TNO-REPORT

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TNO Environment, Energy and Process Innovation

Efficiency Increase of Waste-to-Energy Plants
Evaluation of Experience with Boiler Corrosion and Corrosion Reduction

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Preface

Corrosion reduction is an important item within the 'Combustion' section of the Dutch VVAV (Dutch Waste Processing Association). As almost all Waste-to-Energy plants are subject to more or less corrosion, this item is very suitable for a collaborative approach.

Previously (7 September 2001) the topic was discussed in a thematic meeting on "Refractory Lining and Corrosion in Waste-to-Energy Plants" (Bemetseling en corrosie bij AVI's). As a result of the positive reactions, the 'Combustion' section of the VVAV has decided to start a specific research project on the experience of VVAV members (plant owners) with boiler corrosion and corrosion reduction.

A second reason for this research is the potential application of a higher steam pressure and temperature for reasons of efficiency. Experience with the current types of Waste-to-Energy plants indicates that, without additional measures, corrosion would increase strongly. The research project is to increase the knowledge about the possibility of applying higher steam conditions in a technically and economically feasible way.

The research was initiated as a knowledge transfer project. To maximize the output of the project for the members of the 'Combustion' section of the VVAV, a well-attended workshop was organized on 21 January 2003.

The project was financially supported by NOVEM, while TNO-MEP carried out the research.

This report is also available in Dutch.

TNO   VVAV

1. Introduction

The Dutch VVAV (Dutch Waste Processing Association) and TNO-MEP, with support from Novem, have carried out a study on corrosion in Waste-to-Energy plants. They evaluated the effects of corrosion as related to water/steam temperatures with a view to increasing the electric efficiency of these plants. The aims of the study were:

- To review experience with corrosion and possible corrosion reduction measures in Waste-to-Energy plants in the Netherlands and abroad. Both the normal steam conditions of 40 bar 400°C and higher steam conditions were considered.
- To evaluate whether there is sufficient knowledge and experience to enable higher efficiencies by increasing steam temperature and pressure in future Waste-to-Energy plants.

Questions to be answered are:

- Is there sufficient know-how available for plant owners and operators to decide on corrosion reduction measures?
- What kinds of effective measures are available?
- Is it possible to apply higher steam conditions in a technically and economically acceptable way?
- What kind of additional research would be needed to achieve this?

2. Execution

The investigation was subdivided into two tasks:

1. Collecting and evaluating the know-how on corrosion and corrosion reduction:
   - From literature.
   - From plant owners in practice.

   In addition to the literature search, Dutch Waste-to-Energy plants were visited from May to July 2002. The researchers also included experiences abroad by contacting Onyx, IEA and ISWA and visiting the plant in Düsseldorf, Germany, which is operated with 500°C steam.

2. Using this inventory to assess the applicability of the knowledge both for the current situation as well as for higher steam conditions. This evaluation was carried out from August to December 2002. Special attention was given to applying corrosion reduction measures in Waste-to-Energy plants designed to use higher steam conditions, e.g. temperatures > 500°C and 100 bar.

2.1 Results and Recommendations From Literature

2.1.1 Process conditions and corrosion

Above the grate in the first pass, combustion temperatures are mostly between 850 °C and 950 °C, though occasionally as high as 1100°C. Although excess air is used, local variations in waste and process conditions can result in products of incomplete combustion (PIC) such as C_xH_y, unburned (sticky) particles and other compounds, and high CO concentrations. The European authorities have introduced guidelines for solid waste combustion. These guidelines regulate the process conditions in the furnaces. According to these guidelines, the temperatures at the 2-second residence time

(considered from the 1 m level above the last air injection point (secondary air or tertiary air)) should be above 850°C.
In the first pass of the boiler, heat is transferred from hot flue gases to the water walls, which consist of membrane type evaporator tubes. In most plant designs the lower parts of these walls are covered with refractory or tiles. Water walls and evaporator screen tubes can reduce the flue gas temperature to values of about 600° to700°C, before the superheaters. Subsequently, heat is transferred from the hot flue gas to the tubes of the superheaters, evaporators and economizers and/or air heaters.

The membrane water walls in the first pass of the boiler and the superheater tube bundles are particularly subject to corrosion. The corrosion is caused by aggressive flue gas components like CO, Cl_2, HCl, S, alkali metals and heavy metals such as Zn and Sn, which are able to form chlorides with high vapour pressures, as will be explained later. In the process of cooling down, deposits will be formed on water walls and tube bundles by condensation or sublimation.
As high temperatures and high temperature gradients increase corrosion, it is important to keep temperature differences between gas and metal small. Temperature peaks near superheaters can be reduced by the application of screen tubes and evaporator tube bundles in front of the superheaters. With respect to corrosion, the most sensitive areas are shown in Figure 1.

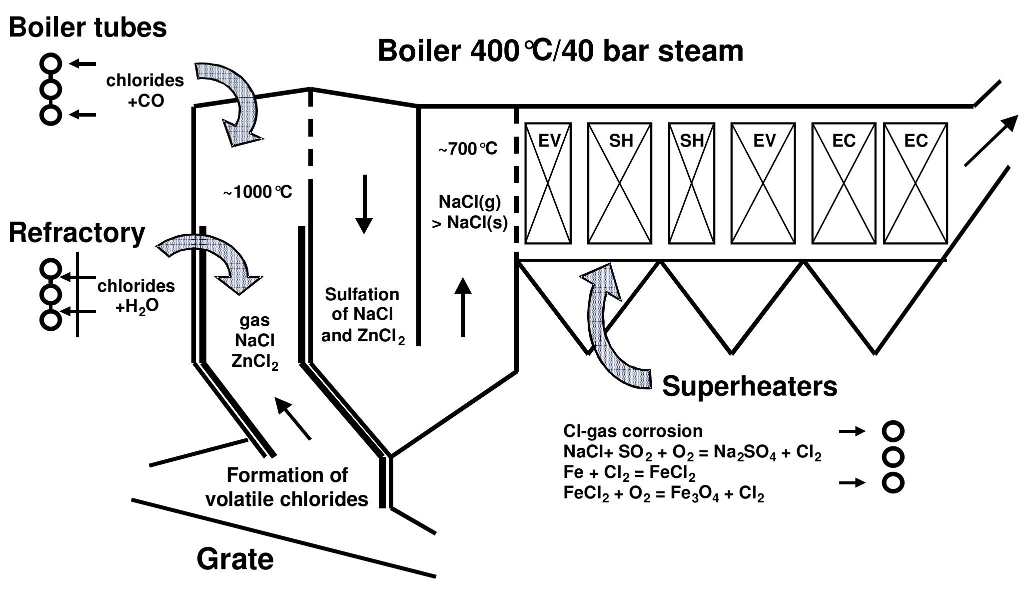

Figure 1. Typical corrosion problems in Waste-to-Energy plants

The metal temperature of water walls and tube bundles is determined by the flue gas temperature on the one hand, and the water-steam system which provided the heat transfer and cools the metal on the other hand. Current steam conditions are 400°C and 40 bar. Indications for temperature levels are given in Table 1.

Table 1. Boiler parts and indicative temperature levels.

Boiler part	Steam system	System	Metal	Flue gas

		temperature [°C]	temperature [°C]	temperature [°C]
Water wall	Evaporator	265	~ 300	~ 1000-800
Screen tubes	Evaporator	265	~ 300	~ 800-700
Superheater	Steam generator	400	~ 450	~ 700-600

2.1.1 Corrosion mechanisms

Literature provides much information on corrosion mechanisms and the effect of temperature and deposit formation. Here the experiences are summarized without reference to a specific article.
It is generally accepted that the high level of chlorides in waste is the main reason for corrosion. High temperature corrosion in waste incinerators is caused by chlorine either in the form of HCl, Cl_2, or combined with Na, K, Zn, Pb, Sn and other elements. In particular, both gaseous HCl with a reducing atmosphere, and molten chlorides within the deposit are considered major factors. Sulphur compounds, which at high temperatures can be corrosive compounds themselves, can enhance or reduce the corrosion caused by chlorine.

In the first pass of the boiler above the grate, corrosion is primarily caused by a combination of:
- High CO levels and a local reducing atmosphere;
- A significant temperature difference between the flue gas and the membrane water wall, resulting in the formation of deposits containing, among other things, metal chlorides;
- Reducing conditions under these deposits, enhanced by unburned substances.

Corrosion of membrane water walls by CO under reducing conditions has been studied in the past in relation to staged combustion aimed at reducing NO_x formation. Figure 2 shows how, in pulverized coal-fired boilers, carbon-steel and low alloy steel corrosion is influenced by the flue gas composition near the boiler wall. The corrosion rate tends to increase strongly at CO levels of about 0.5 to 1.5 vol% and O_2 levels of about 1 vol% and lower (approx. 12,500 mg/m^3 ind). Under these conditions the protective properties of the oxide layers are lost. This process is enhanced by the presence of impurities like chlorine and sulphur. Normally, boiler steels are covered with a solid and tight oxide layer mainly consisting of Fe_2O_3 and Fe_3O_4. This layer limits further oxidation in such a way that the oxidation rate slows down. The oxidation rate as a function of time (reaction kinetics) can be described as a parabolic or a logarithmic function. In this way oxide layers formed under sufficiently high oxygen levels provide protection for the steel.
However, unless there is enough oxygen the combustion is not complete, which causes relatively high CO concentrations. If conditions of O_2 reduction and enriched CO contents exist for longer times, oxide layers will be formed which are rather porous and laminated. This will change the kinetics of the oxidation reaction to a linear function with time. Also, under low O_2 contents (low oxygen partial pressure) in the presence of sulphur and/or chlorine, iron will tend to form FeS and $FeCl_2$ instead of Fe_2O_3. This worsens the quality of the oxide layers, and already existing layers can be converted, resulting in loss of protection and enhanced corrosion. FeS and $FeCl_2$ do not form tight protective layers.

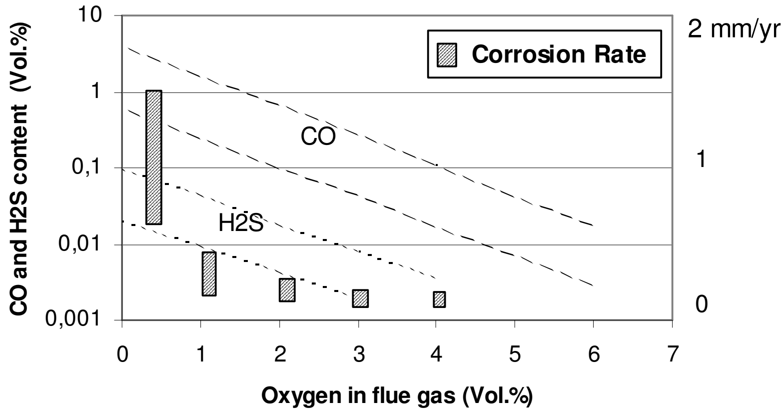

Figure 2. Corrosion of carbon-steel at 450° as a function of the flue gas composition in pulverized coal-fired boilers

In addition to CO-reducing conditions near the membrane water walls of the boiler, the temperature difference between gas and metal is very high. The temperature gradient enhances the formation of deposits consisting of chlorides of both alkali metals and heavy metals. And pure alkali metal chlorides have been found in deposits near the metal surface. In these boiler parts, the formation of chloride-rich deposits in combination with local high CO levels is believed to be the main reason for corrosion of membrane water walls.

Downstream in the boiler system, the following corrosion processes are expected to control metal losses, in particular in superheaters:

- Corrosion by chlorine in HCl/Cl_2 and SO_2/SO_3 containing gas under oxidizing or reducing conditions;
- Corrosion by deposits of metal chlorides and sulphates.

The mechanisms consisting of cyclic reactions in deposits have been described by various authors in many papers. An overview is given in Figure 3. The main reactions include inward diffusion of chlorine, lack of oxygen, formation of volatile Fe chlorides near the metal surface, outward diffusion and oxidation, and, again, penetration of chlorine. The mechanism that interferes with the formation of protective oxide scales is called ‘active oxidation’ and results in high corrosion rates.

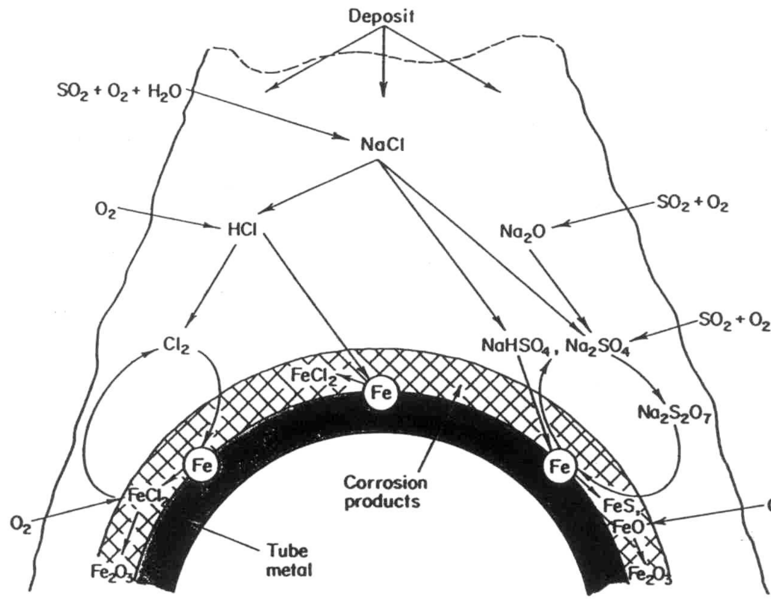

Figure 3. Sequence of chemical reactions explaining corrosion of incinerator boiler tubes (Ref. Krause, 1986, 1993)

It is generally accepted that formation of salt mixtures is the main reason for more or less local corrosion in the 250 to 400°C temperature range. Provided the local build-up is high enough, molten salts are able to convert the protective oxide layers in complex metal oxichlorides.

2.1.3 Corrosion-resistant materials

In practice, the strategy with respect to operation times and maintenance plays an important role for the selection of corrosion-resistant materials. In the past, a great deal of research was carried out and data on materials behaviour were obtained. During the last ten years, much information has been obtained in Europe from WtE plants concerning candidate boiler materials, corrosion rates and life times.
To protect the water walls in the first pass of the boilers, a refractory lining or SiC tiles are applied in most incinerators. However, these linings are not without problems, and frequent maintenance is needed. In many boilers severe corrosion occurs just above the lining, and extension of the lining always results in movement of the attacked zone. In practice, the application of metallic weld overlays consisting of a resistant alloy 625 type has proven very successful because of low maintenance costs, a high heat transfer and a low fouling tendency.

With respect to the behaviour of superheaters, the long-time exposure of candidate materials in the AVR-Avira plant in the Netherlands has contributed considerably to our insight in this area. As corrosion is a thermally enhanced process, results were used to calculate the activation energies and to make extrapolations for different temperatures and times. Results are given in Figure 4. The 15Mo3 steel is a low alloy steel with 0.3% Mo; the alloy 625 is an Ni-base material with Cr, Mo and Nb.

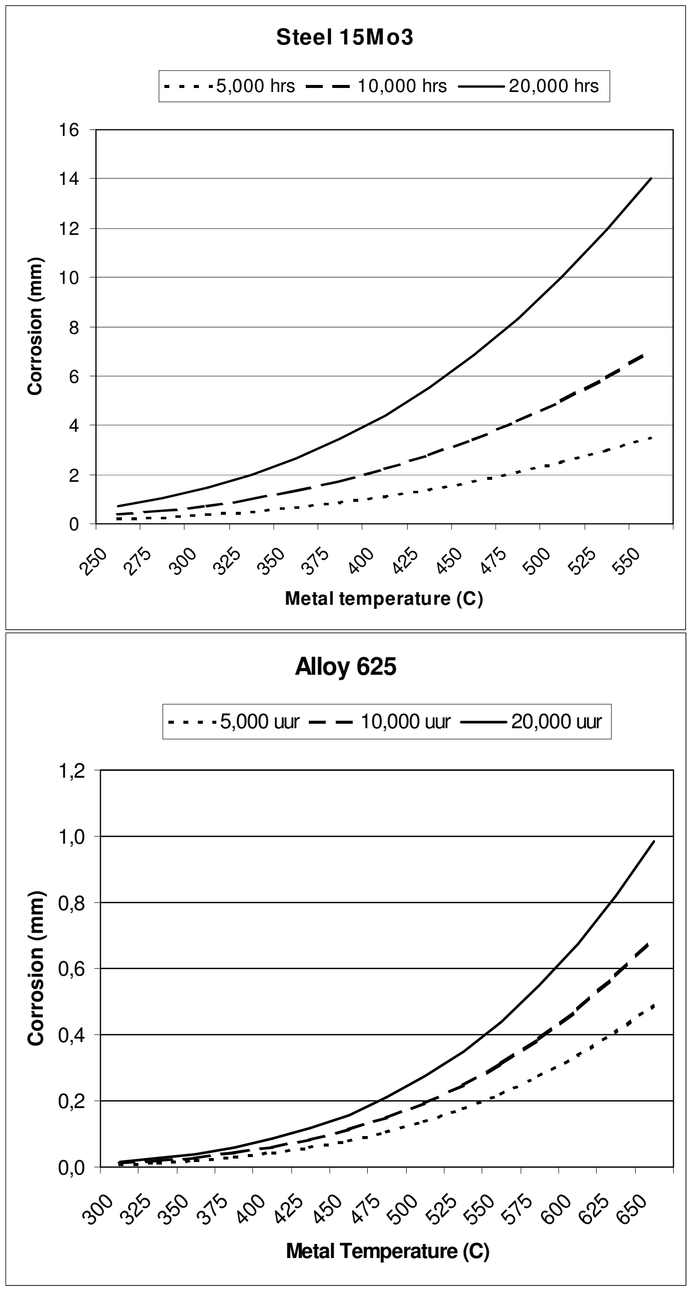

Figure 4. Extrapolated superheater corrosion data for boiler steel 15Mo3 and alloy 625 (18)

It has to be emphasized that the results depend very much on the specific boiler, the superheater entrance temperatures and the bundle configuration (horizontal tubes). Nonetheless, others have reported similar corrosion rates. Indicative data from Dutch incinerators and from abroad, both on water wall corrosion and superheater corrosion, are given in Table 2. Note that the wall thickness is usually limited to about 5 or 6 mm. The high corrosion rates have to be regarded as unacceptable because they will result in frequent and costly repairs, e.g. of superheaters after one or two years and of membrane walls after two to five years.

Table 2. Experience on corrosion rates for boiler parts of WtE plants

Boiler part	**Evaporator tubes**	**Superheater tubes**
Tube wall temperature	~ 250-300 °C	~ 400-530 °C
Tube arrangement	Membrane wall	Bundles
Material	C steel (St.35.8)	Low alloy steel (15Mo3)
Typical corrosion rates	0.15-0.30 mm/yr	0.20-0.40 mm/yr
High corrosion rates	0.30-2.0 mm/yr	0.40-4.0 mm/yr

As indicated before, Ni-base alloys have proven themselves to be the most resistant tube materials thus far. From the corrosion mechanisms it can be understood that nickel is more resistant, because Ni chloride is less easy to form and has a much lower volatility than Fe chlorides. The resistance of an alloy increases as the Fe content is lower. The corrosion by HCl decreases with an increase of the Cr and Mo content. The rate of maximum local penetration decreases with Mo contents up to about 5 wt%. Table 3 shows already applied and candidate materials together with boiler steels.

Table 3. Overview of candidate materials and their nominal composition (wt%)

Material	**Type (DIN)**	**Nominal composition (wt%)**				
		Fe	Cr	Ni	Mo	Other
Boiler steel	St37.8	Base	-	-	-	C
Boiler steel	15Mo3	Base	-	-	0.3	C
Boiler steel	13CrMo44	Base	1.0	-	0.5	C
Boiler steel	10CrMo9.10	Base	2.25	-	1.0	C
Alloy 28 *	1.4563	~38	26	31	4.0	Cu
AC66 *	1.4877	~ 40	27	32	-	Ce,Nb
Alloy 33 *	1.4591	~ 32	33	31	1.6	Cu
Alloy 825 *	2.4858	~ 38	20	38	3.0	Cu,Ti
NiCr 45-TM *	2.4889	~ 26	27	46	-	Si, Ce
Alloy 622 *	2.4602	2-6	21.5	Base	13.5	Co
Alloy 625 *	2.4856	~ 5	22	60	9.0	4Nb
Alloy 63 *	~ 2.4856	~3	21	Base	8.5	3Nb
Alloy 65 *	Mod. 625	~4	21	Base	8.5	-

* Usually more producers; trade names include Sanicro (Sandvik), Nicrofer (Krupp-VDM), Inconel (Special Metals), etc.

With respect to the selection of materials the following options exist, although experience with some of them is limited.

- ‘Composite’ tubes, consisting of an inner layer of boiler steel and an outer layer of a highly resistant material, e.g. a Ni-base alloy. Composite tubing has been applied successfully in superheaters, among other things.
- Weld overlays (cladding). Both water walls and other tubes, e.g. superheaters, are clad with a resistant and available wire material like alloy 625.
- Advanced powder coatings of resistant material by a thermal spraying technique like HVOF (High velocity oxygen flame). Experience with this option is limited.
- Ceramic refractory materials as a casting concrete or SiC tiles, particularly on the water walls of the first boiler passes.

2.2 Summary of Practical Experience

2.2.1 Locations sensitive to corrosion

The plant visits made during this study proved that all Waste-to-Energy plants suffer from corrosion to a greater or lesser degree.
However, this study revealed significant differences in the sensitive areas and in the corrosion rates encountered. In general, most corrosion problems in Waste-to-Energy plants occur near the following parts:

- Covered walls in the first pass above the grate – problems with the refractory linings;
- Boiler water walls above the refractory lining – corrosion of the metal on the water wall;
- Superheaters, in particular in the first tube rows of the final (and hottest) superheater.

2.2.2 The main causes and mechanisms

Several factors influence corrosion, and differences exist between membrane water walls and other parts, like superheaters.
On water walls, the corrosion of tubes is caused by a combination of:

- Occurrence of deposits which, added to the heat transfer, cause a chemical load, interfering with the formation of protective oxide layers on the steel;
- Increased CO concentrations (CO-enriched flows) causing reducing conditions;
- Erosion-enhanced corrosion due to high velocities of the flue gas loaded with particles.

In many cases wall tubes were attacked by the aggressive atmosphere even after refractory lining or tiles were in place, either by penetrating cracks and holes in the lining or holes due to missing tiles.
Corrosion of superheater tubes has to be ascribed mainly to the formation of aggressive deposits, in combination with high flue gas temperatures, which tend to increase during operation as a result of fouling.
With respect to the temperature, the following effects have to be distinguished:

- The temperature (and composition) of the flue gas and entrained particles. At higher temperatures the gas can contain higher amounts of volatile and sticky compounds.
- The temperature difference between gas and metal. This determines the driving force for condensation or sublimation of substances from the gas onto the cooler metallic parts. The greater the temperature difference, the higher the thermal and chemical load, which controls formation of corrosive deposits and the cyclic reactions in the deposits.

- The metal temperature itself, which is ruled by the steam conditions. The metal temperature is relatively constant, except in cases in which cooling is lacking. In superheaters the metal temperature increases in the downstream direction of the steam, and high metal temperatures can exist up to the next injection cooler, which determines the local corrosion rate. Although gas temperatures are limited in the superheater area, the metal temperature can be quite high, depending on the steam flow and the way the subsequent bundles are located.

2.2.3 Corrosion reduction

Corrosion reduction measures can be subdivided as follows:
1. Improvement and control of the process conditions for the exposed materials, such as temperatures, temperature variations, and fouling phenomena;
2. Selection and application of more resistant materials, and improvement of design and construction.

Improvement of process conditions in order to get less corrosive conditions can be achieved by:

1.1 Optimizing the combustion process and the combustion control
- Control air distribution and flue gas mixing (modify the primary/secondary air ratio, relocate secondary air nozzles, install air inlet and mixing ‘prism’);
- Optimize combustion control (anticipate feed input reduction, control superheater gas inlet temperature to < 650°C);
- Reduce temperature levels (excess air, reduce refractory lining area by increased weld overlay area in first pass, use additional evaporation bundles);
- Control heating value of the waste, and if necessary limit certain amounts;
- Pre-mix the waste.

1.2 *Improving the boiler cleaning*
- Modify or remove soot blowers;
- Optimize knocking mechanisms used on pending tube bundles;
- Apply explosive cleaning techniques (detonation, gas);
- Clean empty passes by means of a water jet.

Improvement of materials and construction can be achieved by:

2.1 Selecting more resistant materials
- Weld overlays of e.g. alloy 625, in particular on membrane walls;
- Composite tubing (2 layers) for tube bundles;
- Modify the anchors for SiC tiles
- Advanced tile systems
- Advanced cast refractory.

2.2 Modifying design and/or construction
- Modify air amounts, distribution and inlet system (‘prism’, secondary air nozzles, reduce flue gas recirculation);
- Modify the sequence of superheater bundles and the direction of the steam flow;
- Optimize injection cooling in steam system;
- Install a water-cooled grate;
- Modify a surface area covered by refractory.

3. Evaluation

3.1 Experience in Waste-to-Energy Plants

Factors determining lifetime
On the basis of both practical experience and theoretical considerations we have attempted to identify factors that enhance corrosion of water walls and superheaters on the one hand, and factors that are believed to contribute to lifetime extension on the other hand. It is obvious that several factors are connected in such a way that the influence can only be indicated qualitatively.
The following tables show the factors that can be regarded as most important. As several aspects are considered, the possible effects are divided into three groups:

- Waste composition (Table 4);
- Construction and materials (Table 5);
- Plant operation (Table 6).

In the tables an expected effect is indicated as obvious with ‘x’.
Effects expected to be strong are indicated with ‘xx’.

Table 4. Effects of waste composition on the lifetime of membrane walls and superheaters

Aspect of waste	Negative	Positive	Remarks
High chlorine content	xx		Primary cause of corrosive environment both in flue gas and in deposits
High heating value (>10 MJ/kg)	x		High temperatures may be positive for combustion
Homogeneous		x	Fewer CO peaks near walls
High sulphur/chlorine ratio	x		Positive only at high ratios, e.g. SO_2/HCl = 3/1
High moisture content	x		Bad combustion

Table 5. Effects of construction and materials on lifetime of membrane walls and superheaters

Aspect	Negative	Positive	Remarks
Big bunker, mixing allowed		x	More constant fuel
Roller grate	x		Less combustion process control
Moving grate		x	Better process control
Water-cooled grate		x	Better control range primary air
2 pass system	x		Limited mixing of gas, no ash removal, more fouling of bundles
4 pass system		x	Temperature decrease, better mixing, ash removal before convection section, less fouling of bundles
Refractory 1e pass		x	Wall protection
SiC lining wall		x	Good heat transfer, low fouling tendency

Weld overlay wall		x	Excellent heat transfer, low fouling tendency
Pre-evaporator(s)		x	Temperature reduction before superheater
Vertical convection section	x		With horizontal bundles more fouling
Horizontal convection section		x	Vertical bundles, less fouling, better cleaning facilities possible
Superheater counter flow	x		High tube wall temperatures
Superheater co-current flow		x	Lower tube wall temperatures
End superheater first	x		High temperature difference with flue gas
End superheater second		x	Low temperature difference with flue gas

Table 6. Effects of operation variables on lifetime of membrane walls and superheaters

Aspect	**Negative**	**Positive**	**Remarks**
Good mixing flue gas		x	Less CO
Complete combustion		x	Less unburned particles in deposits
Regular cleaning of main boiler parts		x	Amount of aggressive deposits limited
Soot blowing	x		Local erosion/corrosion
Gas temperature before superheater > 650°C	x		Corrosion enhanced, resistance of tube materials limited
Heavy fouling	x		Chlorine and iron transfer across deposit layer
High waste load	x		High temperatures and more fouling
Explosive cleaning during operation		x	Less deposits, increased availability

Generally, it can be observed that Waste-to-Energy plants that show high corrosion rates combine several of the factors which are expected to have a negative effect, and plants that show low corrosion rates combine more factors which in the tables are indicated as positive.

3.2 The Effect of Higher Steam Conditions

The application of higher steam conditions (e.g. 500°C and 100 bar) will change the situation. Not only will the superheater temperatures increase, but so will the evaporators due to the higher pressure and the higher saturation temperature. As a result, the metal tube wall temperatures will also reach higher temperature levels, as indicated in Table 7, and higher corrosion rates are likely for both water walls and superheaters. In practice of one of the visited plants evaporation tubes showed increased corrosion, most likely because of the higher steam pressure of 100 bar.

Table 7. Estimated temperatures for a steam system operating at 500°C and 100 bar.

System part	**40 bar**	**40 bar**	**100 bar**	**100 bar**
	Water/steam	Metal wall	Water/steam	Metal wall
Membrane wall	265°C	~ 300°C	310°C	~ 345°C
Evaporator	265°C	~ 300°C	310°C	~ 345°C
Superheater	400°C	~ 450°C	500°C	~ 550°C

On the basis of these temperatures and the extrapolated corrosion data (Fig. 4) the effect of higher steam conditions can be estimated. The results are given in Table 8.
For a plant that has not been optimized but does have similar design and tube bundle configurations, increased steam conditions according to Table 8 would result in an increase in corrosion of a 15Mo3 evaporator tube with a factor 1.5 to 1.8. The corrosion of a 15Mo3 superheater tube would increase with a factor 2.0 to 2.5. With regard to more resistant materials like Alloy 625, higher steam conditions, particularly in the superheater, would increase the corrosion rates as well, albeit that corrosion rates are expected to be limited to about 0.3 mm a year.

Table 8. Estimated increase of corrosion for a not-optimized conventional plant designed to operate under higher steam conditions of 500°C and 100 bar

System part	**Wall temperature**	**Corrosion factor**	**Possible measures or applications**
Membrane wall	~ 345°C	1.5 – 1.8	Weld overlay / cladding
Evaporator	~ 345°C	1.5 – 1.8	Weld overlay / composite tubes
Superheater	~ 550°C	2.0 – 2.5	Weld overlay / composite tubes

This study only briefly describes some of the aspects connected with a Waste-to-Energy plant designed for high steam conditions of 500°C and 100 bar. It is obvious that all aspects have to be considered in more detail in order to optimize and redesign a plant and to estimate the possible benefits of higher steam conditions. With respect to the additional investment required, the economic feasibility of higher steam conditions will depend on the developments of the waste gate fees and energy prices (kWh tariffs).
In a previous study, the effects of higher steam conditions on the boiler configuration, in particular on the heat exchanger surface area, have been estimated. For a reference boiler with a capacity of 18 tonnes of waste per hour, some figures are given in Table 9 (figures for 500°C steam not available).

Table 9. Reference boiler 18 t/h; heat exchanger surfaces (m^2) under different steam conditions.

System part	**Standard conditions**	**High efficiency**	**Materials / measures**
	40 bar 400°C	100 bar 520°C	
Membrane wall	910 m^2	966 m^2	Weld overlay / cladding
Evaporators	1249 m^2	501 m^2	Weld overlay / composite tubes
Final superheater	853 m^2	790 m^2	Weld overlay / composite tubes
Superheater 1-2	1875 m^2	-	Weld overlay / composite tubes
Superheater 1-2-3	-	2961 m^2	15Mo3
Superheater 4	-	511 m^2	15Mo3
Economizer	2797 m^2	3304 m^2	St.35.8

The main effect of higher steam conditions is a substantial increase of the total superheater surfaces from 2728 m^2 to 4262 m^2. The main reason for this is the decrease in temperature differences between flue gas and tube wall, which causes a decrease in heat transfer, which only can be compensated for by more surface. As the amount of tubing increases, it is desirable to apply more separate bundles for the sake of maintenance.

The expected results of the application of higher steam conditions are summarized qualitatively in Table 10. As said before, the additional investment costs have to be calculated in detail for a new design, and regarding the plant capacity costs have to be compared with the increased energy benefits.

Table 10. Consequences of higher steam conditions for a Waste-to-Energy plant design

System part	**Remark**
Grate	Water cooling desired, depending on calorific value
Combustion zone	High volume, more passes, low velocities, ash removal
Membrane wall	Advanced refractory and extension of weld overlay surfaces
Superheaters, total	Increase of heat transfer surface with about 50%
	Increased amount of tube bundles
	Extension of parts from resistant materials
Convection pass	Extension due to increased superheater surfaces
Weight, total	Considerable increase, more bundles
Steam system	Dimensions and weight of pressure parts increase
Feed water pumps	Higher capacities required
Turbine-generator	Dimensions, weight and capacity to be higher

The previous study clearly showed that higher temperatures require more plant parts to be protected by advanced materials or weld overlays. With the same plant availability the advantage of a higher efficiency would hardly compensate for the additional investment.
However, the present study revealed that the situation has changed considerably.
Part of the measures required for higher steam conditions are already a part of current plants for reasons of lifetime extension and enhanced availability. The question is whether these measures will also be sufficient in case of higher steam conditions, which raises demands on components. This has been confirmed at the Waste-to-Energy plant in Düsseldorf, Germany, which has operated for many years with steam of 500°C and 100 bar. Despite many corrosion reduction measures in the past few years, the plant suffers from severe corrosion. Because the total combustion capacity is more than is necessary, there is no problem with availability.

If one has the opportunity to start with a new design for a Waste-to-Energy plant to be operated under high steam conditions, several potential plant optimization options present themselves. According to expectations, plants can be optimized in such a way that the disadvantage of the higher metal temperatures probably can be compensated to allow economic lifetimes under higher steam conditions.
Several measures can be applied:
- Improve the combustion process, in particular the temperature control and the mixing of the flue gas (water-cooled grate, ‘prism’ system for air injection, locations of secondary air injection);
- Apply correct plant dimensions (adequate sizing), consisting of several passes with ash removal, additional mixing, and a horizontally convective pass with pending tube bundles;
- Reduce fouling, for instance by cleaning boiler parts more thoroughly with improved systems.
- Use resistant materials. Part of the first pass could be covered with advanced refractory and tiles systems. Other parts could be clad with resistant weld overlays. If heating values are high enough to meet the requirement for temperatures to be above 850°C for at least 2 seconds, extension of clad surfaces and reduction of refractory lined area would be worth considering;
- Install evaporator bundles in front of the superheaters (in addition to e.g. screen tubes);
- Optimize the configuration and flow direction of superheater tube bundles;

- Optimize injection coolers in the steam system for enhanced temperature control;
- Use corrosion-resistant materials, either as cladding or as composite tubing, in the superheater parts that are subject to the most severe conditions;
- Design the plant in such a way that tube bundles can be easily replaced.

It has to be emphasized that the effect of these measures on the availability of a Waste-to-Energy plant is still uncertain. In this respect it is important to mention that GDA in Amsterdam is studying the possibility of constructing an advanced steam system (high temperature, high pressure) for application in a new WtE combustion line.

4. Conclusions and Recommendations

Both from literature and from practice, this study has contributed much to a better understanding of the ruling corrosion mechanisms in Waste-to-Energy plants. The study has resulted in comprehensive lists of factors that have either a positive or a negative effect on the corrosion of membrane water walls and superheaters. These lists can be used to assess an installation and its parts with respect to the corrosive conditions and the potential danger of lifetime reduction by corrosion. Factors can be subdivided into waste composition, construction, type of materials used, and the plant operation. With this knowledge, both (future) plant owners and operators can decide on measures to be taken to reduce corrosion and to increase plant availability. Observations revealed that examples of increased corrosion rates could be explained by a combination of those influencing factors.

The main two reasons for corrosion of membrane water walls of Waste-to-Energy plants are the thermal and chemical load that results in the formation of salt deposits, and the alternating oxidizing and reducing conditions in the flue gas. This combination decreases the protective properties of the oxide layers, which in turn increases corrosion. Despite the presence of refractory on part of the walls, the membrane walls often suffer local corrosion under the refractory due to defects such as cracks, or lost refractory material or tiles.
Corrosion of superheater tubes in Waste-to-Energy plants is mainly caused by high flue gas temperatures (both incidental peaks and temperature increase by fouling), in combination with formation of deposits containing aggressive substances.
In addition to this, our study revealed that various practical plant improvements are necessary, especially with respect to the control of the combustion process, the accuracy of temperature measurements, and the accuracy of repeated wall thickness measurements. So far, experience with higher steam conditions is limited and subject to uncertainties.

The study shows several methods for reducing corrosion and reaching economic lifetimes for the main plant components. In summary these methods can be subdivided as follows:

- Improvement of conditions to which the materials are exposed, i.e.:
  - Optimization of the combustion process and the operation;
  - Improvement of boiler cleaning;
- Improvement of materials and construction details.

The success of the different methods strongly depends on the specific properties of an installation. From the present experience it can be concluded that corrosion reduction and increased plant availability have already been achieved at many plants. The application of alloy 625 weld overlays and cleaning by explosives are mentioned specifically as being very effective. These measures are very valuable for future advanced Waste-to-Energy plants.
The application of higher steam conditions will result in an estimated temperature increase of the metal temperature of approximately 45°C for evaporators and 100°C for superheaters. This can result in an increase of corrosion rates with 50% to 150%, assuming long-term in-plant exposure of metallic components. The practical experience with these increased metal temperatures is very limited, and not directly applicable to the Dutch situation. With respect to the applicability of higher steam conditions it can be concluded on the basis of experiences so far that , on the one hand, higher steam conditions are likely to be technically feasible, but on the other hand they are subject to many uncertainties, especially regarding the effect on plant availability.
This study indicates which provisions – of those already applied in current Waste-to-Energy plants operated under steam conditions of 400°C and 40 bar – are minimally required for creating a system

that can handle higher steam conditions. These provisions, in particular those related to the steam system, are so extensive that they can be applied only in new Waste-to-Energy plants. The economic feasibility of higher steam conditions is uncertain and is particularly dependent on future political developments with respect to tariffs for waste and electricity.

On the basis of this study the following recommendations for development work can be done:

- Develop intelligent control systems for enhanced process control (e.g. entrance temperatures for superheaters), and to control fouling and thermal overloading of superheaters;
- Study the applicability of high temperature gas cleaning (cyclones, ceramic filters), to be applied before the superheaters. Assessment of the possible effects on corrosion reduction;
- Research possibilities for reducing the chlorine content of the waste;
- Critically review the methods used to measure temperatures in the boiler, as some corrosion problems may be ascribed to wrong information on the thermal load of the plant;
- Optimize wall thickness measurements for boiler tubes;
- Develop monitoring techniques that can be coupled with process control. The following factors qualify for monitoring: the amount of aggressive substances in the flue gas, the thermal load of specific parts and the actual corrosion rates of specific parts;
- Review and monitor plants abroad that operate under higher steam conditions. The following Waste-to-Energy plants qualify for monitoring: Düsseldorf (500°C steam), Mannheim (500°C steam) and Paris (470°C steam).

In summary, it can be concluded that in all the different Waste-to-Energy plants corrosion problems occur to a greater or lesser extent. On the basis of experiences with corrosion reducing measures, an overview of important corrosion factors has been made, and corrosion reduction measures have been recommended. These measures have resulted and will result in a higher availability of the existing Waste-to-Energy plants. For Waste-to-Energy plants that are yet to be built, the option of higher steam conditions could be considered. Experience so far indicates that advanced steam conditions are technically feasible but are also still subject to many uncertainties, such as their effect on plant availability.

5. Authentification

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