

**MASS AND ENERGY BALANCES OF THE THERMOSELECT®
DEMONSTRATION PLANT: PART III**

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ABSTRACT

This is an original paper entitled, Part III: Material and Energy Balances of the Thermoselect Demonstration Plant in Italy. The planning and implementation of the demonstration plant was the result of theoretical studies that were independently proved and then combined into a facility that coupled the process steps: waste compression, drying and degassing, gasification with oxygen, and the subsequent direct melting of inorganic waste components. Special emphasis was placed on the equipment layout for the 'synthesis gas purification' and 'process water treatment' sections each of which is designed from calculations made during the preliminary phases of plant design.

The experiences gained from the industrial-scale demonstration plant (100+ t/d) have resulted in good agreement with the design parameters of operation and confirmed the correctness of the overall concept. Further developments relative to initial 1991 design concern in particular:

- Modification of the process step for the removal of the sulfur compounds as elemental sulfur from the synthesis gas. The recovery of elemental sulfur now being achieved by means of a regenerable iron-III complex, in solution rather than by oxidation of the hydrogen sulfide, followed by conversion of the resulting sulfur dioxide into calcium sulfate,
- The installation of a reverse osmosis unit to the process water recovery loop prior to the evaporator,
- The installation and normal operation of a 1 MW gas-motor generator module for the testing of the energy of synthesis gas in gas engines. In the commercial facility, the electrical requirements of an air separation plant (oxygen/nitrogen supply) and process heat

requirements to dry the generated synthesis gas are covered by the thermal power coupling of the block thermal power plant that consists of several modules in a commercial plant. The engines also serve to discharge excess energy -- electrical energy and heat -- from the plant.

The experience gained in the demonstration plant has required only slight modification of the Thermoselect® process itself. On the other hand, the site-determined framework conditions have a significant influence upon the project-related material and energy balances, for example:

- The calorific value of waste and its cycle of availability,
- The component composition of the waste; water content, organic component, inorganic fractions which in particular are also subject to seasonal variations,
- The pollutant fraction of the waste and pollutant composition; heavy metals, chlorine content, etc. and the selected energy conversion method for synthesis gas utilization, synthesis gas utilization as an energy source using for example internal combustion engines, ignition-ray motors, steam turbines, gas turbines or the use of the clean synthesis gas for alternative fuels such as methanol, etc.

The results of studies at the demonstration plant provide the basis for the planned scale-up to the standard commercial plant (multiple 2 line process lines). The dimensional scale-up of the Fondotoce demonstration plant with the authorized capacity of a single thermal disposal line of 4.2 Mg/h (for $H_u \leq 10$ MJ/kg) to a series-plant thermal line with a 10 Mg/h capacity is surely possible with the aid of the knowledge gained from the practical operation of the Fondotoce plant. Planned on this basis of the

operational experiences are series of plants with two or more lines (528 short tons/d).

1. Introduction

The planning and construction of the THERMOSELECT® demonstration plant was the result of theoretical studies on mass and energy balances which led to a facility capable of coupling, in-line, the process steps of: waste compacting of commingled solid wastes, the drying and degassing of the compacted waste, followed by gasification of the resulting dry carbonized organic fraction using oxygen. The resulting exothermic reaction of carbon in the presence of oxygen provides the heat necessary to smelt the inorganic waste components which are an integral part of the original solid waste input.

Special emphasis was placed on equipment layout including an efficient synthesis gas cleaning system and a process water recovery and cleaning section to ensure the in-line concept, process stability and to provide ease of maintenance operations. Each of these systems was designed based on theoretical calculations made during the early stages of the process design [2].

The experiences gained from the construction of an industrial-scale demonstration plant (100+ t/d), which has operated in excess of 15,000 hours through December 1994 [3-7], has resulted in confirmation of the design correctness, process operation parameters and proved its consistency of operation. Further developments relative to the initial design level achieved in 1991 include:

- A change of the processing technique for the removal of the sulfur compounds from the gas stream. The initial technique was oxidation of hydrogen sulfide followed by conversion of the resulting sulfur dioxide into calcium sulfate (gypsum). The current process uses a liquid phase oxidation loop that is capable of regeneration which transforms the sulfur component into elemental sulfur by means of a Fe(III)-chelation complex. The sulfur is removed as an easily managed solid product of industrial quality.
- The redesign of the process water recovery loop to include a reverse osmosis unit prior to the process water distillation unit. This unit removes from the process water the salts produced from the acid gases prior to distillation and eventual reuse. The Thermoselect process recovers the water component naturally contained in the input solid waste; this water becomes part of the body of process water. After cleaning, the excess volume of water is sprayed on hybrid heat exchangers and evaporated. The process itself is capable of close to zero discharge if necessary.
- The installation and testing of a 1 MW synthesis gas engine/generator module to demonstrate the conversion of process generated synthesis gas into electrical energy. In the commercial facility, the electrical requirements of the facility which include a cryogenic air

separation plant (oxygen/ nitrogen source) and the process heat requirements for the drying of the synthesis gas and any raw incoming sludges are handled by heat recovered from several gas engine modules. Excess energy, as either electrical or thermal, is sold.

It is to be anticipated that site-specific conditions will impact the mass and energy balances for each individual commercial facility; important factors necessary for efficient design include:

- Solid waste input quantity and calorific value.
- The seasonal fluctuation and expected component composition of the waste.
- The pollutant fraction and the composition of the solid waste input relative to heavy metals concentration, chlorine content and sulfur containing components such as rubber tires.
- The selected method to be used to recover the energy contained in the synthesis gas: internal combustion engines, diesel assisted engines, steam turbines, gas turbines, or the use of the synthesis gas to produce alternative fuels such as methanol or hydrogen [1].

The demonstration plant, which was permitted as a thermal disposal line with a throughput of 4.2 Mg/h (LHV \leq 10 MJ/kg or 4,308 Btu/lb), has provided sufficient consistency of results obtained from several measurement studies and demonstrated stability in process control to provide the basis for the scale-up to a commercially sized line of continuous operation of 10 Mg/h, (LHV $<$ 12 MJ/kg; 5,169 Btu/lb). Multiples of this standard line, 10 Mg/h (~11 short ton/h) will provide considerable flexibility in the design of commercial facilities.

The scope of the work presented in this paper is as follows:

- Waste analysis:
 - Waste sampling and characterization
 - Quantitative and qualitative analysis of the waste fractions
 - Theoretical characterization of the waste (heat value)
 - Calibration of the crane, weighing device, oxygen flow and natural gas flow.
- Output analysis:
 - Description of operational conditions and limitations of the facility
 - Quantitative and qualitative measurement of the main output flows (syngas, mineral aggregate, side flows).
- Thermodynamic equilibrium calculation vs measured syngas composition:
 - Measured syngas composition compared to theoretical equilibrium composition derived from previous input flows
 - Discussion of results.
- Mass and Energy Balances:
 - Development of the balances starting from waste input and using equilibrium calculations
 - Derivation of balances beginning from measurement data (a reverse approach)
 - Comparison of the two methods
 - Discussion of scale-up feasibility and syngas-to-energy conversion methods.

2. Waste Characterization and Characteristics of the Facility

Classification of the Waste Input

The following assessment was carried out, with the participation of TÜV Energy and Environment, following consultation with those participating in the earlier reported June-September 1994 measurement period (Part II). This study was designed to identify the material composition of the waste processed in the demonstration plant during the measurement period as a basis for the development of material and energy balances and to develop the data necessary to determine the distribution of the chemical elements in the substance flows:

- Visual inspection and quantity assessment of delivered refuse during unloading and storage in the bunker,
- Video taping (~8s) of each charge of waste, ~200 to 400 kg per charge, before being dropped by the weighing crane into the press hopper,
- Classification of the solid waste input by means of ~100 kg bunker samples which were then sorted into 10 fractions on which calorific values were determined.

The results from this classification were included in evaluations for the June-September 1994 study period [6].

The calorific value range of the wastes processed is contained in Figure 1: Results of the refuse analyses for determination of the calorific values. The calorific-value spectrum of 10 to 16 MJ/kg (4,308-6,893 Btu/lb) was obtained with the aid of the refuse classifications and interpretation by: TÜV Energy and Environment Institute, Steiger Environment Technology and UEC data. The photographs taken during the refuse classifications are contained in Figures 2 - 4 and document the procedure.

The calorific-values obtained are in agreement with the specific quantities of synthesis gas measured and are consistent with earlier studies from March 1993 [13]. Smaller quantities of synthesis gas reported from measurement studies conducted during May 1993 and reported in the Lombardi report [8] resulted from solid wastes having lower calorific values (<7 MJ/kg; < 3,000 Btu/lb).

Processing Throughput

Through November 20, 1993, the demonstration plant processed commingled solid wastes at a varying throughput rate of 300 kg/h to 4,000 kg/h; the throughput total was 5,500 Mg. This period provided: in-line processing optimization. study under varying loads. heat stress cycling and included a key section tear-down assessment and analysis at 4,000 hours. During March 1993, a measurement period was carried out by RWTÜV with an average throughput of 3 Mg/h. In the June-September 1994 measurement study [6] a throughput average of 3 Mg/h was processed; during week 39 when the direct measurement phase took place. 3.8 Mg/h was processed.

To certify the accuracy of the quantity of waste throughput:

- The calibration of the crane scale was confirmed,

- The delivered quantities in weighing containers as well as calculations of the residual waste present in the bunker before and after the studies were compared to recorded values,
- Recordings in the crane scale log were cross checked to confirm quantities and weights.

The waste throughput was supervised by RWTÜV and TÜV Energy and Environment Institute.

The following figures 5-11, provide information on the waste throughput, specific synthesis gas production and metal/mineral granulate production during this measurement period:

Limiting Throughput Factors of the Facility

A. The throughput and operational capacity of the demonstration plant resulted from the following construction parameters and peripheral conditions: the authorization permit for the construction of the demonstration plant was issued with a restriction of 4.2 Mg/h maximum waste throughput. If we assume a calorie content in the solid waste input of ≤ 10 MJ/kg (4,308 Btu/lb), a synthesis gas flow volume of 4,500 - 5,800 Nm³/h would result.

Using this gas volume data, it was clear that there were not adequate gas users on-site. To solve this dilemma, a synthesis gas combustion chamber with flue was designed to be used for the disposal of the excess quantity of cleaned synthesis gas produced.

The present level (1/95) of the demonstration plant utilizes synthesis gas to heat the degassing channel, fire a boiler and operate a synthesis gas engine (1 MW). The main portion of the produced synthesis gas continues to be sent to the combustion chamber with flue. In a commercial application, the combustion chamber would only receive synthesis gas for combustion during an up-set plant condition.

The volume of synthesis gas produced is a function of heat content in the waste input. The demonstration plant is, therefore, limited by the combination of throughput and the heat content contained in the input waste which sends to the combustion chamber and flue a maximum volume of 4,000 Nm³/h of synthesis gas. This quantity of synthesis gas allows the temperature design limits of the combustion chamber, ~1,350°C to be maintained.

In the demonstration plant with the restrictions noted above, solid waste having high calorific content which will generate higher specific synthesis gas quantities are handled by reducing the processing throughput.

B. During the measuring period, a lack of household wastes developed. The testing program, therefore, had to be carried out using random mixtures of household refuse and commercial waste fractions having up to ~16 MJ/kg (6,893 Btu/lb) calorific value. This was confirmed by the waste classifications identified during the respective measurement period.

High-load runs designed to be over the capacity limit were carried out to demonstrate the carrying capacity of the plant to the participants in the measuring study. The 1500-1700h segment from June 15, 1994 serves as an example:

- The degassing channel, using synthesis gas to develop heat energy, was on-line.

- The synthesis gas engine using synthesis gas to develop electrical energy was on-line,
- A refuse throughput over 10 hours of 3.6 Mg/h was confirmed,
- Peak values of synthesis gas flowing to the combustion chamber were observed resulting in combustion chamber temperature overload ($>1,358^{\circ}\text{C}$) forcing a reduction of waste input and a resulting reduction of gas production. The above factors and comparison with earlier demonstrations lead to the following basic assertions regarding the limitation of the waste throughput to the thermal capacity of the demonstration facility:
- To avoid thermal overloading of the combustion chamber and thus to maintain the temperature of the combustion chamber below its design limit of $1,350^{\circ}\text{C}$, a reduction in waste input to the press is necessary. It must also be taken into account that the combustion chamber and flue must always be able to dispose of the entire quantity of synthesis gas generated,
- It follows that the plant was not operated during the testing period at the quantity limits of its waste capacity throughput, and that the thermal capacity of the demonstration facility is controlled by the maximum temperature capability of the synthesis gas combustion chamber,
- The result of these peripheral physical conditions is an average waste flow of 2.8 Mg/h during the June - July study period. The interpretation of the data from the refuse classifications performed (13 random samples) during this period disclosed an average calorific value of approximately 12.5 MJ/kg (5,385 Btu/lb); the samples ranged from 10 MJ/kg (4,308 Btu/lb) to 16 MJ/kg (6,893 Btu/lb). Evaluations of the random samples taken during the September period disclosed calorific values from ~ 10 to 12 MJ/kg, an average of 10.8 MJ/kg (4,459 Btu/lb). In September, an average waste throughput during the measurement period of 3.8 Mg/h was recorded,
- If, as an example, a calorific value of 8.5 MJ/kg (3,662 Btu/lb) is assumed for the waste input, then a throughput approximately 40% higher will be possible due to the smaller volume of synthesis gas generated, allowing the waste throughput to be > 4 Mg/h. This temporarily restricted the throughput to 4.4 Mg/h; a throughput of greater than 5 Mg/h during September confirms the quantitative carrying capacity of the plant.

These interpretations show the interconnection between processed waste, the calorific value of the waste and the specific synthesis gas quantity generated. Calorific value fluctuations in the waste from between 10 MJ/kg (4,308 Btu/lb) to 16 MJ/kg (6,893 Btu/lb) yield the measured quantities of synthesis gas of 800 to 1,200 Nm³/Mg. This shows agreement with earlier synthesis gas volumes measured and thus confirms the balances. Practical results show anew that the design of the demonstration plant is essentially based upon correct theoretical considerations and sufficient practical experience developed from the 1,000 kg/h precursor processing unit.

The measured specific mineral granulate quantities show deviations from 150 kg/Mg to more than 300 kg/Mg, relative to the waste input. Average values of 24.6% and 25.9% show excellent agreement with the 24.7% value measured from the two six-month pilot phases and confirm that the local refuse does not differ significantly from wastes of other industrialized nations within Europe. The results also agree with reports from earlier studies, RWTÜV 03/93 and Lombardi [8], in which a granulate level of 23.3%, relative to the waste input was reported.

Table 1: Average values of the key parameters during the study period show key parameters developed during the study periods. The specific-flow values presented in the table depend upon the composition, the calorific value and the throughput of the waste. The results differed only slightly during the two study periods.

The effectiveness of the complete substance conversion in the Thermoselect process is apparent from the quality and quantity of the products exiting the HTC: vitrified mineral granulate and metal alloys in molten form from the homogenization section, synthesis gas from the upper section of the HTC in gaseous form. The granulate and synthesis gas quantities, combined with the waste classification data and the calorific values of the waste input, show that the resulting quality and specific quantity products agree very well with prior results. Thus, the reproducibility of the entire course of the process is comprehensively demonstrated [11, 12].

3. Comparison of Thermodynamic Calculations to Measured Synthesis Gas Compositions

This comparison is based on recent measurements taken during operation of the plant and represents the major components of the synthesis gas: CO, CO₂, H₂, H₂O and the addition, in trace concentrations of natural gas (CH₄), which has been documented as the leading component of unwanted hydrocarbon compounds in several research reports [8, 10].

Using the in-line process steps of simultaneous gasification and smelting in a high-temperature chamber (HTC) as part of the core of this process, the achievement of thermodynamic equilibrium was analytically proved in an earlier paper [13] and is assumed. Gasification using pure oxygen is controlled in such a manner that temperatures up to $1,200^{\circ}\text{C}$ ($2,190^{\circ}\text{F}$) are reached in the upper section of the HTC, and yet higher temperatures ($\sim 2000^{\circ}\text{C}$) are reached in the lower section of the HTC where carbon and oxygen combine in exothermic reactions. A molten mass of mineral and metal components common to solid wastes forms in the lower section of the HTC and flows into a homogenization chamber where further oxidation ensures complete reaction of any remaining carbon or organic components. Additional outside fuel becomes necessary to maintain the melt state of the mineral-metal component as the heat of the reaction decreases from lack of carbon and organic material. This outside fuel can include process generated synthesis gas or natural gas. The important fact is that the resulting vitrified mineral granulate is inert and non-toxic, while the recovered metals portion is ready for reuse by a smelter.

Table 1: Average values of the key parameters during the study period (6/94)

Parameter	Dimension	June/July '94	September '94
Waste quantity	Mg/h	2.8	3.2
Calorific value LHV	MJ/Mg	12.5	10.8
Natural gas	kg/Mg	47.8	49.3
Oxygen	Nm ³ /Mg	431.0	414.0
Synthesis gas	Nm ³ /Mg	963.0	794.0
Synthesis gas	Nm ³ /h	2874.0	2458.0
Process water	kg/Mg	606.0	467.0
Mineral Granulate	kg/Mg	246.0	259.0

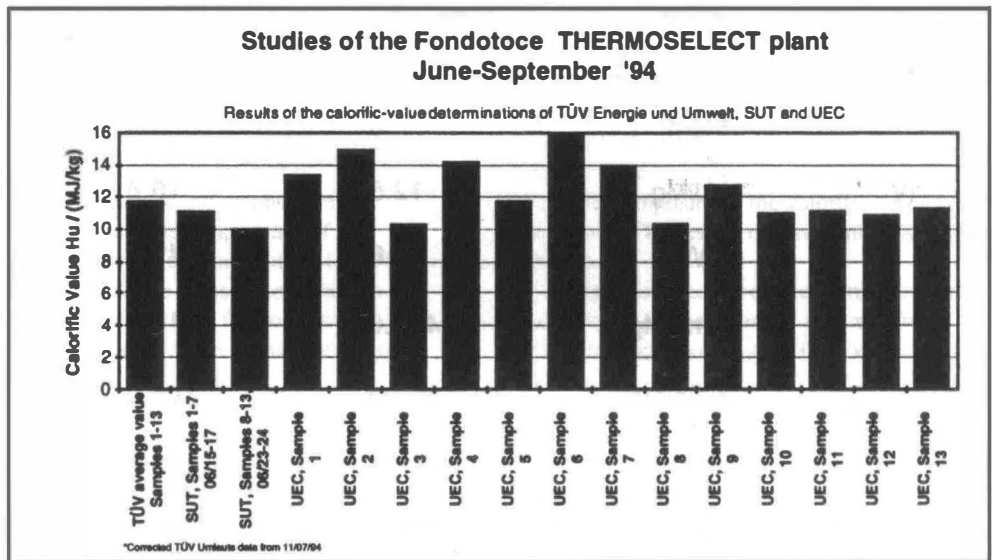
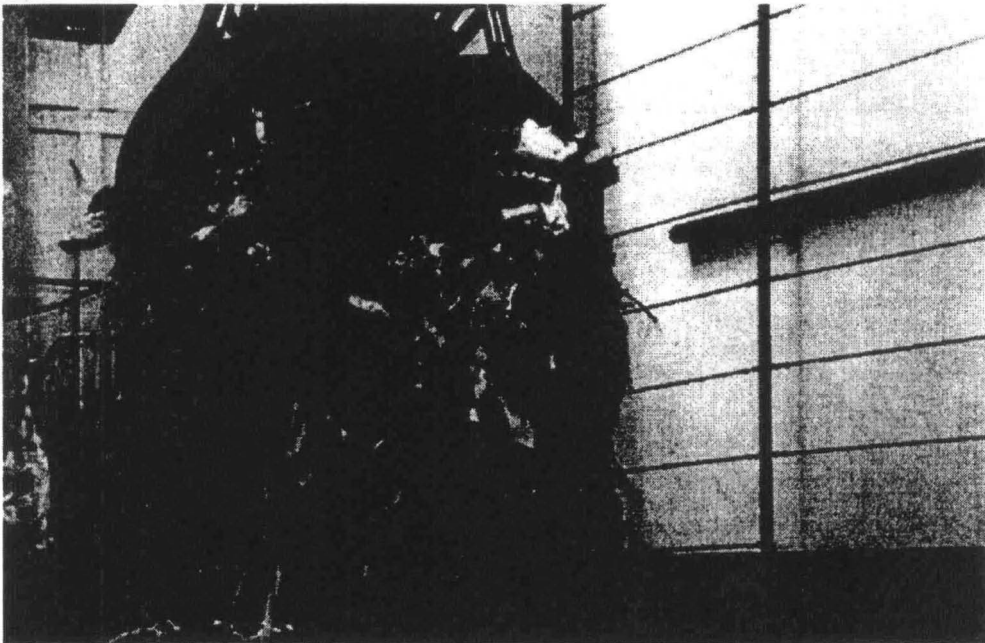


Figure 1: Result of refuse analysis for the determinaton of calorific value: $H_{\mu} = LHV$



Figure 2: Photographic documentation of refuse classification (taken on 6/15/1994)



*Figures 3 and 4: Photographic documentation of refuse classification
(taken on 6/15/1994)*

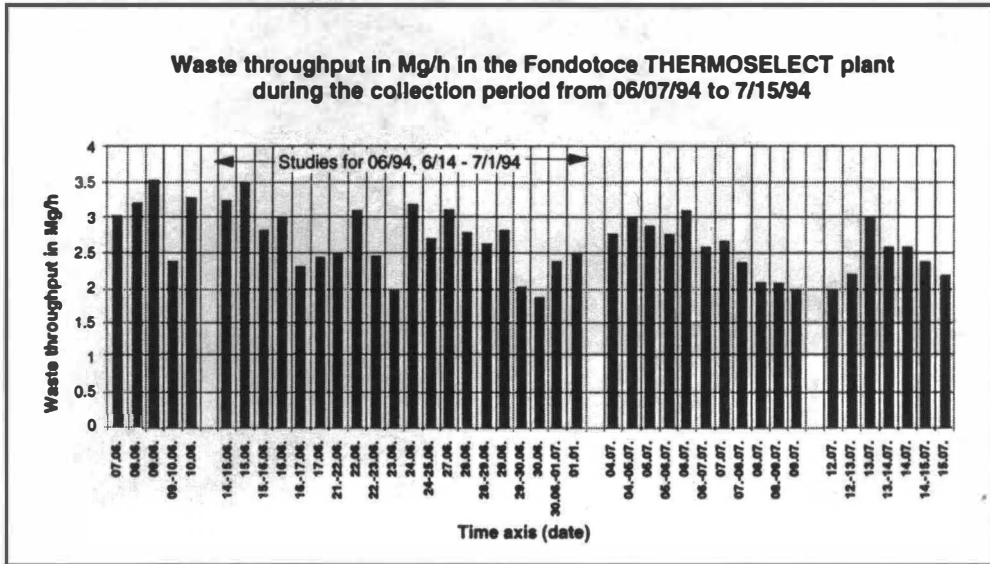


Figure 5: Waste throughput 06/07 - 07/15/94

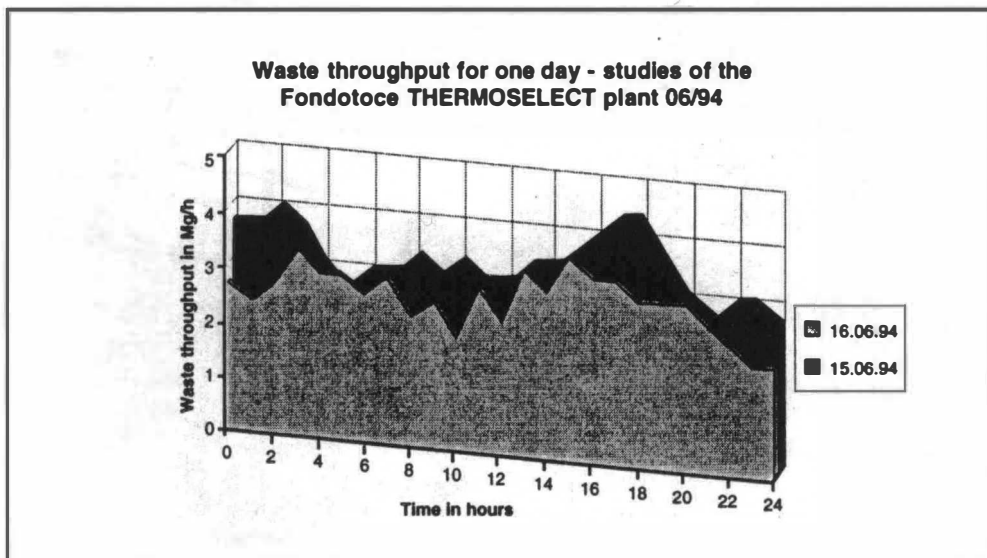


Figure 6: Waste throughput for one day 06/15 and 6/16, 1994

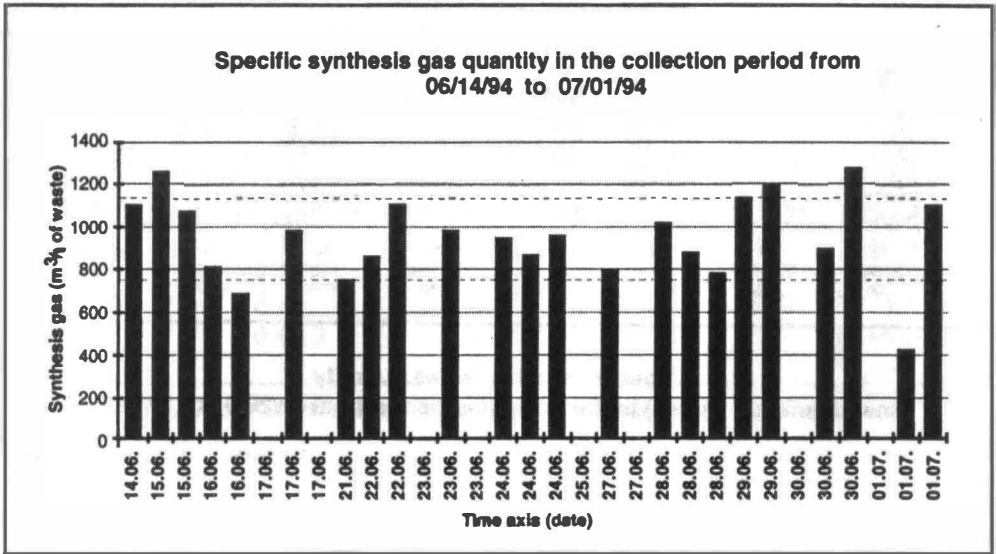


Figure 7: Specific synthesis gas quantity 06/14 - 07/01/94

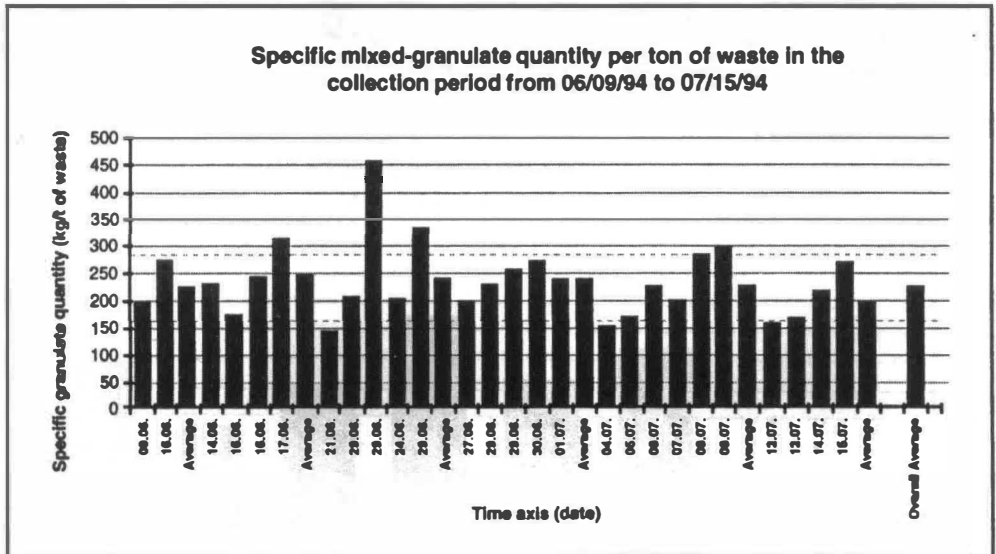


Figure 8: Specific mixed granulate quantity 06/09 - 07/15/1994

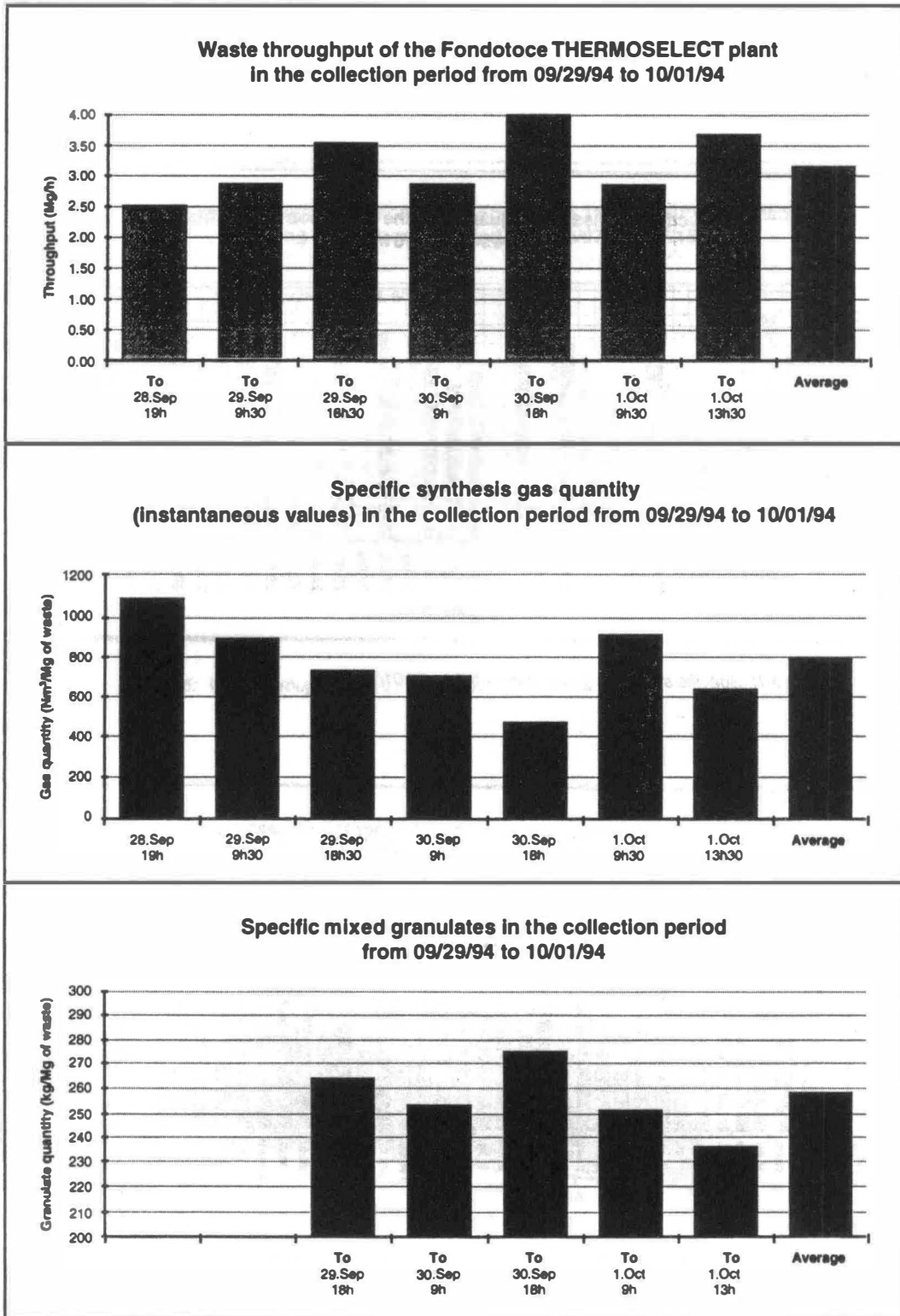


Figure 9 – Figure 10 – Figure 11

Table 2: Synthesis gas composition: comparison of thermodynamic equilibrium calculations and measured results from studies at the THERMOSELECT demonstration plant.

Synthesis gas components	RWTÜV	Lombardi	RWTÜV		RWTÜV	Thermodynamic equilibrium calculation**		
	03/93	05/93	June-Sept. 94		Average	1000°C	1200°C	1400°C
Volume %	2/16-18 1993	2/1-4/30 1993	6/15-6/17 1994	9/29-10/1 1994	06/94 + 09/94			
CO	>34.0	39.0	38.0	35.0	36.5	29.0	33.8	37.2
H ₂	>32.0	35.7	34.0	35.0	34.5	36.4	34.1	32.4
CO ₂	25.0	22.5	23.0	27.0	25.0	29.0	26.5	24.4
N ₂	3.0	2.8	3.7	2.8	3.3	4.5	4.7	5.0
CH ₄ *	-	0.013	<0.1***	<0.1***	<0.1***	<0.0001	<0.0001	<0.0001

* CH₄: 2/1 thru 4/30/93 using FID analysis, 6/15-17/94 and 9/29-10/1/94 using NDIR analysis

** H₂O component at times ~ 1%

*** below detection capability of measuring equipment

The organic components contained in the waste input are transformed within the process to their lowest chemical form by:

- High temperature exposure in the upper section of the HTC, ~1200°C (2190°F); and in the lower section ~2000°C (3600°F).
- Extended residence time of the gaseous phase at high temperature.
- Exiting gas temperatures at ~1,200°C (2190°F) ensure a state of equilibrium.

The organic components, having been reduced to carbon monoxide and hydrogen, become the main energy components in the synthesis gas.

In the homogenization section, addition of natural gas (or some other form of combustible) is required to ensure a melt as the heat of reaction dissipates with the elimination of available reactants with oxygen.

The volume of oxygen consumption used for gasification is dependent upon the waste input composition and, to a lesser degree, upon the additional oxygen required for oxidation of the natural gas added to maintain the melt in the mineral/metals flow.

The gasification reactions in the HTC are essentially influenced by the energy and material transport processes. This includes convective transport of the oxygen and additional gaseous reaction partners such as H₂O, CO₂ and other gasification products; it also includes diffusive transport into solid particles yet to be gasified, and the heat transport processes; convection, conduction and radiation.

The data generated during the first week of the June-September 1994 measurement period was used to develop the mass and energy balances and included measurement data on the synthesis gas composition generated by the independent engineering group RWTÜV, and the solid waste sorting analysis developed by the TÜV Energy and Environmental group.

The process balances include the solid waste throughput, elemental composition of the waste and measured oxygen and natural gas consumption. Elemental composition of the solid waste was developed using the sorting analysis referenced above; heat values for the waste were established by TÜV Energy and Environment. UEC Inc. of Potsdam and Steiger Environment Technology, Inc. of Liestal, Switzerland. On the basis of these groups, C-, H-, O-, H₂O and inert substance balances for the waste input were determined.

All output flows of the process which included gas cleaning and process waste treatment products and residues were included in the balances data base.

The theoretical calculation of chemical equilibrium was developed from the analytical results of the synthesis gas composition using a computer program to address the multitude of components.

The theoretical basis of such a computer program is the chemical equilibrium condition $\sum \mu_i \nu_i = 0$, where temperature and pressure are constant: (dT=0, dP=0). μ_i is the chemical potential of the component i, and ν_i is the stoichiometric coefficient of the component i for the gross reaction equations. The number of gross reactions is determined by the number of chemical elements and compounds to be considered. As an example, the Boudouard reaction or the water gas equilibrium alone yields only partial

information and does not replace the need for detailed thermodynamic calculations.

Theoretical equilibrium calculations of the generated synthesis gas composition compared to values measured over several measurement periods are presented in Table 2 and graphically in Figure 12.

The agreement of the closest theoretical values and the assumed equilibrium temperature of the synthesis gas, 1,400°C when compared to the actual measured synthesis gas exiting temperature of 1,200°C, suggests a higher reaction temperature in the upper chamber section of the HTC. Measurements of the synthesis gas composition taken over a considerable time interval differ from each other only slightly and are due to varying waste compositions. Important to note is the very slight trace quantity of natural gas found in the synthesis gas and the absence of oxygen, which are both key indices for the confirmation of equilibrium in the gaseous phase. This further confirms the effectiveness of the process and validates the in-line layout of the thermal line. This is further confirmed in reference [9].

Figure 13: Calculated synthesis gas composition as a function of temperature shows the results of the equilibrium calculations at different temperatures and the resulting purified synthesis gas composition assuming constant oxygen and natural gas consumption. As the figure shows, when in thermodynamic equilibrium, the quantity of CO decreases and that of H₂ and CO₂ increase as the temperature decreases. The quantity of H₂O in the raw synthesis gas at the HTC outlet just prior to shock cooling also decreases (not shown here).

The natural gas component, in the raw synthesis gas and in the purified synthesis gas, rises above 0.0001% in the equilibrium calculations only at temperatures below 800°C.

This essential difference, relative to a pyrolysis process which excludes air, is the result of the addition of gasification using oxygen in the overall process and process-control capability that ensures that the developing gasses receive high temperature exposure with adequate residence time in the upper section of the HTC. Thus, any concern for the presence of higher natural gas (CH₄) content in the synthesis gas when the gas exit temperature exceeds 800°C lacks any material basis.

The sulfur and nitrogen components of the waste were also included in the thermodynamic calculations. The calculated volume quantities for the components: HCN, COS, CS₂ and NH₃, lie far below 0.0001% in the temperature ranges under consideration.

The comparison of the average values of the synthesis gas compositions sampled and measured by RWTÜV against the calculated values are presented in Table 2: Synthesis gas composition: comparison of thermodynamic equilibrium calculations and measured results. The results show good agreement, particularly when one compares the equilibrium composition calculated for T = 1,400°C, which demonstrates that sufficiently high temperature and assured equilibrium conditions are reliably present within the HTC. Even the trace quantities of HCN, COS, CS₂ or NH₃, lying within the range of the detectable limits, confirm the theoretical results [10].

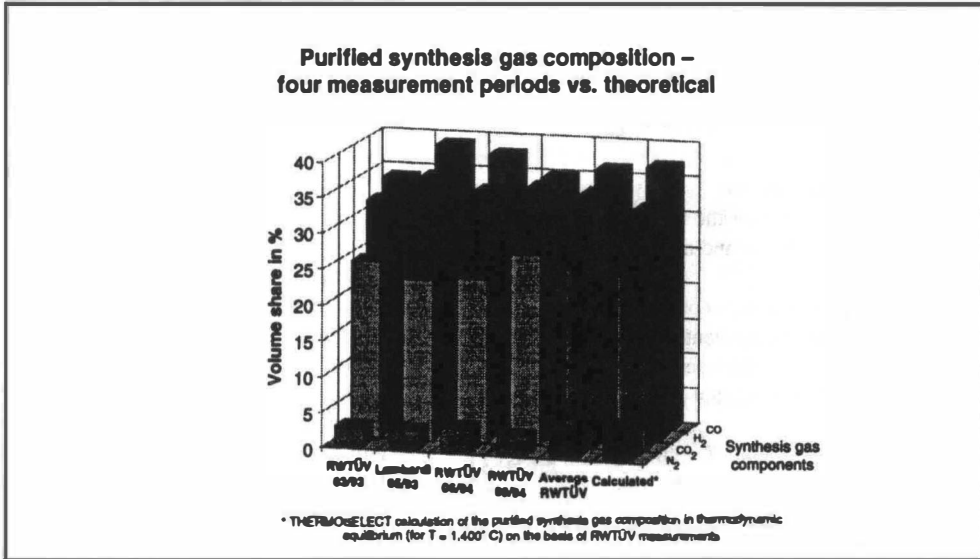


Figure 12: Purified synthesis gas composition

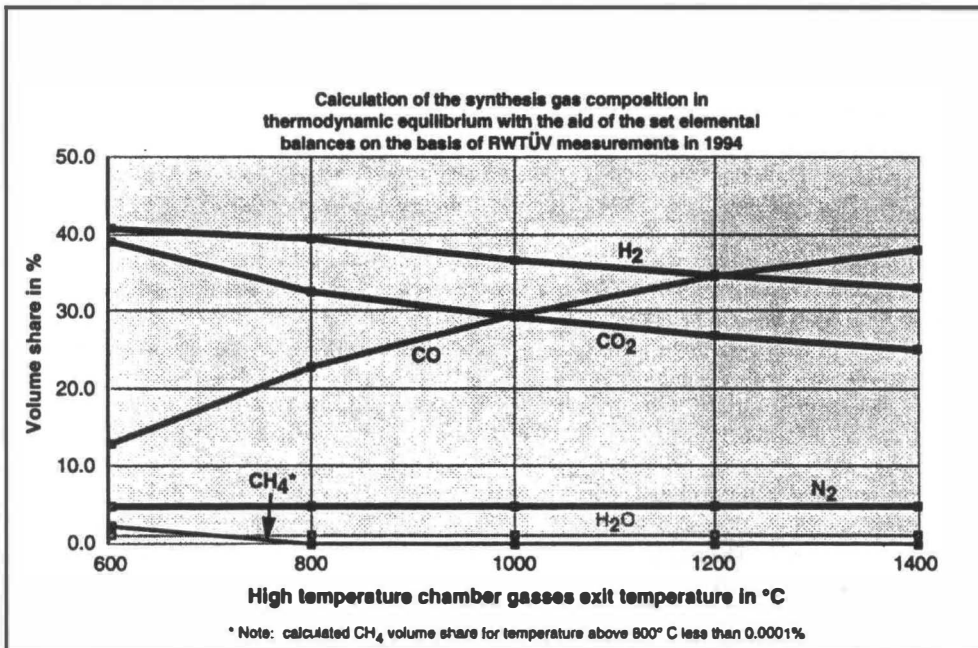


Figure 13: Purified synthesis gas composition as a function of the temperature

4. Mass and Energy Balances

The results from June-September 1994 measurement period show excellent agreement with earlier measurement studies and thus provide a very comprehensive basis for the development of material and energy balances. Assessment of the product quality results from all measurement periods also confirm the consistency of the process [10, 11].

The interpretation of the data was carried out in two different ways each independent from the other: jointly by Thermoselect/Steiger Environmental Technology Inc. and by the Badenwerk AG project team [11]. This ensured that the results would be as free as possible from systematic errors and allowed for an unequivocal interpretation of the data.

Calibration of operating data measurements was confirmed and certified by RWTÜV. All data obtained independently of the automatic operating-data recording system was processed with the assistance of RWTÜV, TÜV Energy and Environmental Institute and the other participants in the study.

The joint Thermoselect/Steiger Environmental Technology Inc. interpretation uses the results of the sorting analysis from the solid waste input differently from the Badenwerk team. It utilizes the balanced quantities of carbon (C), hydrogen (H), oxygen (O) and water (H₂O) from the sorting study and the process obtained measured data (RWTÜV), to develop a material and energy balance.

The Badenwerk AG interpretation, on the other hand, proceeds from the process obtained data measurements and uses that data to derive the mass and energy balances. The solid waste composition was then computed in reverse from the elemental balance of the products [11].

The results from TÜV Energy and Environment Institute and of the Institute for Engineering Thermodynamics at Karlsruhe University confirm the evaluations and the resulting mass and energy balances derived from the data [9, 12]. Table 3: Material balances in the Thermoselect demonstration plant, show the agreement with the design calculations for a standard two line plant, 150,000 Mg/y using two, 10 Mg/h thermal lines with common process water cleaning systems.

The energy output established for the system and balance limits is composed of the heat given off from gas cooling (quench and cooling), the energy flow of the cold synthesis gas and from the flow of energy removed by the molten materials.

The heat given off by convection, radiation and other cooling is applied as a constant value.

The differences between the energy input and output, which resulted on the basis of the balance of elements and masses, were between 0.1% and 5% for the weeks of the study. The results further agree very well with the independently completed assessment of the data developed by TÜV Energy and Environmental Institute and the Institute for Engineering Thermodynamics at the University of Karlsruhe [9, 12].

The following tables and figures, together with the basis afforded by the test results, summarize the verified balances for the standard plant (2 lines, 10 mg/h/line, common process water cleaning system):

- Figure 14: [Water balance](#)
- Table 4: [Mass balance](#)

- Figure 15: [Mass balance](#)
- Figure 16: [Energy balance](#)
- Figure 17: [Synthesis gas production as a function of waste heat content and throughput](#). This is a graphic representation of the relationship between: throughput, heat content of the waste input and the volume of synthesis gas produced per metric ton of waste.

A study of synthesis gas utilization having sewage sludge pre-treatment was published by the Institute for Environmental and Safety Technology Inc. (UMSICHT). The study reports consumption of the synthesis gas using various types of gas conversion:

- Gas turbine and thermal recovery.
- Gas and steam turbine (combined cycle) with thermal recovery.
- Block thermal plant with internal combustion gas engines with thermal recovery.
- Block thermal power plant with diesel fuel assisted engines with thermal recovery.
- Figure 18: Synthesis gas: comparison of different methods of utilization. The ecological advantage of synthesis gas becomes particularly apparent from the fact that the resulting specific volume of flue gas, when related to the incineration thermal technique, is approximately 30% lower when synthesis gas is employed as an energy source.
- Figure 19: A comparison of the specific exhaust or flue gas volume between a Thermoselect standard plant and the European incineration process.

In conjunction with lower emission concentrations, this leads to a dramatically reduced burden on the overall environment. Such a comparison, combined with the integrated conversion of the solid wastes into synthesis gas, vitrified mineral product, recovered metals, water, salts and a metal hydroxide concentrate demonstrates the ecological advantages of this process.

The studies of the Thermoselect Demonstration Plant, the interpretations of the mass and energy balances and the studies of the chemical element distribution in the substance flow analysis confirm that the in-line design of the process is correct and capable [11]. TÜV Energy and Environmental Institute, commissioned by the Baden-Württemberg Ministry (FRG) for the Environment also confirm in their research report... "that the mass and energy balances determined at the large-scale plant in Fondotoce provide a reliable basis for the evaluation of the process." Consequent translation of the experiences attained and with optimization of projections, leads to prognostication that the Thermoselect figures for both auxiliary material consumption for mass and energy balances, and electrical energy surplus are attainable [9]. The enlargement of the scale to that of a standard two line plant is accomplished with a factor of only 2 to 3, and is judged as being manageable and without apparent risk.

Table 3: Material balances In the Fondotoce THERMOSELECT plant for comparison:

THERMOSELECT standard plant, 2 thermal lines, 10 Mg/h/mine, data per Mg of waste

Charge materials: kg/Mg		Products: kg/Mg	
Waste	1000.0	Purified synthesis gas	895.0
Organic	500.0	CO	421.0
Inorganic	250.0	CO ₂	444.8
Water	250.0	H ₂	26.5
		H ₂ O	5.5
		N ₂	27.2
Natural gas *	23.3	Mineral substances	230.0
		Metals	29.0
Oxygen	514.0	Process water **	381.8
		Mixed salt (~90% solids)	12.0
Max. additional materials (for synthesis gas and process water cleaning)	20.0	Me(OH) _x (~40% solids)	7.5
		Sulfur (~80% solids)	2.0
Total	1557.3	Total	1557.3

1. Study week 06/14 - 06/17/94, data per Mg of waste

Charge materials: kg/Mg		Products: kg/Mg	
Waste	1000.0	Purified synthesis gas	967.4
Organic	552.7	CO	447.8
Inorganic	242.1	CO ₂	457.3
Water	205.2	H ₂	27.2
		H ₂ O	27.6
Natural gas	32.1	N ₂	7.5
		Mineral substances	216.0
Oxygen	583.5	Metals	21.5
		Process water ****	394.8
Max. additional materials*** (for synthesis gas and process water cleaning)	6.1	Mixed salt (~90% solids)	9.0
		Me(OH) _x (~40% solids)	11.6
		Sulfur (~80% solids)	1.4
Total	1621.7	Total	1621.7

* Without natural gas for hot water boiler or combustion chamber flare (not part of a commercial facility.)

** Water from process water preparation without recycling of: side product slurry water, or vacuum pump exhaust condensation.

*** NaOH, HCl-, additive consumption.

**** Process water from the synthesis gas purification.

Table 3: (continued) Material balances in the Fondotoce Thermoselect plant for comparison:

2. Study week 06/21 - 06/25/94, data per Mg of waste

Charge materials: kg/Mg		Product: kg/Mg	
Waste	1000.0	Purified synthesis gas	957.1
Organic	513.0	CO	416.8
Inorganic	238.7	CO ₂	482.7
Water	248.3	H ₂	24.3
		H ₂ O	26.2
Natural gas	57.4	N ₂	7.1
		Mineral substances	210.8
Oxygen	633.1	Metals	22.2
		Process water ****	478.0
Max. additional materials*** (for synthesis gas and process water cleaning)	8.5	Mixed salt (~90% solids)	15.4
		Me(OH) _x (~40% solids)	14.3
		Sulfur (~80% solids)	1.2
Total	1669.0	Total	1699.0

3. Study week 06/27 - 07/01/94, data per Mg of waste

Charge materials: kg/Mg		Products: kg/Mg	
Waste	1000.0	Purified synthesis gas	966.4
Organic	514.0	CO	434.3
Inorganic	209.0	CO ₂	465.8
Water	277.0	H ₂	29.9
		H ₂ O	28.3
Natural gas	47.6	N ₂	8.1
		Mineral substances	183.6
Oxygen	589.1	Metals	19.8
		Process water ****	444.1
Max. additional materials*** (for synthesis gas and process water cleaning)	7.4	Mixed salt (~90% solids)	9.6
		Me(OH) _x (~40% solids)	19.5
		Sulfur (~80% solids)	1.1
Total	1644.1	Total	1644.1

* Without natural gas for hot water boiler or combustion chamber flare (not part of a commercial facility.)

** Water from process water preparation without recycling of: side product slurry water, or vacuum pump exhaust condensation.

*** NaOH, HCl-, additive consumption.

**** Process water from the synthesis gas purification.

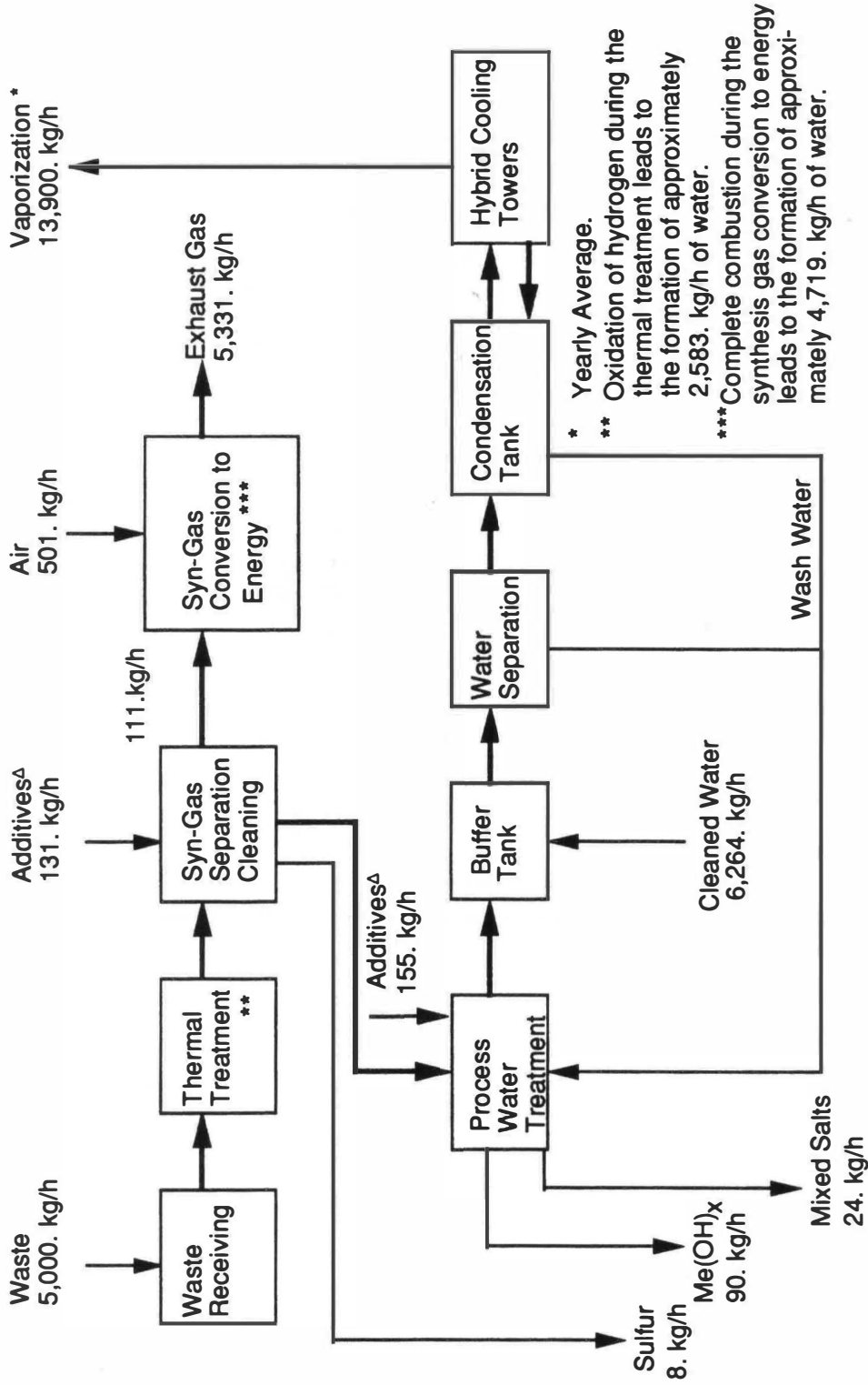


Figure 14: Water Balance - Two lines, 10 Mg/h/line: 150,000. metric ton/year.

^Δ Assumes maximum amount of additives required for synthesis gas and process water cleaning.

- Heat value of the waste: LHV: 10 MJ/kg; mass fraction of hydrogen in the organics is approximately 4%.

Table 4: Mass Balance

Charge Materials: kg/h		End Products: kg/h	
Waste	20,000.	Purified synthesis gas	17,900.
Organic	10,000.	CO	8,419.
Inorganic	5,000.	CO ₂	8,297.
Water	5,000.	H ₂	529.
		N ₂	544.
		H ₂ O	111.
Natural gas	466.		
Oxygen	10,280.	Mineral substances	4,600.
Additive substances	<400.	Metals	580.
• synthesis-gas purification requirements*		Operating Water	7,636.
Additive	<12.	Mixed salt (90% solids)	240.
NaOH	<90.	Me(OH) _x (40% solids)	150.
HCl	<75.	Sulfur (80% solids)	40.
• process-water preparation requirements*			
NaOH	<110.		
Na ₂ S	<93.		
FeCl	<13.		
FHM	<0.6		
HCl	5.		

*Indicated in each case are the maximum quantities of additives expected.

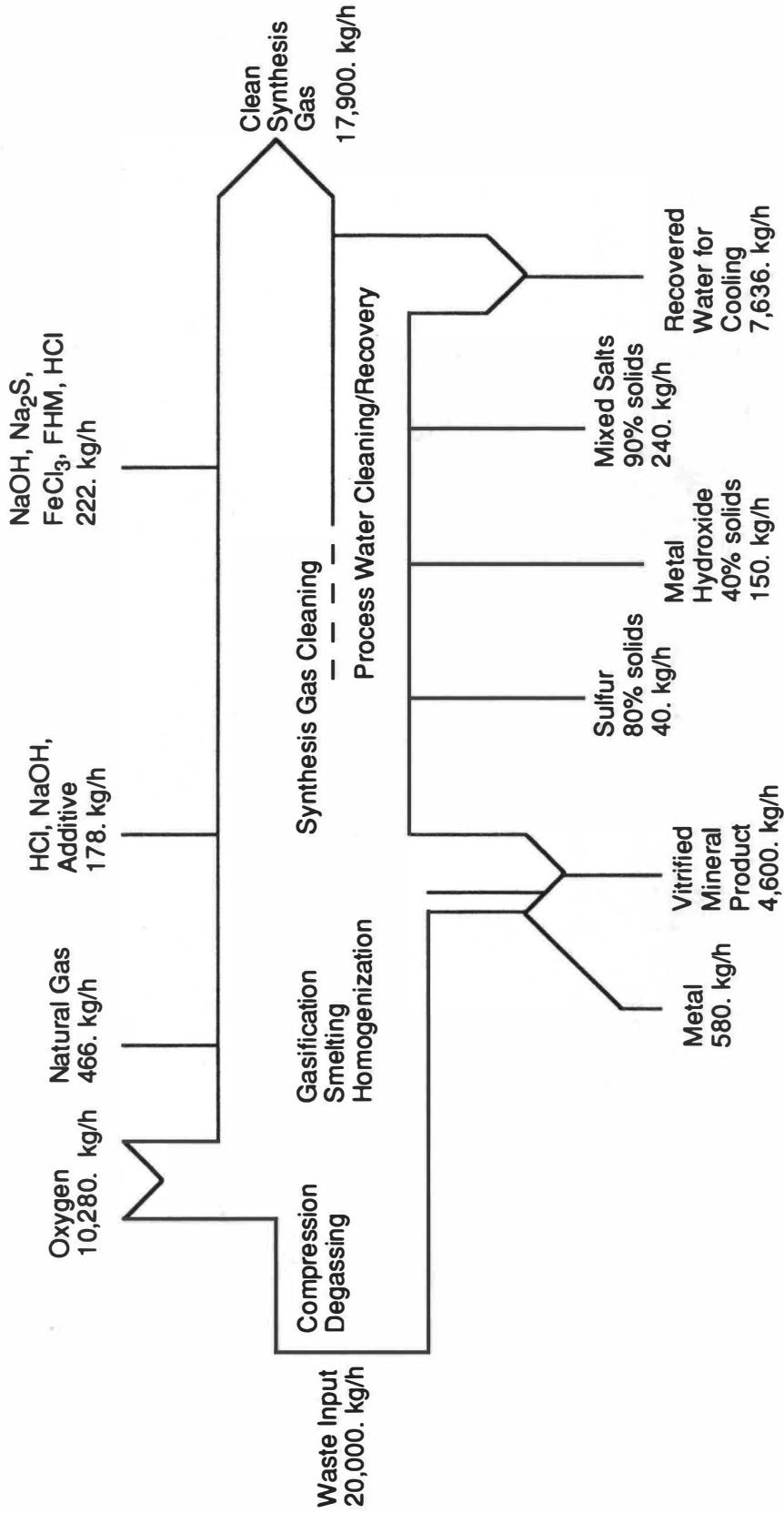


Figure 15: Mass Balance - Two lines, 10 Mg/h/line: 150,000 metric ton/year. Maximum quantity of additives included for synthesis gas and process water cleaning.

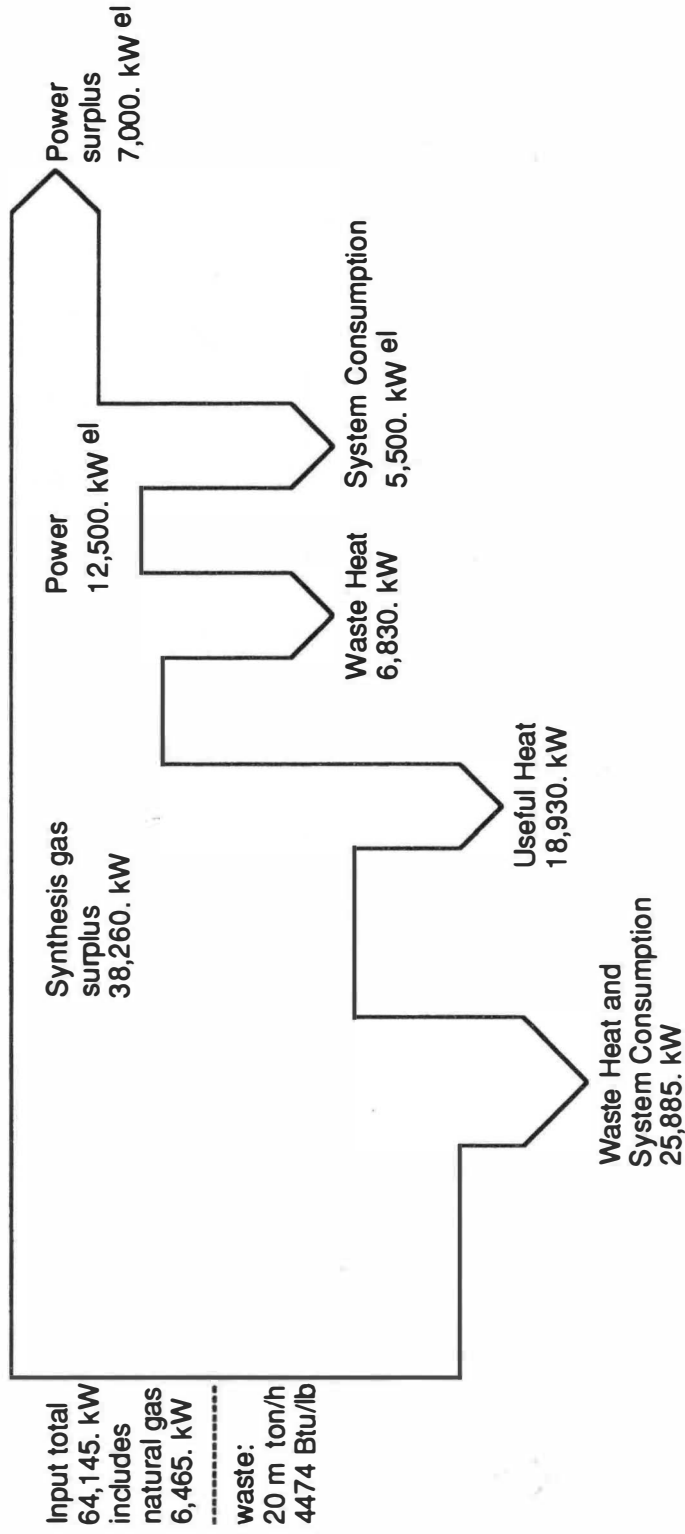
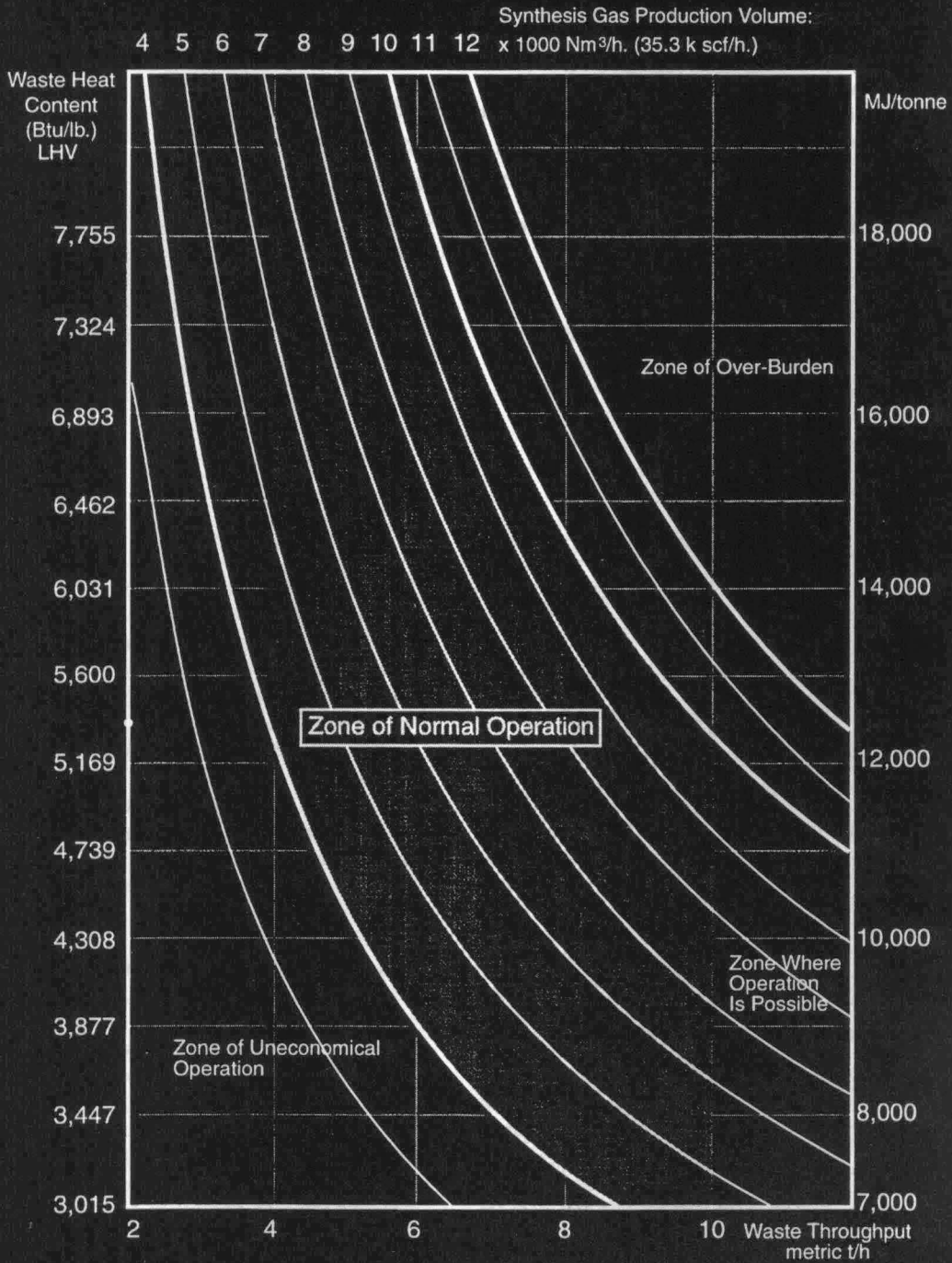


Figure 16: Energy Balance - LHV = 2,884 kWh/Mg; Efficiency of Gas Engine: 34%
Two lines, 10 Mg/h/line: 150,000 metric ton/year.

THERMOSELECT



Synthesis Gas Production

as a function of: **Waste Heat Content and Throughput**

96-730 Rev. 1/25/96

Figure 17

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