press, 1981. 213-233.
5. General Electric Company. Solid Waste Management: Technology Assessment. New York: Van Nostrand Reinhold Company, 1975. 139-151.
6. Domino, Francis A., ed. Energy from Solid Waste: Recent Developments. New Jersey: Noyes Data Corporation, 1979. 160-165.

7. Wilson, David C. Waste Management: Planning, Evaluation, Technologies. New York: Oxford University Press, 1981.348-352.
8. "Hydrogen." Encyclopedia of Technology. 1995.
9. "Ammonia." Encyclopedia of Chemical Processing and Design. 1976.
10. "Ammonia." Encyclopedia of Chemical Technology. 1992.
11. Kirschner, Mark. "Urea." Chemical Market Reporter. 19-25 September 2005.
12. "Urea." Ullman's Encyclopedia of Industrial Chemistry. 1996.
13. "Urea." Encyclopedia of Chemical Processing and Design. 1997.
13. Lerner, Ivan. "Fertilizers Helping Biofuels – and Vice Versa." ICIS Chemical Business Americas. 19-25 Feb 2007.
14. "Methanol." Encyclopedia of Chemical Processing and Design. 1989.
15. "Methanol Price Report." ICISpricing.com. 20 Feb. 2007.
http://www.icispricing.com/il_shared/Chemicals/SubPage406.asp
16. SRI Consulting. "Acetic Acid from MeOH by the Celanese Process." 2002.<http://www.sriconsulting.com/PEP/pdf/Yearbook%20Page.pdf>.
17. "Acetic Acid Price Report." ICISpricing.com. 20 Feb. 2007
http://www.icispricing.com/il_shared/Chemicals/SubPage479.asp
18. "Formaldehyde." Encyclopedia of Chemical Processing and Design. 1985.
19. Kirschner, Mark. "Chemical Profile: Formaldehyde." Chemical Market Reporter. 28 Jun 2004.
20. Air Products and Chemicals, Inc. "Market Outlook for Dimethyl Ether." 2002. Pennsylvania, 14 March 2007.
http://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/bibliography/demonstration/pdfs/estmn/DME2_Top.pdf
21. Ohno, Yotaro and Mamoru Omiya. "Coal Conversion into Dimethyl Ether as an Innovative Clean Fuel." JFE Holdings, Inc., 2003.
22. "*Prices Rise on Feedstock Costs*." ICIS Chemical Business Americas. 4-10 Sep. 2006.
23. Choi, Gerald N. et. al. "Design/Economics of a Once-Through Natural Gas Fischer-Tropsch Plant with Power Co-Production." 14 March 2007.
< <http://www.netl.doe.gov/publications/proceedings/97/97cl/choi.pdf>.

Other References

1. "Spot Prices." March 2007. Department of Energy. 10 Feb 2007.
http://tonto.eia.doe.gov/dnav/pet/pet_pri_spt_s1_a.htm
2. New York City Department of Sanitation. Request for Information: New and Emerging Solid Waste Management and Recycling Technologies and Approaches. New York: GPO, 21 April 2004.
3. Congressional Research Service. Interstate Shipment of Municipal Solid Waste: 2004 Update. James E. McCarthy. 2004.
4. New York City Department of Sanitation. DSNY Annual Report:2005. New York: GPO, 2006.
5. Khuirati, Ainie. "Application of Aspen plus for municipal solid waste plasma gasification simulation: case study of Jatibarang Landfill in Semarang Indonesia." J. Phys.: Conf. Ser. 1025 012006, 2018.

6. Bartels, Jeffrey Ralph, "A feasibility study of implementing an Ammonia Economy" (2008). *Graduate Theses and Dissertations*. 11132.
<https://lib.dr.iastate.edu/etd/11132>
7. Constant, K. M. and W. F. Sheldrick. "World Nitrogen Survey". The International Bank for Reconstruction and Development. Technical paper. 1992
8. Buchanan T. L., M. G. Klett, R. L. Schoff. "Capital and Operating Cost of Hydrogen Production From Coal Gasification: Final Report April 2003". The United States Department of Energy National Energy Technology Laboratory. 2003
9. Torkelson, J., N. Ye, Z. Li, D. Coutinho, and M. Fokema. "Robust Low-Cost Water-Gas Shift Membrane Reactor for high-purity hydrogen production from coal- derived syngas." Aspen Products Group, Inc., 2008.
10. Yavini, T. D., "Economic Evaluation of Selexol- Based CO₂ Capture Process for a Cement Plant Using Post- Combustion Technology." *IJSRST: Science and Technology*. Vol 1, Issue 5, 2395-6011. 2015.
11. Collodi, G. A. Giuliana, N. Ferrari. "Techno-Economic Evaluation of HYCO Plant Integrated to Ammonia/Urea or Methanol Production with CCS." IEAGHG Technical Report 2017-03. IEA Greenhouse gas R&D programme. 2017.
12. "Louisiana Ammonia Plant Presentation April 2013". Incitec Pivot Limited: Dnyo Nobel. 2013.