

## Publication P412

# Stainless steel tanks for biogas production

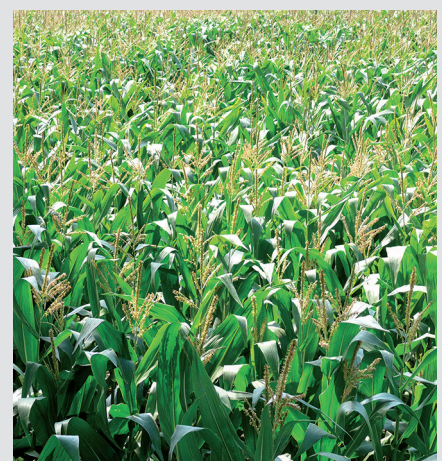
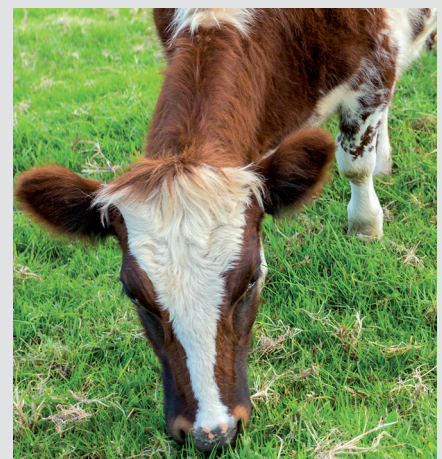
This publication is written for designers and owners of biogas plants and gives information on the design, fabrication and installation of stainless steel biodigester tanks. Much of the information in the brochure was developed during the EU's Research Fund for Coal and Steel project: *Innovative and competitive solutions using stainless steel and adhesive bonding in biogas production (BIOGASS)*. This was a three year research project which was completed in 2016. The project partners included stainless steel producers, research institutes, universities and a tank manufacturer. Through experimental tests, field trials and numerical analysis, the project generated design guidance for a range of grades of stainless steels which are suitable for application in biodigesters.

### Key advantages of stainless steel tanks for biogas production

- Excellent corrosion resistance
- No need for protective coatings or a corrosion allowance
- Low maintenance which minimises lost revenue due to process downtime
- Long service
- Quick installation
- Residual value at end of life

### Summary

Anaerobic digestion (AD) is a well-established process for renewable energy production in which biomass is broken down and converted to biogas (a mixture of methane, carbon dioxide and traces of other gases) by micro-organisms. The environment inside a biodigester is complex, depending on the composition of the feedstock and operating conditions, and some of the by-products are corrosive to certain structural materials. It is essential to minimise maintenance because each time the AD process is interrupted, it takes 3-4 weeks for production to start up again. Stainless steel is an ideal material for biogas tanks because it is inherently corrosion resistant, as well as being strong and easy to fabricate. The range of stainless steel grades available enables a cost-effective material choice to be made, leading to trouble-free performance throughout the life of the biodigester.



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## Introduction to biogas production

Anaerobic digestion (AD) is the breakdown of organic material (also known as biomass) by naturally occurring micro-organisms in the absence of oxygen. The process produces biogas which can subsequently be burned to produce heat. Alternatively it can be fed into a combined heat and power (CHP) generator to produce both heat and electricity or it can be cleaned and used in the same way as natural gas or as a vehicle fuel. The material left over after digestion, called digestate, can be used as a fertiliser and soil improver. The air-tight tank in which this process takes place is called a biodigester (also known as an anaerobic digester or fermenter).

Biogas can be produced from a variety of feedstocks, commonly manure or slurry from livestock. The advantage of using manure as a feedstock is that it reduces the gaseous releases compared to conventional storage and field application of manure. However, as it has already been digested by the livestock, gas output is relatively low. To boost gas production it is usually necessary to add energy crops such as maize or silage. This is worthwhile if the cost of production is sufficiently low. Food processing or catering waste can also be added, which not only boosts the gas output but may generate a gate fee which contributes to the profit. Adding food wastes will increase the administrative complexity of the plant as well as adding to the capital cost. Around 57% of biogas in Europe is produced from agricultural waste, 31% from landfill and 12% from wastewater treatment plants. Elsewhere in the world, biogas is produced primarily by landfill-based plants or small-scale family digesters.

Advantages of AD are as follows:

### **Generates electricity and heat**

The captured biogas can be burned to produce heat, or used in a combined heat and power generator to

produce both heat and electricity. The biogas can also be cleaned up to use as a fuel for converted road vehicles.

### **Reduces fertiliser bills**

The residue organic material can be used in both solid and liquid form as a highly nutritious organic fertiliser, thereby reducing the need for expensive and potentially harmful non-organic chemical fertilisers. It is nutrient-rich with less odour than slurry. Biogas manure also has a lower viscosity than animal manure and therefore penetrates into the ground more quickly.

### **Reduce greenhouse gas emissions**

Biogas comprises about 60% methane and 35% carbon dioxide, as well as some other gases including the noxious hydrogen sulfide. Methane and carbon dioxide are both greenhouse gases that are damaging to the environment. The AD process captures these gases, which under normal circumstances would be released directly to the atmosphere from the decomposition of animal waste, vegetable waste etc. Since the greenhouse gas potential of methane is higher than that of carbon dioxide, capturing methane and burning it to produce carbon dioxide is beneficial.

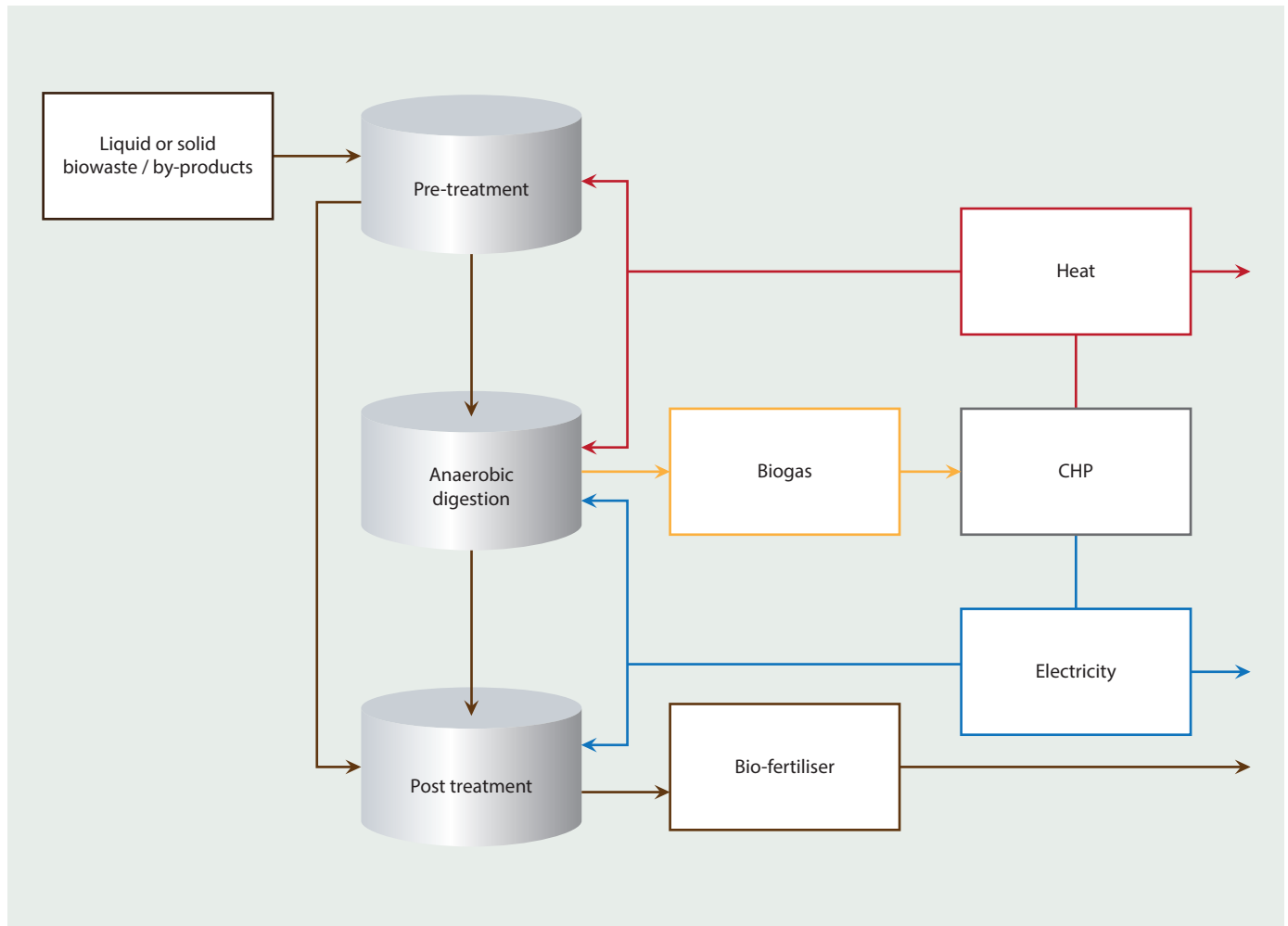
Installing an AD plant enables farmers to diversify and bring in a predictable income stream and energy source, reducing their use of fossil fuel and mineral fertilisers. For the food and drink sector, AD provides a means of processing its by-products in an environmentally acceptable way avoiding landfill fees.

Biogas facilities, unlike wind power, can be ramped up and down at the touch of the button. As renewable energy sources make up a greater share in energy supply, the ability of biogas to cover peak demands and balance down periods of other renewables becomes more important.



**Figure 1** Stainless steel biogas plant in Coleraine, Northern Ireland

## Introduction to biogas production



**Figure 2** Typical AD plant process

The AD sector is a niche but thriving industry, with plants producing biogas for many years around the world. More than 14,560 biogas power plants operate in Europe, with total capacity approaching 7.9 GW <sup>[1]</sup>. Germany accounts for half of this capacity (almost 3.9 GW) and for annual electricity generation from biogas of around 29 TWh, followed by Italy (1,391 plants), Switzerland (620), and France (610). The popularity of biogas in Germany was due to the high feed-in tariffs which were in force for 12 years; the tariffs were reduced in 2012.

Biogas plants are also widespread in the Americas and Asia, for example in China there are 100,000 large-scale modern biogas plants.

The economic viability of an AD plant is very dependent on the type and quantity of feedstock and the utilisation of the by-products; biogas, bio-fertiliser and, to a lesser extent, heat. The process of AD requires careful management to exploit its potential and there are several

design options covering different temperature levels, moisture contents and tank layouts with either continuous or batch systems and single, double or multiple digesters. These all have different cost implications, design requirements, and returns on investment.

While there are thousands of functioning biogas plants around the world, in the vast majority of cases operation can only be sustained with the help of subsidies to be able to compete with the fossil energy industrial sector. There are clear opportunities to improve many of the process steps in the biogas production chain in order to reduce both investment and operating costs.

Low prices for oil and natural gas and high production costs for renewables have led to a stagnation of growth of biogas production in Europe, but in the long term, it is expected that the role of biogas in the European energy mix will grow, especially as it is easier to store and transport than electricity.

## The anaerobic digestion process

AD is a very flexible process that can be configured in multiple ways, according to the inputs, outputs, site access, space and layout. The process is affected by many factors including:

### Temperature

The operation temperature depends on what material is being digested and what type of system is used. Mesophilic systems operate at 25-45°C and thermophilic systems operate at 50-60°C or above. Thermophilic systems have a faster throughput with faster biogas production per unit of feedstock and m<sup>3</sup> digester and there is greater pathogen kill. However, the capital costs of thermophilic systems are higher, more energy is needed to heat them and they generally require more management. For this reason, mesophilic systems are more common.

### Dilution

Water is usually added to the raw material to generate a slurry, which is generally 10-25% solids.

### pH

Optimum biogas production is achieved when the pH of the input mixture is between 6.5 and 8.

### Retention time

The length of time which the feedstock remains in the biodigester affects the extent of degradation and quantity of gas produced.

### Toxicity

Mineral ions and detergents present in the feedstock can inhibit normal growth of bacteria in a biodigester.

### Mixing/agitation

Mixing is required to combine the incoming material with the bacteria, to stop the formation of scum and avoid pronounced temperature gradients within the biodigester.

The environment inside a biodigester is very complex to characterize, depending on the composition of the feedstock and operating conditions. It cannot be finely controlled and maintenance cannot be carried out regularly because each time the anaerobic process is interrupted, it takes about 4 weeks to start producing biogas again.

During the AD process, organic acids such as acetic acid (CH<sub>3</sub>COOH) will be formed and trace gases may build up in the biodigester such as hydrogen sulfide

(H<sub>2</sub>S) and halides. The concentration of these trace gases depends on the concentration of nitrogen and sulfur in the feedstock and the conditions in the biodigester. The level of H<sub>2</sub>S must be substantially reduced prior to feeding into a combined heat and power (CHP) generator in order to avoid excessive corrosion and rapid and expensive deterioration of lubrication oil.

Removal of H<sub>2</sub>S from biogas (desulfurization) can be done by various methods, either biological or chemical, taking place inside or outside the biodigester. The method depends on the content of H<sub>2</sub>S and the throughput rate in the desulfurization equipment.

Biological desulfurization involves the addition of oxygen in small volume (a maximum 1 % volume concentration). This reaction produces sulfur, a yellow substance which deposits on the upper part of the biodigester (Figure 3). Sulfurous acid (H<sub>2</sub>SO<sub>3</sub>) may also be formed, depending on the concentration of oxygen in the biodigester.



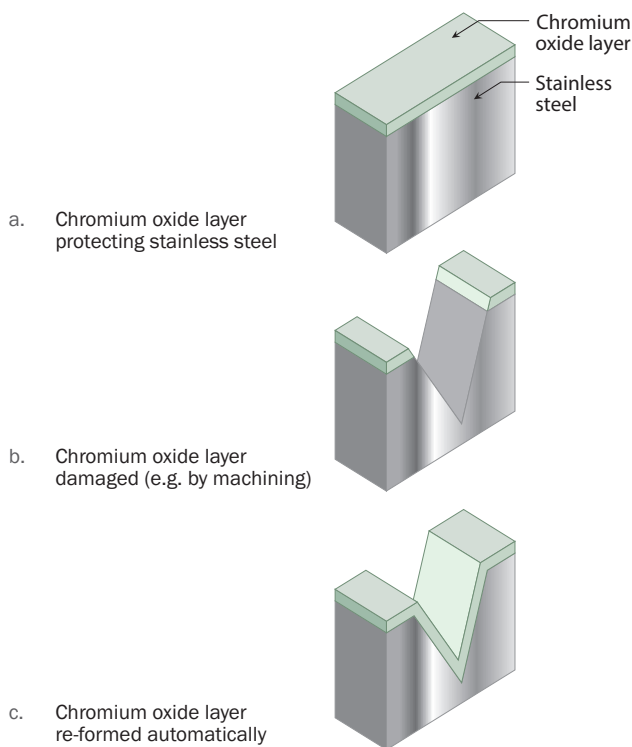
**Figure 3** Build-up of sulfur inside a biodigester, as a result of desulfurization

Chemical desulfurization involves the addition of chemicals like iron hydroxide Fe(OH)<sub>2</sub> which leads to the precipitation of iron sulfide (FeS). Iron chlorides (FeCl<sub>2</sub> and FeCl<sub>3</sub>) are not recommended because chloride ions can cause corrosion of some grades of stainless steel.

The most benign feedstock is herbal waste, or products like energy crops, harvesting residues, or fruits or vegetables which have not undergone any additional processing. High values of sulfur will be produced if the feedstock contains residues of meat or fish processing. If the feedstock contains convenience products or leftover food, sodium chlorides (NaCl) will be present.

## Introduction to stainless steel

Stainless steel is a family of corrosion and heat resistant steel alloys containing a minimum of 10.5% chromium. There is a range of stainless steels meeting different corrosion resistance, strength, weldability and toughness requirements. With a chromium content above 10.5%, a clean surface and exposure to air or any other oxidizing environment, a transparent and tightly adherent layer of chromium-rich oxide (passive layer) forms spontaneously on the surface of the stainless steel. If scratching or cutting damages the film, it will reform immediately in the presence of oxygen.



**Figure 4** Stainless steel has a protective chromium oxide surface film

The stability of the film depends on the composition of the stainless steel and the corrosiveness of its environment, as well as other factors. Its stability increases as the chromium content increases and is further enhanced by alloying additions of molybdenum. Unlike galvanized or painted steel, there are no applied protective surface layers.

The three families of stainless steel suitable for use in biodigesters are:

### a. Ferritic stainless steels

The chromium content of the most popular ferritic stainless steels is between 10.5% and 18%. They contain little, or no nickel, which makes them relatively cost-effective and price-stable compared with austenitic stainless steels, the family of stainless steels more commonly used in structural applications. Apart from enhanced durability, ferritics have similar properties to structural carbon steels, although the toughness is somewhat limited at low temperatures and in heavy sections, except for grade 1.4003. However, ferritics are suitable for a wide range of applications. High chromium ferritic steels with more than 18% Cr and/or additions of molybdenum can be used in quite aggressive conditions. Ferritics are not as formable as austenitic stainless steels.

### b. Austenitic stainless steels

The common types of austenitic stainless steel are based on 17 to 18% chromium and 8 to 11% nickel additions. They have excellent weldability and formability. Corrosion resistance can be enhanced by adding chromium, molybdenum and nitrogen. They work harden during cold forming to high strength levels whilst retaining a useful level of ductility and toughness. Relative to structural carbon steels, they also have significantly better toughness over a wide range of temperatures.

### c. Duplex stainless steels

Standard duplex stainless steels have excellent corrosion resistance, typically containing 20 to 26% chromium, 1 to 8% nickel, 0.05 to 5% molybdenum, and 0.05 to 0.3% nitrogen. They have a microstructure which is approximately 50% ferritic and 50% austenitic. This gives them a higher strength than either ferritic or austenitic steels. There is also a range of "lean duplex" steels which contain less nickel and molybdenum and more manganese than standard duplexes. They have corrosion resistance which is similar to the austenitic stainless steels but with enhanced strength. Duplex stainless steels are weldable but need care in selection of welding consumables and heat input. They have moderate formability.

## Grades of stainless steel

### Material grades

There are a range of stainless steels meeting different requirements for corrosion resistance, strength, weldability and toughness. They are specified in accordance with European Standard EN 10088 [2]. The relevant parts for use in construction applications are Part 4 and Part 5, which are harmonised standards.

Part 1 of EN 10088 gives chemical compositions and reference data on some physical properties relevant for structural applications such as the elastic modulus, *E*.

Part 4 of EN 10088 gives the properties and compositions for sheet, strip and plate and Part 5 gives the equivalent

information for long products, like bar and rod. These standards also define the type of process route and surface finish.

This publication covers the grades of stainless steels shown in Table 1. Table 1 gives the grade designations in accordance with EN 10088, the US system specified by the American Iron and Steel Institute (AISI) and the Unified Numbering System (UNS). Hereafter, this publication will refer to the grades by their European number. The durability and cost of the grades increases as the content of additional alloying elements increases.

	EN	AISI	UNS	Chromium content (%)	Nickel content (%)	Molybdenum content (%)	Other key alloying elements (%)
Ferritic	1.4003	–	S41003 / S40977	10.5-12.5	0.3 – 1.0	–	–
Ferritic	1.4509	441	S43932	17.5-18.5	–	–	Titanium, Niobium
Ferritic	1.4521	444		17.0 – 20.0	–	1.8 – 2.5	Titanium, Niobium
Austenitic	1.4318	301L	S30153	16.5 – 18.5	6.0 – 8.0	–	Nitrogen
Austenitic	1.4301	304	S30400	17.5 – 19.5	8.0 – 10.5	–	
Austenitic	1.4404	316L	S31603	16.5 – 18.5	10.0 – 13.0	2.0 – 2.5	
Austenitic	1.4571	316Ti	S31635	16.5 – 18.5	10.0 – 13.5	2.0 – 2.5	Titanium
Duplex	1.4482	2001	S32001	19.5 – 21.5	1.5 – 3.5	0.1 – 0.6	Manganese, Nitrogen
Duplex	1.4162	2101	S32101	21.0 – 22.0	1.35 – 1.7	0.1 – 0.8	Manganese, Nitrogen
Duplex	1.4462	2205	S32205	21.0 – 23.0	4.5 – 6.5	2.5– 3.5	Nitrogen
Duplex	1.4662	2404	S82441	23.0 – 25.0	3.4 – 4.0	1.5 – 4.0	Manganese, Nitrogen

**Table 1** Grades of stainless steels covered in this publication

### Surface finish

Stainless steels offer a significant advantage over carbon steels because they can be used unprotected in a range of surface finishes, from mill finish through dull finishes to bright polish. The various finishes are standardised in EN 10088. Biodigesters are usually made from cold rolled strip material, which is available in thicknesses from 0.4 to 6.0 mm. The typical range of thicknesses for hot rolled coil is 2.0 to 8.0 mm.

Suitable finishes for tanks are:

**2B:** *Cold rolled, heat treated, pickled, skin passed*  
A standard cold rolled mill finish.

**2E:** *Cold rolled, heat treated, mechanically descaled*  
A cold rolled finish, rougher than 2B (the material has been mechanically descaled (e.g. by shot blasting) before final pickling to facilitate the removal of annealing oxide).

**2H:** *Work hardened*  
A work hardened, cold rolled finish, in which the material has been work hardened (also known as temper rolled) to strengthen it.

# Properties of stainless steel

## Physical properties

The physical properties of the stainless steels covered in this publication are given in Table 2, typical values for structural carbon steel are also shown for comparison. These values are taken from EN 10088-1 for stainless steel and EN 1993-1-2 [3] for carbon steel.

Stainless steels have a lower value of thermal conductivity compared to carbon steels. The thermal expansion coefficient for austenitic stainless steels is higher than carbon steels. Unlike austenitic stainless steels, ferritics are magnetic (duplex stainless steels are less magnetic than ferritics due to the presence of austenite in the microstructure).

Grade	Density kg/m <sup>3</sup>	Specific thermal capacity at 20°C J/kgK	Thermal conductivity at 20°C W/mK	Coefficient of thermal expansion 10 <sup>-6</sup> /K 0~100°C
1.4003	7700	430	25	10.4
1.4509	7700	460	25	10.0
1.4521	7700	430	23	10.4
1.4318	7900	500	15	16
1.4301	7900	500	15	16
1.4404	8000	500	15	16
1.4571	8000	500	15	16.5
1.4482	7800	500	15	13
1.4162	7700	500	15	13
1.4462	7800	500	15	15
1.4662	7700	500	15	13
Carbon steel S355	7850	440	53	12

Table 2 Physical properties of stainless steels

## Strength and stiffness

The stress-strain behaviour of stainless steels differs from that of carbon steels in a number of respects. The most important difference is in the shape of the stress-strain curve. Whereas carbon steel typically exhibits linear elastic behaviour up to the yield stress and a plateau before strain hardening is encountered, stainless steel has a more rounded response, with no well-defined yield stress.

The response of ferritic stainless steel lies somewhere between that of carbon steel and austenitic stainless steel in that it is not quite as 'rounded' or nonlinear as the austenitic grades.

Figure 5 compares the stress-strain curves for ferritic, duplex, austenitic and S355 carbon steel for the full strain range. Figure 6 shows the stress-strain characteristics at low strain. In the absence of a clearly defined yield point, the '0.2% proof strength' is conventionally adopted as the design strength, which is the strength at 0.2% permanent strain.

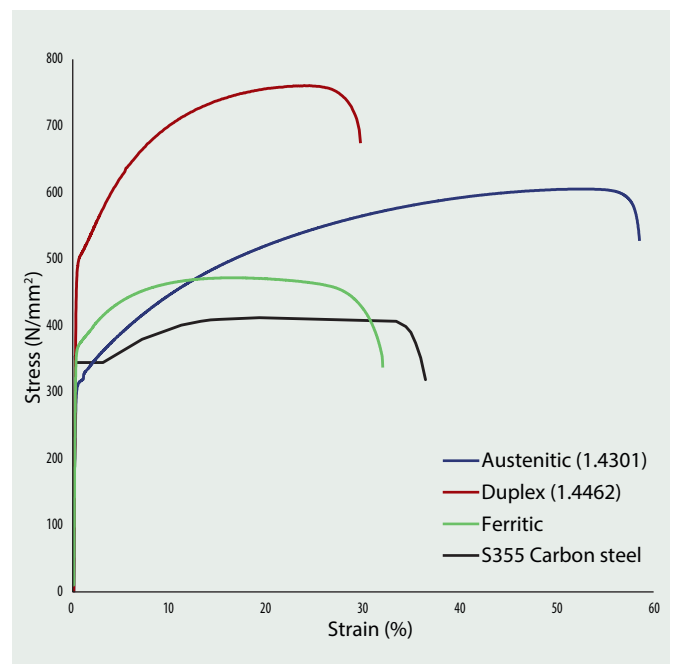


Figure 5 Full range stress-strain curves for stainless and carbon steels

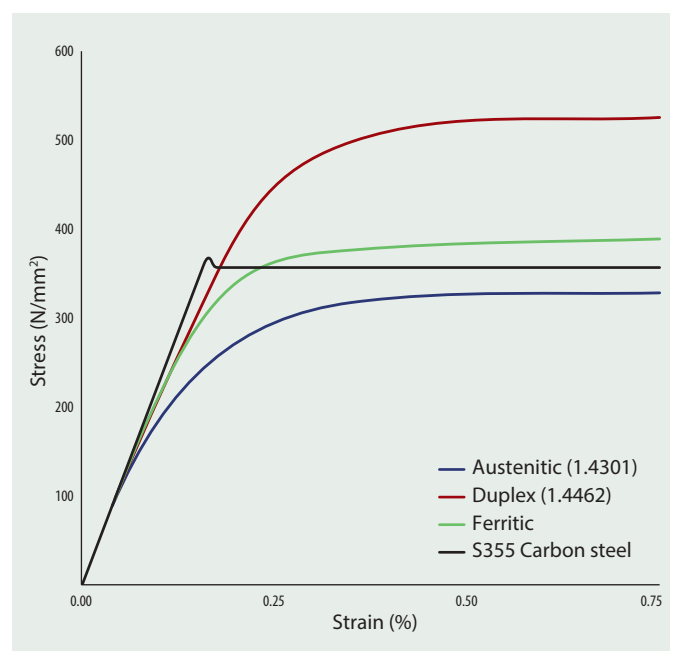


Figure 6 Stress-strain curves for stainless and carbon steels from 0 to 0.75% strain

## Properties of stainless steel

The design values for the 0.2% proof strength ( $f_y$ ), tensile strength ( $f_u$ ) and elongation ( $A$ ) for each grade covered in this publication are presented in Table 3, taken from EN 10088-4. Note that the measured 0.2% proof strength and elongation are likely to exceed these minimum specified values by between 25 to 40%.

Note that the ratio of  $f_u/f_y$  for duplexes and ferritics is typically between 1.4 and 1.9, which is a similar value to carbon steel; the ratio for austenitics is around 2.5 which demonstrates the significant work hardening the material undergoes.

For structural design, it is recommended that a value of  $200 \times 10^3 \text{ N/mm}^2$  is adopted for the elastic modulus for all grades.

Austenitic stainless steels are not susceptible to brittle fracture, even at low temperatures. Duplex stainless steels exhibit a ductile to brittle transition at low temperatures, like carbon steels. Ferritic stainless steels demonstrate the lowest toughness of the grades of stainless steel considered in this publication. However, brittle fracture is highly unlikely to occur in the thin material that is used for the biodigesters since the plane stress condition prevails for thin material loaded in tension, and failure is characteristically in a ductile manner.

Grade	0.2% proof strength $f_y$ (N/mm <sup>2</sup> )	Tensile strength $f_u$ (N/mm <sup>2</sup> )	Elongation after fracture $A$ (%)
1.4003	280	450	20
1.4509	230	430	18
1.4521	300	420	20
1.4318	350	650	35
1.4301	230	540	45
1.4404	240	530	40
1.4571	240	540	40
1.4482	500	700	20
1.4162	530	700	20
1.4462	500	700	20
1.4662	550	750	20
Carbon steel S355 to EN 10025-2 <sup>[4]</sup>	355	510	14–20

**Table 3** Minimum specified mechanical properties for cold rolled strip for stainless steels from EN 10088



## Stainless steel in biogas production

### Why use stainless steels for biodigesters?

Small-scale biodigesters, used for domestic and farming purposes, are often made from plastic. For larger biodigesters, concrete is the most common material choice, though both carbon steel and stainless steel are also popular. Special protective coatings are necessary to avoid corrosion in concrete or carbon steel tanks, for example carbon steel tanks are often coated with a glass fused or epoxy layer.

Stainless steel biodigesters are generally circular tanks, assembled on site by bolting flat sheets together. Depending on the type of AD process, the tank may be thermally insulated, for example with a 50-100 mm layer of rockwool which is clad in carbon steel sheeting.

Reasons why stainless steel is an ideal material for a biodigester are:

#### Corrosion resistance

The shell of a biodigester comes into direct contact with a wide range of potentially aggressive products, including hydrogen sulphide, chlorides and organic acids. Providing the correct grade is specified, and simple design and fabrication rules are followed, stainless steel will be able to resist the corrosive elements in a biodigester. No expensive additional coatings are required, which often degrade in contact with warm water containing organic compounds over the years of service.

#### Economic design

Stainless steels have excellent mechanical properties (strength, stiffness, ductility, toughness). There is no need to include a corrosion allowance when designing the tank wall thickness. In some cases, the high strength of duplex stainless steels will enable the wall of the tank to be reduced.

#### Low maintenance and repair requirements

It is very important to keep maintenance inside a biodigester to a minimum due to the delay in biogas production which follows an interruption in the AD process. The use of stainless steel will lead to significantly lower maintenance costs than other coated materials.

#### Hygienic surface

Stainless steel has a smooth surface which is easy to clean with minimal risk of leaching of any elements from the stainless steel to the digestate.

### Quick installation

Stainless steel tanks are quick to install and there is no requirement for expensive, heavy machinery, scaffolding or craneage.

### Recyclable

Stainless steel has a high residual scrap value; typical end-of-life recycling rates for stainless steel for building and infrastructure applications are 92%.



**Figure 7** Inside view of a stainless steel biodigester, showing the agitator mechanism on the left hand side

In addition to being used for biodigesters, stainless steel is an ideal material for a range of other components in a biogas plant, including storage tanks, pumps and valves, agitators, pipes and fittings and purification applications.

The most corrosive zone inside a biodigester is the splash or tidal zone, where corrosive substances may concentrate on the tank walls during wetting and drying cycles. Dirt on the walls may also lead to the formation of crevices, which can be initiation points for crevice corrosion. For this reason, the upper part of a stainless steel biodigester, which is partly in the splash zone and partly in the gas phase, is often made from a more highly alloyed grade of stainless steel. The lower part of the biodigester is permanently submerged in the digestate, a less highly corrosive environment, and hence can be made of a less durable grade of stainless steel.

## Material selection and durability

### Corrosion resistance

The selection of stainless steels for a particular application is dependent on the service environment. The more severe the environment, the more highly alloyed stainless steel is required to provide corrosion-free performance. Generally, the higher the content of chromium, molybdenum and in some cases also nickel, the better the corrosion resistance. The corrosion performance is also affected by the quality of the surface finish: generally the smoother the finish, the less risk of corrosion, especially where splashing can occur.

Pitting resistance equivalents (PRE) are a theoretical way of comparing the pitting corrosion resistance of various types of stainless steels, based on their chemical compositions. The PRE numbers are useful for ranking and comparing the different grades, but cannot be used to predict whether a particular grade will be suitable for a given application, where pitting corrosion may be a hazard. The PRE number chosen for use in BIOGASS was the PRE(Mn) which takes into account the negative effect of manganese on pitting resistance. PRE(Mn) values for the grades of stainless steel studied in BIOGASS are given in Table 4.

Grade	PRE(Mn)		Family of stainless steel
	Based on upper & lower limits of alloying elements in EN 10088	Measured values	
1.4003	9.0 – 13.4	11.3	Ferritic
1.4509	16.5 – 18.5	18.9	Ferritic
1.4482	15.3 – 25.5	20.7	Duplex
1.4318	17.5 – 24.5	21.1	Austenitic
1.4404	21.1 – 29.8	23.2	Austenitic
1.4162	21.3 – 28.1	23.9	Duplex
1.4521	21.9 – 29.2	25.4	Ferritic
1.4662	28.3 – 38.1	34.0	Duplex
1.4462	30.3 – 41.2	37.2	Duplex

PRE(Mn) = %Cr + 3.3%Mo + 30%N – %Mn

**Table 4** Range of PRE(Mn) values for candidate grades of stainless steel

### What is the environment inside a biodigester?

In order to select an appropriate grade of stainless steel, it is necessary to characterize the corrosivity of the environment within a biodigester. The corrosivity depends on the operating conditions (internally and externally, pressure, electrolyte, etc.), the design and detailing (crevices, bimetallic contact, inaccessibility, welds) and location within the biodigester.

### Laboratory tests

In the BIOGASS project, different feedstocks, intermediate species and digested residues were characterised by chemical analysis in order to develop artificial test solutions simulating the real conditions in biodigesters. Artificial solutions and real feedstock were used for a range of laboratory tests to study the corrosion resistance of the different stainless steel grades in these environments.

The following laboratory tests were carried out:

- Immersion testing in FeCl<sub>3</sub> and artificial test solution (to demonstrate the detrimental effect of iron chloride solutions on stainless steels);
- Potentiodynamic polarization tests in artificial test solutions (to compare the resistance of stainless steels to localised corrosion (pitting and crevice));
- Critical pitting temperature measurements (to demonstrate the importance of the redox potential of the environment on the performance of stainless steels);
- Pitting susceptibility by electrochemical noise (to evaluate the suitability of electrochemical noise technique for localized corrosion monitoring purposes);
- Pitting susceptibility with simulated microbiologically induced corrosion (MIC) (to examine the influence of chemical and physical conditions which can be expected underneath biofilms on the localized corrosion of stainless steels);
- Performance evaluation in laboratory scale biodigesters (to study the risk of MIC under different operational conditions).

The experiments allowed the different stainless steels to be ranked according to their corrosion resistance under the different test conditions.

## Material selection and durability

### Field trials

Samples of different grades of stainless steels were placed inside two mesophilic biodigesters operating at around 39°C, one in Finland and one in Germany. Some of the samples were continuously immersed, others were in the tidal zone and others in the gas phase. After 5 and 6 months respectively, the samples were removed from the Finnish and German biodigesters and the extent of corrosion experienced by each sample was analysed in the laboratory.

Three sets of 10 creviced stainless steel samples were installed in the Finnish biodigester. This biodigester used cow manure as feedstock and removed H<sub>2</sub>S contamination by oxidation with air in a second stage tank. Only the least alloyed grade of stainless steel tested (1.4003) showed signs of any corrosion after 6 months.

The German biodigester used corn and manure as feedstock. The biogas was desulfurized by regular Fe(OH)<sub>2</sub> additions and by feeding air into the gas space over the digestate, maintaining the oxygen content in the biogas at 0.5% volume concentration. Crevices were also present in these samples. Upon removal after 5/6 months, the samples were cleaned, inspected visually and re-weighed. The depth of corrosion attack and the affected area were determined. The corrosion damage and remaining residue were studied using a scanning electron microscope equipped with an energy dispersive spectrometry (EDS) microprobe for localized elemental analysis.

The conditions inside the German biodigester were shown to be more corrosive than those inside the Finnish biodigester as grades which corroded in the German tank did not corrode in the Finnish tank. As expected, in the German biodigester, corrosion attack was most severe in or near the creviced areas of the samples in the tidal zone. The fully immersed areas and the areas continuously exposed to the gas phase suffered less from corrosion.



**Figure 9** Sample 1.4509/2B after exposure for 6 months in a biodigester

- Left: In the sample holder, showing black corrosion deposits
- Centre: Before cleaning in the lab, showing black, white/yellow and rust-coloured deposits/corrosion products
- Right: After cleaning, showing corrosion damage at locations where black deposits/corrosion products were present

It is clear that the type of feedstock and the method of desulfurization have a significant effect on the corrosivity of the environment.



**Figure 8** Stainless steel specimens inside the German biodigester

## Material selection and durability

As a result of the laboratory investigations and field trials, the following material selection recommendations can be made for bolted stainless steel tanks. The recommendations apply to stainless steels in the investigated feedstocks. The suitability of a stainless steel grade for use in significantly different feedstocks should be evaluated separately. Increasing H<sub>2</sub>S concentrations and increased dosing of oxygen for desulfurisation will require steel grades with a relatively

high PRE(Mn). Because grade 1.4462 did not corrode under any of the relevant electrochemical, laboratory or field tests, it appears to be a suitable material for the most aggressive feedstocks, such as food waste containing relatively high amounts of NaCl.

It should be noted that these guidelines may not apply to welded stainless steel tanks (no welded samples were studied in this project).

Feedstock	Mesophilic or thermophilic conditions	Method of desulfurization	Position	Recommended grades* based on performed tests in biogas digesters
Cow manure	Mesophilic	None	Liquid phase**	1.4509, 1.4521, 1.4318, 1.4404, 1.4482, 1.4162, 1.4662, 1.4462
			Tidal zone & gas phase	
Maize silage and liquid manure	Thermophilic	Air	Liquid phase**	1.4521, 1.4318, 1.4404, 1.4482, 1.4162, 1.4662, 1.4462
			Tidal zone & gas phase	
Corn and manure	Mesophilic	Air & Fe(OH) <sub>2</sub>	Liquid phase**	1.4521, 1.4318, 1.4404, 1.4482, 1.4162, 1.4662, 1.4462
			Tidal zone & gas phase	
Maize silage and liquid manure	Thermophilic	FeCl <sub>3</sub>	Liquid phase	Iron chloride desulfurization is generally not recommended in stainless steel biodigesters.
			Tidal zone & gas phase	

\* Skin-passed surface finish 2B is commonly preferred over surface finishes 2E and 1D.

\*\* Although not tested in this project, grade 1.4301 has a track record of satisfactory performance in the liquid phase and grade 1.4571 has a track record of satisfactory performance in the tidal zone/gas phases of biodigesters.

\*\*\* Only in surface finish 2B.

The suitability of stainless steels for use with significantly different feedstocks should be evaluated separately. The greater the level of chlorides in the feedstock, the more highly alloyed the grade of stainless steel required.

**Table 5** Grade selection recommendations for different biodigester conditions

## Design of stainless steel tanks

### General design issues

A biodigester is designed to resist axial and circumferential loading. Axial loads are due to self-weight (the tank shell, ring stiffeners and roof) and snow. Circumferential loading is due to the internal pressure exerted on the tank by the digestate, and wind on the outside of the tank. Extreme events such as earthquake or impact loading may also need to be taken into consideration. Biodigesters are thin-walled shells where buckling is the predominant design constraint. Axial forces are relatively low and a biodigester is likely to be at its most vulnerable when exposed to wind loading during installation. Once in service and filled, the contents actually contribute to its stability. In order to prevent overall failure of the empty tank under wind loading, a ring stiffener is required at the top of the tank.

Whereas carbon steel tanks are often designed with a constant wall thickness, the greater cost of stainless steel necessitates optimisation of design to save material. As a result, stainless steel biodigesters have variable wall thickness, with the thickness increasing down the tank as the internal pressure due to the digestate increases. The outer surface of the tank is smooth and inner surface stepped. Ring stiffeners are positioned at regular intervals to enhance buckling resistance. Note that unprotected carbon steel tanks are often supplied with a corrosion allowance, i.e. the thickness of the shell wall is increased to allow for the metal which is expected to corrode over the life of the tank. This is not necessary for stainless steel tanks.

Stainless steel biodigesters generally vary from 6 m to 35 m diameter. Heights vary from 5 m to 20 m, with a preference for shorter tanks. Radius to height ratios vary from 1:2 to 2:1.

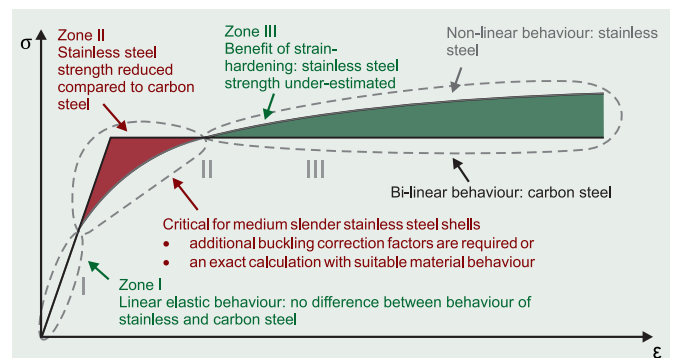
### Design standards for tanks

Eurocode 3: Part 1-4 (EN 1993-1-4) gives rules for the structural design of stainless steels<sup>[5]</sup>. EN 1993-1-4 is the part of Eurocode 3 which covers the design of steel tanks<sup>[6]</sup>; it refers extensively to EN 1993-1-6, which gives rules for determining the strength and stability of shell structures<sup>[7]</sup>. Along with all modern structural design standards, Eurocodes adopt a Limit State design philosophy.

The nonlinear stress-strain characteristics of stainless steels lead to differences in structural performance compared to carbon steel (Figure 10). In Zone I, strains are low and response is in the linear portion of the

stress-strain curve; stainless steel will perform like carbon steel. Buckling failures generally occur at these low strains.

In Zone III, the benefits of work hardening become evident and stainless steel shells will perform at least as well as carbon steel. In Zone II, where stresses lie between the limit of proportionality and the 0.2% proof stress, a stainless steel shell will become less stiff than a carbon steel shell and will have lower buckling resistance compared to an equivalent carbon steel shell.



**Figure 10 Comparison of stainless and carbon steel structural response**

For steels with nonlinear stress-strain curves, EN 1993-1-6 conservatively requires that a reduced value of the elastic modulus should be used in buckling calculations. It even suggests the use of the secant modulus at the 0.2% proof strength which leads to very low buckling strength evaluations. The ECCS Recommendations on Shell Buckling<sup>[8]</sup> act as a commentary on EN 1993-1-6 and give a less conservative approach for determining the buckling strength of austenitic stainless steel cylinders under axial compression, based on work by Hautala<sup>[9]</sup>. This approach uses the initial elastic modulus and only reduces the buckling strength selectively, applying reductions to medium slender shells which buckle under stresses in the stress-strain Zone II. (A bilinear stress-strain curve using the elastic modulus and  $f_y = 0.2\%$  proof strength give appropriate buckling strength values in Zones I and III.)

The reduced axial (also called meridional) buckling strength  $\sigma_{x,Rd,red}$  is given by:

$$\sigma_{x,Rd,red} = \psi_x \sigma_{x,Rd}$$

where

$\sigma_{x,Rd}$  is the axial design buckling stress according to EN 1993-1-6 cl. 8.5

$\psi_x$  is the correction factor in Table 6, expressed as a function of relative slenderness  $\bar{\lambda}_x$

## Design of stainless steel tanks

$\bar{\lambda}_x$	Buckling correction factor $\psi_x$
$\leq 0.40$	1.0
0.40 – 0.65	$1.0 - 0.8 (\bar{\lambda}_x - 0.4)$
0.65 – 0.80	0.8
0.80 – 1.0	$0.8 + 1.0 (\bar{\lambda}_x - 0.8)$
$\geq 1.0$	1.0

**Table 6** Buckling correction factor  $\psi_x$  for austenitic stainless steels (for temperatures up to 100°C) [6]

For global numerical analysis, EN 1993-1-6 refers to the use of the analytical stainless steel material model, which is given in EN 1993-1-4.

### Investigations under the BIOGASS project

Under the BIOGASS project, a series of laboratory tests and numerical analyses was carried out to extend the design rules for stainless steel shells under various types of loading.

#### Axially compressed cylindrical shells

12 tests were carried out on ferritic (1.4521) and duplex (1.4462) stainless steel shells of height 370 mm, with radius to thickness ( $r/t$ ) ratios varying from 50 to 400. The shells were formed by tungsten inert gas (TIG) welding and re-rolled after welding to eliminate weld distortion. Material properties and initial geometric imperfections were measured. Fabrication tolerance quality classes were determined. Figure 11 shows the buckling patterns observed in three duplex shells of increasing slenderness.

The tests were modelled numerically and then a parametric study was undertaken to study the impact of varying key parameters, such as the size and shape of imperfection. The tests and numerical analysis confirmed that less punitive correction factors are needed for ferritic and duplex shells than for austenitic shells because their stress-strain behaviour is less nonlinear (Figure 6). The recommended factors are given in Table 7.

$\bar{\lambda}_x$	Buckling correction factor $\psi_x$
$\leq 0.40$	1.0
0.40 – 1.1	0.95
$\geq 1.1$	1.0

**Table 7** Buckling correction factor  $\psi_x$  for ferritic and duplex stainless steel shells subject to axial loading



**Figure 11** Buckling patterns in duplex shells subject to axial loading  
Left:  $r/t = 50$  Middle:  $r/t = 150$  Right:  $r/t = 333$

#### Circumferentially compressed shells

The behaviour of austenitic, duplex and ferritic stainless steel shells was investigated numerically, studying  $r/t$  ratios varying from 9 to 1000, and relative slenderness values  $\bar{\lambda}_\theta$  from 0.2 to 4.3. A linear elastic bifurcation analysis /materially nonlinear analysis (LBA/MNA) was adopted.

The reduced circumferential buckling strength  $\sigma_{\theta,Rd,red}$  is given by:

$$\sigma_{\theta,Rd,red} = \psi_\theta \sigma_{\theta,Rd}$$

where

$\sigma_{\theta,Rd}$  is the circumferential design buckling stress according to EN 1993-1-6 cl. 8.5

$\psi_\theta$  is the correction factor in Table 8, expressed as a function of relative slenderness  $\bar{\lambda}_\theta$

Stainless steel	FTQC	Circumferential buckling correction factor $\psi_\theta$	
		$\bar{\lambda}_\theta \leq \bar{\lambda}_{\theta,0}$	$\bar{\lambda}_{\theta,0} < \bar{\lambda}_\theta$
Austenitic	A		0.82
	B	1.0	0.81
	C		0.79
Duplex	A		
	B	1.0	0.92
	C		
Ferritic	A		0.85
	B	1.0	0.84
	C		0.84

FTQC = Fabrication Tolerance Quality Class.

Class A:  $\bar{\lambda}_p = 1.37$ , Class B:  $\bar{\lambda}_p = 1.27$ , Class C:  $\bar{\lambda}_p = 1.12$ , where  $\bar{\lambda}_p$  is the plastic limit relative slenderness.

$\bar{\lambda}_{\theta,0}$  is the squash limit slenderness, which EN 1993-1-6 takes as 0.4 for circumferential loading.

**Table 8** Buckling correction factor  $\psi_\theta$  for stainless steel shells subject to circumferential loading

## Design of stainless steel tanks

### Post critical strength of circumferentially loaded shells

EN 1993-1-6 does not take into account any benefit from the post-buckling strength of open thin-walled cylindrical tanks under external pressure, which is a potentially critical design scenario for biogas tanks subject to wind loading prior to being filled. Under the BIOGASS project, a programme of experimental investigations was undertaken to derive design expressions for stainless steel which enables this additional strength to be exploited.

Nine tests were carried out on specimens with  $r/t$  from 2500 to 5000 and length from 430 mm to 960 mm, with varying designs of ring stiffener. The stainless steels tested were austenitic grade 1.4301 and duplex grade 1.4462. The shells were formed into cylinders from flat sheets by gluing and a base plate was securely attached to one end of the shell. Material properties were measured. Photogrammetry was used to measure the dimensions and shape of the shells to a very high degree of accuracy both at the start and during the tests. The fabrication tolerance quality classes for the shell models were determined.

The open face was inserted into a water basin to seal the cylinder. Internal pressure was then reduced using a vacuum pump, which simulated wind loading on the outside of the tank. The specimen was initially subject to reduced internal pressure until the first buckle was observed. The shape of the shell was photographed for photogrammetry evaluation. Then the shell was unloaded to verify that it was an elastic buckle and the shape was documented again. The procedure was repeated with reducing internal pressure until the first plastic buckle was visible upon unloading. At this point the internal pressure was reduced in larger steps until the shell collapsed (Figure 12).

The investigations concluded that significant strength enhancements are possible by taking advantage of the post critical strength. EN 1993-1-6 recommends a value for  $\alpha_0 = 0.5$  for the circumferential elastic imperfection reduction factor for fabrication tolerance quality class C. This value can be increased to between



**Figure 12 Austenitic stainless steel shell under reducing internal pressure**

- Left: Showing the unloaded shell
- Middle: Development of elastic buckling
- Right: Collapse

0.6 and 1.0 by taking advantage of the post critical strength for austenitic stainless steels, depending on the tank geometry. For the geometries of duplex tanks investigated, values for  $\alpha_0$  could be increased to around 1.2. In terms of strength, this means an increase in strength of 20 – 100% for austenitic shells, and around 140% duplex shells. Numerical parameter studies will be carried out based on these promising results in order to formulate design recommendations in EN 1993-1-6.

Alternative design standards for steel tanks which adopt the Allowable Stress design philosophy are:

#### API 650 Welded tanks for oil storage <sup>[10]</sup>

This standard is used worldwide. It covers design, fabrication, erection, and testing. It gives simple empirical design methods for stiffening a tank shell based on its thickness, height and design wind velocity, also taking advantage of the post-critical buckling strength. Appendix S gives guidance for austenitic stainless steel storage tanks and Appendix X for duplex tanks.

#### EN 14015 Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above <sup>[11]</sup>

This standard provides detailed guidance on almost every aspect of tank design, from joint specifications to venting requirements and the effects of different roof configurations. It gives brief guidance on the use of austenitic and duplex stainless steels, including a table of permissible grades. Minimum wall thicknesses for carbon or stainless steel tanks are given but the scientific basis for these values is unknown.

## Connections

### Bolted connections

The composition and mechanical properties of stainless steel bolts and nuts are covered by EN ISO 3506-1 and -2<sup>[12]</sup>. In this standard, bolts and nuts are designated by a letter followed by three numbers, e.g. A2-70 or A4-80. The letter refers to the group of stainless steel (e.g. A for austenitic). The letter is followed by a number (1, 2, 3, 4 or 5) which reflects the corrosion resistance; 1 representing the least durable and 5 the most durable. The final two numbers denote the property class, which describes the mechanical properties (see Table 9).

Grade <sup>(b)</sup>	Property class	Ultimate tensile strength (N/mm <sup>2</sup> )	Stress at 0.2% permanent strain (N/mm <sup>2</sup> )
A1, A2, A3, A4 and A5	50	500	210
	70	700	450
	80	800	600

Notes:

- The properties apply to fasteners with nominal thread diameters  $d \leq 39$  mm.
- In addition to the various steel types covered in EN ISO 3506 under property class 50, 70 and 80, other steel types to EN 10088-3 may also be used.

**Table 9** Minimum specified mechanical properties of austenitic grade bolts to EN ISO 3506<sup>(a)</sup>

For most structural applications, it is generally recommended that austenitic bolts grade A2 or A4 and property class 70 or 80 are used. Steels of grade A2 have equivalent corrosion resistance to grade 1.4301. Steels of grade A4 contain molybdenum and have equivalent corrosion resistance to grade 1.4401. Property class 70 fasteners are made from cold drawn bar. Property class 80 fasteners are made from severely hard cold drawn bar, with mechanical properties similar to carbon steel and alloy steel grade 8.8 bolts to ISO 898<sup>[13]</sup>.

A duplex composition (designated FA which stands for ferritic-austenitic) is mentioned in Annex B of EN ISO 3506-1 and it is likely that this group of stainless steels will be included in future revisions of the standard. Although not included in the standard, property class 100 bolts and nuts are available up to size M20 (stress at 0.2% permanent strain = 800 N/mm<sup>2</sup> and ultimate tensile strength = 1000 N/mm<sup>2</sup>). Additionally, duplex bolts and nuts are available in grade 1.4462 with mechanical properties in accordance with property class 80 and superior corrosion resistance to austenitic fasteners.

When choosing a stainless steel fastener, consideration should be given to matching the strength and corrosion resistance of the bolts and parent material. To avoid the risk of bimetallic corrosion, stainless steel bolts should always be used when connecting stainless steel members. (Stainless steel bolts are also suitable for connecting galvanized steel and aluminium members.)

### Adhesive bonding

The potential of using adhesives to construct a stainless steel biodigester was explored in the BIOGASS project as a way of reducing the cost of fabrication. To replace (part of the) bolted connections, the adhesive would have to be applied in a continuous film to provide structural strength and to replace the seal that is currently used to prevent leakage of liquid and gas. Degradation of the adhesive bond due to exposure to the feedstock and by-products of anaerobic digestion were investigated in the laboratory and in field trials. The effect of temperature on the adhesive performance was also examined (25°C - 55°C range). The bond strength was also studied numerically.

Three different adhesive types were investigated, namely an epoxy, a polyurethane and an acrylate. Laboratory trials showed that the acrylate was not suitable for this type of application, particularly for temperatures higher than 35°C. The epoxy adhesive was the most stable in all conditions (mesophilic and thermophilic). The polyurethane-based adhesive was also stable but exhibited signs of instability with increasing temperature. However, if excessive adhesive is not removed, the epoxy-based adhesive was found to increase the likelihood of localised corrosion occurring in some grades of stainless steel.

The structural testing on both these adhesives demonstrated that their strength is satisfactory at 25°C. However, poor performance was observed at 35°C and 55°C. The structural tests also studied the role of surface preparation, which was found to be very important. Roughening of the surface by grit-blasting or abrasion with emery paper was shown to enhance bonding. However, such preparation may have an adverse effect in terms of corrosion. From the work undertaken, it was concluded that adhesive bonding does not appear to be a suitable method for fabricating stainless steel biodigesters, although expanding the study to include more adhesives and more rigorous surface preparation should be undertaken before a definitive recommendation can be made.



## Fabrication

### Fabrication

Stainless steels are relatively easy materials to work with and many of the fabrication and joining techniques are similar to those of carbon steel.

Appropriate storage and handling procedures should always be adopted to avoid iron contamination and surface damage, both of which may subsequently initiate corrosion. Iron particles embedded in stainless steel surfaces during fabrication are a frequent cause of 'surface rusting' on commissioning. It is important, where possible, to reserve a fabrication facility exclusively for stainless steels. In addition, handling equipment and tools which are dedicated to fabricating stainless steels should be used to avoid contamination with carbon steels. Guidance on the removal of contamination is given in ASTM A380 <sup>[14]</sup>.

Stainless steel may be cut by usual methods, e.g. shearing and sawing. It is advisable to remove any sharp burrs formed during shearing operations. Stainless steels work harden more than carbon steels; thus cutting, forming etc. require increased machine tool power and re-working is more difficult. Stainless steels exhibit greater springback than carbon steel and this should be compensated for by over-bending. Holes may be drilled, punched or laser cut.

Stainless steel biodigesters are usually formed by bolting flat sheets together. However, welding is used for the connection of pipes and other equipment to the tank. Austenitic stainless steels are readily welded with or without filler wire. Duplex and ferritic stainless steels require more control when being welded and may involve post-weld heat treatment or special welding consumables. Excessive heat input and high weld interpass temperatures should be avoided. Austenitic grades have a high coefficient of thermal expansion and low conductivity, so high heat input will result in excessive distortion and residual stress. Weld scale and heat tint must be removed from welds by treating with pickling paste (a mixture of nitric and hydrofluoric acid) especially in applications where micro-organisms are present, to avoid microbially induced corrosion. If in doubt about welding and fabrication techniques, then consultation of the parent material or welding consumable supplier / manufacturer is recommended.

EN 1090-2, the European specification for fabrication and erection of structural carbon and stainless steel, gives requirements for storage and handling, forming, cutting, joining methods, tolerances, and inspection and testing <sup>[15]</sup>. Specific guidance just for stainless steels, based on this

standard, has also been published <sup>[16]</sup>. Information on the fabrication of duplex stainless steels is also available <sup>[17]</sup>.

### Installation

Generally no significant ground works are required for the tank foundations; top soil is removed, the site levelled and the base excavated. The base comprises compacted hardcore and a membrane onto which a reinforced concrete slab is cast.

Stainless steel biodigesters are usually constructed on site by bolting together individual stainless steel sheets (1.25 – 1.5 m x 2.5 - 3.0 m). The sheets are not curved prior to erection. The segment construction allows the parts to be easily transported and expensive and labour intensive scaffolding is not needed.

The bolted connections are sealed to prevent leakage of gas or liquid. Care is needed in choosing the right sealant to ensure satisfactory long-term performance under the operating conditions in contact with the digestate. Sealants may take the form of semi-rigid gaskets or adhesives:

- A semi-rigid gasket can be made of neoprene, nitrile, silicone, or other similar material and has firm outer edges around a pliable inner surface.
- A sealant is typically a single-component material in a tube that is dispensed as a bead using a tool similar to a caulking gun; the sealant is then air-cured so that its outer edges become firm while its inner volume remains pliable.

Stainless steel biodigesters are assembled from top to bottom. Ring stiffeners give the tank stability during installation. The procedure begins with the top ring of the tank. Once the top ring is complete, it is lifted and the next ring constructed beneath it. The tank wall is secured with an anchoring system onto the base and permanently sealed. It usually takes about two weeks to erect the shell of a stainless steel biodigester. Further time is needed after that to install the necessary equipment within the tank.

At the end of the service life of a bolted stainless steel biodigester, it can be dismantled, cleaned and re-assembled in another location.

## Whole life cost and carbon assessments

The performance of biodigesters is strongly dependent on the specific AD process. Additionally, there is sparse information on their long-term performance and maintenance requirements because AD is a relatively new technology. An important factor for clients in AD investment is the expected return on investment (ROI). Predicted ROI is often dependent on government subsidies which are generally offered for limited or uncertain timescales. Typically, a private investor is likely to invest in an AD plant with a relatively short design life whereas a public client, investing for example in water treatment and supply, is more likely to consider investing in more expensive (capital cost) assets with a longer design life. As a rule of thumb, bolted carbon steel biodigesters would generally have a 20 to 25 year design life whereas the design life of concrete tanks would generally be 50 to 60 years. Maintenance-free stainless steel tanks are likely to have design lives between these two ranges.

### Whole life cost assessments

The AD tank market is very competitive. Costs reflect market conditions and this should be borne in mind when considering the results of theoretical whole life cost assessments summarised here. The capital cost of the suitable grades of stainless steel for biodigesters is currently 3 to 4 times that of uncoated carbon steel. However, the relative strength of stainless steel, compared to carbon steel, can lead to some weight and hence capital cost savings, depending on the design of the tank. Stainless steel biodigesters are also inherently corrosion resistant, therefore maintenance, repair and downtime costs will be lower compared to carbon steel or concrete tanks.

Bolted carbon steel biodigesters are generally either coated in vitreous enamel (glass fused) or bonded epoxy powders. Currently there is sparse performance data on these coatings in AD tank applications, though the cost of repairing these coatings is very high.

The capital cost of in-situ concrete biodigesters is generally higher than carbon steel AD tanks because they take longer to construct and are less straightforward to erect requiring fixing rebar and temporary formwork. Maintenance requirements of in-situ concrete tanks appear to be dependent on the AD process and the concrete grade specified; coatings are often initially applied to the internal surface in the gas zone. Longer-term maintenance requirements of concrete biodigesters are less certain but it is likely that complete internal relining will be required after 10 to 15 years for most AD processes.

For a 6 m tall, 32 m diameter biodigester, the costs of the base and shell of equivalent in-situ concrete, carbon steel and stainless steel tanks were assessed using cost and maintenance data gathered from an extensive review of the industry. A 3% discount rate was applied to calculate whole life costs. Stainless steel was the cheapest option in terms of whole life costs over a 25 year lifetime (Figure 13). The cost differential slightly increased over a 40 year lifetime.

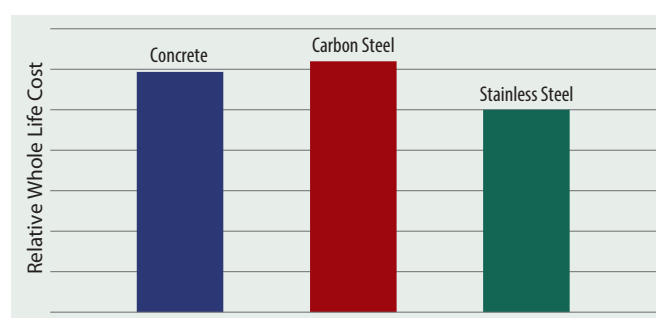


Figure 13 Relative whole life costs (25 year lifetime)

### Whole life embodied carbon assessments

A simplified whole life carbon assessment was undertaken using published embodied carbon coefficients. The study included the carbon impact of all the materials which were required to construct and maintain the tank base and shell. The shell was assumed to be thermally insulated. Construction and deconstruction impacts were not included. Generic environmental data on coatings were used in the absence of accurate data. In accordance with CEN/TC 350 requirements [18], a modular approach was adopted, i.e. 'cradle to gate with options' which included the production stages (Modules A1 to A3) and the supplementary information beyond the tank life cycle (Module D). Module D impacts were included for the shell materials because of the significant longer term recyclability benefits of steel products. Over both a 25 and 40 year lifetime, the embodied carbon impact (Modules A1 to A3 and D) of the steel and stainless steel tanks were about 15% lower than that of concrete (Figure 14).

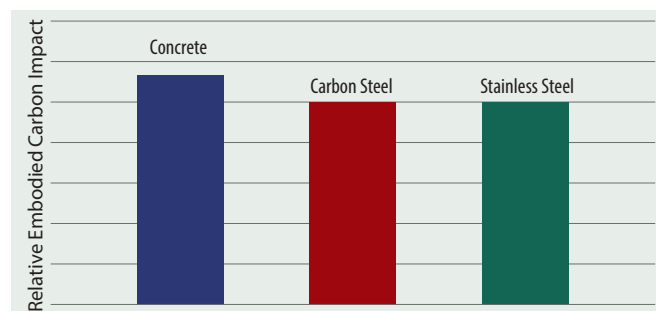


Figure 14 Relative embodied carbon impacts (25 year lifetime)

## Case studies

### Plant for organic wastes, Darżyno, Poland

#### Project data

Start of construction: September 2012  
 Commissioning: August 2013  
 Input materials: Potato waste from a local potato chips factory, maize silage, slurry

#### Technical data

Dosing feeder: 4 × 50 m<sup>3</sup> made from stainless steel  
 Pre-storage tank: 2 × 192 m<sup>3</sup>, 2 × 342 m<sup>3</sup>  
 Biodigester: 4 × 4,483 m<sup>3</sup> — stainless steel grade: 1.4301 (liquid phase) and 1.4571 (gas phase)  
 Storage tank: 4 × 5,000 m<sup>3</sup> — stainless steel grade: 1.4301  
 CHP: 2 × 1.2 MWel

#### Characteristics

This biogas plant is completely self-sufficient because the required energy to operate the plant is produced by itself.



### Plant for renewable products, Harpstedt, Germany

#### Project data

Start of construction: August 2011  
 Commissioning: December 2011  
 Input materials: Maize silage, pig slurry, fowl manure, grass silage, cereals

#### Technical data

Dosing feeder: Push floor system (80 m<sup>3</sup>)  
 Biodigester: 1 × 3,500 m<sup>3</sup> — stainless steel grade: 1.4301 (liquid phase) and 1.4571 (gas phase)  
 Storage tank: 2 × 4,500 m<sup>3</sup> — stainless steel grade: 1.4301  
 CHP: 2 × 265 Wel, and one satellite CHP with 250 kWel

#### Characteristics

The heat produced is used for drying the digestate.  
 The heat of the satellite CHP is used to heat the buildings (house, stables etc.) on the farm.



## References and sources of further information

### References

1. Renewables 2015 global status report REN21, Renewable Energy Policy Network for the 21st Century, [www.ren21.net](http://www.ren21.net).
2. EN 10088 Stainless steels  
Part 1: List of stainless steels, CEN, 2014  
Part 4: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for construction purposes, CEN, 2009.
3. EN 1993-1-2 Eurocode 3. Design of steel structures — Part 1-2: Structural fire design, CEN, 2005.
4. EN 10025-2 Hot rolled products of structural steels — Part 2: Technical delivery conditions for non-alloy structural steels, CEN, 2004.
5. EN 1993-1-4 Eurocode 3. Design of steel structures: Part 1 4: General rules — Supplementary rules for stainless steels, CEN, 2006.
6. EN 1993-4-2 Eurocode 3. Design of steel structures — Part 4-2: Tanks, CEN, 2007.
7. EN 1993-1-6 Eurocode 3. Design of steel structures — Part 1-6: Strength and stability of shell structures, CEN, 2005.
8. Buckling of steel shells, European design recommendations, Eurocode 3, Part 1-6. ECCS Technical Committee 8 Structural Stability, TWG 8.4 - Shells, 5th Edition, ECCS, 2008.
9. Hautala, K T, 1998. Buckling of axially compressed cylindrical shells made of austenitic stainless steels at ambient and elevated temperatures. Doktor-Ingenieurin Dissertation at University of Essen.
10. API Standard 650 Welded tanks for oil storage, 12th Edition, API, 2013.
11. EN 14015 Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above, CEN, 2005.
12. EN ISO 3506 Mechanical properties of corrosion-resistant stainless steel fasteners.  
EN ISO 3506-1: Bolts, screws and studs, CEN, 2009  
EN ISO 3506-2: Nuts, CEN, 2009.
13. EN ISO 898-1 Mechanical properties of fasteners made of carbon steel and alloy steel, bolts, screws and studs with specified property classes. Coarse thread and fine pitch thread, CEN, 2013.
14. ASTM A380 / A380M - 13 Standard practice for cleaning, descaling, and passivation of stainless steel parts, equipment, and systems, ASTM, 2013.
15. EN 1090-2 Execution of steel structures and aluminium structures, Part 2: Technical requirements for steel structures, CEN, 2008.
16. Baddoo, N R, Execution of stainless steel structures, ED018, The Steel Construction Institute, 2014.
17. Practical guidelines for the fabrication of duplex stainless steels, IMO A, 2009 (available from [www.imoa.info](http://www.imoa.info)).
18. CEN/TC 350 Sustainability of construction works, [www.cen.eu](http://www.cen.eu).

### Sources of Further Information

Stainless steel in biogas production, ISSF, 2012 (available from [www.worldstainless.org](http://www.worldstainless.org)).

This publication can be downloaded from the Online Information Centre for Stainless Steels in Construction [www.stainlessconstruction.com](http://www.stainlessconstruction.com) which is a website giving technical guidance, design data, case studies and research papers about the design, specification, fabrication and installation of stainless steel in construction. It is also available from [www.steelbiz.org](http://www.steelbiz.org).

The photos on pages 1, 2, 9 and 19 are provided by WELTEC BIOPOWER GmbH.



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