A Review of the Options for the Thermal Treatment of Plastics

Prepared by: Environment and Plastics Industry Council (EPIC)

December 2004

This report was prepared by the Environment & Plastics Industry Council (EPIC) a council of the Canadian Plastics Industry Association (CPIA.

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Introduction

All organic materials have energy embodied in them in the form of carbon. Theoretically this energy can be captured and transformed into other useful forms. It is a well known fact that energy can neither be created nor destroyed but merely transformed.

One of the most common methods of transforming energy from for example, a solid to another form is thermal treatment. Through the various methods of thermal treatment one may obtain heat, electricity or chemicals suitable for other applications.

Municipal solid waste (MSW) is a mixture of inorganic materials such as metals and glass and organic materials ranging from food waste, to paper, to plastics. With the exception of the inorganics all of the other materials have a calorific value that varies from one material to another. The calorific value of a number of materials is shown in Table 1.

Table 1
Calorific Value of Materials

Material	Btu per pound	kilojoules per kilo
# 2 fuel oil	20,900	48,500
Plastics		
Polyethylene	20,000	46,500
Polypropylene	19,300	45,000
Polystyrene	17,900	41,600
PET	9,290	21,600
PVC	8,170	19,000
Coal	11,500	27,000
Newspaper	7,200	17,000
Wood	6,700	15,500
Average MSW	4,650	10,800
Yard Waste	3,000	7,000
Food Waste	2,600	6,000

The ease and desirability of using a specific material as a source of energy is often directly related to its calorific value.

It is obvious from Table 1 that many of the common plastics have relatively high calorific values that in some instances approach the value for fuel oil. Plastics are hydrocarbons in the same way that fuel oil is an hydrocarbon. Their chemical structures are composed of primarily carbon and hydrogen. Some plastics contain other elements, for example, PET contains oxygen, PVC contains chlorine and nylon contains oxygen and nitrogen. The higher the relative content of carbon the higher the calorific value and polyethylene which is composed totally of carbon and hydrogen could be labeled as “frozen natural gas or fuel oil”.

Plastics are commonly derivatives of oil and natural gas. Approximately 4% of Canada’s use of oil and natural gas goes into the manufacture of plastics and rubbers. Most of Canada’s oil and gas is used in transportation and heating fuels.

Recently a number of new plastic resins have been derived on a relatively large scale from plant material. Polylactic acid, a plastic that can be used in films and other conventional applications is derived from starch grown as corn. Although the development seems revolutionary it is sobering to remember that the first nylon was made 65 years ago from chemicals derived from corn cobs.

The plastics derived from plants have a significant characteristic that differentiates them from their petroleum based cousins; they are biodegradable under appropriate conditions. Before we can say that plastics derived from farmed crops are to be preferred environmentally over those based on petroleum it is necessary to carry out a life cycle assessment (LCA). A life cycle assessment will determine the environmental impact of the manufacture, use and disposal of the material. The results of the LCA should then be related to the economics of manufacture and use of the products so that we have created a measure of eco efficiency for each product.

Waste Management

Waste is sometimes defined as ‘material generated by human activity which is discarded as having no further value’[1].

Before we can say that something has no value we require a management system for the material that is capable of assessing the value of the material. ***Integrated Solid Waste Management*** (ISWM) is a practice that can extract the maximum value from the waste stream. Some groups such as the International Energy Agency (IEA) define ISWM as
‘An optimized system of waste management practices designed to protect human health and the environment, based on the sound application of environmental, energy, economic and socio-political considerations, which includes one or more components of the “waste management hierarchy” Reduce, Reuse, Recycle, Recover energy, Dispose’[2]

The use of the term “hierarchy” would seem to indicate that the options are listed in a rigid order. The IEA prefers to see the list of options as a menu from which the appropriate options or combinations of options can be selected based on an environmental assessment.

It is interesting to note that based on greenhouse gas emissions the U.S. Environmental Protection Agency (EPA) states that it is better to recycle aluminum than source reduce.[3]

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[1] International Energy Agency, Integrated Waste Management Group
[2] ibid
[3] EPA publication EPA530-R-02-006 May 2002

From an energy perspective it can be shown that energy recovery from plastics in plants having high recovery efficiencies provides a greater energy benefit than recycling when the recovered energy displaces the energy produced from a fossil fuel such as coal.

Plastics

The use of plastics has transformed modern living over the last 60 years. It is a little known fact that about two thirds of the plastics used go into durable applications such as transportation vehicles and construction materials where they have displaced many older materials based on their light weight, strength and durability. It is the one third of plastics production that goes into packaging that receives attention from the public.

It is packaging materials along with printed materials and food and yard waste that fill our household trash containers.

Most often the public does not realize the benefit of plastics over other materials in keeping food fresh and free from damage, in reducing the energy needed to bring products to the store shelves because of their light weight and in reducing breakage and loss because of their inherent resistance to fracture. Even an ubiquitous container such as the PET soft drink bottle which has been reduced in weight by over 50% since it was introduced 20 years ago gets no kudos regardless of its high packaging efficiency (weight of contents divided by weight of container) since, when the contents have been consumed, there remains an empty bottle to be managed. Source reduction makes both economic and environmental sense. However, when it comes to waste management it means handling more of the lighter weight containers to gather a tonne of bottles for sale to a recycler.

The plastics industry believes that plastics should be recycled when this can be done in an environmentally and economically sustainable manner. The demand for used PET and High Density Polyethylene (HDPE) containers exceeds their supply and groups such as the Environment and Plastics Industry Council (EPIC) of the Canadian Plastics Industry Association (CPIA) have promoted and continue to promote the recovery of them.

There are however plastic materials in the waste stream that cannot be recycled in an economically and environmentally sustainable way. They are perhaps multi-component materials designed for particular applications eg. cheese wrap or they are meat packages that are contaminated with fats, oils and blood that can pose health risks in a recycling operation, perhaps they are films of various sorts that are dirty, difficult to sort or intimately mixed or contaminated with other wastes. While these products may seem to have no value and are therefore wastes such is not the case because they carry an energy component that can be recovered in an environmentally sound fashion.

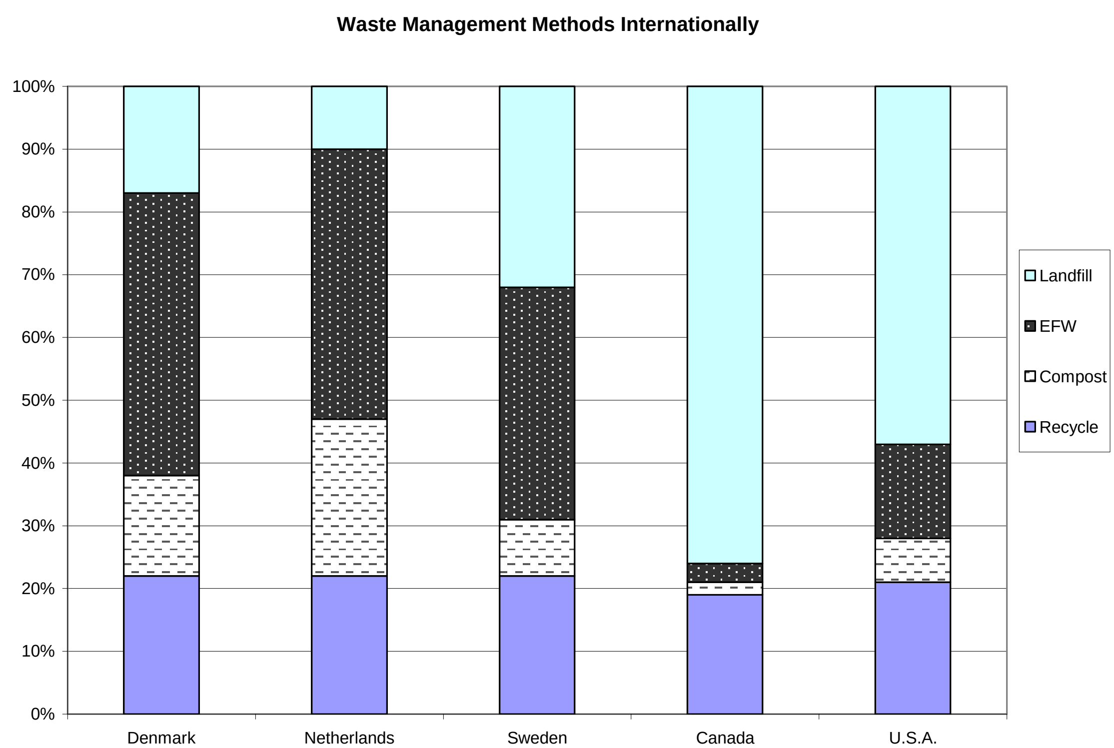
Why Energy Recovery Now?

The price of crude oil recently exceeded $U.S 50.00 a barrel. A barrel of oil contains 42 U.S. gallons, 159litres and weighs about 127kg. A large part of the doubling in price of oil over the last year or so has been attributed to disruptions and potential disruptions in supply. Oil prices and shortages drive up the price of other sources of energy such as natural gas and high energy prices can have a very negative effect on a nation's economy.

Many countries, Canada included, have initiated projects to seek out new sources of energy, primarily so called "green energy" such as solar, wind, geothermal and hydro power. Many of these developments are in their infancy. Additional sources of hydro electric power are in remote parts of the country, require long building times and may pose environmental concerns. In spite of the concern for energy North Americans are particularly blind to or afraid of embracing the potential to harvest energy from waste.

Such is not the case in many parts of the world. Figure 1 illustrates the use of waste to energy in a number of different countries.[4]

Figure 1



The Scandinavian countries of Europe particularly have embraced the concept of energy recovery from waste and many institutions in the cities of Sweden and Denmark are heated by hot water coming from the EFW plants after electrical energy first has been generated for the national power grids. Plastic residues are a welcome component of the municipal waste being combusted in the Scandinavian energy from waste plants because they provide the calorific value necessary to more completely burn other materials.

[4] Adapted from "Ontario's 60% Waste Diversion Goal – A Discussion Paper" Ministry of the Environment, June 2004.

Why should we in North America continue to put tonnes of plastic residues into landfills when it is akin to burying tonnes of oil or natural gas? (Residue is what is left over after all the materials that are amenable to sustainable recycling have been removed.)

The Technology of Energy Recovery

There are many ways to capture and/or make use of the energy embodied in plastic residues. The old fashioned incinerator of 50 years ago is not one of them. Rudimentary incineration as practiced from the 1910's to the 1960's did not capture energy. The incinerator was simply a means of reducing the volume of trash that had to be landfilled. Lacking pollution control equipment and belching smoke and ash the image of an incinerator has been genetically passed down to today's generation who have never seen an old plant but have been imprinted so that all combustion plants are old incinerators and are poisonous to approach.

The word dioxin sparks fear whenever it is mentioned and the word is always associated with the combustion of waste.

The United States Environment Protection Agency (EPA) has recently updated their records on sources of dioxins. A portion of their table is reproduced below.

Table 2

Inventory of Sources of Dioxin in the United States[5]

Source	Emitted to	Quantity (grams TEQ/year)
Backyard Barrel Burning	Air	628.0
Sewage Sludge applied to land	Land	76.6
Residential Wood Burning	Air	62.8
Coal Fired Utilities	Air	60.1
Diesel Trucks	Air	35.5
Industrial Wood Burning	Air	27.6
Chlorine Bleached Pulp & Paper	Water	12.0
Municipal Waste Incineration	Air	12.0
Crematoria	Air	9.1
Unleaded Gasoline	Air	5.9
Cigarette Smoke	Air	0.8

The principal source of dioxin in the United States is backyard burning. One family burning its waste in the backyard generates as much dioxin in a year as a municipal waste plant serving a city of 50,000 homes. It is suspected that many of the people that oppose

[5] U.S. EPA 2004

energy from waste are very content to gather around a wood burning fireplace completely ignorant of the toxic effluents from that fireplace. How much closer to a source of dioxin can one get than inhaling the smoke of a cigarette?

Since 1987 the emissions of dioxins from municipal incineration have been reduced by a factor of 750. Some of this may be attributed to the closing of old plants. Since 1995 emissions have been reduced by a factor of 100. Since the percentage of waste combusted has remained relatively constant over the period the improvement may be attributed to the addition of modern emission controls and new technology.

Some of the technologies to be discussed below have been operated for a considerable time and there are many equivalent facilities around the world. In today's climate they all meet stringent environmental guidelines. Other processes, as will be noted, are of more recent development in so far as dealing with MSW. Some of them have been termed advanced thermal technologies.

Mass Burn

Municipal solid waste (MSW) can be directly combusted as a fuel in waste to energy facilities with minimum processing. Without going into great detail the mass burn process takes the following form:

Incoming collection vehicles deposit the refuse into pits, where a crane removes any bulky or large non-combustible items such as large appliances. The crane also mixes the garbage to facilitate a mass of material having a more or less homogeneous calorific value. Such homogeneity permits easier control of the combustion process. The crane transfers the waste from the pit to the charging hopper of the combustor from which the material drops typically onto a moving grate. Heat from the combustion is directed to a boiler where steam is produced. The steam is routed to a turbine which generates electrical power. In many modern plants residual heat from the steam is used to produce hot water which in Europe is used for district heating. The combined process is called co-generation and increases the efficiency of the waste to energy considerably. Whereas the efficiency of a typical mass burn facility in the United States is 17% to 23% cogeneration as practiced in Europe can raise the efficiency to over 50%. The residues produced include "bottom ash" which falls to the bottom of the combustion chamber, fly ash which exits the combustion chamber with the flue gas (hot gases) and residues from the flue gas cleaning process. Fly ash is taken out of the system by electrostatic precipitators and fabric bag houses. Fly ash is a valuable addition to cement. Metals recovered from the bottom ash are sent to recycling. The bottom ash may be landfilled or used as aggregate. The flue gases are treated by wet and dry scrubbing to remove materials deemed undesirable. In modern facilities activated carbon may also be added before release of the remaining flue gases.

Stringent regulations are imposed on emissions by most jurisdictions. In Ontario this is Ontario Guideline A-7; in the United States U.S. MACT Standards; in Germany 17.BImSch V (Seventeenth Ordinance on the Implementation of the Federal Emission Control Act).

N.J. Themalis in a review article[6] stated that worldwide, about 130 million tonnes of MSW are combusted annually in over 600 waste-to-energy (WTE) facilities that produce electricity and steam for district heating and recovered metals for recycling. Since 1995, the capacity of the global WTE industry increased by more than 16 million tonnes. In 1999 the European WTE industry produced 110 million gigajoules (10^9 joules) of thermal energy and 41 million gigajoules of electric energy. In his article Themalis also points out that "according to a directive from the European Union, landfilling of combustible materials must be phased out within the decade."

The addition of plastic to the feedstock of EFW plants has been investigated extensively. R. Mirza working on behalf of EPIC reviewed full scale and pilot scale investigations of plastics in EFW undertaken in the 10 years prior to 1997. Mirza's findings were published in Chemosphere in 1999.[7] The investigations reported on were:

1. Wurzburg Study: A very comprehensive study to examine the effect of increased plastic content in the feed stream of a modern EFW facility carried out at the municipal waste combustor in Wurzburg, Germany in October 1993 and January 1994.
2. SELCHP Study: A series of trials carried out in February/March 1995 at the South East London Combined Heat and Power facilities in England.
3. VICON Study: Trials carried out at the VICON Resource Recovery Facility in Pittsfield, Massachusetts between May and July 1986.
4. Ebara Study: Tests conducted at the Ebara Corporation incineration plant located in Fujisawa City Japan on the combustion of non-recyclable plastic wastes separated from municipal solid waste in 1995.

In addition the results from a number of pilot scale investigations were reviewed. These included:

1. Work carried out on a fluidized bed reactor at the University of Umea that studied the effect of varying the chlorine and copper content of the feed.
2. Results from an investigation of stack emissions measurements made at the University of Florida-Tacachale-Clean Combustion Technology Laboratory between 1988 and 1992.
3. Testing conducted at the Neste Chemicals facility in Kulloo Finland in 1993 and 1994.

For full details on the results of all of this work please refer to the reference. In summary, the addition of plastics to feedstocks of EFW plants appears to improve combustion and waste burn out. The addition of plastics had no effect on stack emissions of particulate matter, heavy metals, and dioxins and furans. Similarly, the studies showed that the addition of plastics had no effect on the concentrations of heavy metals or trace organics in the solid residues remaining after combustion. A comparison with emission limits in municipal waste combustion standards and guidelines in Canada, the United States and Europe indicates that modern energy from waste facilities are able to meet these limits even when additional plastics are added to those normally found in municipal solid waste.

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[6] N.J. Themelis, Waste Management World, Review Issue, July – August 2003, p. 40-47
[7] R. Mirza, Chemosphere, Volume 38, Issue 1, January 1999, p. 207-231

Thermal Fired Plants Generating Electricity

Throughout the world very large quantities of electricity are generated from plants burning a variety of fossil fuels such as oil, natural gas, coal and in some instances peat. In the developed world the emissions from these operations are controlled to essentially the same standards as the emissions from the EFW plants handling MSW. Once again opportunities exist to use certain plastic residues in these facilities. The Association of Plastic Manufacturers of Europe (APME) has conducted experiments in the use of degraded polyethylene plastic film removed from greenhouses as a fuel in a coal fired thermal generating plant in Spain.[8] The film degraded by sunlight and unsuitable for recycling was shredded and fed to the facility at a rate of 3 tonnes per hour along with coal. Since the plastic has a calorific value 66% higher than that of coal the quantity of coal being fed was reduced to maintain the same rate of steam production in the facility.

The addition of the plastics had no effect on heavy metals in the flue gas and the slag from the unit. The extremely low emissions of dioxins and furans from the facility were not affected by the addition of the greenhouse film. Since the film contained no sulphur, sulphur dioxide emissions from the facility were reduced when co-firing with the film. (Coal contains some sulphur.)

Cement Kilns

The manufacture of cement is an energy intensive process operated at very high temperatures. It is unique when compared with other thermal combustion processes in that any solid residues left from the combustion of the fuel are incorporated into the clinker which is mixed with gypsum to form cement. Modern cement kilns operate with due regard to emissions of dust and other effluents. Most operators of cement kilns seek out alternate sources of energy to use with their primary fuel. These additional sources of energy range from shredded automobile tires to heavy oils and other organic liquids.

Plastic residues would seem to be ideal fuels for co-firing in cement kilns. The testing of this hypothesis has been carried out by the previously mentioned APME and Bünder Cement Untervaz of Switzerland. The plastics used were a mixture of packaging waste derived from a municipal collection. Up to 30% of the fuel to the kiln was substituted by plastics.

Particular attention was paid to the effect of plastics on heavy metals in the clinker. The concentration of heavy metals is regulated by the Swiss government (BUWAL). In addition the concentrations of dioxin and furans in the raw gas and in the solids captured at the electrostatic precipitator were monitored. The conclusions of the experiments were:

1. Source separated plastic packaging waste in Switzerland has a lower heavy metal content than average coal.
2. The effect of the heavy metals from the plastics can be neglected.

[8] Details on experiments conducted under the auspices of the APME may be accessed under “publications” on their website www.apme.org

3. High combustion efficiency is achieved with no negative impact on emissions of carbon monoxide, nitrogen oxide and sulphur dioxide and kiln operation/product.
4. Dioxin and furan concentrations were in the range of normal operation even when 30 percent of the fuel was plastic.

Plastics as a Reductant and Energy Source in Blast Furnaces

Large quantities of plastics are used in the blast furnaces of Germany as a source of energy replacing heavy oil. In addition the hydrogen in common polymers serves as a reductant in the conversion of iron ore. This kind of application was approved as raw material recycling by the Landerarbeitsgemeinschaft Abfal.[9]

The process is simple. Shredded agglomerated plastics are blown into the blast furnace through the tuyers (tubes through which oxygen is fed). At temperatures of roughly 2100^{o} Celsius the plastic material decomposes into carbon monoxide and hydrogen. Part of the energy in the plastic is released as heat. The major part is used as chemical energy for the reduction of iron ore. H_2 and CO molecules are oxidized by the oxygen molecules of the iron compounds to water and CO_2. According to Bremer Stahlwerke (a German steel company) the total energy efficiency is about 80 per cent. The use of plastics also reduces the quantity of coke needed in the process. The production of coke can have negative environmental impacts.

Plastics from Waste Electrical and Electronic Equipment as an Energy Source in Non Ferrous Metal Processes

A growing range of waste electrical and electronic equipment can now be used as a feed stream in non ferrous metal smelting plants. Non ferrous smelters produce primarily zinc and copper and are operated by large multi-national companies. In Canada, Noranda is a major producer of non ferrous metals.

The Association of Plastics Manufacturers in Europe (APME) and Boliden Minerals AB, a Swedish manufacturer of Zinc and Copper carried out a joint project in which scrap obtained from old personal computers was fed to Boliden’s zinc fuming furnace. PC scrap was collected from various sources in Scandinavia, inspected at a central place where known components containing Mercury were removed. The scrap was then shredded using a hammer mill equipped with a magnetic iron separator. The fragmented PC scrap was mixed with what is termed revert slag from the zinc process and fed to the zinc fuming furnace. The amount of PC derived material was about 10 tonnes per furnace charge. At the normal feed rates studied, co-treatment of PC scrap did not harm the fuming process. The heat released by the plastic reduced the need for coal. The project report states “that the influences on the environment are considered as being positive ones, as the process represents an effective sink for dioxins and heavy metals.”

Thermal Cracking Using Steam, Hydrogen and Catalysts

[9] Dietrich Brune, Research Centre Karlsruhe, Proceedings International Energy Agency Solid Waste Management Group, Kyoto Japan, September 1997, p. 13-5

These processes should be considered as distinct from conventional pyrolysis which will be discussed in a later section of this review. Steam, hydrogen and catalytic cracking are major processing techniques used by large oil companies to deal with products and by products of their refining operations.

VEBA Oel of Germany has cracked plastics mixed with petroleum residues using hydrogen and steam.[10] After further treatment with hydrogen a "syncrude" was produced that could be converted to monomers for polymerization. The by-products were industrial gases and bitumen.

British Petroleum has developed a process to convert mixed plastic waste to olefins by pyrolytic liquefaction followed by steam cracking. Excellent yields of ethylene and propylene have been obtained.

Steam crackers are relatively common in Europe but less so in North America. To make the cracking of waste plastics viable very large quantities need to be gathered and shipped to a refinery.

Pyrolysis

Pyrolysis differs from gasification and combustion in that it is "an endothermic process". This means that it requires energy in the form of heat to carry out the reaction.

Pyrolysis is the thermal degradation of materials containing carbon. The process is carried out usually at temperatures in the range of 400 to 600^{o} Celsius in an atmosphere in which oxygen is very limited or excluded to preclude combustion. At the temperatures indicated, solid organic materials give off gases and decompose. The products of pyrolysis include gas, liquids and solid char. The relative quantities of gas, liquid and solid depend on the method of pyrolysis and such factors as temperature, rate of heating, pressure and residence time. More liquid is produced at lower temperatures and more gas at higher temperatures.

Often the gas produced during the pyrolysis is used to heat the vessel. This was the case in the work carried out by the American Plastics Council using a pyrolyser operating at Conrad Industries in Chehalus Washington.

The vessel used in the Conrad pyrolyser was a sloping retort in which the pyrolysis gases were burned in an outer jacket to heat an inner rotating cylinder through which a mixture of polyethylene, polypropylene and polystyrene was passed. The unit operated successfully and the recovered liquids were sent to a refinery in California for additional upgrading.

[10] Ibid.

Pyrolysers have been developed for treating a number of waste streams such as scrap tires, mixed plastic wastes and certain forms of biomass such as wood waste. One of the earliest applications of pyrolysis was the "destructive distillation of wood" to yield methanol and terpenes for use as chemicals and a solid charcoal.

The Japan Waste Research Foundation located in Tokyo has conducted extensive research into the pyrolysis of plastic wastes and with the assistance of the Japanese Ministry of Health and Welfare has built a demonstration plant using plastics as a feedstock.[11]

CANMET a division of Natural Resources Canada (NRCan) also investigated the pyrolysis of plastics under conditions which yielded chemicals suitable as precursors for detergents. The CANMET work was carried out in batch autoclave reactors operated at 400 to 500^{o} Celsius and pressures from1 to 160 bars. The feedstock for CANMET was a mixture of polyethylene, polypropylene and polystyrene.

Also in Canada, the University of Laval and ETP Technologies studied the vacuum pyrolysis at 500^{o} Celsius of auto shredder residue (the material remaining after metals have been removed in the shredding of obsolete automobiles). The products were: 18.3% oil, 15.8% pyrolytic water, 3.9% gas, 37.5% inorganic materials (silica etc.) and the rest metals and alloys.

Much of the reported work on pyrolysis was conducted during a period of low energy cost and hence investment in the technology was not deemed prudent. In the current environment the economics are much more attractive and commercial pyrolyser units are being offered for sale by the Chinese and Japanese among others.

Whereas many of those selling the equipment maintain that the products of their processes are suitable as diesel fuels or heating oils there continues to be some skepticism regarding the on going quality of the product unless the unit is equipped with a distillation train or the product has been subjected to an external refining process.

Gasification

Gasification is perhaps one of the most versatile of what has been termed advanced energy technologies. The process is not new but has existed in a variety of forms for many decades. During World War II the German petrochemical industry used the gasification of coal to produce chemical feed stocks and fuels when supplies of petroleum were cut off. Similarly the South African chemical industry relied on the products of gasifiers when the country was subjected to an embargo on oil. Large refiners of petroleum have used gasifiers for many years to recover valuable materials from refinery residues.

[11] Tetsushi Sato, Japan Waste Research Foundation, Tokyo, Proceedings International Energy Agency Solid Waste Management Group, Kyoto Japan, September 1997, p. 15-2

Through the process of gasification a wide variety of carbon based materials, from coal to biomass to municipal waste can be converted from a solid form into a gas by reacting the feedstock with a limited amount of oxygen and steam. The reaction is carried out at high temperatures under what are called reducing conditions. Reducing conditions occur when there is insufficient oxygen in the atmosphere to sustain combustion. Once the gasifier is operational the partial oxidation of the feedstock supplies the heat necessary to sustain the chemical reactions. Together the heat and pressure in the vessel break the chemical bonds of the constituents of the feedstock yielding what is known as "syngas" which is largely composed of carbon monoxide and hydrogen.

Minerals in the feedstock separate and leave the bottom of the gasifier as an inert glass-like slag or an ash. In the reducing atmosphere the oxides of nitrogen and sulphur normally produced during combustion (combustion occurs in an oxidizing atmosphere) are not produced. In addition, in gasification, compounds containing chlorine do not produce free chlorine which is necessary for the formation of dioxins.

The "syngas" from the gasifier may be used to

1. Produce a wide variety of chemicals and clean fuels using well known processes.
2. Provide hydrogen for use as a chemical or as a fuel for a fuel cell.
3. In many applications the "syngas" is used directly after cleaning to power an internal combustion engine or a turbine to drive an electrical generator. The heat from the turbine is used to generate steam to power a steam turbine producing electric power. This system is called an "Integrated Gasification Combined-Cycle". Such systems are very efficient in capturing the energy inherent in the feedstock.

Gasification is NOT Incineration

As previously mentioned many detractors of the recovery of energy from residues and wastes liken all thermal processes to incineration and particularly incineration of the old fashioned kind. Table 3 below summarizes the differences between the two technologies.

Table 3
Key Differences between Gasification & Incineration

Subsystem	Incineration	Gasification
Combustion vs, Gasification	Maximize conversion of feedstock to CO_2 & H_2O	Maximize conversion of feedstock to CO & H_2
	Excess air	Limited Oxygen
	Oxidizing Environment	Reducing Environment
	Temperatures are below the melting point of ash. Minerals are converted to bottom ash & fly ash	Temperatures are above the melting point of ash. Minerals are converted to glassy slag & char,
Gas Cleanup	Cleaned at atmospheric	Cleaned at high pressure

	pressure	
	Treated gas is discharged to atmosphere	Treated syngas is used for chemicals or power
	Sulphur in the fuel is converted to SO_2 & discharged to atmosphere	Sulphur is recovered as a high purity element or acid
Residue & Ash/Slag Handling	Bottom ash & fly ash are collected, treated and disposed, Fly ash is a hazardous waste.	The slag is nonleachable, nonhazardous and suitable as construction material. Fine particles are sent back to the gasifier or processed for metal recovery.

The U.S. Department of Energy lists in its database 161 real and planned commercial-scale gasifiers representing a total of 414 units with a combined rating of 446 million Nm^3 per day of synthesis gas which equates to 33,284 $MW_{electrical}$ of power equivalent.[12]

The Dept. of Energy report referenced above goes on to state that 'Continuing convergence of oil, gas and electric power marketing with deregulation improves the potential for gasification. Increasing interest in improved energy efficiency, reduced emissions and increased recycle of waste also helps gasification'. This statement is borne out by a recent announcement by American Electric Power Co., the United States' largest utility, that it plans to build a 1000-megawatt synthetic-gas-fired plant. Such a plant would emit less mercury, carbon dioxide and particulate matter than a conventional coal fired plant.[13]

For those interested in pursuing the subject of gasification in extensive depth a 159 page report entitled "Gasification, The key to a cleaner future" written by David J. White has been published and distributed by Financial Times Energy, a division of Financial Times Business Limited (London) 2000, ISBN 1 84083 217 7, is recommended. White describes many of the commercial systems currently in operation.

EPIC, in 2001, commissioned a pilot scale investigation of the gasification of plastic residues at the laboratories of the CANMET division of Natural Resources Canada. These experiments which were small in scale were none the less sufficient in scope to suggest that additional work be conducted on a larger facility. The results of the CANMET investigation have been reported publicly.[14]

In 2003 EPIC engaged with Enerkem Technologies of Sherbrooke Quebec to investigate the gasification of low density polyethylene film and a mixture of rigid plastic residues made up of what is commonly known as #3 to #7 plastics.

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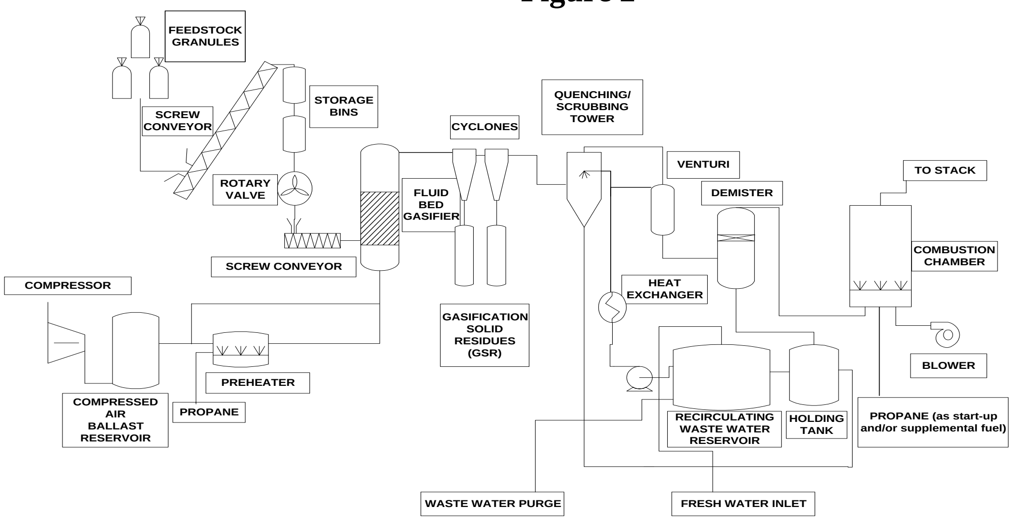
[12] U.S. Dept. of Energy, report contract DE-AMO1-98FE65271, October 1999.
[13] Wall Street Journal as reported in the Globe and Mail, Toronto, 31 August, 2004, pB13
[14] Lu,D.Y.,Anthony,E.J.,and Edgecombe,F.H.,17th International (ASME) conference on Fluidized Bed Combustion, Jacksonville, Florida, May 2003.

ENERKEM an off growth company from the University of Sherbrooke has developed what is known as the BIOSYN™ gasification process. ENERKEM is a co-operator of a commercial facility based on the process in Spain using contaminated plastic drums as a feedstock. In Sherbrooke ENERKEM maintains a fully instrumented pilot plant with the capacity to gasify 100 to 150 kilograms of material per hour. Figure 2 schematically represents the ENERKEM BIOSYN™ Process.

Figure 2



In late 2002 EPIC contracted with ENERKEM to carry out a series of experiments in which plastic residues taken from an Ontario municipal recycling programme were to be gasified. The residues used as feedstocks for the experiments would normally have been disposed of by landfilling. In order to determine with precision and accuracy the various chemical species emitted by the process to atmosphere, water and land, EPIC engaged the services of *Arthur Gordon Environmental Evaluators Ltd.* a Quebec based independent testing contractor to carry out a detailed chemical analysis. The analytical methods employed by Arthur Gordon Ltd. followed standards recognized by the Canadian Government or the U.S. EPA. A complete list of the species for which an analysis was carried out is available in the full report describing the experiments.

With regard to atmospheric emissions, analyses were done for dioxins and furans, polychlorinated biphenyls (PCB's), chlorophenols (CP), chlorobenzenes (CB), heavy metals such as Lead, Mercury and Cadmium, particulate matter and hydrochloric acid as well as the oxides of Sulphur, Nitrogen etc. amongst other species. In addition the chemical species making up the "syngas" were determined using the technique of gas chromatography.

All of the water used for cooling the process and scrubbing the gases produced, as well as any water produced from the chemical reactions, was accumulated and analyzed before treatment for discharge to the local sewer system. These analyses considered oils and greases, poly-aromatic hydrocarbons, pesticides, suspended solids, biological oxygen demand (BOD), heavy metals and a number of other chemicals.

Solid residues were "leached" using standard procedures and analyzed for heavy metals, as well as Arsenic, Barium, Selenium and Boron. In addition the solids were also analyzed to determine their residual Carbon content.

In order to determine the extent of the conversion of the feedstock into "syngas" detailed elemental analyses of the feedstocks were carried out.

In these experiments emphasis was placed on accounting for all of the carbon in the initial samples as the materials were gasified. This was done by comparing the carbon in the samples against the carbon contained in the species produced by gasification. Over 99% of all the carbon was accounted for.

The energy available in the samples was measured before gasification and then accounted for in the chemical species produced by gasification and in the losses incurred through processes such as cooling. The balance is shown in Table 4 below.

Table 4
Energy Balance

	Sample 1	**Sample 2**
Feed energy converted to "syngas" energy	71.8%	76.9%
Heat loss from solid residue recovery	0.01%	0.02%
Chemical energy in solid residue	0.1%	0.1%
Chemical energy in water	4.9%	4.7%
Heat loss from cooling	13.5%	14.3%
Closing	90.3%	96.1%

The energy balances clearly show that plastics exhibit high energy efficiencies in gasification since the energy in the feed is largely converted to energy in the "syngas".

In the experiments the "syngas" was burned in a combustion chamber. In large scale situations the "syngas" could be used to power an engine generating electricity or it could be used as a source of chemicals to form new chemicals or the Hydrogen could be extracted for use in fuel cells.

Exhaustive results on flue gas analyses are presented in the test reports from Arthur Gordon Ltd. Using guidelines produced by the province of Ontario as a reference point all emissions, adjusted at 11 vol% Oxygen, are well below the allowable limits. The main results from the analyses are summarized in Table 5 below.

Table 5
Summary of Atmospheric Emissions

No	Categories	Descriptions	Sample 1	Sample 2	Ontario limits	Units
1	Continuous sampling (average)	O_2	11	11	-	%
		CO_2	8.68	7.94	-	%
		CO	0.9	1.3	50	mg/Rm^3
		SO_2	1	1	56	mg/Rm^3
		NO_x	48.6	47.1	110	PPMV
		Total Hydrocarbon (equiv. CH_4)	15	10	100	mg/Rm^3
2	Dioxin/Furan	TEQ equivalent	0.005	0.03	0,08	ng/Rm^3
3	Particles	Total	4.5	4.4	17	mg/Rm^3
4	HCL	Total	2.3	1.5	27	mg/Rm^3
5	Metals	Chrome	20.08	7.73	-	µg/Rm^3
		Cadmium	1	7.46	14	µg/Rm^3
		Mercury	0.62	3.82	20	µg/Rm^3
		Lead	35.27	44.19	142	µg/Rm^3
6	PCB	Total	0.1	0.11	-	µg/Rm^3
7	Chlorophenols	Total	0.64	0.33	-	µg/Rm^3
8	Chlorobenzene	Total	0.51	0.55	-	µg/Rm^3

The measured levels of dioxins and furans, already as much as 16 times lower than the Ontario emission limits, could be further decreased to essentially whatever level is desired by (a) filtering the air used for combustion and (b) additional gas conditioning steps. A commercially built unit would incorporate (a) and (b) to reach levels that correspond to “analytically detectable limits” (0.0015 ng/Rm^3).

The quantities of solid residues remaining after the gasification of the plastics were very small. The residue from Sample 1 was 0.82% of the plastic processed while that from Sample 2 was 1.37%. Following leaching of the residues it was determined that any quantities of heavy metals, Cadmium, Chromium, Lead and Mercury were below the limits of detection. As a result it may be stated that the residues would comply with environmental regulations if they were used as ground cover.

The gasification process generates some particulates (organics and inorganics) and, as well, volatile organic intermediates. Cyclones can capture particulates down to 10 µm. Smaller particulates as well as volatile organics are captured by the scrubbing system and accumulate in the scrubbing water. A three step waste water treatment system such as employed routinely by petrochemical industries would guarantee that regulations concerning purge to the sewage system would be met. The treatment would include the use of flocculants and coagulants to remove as much organic and inorganic material as possible, a wet oxidation treatment to partially oxidize any polyaromatic hydrocarbons and phenols and finally biological treatment to convert acids into biomass and CO_2.

Conclusions

- Gasification of granulated plastic residues from municipal recovery facilities via the BIOSYN™ process has shown that it can produce a synthetic gas that, upon combustion, results in atmospheric emissions of particulates, metals and organics well below the accepted emission limits in Ontario, which are among the most stringent in the world.
- In both tests very small quantities of gasification solid residues (GSR) have been found. The solid residues contain most of the inorganic material initially present in the waste pellets and some unconverted carbon. Lixiviation (leaching) tests have shown that such residues comply with environmental regulations and can be used without any treatment as ground cover in embankments or a matrix for compost.
- The wastewater resulting from the scrubbing operations has been characterized. It needs to be treated. Technologies to treat this type of wastewater are known and operational all over the world.

Other Processes

Use of Microwave Energy

Rubber tires have been processed using microwaves. The process is essentially a form of pyrolysis in which the energy used to heat the material is supplied in the form of microwaves. Oils and gases are produced along with a residue comprised primarily of carbon and small quantities of inorganic materials such as zinc oxide. Experiments using the technology were conducted in Ontario a number of years ago but to the knowledge of the author the process was not commercialized.

Most plastics such as polyethylene are transparent to conventional microwave frequencies and as a result would not become hot. To use the technology to pyrolyse polyethylene would require that the plastic be suspended in a bed of another material capable of absorbing the energy and by physical contact heat the plastic.

Use of Plasma Technology

Plasma consists of a collection of free moving electrons and ions (atoms that have lost electrons). Plasmas can be “steered” by electric and magnetic fields and can have very high temperatures even greater than 100,000^{o} Celsius. Commercial plasma torches normally operate in the range of 3000 to 4000^{o} Celsius. A plasma process is very high temperature gasification. At the temperatures of operation inorganic materials such as metals, soil, silica, glass etc. are vitrified to a slag. Metals can be recovered from the slag. Organic materials are transformed to a “syngas”.

Westinghouse Plasma Corporation has developed a plasma gasification process for municipal solid waste (MSW) in Japan. Hitachi has built three facilities of which two are in operation (50 and 300 tonnes/day). The third is said to be in start up mode.

PyroGenesis Inc. in a proposal to the City of Toronto[15] described the Plasma Resource Recovery System which they state was developed by them in conjunction with Natural Resources Canada and the U.S. Navy. It is said that two systems each having a capacity of 10 tonnes/day have been operating in their Montreal facilities for three years.

The author has observed a plasma furnace in what were the laboratories of Phillip Environmental. The device was used primarily to recover metals such as zinc and copper from contaminated streams such as bag house dusts and foundry sands.

No reference has been found regarding the direct application of plasma to the gasification of plastics. Without any doubt the technology would work subject to the ability to feed low melting plastics to the plasma torch.

[15] Macviro and EarthTech Summary of Individual Responses to Toronto REOI on New and Emerging Waste Management Technologies, October 2003, p.3-84