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**Thermal Processing of Domestic Solid
Waste Part 2 of 2 – Conversion
Processes**

Instructor: Walter R. Niessen, PE, BCEE

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

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Thermal Processing of Domestic Solid Wastes

Part 2 of 2 - Conversion Processes

Walter R. Niessen, P.E., B.C.E.E.

COURSE CONTENT

In the last two decades of the 20th century, environmental action groups and the regulatory community put the spotlight on air and ash emissions from municipal waste combustors (MWCs). This scrutiny and new data on the health effects of a wide spectrum of heavy metals and chemical compounds fostered vigorous opposition to proposed plants, to the adoption of increasingly stringent emission and ash management requirements and to other restrictive statutes at the federal, state and even the local level. One response in this adversarial environment is to upgrade the processes and enhance the control technology for "conventional" combustion-type MWC systems. The engineering and scientific skills of the mass burn industry, world-wide, have aggressively and successfully pursued this strategy. An alternative approach, however, is to develop altogether new thermal processing technologies that are inherently low in emissions yet still achieve the goal of minimizing landfill space consumption while accepting the wide range of feedstocks comprising MSW. One such class of new, environmentally benign technologies is based on the gasification of refuse coupled with intensive cleanup of the product gas. The members of this class have been given the name "Conversion Processes" by the waste management community.

The penetration of the thermal processing market by advanced technologies is paced by their environmental, economic, and performance acceptability. From an environmental viewpoint, the gasification technologies appear to represent a sound response to the regulatory challenges of U.S. EPA. However, economics has always been a critical and probably pacing factor affecting the commercial success of thermal processing technology along with performance acceptability (which most importantly focuses on on-line availability, achievement of guarantees and safety). These key cost and process characteristics will only be confidently known when commercial operation of conversion technologies has been demonstrated over an extended period of time.

This second course in domestic solid waste technology assumes an understanding of chemistry and mathematics and presumes familiarity with combustion fundamentals and equipment through completion of the two-part *Fundamentals of Combustion* course and the *Thermal Processing of Domestic Solid Waste –Part I– Combustion* course. This course includes:

- The principles and process strategy of conversion technology;
- The design and operating characteristics of examples of each of the conversion-based waste processing categories;
- The utilization options for the synthesis gas generated by conversion technologies; and
- The recommended approach to system selection for emerging technologies.

Conversion technologies, in general, do not go as far in oxidizing the waste as do mass burning or RDF combustion but involve a different process concept that seeks to move only part-way along the path to CO₂ and water vapor. Thus, in all cases, for the wide range of conversion concepts, there are at least regions within the process flow sheet where feed streams are broken down by applied heat or partial combustion to form gaseous intermediate products. In all cases, these intermediates include carbon monoxide (CO) and hydrogen (H₂) along with lesser concentrations of hydrocarbons ranging from simple methane (CH₄) and ethane (C₂H₆) to longer chain paraffins, unsaturates, aromatic and polynuclear compounds, partially oxygenated species and complex "tars."

Other compounds present can include acid gases such as hydrochloric acid (HCl) and diluents such as nitrogen (N₂). Since these gas mixtures are less than fully oxidized, sulfur in the waste is usually found in reduced forms in the mixed gas; especially as hydrogen sulfide (H₂S) and carbonyl sulfide (COS). The reduced-state gas mixture is not an intermediate but

is the ultimate process product of the conversion technology stage of the process although there may be add-on steps that utilize the gas in other processes that bring the gas composition to the fully oxidized state. Alternatively, the gases formed can be cleaned so as to be essentially pollutant-free for use as a fuel or a chemical feedstock.

In addition, the conversion technologies all produce one or more solid side streams including rejected feedstock in the waste preparation steps, particulate matter in the off-gases, and more massive residues from the conversion technology process modules.

A. Conversion Technology Processes

Unlike the inherent simplicity of mass burn systems, most conversion technologies require that the flowsheet include a number of steps including waste preprocessing, heating and, ultimately, gasification (with sub-steps of tar destruction and synthesis gas reformation), followed by relatively sophisticated gas clean-up.

1. Pre-Processing

In almost all cases, conversion technologies require preprocessing of the waste ahead of the heating step. Preprocessing can include:

- *Drying* – The thermal efficiency of all gasification processes (the fraction of the chemical heat content of the waste remaining in the heat content of the synthesis gas) is reduced significantly by the thermal burden of evaporating free moisture. Even though drying may not be required for the process to function, removal of free moisture greatly benefits all of the processes and increases the yield of CO/H₂ synthesis gas. Most often, a trommel-like device with warmed air is used to dry the waste.
- *Size Reduction* – Shredding to reduce the cross-section of waste components reduces the residence time needed for heat conduction into the waste components in the course of raising the organic material to pyrolysis temperatures. Conversion technologies often require subdivision at or below 5 cm (at a substantial cost and processing system complexity) followed by a classification stage to recover valuable recyclable fractions such as aluminum, ferrous and other metals and/or to remove undesirable fractions such as glass, “dirt,” rocks and ceramic.

2. Heating

a. General

Almost all of the emerging conversion technologies (save those based on aerobic composting or anaerobic digestion) involve application of heat to MSW components. Heating induces profound chemical and physical changes in the waste. First, remaining water is evaporated since the presence of liquid water limits the temperature to 100 °C. When the temperature exceeds 300-400 °C, aluminum melts and organic compounds begin to degrade to form mixtures of compounds that range from low molecular weight gases such as methane and ethane, intermediate hydrocarbon and partially oxygenated species (alcohols, ketones, aldehydes, organic acids etc.) and high molecular weight tars such as (often carcinogenic) polynuclear compounds. Carbonaceous char remains as a solid residue along with the other inorganic “ash”. At temperatures above 850 °C, glass softens and becomes liquid. Above 1500 °C, even ceramics and most common metals soften and melt.

Paralleling increases in temperature, the reactivity of the chemical species present increases. This fosters oxidation, re-arrangement and re-forming reactions. Oxygen that is inherent in many wastes (e.g. in cellulose) or is added in air, as pure oxygen or carried in vaporized water molecules (steam) reacts to form CO, CO₂, and myriad aldehydes, ketones and other partially oxygenated compounds. If the gas remains oxygen-deficient, a fraction of the hydrogen present in water and hydrocarbons appears as elemental H₂. The chemistry set of rearrangement and polymerization reactions becomes fully engaged.

Such heating steps can be accomplished in several ways but, primarily, involve:

- *Pyrolysis* – by decomposition of organic matter by heating in the absence of air using hot surfaces, inert gas heated by a non-transferred plasma arc or other means, a plasma arc that directly interacts with the waste (a transferred arc), or electrically induced heating; or

- *Partial Combustion* – by addition of oxygen or limited amounts of air to release a portion of the fuel energy in the waste thus raising the temperature of the remaining MSW components. Combustor designs for this heating strategy include fluidized beds (bubbling or circulating), kilns, shaft furnaces (updraft or downdraft) and hearths.

b. Hot Surfaces

In most instances, this heating strategy involves a rotating, kiln-like unit with external heating of the kiln shell or an internally heated augering screw. Often, a portion of the synthesis gas is burned to provide the heat although some technologies favor the use of purchased natural gas. Rotating the kiln or auger abrades the waste mass against a hot surface with exchange of heat by a kind of rubbing convection. The tumbling action of the waste assures uniform contact of the waste with the hot surface and, by stoking the mass, helps to break up the charge. The inclination of the kiln or the pitch of the screw act to move the waste from the feed point to discharge.

c. Hot Gases

- *Heated gases* – Gas heated in a secondary heat exchanger or other device or generated by combustion of natural gas or a portion of the product synthesis gas is contacted with incoming waste to rapidly and effectively raise the waste temperature to pyrolysis temperatures.
- *Non-transferred arc (NTA) plasma torch* – Plasma, (sometimes called the “fourth state of matter”) applies to a gas infused with sufficient energy to be ionized. Since this superheated gas stream is conductive, it can be heated further by an electric current to levels exceeding 5,000 °C.

A plasma torch is comprised of a stainless steel cylinder containing the electrodes, insulators, gas injectors, and water passages integrated into a functional torch [1]. The two electrodes are separated by an electrical insulator. Cooling water is circulated through the electrodes to prevent melting at plasma arc temperatures. The gas to be heated is injected tangentially and the electric arc discharge is magnetically rotated at extremely high speeds. The gas feed replenishes the gas for the plasma and stabilizes the plasma arc column. By varying the gas flow rate, the contact location of the arc can be changed to control consumption rates of the copper electrodes. Air is commonly used as the gas source. A schematic view of an NTA system is shown in Fig. 1.

Plasma torches have been used for decades in many industrial applications. The gas presents a high electrical resistivity to the current and generates significant heat. At 2,000 °C the gas molecules dissociate into the atomic state. That is, O₂ breaks down into two highly energetic oxygen atoms; CO₂ into an atom of carbon and two oxygen atoms and so forth. At 3,000 °C, the gas molecules become ionized as electrons are stripped away. The ionized gas (or “plasma”) is electrically conducting and can be confined by electromagnetic fields. Due to strong interactions between the plasma components, the viscosity of the plasma is more like that of a liquid than a gas. If desired, higher temperatures (say, to 20,000 °C or more) can be achieved by increasing the electrical current. Due to the physical dimensional constraints of many of the NTA mode systems, the plasma feed is limited to liquids or gases. A plasma torch is, therefore, simply a method for producing an ultra-hot fluid stream with which to transfer heat.

NTA Plasma arc waste management technology refers to processes that use a sustained electrical arc to heat municipal or other solid wastes to high temperatures (up to 5,000 °C) in an oxygen-free or oxygen-starved environment. The waste then pyrolyzes into a primary product of relatively large molecules that, in subsequent passage through the system, are ultimately discharged as simpler molecules. The gases leaving the furnace are defined by the relevant chemical equilibria and kinetics (see Fundamentals of Combustion – Part 1 course or Reference 1) in the plasma zone as modified in the subsequent time-temperature history of the gas as it moves up and out of the gasification reactor. Volatile metals vaporize in the plasma chamber and are carried out of the unit with the gas stream to condense as a finely divided fume or deposit on small particles (having the majority of surface area) in the gas stream.

The products of the process are a combustible gas derived from the organic matter and a molten slag from the inorganic matter. The latter, when cooled, becomes a vitreous material with excellent leaching characteristics. Gasification of the waste is a non-combustion process and occurs in the plasma furnace where the energy from the electrical arc is applied. Since the unit operates at high temperatures, water cooling is required for the survival of the treatment vessel. There are risks, therefore, that leaks in the water cooling jacket may lead to steam explosions and injury to personnel and equipment destruction.

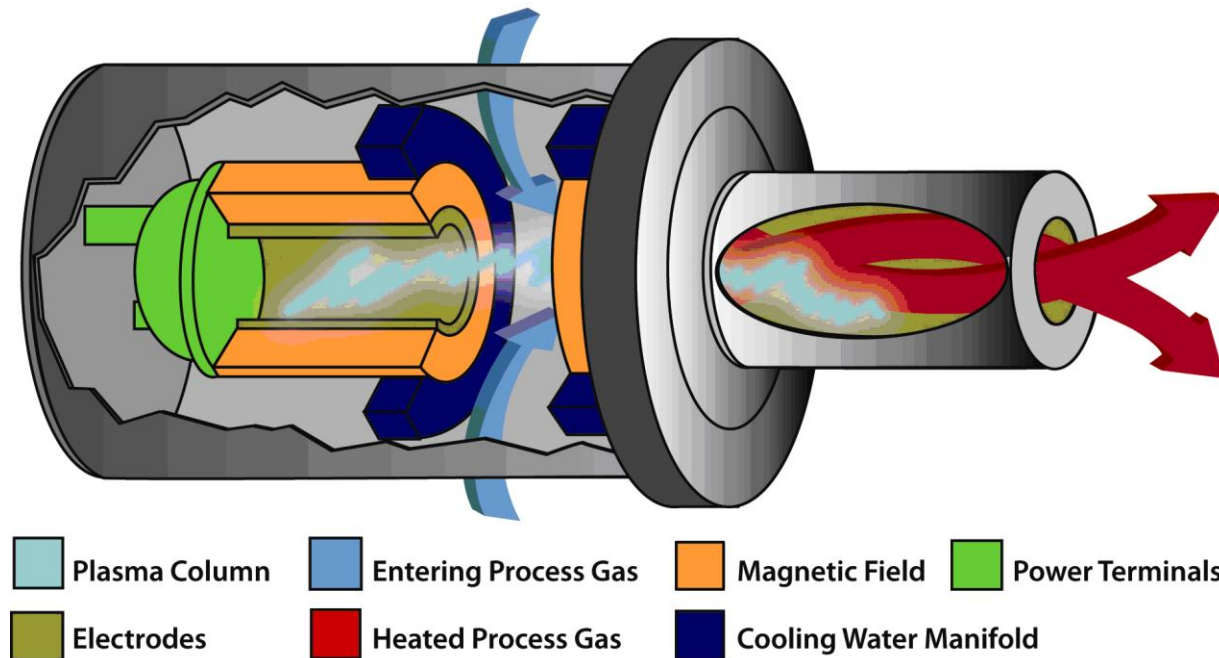


Fig. 1 Cutaway of NTA Plasma Torch (Courtesy of Alter NRG Ltd.)

High arc rotation speeds and high gas flow rates provide excellent heat transfer between arc and gas. The gas exits the torch as a superheated gas jet that can be directed into a furnace or other process reactor to accomplish a heating function.

The off-gas clean-up needs to treat a hot, dusty and combustible gas mixture. This may include an afterburner, a particulate control system, and, most often, several treatments tailored to the chemistry of the various gaseous species present in the gas. Often, some measure of cooling is accomplished before gas clean-up; sometimes with energy recovery using boiler surface or, more simply, by injection of water. If the fraction of the waste containing inorganic material is large, the reliable management of the molten residue is critical to on-line availability of the unit. Freezing of the slag discharge ports and/or build-up within the plasma chamber is unacceptable.

In principle, the plasma environment can be used to process almost any waste to produce a glassy, non-leachable vitrified residue and, compared with full oxidation in an incinerator, a minimal volume of gaseous product requiring cleanup. Organic molecules break down to benign species such that the original chemical identity of the organic fraction of the feed is completely lost. In development hardware, plasma units have shown excellent DRE performance to include tests showing better than 99.9999% DRE even for hard-to-burn PCB materials. Performance in this DRE range is a reflection of the extremely high working temperature of plasma systems such that total thermal dissociation is achieved, rather than kinetically controlled oxidation processes.

Halogens in the waste are also found in the gaseous effluent stream; often appearing in the off-gases as the element rather than as the more easily captured acid. Since the off-gas is usually oxygen-deficient (reducing), sulfur generally appears as a mixture of H_2S (the dominant sulfur form) and COS . Lesser, but significant concentrations of HCN and ammonia (NH_3) are also present. Metallic waste components often melt, sink to the bottom of the liquid pool of condensed phase products and can be drawn off as a potentially recyclable scrap metal stream. Inorganic fractions of the waste form a molten slag layer floating on top of any metallic layer. The overall volume reduction depends on the proportions of organic matter, ash and metallic components in the feed waste.

d. Direct Heating

- *Induction Heating* – If an alternating electrical current is applied to the primary coil of a transformer, an alternating magnetic field is created. If the secondary coil of the transformer is located within the magnetic field, an electric current will be induced [1]. In a basic induction heating application, a solid state, radio frequency power supply sends an AC current through a water-cooled copper coil. Material to be heated is placed inside the coil.

The coil serves as the transformer primary and the part to be heated becomes a short circuited secondary. When a conducting metal is placed within the induction coil and enters the magnetic field, circulating eddy currents are induced within the metal generating precise and localized heat without any direct contact between the metal and the coil.

One notes that magnetic materials also produce heat through what is called the hysteresis effect. During the induction heating process, conductive magnetic materials offer resistance to the rapidly alternating electrical fields, and this causes enough friction to provide a secondary source of heat as long as the temperatures is below its Curie Point whereupon a magnetic material loses its magnetic properties. The relative resistance of magnetic materials is rated on a “permeability” scale of 100 to 500; while non-magnetic material has a permeability of 1, magnetic materials can have a permeability as high as 500.

- *Transferred arc plasma torch* – In contrast to the case of the NTA, the transferred arc is struck between the torch electrode and the melt or between two graphite electrodes; similar to metal arc furnaces whereupon a substantial fraction of the electric energy passes directly into the melt. This mode has the advantage that large masses of material can be heated to the fusion point with less pretreatment. In waste processing, the arc is struck between the torch and a pool of metal (derived from the waste) on a refractory hearth.

e. Partial Combustion

For many of the heating concepts discussed, the energy source is purchased or self-generated electricity or fuel. These energy inputs reduce the net energy yield of the process or represent a significant operating expense. An alternative strategy involves addition of a quantity of oxygen to the waste mass that is less than stoichiometric but which generates a quantity of hot flue gas sufficient to effect drying and pyrolysis. While some of the waste’s energy content is consumed, the form value of the energy is at the lowest level of any other energy source. If pure or highly enriched oxygen is used to release the heat, there is minimal dilution of the product gases. If air is used, the atmospheric nitrogen in the air adds to the volume of flue gas produced thus increasing the size and both capital and operating cost for subsequent air pollution control, fans, ducts etc. and decreases the product gas heat content and its utility as a chemical feedstock.

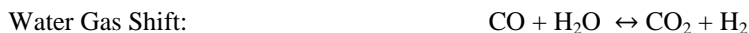
3. Gasification

Gasification is old technology but gasification of waste materials is a quite recent application. Waste gasification is still in the advanced developmental stage with only a few plants, worldwide, that have continuous operating experience under commercial conditions. In its simplest embodiment, gasification occurs by simple heating of organic material to temperatures to 400 to 600°C (or higher) to break complex molecules into shorter chain, gaseous species (at the extant conditions). This is pyrolysis-type gasification. The products of pyrolysis include low molecular weight gaseous compounds such as CO, CO₂, H₂, and a wide spectrum of hydrocarbons to include methane, ethane, ethylene and the like; medium molecular weight compounds that may be gases at high temperatures but which would condense to liquids at normal ambient temperatures; and high molecular weight carbonaceous char and viscous, tarry material. The chemistry of the products also includes myriad compounds with carbon, hydrogen, oxygen, sulfur, nitrogen and halogen atoms. The chemical structures comprising these compounds include saturated and unsaturated forms, aldehydes, ketones, ethers, alcohols etc.

Gasification processes using partial oxidation applied to MSW are often (but not exclusively) fed waste previously subjected to recycling and refined to an RDF and, in some instances, dried. Clearly, the partial combustion approach is simple but some of the heat content of the original organic material is lost and, if air is used as the oxidant, the product gas includes diluent nitrogen. The latter can be eliminated or reduced by use of pure oxygen or oxygen-enriched air.

A second strategy used to effect gasification exposes the organic material to hot or superheated steam that both heats the material (inducing pyrolysis) and acts as an oxidant which, through the water gas and water gas shift reactions yields a gaseous fuel product with minimum char residual and without addition of nitrogen.

The most important final gasification reactions include:



A detailed heat and mass balance is essential to assess the energy conversion efficiency and to identify the liquid, solid, and gaseous side streams that require either additional treatment or disposal. Product gas can be characterized by its relative heat content class:

Low heat content gas	950 to 2,800 kcal/Nm ³	100 to 300 Btu/sft ³
Medium heat content gas	2,800 to 5,700 kcal/Nm ³	300 to 600 Btu/sft ³
High heat content gas	>5,700 kcal/Nm ³	>600 Btu/sft ³

Typically, methanation reactions are important in lower-temperature systems, while reforming reactions are more prominent in high-temperature systems. The reactions that predominate in the gasifier strongly depend on temperature (establishing gas phase equilibria and reaction rates) and the attack of the solid phase material by oxygen and/or water vapor.

After heating has gasified the waste, some flow sheets include a “cracker” where tars (high molecular weight compounds) are broken down into simpler molecules. Many processes remove a portion of the sensible heat from the product gases using a waste heat boiler or by simple water sprays. These steps are then followed by one or more stages of gas clean-up which may include:

- Particulate removal
- Acid gas removal
- Hydrogen sulfide (H₂S) removal
- Amine/ammonia removal
- Other control requirements (tars, COS, etc. impacting downstream components)

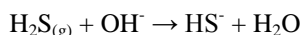
The gas cleanup effort deals with the relatively small product gas stream from the gasification reactor. This contrasts with the scale of cleanup for conventional incinerator flue gases that have been greatly expanded in volume by the addition of almost twice the theoretical quantity of combustion air and the consequent dilution associated with nitrogen and excess oxygen. Therefore, the equipment and operating cost for environmental emissions control for the gasification off-gas can be substantially lower.

B. Process Streams

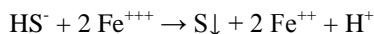
1. Fuel Gas Intermediates

Much of the gaseous stream (CO, H₂, light hydrocarbons) is usable as a fuel (releasing heat when fully oxidized). In concept, the gas is usable as a feedstock (a “synthesis gas”) for input to an add-on process train(s) for the manufacture of industrially useful chemicals. However, the adverse economy of scale of such chemical manufacture, transportation and marketing may be unattractive for many of the low value commodity chemicals that can be made. Also, since the raw gas stream is contaminated with a range of hydrocarbons and potential air pollutants including carcinogenic tars (which are inherently destroyed in the course of full combustion), its use as a fuel gas is simple, reliable, uses conventional burners and boiler equipment and generates readily salable energy products (steam, hot water and/or electricity)

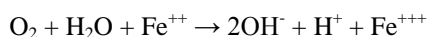
If the initial gasification process yields a gas with a high tar content, some kind of tar cracking step (often dolomitic lime is used as a low-cost cracking catalyst). Subsequent purification of the conversion process off-gas usually involves wet electrostatic precipitators or wet scrubbers for the removal of particulate matter that includes a large fraction of the heavy metals. The scrubber train often involves acidic solutions to absorb ammonia and amines; alkalis to absorb acid gases and form neutral salts; and mixtures of iron salts that can absorb H₂S as a sulfide precipitate. In the latter case, the H₂S dissolves in the alkaline scrubbing medium and is ionized to the hydrosulfide ion HS⁻ in the reaction:



The HS⁻ ion reacts with a solution of a ferric salt to precipitate sulfur and reduce the ferric ion according to the reaction:



The solid sulfur is removed and the ferrous solution is blown with air (oxygen) to regenerate the ferric iron (which is then recycled) according to the reaction



COS (carbonyl sulfide), formed in high temperature processes at about 10% of the H₂S concentration, can be converted to H₂S by hydrolysis with steam in a separate reactor.

Such a clean-up train yields a mixture of clean gases (plus, perhaps, some diluent N₂) that can be burned in combined cycle diesel engines or gas turbines for power generation. Also, the cleaned gas can be used in fuel cells to directly generate electricity. Alternatively, one may simply burn the gas in a boiler to generate process or heating steam or hot water. Other than the nitrogen oxides (NO_x) formed in the course of combustion, the flue gases from these combustors is essentially free of heavy metals, dioxin-like species, and acid gases (HCl and SO₂).

2. Synthesis Gas (Syn-gas) Intermediates

Mixtures of CO and H₂ (after suitable clean-up) can be used as the starting point for a range of conventional and development-stage processes to produce methanol, ethanol and other simple petrochemical type industrial chemicals. In many cases, this synthesis technology is reliable and well-developed and can be accessed through several industrial chemical design firms. However, the economics of manufacture, transportation and sale of these chemicals may not lend themselves well to the limited scale of most municipal waste management systems. Using other development-stage processes introduces additional capital and operating costs and a second level of risk and uncertainty into the process selection decision.

One of the most important routes to more complex fuels and chemicals involves Fischer-Tropsch (F-T) catalytic synthesis reactions. The principal application of the process has been to produce a synthetic petroleum substitute, typically from coal, natural gas or biomass, for use as synthetic lubrication oil or as synthetic fuel. However, the F-T catalysts are notoriously sensitive to the presence of sulfur-containing compounds among other poisons.

3. Biosynthesis Nutrients

Mixtures of CO and H₂ (after suitable clean-up as described above) can also be used as a nutrient feedstock to biological processes. Using broths seeded with biota that have been tailored to the task, the primitive starting chemicals in the MSW off-gas can yield salable chemical products such as ethanol. Many of these biosynthesis technologies only process a portion of the synthesis gas components so that a residual and lower heat content fuel gas remains as a byproduct usable for plant steam, electrical generation etc. One such process for biosynthesis has been developed by BRI Energy of Fayetteville, AR.

D. Side Streams and Residues

There are several possible side streams and residues from conversion technologies: RDF unprocessables, recyclable metals, vitrified ash, ash and char solids and scrubber blow down.

The technologies involved in the add-on process steps for side stream and residue management are not, necessarily, problematic. However, they add to both capital and operating cost and they add additional risks and operating challenges to the flow sheet. Some conversion technology developers claim revenue streams from marketing these materials. In general, it is wise to require presentation of firm and unambiguous contract offers for the materials showing a plausible price structure from reliable and established residue customers before such revenue streams are included as dependable elements of a project's economic analysis.

a. RDF Unprocessables

Some conversion process concepts require the incoming MSW to be shredded and, often, classified or otherwise pre-processed to concentrate one or another streams either because they are desirable (e.g. they have a high energy content) or are undesirable in the downstream steps (e.g. they are wet, they generate a problematic slag, contribute an important air pollutant, or can jam the materials handling systems). The unprocessable shredder byproduct (which can be as much as 25-35% of the raw MSW stream) usually goes to landfill. This major sidestream detracts significantly from the assertion that the conversion technology involved is a "Zero Waste" (no landfilling) alternative even though the core, conversion technology stage itself may, indeed, have no net residuals to be shipped to a landfill.

b. Recyclable Metals

MSW includes numerous components that cannot be gasified. These elements and compounds thus leave any processing system in solid form. For technologies that vitrify inorganic residues, the vitrified material includes some of the metal content of the MSW which appears as pellets (much in the 2-5 mm diameter range). A fraction of the metals may correspond to "items of commerce" such as ferrous iron, aluminum, and various other metals and alloys such as copper, brass, stainless steels and so forth.

c. Vitrified Ash

Some of the conversion technologies include zones where temperatures are high enough to melt residual solids to glassy, non-leaching materials. With minimal grinding and grading, these residues can and have been used as clean fill or as aggregate for building blocks, asphalt or road base.

d. Ash and Char Solids

Some conversion technologies (and conventional incineration) produce residue streams that are a mix of inorganic solids, glass, metals and some unburned char. After ferrous metal removal, some or all of these residues have been used as landfill cover, asphalt aggregate ('Glassphalt') or road base. Often, however, these materials are simply landfilled.

e. Wastewater Streams

The final class of side streams includes the process-specific aqueous streams; some of which require treatment before sewer discharge. For example, scrubber blowdown may require specialized wastewater treatment (more like industrial wastewater treatment than plants for domestic wastewater); one or more stages of precipitation; pH adjustment; and concentration or other chemical, thermal or biological steps that, ultimately, may result in a benign residue suitable for the sewer or appropriately permitted landfill. Note that there may be significant heavy metal content in the sludge generated in these treatment processes that may limit or place special requirements on sludge disposal options.

f. Other Solid Streams

Some of the conversion technology firms offer additional by-product recovery steps such as the sulfur recovery from H₂S removal, recovery of metal (esp. zinc) salts from the scrubber water treatment, metal pellets from slagged residues etc. In principle, these sidestreams may find a market that either defrays or exceeds their recovery cost. In any event, selling or otherwise disposing of these streams without landfilling is viewed by the environmental community as a net benefit.

C. Conversion Technology Examples

A number of technologies are described in the sections below to characterize various heating strategies for waste gasification. Unlike the somewhat generic mass burn technology patterns described in Part 1 of this course pair, each of the conversion technologies are significantly different (or are claimed to be) from one another and they are offered by developer firms who assign their name to the process. Within each heating classification, the specific technology presented is not represented to be the best available or possible for that classification but to be a reasonable, illustrative example of the features of that type of system and one for which a good process description and some data were available.

In preparing the manuscript for this course, it was your author's objective to provide examples of several heating concepts. However, presenting design details, operating data (where available) etc. to give an engineer wishing to evaluate alternatives an understanding of the fine points of process concepts and a quantitative basis for comparisons is far beyond the scope of this course. For these details, the interested student is directed to recent handbooks/texts [1].

In general, the processes have been operated for relatively long periods of time at a scale one might characterize as "commercial" although this often does not equate to the 20-year history of 1,000 to 3,000 tpd scale for, say, mass burn incineration facilities. However, the goal was to limit the presentation to concepts that were definitely beyond the small, laboratory scale of development operated for hours rather than months.

Because of the strong interest in these technologies by communities throughout the world, a number of developers simply string together a series of process steps, declare the result as "their process," and enter the waste management marketplace. I, however, have limited the processes presented to those where a reasonable level of demonstration (not necessarily fully successful as yet) and testing has been done. As discussed below, it is critical for the potential client of these technology

vendor firms to thoroughly analyze the developmental status of the offerings at the time of preparing a contract and to assure themselves through engineering analysis and careful drafting of the language of the Service Agreement that they are fully protected against being caught up in the delight of some exciting feature of a new process and not devastated by the mundane but critical requirement that the process works well, at design capacity, cost effectively, and with environmental soundness on a “24/7 basis.”

Perhaps no evaluation criterion is more important in assessing these process concepts than is the “state of technology” since it directly explores the fundamental issue of risk. The dimensions of “state of technology” include the throughput, waste type, operational duration and reliability, and the completeness of the prior test history.

- *Throughput* is important because of the complexity of thermal processes, compounded by the variable chemistry, heat and moisture content and physical form of waste materials. This complexity makes the scale-up of processes from “bench” to “pilot” to commercial scale inherently risky. The larger the “step”, the greater the likelihood that difficulties and problems will arise that will impede development.
- *Waste type* is important since wastes are different; chemically, physically and thermally. Thus, achievement with one waste does not guarantee success with another. Nowhere is the impact of variability more important than in material handling characteristics.
- *Duration* is important because of the long time-constant for thermal equilibrium in large systems and the grinding, slow degradation (corrosion, erosion, etc.) of materials over time. One needs operating hours to allow visibility of performance over the wide range of operational challenges presented by the processing of “real” waste streams. Designs that are frail because the developer did not provide for threats that “might” happen, may fail when, in fact, they do happen
- *Operational reliability* is a key requirement for 24/7 waste management systems. Knowledge of the operational reliability of a given system design can be guessed at by looking at the system’s component parts and/or reviewing the history of other developments. But for a new system, with new elements having dimensions, materials and process requirements that cannot be found in the historical record, such research is of uncertain value.
- *Comprehensive system experience* is critical. The developer must have experience with the full process flowsheet, not just the part that is interesting or even that viewed as especially problematic. Often there is not enough development time devoted for components and systems that were thought to be simple for the proposed waste to be processed, but were only tested with generic types of wastes that were not fully representative.

1. Pyrolysis

a. Hot Surface Heating (Pan American Resources Batch Process Technology)

A waste pyrolysis system was developed in the 1950’s by Pan American Resources (PAR), of Albuquerque, NM. Their pilot unit consisted of a sealed, externally heated, cylindrical stainless steel kiln retort revolving slowly around an inclined axis. 4 tons per day of refuse that had been preprocessed to remove large items, metals and inorganic matter, shredded and dried to under 10% moisture was admitted through an air-lock system and pyrolyzed at temperatures of 480°C to 815°C depending upon the refuse composition. 85 percent of the converter product gas was burned in a nearby boiler and 15 percent of the gas was used to heat the converter. A 40-50 tpd unit was operated at the Ford Motor Company plant in San Jose, CA starting in 1968. The U.S. Department of Energy conducted comprehensive engineering evaluation tests on a 50 tpd converter at the Marcal paper mill in New Jersey from 1982-1984.

b. Hot Surface Heating (International Environmental Solutions Continuous Feed Process Technology)

International Environmental Solutions Inc. (IES) of Romoland, CA is the developer of the Advanced Pyrolytic System © (APS) which indirectly applies heat to a retort chamber that processes shredded waste in an air/oxygen-free atmosphere. Through pyrolysis, the wastes are converted to gases and a mix of carbon char and residual inorganic matter. The solids are expelled for sale or to a landfill. In its present configuration, the gases from the retort are directed to a thermal oxidizer and burned. The hot exhaust from the thermal oxidizer is passed through a boiler.

IES received a permit to construct and operate a 41 metric tpd pilot demonstration plant in May of 2000. Construction of the pilot plant in Romoland, CA (Riverside, County) was spread over the next several years with start-up in the spring of 2004. A 115 Ton/day, “standard module,” commercial-scale furnace system is under construction for start-up in 2009.

- Process Description** IES technology processes post-MRF, minus 5-cm waste that is both concentrated and dry through an air-lock seal into the gasification chamber: an insulated, refractory-lined cylindrical outer housing coaxially surrounding a three-arch, triangular retort. The two bottom arches include auger screw assemblies that rotate inside the horizontal retort chambers to mix, enhance heat transfer and translate the waste and residual matter through the retort as pyrolysis occurs. The retort chambers are externally heated with a natural gas or synthesis gas flame at temperatures from 760 to 980°C where the waste pyrolyzes. The gasification retort is shown in Fig. 2.

The pyrolysis gas burns at a flame temperature of about 1100°C in an insulated, horizontal, two-stage, cylindrical thermal oxidizer. The first stage of the oxidizer runs with less than stoichiometric air, while the second stage runs with excess air. This staged process minimizes flame impingement in the thermal reactor. The fully burned gases are drawn through a waste heat boiler. The IES pollution potential is not unlike that for mass burn incineration and will include heavy metals, dioxins, sulfur dioxide, NO_x and HCl. Control systems include a bag house with carbon addition followed by a wet scrubber of corrosive resistant alloy with sodium bicarbonate. NO_x is reduced using urea-based SNCR technology.

- Romoland Semi-works Plant** IES's current operating experience is limited to the 41 TPD Romoland facility. The Romoland facility has operated about four years (in a development mode) with a variety of waste feeds including MSW. Plant operational experience through late 2008 included a two week long, continuous operation.

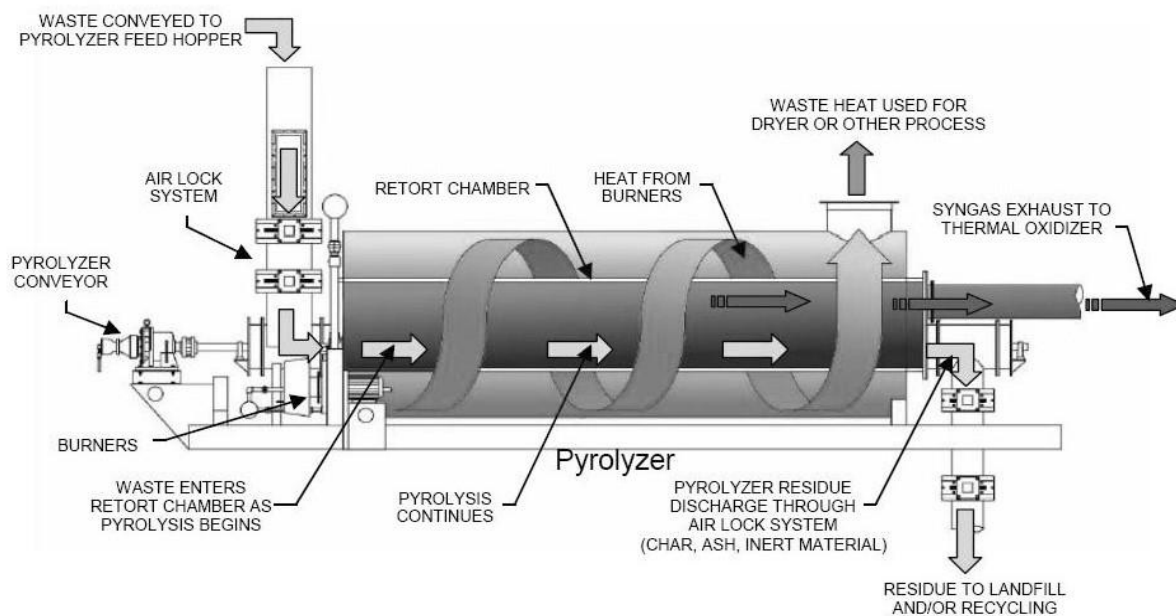


Fig. 2 Advanced Pyrolytic System © (Courtesy IES Inc.)

c. Hot Gas (Steam) Heating (SilvaGas Technology)

The by SilvaGas Corporation (Atlanta, GA) MSW gasification technology was originally developed by Battelle Columbus Laboratory in 1977 as the Battelle High Throughput Gasification System (BHTGS). SilvaGas directly heats a prepared RDF in twin circulating fluidized beds (CFB) as shown in Fig. 3. Detailed process development activities in the mid-1980s demonstrated the technical feasibility of the gasification process in 15 and 25 cm diameter gasifiers at rates from 0.22 to 9.1 tons/day of dry RDF. A wide range of feed materials, including RDF, were tested in the system. The first commercial-scale embodiment of the SilvaGas process was as a 200 tpd wood chip processing system at the 25 MW McNeil power station in Burlington, VT.

- RDF Preparation – Waste is processed using horizontal shaft hammermills, air separators and similar conventional RDF processing equipment such that 95% by weight passes through a 5-cm-square mesh screen. Interim storage of the RDF is provided by a live bottom bin or similar device (“1” in Figure 3) to act as an accumulator and to continually recirculate the RDF to avoid felting entanglements that often result in an irregular feed rate.

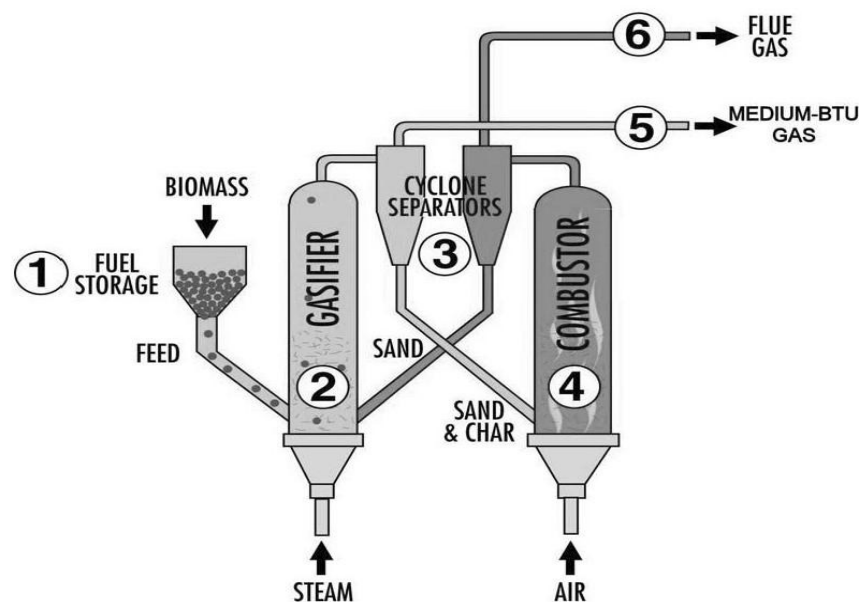


Fig. 3 SilvaGas Twin CFB Reactor MSW Conversion System

- SilvaGas Reactor – On entering the first CFB (“2” in Fig. 3), the RDF first dries and then is rapidly heated to facilitate reactions between the steam fluidizing medium and the organic material in the RDF to form the product fuel gas (“5” in Fig. 3). Heat for the endothermic drying, heating and pyrolysis steps is supplied to the reactor by introducing sand that has been heated to 980°C which brings the gasifier working temperature to approximately 800°C. Fluidizing gases enter the gasifier at a level below the RDF feed entry port and an L-valve sand recycle entry.

The product gas and the sand and char from incompletely consumed RDF organic matter (typically, 20 percent of the feed material) exit at the top of the gasifier at 815°C and enter the gasifier cyclone separator system (“3” in Fig. 3). The primary cyclone separates the sand and char from the product gas. The product gas, with a small amount of sand, char and ash is then directed to the secondary cyclone separator to complete the gas cleaning by mechanical dust collection. The gaseous product of this bed is a medium heating value fuel gas containing 19 to 22.4 MJ/Nm³.

- The Char Combustor – The char from the reactor is passed to a second, bubbling, air-fluidized bed with a refractory lining (“4” in Fig. 3); operating at 975°C. Cool sand from the gasifier bed cyclone enters the combustor

bed through a closed chute line. Exhaust gases from the combustor pass through a cyclone separator, which discharges the fine separated particles directly back into the reactor bed.

- Boiler – Waste heat in the flue gas from the char combustor can be used to (1) preheat incoming air to 400 °C and (2) dry the incoming feed to increase product yield and overall energy efficiency by recycling low grade waste heat to meet process requirements.
- Experience at McNeil Power Station – Commercial scale demonstration of the SilvaGas process was operated in 1997 at the 50 megawatt Burlington Electric Company McNeil Generating Station in Burlington, VT. The unit was operated for approximately 2,000 hours using wood chips at 182-Mg/day (200-t/d). The product gas was burned in the existing boilers. Gases from both fluid beds were used directly in an existing gas-fired utility boiler. Table 1 illustrates the composition of the product gas at McNeil compared with the gasifier gas composition during the Battelle pilot testing program.

Table 1 Comparison of McNeil Gasifier Gas to Battelle Pilot Data [2]

Component	Battelle Volume % Data	McNeil Volume % Data
H ₂	17.5	22.0
CO	50.0	44.4
CO ₂	9.4	12.2
CH ₄	15.5	15.6
C ₂ H ₄	6.0	5.1
C ₂ H ₆	1.1	0.7
HHV		
MJ/Nm ³	18.5	17.3
Btu/scf	499	468

Exploration of the relationship between feed moisture content and the product gas characteristics showed that gas quality (HHV) was unaffected by fuel moisture. The gasifier supplied additional heat to evaporate the moisture, reducing the product gas volume and the process efficiency but the HHV parameter could be sensed and the process adjusted rapidly enough to increase the incoming biomass feed rate to compensate. The feed waste should be pre-dried to maximize process efficiency (ideally with low-end, waste heat). Data showed no change in the product gas HHV as the incoming biomass moisture content ranged from 10 percent to more than 50 percent.

The McNeil tests confirmed the gas production rate expressed as CC (the carbon conversion expressed as the percent of the carbon found in the product gas relative to the carbon in the incoming feed) as a function of the gasifier temperature (T_g °C). Over the temperature range from 650 – 760°C the correlation is shown in Eqn. 1 which closely tracks the Battelle CC results.

$$CC = 0.153T_g - 63.28 \quad (1)$$

d. Hot Gas (Alter NRG Non-Transferred Arc Plasma Technology)

In the Alter NRG concept, the waste is pre-processed (if necessary) and fed to a chamber where it is rapidly heated with energy from a non-transferred arc (NTA) plasma torch. The gasification chamber holds the reaction mass until equilibrium is achieved, and discharges the product gas to downstream process steps for cooling, pollutant removal etc. The concept has been tested in the processing of MSW and biosolids.

Early work on plasma applications was conducted by Westinghouse Electric Corporation at a pilot plant in Madison, PA. In the early 1990's, Westinghouse (and, later, Westinghouse Plasma Corporation) joined with Hitachi Metals Ltd. to develop MSW and biosolids applications in a demonstration facility in Yoshi, Japan to produce detailed operational and design information for projection to full scale furnaces. A furnace embodying the PGVR concept is shown in Fig. 4.

- Process Description – The Alter NRG plasma treatment system includes a waste preparation and feed system, the gasification chamber, a molten residue removal and handling system, off-gas cleanup and handling systems, and operational controls and monitors. These supporting components, though similar to counterparts in conventional combustion systems, often have a number of special requirements or unusual features that relate to

the coupling of the component to an extremely high temperature system handling materials that may present a significant health risk. The elements noted do not include the components involved in the utilization of the product gas: boilers and, possibly, a turbogenerator, a fermenter etc.

- Waste feed systems – The Alter NRG system requires less feed subdivision than many other gasification technologies: subdivision to no less than 30 cm is necessary for larger furnaces. A rule of thumb suggests that the maximum waste element should be no greater than 1/3 of the gasifier feed pipe minimum inside dimension to eliminate the potential for jamming.

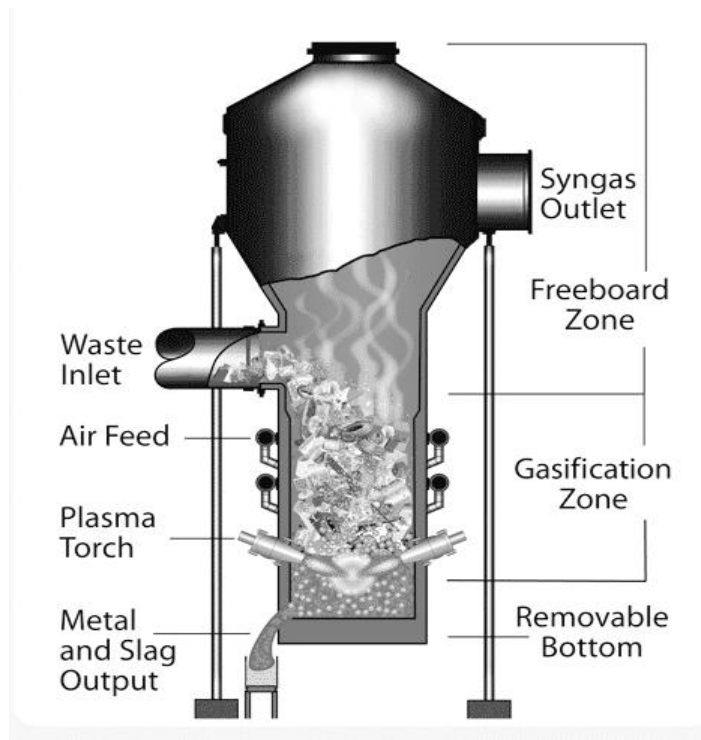


Fig. 4 Alter NRG Furnace (Courtesy Alter NRG Inc.)

- The gasifier chamber – The chamber is operated slightly sub-atmospheric. The diameter for commercial facilities range from 1 to 4.6 m and the volume above the bed of pyrolyzing waste provides about a 30 second residence time for the gas. The torches, located near the bottom on the periphery of the chamber, are rated for 1,200 hours of continuous duty and can be replaced without shutting down the unit. The water-cooled torches typically use air as the plasma gas.

The plasma-heated gas stream from the torches is directed at a bed of foundry coke (comprising about 4% of the total mass input) fed with the waste. The coke supports the waste as it vitrifies and pyrolyzes and provides a porous surface through which the molten inorganic fraction of the feed can drain to a discharge point. Superheated combustion products from the coke, rising up through the coke bed, gasify the incoming waste feedstock. Also, limestone or sandstone, in quantities up to 10% by volume of the feed depending on the ash chemistry, may be comingled with the waste feed as fluxes to modify the melting point of the mix of inorganic residues.

- Injected Gases – Oxygen and/or oxygen-enriched air is injected into the middle of the coke bed through the primary tuyérs. Atmospheric air can also be used as the oxidant but the diluent nitrogen decreases the heat content of the product gas and reduces the flame temperature. The oxidant gas increases the heat release within the coke bed and transfers heat to the pyrolyzing mass to bring temperatures in the middle of the coke bed zone over 3,000°C. Oxygen and/or air are also added above the coke bed. The ultimate gas temperature leaving the top of the bed is about 1650°C counter-current to the incoming feed to dry and begin the (endothermic) pyrolysis reactions so that the final product gas temperature is between 900 and 1,000°C.

- Residue – Inorganic components of the feed waste, the coke and the fluxing agent are fused within the coke bed and percolate down through the bed to a slag pool and slag tap in the bottom of the gasifier chamber. The molten slag is subjected to a water spray and falls into a quench tank where it is withdrawn using a drag chain conveyor. The resulting vitrified residue shows very limited leaching and has found use in Japan as an aggregate or “clean fill” material.
- Commercial Plants – Two plants were built in Japan: the Utashinai plant and the Mihama-Mikata plant. Two, 70 tpd gasification plants for a mixed hazardous waste feed are under construction in Pune and Nagpur, India. The Utashinai plant was started up in 2002 has a total plant rated capacity of 220 tpd of municipal waste. The facility has demonstrated a 95% availability factor. The results of air emission tests showed full compliance with federal regulations.

The Mihama-Mikata plant was started up in 2002 to burn a mix of shear-shredded MSW (17.2 tpd) and dried biosolids (4.8 tpd). As at Utashinai, all of the system output gas is burned in an adjacent boiler but, in this case, for hot water generation. Because of its negligible leaching characteristics, the glassy residue from this plant is presently sold for use as an aggregate. In both of the existing Japanese plants, air pollution control is applied after the synthesis gas has been burned fully. Thus the benefits of gas cleaning of the smaller, undiluted (with nitrogen and excess combustion air) flue gases are not realized.

e. Transferred Arc Plasma Heating (InEnTec LLC Plasma Enhanced Melter ‘PEM’ Technology)

- Process Description – InEnTec LLC (previously Integrated Environmental Technologies LLC) Plasma Enhanced Melter (PEM) technology involves a transferred DC arc plasma between graphite electrodes entering near the center at the top of the process chamber and a two-layer molten pool of inorganic waste constituents. The top layer is a glass composed of complex silicates and inorganic oxides. The lower layer is a mix of metals. Additional energy is introduced to the hot zone by equally-spaced, AC, joule-heating electrodes mounted at the perimeter of the chamber and submerged in the glassy melt. The AC electrodes are protected by Inconel alloy sheaths. The voltage across the joule-heating electrodes flows current through the glass which acts as an electrical resistor to directly heat the bath. The electrical path for the AC electrodes can be modified to flow (in part) to the floor of the melt tank to increase the metal temperature to facilitate pouring material through the metal drain. A schematic of the PEM process chamber is shown in Fig. 5.

PEM technology heats auger fed RDF from a hopper in a water-jacketed, refractory-lined chamber at temperatures near 1,400°C. The waste enters the process chamber at the top and falls to the molten pool through the DC arc and countercurrent to the flow of vapors rising from waste pyrolysis. The resistance of the molten glass determines the corresponding potential and the power added. Refractories used in the chamber include high refractoriness materials for the inner lining backed with insulating firebrick at the wall.

Fluxing agents (limestone or sandstone) are added with the waste to control residue melting. Steam is added to the process chamber plenum just above the melt pool to facilitate gasification of char residues via the water gas reaction. A small nitrogen flow is maintained for cooling. The chamber is run under draft. The glassy residues are drawn off from the process chamber through a side drain at temperatures from 1,200 to 1,400°C. Metals are discharged through a bottom drain.

- Gas Cleaning – Synthesis gas cleaning begins with water sprays to reduce temperature followed by a bag house. Particulate carry-over is very low. Following the bag house, additional water sprays bring the gas temperature to the dew point after which a wet packed tower is used to scavenge remaining particulate and remove acid gases. Carbon filters are used for mercury control.
- Commercial Plants – Long-term and successful commercial tests demonstrating both acceptable solid residues and acceptable effluent controls have been conducted when processing radioactive wastes, PCB-containing wastes and asbestos. Commercial operations are on-going; A facility processing medical and industrial wastes with generation of electricity using the synthesis gas has operated in Taiwan since 2005. A 22.7 tpd industrial and hazardous waste processing system for chlorinated organic residuals is now under

construction for use under a 10-year contract with Dow Chemical Corporation at their Midland, MI works [710] to form 12.4 metric tons/day of HCl and 11,600 MJ/hr of clean synthesis gas.

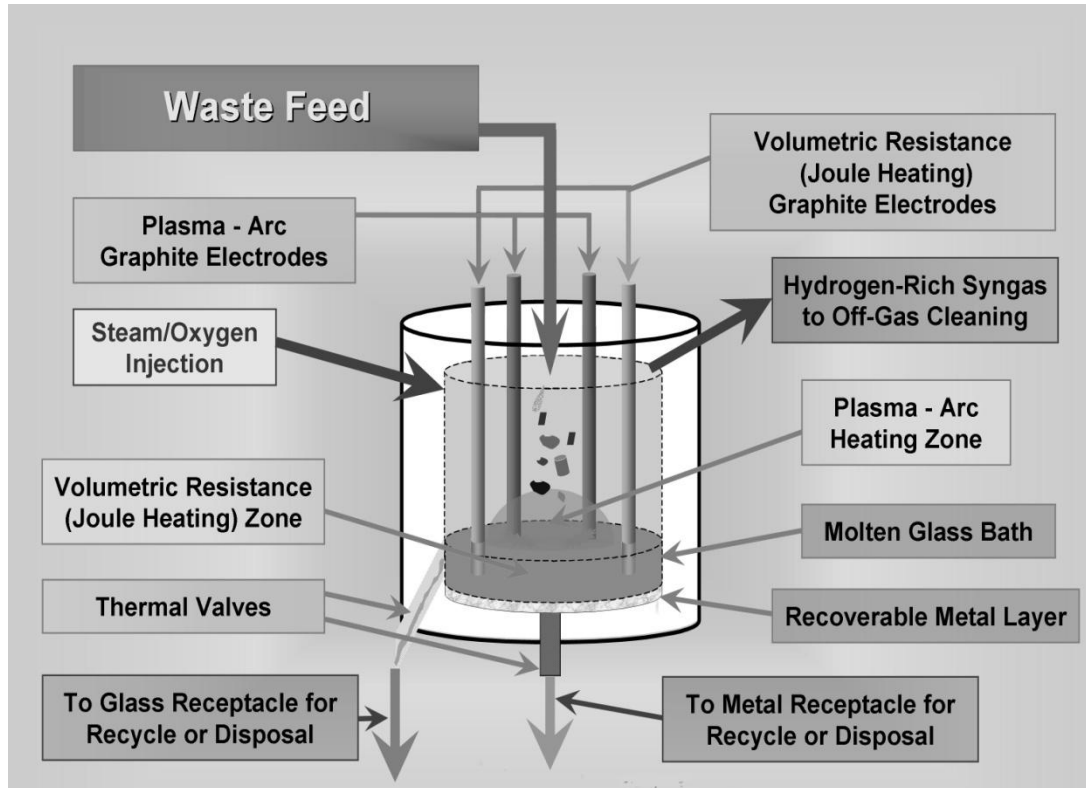


Fig. 5 Transferred Arc Plasma Heating (Courtesy InEnTec LLC)

2. Partial Combustion

This class of pyrolysis systems involves combustion of a fraction of the organic material in a waste to release sufficient heat to pyrolyze the remainder. Pure oxygen, oxygen-enriched air or air alone are oxidizer options. The process concept can then involve clean-up of the product gas to produce a high quality (though more dilute) synthesis gas for use in clean-gas energy conversion (gas engines or gas turbines) or chemical manufacture. Alternatively, the process concept can involve immediate addition of additional air to the gasifier output to complete the oxidation to CO_2 and water vapor.

The latter technology is very much like a refuse derived fuel (RDF) or mass burn system where the pyrolyzer function is similar to the burning bed (acting as a gasifier) and the downstream oxidizer parallels the overfire combustion space (effecting burn-out of CO , H_2 , char carry-over and "tars"). The final process stage is a boiler most likely of the compact, "waste heat recovery" type rather than the large, staged radiant section followed by screen tubes and a convection section, superheater and economizer that are characteristic of a conventional mass burn furnace system. This parallelism extends further since such immediate burn systems exhibit a pollution potential is not unlike that for mass burn include control concepts for heavy metals, dioxins, SO_2 , NO_x and HCl.

One notes that the gasifier outlet gas has high energy content. This gas must and/or will be substantially cooled if the gas is to be cleaned using dry scrubbing/carbon and a temperature sensitive bag house or wet scrubbing. Some technologies insert a boiler between the gasifier outlet and any downstream stages (air pollution control or chemical processes) to maximize the recovery of useful gas enthalpy. Others simply use water sprays that, while cooling the gases very effectively and at low cost, provide no energy recovery.

a. Air Oxidized Conventional Fluidized Bed (TPS Termiska AB Technology)

TPS Termiska Processor (Thermal Processes) or TPS, a company located near Nyköping, Sweden, works in energy and environmental process research and technology development. Their TPS Termiska AB gasification technology is comprised of a bubbling fluid bed operating under sub-stoichiometric conditions into which RDF or RDF pellets are fed. Addition of secondary air partway up the furnace transforms the bed aerodynamic balance such that smaller, lighter particles are blown from the bed: a circulating bed. Heavy, still-burning "chunks" remain in the dense bubbling fluid bed until they are consumed or substantially reduced. Ground dolomitic lime is added in a second, tar cracker bed to catalyze the breakdown of high molecular weight hydrocarbons into lighter products. The product gas may be cleaned to generate a fuel gas suitable for use in a gas engine or turbine or can be burned directly in a boiler or process furnace. The flowsheet is shown in Fig. 6.

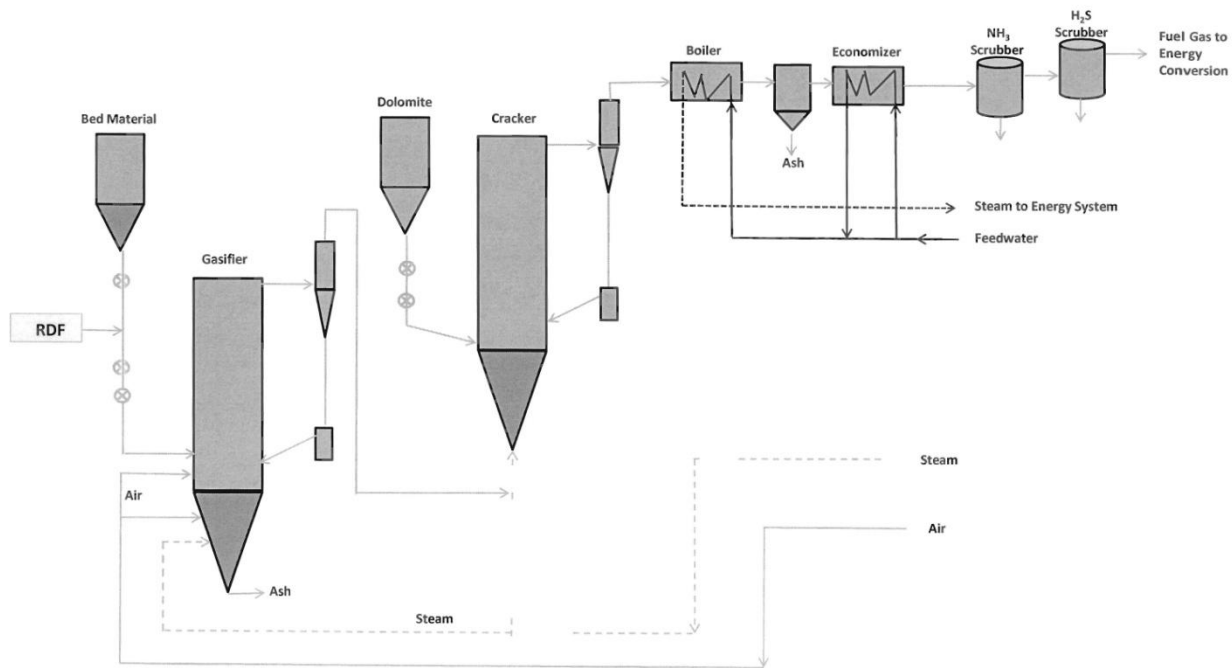


Fig. 6. TPS Termiska Dual Circulating Fluidized Bed Gasifier

In 1992, Ansaldo Aerimpianti SpA of Italy installed a commercial, two-bed unit in Grève-in-Chianti Italy. The Grève units have a combined heat release capacity of 25.8×10^6 kcal/hr when burning 100 percent pelletized RDF fuel. The beds have also processed biomass (coarsely shredded wood or agricultural wastes). Fuel gas generated at the plant is either burned in a boiler to generate electricity or used as a fuel in an adjacent lime kiln operation.

- **Process Description** – In the TSP feed bed, the RDF feed rate is set such that the air rate is lower than the theoretical oxygen quantity needed for full oxidation of the feed material. Under these conditions, the product gas and solids leaving the bed contain unreleased fuel value. The heating value of the gases, the bed temperature, and the yield of char increases as the air setting decreases relative to the theoretical oxygen demand. This is the gasification mode of operation.

As the temperature of a fluidized bed increases, the system approaches a state of bed defluidization: the bed temperature approaches the fusion point and the sand becomes sticky. Operation in the gasification mode has the advantage that the operating temperature for satisfactory gasification is considerably below that where RDF ash fusion is likely. Under these conditions (750 to 900°C), most organic refuse components and biomass materials (e.g., wood) break down into volatile components. The remainder is found as a solid char. The cyclone device in the leaving gas captures and returns the solids such that an acceptable level of carbon burnout is achieved. The feasibility of the CFB as a gasifier is greatly enhanced by the large fraction of the organic material present as

“volatile matter”. This quality of the RDF is reported by the proximate analysis and reflects the fraction of the waste which is distilled off upon heating.

The volatilized organic matter can appear in the off-gas in various forms. For convenience, one can categorize them as basic synthesis gas (carbon monoxide and hydrogen), low to medium molecular weight hydrocarbons (say, those with boiling points at or below 100 °C) and high molecular weight hydrocarbons sometimes called tar. The combination of heating values of these gases and tarry compounds constitutes the fuel value of the resulting gas. Another potentially useful energy form found in the CFB off-gas is the sensible heat (enthalpy) associated with gas temperature.

The tarry material in the off-gas from a gasifier normally presents a problem. If the gas is cooled and scrubbed of the tars using a water scrubber, both the enthalpy of the gases and the fuel value of the tars is substantially lost. Further, the water-borne tars present a difficult wastewater treatment challenge and cost. If a boiler is installed between the CFB and the scrubber, the sensible heat will be captured for a time but the tars may condense on the tubes, fouling the heat transfer surface. If the off-gas is burned without removing the tars, it is often found that combustion of the tarry compounds is less complete than that of the lower molecular weight hydrocarbons and synthesis gas components. This may lead to soot formation. Once soot has formed, relatively severe combustion conditions (temperature and residence time) may be required for adequate burn-out. The tars are quite odorous and may be carcinogenic.

Therefore, TSP added a second CFB fed with crushed dolomite (a mixed calcium and magnesium carbonate) which acts as a catalyst at about 900 °C to crack most of the tars to lower molecular weight hydrocarbons. Only an unimportant portion of the heating value of the tarry organic compounds is lost in the processes. In catalyzing the cracking reactions, the alkaline dolomite also scavenges the flue gases for acid gases such as hydrochloric acid (HCl) and sulfur oxides (SO₂ and SO₃). At elevated temperatures, HCl absorption is limited. The net product gas can be sent through a boiler for recovery of sensible heat and clean, relatively soot-free combustion.

- **RDF Preparation** – RDF is produced through horizontal shaft hammermill or shear shredder primary shredding; secondary hammermill shredding; magnetic separation; air classification; and disc screening of the fines for removal of glass and grit. Grève and the TPS pilot plant used pelletized RDF in their initial operation to reduce hauling expense because of the remoteness of Grève relative to the waste source. If pelletization is found to be a process requirement, that would add a costly and problematical processing step. TPS believes that the RDF pellets degrade to a “fluff state” through mechanical abuse in the handling system. It is common to incorporate some kind of intermediate RDF storage as a buffer between RDF preparation and the combustion facility. At the Grève facility, four, 80 ton steel silos were used.

The Pelletized RDF feed specifications for the Grève system are:

Diameter:	0-15 mm	Moisture (typical)	6.5 percent
Length	50-150 mm	Volatile Matter	71.1 percent
Bulk Density	500-700 kg/m ³	Fixed Carbon	11.4 percent
Net Calorific Value	4,104 cal/kg	Sulfur	0.5 percent
Total non-combustibles	11.0 percent	Chlorine	0.4 - 0.6 percent

- **RDF Reclaiming and Feeding** – RDF is reclaimed from storage silos, moved to a small feed hopper and then fed to the gasifier. The Grève plant uses twin-screw reclaimers that “dig” the waste from the silos and deposit it into a bucket conveyor. The RDF is moved by a screw conveyor that runs the length of the building, discharging into the feed hopper. RDF fuel is augered from the hopper with a twin-screw reclaimer, passed through a rotary valve, and chuted into the gasifier.

- **Fluid Bed Gasifier** – The heart of the TPS process is the fluid bed gasifier: a cylindrical, bubbling bed system, operating at about atmospheric pressure at the top of the bed. Feed is distributed across the lower “dense bed” and begins to volatilize. The temperature in this zone is approximately 700-800 °C. Residence time in the dense bed (for larger particles) can be quite long. As the particles are reduced, they are lifted up and out of the dense, bubbling bed zone. Steam can be added to the dense bed if required to facilitate gasification of carbon in wastes with high fixed carbon content.

Above the dense bed zone, secondary air is injected. The combination of heat release (temperature increase with density reduction) and greater mass flow increases the upward gas velocity and facilitates carbon oxidation. The temperature increases to about 850-900°C in the upper reaches of the bubbling bed zone described by TPS as the "fast bed". In beds firing fuels with limited moisture content, it is necessary to add steam to the fluidizing gas flow. Water acts as an oxidizer to gasify carbon to CO and hydrogen.

The gases leaving the bed pass through a duct incorporating hanging U-beam particulate interception. The gas then passes to a large diameter, refractory-lined cyclone where additional particulate recovery occurs. The solid streams from the U-beam and cyclone hoppers accumulate in a vertical pipe where they form an air seal or plug. At the very bottom of the accumulation pipe, a small amount of nitrogen is introduced to fluidize the lower mass of solids. Then, by gravity, the fluidized solids flow from the pipe and are reintroduced into the dense-phase, bubbling fluidized bed. Oxygen-free gas is used as the fluidizing medium to avoid the high temperatures that would obtain if air (with oxygen) was used to move the still-hot, ignitable char solids.

For industrial combustors that already incorporate air pollution control systems (e.g., rotary cement or light weight aggregate kilns or process furnaces), the gasification reactor's product gas can be used directly as a medium heat content fuel gas. An air pollution control train may be required to remove HCl, HF, SO₂, Hg and other heavy metals, particulate etc. depending on the chemistry of the RDF and regulatory requirements. Alternatively, the fluid bed off-gas can be cleaned before being burned to the degree required for combustion in a gas engine or gas turbine for the direct generation of electricity. Without the dolomite cracker circulating bed and associated cyclone appended to the gasifier, this would result in the loss of the sensible heat of the fuel gas. With the cracker, almost all of the tar is converted into lower molecular weight compounds and a small amount of benzene, toluene, and naphthalene. Nitrogen-containing compounds and hydrogen cyanide either decompose into nitrogen gas or ammonia. Carbon-containing dust is gasified by the residual oxidizing gases (e.g., H₂O and CO₂) at the higher temperatures of the cracker bed. Following the cracker, a heat recovery boiler surface brings the temperature down to about 200°C where a fabric filter system removes particulate matter. The particulate consists mainly of calcined dolomite and fine soot and is of a non-abrasive nature. At this point, the gas is suitable for use in many fuel-sensitive combustors.

b. Air Oxidized Internally Circulating Fluidized Bed (Ebara Ltd. TwinRec Technology)

Over 32 plants in Japan make use of a fluidized bed process that, in a sense, is half-way between grate systems and circulating fluidized beds: the "Turning Stream Bed Incinerator type Fluidized" (TIF) furnace. The TIF furnace burns waste in a refractory-lined chamber without fine pre-shredding. Only rough tearing in a twin screw feed mechanism is applied. Large items (furniture, whole bicycles or mattresses etc.) require coarse shearing. The units have been operated with high-plastic (high heat content) waste, ordinary refuse, and 79% moisture content sewage sludge or night soil (with auxiliary firing). The characteristics of this process concept favor smaller units (say, 60 to 130 metric tons per day). Co-incineration of sludge and refuse is practiced in several facilities.

The TIF furnace is fed through the freeboard (left side, Fig.7). The feed falls into a vigorously moving bed with a constriction (the "deflector") which reduces the cross-sectional area of the furnace to about 40 percent of the distribution plate plan area. This leads to both vertical and lateral rotation of bed sand (0.4 to 0.8 mm diameter) and of burning refuse in the volume between the distribution plate and the plane of the constriction. The lateral motion is aided by a peaked conical shape to the distribution plate that directs noncombustible residues and some sand to water-cooled screw conveyor discharge points on the periphery. Bed temperatures are maintained between 600 and 700°C. The bed geometry promotes horizontal mixing; poor in conventional BFB designs. Further, the bed recirculation injects burning bed material above newly charged waste thus facilitating rapid drying and ignition and avoiding floating of light density material on top of the bed.

If the Ebara TIF bed is operated with less than stoichiometric air, the bed effluent is a synthesis gas with a substantial residual heating value. The primary furnace off-gas can then be burned in a second chamber both for the burn-out of organic compounds and the vitrification of inorganic carry-over. Since 2000, Ebara Ltd. has operated systems in this mode (their TwinRec process) in more than 10 large commercial installations: fluidized bed gasification in combination with ash melting in an associated cyclonic ash melting chamber as illustrated in Fig. 7.

- Process Description – The commercial TwinRec operating concept involves ash vitrification and material recycling in combination with energy recovery. The process has been demonstrated using a variety of waste materials to include automobile shredder residues, waste plastics, electronics waste and other industrial residues,

municipal solid waste and sewage sludge. The gasifier operates at 550 to 600°C at atmospheric pressure with internal bed circulation combined with external metals separation. About 30% of theoretical oxygen is supplied to the gasification stage. Metal in the waste can be recovered from the primary gasification chamber and recycled as it is neither burned, melted nor sintered in the first stage of the process. The fine ash, char and combustible gas is transferred to the second stage, the cyclonic combustion chamber, where additional air is added to release the fuel value to vitrify the ash to a stable glass granulate.

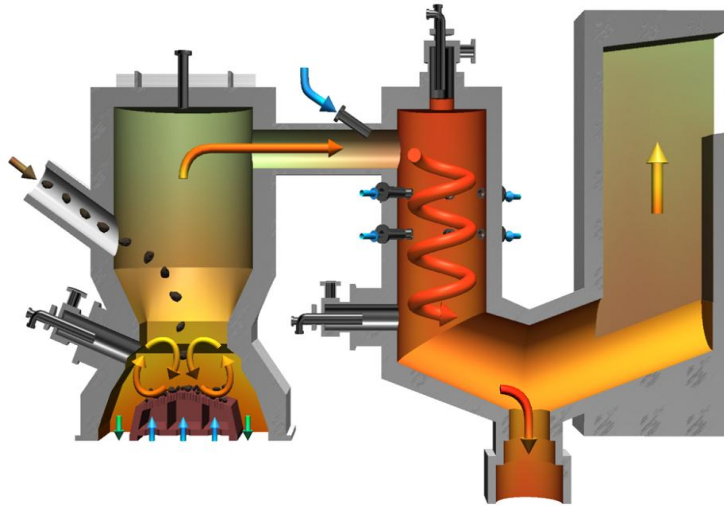


Fig. 7 TwinRec Technology (Copyright Ebara Corporation)

- **Cyclonic Melter** – Addition of secondary air to the fuel-rich gasifier effluent at the entrance to the cyclonic ash melting chamber brings the temperature to 1,350 - 1,450 °C. The melted, fine particles accumulate on the walls, where they are vitrified and drain slowly down through the furnace. The molten slag is discharged and quenched in a water bath to form a granulate with excellent leaching resistance.
- **Heat Recovery** – Both the gasifier and the ash melting furnace operate at near-atmospheric conditions, without consumption of fossil fuels (except for start-up) or purchased oxygen. Due to the overall low excess air ratio the steam boiler can be compact. In some plants, tertiary air is added ahead of the boiler. The overall air ratio is about 30% excess air at the entrance to the boiler except in the smaller plants where operation at 50 to 60% excess air may be necessary to assure good mixing.
- **Air Pollution Control** – A conventional train of air pollution control steps are installed for particulate, mercury, nitrogen oxides, and acid gases but may be smaller (less costly) than for conventional mass burn systems due to the low excess air level. The high combustion temperature in the melting chamber ensures dioxin emission regulations below 0.1 ng TEQ/Nm³ can be met.
- **Recycling and Recovery** – The process generates several product streams which allow useful recovery:
 - Mineral dust and metal oxide powder is vitrified into the glass granulate and recycled afterwards;
 - The zinc-rich bag house catch is recycled in the zinc industry;
 - Volatile metal salts are concentrated into the secondary fly ash and available for zinc, lead and copper recycling in the zinc industry;

- The energy efficiency of TwinRec is better than in thermal waste treatment processes which require oxygen and consume therefore a good part of the energy internally; and
- Ash melting furnace is integrated into the water steam cycle, making use of the highest temperature level for steam production.

- Experience at the Aomori plant – The Aomori plant in Japan, started up in February 2000 with a thermal capacity of 2 x 40 MW, corresponding to 2 x 60,000 t/d of shredder residue (SR) per year. The SR is delivered from 5 shredder plants (input to shredder: cars and brown/white goods) and from two, non-ferrous separation plants. All shredder residues meet the requirement of minus-30 cm top size and, therefore, are fed to the gasifier without further treatment. The plant also processes mechanically dewatered sewage sludge in amounts from 0% to 30% (by weight) of the SR amount. Other waste plastic materials and bone meal (in 1,000 ton quantities) are treated as available and a feeding system for boxed, hospital wastes was added.

Since the start-up of the Aomori plant with operating experience from 20, continuous service, commercial-scale process lines by 2008. A variety of wastes are treated in these facilities, including waste plastics, ASR, biological wastewater treatment sludge, industrial wastes, and municipal solid waste (MSW). The Kawaguchi plant in Japan, largest of the MSW installations, was started in 2002 to process 140 tpd of municipal solid waste in each of its three process lines. The plant has a total rated output of 63MW. Their smallest Ebara TwinRec unit size is 40 tpd (4 MW power output) and is fully scalable. The net power output for the smaller plant is 455 kwh/ton compared with 623 kwh/ton at Kawaguchi. The Kawaguchi plant can accept mixed MSW including bulky waste with screening and shredding to achieve the maximum particle size of 30 cm. Air pollution control includes a bag filter, wet scrubber and a catalytic catalyst reactor (fed with ammonia) for NOx control.

c. Air/Oxygen Oxidized Upflow Shaft Furnace Gasifier (Nippon Steel Engineering Co. Ltd. Technology)

- Process Description – Nippon Steel Engineering Co. Ltd. has developed their Direct Melting Furnace (DMF) concept for the processing of MSW: an oxygen-augmented, air-blown upflow gasifier that generates a synthesis gas product. The synthesis gas is subsequently burned in a cyclonic furnace with downstream heat recovery. The cyclonic chamber uses tangential air injection at several levels. Following the boiler, gas cleaning is performed prior to discharge through a stack. Air pollution control includes addition of an adsorption agent for acid gases and mercury followed by a bag house. Ammonia is used as the reductant in a selective catalyst reactor for NOx control.

- Gasifier – The gasifier furnace is fed a mixture of MSW, coke (as both an energy source and to support the waste on a porous bed) and limestone (as a flux for the vitrified residue). The charge moves countercurrent to the rising O₂/air stream as shown in Fig. 8. The residue is quenched to yield a non-leaching, sand-like residue mixed with metal granules. The glass frit has use as a fill or an aggregate and the metal can be recycled. In some of their plants, waste is reclaimed from a local landfill for processing with fresh MSW as a means to recover landfill volume.

The feed material does not require pre-treatment except for larger, bulky waste items. Waste drying, pyrolysis and residue melting occur sequentially as the load works its way down the gasifier shaft. Stay-time for waste in the gasifier shaft is from 3 to 5 hours. The long processing time levels out variations in furnace conditions and off-gas properties as the waste composition changes from time to time.

Since air pollution control is applied to the diluted flue gas stream after the boiler, there are no savings in air pollution control capital or operating cost. However, because of the ash melting feature, the residue quantity and volume are significantly reduced or, if a market can be found, eliminated. In Japan, this is a great process benefit.

- Commercial Plants – 20 DMF plants with MSW capacities from 88 to 500 metric tons per day have been constructed by Nippon Steel Engineering between 1979 and 2004.

d. Air Oxidized Hearth Gasifier (Consutech Systems, LLC Technology)

- Process Description – The Consutech modular combustion system furnace (see Modular, Starved Air systems in the Part 1 course) in its normal configuration, is operated with the primary furnace air-starved. Typically, the

primary air is introduced at about 25 to 30 percent of the stoichiometric air requirement. Additional air is added in the upper, secondary chamber and through the secondary chamber burner so that the overall system stoichiometry is typically at the 50 to 150 percent excess air level, as determined by waste heating value. However, the primary chamber can also be viewed as a robust, well-proven pyrolysis gasifier, operating in the partial combustion mode. In this scenario, the off-gas from the primary can be used as a chemical feedstock or in other applications where a CO/H₂ mixture is sought.

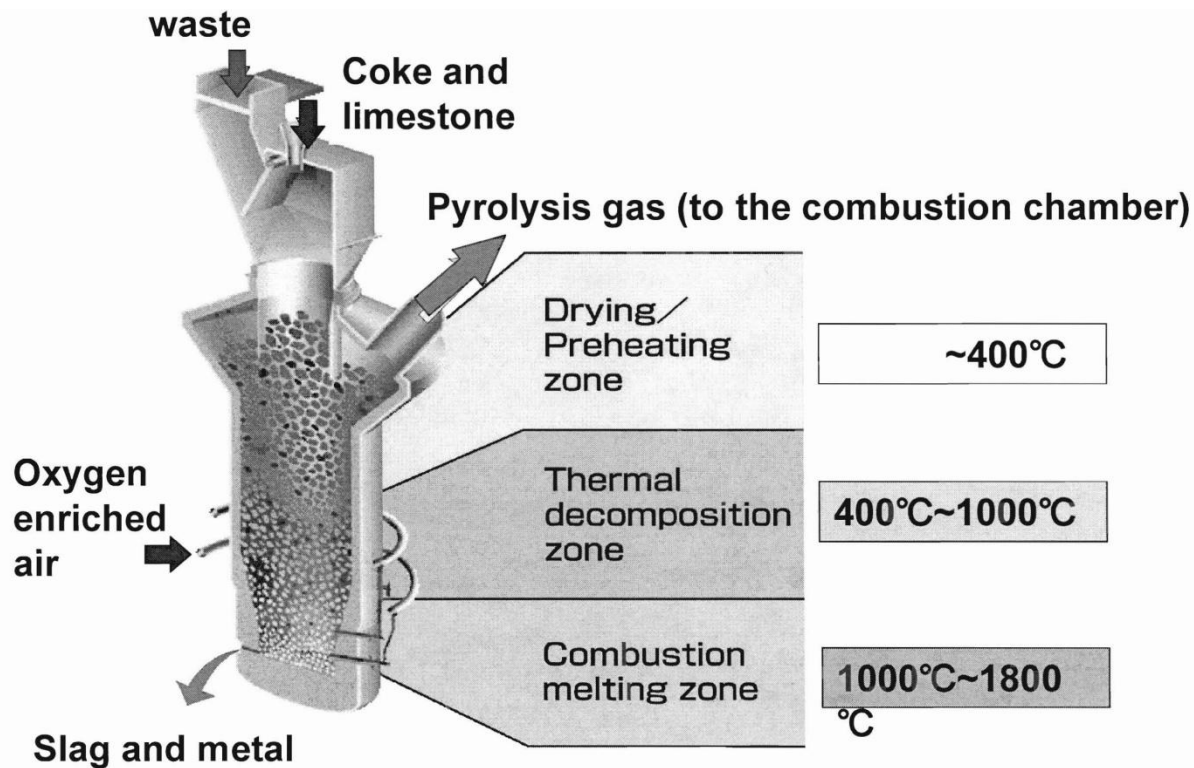


Fig. 8 Nippon Steel Engineering Co. DMF MSW Processing System [4]

- **Synthesis Gas Applications** – Consutech has provided a pilot-scale furnace to generate synthesis gas for a proprietary biological ethanol process. For this application, there is merit in using 100% oxygen or oxygen-enriched air as the oxidant to minimize the dilution of the syngas with atmospheric nitrogen. Such furnace configurations, followed by gas clean-up, are well adapted to generate a feed gas for commercial-scale synthesis. The gasifier configuration is similar to the conventional multi-hearth Consutech furnace designs which are capable of continuous operation with capacities up to 150 tons/day of un-processed solid wastes. Special consideration of insulating and refractory/fire brick materials is required for the higher temperatures generated in the secondary chamber during operation as a gasifier. The solid residue is periodically discharged into a water-sealed quench tank/conveyor. The gases generated in the primary chamber, when operating as a gasifier, are not completely oxidized in the secondary chamber as would be the case when operating in conventional, starved air applications. Instead, the gases are further processed in the secondary chamber by proprietary techniques, to further increase the syngas yield, before subsequent gas conditioning stages ahead of the biological fermentation reactor.

e. Air/Oxygen Oxidized Hearth Gasification (Thermoselect Technology)

Thermoselect SA is a privately held Swiss company created to commercialize the Thermoselect process, for which over 31 patents have been issued. Thermoselect processes commingled MSW and "selected" industrial waste and converts them into products: a cleaned fuel or synthesis gas, vitrified solid granules, elemental sulfur, and dry sodium salts. If the full system of recovery features is selected by a client, no liquid effluents are discharged into the environment. Process water is treated, distilled and totally recycled. The process is intended to minimize both the formation and emission of particulate matter, nitrogen oxides, and other pollutants. The Thermoselect Demonstration Plant was located at Fondotoce, Italy, near

Lago Maggiore in the southern foothills of the Alps. Their testing facility consisted of one process line with a nominal capacity of 4 tons per hour that was housed in a low-level building with two relatively short stacks.

- Process Description – Figure 9 shows a schematic of the Thermostelect gasification system. The various stages of this process are described in the following subsections.

COMPACTION. The raw waste is dropped by grapple from the waste pit into the housing of the compactor, in which the loose material can be pressed against a heavy metal gate. An industrial scrap metal hydraulic compactor is used to compress commingled waste to less than 10 percent of its original volume (to a density of about 1,250 kg/m³) thereby removing the air contained in the original loose material. As the thermal process calls for feed, the gate opens, and the compact tor moves the plug of waste though an unheated transition section into the degassing channel.

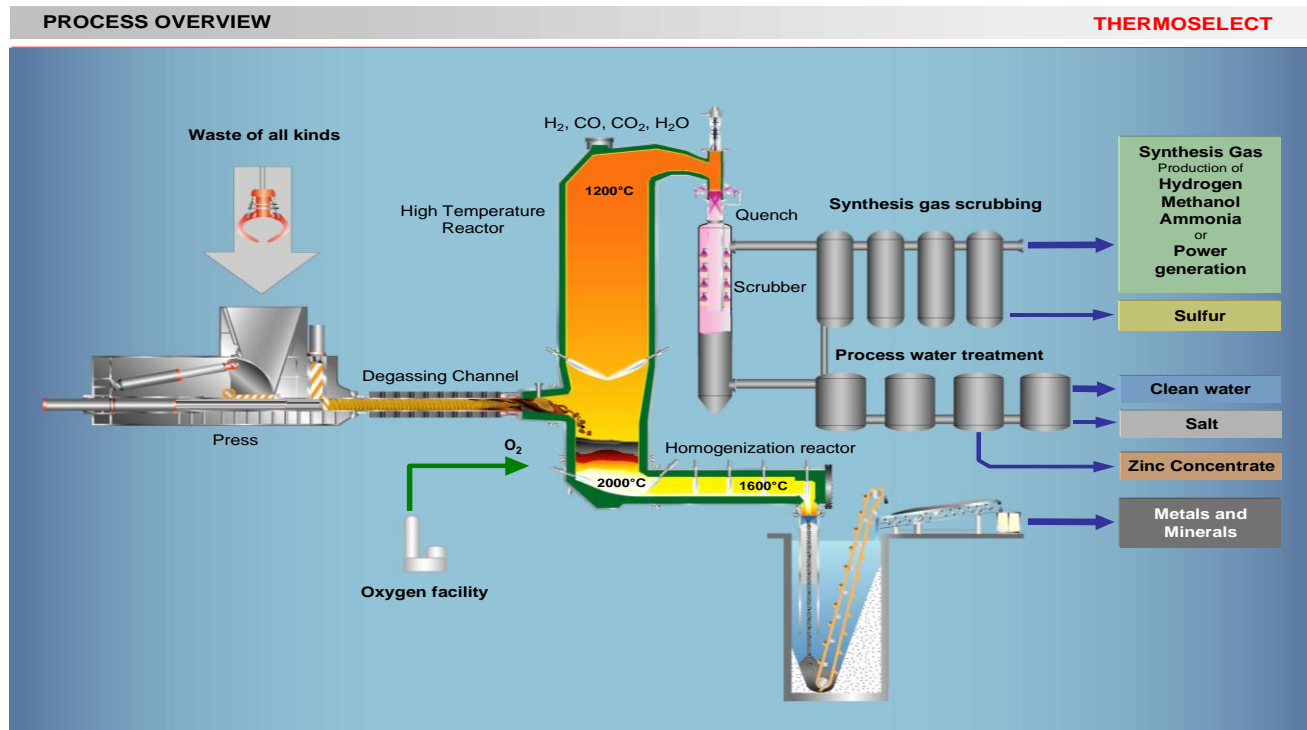
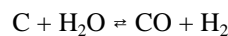


Figure 9 Thermostelect Processing System (Courtesy Thermostelect Ltd.)

DEGASSING AND PYROLYSIS. The degassing channel containing the extruded plug of compacted material is externally heated by the radiant heat flowing back from the next stage called the “high temperature chamber” (HTC). As the compacted waste plug heats, volatile components from the pyrolyzing waste vaporize. The heated vapors also include steam from the free water carried in with the solid waste. The temperature in this area is 800 °C. During the degassing stage, the conditions and ingredients of the water-gas reaction are present:



Hydrogen and carbon monoxide thus move with the vaporized organic matter from the degassing channel into the upper section of the HTC, which is maintained at 1200 °C.

At this point, the waste plug is much smaller because it has lost volatile components (water and organic matter). The nonvolatile organic portion has been carbonized to a high degree. The inorganic portion of the waste has remained virtually unaffected and is part of the carbon matrix. Upon reaching the transition point with the HTC, the carbon matrix breaks apart and falls into the lower section of the HTC. The travel time through the degassing channel is normally less than 2 hours.

HIGH TEMPERATURE GASIFICATION. The matrix of carbon and inorganic material fills the lower section of the HTC, where oxygen is introduced. The vigorous reaction of oxygen with the hot carbon produces a local temperature of

2000°C. This controlled exothermic temperature provides the heat necessary to melt the inorganic fraction; composed primarily of glass products and various metals that are contained in the carbon matrix. In effect, this lower section performs as a smelter. The inorganic molten mass of mineral and liquid metals flows from the lower HTC into the homogenization stage, where it is prepared for removal from the process.

In the lower section of the HTC, the equilibrium reaction $C + O_2 \rightarrow CO_2$ produces carbon dioxide (CO_2). By shifting the equilibrium in the presence of CO_2 (viz. $C + CO_2 \rightarrow 2 CO$), a high-volume percentage of the energy carrier (CO) is formed. Both these gases, the CO and a reduced volume of CO_2 , flow to the upper section of the HTC, and join the other gaseous products received from the degassing channel of the process.

In the upper chamber of the HTC, the addition of oxygen maintains the temperature at 1200°C. This upper chamber is the collection point for all of the process gases. The temperature provided in this section through a proprietary oxygen introduction technique, combined with a residence period approaching 4 seconds and turbulence, is adequate to destroy the most complex organic compounds. The resultant hot gas at 1200°C exits the HTC and is immediately water quenched in a spray chamber to below 70°C.

HOMOGENIZATION CHAMBER. The metal and mineral flow from the lower HTC and enter the homogenization chamber where additional oxygen is introduced to react with any remaining carbon particles in the mineral/metal melt flow. The overall oxygen consumption in both HTC and the homogenization chamber is approximately 514 kg/metric ton of waste charged. As the remaining carbon is depleted, additional heat is required to maintain the melt. Burners fired with natural gas or product gas provide this heat at the rate (for natural gas) of 23 kg/ton of waste or 31.15 m³/ton. The combined molten metal and mineral melt streams are quenched in a water bath. As the flow enters the water bath, the vitrified mineral stream cools rapidly to form a granulate. The metal mix freezes, forming metal alloy pellets. The resultant mix of granulate and metal pellets is recovered using a drag chain conveyor.

Thermoselect believes that the low leachability of the solids make the use of this glass-like mineral acceptable as a raw material component for clinker brick and other inorganic aggregate uses.

The redox processes occurring above 1800°C reduce the metal oxides and cause typical alloy-forming metals such as nickel, chromium, and copper to pass into an iron-rich metal melt. Since this melt has a very low concentration of high-vapor-pressure components (such as mercury, zinc, cadmium, lead, and arsenic) Thermoselect's exploration of potential markets indicates that it can be used directly for metallurgical purposes.

Because of the severe duty imposed on the refractory in the Homogenizer Section, the elbow between the Homogenizer and the HTC is flanged to both vessels and it is replaced about once every year. Thermoselect has stated that cooling and removal of the spent unit, positioning of the refreshed unit, and restart can be accomplished in about a week.

GAS COOLING AND SEPARATION FROM PROCESS WATER. The hot gases contained in the upper section of the HTC exit are rapidly water quenched to below 70°C. The reactor gases and sulfur-bearing gases (H_2S in the reducing environment of the furnace) are separated from the quench water and passed through successive scrubbers: an acid wash at ~60°C, specialized treatment for H_2S removal, and an alkaline wash at 40°C. They are then chilled to 5°C to remove water vapor and are passed through a wet ESP and warmed to ambient temperature before use.

The high-volume water quench of the hot process gases quickly lowers the temperature of the gases; the water serves as a sink for particulate matter including heavy metals, and water-soluble acid gases such as Cl_2 and F_2 which form HCl and HF respectively.

The sulfur-removal system converts hydrogen sulfide (H_2S) to sulfur using a ferric iron complex via a well-proven, proprietary process. The resultant ferrous iron complex, proportionately formed, is regenerated in an adjoining stage using oxygen from air and recycled. The sulfur is precipitated as the element.

PROCESS BY-PRODUCTS. The processing-water solutions generated from the gas-cleaning sections can be sewered. Alternatively, the process water can be subjected to conventional chemical material separation processes. In addition to the product gas, the following vitrified mineral product, and metal alloy pellets are produced: industrial-grade sodium chloride (salt), elemental sulfur, and a heavy metal hydroxide concentrate.

The metal and vitrified mineral granulates collected from the homogenization chamber can be density separated when in molten form, but they are more easily handled in granulate and metal-pellet form. These pellets can then be separated by a magnet into vitrified mineral product and metal alloy pellets. The metal pellets consist of iron alloy (>90%), with

considerable amounts of copper (3 to 5%), nickel (0.6%), chromium (0.3%), tin (0.4%), and phosphorus (0.1%). Concentrations of heavy metals that find their way into these by-products are generally at acceptable levels.

- Environmental Aspects – An extensive testing program was conducted between June and September 1994 by ten institutions from Germany, Switzerland, and Italy. Data from gas engines fired with the cleaned process gas were substantially below U.S. EPA emission limits for MWCs.

Thermoselect’s analysis of the solid process streams indicates that the system has, in effect, no solid waste residues. They believe that all of the solids produced by the process can be sold or disposed at no net cost and, indeed, are suitable and can be valued for use rather than disposal. The validity of these commercial assumptions must be tested for any specific proposed plant location.

- Product Gas and Residue – When a waste feed containing 50% organic matter/ 25% organic matter/ 25% water at 2,480 kcal/kg is processed, a 8.3 MJ/Nm³ reactor gas is generated. The CO and H₂ concentrations in the gas are close to those predicted by the assumption of thermodynamic equilibrium at 1200 °C (see Fundamentals of Combustion – Part 1 course). The cleaned reactor gas is an energy source for the production of electricity using a gas engine or gas turbine or as a fuel to a steam boiler for use as either process steam or for the generation of electricity via a conventional Rankin cycle. In concept, the reactor gas can also be a chemical feedstock for methanol or other chemical manufacturing use.

- Commercial Plants – Eleven commercial scale plants using Thermoselect technology have been constructed since 1992. Nine are still operating at capacities between 105 and 780 metric tons/day

D. System Selection for Developing Technologies

The explosion of new technologies in the U.S. in the late 1960’s and early 1970’s was driven by the political tension surrounding a national perception of a “Landfill Crisis” and the federal process development and demonstration funding that accompanied it. One notes, however, the emergence and demise of several highly profiled technologies such as Purox, Landgard, Torrax, CEA, Melt-Zit, Red Lion Pennsylvania’s Ecogenics, Parsons & Whittemore, Garrett Corporation, and many others. Table 2 summarizes the areas of weakness that contributed most strongly to the disappearance of several of these technologies from continuing development.

One-by-one, implementation of pilot and prototype facilities based on these and many other of the “advanced process technologies” that had emerged during that time period revealed critical process flaws, unsolvable economic challenges and/or operational weakness. In time, their development effort shriveled and died as the economic, technical and environmental challenges of actually providing a fully sound response to the “Solid Waste Crisis” chipped at the glitz and the glamour.

Table 2 –Problem Areas in Discontinued Conversion Technologies [1]

Process	Developer	Capital Cost	Operating Cost	Side Streams	Operations	Maintenance
Purox	Union Carbide	X	X	X	X	X
Landgard	Monsanto	X		X	X	
Torrax	Carborundum Company		X		X	X
Garrett	Garrett Corp.		X		X	X
CEA	Combustion Equipment Associates	X	X		X	X
Parsons & Whittemore	Parsons & Whittemore		X	X	X	X

Left standing was “Mass Burn, Waste-to-Energy.” This option was not as exciting and still had problems. However, the ASME and other professional societies, the academic community, the vendor industry and owner-clients in the U.S. and Europe set about enhancing and refining this basic and reliable technology. Through equipment and operational changes, they substantially addressed the emission and residue problems and spoke to the economic challenge through power generation to yield a reliable, environmentally sound and effective waste management solution that is now embodied in literally thousands of furnaces operating today world-wide. Mass burn is still the Gold Standard when it comes to demonstrated, reliable performance.

At the close of the first decade of the 21st century the world is now in the early years of a similar explosion in new technologies. As before, it is partly driven by the shrinking availability and increasing cost and complexity of in-close landfills; projected increases in the value of energy; and strategic concepts that seem excitingly “New” . . . gasification instead of incineration, pyrolyzing plasma arcs instead of oxidation, and promises to achieve Zero Waste objectives by slagging residues to non-leaching glasses. The hard lessons of the first explosion, however, suggest that the consulting engineers, environmental organizations, and the leadership of potential owner communities should thoughtfully reflect on the experiences of the earlier time to more insightfully and critically evaluate the emerging technologies, to structure fair but protective contract documents, to ask hard questions and apply proven methods for process assessment. Ultimately, such efforts will guide the cities and counties considering such systems in making better, wiser decisions for their citizens.

The sections below are structured around a series of issues that should be considered by a decision-maker in selecting and implementing a “new” technology . . . where there are not numerous plants in-being based on the technology with many years of demonstrated performance as a credential of great merit in such a selection and implementation decision. Most importantly, these issues must be considered without imposing bias based on what the decision-maker himself, any relevant investors or stakeholders, or a client organization wants to hear.

1. Consider the Waste

Waste Source & Nature are important since wastes are different: chemically, physically and thermally. Thus, achievement with one waste feed does not guarantee success with another. Frequently, “surrogate” wastes are used in development pilot plants for convenience, uniformity, accessibility or cost that, perhaps unbeknownst to the developer, simplifies the achievement of test objectives. Ordinary, variable and aggressive MSW presents a severe challenge but is a challenge that, eventually, must be met head-on.

Waste Chemistry is increasingly important through the micropollutants that have become the focus of regulatory concern regarding air emissions and residue disposal and from the impacts of elements like fluorine, chlorine, alkali metals (sodium and potassium) and phosphorous and the balance of Lewis acids and bases in residue that impacts on corrosion, refractory penetration and spalling and slag fusion characteristics.

Waste Heating Value is obviously important and prospective owner/operators need to understand that the scale of capacity of thermal processing devices is the heat release rate not the mass throughput (tons per day). That is the true measure of processing potential. If the heat content goes up, the mass throughput must go down.

Materials Handling is critical. Perhaps no aspect of waste management causes more downtime, more operating problems and is more difficult to resolve than problems relating to the handling of waste. The major challenges of getting and keeping RDF plants on-line amply illustrate this fact. Consequently, the pilot and demonstration units involved should have handled and processed waste that is very closely similar to that expected in the prototype facility. For example, the Americology RDF failures in Milwaukee where pilot shredding and handling in an affluent small town did not adequately predict behavior with an urban waste stream.

Average vs. Distributions are important since the high variability of waste composition and characteristics in MSW inevitably leads to spatial and temporal variation in process variables and material parameters. Expect this variability and its consequences.

2. Benefit from the Power of Process Analysis

Pencils and paper are MUCH cheaper to change than are concrete and steel. The several tools and disciplines applicable to the analysis of a proposed process [1] produce many benefits in understanding the upsides and the downsides, the benefits and the costs of implementation. The topics below suggest the focus of such analytical efforts.

It all has to work. This is the overriding tenant of process success. The process starts with waste receipt, considers all sidestreams, and ends with residue disposal. Too often, developers focus all of their attention on the gleaming jewel that distinguishes their process and delights their investors but are struck down by the prosaic materials handling, corrosion or other “side issues” that are critical to commercial success. Also, whereas there is often a firm that promotes the special process feature, in most cases there is no single firm with the technical skills, experience and economic strength to design, build and guarantee the “wrap-around” of other critical total process elements that must work together with reliability and acceptable maintenance expense.

Pre-processing is not a “gimme.” Pre-processing of waste to produce a refuse-derived fuel (RDF) feedstock to a process has a profound effect on the achievement of “Zero Waste” goals. RDF processing often has a rejection rate of 20-35% depending on the sensitivity of the receiving process. Unless this “sidestream” is somehow processed, this large quantity of waste detracts directly from the Zero Waste objective. Further, the cost, risk and development time impacts of implementing RDF-based systems have, without exception been significant and adverse. Industry “war stories” to this point from the RDF industry are abundant.

Heat & material balances (detailed) confirmed by operating data should be asked for and expected from the developers before the contract is signed. The posture of developers that all such information is “proprietary” should not be accepted since, without this basic and critical presentation of the characteristics of a process, the prospective client cannot adequately assess the viability of the developer’s claims and the likely energy recovery potential (a critical economic parameter) of the system.

Use “what-if” scenarios with a process model over a reasonable range of waste characteristics and system operating conditions to anticipate performance variations. Waste is variable and the heat and material balances and other assessment tools should be exercised over the full range of potential waste characteristics. For example, what happens when (not if) the waste is unusually wet (as in the fall when wet leaves are dumped or when heavy rains wet down the waste)?

Apply sophisticated tools such as kinetics and thermodynamics (equilibrium) calculations that often have a place in process analysis and should not be overlooked because they appear “too scientific.” While such calculations include some uncertainty, they give insights that may be valuable.

Use the literature . . . the past is the foundation (and can save money) of the future. To quote George Santayana, “Those who do not learn from history are doomed to repeat it.”

3. Analyze the Data

Signal to Noise Ratio . . . Waste management technologies, working with a variable feedstock, show concomitant variability in the degree of closure of balances, agreement in calculated outputs from inputs etc. Expect this and collect sufficient data and treat it statistically to gain comfort. Recognize that many parameters are log-normally distributed and not normally distributed.

Data to insist upon include:

Process data. Detailed and “real” information about the behavior and performance relative to expectations or standards) is a reasonable expectation for communities that will depend on a process for vital and politically sensitive services. Don’t accept “it’s proprietary” as a block to seeing “inside the box.”

Evaluations for extended operating times at a commercial scale. Operating time is important because of the long time-constant for thermal equilibrium in large systems and the grinding, slow degradation (corrosion, erosion, etc.) of materials over time. Tests that run only a few hours or even days are meaningless when “success” requires 24/7 availability. Refractory that never really gets to equilibrium operating temperature may not experience the corrosive attack of refractories (fluxing) or slag build-up that may presage failure in operation. Also, one needs operating hours to allow visibility of performance over the wide range of operational challenges presented by the processing of “real” waste streams with all their variability. Designs that are frail because the developer did not provide for threats that “might” happen, may fail when, in fact, they do happen. Real people throw away old mortar shells and live ammunition, cans of gasoline and full propane tanks.

Data to confirm heat & material balances. Include sidestreams (bypass, residues, etc.) in the scope of data requirements.

Emission data (air and water) and residue analysis results from commercial scale equipment with the proposed air pollution control train. Hopes and aspirations or predicted performance don’t compare with delivered results. Include in data requirements those characterizations that are important for the marketability of sidestreams.

Data to cross-check. The complexity of the process and variability in the working fluid (the waste) means that balances, benchmarks etc. may not always meet expectations. Test the validity of results by cross-checking.

Acknowledge that although the data may be wrong or not make sense, it is a reflection of reality . . . whereas the promises of a developer are vapor. If the data don’t prove out the developer’s promises, get new data or a new developer.

4. Solicit Input from the Operators

Process operators know what really happens. They deal with reality without glitz or fantasy. Disrespect their unique grasp of process characteristics and behavior at your peril. Seek them out, respectfully solicit their observations, and ask their opinion and their counsel. If you can, respond to their suggestions and then give them tangible and professional credit for the improvements they contribute.

5. Use Your Common Sense

A prospective client should question those assumptions that are critical for process success. These include the markets and prices for by-products; energy prices; system availability and maintenance costs; ruggedness; total process flowsheet flexibility as the waste changes and so forth. Believe the old saw about what “assume” makes.

Acknowledge that the complexities of “advanced processes” make the scale-up of processes from “bench” to “pilot” to commercial scale inherently risky. The larger the “step”, the greater the likelihood that difficulties, problems etc. will arise that will impede development. This observation is not simply general “conservatism” but rests on the repeated history played out in the process development world. That is not to say that progress will be stopped by such unanticipated setbacks but, rather, that there is a significant risk that more time and money will be required to get back on-track and, often, that some compromises, short-falls etc. in performance may be necessary to progress.

There should be no “gimmies.” That is to say – The Service Agreement should include no explicit or implicit assumptions of likely but undemonstrated success on key characteristics (such as on-line availability, maintenance expense, refractory maintenance, side stream disposal technology and cost). The projected costs are very large as should be the expectation of success based on confirming data. Assumptions, however plausible, represent risks that should be borne by the developer and not the client community . . . just as the rewards (a performance achievement that supports future process marketing successes) will be received by the developer.

Look at the “deal.” If the developer says that “all he wants is a 20 year, fixed price delivery of “X” tpd” . . . and that looks too good to be true, perhaps it is. Especially if outages or capacity short-falls result in continuously redirecting collection vehicles and bypassing waste to landfills at costly “spot” disposal fees. Is there an “escape clause” in the Service Agreement with escrowing of funds to remove the failed plant if specified capacity, environmental and availability goals are not met within some reasonable time frame? Who makes the call and what is the treatment of partial failures? What happens if there are persistent odor or noise issues or other “soft” environmental failures? What happens if changes in law or commercial changes increase the income for byproduct or power sale? Who gets the power revenue or the income from selling byproducts? Who pays for side stream treatment such as the disposal costs for bypass material from waste processing or for wastewater treatment? Who suffers and how much if there are unfavorable changes in the value/cost of

recovered power, the cost of labor, taxes or utilities, etc. over the assumptions used in the Service Agreement? Who takes on the risk of a tipping fee change (up or down) if power generation per ton processed is higher or lower than projected, if utility quantities or reagent consumption or other consumable rates exceed (or are below) expectations? Who pays for disposal of excess wastes bypassed if there are outages of the facility due to unscheduled shutdowns or capacity shortfalls because the process does not live up to expectations in either availability or throughput capability? The Service Agreement is a 20 year marriage contract that needs to be crafted and reviewed by experts. It should be drafted by a mix of legal, financial and engineering professionals with the protection of the community foremost in their mind.

E. Summary

The experience of this author in the evaluation of new processes for solid waste management suggests that thoughtful, critical and penetrating evaluation is necessary to protect the interests of the citizens that, ultimately, pay the bills. Waste management is a 24/7 operation that imposes profound challenges on equipment and operators. While innovation is desirable, evolution from strength also merits consideration when deciding on directions that will impact on municipal budgets for decades. Be careful! And use all the skills and tools at your command to be sure the recommended decision is the right one.

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