

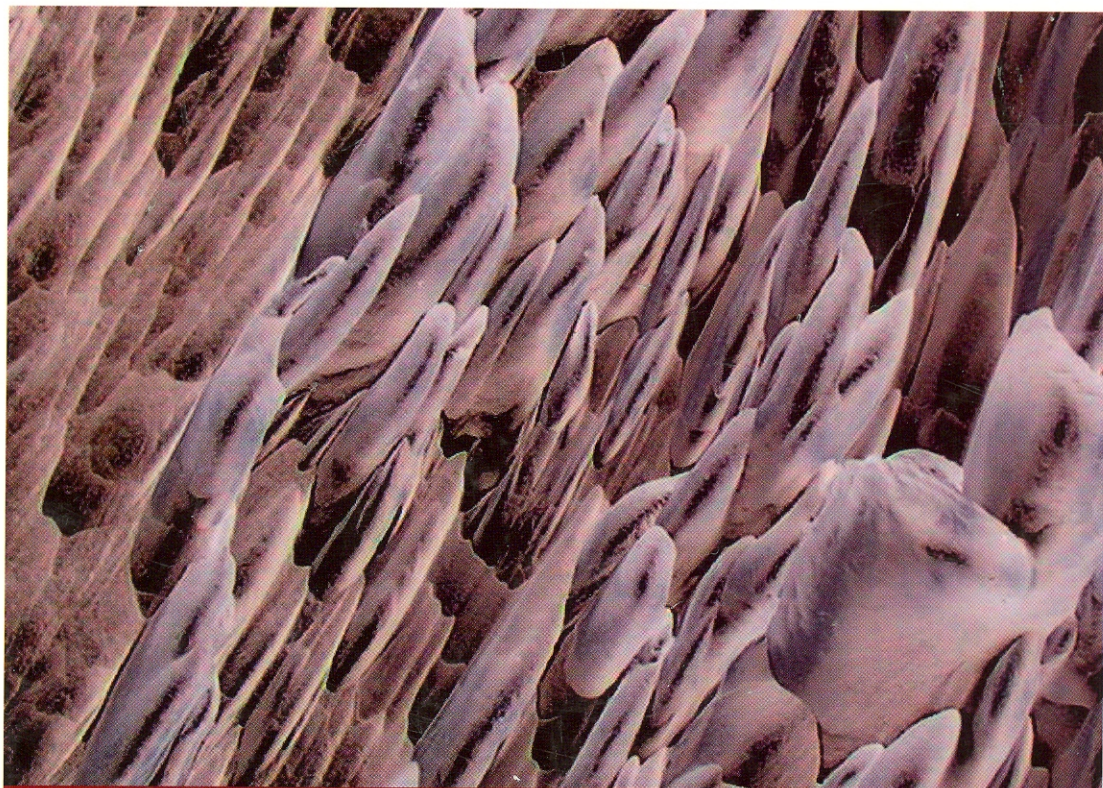
Edited by
G. Kreysa and M. Schütze

 WILEY-VCH

Corrosion Handbook

Corrosive Agents and Their Interaction with Materials
**Volume 4: Drinking Water, Waste Water (Municipal),
Waste Water (Industrial)**

Second, Completely Revised
and Extended Edition



**DECHEMA the prime source of
corrosion expertise**



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Volume 4

Drinking Water, Waste Water (Municipal),

Waste Water (Industrial)

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Volume 1

Sodium Hydroxide, Mixed Acids

Volume 2

Hydrochloric Acid, Nitric Acid

Volume 3

Hypochlorites, Phosphoric Acid

Volume 4

Drinking Water, Waste Water (Municipal),
Waste Water (Industrial)

Volume 5

Carbonic Acid, Chlorine Dioxide,
Seawater

Volume 6

Atmosphere, Industrial Waste Gases

Volume 7

Sodium Chloride

Volume 8

Chlorinated Hydrocarbons –
Chloromethanes,
Chlorinated Hydrocarbons –
Chloroethanes, Alkanols

Volume 9

Potassium Hydroxide, Ammonium and
Ammonium Hydroxide

Volume 10

Sulfur Dioxide, Sodium Sulfate

Volume 11

Sulfuric Acid

Volume 12

Ferrous Chlorides (FeCl_2 , FeCl_3)

Volume 13

Index

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Volume 4

**Drinking Water, Waste Water (Municipal),
Waste Water (Industrial)**



DECHEMA e.V.



**WILEY-
VCH**

WILEY-VCH Verlag GmbH & Co. KGaA

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Contents

List of Contributors VII

Preface IX

How to use the Corrosion Handbook XI

Drinking Water 1

Author: G. Heim, K. Reeh/Editor: R. Bender

A Metallic materials 15

Aluminium and aluminium alloys, copper and copper alloys, iron, iron-based alloys and steels, nickel and nickel alloys, titanium and titanium alloys, zinc cadmium and their alloys

B Non-metallic inorganic materials 89

Carbon and graphite, binders for building materials, glass, quartz ware and quartz glass, enamel, oxide ceramic materials, metal ceramic materials

C Organic materials/plastics 118

Thermoplastics, thermosetting plastics, elastomers, duroplasts

D Materials with special properties 123

Coatings and linings, seals and packings, composite materials

Bibliography 126

Waste Water (Municipal) 139

Author: G. Heim, K. Reeh/Editor: R. Bender

A Metallic materials 156

Aluminium and aluminium alloys, copper and copper alloys, iron, iron-based alloys and steels, nickel and nickel alloys, titanium and titanium alloys, zinc, cadmium and their alloys

B Non-metallic inorganic materials 172

Carbon and graphite, binders for building materials, glass, quartz ware and quartz glass, enamel, oxide ceramic materials, metal ceramic materials

C Organic materials/plastics 205

Thermoplastics, thermosetting plastics, elastomers, duroplasts

D Materials with special properties 211

Coatings and linings, seals and packings, composite materials

Bibliography 219

Waste Water (Industrial) 233

Author: E. Heitz, G. Subat/Editor: R. Bender

A Metallic materials 251

Aluminium and aluminium alloys, copper and copper alloys, iron, iron-based alloys and steels, nickel and nickel alloys, titanium and titanium alloys, zinc, cadmium and their alloys

B Non-metallic inorganic materials 283

Carbon and graphite, binders for building materials, glass, quartz ware and quartz glass, enamel, oxide ceramic materials, metal ceramic materials

C Organic materials/plastics 308

Thermoplastics, thermosetting plastics, elastomers, duroplasts

D Materials with special properties 335

Coatings and linings, seals and packings, composite materials

E Materials recommendations 355

Bibliography 364

Key to materials compositions 385

Index of materials 415

Subject index 424

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Preface

Practically all industries face the problem of corrosion – from the micro-scale of components for the electronics industries to the macro-scale of those for the chemical and construction industries. This explains why the overall costs of corrosion still amount to about 2 to 4% of the gross national product of industrialized countries despite the fact that zillions of dollars have been spent on corrosion research during the last few decades.

Much of this research was necessary due to the development of new technologies, materials and products, but it is no secret that a considerable number of failures in technology nowadays could, to a significant extent, be avoided if existing knowledge were used properly. This fact is particularly true in the field of corrosion and corrosion protection. Here, a wealth of information exists, but unfortunately in most cases it is scattered over many different information sources. However, as far back as 1953, an initiative was launched in Germany to compile an information system from the existing knowledge of corrosion and to complement this information with commentaries and interpretations by corrosion experts. The information system, entitled “DECHEMA-Werkstoff-Tabelle” (DECHEMA Corrosion Data Sheets), grew rapidly in size and content during the following years and soon became an indispensable tool for all engineers and scientists dealing with corrosion problems. This tool is still a living system today: it is continuously revised and up-dated by corrosion experts and thus represents a unique source of information. Currently, it comprises more than 9,000 pages with approximately 110,000 corrosion systems (i.e., all relevant commercial materials and media), based on the evaluation of over 100,000 scientific and technical articles which are referenced in the database.

Last century, an increasing demand for an English version of the DECHEMA-Werkstoff-Tabelle arose in the 80s; accordingly the DECHEMA Corrosion Handbook was published in 1987. This was a slightly condensed version of the German edition and comprised 12 volumes. Before long, this handbook had spread all over the world and become a standard tool in countless laboratories outside Germany.

Now that almost 20 years have passed since the first DECHEMA Corrosion Handbook was prepared for publication, it seems timely to publish a completely revised edition which takes into account the advances that have been made in the meantime. A large-scale research programme, which was funded by the German Federal Ministry of Research and Development over a period of two decades and ended only

a few years ago, played an important role in the discovery of much of this new knowledge. In addition, the international state-of-the-art has developed significantly and this has also been taken into account in the new edition, which is now called "Corrosion Handbook".

The general character of the handbook remains unchanged. The chapters are arranged by the agents leading to individual corrosion reactions, and a vast number of materials are presented in terms of their behavior in these agents. The key information consists of quantitative data on corrosion rates coupled with commentaries on the background and mechanisms of corrosion behind these data, together with the dependencies on secondary parameters, such as flow-rate, pH, temperature, etc. This information is complemented by more detailed annotations where necessary, and by an immense number of references listed at the end of each chapter.

An important feature of this handbook is that the data was compiled for industrial use. Therefore, particularly for those working in industrial laboratories or for industrial clients, the book will be an invaluable source of rapid information for day-to-day problem solving. The handbook will have fulfilled its task if it helps to avoid the failures and problems caused by corrosion simply by providing a comprehensive source of information summarizing the present state-of-the-art. Last but not least, in cases where this knowledge is applied, there is a good chance of decreasing the costs of corrosion significantly.

Finally the editors would like to express their appreciation to Birgit Czack and Dr. Roman Bender for their admirable commitment and meticulous editing of a work that is encyclopedic in scope.

They are also indebted to Karin Sora of Wiley-VCH for her valuable assistance during all stages of the preparation of this book.

Gerhard Kreysa and Michael Schütze

How to use the Corrosion Handbook

The Corrosion Handbook, abbreviated to CHB in the following, provides information on the chemical resistance and the corrosion behavior of materials in approximately 1000 different attacking chemical media and mixtures of materials.

The user is given information on the range of applications and corrosion protection measures for metallic, non-metallic inorganic, and organic materials, including plastics.

Research results and operating experience reported by experts allow recommendations to be made for the selection of materials and to provide assistance in the assessment of damage.

The objective is to offer a comprehensive and concise description of the behavior of the different materials in contact with a particular medium.

Every chapter is a self-contained work that is subdivided according to four groups of materials A-D:

- **A Metallic materials**
- **B Non-metallic inorganic materials**
- **C Organic materials and plastics**
- **D Materials with special properties**

These material groups are each subdivided according to their chemical formula, the metals are classed according to different alloy groups. These groups are shown in the uniformly designed overview table at the start of each chapter.

Material recommendations are given for each of the four groups of materials. In more recent editions, these are summarized in the section

- **E Materials recommendations**

The information on resistance is given as text, tables, and figures. The literature used by the author is cited at the corresponding point. There is an index of materials as well as a subject index at the end of the book so that the user can quickly find the information given for a particular keyword.

The Corrosion Handbook is thus a guide that leads the reader to materials that have already been used in certain cases, that can be used or that are not suitable owing to their lack of resistance.

The resistance is coded with three evaluation symbols in order to compress the information. Uniform corrosion is evaluated according to the following criteria:

Symbol	Meaning	Area-related mass loss rate ¹⁾		Corrosion rate
		g/(m ² h)	g/(m ² d)	mm/a
+	resistant	≤ 0.1	≤ 2.4	≤ 0.1 ²⁾
⊕	fairly resistant	< 1.0	< 24.0	< 1.0
–	not resistant	> 1.0	> 24.0	> 1.0

¹⁾ for Al, Mg, and its alloys, 1/3 of the value must be used

²⁾ the values for Ta, Ti, and Zr are too high (possible embrittlement due to hydrogen absorption in the event of corrosion! Therefore, corrosion rate = 0.01 mm/a, see the individual cases)

The evaluation of the corrosion resistance of metallic materials is given

- for uniform corrosion or local penetration rate, in: mm/a
- or if the density of the material is not known, in: g/(m²h) or g/(m²d).

Pitting corrosion, crevice corrosion, and stress corrosion cracking or non-uniform attack are particularly highlighted.

The following equations are used to convert mass loss rates, x , into the corrosion rate, y :

$$\begin{array}{lll}
 \text{from } x_1 \text{ into g/(m}^2\text{h)} & \text{from } x_2 \text{ into g/(m}^2\text{d)} & \text{where} \\
 \frac{x_1 \cdot 365 \cdot 24}{\rho \cdot 1000} = y \text{ (mm/a)} & \frac{x_2 \cdot 365}{\rho \cdot 1000} = y \text{ (mm/a)} & x_1: \text{ value in g/(m}^2\text{h)} \\
 & & x_2: \text{ value in g/(m}^2\text{d)} \\
 & & \rho: \text{ density of material in g/cm}^3 \\
 & & y: \text{ value in (mm/a)} \\
 & & d: \text{ days} \\
 & & h: \text{ hours}
 \end{array}$$

In those media in which uniform corrosion can be expected, if possible, isocorrosion curves (corrosion rate = 0.1 mm/a) or resistance ranges for non-metallic materials are given. The evaluation criteria for non-metallic inorganic materials are stated in the individual cases; depending on the material and medium, they may also be given as corrosion rates (mm/a).

The suitability of organic materials is generally evaluated by comparing property characteristics (e.g. mass, tensile strength, elasticity module or ultimate elongation) and other changes (e.g. cracking) after exposure to the medium with respect to these characteristics in the initial state before exposure. The extent of changes in the properties after exposure to the medium is decisive for the evaluation of the resistance to chemicals or the durability of the materials. The criteria listed below for the evaluation of the chemical resistance apply to thermoplastics used to manufacture pipes and are based on results from immersion tests with an immersion time of 112 days (see ISO 4433 Part 1 to 4). In principle, they are also applicable to other organic materials; however, they should be adapted to the individual material,

because, as the following table shows, the evaluation criteria are not consistent, even within a group of thermoplasts, but depend on the type of thermoplastic material.

Symbol	Meaning	Permissible limiting value¹⁾			
		of the mass change²⁾ %	of the tensile strength³⁾ %	of the elasticity module³⁾ %	of the ultimate elongation³⁾ %
+	resistant/ durable	PE, PP, PB: –2 to 10	PE, PP, PB, PVC, PVDF: ≥ 80	PE, PP, PB: ≥ 38 PVC: ≥ 83 PVDF: ≥ 43	PE, PP, PB: ≥ 50 to 200 PVC, PVDF: 50 to 125
		PVC, PVDF: –0.8 to 3.6			
⊕	limited resistance/ limited durability	PE, PB, PB: > 10 to 15 or < –2 to –5	PE, PB, PB, PVC, PVDF: < 80 to 46	PE, PB, PB: < 38 to 31 PVC: < 83 to 46 PVDF: < 43 to 30	PE, PB, PB: < 50 to 30 or > 200 to 300 PVC, PVDF: < 50 to 30 or > 125 to 150
		PVC, PVDF: < –0.8 to –2 or > 3.6 to 10			
–	not resistant/ not durable	PE, PP, PB: < –5 or > 15	PE, PP, PB, PVC, PVDF: < 46	PE, PP, PB: < 31 PVC: < 46 PVDF: < 30	PE, PP, PB: < 30 or > 300 PVC, PVDF: < 30 or > 150
		PVC, PVDF: < –2 or > 10			

¹⁾ The data applies to the values determined in the initial state without exposure to the medium which correspond to 100 %

²⁾ Relative mass change according to DIN EN ISO 175

³⁾ Tensile strength, elasticity module, and ultimate elongation according to DIN EN ISO 527-1

Scope of validity for PVC: PVC-U, PVC-HI, and PVC-C; for PE: PE-HD, PE-MD, PE-LD, and PE-X

Unless stated otherwise, the data was measured at atmospheric pressure and room temperature.

The resistance data should not be accepted by the user without question, and the materials for a particular purpose should not be regarded as the only ones that are suitable. To avoid wrong conclusions being drawn, it must be always taken into account that the expected material behavior depends on a variety of factors that are often difficult to recognize individually and which may not have been taken deliberately into account in the investigations upon which the data is based. Under certain circumstances, even slight deviations in the chemical composition of the medium, in the pressure, in the temperature or, for example, in the flow rate are sufficient to have a significant effect on the behavior of the materials. Furthermore, impurities in the medium or mixed media can result in a considerable increase in corrosion.

The composition or the pretreatment of the material itself can also be of decisive importance for its behavior. In this respect, welding should be mentioned. The suitability of the component's design with respect to corrosion is a further point which must be taken into account. In case of doubt, the corrosion resistance should be investigated under operating conditions to decide on the suitability of the selected materials.

Drinking Water

Authors: G. Heim †, K. Reeh/Editor: R. Bender

	Page		Page
Survey Table	2	A 22 Austenitic chromium-nickel steels with special alloying additions	48
Introduction	6	A 33 Lead and lead alloys	55
A Metallic materials	15	A 39 Zinc, cadmium and their alloys	56
A 2 Aluminium	15	B Non-metallic inorganic materials	89
A 3 Aluminium alloys	15	B 1 Asbestos	89
A 7 Copper	25	B 4 Binders for building materials (e.g. mortar and concrete)	90
A 8 Copper-aluminium alloys	29	B 8 Enamel	115
A 9 Copper-nickel alloys	29	C Organic materials	118
A 10 Copper-tin alloys (bronzes)	29	C 2 Bituminous compositions (bitumen, asphalt, pitch)	118
A 11 Copper-tin-zinc alloys (red brass)	29	C 7 Polyolefins and their copolymers	119
A 12 Copper-zinc alloys (brass)	29	C 8 Polyvinyl chloride and its copolymers	119
A 13 Other copper alloys	29	D Materials with special properties	123
A 14 Unalloyed steels and cast steel	32	D 1 Coatings and linings	123
A 15 Unalloyed cast iron	47	D 5 Natural and synthetic elastomers	124
A 17 Structural steels with up to 12% chromium	48	Bibliography	126
A 18 Ferritic chromium steels with more than 12% chromium	48		
A 19 Ferritic-austenitic steels with more than 12% chromium	48		
A 20 Austenitic chromium-nickel steels	48		
A 21 Austenitic chromium-nickel-molybdenum steels	48		

Survey Table

The table below contains general data on the corrosion behavior. For additional comments, refer to the material numbers in the text.

Material Type No.*	Behavior**	Material Type No.*	Behavior**
A	Metallic materials	A 35	Platinum metals (Ir, Os, Pd, Ru) and their alloys
A 1	Silver and silver alloys	A 36	Tin and tin alloys
A 2	Aluminium	A 37	Tantalum, niobium and their alloys
A 3	Aluminium alloys	A 38	Titanium and titanium alloys
A 4	Gold and gold alloys	A 39	Zinc, cadmium and their alloys
A 5	Cobalt and cobalt alloys	A 40	Zirconium and zirconium alloys
A 6	Chromium and chromium alloys	A 41	Other metals and alloys
A 7	Copper	B	Non-metallic inorganic materials
A 8	Copper-aluminium alloys	B 1	Asbestos
A 9	Copper-nickel alloys	B 2	Natural stones
A 10	Copper-tin alloys (bronzes)	B 3	Carbon and graphite
A 11	Copper-tin-zinc alloys	B 4	Binders for building materials (e.g. mortar and concrete)
A 12	Copper-zinc alloys (brass)	B 5	Acid-resistant building materials and binders (putties)
A 13	Other copper alloys	B 6	Glass
A 14	Unalloyed steels and cast steel	B 7	Quartz ware and quartz glass
A 15	Unalloyed cast iron	B 8	Enamel
A 16	High-alloy cast iron, high-silicon cast iron	B 9	Porcelain
A 17	Structural steels with up to 12% chromium	B 10	Stoneware
A 18	Ferritic chromium steels with more than 12% chromium	B 11	Refractory materials
A 19	Ferritic-austenitic steels with more than 12% chromium	B 12	Oxide ceramic materials
A 20	Austenitic chromium-nickel steels	B 13	Metallo-ceramic materials (carbides, nitrides)
A 21	Austenitic chromium-nickel-molybdenum steels	B 14	Other inorganic materials
A 22	Austenitic chromium-nickel steels with special alloying additions	C	Organic materials
A 23	Special iron-based alloys	C 1	Natural fibers (wool, cotton, silk etc.)
A 24	Magnesium and magnesium alloys	C 2	Bituminous compositions (bitumen, asphalt, pitch)
A 25	Molybdenum and molybdenum alloys	C 3	Fats, oils, waxes
A 26	Nickel	C 4	Wood
A 27	Nickel-chromium alloys	C 5	Modified celluloses
A 28	Nickel-chromium-iron alloys	C 6	Furan resins
A 29	Nickel-chromium-molybdenum alloys	C 7	Polyolefins and their copolymers
A 30	Nickel-copper alloys	C 8	Polyvinyl chloride and its copolymers
A 31	Nickel-molybdenum alloys	C 9	Polyvinyl esters and their copolymers
A 32	Other nickel alloys	C 10	Phenolic resins
A 33	Lead and lead alloys	C 11	Acrylic resins
A 34	Platinum and platinum alloys	C 12	Polyamides
		C 13	Polyacetals

Material Type No.*	Behavior**	Material Type No.*	Behavior**
C 14	Polyesters	D	Materials with special properties
C 15	Polycarbonates	D 1	Coatings and linings + to –
C 16	Polyurethanes	D 2	Seals and packings
C 17	Alkyd resins	D 3	Composite materials
C 18	Epoxy resins	D 4	Heat-resistant and scaling- resistant alloys
C 19	Fluorocarbon resins	D 5	Natural and synthetic + elastomers
C 20	Polyvinylidene chloride	D 6	Powder metallurgical materials
C 21	Amino resins		
C 22	Silicones		
C 23	Other synthetic materials		

* Any notes in the text are entered under the same number as the materials, (for example A2, B8, C7)

** + resistant / ⊕ fairly resistant / – unsuitable. Where no indication of corrosion resistance is made, experimental data are not available.

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Introduction

Index of the Introduction

V 1	General	6	V 6	Overview of the use of materials and material protection measures	10
V 2	Water quality	9	V 7	Long-distance pipelines	11
V 3	Temperature	9	V 8	Distribution pipelines	12
V 4	Flow conditions	10	V 9	Service pipelines	12
V 5	Installation	10	V 10	Domestic installation	12

Introduction

V1 General

Drinking water is water suitable for human consumption and use. When materials or coatings come into contact with it, no substances should be released which lead to a deterioration in its quality. The EC Directive [1] and the drinking water legislation specify limiting values both for toxic and non-toxic substances. These define a restricting framework for drinking water which must be observed within the European sector. Differences exist between the EC Directive and the drinking water legislation, which will be referred to where necessary. The parameters relevant to corrosion have been taken from [2] and summarized in Tables 1, 2 and 3.

Chemical substance	Limiting value mg/l	Calculated as	Corresponding to approximately mmol/m³	Allowance in measured value $\pm$ mg/l
Arsenic	0.04	As	0.5	0.015
Lead	0.04	Pb	0.2	0.02
Cadmium	0.005	Cd	0.04	0.002
Chromium	0.05	Cr	1	0.01
Cyanide	0.05	CN ⁻	2	0.01
Fluoride	1.5	F ⁻	79	0.2
Nickel	0.05	Ni	0.9	0.01
Nitrate	50	NO ₃ ⁻	806	2
Nitrite	0.1	NO ₂ ⁻	2.2	0.02
Mercury	0.001	Hg	0.005	0.0005

Table 1: Limiting values for chemical substances in drinking water [2]

Parameter	Limiting value	Allowance in measured value	Stipulated method/ observations
Temperature	298 K (25 °C)	± 1 K (1 °C)	temperature measurement with a mercury or electrical thermometer; highest value does not apply to warm drinking water
pH	not below 6.5 and not above 9.5 a) the pH of the water in the range 6.5 – 8.0 with metallic or cement-containing materials should not be more than 0.2 pH units below the pH of calcium carbonate saturation b) the pH of the water in the range 6.5 – 9.5 with asbestos cement materials should not be more than 0.2 pH units below the pH of calcium carbonate saturation	± 0.1	potentiometric measurement with a glass electrode; the pH of calcium carbonate saturation is determined by marble* solubility studies experimentally or by calculation
Electrical conductivity	2000 μ S/cm at 298 K (25 °C)	± 100 μ S/cm	potentiometric measurement
Oxidizability (calculated as O ₂)	5 mg/l	–	volumetric determination of the oxidizability by means of potassium permanganate/potassium permanganate consumption

* marble = calcium carbonate

Table 2: Physico-chemical parameters of drinking water [2]

The limiting values referred to clearly differentiate drinking water from all other types of water.

When evaluating the suitability of materials, the deterioration described in the corrosion medium drinking water due to the release of constituents of the material must also be taken into account in the sense of DIN EN ISO 8044 [3], as well as the corrosive attacks leading to weakening of walls or wall fractures. In the majority of cases drinking water comes into contact with the inner surfaces of pipes, tanks and fittings made of various materials. Under these circumstances, as well as depending on the quality of the drinking water, the corrosion behavior of the individual materials

Chemical substance	Limiting value mg/l	Calculated as	Corresponding to approximately mmol/m³	Allowance in measured value ± mg/l	Stipulated method/ observations
Aluminium	0.2	Al	7.5	0.04	–
Ammonium	0.5	NH ₄ ⁺	30	0.1	except with water from a strongly reducing soil
Iron	0.2	Fe	3.5	0.01	does not apply by the addition of iron salts in the treatment of drinking water
Potassium	12	K	300	0.5	except with water from a potassium-containing soil
Magnesium	50	Mg	2050	2	except with water from a magnesium-containing soil
Manganese	0.05	Mn	0.9	0.01	–
Sodium	150	Na	6500	6	–
Silver	0.01	Ag	0.1	0.004	does not apply by the addition of silver or silver compounds in the treatment of drinking water
Sulfate	240	SO ₄ ²⁻	2500	5	except with water from a calcium-containing soil

Table 3: Limiting values for chemical substances in drinking water [2]

is determined by other influencing parameters, such as the operating conditions (flow rate, temperature), construction and installation [4].

Since the influencing parameters referred to are not always constant and known, only probability statements can be made on the resistance of materials [3]. The possibility of corrosion damage to the outer surfaces of the components must be taken into account when evaluating the resistance of materials [5]. This particularly applies to underground pipelines and components, which may be attacked on the outer surfaces by aggressive soils, by the formation of electrochemical cells [6] or by stray currents [7]. In the case of plastic pipes, substances of a dubious hygienic nature may pass from contaminated soils through the pipe wall into the drinking water.

The pipelines and components which come into contact with drinking water on their inner surfaces can be briefly described as follows in the sequence following drinking water treatment by the water supply companies (WSC): drinking water tanks, long-distance lines, distribution lines, domestic service lines, domestic installation (consumer).

V2 Water quality

Drinking water contains dissolved ions and gases which largely determine its corrosion-influencing properties. This is always caused by the interaction of several contents in the water. It is not possible to make statements which apply universally to all materials. The following comments are a brief review of the main contents of water which can be used to evaluate the behavior of the material.

The content of dissolved ions is summarized by the electrical conductivity, which according to Table 2 should not exceed the limiting value of 2000 $\mu\text{S}/\text{cm}$ at 298 K (25 °C). It is influenced particularly by the content of hydrogen and hydroxyl ions, and by cations (mainly Ca^{2+} , Mg^{2+} and Na^+) and anions (mainly Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-} and NO_3^-). The pH within the limits of 6.5 to 9.5 permitted according to Table 2 and the cations and anions mentioned have various effects on the corrosion behavior of the individual materials.

In addition to the pH range, the drinking water legislation specifies that the pH of drinking water should not be more than 0.2 pH units below the pH of calcium carbonate saturation (Table 2). This provision does not meet with unanimous approval, especially in respect of corrosion [8].

Of the dissolved gases, oxygen (O_2) and carbon dioxide (CO_2) should be mentioned above all. On metallic materials – depending on the conditions which exist – oxygen can either promote corrosion or have the effect of forming a surface layer. CO_2 is particularly important for evaluating the resistance of cemented materials in connection with the bicarbonate content.

To evaluate the corrosion properties of drinking water on metallic materials, the following data are necessary according to [9]:

water temperature, pH, acid capacity $K_A4.3$, Ca^{2+} , SO_4^{2-} , Cl^- , NO_3^- , O_2 , DOC, Na^+ , Mn^{2+} , Fe_{2+} , SiO_2 and P.

In the case of cemented materials, such as, for example, the cement mortar linings on steel and cast iron pipes, according to [10] the following data must be known:

pH, $Q_c = K_A4.3 + K_B 8.2$, SO_4^{2-} , excess CO_2 , saturation index I_s .

V3 Temperature

According to the data in Table 2, drinking water intended for immediate human consumption should not exceed a temperature of 298 K (25 °C). Within the temperature range of about 283 to 298 K (10 to 25 °C) stated for cold water, the temperature does not have a very substantial influence on the corrosion behavior of materials.

If drinking water is heated for human consumption, an increased risk of corrosion compared with cold water can be expected on ferrous materials, especially unalloyed ferrous materials, because of the increased temperature. In contrast, copper materials tend to be less at risk from corrosion in hot water than in cold water.

At higher temperatures, agents which cause hardness precipitate as the temperature rises, depending on the hardness of the cold water. The deposits formed on the

surfaces of materials by this process can lead to the formation of electrochemical cells, especially if the surfaces are not coated uniformly, with the consequence of increased local corrosive attack. However, even if the surfaces are coated uniformly, pitting phenomena may occur due to the concentration of anions, especially chloride. This should be remembered, for example, in the case of heat exchanger pipes made of stainless steel.

V4 Flow conditions

Static drinking water initially leads to non-uniform general corrosion on unalloyed ferrous materials, leading to the development of non-protective surface layers and therefore the formation of anodic and cathodic regions. The consequence is then the occurrence of local corrosive attack in the form of wide or deep pitting. The pH drops in the pitting regions and rises in those regions outside the pitting, that is to say an electrochemical cell forms as a result of different pH values (Evans cell). At relatively high flow rates, differences in pH cannot always develop, so that in these cases it is often not local corrosion but uniform corrosion which can occur [11].

In domestic installations, there are alternating periods of static, gently flowing and faster flowing water, depending on what is being drawn off for use. The corrosion conditions are thus less clear, so that no general statements can be made, only material-specific statements.

V5 Installation

In the construction of systems for drinking water transport and distribution, connection elements, for example pipe connections, whose design can significantly affect the corrosion phenomena, must be made. This is clear particularly in the case of domestic installation, where pipe connections are made in the form of screwed, soldered or welded joints [12].

In a domestic installation, a combination of different metallic materials is unavoidable, that is to say the possibility of contact corrosion must be taken into account. Indications of the contact corrosion risk are contained in [13].

Another aspect of constructing a drinking water installation in buildings is the introduction of solids, such as, for example, sand, iron filings etc., into the pipelines. If solids are deposited at certain points on the inner surfaces and remain there, the formation of a protective layer is prevented here. Pitting at these points can cause fractures in the pipe wall.

V6 Overview of the use of materials and material protection measures

Practical experience with materials used for the drinking water supply has shown that the use of a material, as already stated, is largely determined both by the operat-

ing conditions and the production possibilities for the components and the production costs. The historical development is outlined and the materials and coatings currently used are mentioned in the following paragraphs.

Unalloyed ferrous materials, that is to say cast iron and steel materials, are predominantly used in drinking water plants in association with active and passive protective measures. Suitable active measures are cathodic corrosion protection (preferably in water tanks) and the addition of inhibitors to the drinking water. Passive measures include coatings using organic and inorganic coating materials, and metallic coatings.

Unalloyed ferrous materials are used without additional protective measures to a strictly limited degree. The reason for their limited use is the lack of resistance of these materials to local attack, such as wide or deep pitting. In domestic installations, it is the brown discoloration and change in taste of drinking water (rusty water), above all, which are unacceptable to the public – although they are not a health hazard.

If organic and inorganic coatings are used, as well as the question of their resistance, their microbiological properties must be considered. With some organic coating materials, microbial contamination of the drinking water has been found as a result of low molecular weight compounds being dissolved out of these materials. In other cases, a microbial slime, from which bacteria have been washed out, forms on certain coating materials. Only those coating materials which do not display the phenomena described can be used for drinking water plants. Microbial testing is carried out in accordance with [14, 15].

The compilation in Table 4 gives an overview of the proportion of different materials used in long-distance and distribution pipelines [16].

V7 Long-distance pipelines

Pipes made of unalloyed ferrous material, that is to say, cast iron and steel pipes, are used for strength in long-distance pipelines, because of the larger pipe dimensions and the high pressures. Unalloyed steel and cast iron materials are protected by linings because of the possible brown discoloration due to even relatively small amounts of iron dissolving out into the drinking water. A bitumen lining was mainly used for steel pipes in Germany up until about 1950. A thin lining was applied for less aggressive water, while lining layers a few millimeters thick were used for aggressive water. Up until this point in time, cast iron pipes were chiefly lined with a thin bituminous layer applied by heat. Steel pipes have been lined as standard with cement mortar since about 1950 and cast iron pipes since about 1970 [10]. Where steel pipes are still lined with bitumen, according to [17], only a lining thickness of 3.5 mm is suitable.

Another material for long-distance pipes in water pipelines is concrete, from which centrifugally molded concrete and reinforced concrete pipes are produced. In many cases, additional internal protection of these pipes is not necessary.

V8 Distribution pipelines

Cast iron pipes dominate in this field, while steel and plastic pipes are used to a significantly lesser degree. Until the mid-sixties, gray cast iron pipes were used, but these have been replaced by the ductile cast iron pipes which are now used exclusively. Lining of these pipes with cement mortar is considered standard.

V9 Service pipelines

While in previous decades mainly hot-galvanized steel pipes were used for this purpose, plastic pipes consisting of polyethylene are now increasingly being installed. The use of copper pipes in this sector is limited to a few individual cases.

At the start of the 20th century, service pipes made of lead were laid in some towns.

V10 Domestic installation

Technical regulations for drinking water installations (TRWI) are summarized comprehensively in the revised DIN 1988. The materials suitable for domestic installation are dealt with in [18, 19].

The field experiments carried out in the context of the research and development program “Corrosion and corrosion protection” produced results which were significant in practice. These will be dealt with in particular where the individual materials are discussed.

Hot-galvanized steel and copper pipes are preferentially installed for the cold and hot water supply in buildings. Hot-galvanizing is a metallic coating which is said to take over internal corrosion protection of steel pipes without an additional coating. Copper pipes are not given an inner lining. The relevant corrosion problems are dealt with in [12] and will be considered in more detail in the discussion of the materials.

Migration of heavy metals into the drinking water as a function of the water quality and the operating conditions must be taken into account in domestic installations [20].

In spite of a good corrosion resistance, plastic pipes have so far been used to only a very limited extent in the domestic installation sector. The reasons for this are, inter alia, the difficulty in making connections, waste etc. and the fire hazard.

The fittings in domestic installations are made almost exclusively of copper alloys. Corrosion problems may occur by contact corrosion between hot-galvanized steel and valves if protective coatings are not formed due to unfavorable water quality.

In domestic installations, the drinking water is frequently treated by addition of alkalizing substances or phosphates. The success of this protective measure depends on proper incorporation of the units and, above all, their constant maintenance.

Size of company according to total area 10 ⁶ m ²	Number of WSC ¹⁾	Cast iron		Steel		Reinforced concrete		Cement-bound materials		Plastic		Other material		Total length
		km	%	km	%	km	%	km	%	km	%	km	%	
> 20	40	41,724	66.4	7,047	11.2	398	0.6	2,126	3.4	11,483	18.3	97	0.1	62,875
10-20	40	14,957	70.6	1,200	5.7	258	1.2	1,794	8.4	2,975	14.0	14	0.1	21,198
5-10	88	18,584	52.3	1,980	5.6	19	0.1	6,531	18.4	8,212	23.0	207	0.6	35,533
1.5-5	401	41,462	47.3	3,375	3.8	178	0.2	12,279	14.0	29,526	33.7	874	1.0	87,694
0.5-1.5	568	30,433	56.0	2,014	3.7	106	0.2	5,251	9.7	16,102	29.6	427	0.8	54,333
up to 0.5	208	5,425	58.2	312	3.3	51	0.6	728	7.8	2,624	28.2	179	1.9	9,319
1983	1,345	152,585	56.3	15,928	5.9	1,010	0.4	28,709	10.6	70,922	26.1	1,798	0.7	270,952
1982	1,337	150,578	56.7	15,992	6.0	1,000	0.4	28,526	10.7	67,591	25.5	1,850	0.7	265,537

1) with pipeline

Table 4: Length of pipelines and materials used in the drinking water supply [16]

The softening often effected by ion exchange in domestic installations is not a corrosion protection measure. The possible effects on the corrosion behavior are dealt with in the discussion on the individual materials.

Drinking water is heated in tanks which vary widely in construction. The cathodic corrosion protection process is suitable for protecting the inside of tanks. It has a very good protective action if properly planned, installed and maintained [21].

A

Metallic materials**A 2 Aluminium****A 3 Aluminium alloys**

These materials belong to the passivable metals. The corrosion behavior of aluminium and aluminium alloys under exposure to drinking water can therefore be characterized by the potential-dependent passive range and by the pitting potential. The alloy AlMgMn (Table 5) was investigated with various surface states (Table 6) in well water (Table 7) in corrosion chemistry tests in the laboratory [22]. The total current density/potential curve [23] recorded potentiostatically [20] is shown in Figure 1 as an example of this series of experiments. The potential-dependent mean and maximum pit depths and the number of pits per unit area are plotted in the lower part of this diagram. The pitting potential $U_L = -500 \text{ mV}_{\text{SCE}}$ ($U_H = -250 \text{ mV}$) separates the passive region from the pitting region. The U_L values are largely independent of the surface state of the samples and are between -450 mV and -500 mV (Figure 2).

Chemical composition, %									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Be	Al
0.30	0.36	0.01	0.76	1.92	–	< 0.01	< 0.05	< 0.002	balance

Table 5: Chemical analysis of the aluminium-magnesium-manganese alloy [22]

While Veroxal® coatings give aluminium a high resistance to corrosion, other surface coatings provide temporary corrosion protection compared with the “rolled” initial state, by prolonging the induction time until pitting starts in water containing air. As can be seen from the studies (Figures 3 and 4), no pitting occurs in the potential-dependent pitting corrosion range if the specimen remains in this range for a period shorter than the induction time.

Surface treatment
1. AlMgMn with pickled surface: Degreasing with trichloroethane, 1 h exposure to 35 % HNO₃ (295 K (22 °C)), pickling for 1 min in hot, aqueous 10 % NaOH solution (333 K (60 °C)), neutralization in 35 % HNO₃ (295 K (22 °C)) for 15 min.
2. AlMgMn with Boehmite layer: Pickling as in 1., 24-hour treatment in boiling, demineralized water.
3. AlMgMn with green chromating layer: Pickling as in 1., 5-min treatment in Alodine® 401 solution at 318 K (45 °C), rinsing, air-drying 3.1 Green chromating layers 1: after drying the layer below 333 K (60 °C), immediate exposure to corrosion medium 3.2 Green chromating layers 2,3,4: after drying the layer below 333 K (60 °C), exposure of samples for several weeks in desiccator.
4. AlMgMn with yellow chromating layer: Pickling as in 1., 1-min treatment in Alodine® 1200 solution at 295 K (22 °C), rinsing in water, air-drying, exposure of samples for several weeks in desiccator.
5. AlMgMn with Veroxal® layer: Degreasing with trichloroethane, immersion in HNO₃, pickling for 1 min in warm, 10 % NaOH solution (323 K (50 °C)), neutralization in 30 % HNO₃ (295 K (22 °C)), anodic polarization in Veroxal® electrolyte at 293 K (20 °C) up to a layer thickness of > 20 µm, washing, compression of the layer in hot, demineralized water, to which 3 g nickel acetate per liter were added.
6. AlMgMn with electrolytically polished surface: Degreasing with trichloroethane, anodic polishing at 343 K (70 °C) in Aluflex-Spezial® solution, rinsing, drying.

Table 6: Surface treatment of the AlMgMn sheet samples [22]

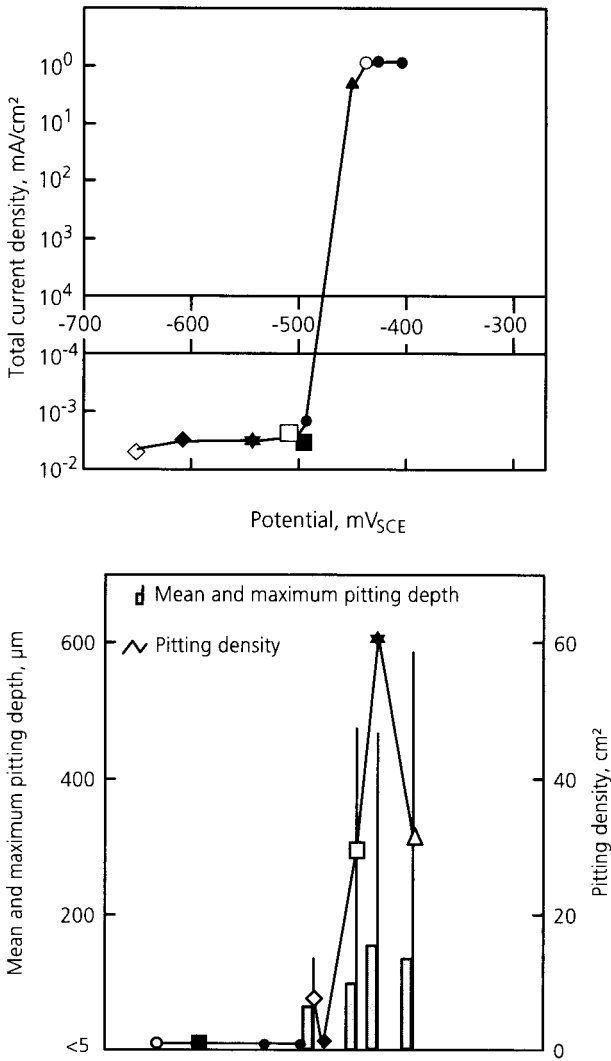


Figure 1: AlMgMn alloy with a rolled surface in well water at 295 K (22 °C) [22]

Laboratory tests were carried out on well and drinking water to find the limits within which aluminium materials can be used in metal-conducting contact with copper, brass, unalloyed iron and zinc [24, 25]. At the chosen area ratio of 1:1, the potential of the AlMgMn alloy in combination with zinc was displaced into the passive range so that no pitting occurred. The metal pairing AlMgSi0.8 (AA 6003)/copper, however, showed pitting in the Al alloy at 295 K (22 °C) in aerated well water (Figure 5). In tests with the same metal pairing in N₂-flushed well water at 295 K (22 °C), there was no pitting (Figure 6) since, due to the absence of oxidizing agents in the water, a shift of the potential in the anodic direction beyond the pitting limit

Parameter	Average value
Chloride	148 mg Cl ⁻ /l
Sulfate	159 mg SO ₄ ²⁻ /l
Exhaust steam residue	931 mg residue l
Annealing residue	624 mg residue l
Carbonate hardness	16.9°
Total hardness	27.5°
Conductivity	1315 µS/cm
pH	6.8

Table 7: Average values determined for certain parameters in well water [22]

did not take place. The corrosion processes on aluminium in water are largely controlled by the mass transfer in the reduction of atmospheric oxygen [26]. This finding explains the result obtained in the tests, according to which pitting occurred on the Al alloy even with addition of copper salts. The cathodic part reactions of corrosion are promoted by the reduction of copper ions and atmospheric oxygen on copper particles which have precipitated on the Al surface.

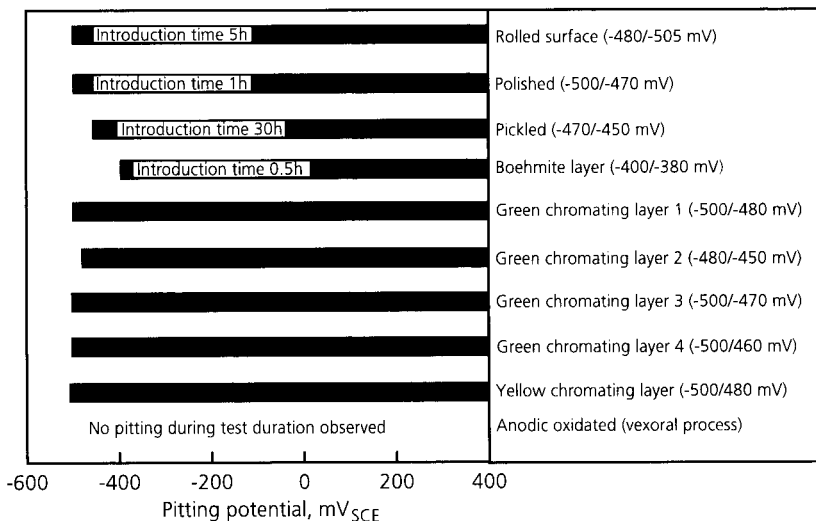


Figure 2: Stationary pitting potential of the AlMgMn alloy with different surface treatment in well water at 295 K (22 °C) [22]

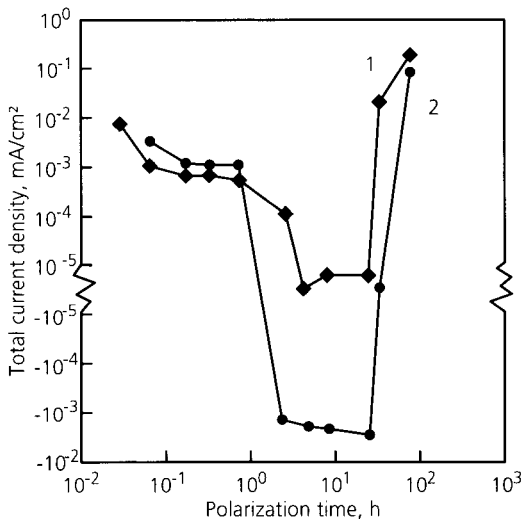


Figure 3: Induction times of the pickled AlMgMn alloy in well water at 295 K (22 °C) [22]

① $U = -445 \text{ mV}_{\text{SCE}}$

② $U = -459 \text{ mV}_{\text{SCE}}$

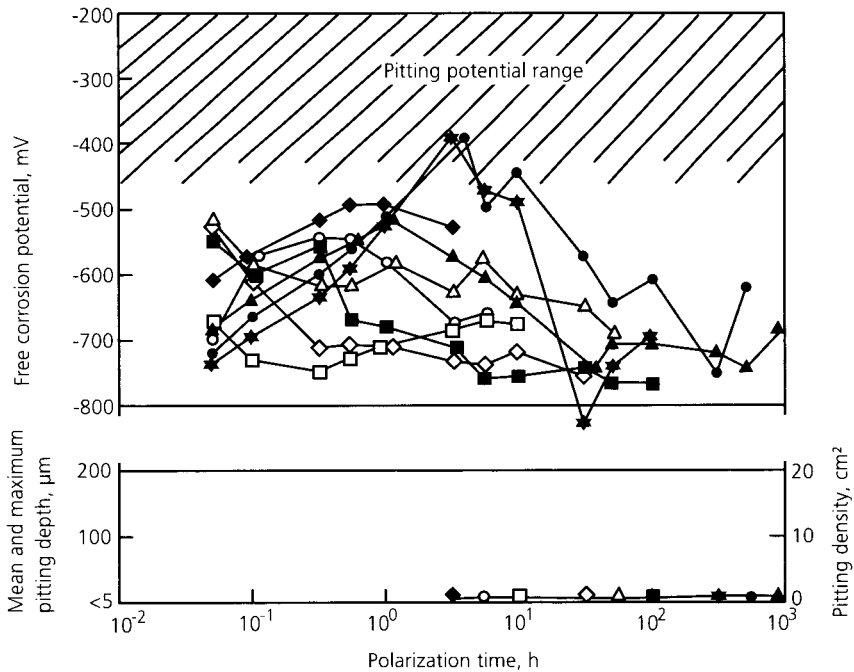


Figure 4: AlMgMn alloy with a pickled surface in well water at 295 K (22 °C) [22]

/// pitting potential range

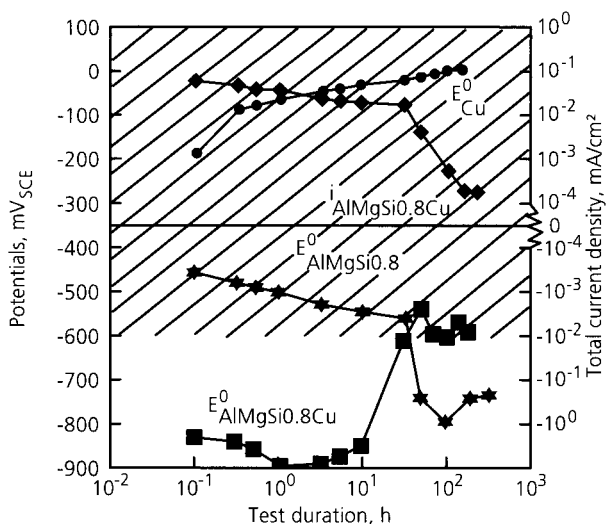


Figure 5: Electrochemical corrosion diagram of the galvanic cell AlMgSi_{0.8} (AA 6003)/copper in aerated well water at 295 K (22 °C) [24]

/// pitting potential range

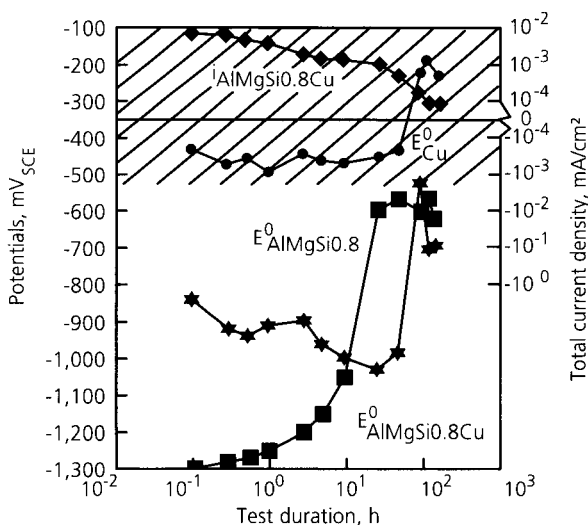


Figure 6: Electrochemical corrosion diagram of the galvanic cell AlMgSi_{0.8} (AA 6003) in well water flushed with N₂ at 295 K (22 °C) [24]

/// pitting potential range

Pipelines made of aluminium and aluminium alloys for drinking water are preferably used where easy handling and fast construction and dismantling are important. Pipes made of the materials listed in Table 8 were therefore studied in a field

test extending over several years in several German waterworks for their corrosion behavior [27].

The analytical values of the water examined are listed in Table 9. To imitate the operating conditions, intermittent operation was chosen. A flow rate of 12 min/h for 12 hours was always followed by a stagnation time of 12 hours.

The extruded pipes dismantled at various times showed, in some cases, pitting and indented corrosion sites, but some showed no corrosive attack. The corrosive attacks depend less on the alloy composition, but more on the water quality. As an example, Figures 7 and 8 show the time dependence of the pitting depth on Al 99.5 (AA 1050, hard-pressed). In spite of the pronounced dependence of the corrosive attacks on the water properties, it was not possible to allocate them clearly to individual water parameters. The influence exerted by the introduction and reduction of the atmospheric oxygen contained in the drinking water on the corrosion behavior of the aluminium materials can be seen from the potential/time curves plotted for flow and stagnation. Under flow conditions, the corrosion potentials shifted in the positive direction beyond the pitting limit determined in stationary polarization tests, and in the stagnation phase, a potential shift in the negative direction was observed, so that pit nucleating sites which had formed could be repassivated. The corrosion reactions are accordingly affected cathodically by the oxygen reaching the aluminium surface and its reduction to hydroxyl ions on the local cathodes – predominantly primary precipitations of binary and ternary intermetallic compounds in the heterogeneous structure.

Pipe material/state
Extruded
High-grade aluminium in the extruded state
High-grade aluminium in the extruded state, drawn, soft annealed
Al alloy AlMg2Mn0.8 (AA 5049) in the extruded state
Al alloy AlMg2Mn0.8 (AA 5049) in the extruded state, drawn
Al alloy AlMgSi0.5 (AA 6060) in the extruded state, artificially aged
Al alloy AlMgSi0.5 (AA 6060) in the extruded state, drawn, artificially aged
Longitudinally welded
Al alloy AlMn, inner roll-bound cladding with binary Al alloy AlZn1 (AA 7072) as galvanic anode

Table 8: Pipe materials in the field tests carried out over the course of several years in a number of German waterworks [27]

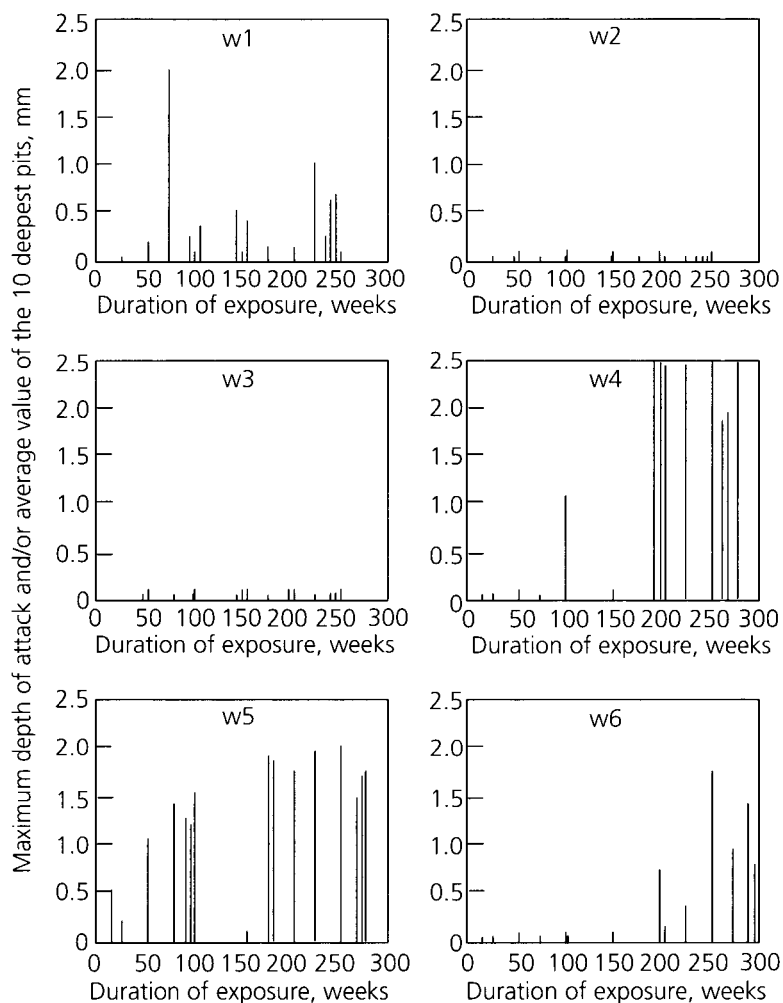


Figure 7: Pitting depth of pressed Al 99.5 (AA 1050) in different drinking waters as a function of the duration of exposure [27]

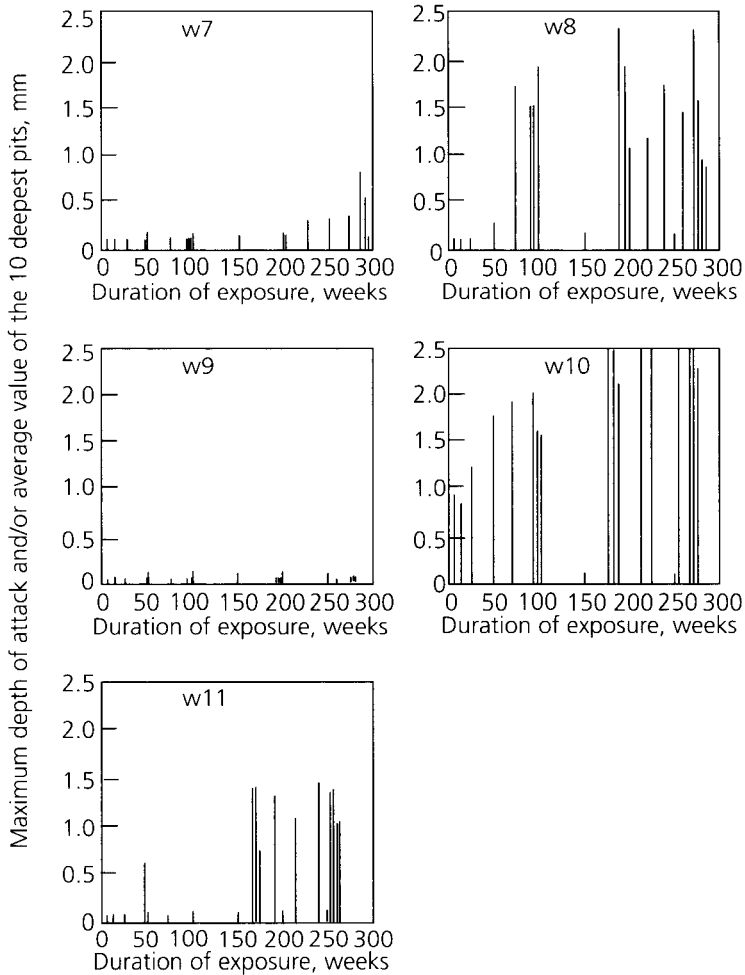


Figure 8: Pitting depth of pressed Al 99.5 in different drinking waters as a function of the duration of exposure [27]

The longitudinally welded AlMn pipes coated on the inside with AlZn1 (AA 7072) showed an advantageous corrosion behavior since, in these, the growth of local pitting corrosion sites in aerated, aggressive drinking water was stopped at the coating boundary (Figure 9). This behavior of the corrosion-affected pipe can be ascribed to the AlZn1 coating which, as a voltaic anode, shifts the potential of the AlMn pipe material from the pitting region into the passive region.

In these field tests, hot-aluminized steel pipes were also investigated. With an aluminium deposit of 874 g/m^2 , the inner surfaces located underneath the Al layer were hardly attacked at all in all the samples.

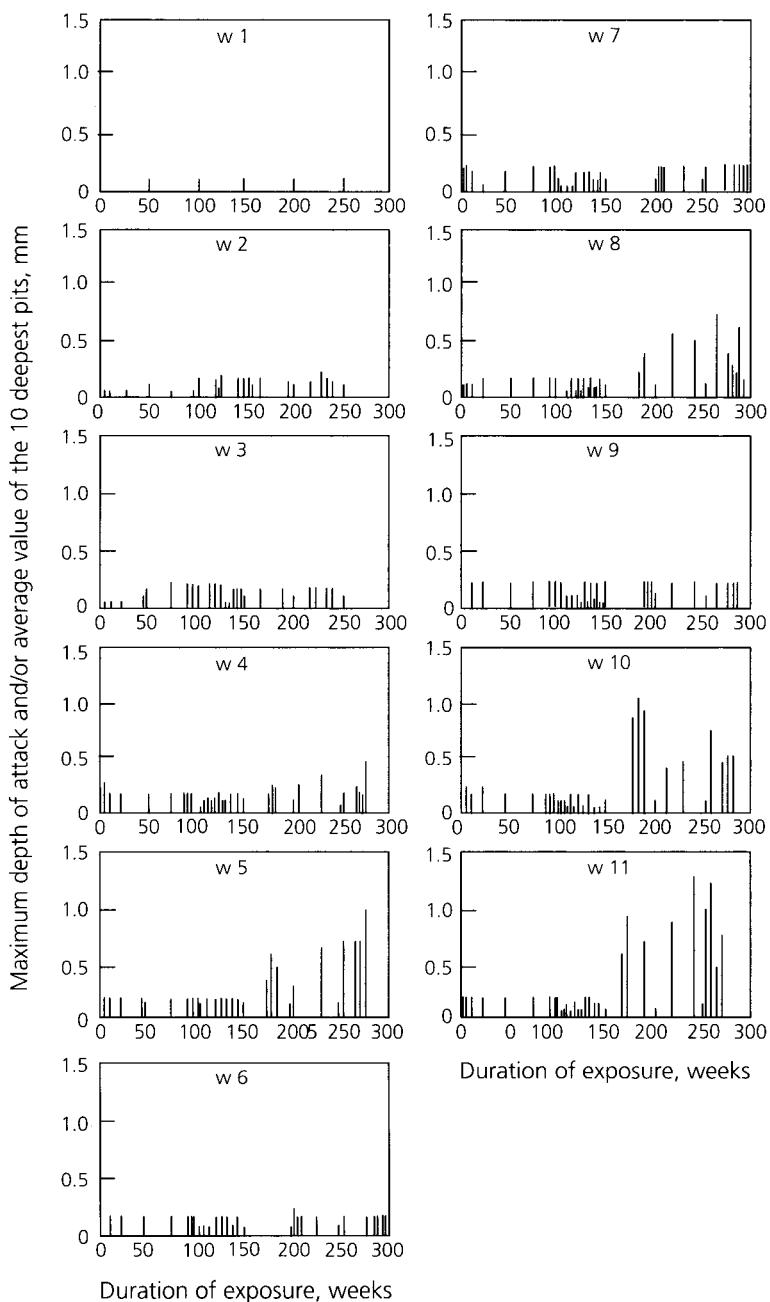


Figure 9: Pitting depth on longitudinally welded AlMn pipes with an AlZn1 inner coating in different drinking waters as a function of the duration of exposure [27]

Characteristics/contents		Water samples										
		01	02	03	04	05	06	07	08	09	10	11
pH		7.2	8.0	6.9	6.9		7.8	7.0	9.2	7.2	7.4	
SK (pH 4.3)		4.5	2.5	2.0	6.4		1.7	5.2	0.6	5.6	3.7	
BK (pH 8.2) or SK (pH 8.2)		0.76	0.06	0.57	1.5		0.05	0.95	0.05	0.82	0.27	
Conductivity (293 K (20 °C))	mS/m	97	43	39	99		60	127	19	58	69	
Ca ²⁺	mol/m ³	3.2	1.3		4.5		2.3	4.1	0.44	2.6	2.3	
Mg ²⁺	mol/m ³	0.66	0.26		0.30		0.21	1.9	0.16	0.1	0.4	
Na ⁺	mol/m ³	27	1.8	1.2	1.2		1.2	3.5	0.35	1.2	1.7	
NO ₃ ⁻	mol/m ³	0.36	0.21		0.06		< 0.03	0.18	0.08	0.02	0.04	
Cl ⁻	mol/m ³	3.3	1.3		1.6		1.7	5.7	0.1	0.65	1.8	
SO ₄ ²⁻	mol/m ³	1.1	0.5		1.4		1.6	2.2	0.34	0.25	0.7	
P _{total}	mmol/m ³	5.0	4.0		36	3	< 0.7	0.8	0.4	16	0.5	
Organic C	g/m ³	0.6	1		2.0		7.1	4.0	2.1	1.5		2.5
O ₂	g/m ³	4	5		10		10	10	10	10	6	

Treatment:

3 → 2 NaOH dosing up to the saturation index SI = 0

5 → 4 polyphosphate dosing

6 → 7 reduction in the humic acid content

Table 9: Water analyses carried out on samples in the field tests [27]

A 7 Copper

Water pipes made of copper are widely used in domestic installations. Copper can be regarded as resistant to drinking water in almost all applications. This statement is applicable without restriction to uniform surface corrosion of copper pipes. In these cases, protective layers of copper-(I)-oxide form on the inner surfaces.

There are, however, cases of corrosion damage in which these layers are locally penetrated, i.e. pitting occurred. Typical pitting phenomena are known, which have hitherto been described in the literature and in [28] as Type I and Type II. Type I occurs almost exclusively in cold water, while Type II is predominantly restricted to hot water. Type I is by far the most frequent form of damage [29]. Damage according to Type II has become much less frequent in recent years, which can be attributed, inter alia, to reduced water temperatures due to energy-saving measures and the decrease in local supplies of acidic water.

The materials listed in Table 10 can be used for drinking water lines [29].

Experience in practice has, however, shown that copper pipes produced from oxygen-containing copper (E-Cu58 and E-Cu57) are more sensitive to pitting than the oxygen-free copper grades. In Germany and other West European countries, oxygen-free copper SF-Cu (CW024A), deoxidized with phosphorus, is used or prescribed [29]. Copper pipes are supplied in rod form (extended length) and in rings according to DIN EN 1057 [30]. According to [28], they are marked by embossing in the longitudinal direction. The marking contains the following data: pipe diameter, wall thickness, DIN EN 1057, manufacturer's name, if appropriate DVGW mark with registration number and the quality mark of the Copper Pipe Quality Association [31].

The state of the inner surfaces of the copper pipes has a marked influence on the corrosion resistance. Campbell found as early as 1950 [32] that a high proportion of copper pipes which contained carbon deposits on the inner surfaces were destroyed by pitting. The same phenomenon was also observed in the Netherlands [33] and in Germany [34]. Carbon deposits are formed by annealing soft pipes.

The lubricants used for drawing are converted into carbon deposits in this process. Hard copper pipes are drawn but not annealed, which means that no carbon deposits are formed on the copper pipes nowadays supplied in Germany. In the region of brazed joints, however, locally restricted carbon deposits can form in the event of high temperatures and prolonged treatment [34].

In cold waters, carbon deposits cause Type I pitting only if the following conditions apply:

- certain types of water [35]
- the carbon deposit must have been formed as a continuous film on the inner surface of the copper pipe.

A definitive method of assessing the water type mentioned is not yet available. There is, however, agreement that it depends on the water composition. In fact, it can be proved that pitting attacks have not occurred in copper pipes with heavy carbon deposits in many drinking waters.

The chemical composition of these inhibitors is at present not precisely known. Campbell [36] presumes that they are amino acids which are present in surface waters as a consequence of biological processes. This view is in line with experience, according to which pitting corrosion is considerably less likely in surface waters which are more heavily polluted with organic substances. This behavior can be explained by the properties of the copper-(I)-oxide layers formed primarily on the inner surfaces [37]. These layers are semiconductors, which means that they can act as the cathode of an electrochemical cell, if current conduction in this layer is possible. This is possible in the case of copper-(I)-oxide layers which grow without disturbance, that is to say in the absence of the inhibitors mentioned. If the growth of these layers is disturbed, for example by inhibitors, as is the case in surface waters, they have a very high electrical resistance. Cathodic reactions do not then proceed, and no anodic dissolution takes place at the pitting sites. In groundwaters, there are no inhibitors, which means that the necessary conditions for the formation of an electrochemical cell and hence for pitting apply.

Material number	Old designation		Composition %	Density kg/dm ³
CW004A	oxygen-containing	2.0065	Cu ≥ 99.90 oxygen 0.005 to 0.040 ¹⁾	8.9
CW005A	copper E-Cu58			
–	E-Cu57	2.0060	Cu ≥ 99.90 oxygen 0.005 to 0.040 ¹⁾	8.9
CW008A	oxygen-free copper, not deoxidized OF-Cu	2.0040	Cu ≥ 99.95	8.9
CW020A	oxygen-free copper,	2.0070 ²⁾	Cu ≥ 99.90	8.9
CW021A	deoxidized with phosphorus SE-Cu ²⁾		P ≈ 0.003 ³⁾	
CW023A	SW-Cu	2.0076	Cu ≥ 99.90 P 0.005 to 0.014	8.9
CW024A	SF-Cu	2.0090	Cu ≥ 99.90 P 0.015 to 0.040	8.9

1) Local exceeding of the upper limit is permissible; restrictions within the given limits should be mentioned in the order.

2) SE-Cu is generally delivered in the soft state with an electrical conductivity of $\geq 57.0 \text{ m}/\Omega \text{ mm}^2$; by arrangement it can also be delivered with an electrical conductivity of $\geq 58.0 \text{ m}/\Omega \text{ mm}^2$ and a low phosphorus content.

3) Phosphorus can be replaced totally or partially by other oxidizing agents.

Table 10: Copper materials suitable for use in drinking water according to [38] (old designations according to DIN 1787)

The influencing parameters which lead to corrosive attack on copper pipes in cold waters have been investigated in field tests lasting five years [39]. The composition of the copper materials investigated is shown in Table 11. The composition of the water investigated is the same as in Table 9. The result found was that some influencing parameters must interact for the occurrence of Type I pitting corrosion, while each of these influencing parameters by itself does not necessarily cause pitting corrosion. It was found in these studies, amongst other things, that the critical pitting potential $U_H \geq 410 \text{ mV}$ and the potential transition region $U_H = 340$ to 410 mV were not reached. The non-occurrence of pitting corrosion is attributed to this, amongst other things. The critical pitting potential was given as 410 mV in [40]. The importance of the pitting potential was confirmed by tests based on this [41, 42]. In the potential transition region, pitting may or may not occur according to [43].

A further important result from the field tests gives an indication of the effect of the water velocity. As already described in [44], pitting preferentially occurs at low flow velocities. The non-occurrence of Type I pitting in the field tests is also ascribed to the high flow velocities (0.5 m/s).

In the field tests, it could already be decided after an operating time of one year whether the pipes develop pitting or show deposits which could develop into pitting areas.

Element	Pipes in strength class	
	F 22	F 37
Copper	99.93%	99.92%
Phosphorus	0.029%	0.034%
Oxygen	46 ppm	34 ppm
Lead	10 ppm	8 ppm
Tin	29 ppm	12 ppm
Nickel	94 ppm	115 ppm
Silver	95 ppm	85 ppm
Arsenic	119 ppm	153 ppm
Antimony	33 ppm	44 ppm
Iron	6 ppm	4 ppm
Selenium	30 ppm	42 ppm
Sulfur	13 ppm	15 ppm

The elements Bi, Te, Mn, Si, Cr, Co, Be, Al, Mg, Cd, Zn, Zr were below the detectable limit.

Table 11: Composition of copper materials used in field tests according to [39]

According to the current state of knowledge, the probability of the occurrence of Type II pitting in warm water is largely determined by the bicarbonate/sulfate molar ratio in the drinking water. If this is less than 2, there is a high probability of damage, especially at low pH values [28, 45].

Flow rates which are too high locally have a clearly detectable influence on the corrosion resistance of copper pipes, since these can lead to erosion corrosion. The flow rates should, therefore, not exceed 2 m/s [28].

Erosion corrosion may occur above all in the circulation pipes of water heaters. Circulation pumps must be adjusted so that the flow rates are between 0.3 and 0.5 m/s, in order to avoid erosion corrosion [46].

As with all materials in which the corrosion resistance is based on the formation of protective surface layers, the initial conditions are also critical in the case of copper pipes. Conditions for later pitting can be created with the first filling with water. These include the introduction of foreign particles and only partial filling of pipeline conduits for a prolonged period of time. In the last case in particular, the formation of the surface layer on the copper/water/air phase boundary can be disturbed to the extent that pit nucleating sites develop here. The later conditions such as the composition of the water and the operating conditions, decide whether the pitting progresses at the pit nucleating sites to the extent of breaking through the pipe wall, or remains static. The latter is known as repassivable pitting, e.g. in the case of stainless steels.

Apart from the forms of corrosion so far mentioned, pitting corrosion due to excessive use of soft solder auxiliaries (fluxes), the so-called soldering pastes, was often reported in the sixties [47]. It is pointed out that corrosion damage to copper pipes is due in a large number of cases to incorrect handling of fluxes and the lack of or incorrect preparation of solder areas. The pitting corrosion caused by fluxes has been greatly reduced by the development of suitable fluxes in accordance with GW 2 [48].

From the hygiene point of view, copper is not damaging to health in drinking water if pipes are installed properly, and usually does not impair the taste [49].

A 8 Copper-aluminium alloys

A 9 Copper-nickel alloys

A 10 Copper-tin alloys (bronzes)

A 11 Copper-tin-zinc alloys (red brass)

A 12 Copper-zinc alloys (brass)

A 13 Other copper alloys

Copper alloys are preferably used for valves and fittings in drinking water installations. According to [28], the materials listed in Table 12 are used for this purpose. The alloying constituents of the copper alloys are shown in percent by weight in this table.

Corrosion phenomena may occur on CuZn alloys as selective attacks known as dezincification. The latter is characterized by a depletion of zinc at the surface. The yellow brass color changes visibly to a copper color. The phenomenon may occur generally (layer-type dezincification) or locally in the form of plug-type dezincification. Dezincification preferentially occurs on lead-containing, two-phase copper-zinc alloys of high zinc content (α -, β -brass). Generally, the probability of dezincification decreases as the copper content increases. Examples of failure are described in [170–172].

According to [44], a changeover to the corrosion-resistant material red brass Rg 5 (Table 12, first line) is recommended in areas where dezincification occurs. According to current knowledge, dezincification depends on the water parameters of chloride content and acid capacity. The pH evidently has little influence. The graph in Figure 10 shows the influence of the parameters mentioned [173–174].

The applicability of this graph has been confirmed in studies on failure [50].

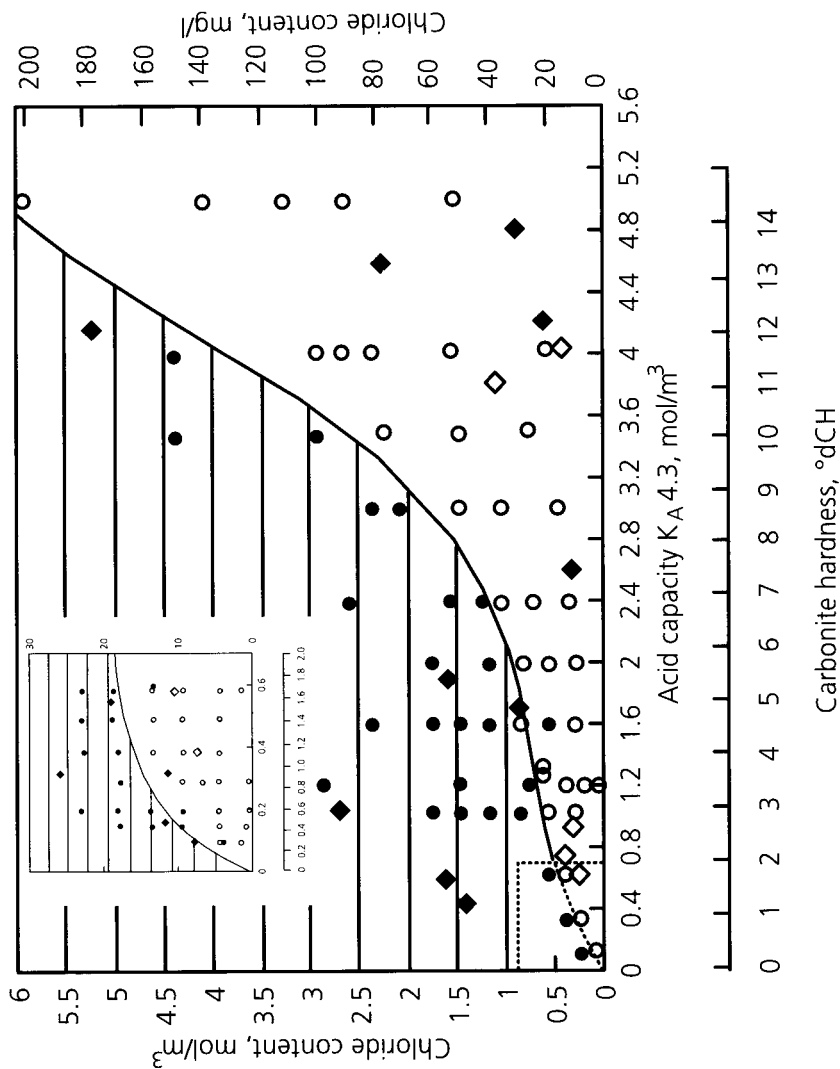


Figure 10: Dezincification as a function of the chloride content and the acid capacity $K_{A4.3}$ [173, 174]

- Laboratory experiments in which meringue dezincification did not take place.
- Laboratory experiments in which meringue dezincification took place.
- ◇ Public water supplies which are known not to produce meringue dezincification.
- ◆ Public water supplies known to produce meringue dezincification.

Material designation	No.	Old designation	Chemical composition, %							Use
			Cu	Sn	Zn	Pb	Ni	Al	V	F
CuSn5Zn5Pb5-C	CC491K	G-CuSn5ZnPb 2.1096.01	84 – 86	4 – 6	4 – 6	4 – 6	2.0	–	X	X
CuZn39Pb1Al-C	CC754S	GK-CuZn37Pb 2.0340.02	58 – 64	(1.0)	balance	(2.0)	–	1.0	X	X
		GD-CuZn37Pb 2.0340.05	58 – 64	(1.0)	balance	(2.0)	–	1.0	X	–
CuZn33Pb2-C	CC750S	G-CuZn33Pb 2.0290.01	63 – 67	(1.0)	balance	1.0 – 3.3	–	(0.1)	X	–
CuZn39Pb3	CW614N	2.0401	57.5 – 59.0	–	balance	2.5 – 3.3	(0.4)	–	X	–
CuZn40Pb2	CW617N	2.0402	57.5 – 59.0	–	balance	1.5 – 2.5	(0.4)	–	X	X

V: valves

F: fitting

Table 12: Copper materials used for fittings in drinking water systems [28]

A 14 Unalloyed steels and cast steel

As already stated in the Introduction in the section – Overview of the use of materials and material protection measures – these materials are preferably used in combination with protective measures. Coatings or coverings are dealt with in the following sections:

- A 39 as hot-dip galvanized steel pipes
- B 4 as cement mortar lining
- B 8 as internal enamelling
- C 2 as bitumen lining
- D 1 as plastic lining

The corrosion behavior of unalloyed steels without protective measures is of importance in respect of evaluation of older long-distance and distribution lines. This also applies to older pipelines in domestic installations, especially in cases where the hot-dip galvanization layer is worn away non-uniformly and too rapidly, so that formation of a good surface layer is no longer possible.

The fundamental importance of acids and bases of high ionic strength in corrosion on unalloyed steel has been demonstrated by laboratory experiments [51]. For local corrosive attack due to electrochemical cell formation, anions such as Cl^- and SO_4^{2-} are needed for stabilization of the anode. However, the cathodes must also be stabilized, which requires the presence of alkali metal ions (not alkaline earth metal ions). The site of formation of $\text{Fe}(\text{OH})_2$ is important in the formation of protective layers. At low flow rates, $\text{Fe}(\text{OH})_2$ is oxidized by O_2 in the water, that is to say surface coatings which provide little protection are formed. At high flow rates, O_2 arrives at the steel surface and oxidizes $\text{Fe}(\text{OH})_2$ here, so that the conditions for the formation of protective surface layers exist.

Steel pipes according to DIN EN 10255 which were pickled and scaled were tested in hard and partly softened drinking water (Table 13) at continuous flow rates of 0.5 and 1.5 m/s in field experiments [52].

The increase in iron corrosion products in the surface layers shown in Figure 11 gives an indication of the corrosion processes. Under the intermittent flow conditions which were also investigated similarly, there was a significantly increased amount of iron compounds in the surface layers. The finding that as the hardness decreases more calcium is incorporated into the surface layers was remarkable (Fig. 12). This resulted in a significant reduction in the protective action of the surface layers, i.e. less impervious, inhomogeneous surface layers which tend to flake off resulted, pustules being formed. The start of wide pitting with pit diameters of up to 1 mm was found in the water softened the most, with $K_A 4.3 = 2.5 \text{ mol/m}^3$. No reliable conclusions could be made on the influence of the neutral salt content. The fact that practically no naturally occurring inhibitors (which – as other experiments show – have a significant influence, especially on local corrosion attacks) are present in the water samples analyzed is important.

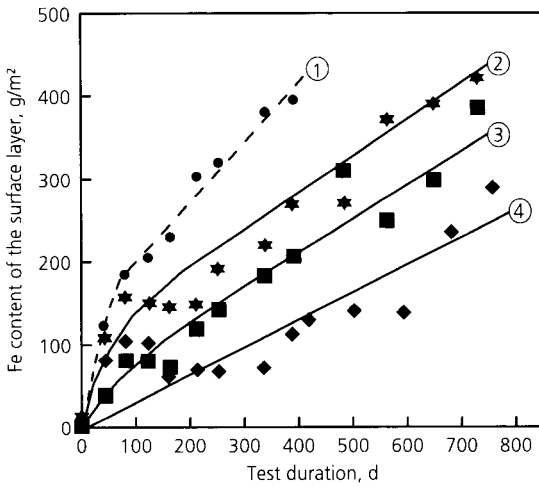


Figure 11: Influence of pH on the accumulation of iron corrosion products during protective layer formation on an unalloyed steel pipe at a flow rate of 0.5 m/s [52]

- ① pH 7.2; intermittent flow rate
- ② pH 7.9
- ③ pH 7.6
- ④ pH 7.2

pH and contents mol/m³	Untreated water Rheinau waterworks (hard)	Water partially softened (medium-hard)	Water partially softened (soft)
pH	7.2	7.6	7.9
Calcium	3.2	2.4	1.9
Magnesium	1.0	1.0	1.0
Hydrogen carbonate	5.3	3.5	2.5
Sodium	0.8	0.8	0.8
Chloride	1.8	1.8	1.8
Sulfate	1.0	1.0	1.0
Nitrate	0.4	0.4	0.4

Table 13: Test values from test waters in Mannheim (RHE) [52]

By recording the cell distribution in the rust spots which formed in the field experiments described in [52] using a microprobe, it was possible to detect the accumulation of chlorides on the steel surface in [53]. On the other hand, no Cl^- ions were detectable on the cathodes. Little calcium was determined in the upper region of the surface layers in hard water of $K_{\text{A}4.3} = 5.3 \text{ mol/m}^3$, while a large quantity of calcium

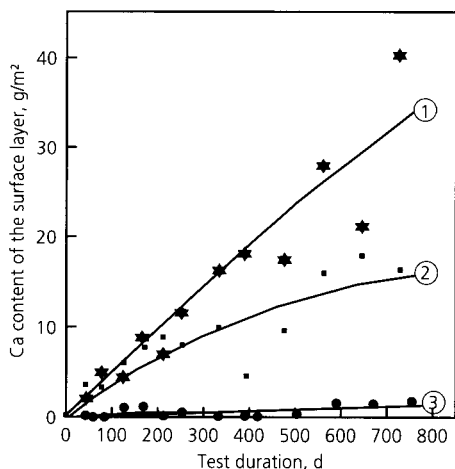


Figure 12: Influence of a pH increase on the incorporation of CaCO_3 into the protective layers during a reduction in the hardness [52]

① pH 7.9; flow rate 1.5 m/s

② pH 7.6; flow rate 1.0 m/s

③ pH 7.2; flow rate 1.5 m/s

was present in the entire surface layer in softened water of $K_A 4.3 = 2.5 \text{ mol/m}^3$. The calcium content in a surface layer is therefore no measure of its protective action, and thus justifies abandoning of the term lime-rust protective layer for unalloyed steels. This is also shown in the standard DIN EN 12502-5 [54], in which, in contrast to the previous version, this term is no longer used for evaluating the corrosion behavior of unalloyed and low-alloy ferrous materials.

The formation of surface layers in synthetic waters was investigated in laboratory experiments in [53], a distinction between the following surface layers being possible:

- in water of high salt content containing Ca^{2+} and HCO_3^- ions, rust layers of low impermeability form almost regardless of the flow rate, Cl^- ions promoting local corrosion.
- at flow rates of 0.35 to 1.5 m/s in ND 20 steel pipes, good surface layers are formed in Cl^- -low or Cl^- -free equilibrium water; the decreases in thickness here are 5 to 10 μm .
- in Ca^{2+} -free, acidic, CO_2 -containing water, as in Ca^{2+} - and HCO_3^- -free water, no protective layers form.
- in Ca^{2+} -free equilibrium water containing NaHCO_3 , the reproducibility of protective layer formation is low.

The results reported apply to inhibitor-free water.

The influence of O_2 content, pH and flow rate in drinking water given the following parameters was investigated in a field experiment lasting 3.5 years [55]:

- steel pipes DIN EN 10255, scaled and pickled,
- O_2 content 0.02, 1, 2 and 4 g/m³,

- flow rate 0.03, 0.1 and 0.5 m/s (constant) and 0.5 m/s intermittently,
- pH 7.2 and 8.0,
- chemical composition of the original water, see Table 14.

Measurable variable	Average	Standard deviation	Units
Temperature	286.1 (13.1)	3.2	K (°C)
pH	7.15	0.14	
$K_A4.3$ (m value)	2.57	0.17	mol/m ³
$c(\text{Ca}^{2+})$	1.97	0.20	mol/m ³
$c(\text{Mg}^{2+})$	0.46	0.20	mol/m ³
$c(\text{Fe}^{2+})$	0.25	0.09	mmol/m ³
$c(\text{Mn}^{2+})$	0.42	0.27	mmol/m ³
$c(\text{NH}_4^+)$	1.11	0.56	mmol/m ³
$c(\text{Cl}^-)$	4.39	0.76	mol/m ³
$c(\text{SO}_4^{2-})$	0.81	0.07	mol/m ³
$c(\text{NO}_3^-)$	0.11	0.06	mol/m ³
$c(\text{NO}_2^-)$	0.43	0.43	mmol/m ³
$c(\text{PO}_4^{3-})$	0.32	0.21	mmol/m ³
$c(\text{SiO}_2)$	78.2	10	mmol/m ³
$c(\text{O}_2)$	8	4	mg/m ³
Conductivity	826	72	μS/cm
Organic C	0.8	0.2	g/m ³
pH	8.03	0.08	
$K_B8.2$ (p value)	0.04	–	mol/m ³
$K_A4.3$ (m value)	3.11	0.21	mol/m ³
Conductivity	855	70	μS/cm

dissolved gases (except O₂ and CO₂) saturated with N₂

$c(\text{CO}_2) = K_B8.2$; $c(\text{HCO}_3^-) \approx K_A4.3$

K_B = base capacity

K_A = acid capacity

Table 14: Chemical composition and parameters of the original water [55]

The results of the study (Figure 13) showed that the corrosion increases as the O₂ content and flow rate increase, with an increased tendency towards local attack (wide pitting). The water adjusted to pH 8.0 by addition of sodium hydroxide solution had a favorable effect, although the local corrosive attacks were not suppressed completely.

Measurable variable	Measured value	Units
Temperature	283 (10)	K (°C)
pH	7.26	
Acid capacity up to pH 4.3	5.08	mol/m ³
Base capacity up to pH 8.2	0.75	mol/m ³
Buffer intensity	1.40	mol/m ³
Nitrate (NO ₃ ⁻)	1	mg/l
Chloride (Cl ⁻)	18	mg/l
Sulfate (SO ₄ ²⁻)	50	mg/l
Silicate (Si _{total})	5.90	mg/l
Nitrite (NO ₂ ⁻)	< 0.01	mg/l
Monophosphate (PO ₄ ³⁻)	< 0.01	mg/l
Calcium (Ca ²⁺)	96.40	mg/l
Magnesium (Mg ²⁺)	10.20	mg/l
Sodium (Na ⁺)	5.40	mg/l
Potassium (K ⁺)	1.90	mg/l

Table 15: Main parameters of the physico-chemical analysis of the original water from the Rheinwald waterworks [57]

[56] describes measurement methods used to evaluate surface layers and the formation of rusty water. By determination of the accumulation of iron on test zones, it is possible to evaluate the quality of the surface layer, while information on the formation of rusty water is not possible directly.

As an introduction to the studies described in [57], it is pointed out that the experiments reported in [51, 52] do not allow an unambiguous conclusion of the influence of neutral salts on the formation of rusty water. Experiments were therefore carried out in water which forms a good surface layer (Table 15) and has very low contents of substances such as organic carbon and phosphate, at a constant flow rate of 0.5 m/s in ND 20 steel pipes. Table 16 provides information on the neutral salt concentrations chosen. The results shown in Table 17 reveal the following trends in respect of the uptake of iron and the formation of rusty water:

- as the test duration increases up to 9 months, the material consumption rate and the uptake rate of iron decrease (Figures 14 and 15); overall, however, the probability of the formation of rusty water increases as the neutral salt content increases.

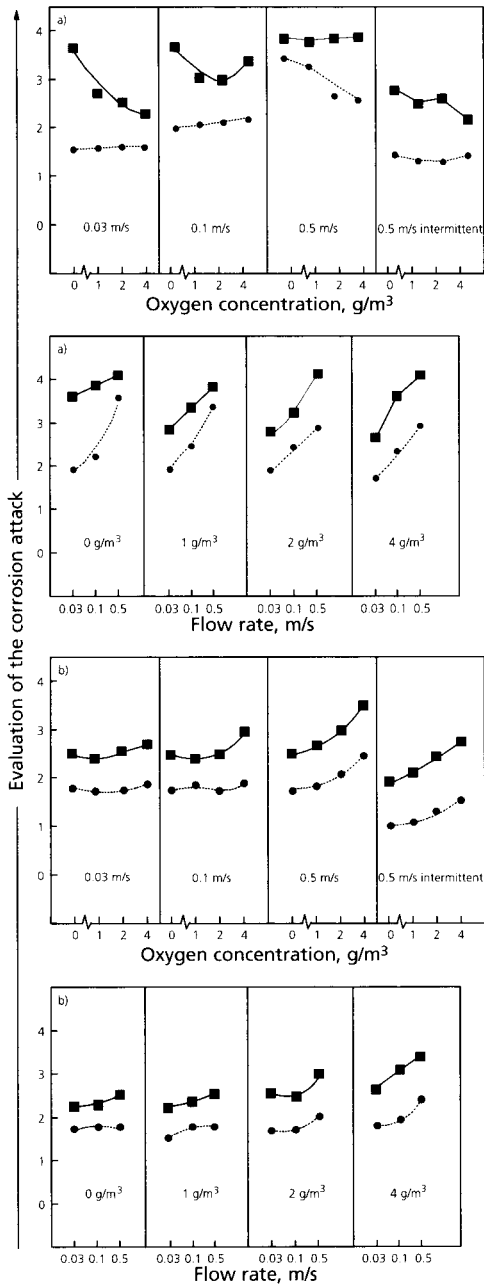


Figure 13: Influence of the oxygen concentration and the flow rate on the type of corrosion for a) galvanized steel and b) non-galvanized steel (mean values of time) as a function of the pH [55]

■ pH 7.2

● pH 8.0

The following ratings are used to evaluate the corrosion state:

1 = general corrosion, roughening < 50 μm

2 = general corrosion, isolated wide pits < 100 μm

3 = general corrosion, wide pitting < 200 μm

4 = wide pitting corrosion > 200 μm

- non-uniform surface layers are formed at an increased neutral salt content, whereby an increased tendency towards local corrosive attacks is assumed, without measurement values being available.
- an increase in the nitrate content up to 250 mg/l has practically no influence on the corrosion behavior.

Salt	Concentration			Arithmetic mean	Standard deviation	Number of measurements
	Reference	Maximum	Minimum			
	mg/l			mg/l	mg/l	
Sulfate	150	166	128	148	8.12	73
	250	271	235	248	9.44	65
	350	367	323	348	9.99	73
	500	540	465	499	24.78	11
Nitrate	20	30	13	21.5	4.14	66
	50	68	36	53	6.12	76
	100	125	84	106	8.20	76
	250	274	226	253	19.93	12
Chloride	50	57	40	46	3.14	67
	100	108	87	97	4.72	78
	250	272	229	250	8.16	78
	350	360	327	345	9.53	12

Table 16: Concentration of the different neutral salts during running time (reference, maximum, minimum, mean and standard deviation) [57]

Tests were carried out on a rotating disk to study the influence of the chloride content on the corrosion of unalloyed steel in drinking water [58]. The killed steel RSt 37–2 (1.0038, cf. UNS K02502) with a ground surface was used. Chloride was added to the initial water types listed in Table 18 in concentrations of 4.3, 7.1 and 11.3 mol/m³. The peripheral speeds of the disks were chosen so that they corresponded to flow rates of 0.04, 0.3 and 1.2 m/s – partly constant and partly intermittent.

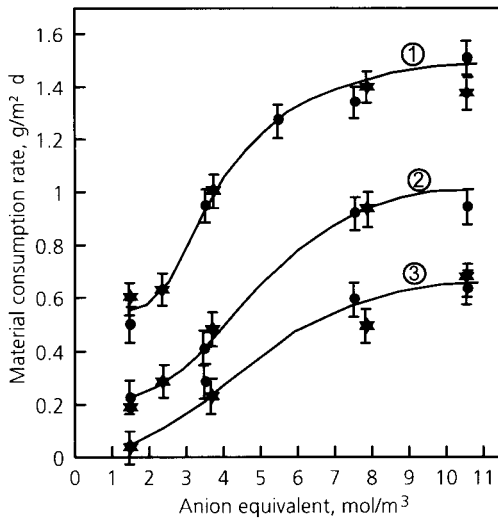


Figure 14: Corrosion rates of the test loops vs. chloride sulfate concentration at different running times [57]

- ① 1–2 months
- ② 6 months
- ③ 9 months

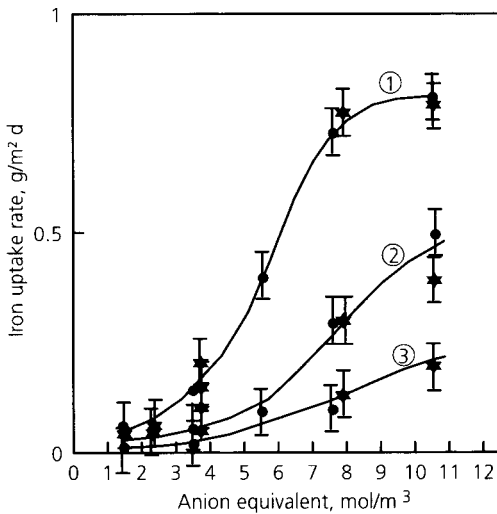


Figure 15: Iron uptake rates of the test loops vs. chloride/sulfate concentration at different running times [57]

- ① 1–2 months
- ② 6 months
- ③ 9 months

<i>Running time</i>	<i>Material consumption rate</i>	<i>Iron uptake rate</i>	
<i>Months</i>	<i>g/m² d</i>	<i>g/m² d</i>	<i>%</i>
Low neutral salt content			
1	0.55	0.05	9
6	0.25	0.02	8
9	< 0.05	< 0.01	–
High neutral salt content			
1	1.40	0.78	57
6	0.95	0.45	47
9	0.60	0.23	38

Table 17: Comparison of the material consumption rates and iron uptake rates for low and high neutral salt contents as a function of the running time as well as the percentage iron uptake rate, referring to the material consumption rate [57]

The graph shown in Figure 16 shows the marked influence of the test duration on the material consumption rate per unit area. According to this graph, the chloride content even has an influence on general corrosion, but only in the initial phase at contents of 4.6 mol/m^3 . The evaluation of the pitting depth shows that it increases initially at low chloride concentrations, only to change into a more general attack at a chloride content of $\geq 4.6 \text{ mol/m}^3$. When the surface layer was analyzed, chloride was detected only at the steel/surface layer phase boundary and calcium only on the side of the surface layer adjacent to the water. Table 19 contains data on the composition of the surface layers after a test duration of 10,000 h.

A further 3 experiments carried out over a year on Berlin drinking water (Table 20) to which chloride was added up to 15.5 mol/m^3 are reported in [58]. The flow rate in 3/4" steel pipes DIN EN 10220 was intermittent, that is to say, the flow rate was 10 l/min in each case for 12 h and zero for 12 h. As can be seen from Figure 17, the material consumption rate per unit area also decreases here with the test duration, without any influence due to the chloride content. The long-term results summarized in Figure 18 show a corrosion rate of 30 to $60 \text{ } \mu\text{m/y}$, from which it can be concluded that under the given conditions unalloyed steel is resistant to local corrosive attacks.

The initially apparently contradictory results of the experiments in [57] and [58] must be seen from the point of view of the types of corrosion. [57] deals primarily with uniform general corrosion (removal of iron) and the formation of rusty water, while the conclusions in [58] primarily relate to wide or deep pitting corrosion.

To clarify whether the saturation index I_s , and the pH can be used for evaluating drinking water, experiments were carried out with scaled and pickled steel pipes in Witten water [59]. Sodium hydroxide solution was metered into the original water (Table 21) so that 4 types of water with the pH and I_s values shown in Table 22 could

be analyzed. The flow rates were a constant 0.5 and 1.0 m/s, and intermittently 0.5 m/s, as is usual in field experiments. On the basis of the analyses carried out on the surface layers over 900 days, one can conclude that the given experimental conditions, the flow rate, pH and I_s values and scaled and pickled surface states have no influence on the phenomenological pattern of the surface layers. This result is thought to be influenced considerably by the high content of phosphate and organic compounds.

Measurable variable	Units	Annual average 1 st year		Annual average 1981 2 nd year		Annual average 1982 3 rd year	
		Bayer	BASF	Bayer	BASF	Bayer	BASF
pH		7.6	7.6	7.6	7.6	7.6	7.3
Conductivity	mS/cm	0.308	0.315	0.310	0.320	0.312	0.325
Ca ²⁺ + Mg ²⁺	mol/m ³	3.26	1.42	2.98	1.40	2.52	1.46
K _A 4.3	mol/m ³	3.57	3.81	3.36	3.77	2.97	3.79
c(Ca ²⁺)	mol/m ³	2.56	1.17	2.32	1.17	1.94	1.20
c(Na ⁺)	mol/m ³	3.65	1.17	3.52	1.17	2.53	1.34
c(K ⁺)	mol/m ³	0.17	0.06	0.16	0.05	0.13	0.07
c(NH ₄ ⁺)	mol/m ³	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
c(Fe ²⁺)	mol/m ³	< 0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.002
c(Mn ²⁺)	mol/m ³	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
c(SO ₄ ²⁻)	mol/m ³	1.08	0.02	0.98	0.02	0.79	0.03
c(Cl ⁻)	mol/m ³	4.23	0.31	3.95	0.31	3.30	0.31
c(NO ₃ ⁻)	mol/m ³	0.34	0.035	0.32	0.03	0.29	0.038
c(NO ₂ ⁻)	mol/m ³	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
c(PO ₄ ³⁻)	mol/m ³	< 0.001	0.005	< 0.001	0.005	< 0.001	0.002
c(O ₂)	mg/l	8.8	6.6	8.8	7.9	8.7	6.3
Number of measurements		53	53	52	52	52	52

Table 18: Results from test waters used for the study of the influence of chloride on the corrosion behavior of RSt 37-2 (1.0038, cf. UNS K02502) [58]

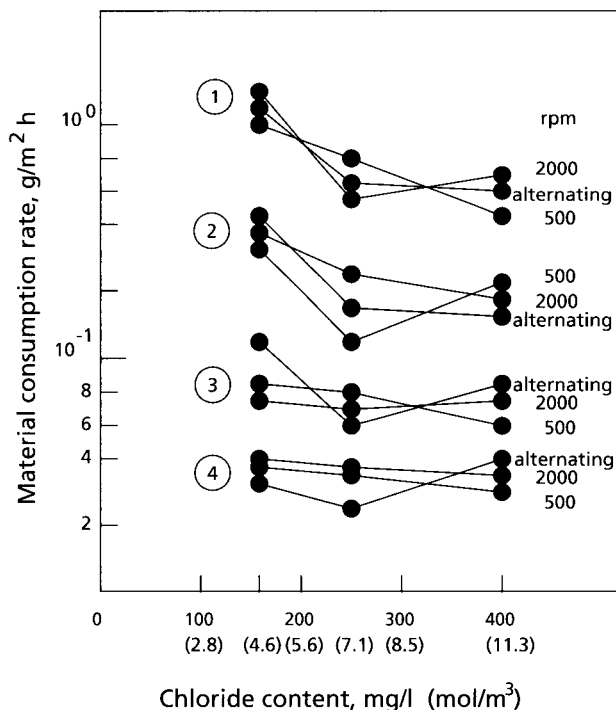


Figure 16: Material consumption rate per unit area on RSt 37-2 (1.0038, cf. UNS K02502), based on the corroded surface, as a function of the chloride content at various rotational velocities and at room temperature (293–298 K (20–25 °C)) [58] after
 ① 100 h ② 800 h ③ 2000 h ④ 10000 h

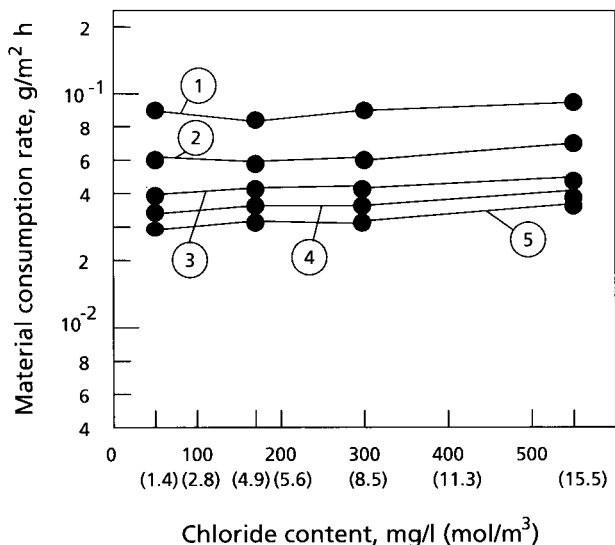


Figure 17: Material consumption rate per unit area on a pipe through which tap water flows (RSt 37-2 (1.0038)) in drinking water as a function of the chloride content and test duration:
 ① 0.5, ② 1.0, ③ 2.0, ④ 2.5 and ⑤ 3 years [58]

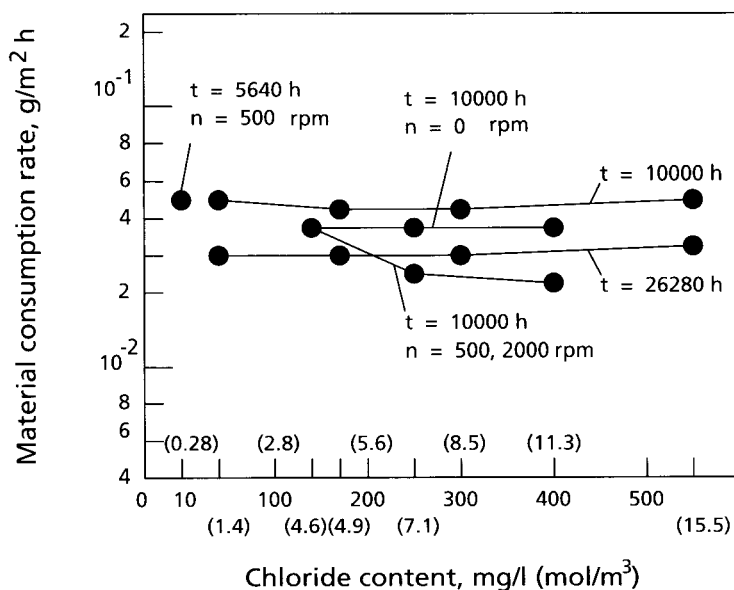


Figure 18: Material consumption rate per unit area on a disk and on a pipe through which tap water flows (RSt 37–2 (1.0038)) as a function of the chloride content. Long-term results [58]

t = test duration

n = rotational velocity

Measurable variable	Chloride ion concentration, mol/m ³	
	7.1	11.3
Measured values, %		
Cl [−]	0.09	0.13
SO ₄ ^{2−}	4.17	3.71
SiO ₂	0.87	1.22
P ₂ O ₅	0.14	0.34
Na ⁺	0.13	0.15
Ca ²⁺	16.30	13.70

Table 19: Analysis of the deposition layers on rotating disks made of RSt 37–2 (1.0038) after a test duration of 1000 h, n = 500 rpm [58]

One field experiment was based on the question of whether and to what extent various deacidification measures influence the corrosion behavior of galvanized and black steel pipes [60]. The soft untreated water containing carbonic acid (Ebnet/Freiburg waterworks) was deacidified by metering in Mg(OH)₂ and Ca(OH)₂ and by fil-

tration over limestone (for the water analyses, see Table 23). Here also, the corrosive attacks decreased over the test duration of three years, largely independently of the flow rate of 0.5 and 1.0 m/s. The highest material consumption rates occurred in the untreated water at 2 g/m² d for up to 600 days, and then remained constant at about 0.8 g/m² d. The initially high material consumption rates of 1.5 g/m² d in water deacidified by CaCO₃ filtration were reduced after 730 days to about 0.1 g/m² d, uniform, largely impervious surface layers being formed. In the pure water which had been deacidified by Ca(OH)₂, the material consumption rates were below 0.1 g/m² d. In respect of resistance, the deacidification methods investigated can be used in practice, depending on the possibility of monitoring.

Measurable variable	Annual average	Units
pH	7.6	
c(Ca ²⁺ + Mg ²⁺)	2.35	mol/m ³
K _A 4.3	3.89	mol/m ³
c(Ca ²⁺)	2.07	mol/m ³
c(Mg ²⁺)	0.28	mol/m ³
c(Na ⁺)	1.65	mol/m ³
c(K ⁺)	0.08	mol/m ³
c(NH ₄ ⁺)	0.004	mol/m ³
c(Fe ²⁺)	< 0.001	mol/m ³
c(Mn ²⁺)	< 0.001	mol/m ³
c(SO ₄ ²⁻)	0.73	mol/m ³
c(Cl ⁻)	1.41	mol/m ³
c(NO ₃ ⁻)	0.01	mol/m ³
c(NO ₂ ⁻)	< 0.001	mol/m ³
c(PO ₄ ³⁻)	0.001	mol/m ³
c(SiO ₂)	0.25	mol/m ³
c(O ₂)	7.1	mg/l
Number of measurements	92	

K_A = acid capacity

Table 20: Water analysis of drinking water (Berlin) in studies on steel pipes according to [58]

Measurable variable	Measured value	Units
pH	6.8	
m value	1.2	mol/m ³
Negative p value	0.35	mol/m ³
c(Ca ²⁺)	1.2	mol/m ³
c(Mg ²⁺)	0.25	mol/m ³
c(NO ₃ ⁻)	0.25	mol/m ³
c(SO ₄ ²⁻)	0.6	mol/m ³
c(Cl ⁻)	0.8	mol/m ³
c(Fe ²⁺)	< 0.1	mmol/m ³
c(Mn ²⁺)	0.2	mmol/m ³
c(PO ₄ ³⁻)	5	mmol/m ³

Table 21: Water analysis of drinking water (Witten) [59]

	Water sample 1	Water sample 2	Water sample 3	Water sample 4
pH	6.8	7.5	8.0	8.5
Saturation index	-1.2 to -1.5	-0.5 to -0.7	approx. ± 0	+0.5

Table 22: I_s and pH values of drinking water (Witten, see Table 21) after metering in different concentrations of NaOH [59]

Rusty water may form if different types of water are mixed. To clarify the corrosive attacks which occur here, unalloyed steel pipes were exposed for in each case about one year to water of constant quality at a flow rate of 0.5 m/s (constant and intermittent). The steel pipes were then installed in a different experimental plant with a different water quality under the same flow conditions. The consequences of changing the water shown in Table 24 were investigated. By way of example of this extensive series of investigations, Figures 19 and 20 show the material consumption rates per unit area and the iron uptake rates with respect to time. In general it can be said that the water to which the steel pipes are exposed after the change determines the material consumption and iron uptake rates. The time taken for the non-influenced state to be reestablished after changing the water can vary from a few weeks to months. Where constantly varying water qualities are distributed, the material consumption and iron uptake rates are higher than in the case of a single type of water. Intermittent flow rates additionally have an unfavorable effect here [61].

Measurable variable	Units	Untreated water	Measured value untreated water		Pure water
			+ $Mg(OH)_2$	+ $CaCO_3$	
pH		6.2	8.4	7.6	8.0
m value	mol/m^3	0.48	1.41	2.11	1.27
p value	mol/m^3	-0.93	–	-0.14	-0.05
Ca^{2+}	mol/m^3	0.30	0.23	1.13	0.7
Mg^{2+}	mol/m^3	0.10	0.53	0.33	0.15

Table 23: Partial analysis of the test waters used according to [60]

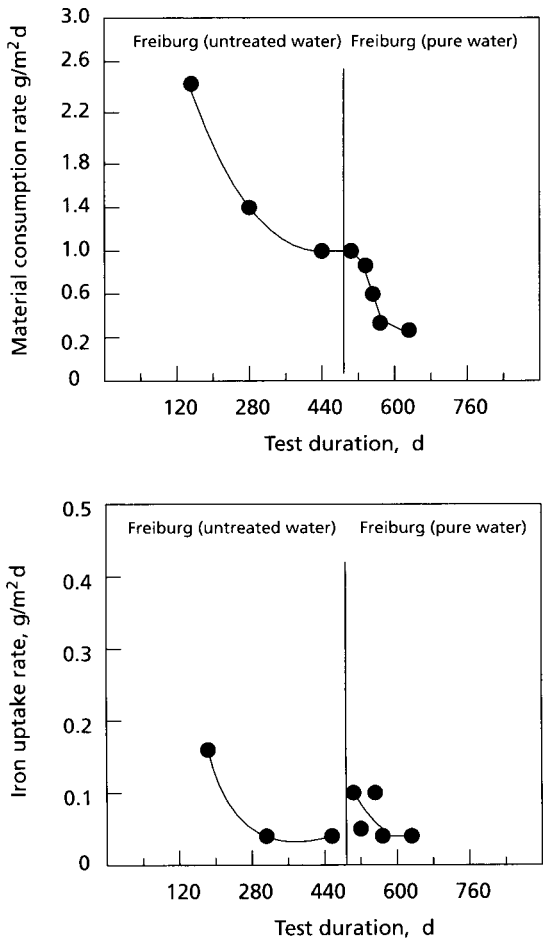


Figure 19: Material consumption rate and iron uptake rate on an unalloyed iron material before and after a change in the water quality. Change from non-deacidified (pH 6.2 – 6.5) to deacidified water (pH 8.0 – 8.2) [61]

A 15 Unalloyed cast iron

Pipes of unalloyed cast iron have been used for more than 100 years for long-distance and distribution lines. By the end of the fifties, gray cast iron was used exclusively for these pipes, and since that time has been replaced by ductile cast iron.

The inner surfaces of the pipes of both materials were, and today still are, provided with a coating or lining. The inner coating of gray cast iron pipes consisted of an approximately 60 to 120 μm thick layer of coal tar pitch produced by dipping [62]. These relatively thin layers are resistant in non-aggressive or only weakly aggressive drinking water, providing adequate protection from corrosive attack on the inner surfaces. In aggressive water – as described in [63] – rust nodules form which weaken or break through the pipe wall. Furthermore, encrustations develop, causing a reduction in pipe cross-section.

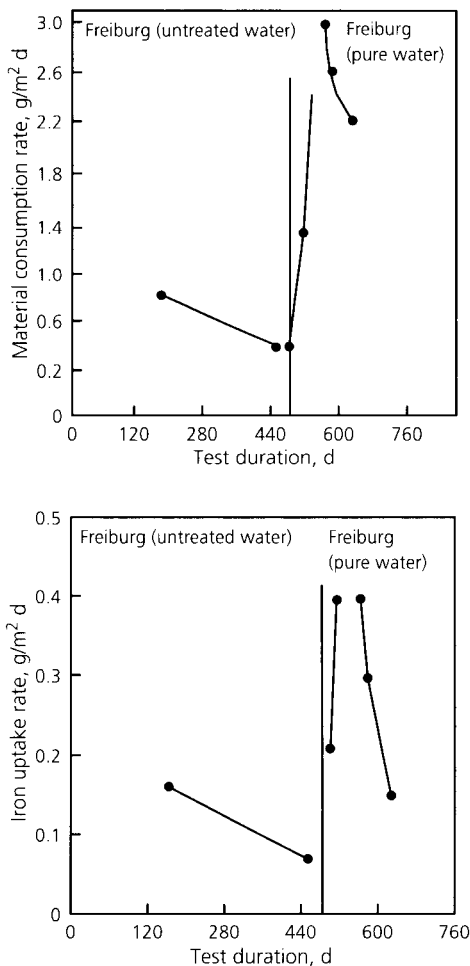


Figure 20: Material consumption rate and iron uptake rate on an unalloyed iron material before and after a change in the water quality. Change from deacidified ($\text{pH} > 8$) to non-deacidified water ($\text{pH} < 6.5$) [61]

Soft, acidic water (low pH)	↔ soft, alkaline water (high pH)
Soft, alkaline water (low mineral content)	↔ soft, alkaline water (high mineral content)
Soft, alkaline water (slightly buffered)	↔ hard equilibrium water (well buffered)
Surface water low in neutral salts (low temperature, negligible neutral salt content)	↔ riverain filtrate rich in neutral salts (high temperature, elevated neutral salt content)

Table 24: Water changes in a test series on steel pipes according to [61]

Because of the disadvantages described, the thin coating of tar pitch was replaced by a cement mortar lining [64]. Ductile cast iron pipes [65] with a cement mortar lining (CM lining) have since been used exclusively in Germany since the mid-seventies.

The resistance of the CM lining is of importance in respect of exposure to drinking water. This is described in detail in Section B4.

A 17 Structural steels with up to 12% chromium

These materials are of only limited resistance to drinking water. Ferritic CrNi steels with 12 % chromium – as described in the following section – may thus be susceptible to pitting, depending on the corrosion conditions.

A 18 Ferritic chromium steels with more than 12% chromium

A 19 Ferritic-austenitic steels with more than 12% chromium

A 20 Austenitic chromium-nickel steels

A 21 Austenitic chromium-nickel-molybdenum steels

A 22 Austenitic chromium-nickel steels with special alloying additions

Amongst the stainless steels, ferritic Cr steels and the austenitic CrNi steels with and without added molybdenum must be considered as passivable materials for domestic installations. These materials are of particular interest for hot water pipes and hot water tanks, as well as for cold water pipes. The stainless steels suitable for domestic installations are summarized in Table 25.

General corrosion of all the materials is low, so that a very good resistance may be reported in this respect. Local corrosion attack in the form of pitting may occur on the materials under certain conditions. Since stainless steels which are susceptible to intercrystalline corrosion (IC) are more susceptible to pitting, only those materials which are IC-resistant due to the choice of an appropriate alloy composition are suitable. Pitting corrosion and the crevice corrosion associated closely with this depend, amongst other things, on the chloride concentration, on the structural conditions [66, 67] and on the flow conditions. The steel/water heat transfer can cause chlorides to concentrate in lime deposits and hence lead to increased pitting.

DIN-Mat.No.	Designation		
Ferritic steels			
1.4510	AISI 439	UNS S43035	X3CrTi17
Ferritic Mo-containing steels			
1.4521	AISI 444	UNS S44400	X2CrMoTi18-2
Austenitic steels			
1.4301	AISI 304	UNS S30400	X5CrNi18-10
1.4306	AISI 304 L	UNS S30403	X2CrNi19-11
1.4541	AISI 321	UNS S32100	X6CrNiTi18-10
Austenitic Mo-containing steels			
1.4401	AISI 316	UNS S31600	X5CrNiMo17-12-2
1.4404	AISI 316 L	UNS S31603	X2CrNiMo17-12-2
1.4436	AISI 316	UNS S31600	X3CrNiMo17-13-3
1.4435	AISI 316 L	UNS S31603	X2CrNiMo18-14-3
1.4571	AISI 316 Ti	UNS S31635	X6CrNiMoTi17-12-2
1.4439	AISI 317 LMN	UNS S31726	X2CrNiMoN17-13-5
1.4539	AISI 904 L	UNS N08904	X1NiCrMoCu25-20-5
Ferritic-austenitic steels			
1.4462		UNS S31803	X2CrNiMoN22-5-3

Table 25: Stainless steels suitable for domestic installations, water heating units and pipes [66]

In a detailed laboratory investigation [68], some possibly suitable stainless steels were investigated. From the results compiled in Table 26, the following conclusions can be drawn:

- Ferritic Cr steels with 18 % Cr are suitable as pipes for hot water up to 368 K (95 °C), especially if they are additionally alloyed with 2 % Mo. On the basis of this result, only steels with at least 16 % Cr were approved in DIN EN 12502-4 [69].
- Although the usual austenitic CrNi steel 1.4301 (AISI 304, UNS S30400) can be used for hot water pipes because of its good resistance, it cannot be used for heat exchanger pipes. The steel 1.4571 (AISI 316 Ti, UNS S31635) or materials with a higher molybdenum content must be used for these.

Materials data general material designation	DIN- Mat. No.	AISI	Corresponding section	Chemical composition, %						Test conditions			Material resistance			
				C	Cr	Ni	Mo	Ti	N	Chlorides ²⁾	Flow ³⁾	Test duration	Pipe	Heat exchanger		
Ferritic steels	1.4512	409	A 18	0.025	12.20	—	—	0.31	—	70	c	428	—	S, P	—	S, P
											dc		—	(S)	—	S, (P)
										500	c		—	S, P	—	S, P
											dc		—	S, P	—	S, P
Mo-containing, ferritic Cr steel	1.4510	430 Ti	A 18	0.049	18.10	—	—	0.70	—	70	c	428	—	n.a.	—	P
											dc		—	n.a.	—	(P)
										500	c		—	(S), (P)	—	S, P
											dc		—	(S)	—	S, (P)
Mo-containing, ferritic Cr steel	1.4521	444	A 18 ¹⁾	0.040	18.15	—	2.12	0.56	0.09	70	c	102	—	n.a.	—	—
											dc		—	n.a.	—	—
													—	n.a.	—	—
										500	c		—	n.a.	—	—
											dc		—	n.a.	—	—
Austenitic CrNi steels	1.4301	304	A 20	0.042	17.94	10.15	—	—	—	70	c	231	n.a.	n.a.	(P)	—
											dc		n.a.	n.a.	n.a.	—
													n.a.	n.a.	n.a.	—
										500	c		n.a.	n.a.	(P)SCC	—
											dc		n.a.	n.a.	(P)	—

Materials data general material designation	DIN- Mat. No.	AISI	Corresponding section	Chemical composition, %					Test conditions		Material resistance				
				C	Cr	Ni	Mo	Ti	N	Chlorides ²⁾	Flow ³⁾ duration	Pipe	Heat exchanger		
Austenitic CrNi steels	1.4301	304	A 20	0.040	17.52	10.60	–	–	70	c	231	–	–	–	P, SCC
									500	c		–	–	–	P, SCC
										dc		–	–	–	P, SCC
	1.4550	348	A 20	0.054	18.36	10.80	–	Nb (Cb) 0.39	70	c	176	n.a.	n.a.	–	
									500	c		n.a.	n.a.	–	
										dc		n.a.	n.a.	–	
Mo-containing, austenitic CrNi steel	1.4571	316 Ti	A 21	0.037	17.65	13.55	2.24	0.37	–	70	c	136	–	n.a.	n.a.
									500	c			–	n.a.	n.a.
										dc			–	n.a.	n.a.

P pitting, S weld seam corrosion, SCC stress corrosion cracking, () slight corrosion, n.a. no corrosive attack detectable

1) with 2 % Mo

2) tap water with and without a Cl[–] addition

3) continuous flow = c, 0.003 m/s and discontinuous = dc, 0.86 m/s

Table 26: Stainless steels usable in domestic installations and water heating systems [68]

In the context of the studies in [68], the pitting or crevice corrosion potential of the steel 1.4301 in tap water which had, due to addition, a Cl^- content of 500 mg/l, was determined as $U_L = + 0.3 \text{ V}$ at 368 K (95 °C) by electrochemical analyses. The rest potential in the nonexposed starting state was determined as $U_H = + 0.52 \text{ V}$ to $+ 0.42 \text{ V}$, that is to say the material ought to have suffered pitting, although this was not the case. In the finished state, the rest potential was $U_H = + 0.2 \text{ V}$, and hence the absence of pitting in the experiment was confirmed, U_L being greater than U_H .

When evaluating pitting data in the literature, the displacement of the potential in the negative direction caused by exposure of the material during the experiment must be taken into consideration.

The hard solder compounds also investigated in [68] showed a loss in adhesion between the solder and steel in the case of the ferritic Cr steels, that is to say knife-line corrosion occurred. It is possible to use a solder which contains 56 % Ag, 26 % Cu, 14 % In and 4 % Ni on austenitic CrNi steels. Solders containing Zn could not be used because of dezincification at the steel/solder phase boundary.

In another study on hard solder compounds, it was found that the silver hard solder L-Ag 40 Cd proved to be resistant in association with the steel 1.4301 in hot water containing up to 50 mg/l chloride [70].

Field experiments were carried out for up to 2 years to study the suitability of 1.4301 in domestic installations [71]. Table 27 shows the test site, the test duration and the operating conditions chosen. The associated water parameters are given in Table 28.

In each unit 8 m long, longitudinally welded pipes with pressed fittings were installed. These pipes were made of the steel 1.4301 (AISI 304, UNS S30400) and had the dimensions 22 mm $\times$ 0.7 mm and 15 mm $\times$ 0.7 mm. The results of these studies are summarized below:

- Neither local nor general corrosion occurred on the inner surfaces of the pipes. Where discoloration was found, this could be attributed to entrained constituents.
- In the Bremen unit, very firmly adhering encrustations occurred on pipes operated at a constantly high temperature of 363 K (90 °C). After removal of the encrustations, no corrosion was detectable on the steel surface. No encrustations occurred when the same unit was operated intermittently with hot water.
- In the case of all the pressed fittings, the surface underneath the butyl rubber sealing rings was still bright after 740 days.

Experiments studying the corrosion behavior of pipes and pipe connections made of the steel 1.4301 (AISI 304, UNS S30400) were carried out in cold drinking water – under the same conditions as have been described for aluminium pipes [26] and for copper pipes in [72] – in field tests lasting five years [73]. Table 29 contains data for pipes in various heat treatment states. The pipe connections were made of the same material as the pipes. Pressed fittings with a non-metallic seal and solder fittings were tested. The chemical composition of the solders used is shown in Table 30.

Test site	Plant type ¹⁾	Pipe samples DIN-Mat.No. 1.4301	Test duration
		mm	d
Stuttgart	A 1		670
	A 2	15 × 0.7	391
	A 3		670
	A 1		740
Wiesbaden	A 2	15 × 0.7	616
	A 3		740
	A 1		678
Bremen	A 2	15 × 0.7	419
	A 3		666
	A 1	15 × 0.7	420
Hamburg ²⁾	A 2	–	–
	A 3	15 × 0.7	420
Berlin ³⁾			
-Kladow	cold	22 × 0.7	428
	warm		428
-Jungfernheide	cold	22 × 0.7	458
	warm		458

- 1) Temperature, K (°C) flow, l/h
 A 1 plant – cold, continuous operation wetting temperature
 278 – 285 (5 – 12) approx. 15
 A 2 plant – hot, continuous operation approx. 363 (90) approx. 35
 A 3 plant – hot, intermittent operation: approx. 363 (90) approx. 75
 downtime 16 h
 remaining period in rotation:
 5 min flow,
 25 min interruption

2) A 2 plant in Hamburg operating since 1974

3) industrial water pipes – both hot and cold (328 K (55 °C))

Table 27: Data from field tests [71]

Test site	pH	Conductivity	Free CO ₂	Total hardness	Carbonate hardness	SO ₄ ²⁻	Cl ⁻	O ₂
		μS/cm	mg/l	°dH	°dH	mg/l	mg/l	mg/l
Stuttgart	7.3	650	29	18.0	15.2	33	16	10.9
Wiesbaden	7.53	860	15.2	16.9	10.1	71	165	8.6
Bremen	8.34	1819	0.3	21.7	5.7	150.1	498	9.7
Hamburg	7.88	150	3.1	5.4	0.03	10	13	5.6
Berlin								
-Kladow	7.27/7.66	350/540	8.8/15.0	10.6/14.3	8.4/10.4	29/69	13/47	7.7/12.9
-Jungfernheide	7.23/7.80	738/945	16.4/19.6	19.1/21.9	10.4/12.9	132/157	63/124	4.8/10.3

Table 28: Test water parameters used in the investigation of the corrosion behavior of 1.4301 (AISI 304, UNS S30400) in domestic installation units [71]

The results of these field tests can be summarized as follows:

- Outside the pipe connections, the pipes were completely corrosion-resistant, regardless of the heat treatment state investigated. According to [68], inter-crystalline corrosion should not exceed 10 mm when testing for resistance to this form of corrosion.
- After exposure for five years, crevice corrosion occurs below the non-metallic seal in pressed fittings at chloride contents of $> 1.3 \text{ mol/m}^3$ and $\text{pH} < 7$. This finding is of great importance, since no crevice corrosion was observed after 2 years in the experiments described in [70]. In [73], it is suggested that the crevice corrosion which occurred after 5 years was due to changes in the composition of the water, e.g. concentration of salts in the region of the pipe connections. On the basis of the results of these studies, pipes and pressed fittings of the corrosion-resistant steels 1.4401 (cf. AISI 316, UNS S31600) and 1.4571 (cf. AISI 316 Ti, UNS S31635) are proposed in [74] for use in drinking water installations.

Knife-line corrosion occurs at the solder joints at chloride contents of $> 1 \text{ mol/m}^3$. The solder L-Ag 40 Cd is more sensitive to corrosion than the other two solders.

The results reported for the investigations have, furthermore, led to on-site weld joints with hard and soft solders not being approved in the new DIN 1988-7 [75].

Mechanical joints (e.g. pressed fittings) on-site are possible, in which case the manufacturer's instructions must be strictly observed.

A summary of the studies on the use of stainless steels for water heaters and pipelines has been compiled by the CEOCOR [76]. Reference is made to the very small amounts of corrosion products released by the materials, which is of great importance in respect of drinking water hygiene.

If stainless steels are used for domestic installations, the release of chloride from sealing materials, amongst other things, must be monitored in order to guarantee

the good resistance of the material. If the release of chloride ions is too high, there is the risk of concentration of chloride, with the possible consequence of pitting and/or crevice corrosion.

Gas bubbles must be avoided in the heated water, since the probability of pitting corrosion or crevice corrosion is greatly increased at the three-phase boundary of stainless steel/water/air as a result.

According to [69], 1.4571 (cf. AISI 316 Ti, UNS S31635) is suitable for water heaters. 1.4558 (X2NiCrAlTi32-20) is recommended for heating elements in water heaters.

In addition to the material properties described for stainless steels in drinking water, the possibility of external corrosion must be considered. [77] provides information on the aspects to be noted in this context.

Chemical composition, %								
C	Si	Mn	P	S	Cr	Ni	N	Fe
0.06	0.04	1.68	0.037	0.015	17.88	9.85	0.029	balance

heat treatment state

- solution annealed in plant
- solution annealed, subsequent sensitization by annealing for 10 min at 923 K (650 °C)/air
- solution annealed, subsequent sensitization by annealing for 20 min at 923 K (650 °C)/air

Table 29: Chemical composition and heat treatment state of longitudinally welded ND 20 pipes (22 mm × 0.7 mm) consisting of 1.4301 (AISI 304, UNS S30400) [73]

Solder no.	Chemical composition, %						
	Ag	Cu	Zn	Cd	In	Sn	Ni
1	40	19	21	20	–	–	–
2	56	26	–	–	14	–	4
3	56	22	17	–	–	5	–

Table 30: Solder designations and chemical composition of solders used in the production of solder joints on pipes made of 1.4301 [73]

A 33 Lead and lead alloys

The resistance of the lead is essentially determined by the influencing parameters of oxygen and carbonic acid content and water hardness. Oxygen-free water, e.g. some groundwaters, do not attack lead even where relatively large quantities of CO₂ are present. If oxygen is present, relatively large amounts of lead are dissolved from lead pipes in soft water containing CO₂ [78].

In harder water containing no aggressive CO₂, protective layers of basic lead carbonate form. Severe attacks on lead have been found in drinking water of pH 9.0 to 9.5, Pb contents of 2 to 5 mg/l having been found in the water [79].

Studies in England [80] have shown that after static periods during the night, Pb contents of 0.5 to 6.99 mg/l were present in drinking water. Prolonged flushing of domestic installation pipes is recommended as a remedy.

According to data in [81], Pb contents of > 0.1 mg/l were found in many drinking water samples in Great Britain.

Further data on Pb contents in drinking water are given in [82], in which the toxic effect of lead is also dealt with in detail.

A limit of 0.04 mg/l is mentioned for lead in the drinking water supply [2]. Since this value is not observed in many supply areas [83], according to DIN 2000 [4] lead pipes should no longer be used for new drinking water pipes because of objections on the grounds of health.

Addition of orthophosphate leads to the formation of sparingly soluble lead phosphate surface layers in lead pipes which significantly reduce the release of Pb. Such metering is of practical importance as an immediate measure when replacing lead pipes by other installation pipes [84].

A 39 Zinc, cadmium and their alloys

Zinc is widely used as a coating on steel pipes in domestic installations. The requirements of zinc coatings applied by hot-dip galvanizing are listed in DIN EN 10240 [85]. The maximum contents allowable (percent by weight) of accompanying elements in the zinc coating are listed in Table 31. These are of importance in respect of the release of toxic substances into drinking water. The weight of the coating per unit area must be at least 400 g/m^2 to achieve good corrosion protection and the coating should have a suitable layer structure characterized by a pure zinc phase and an alloy phase. Practical experience has shown that the probability of corrosion is very high, especially in respect of local attack, in the case of zinc coatings with a structure which does not comply with the standard. Steel pipes which have been blown out with air and not with superheated steam after hot-dip galvanizing have a foam-like galvanized layer which tends to release tricklings of zinc. The zinc coating is fissured in the region of the internal flashes of weld seams which have not been removed, and thus forms starting points for local corrosion [86]. According to DIN EN 12502-3 [87], zinc coatings which do not comply with the standard are classified into groups A, B and C.

There is extensive literature on the corrosion behavior of hot-dip galvanized steel pipes in cold water. In an experiment lasting 3 months on hot-dip galvanized ND 20 steel pipes in the types of water shown in Table 32 at a continuous flow rate of 0.12 m/s, it was found that the corrosion rate depends on the flow rate and the pH [88]. From theoretical considerations, this result is interpreted as follows: a virtually stationary state is established in the three-phase system of metal/surface coating/water, in which the transportation of Zn(OH)^+ ions from the surface of the coating into the water by diffusion is the rate-determining factor.

It has, furthermore, been demonstrated by electrochemical measurements that, in agreement with the investigations according to [89], it is not possible to calculate

Accompanying elements	Content, %
Aluminium	0.1
Antimony	0.01
Arsenic	0.02
Lead	0.8
Cadmium	0.01
Copper	0.1
Bismuth	0.01
Tin	0.1

Table 31: Maximum contents allowable of accompanying elements in the zinc coating according to DIN EN 10240 [85]

the corrosion rate using the Stern-Geary equation with the aid of the polarization resistance. To investigate the removal of Zn(OH)^+ , which determines the corrosion rate, small amounts of ZnCl_2 solution were added to tap water and the material consumption rate (zinc removal rate) was determined on rotating disks [90]. The result shown in Figure 21 confirms the opinion that the material consumption rate is determined by the content of Zn^{2+} ions in the water.

Measurable variable	Units	Water no.					
		5	6	7	8	9	10¹⁾
Temperature	K (°C)	282 (9)	287 (14)	283 (10)	285 (12)	286 (13)	289 (16)
pH		6.90	6.50	6.91	7.38	7.17	6.82
m value	mmol/l	1.6	2.4	6.0	3.4	4.4	1.6
p value	mmol/l	−0.48	−1.2	−1.0	−0.14	−0.48	−0.48
Total hardness	mmol/l	1.40	2.65	4.3	2.85	3.15	1.5
Calcium	mmol/l	1.20	2.05	4.0	2.55	2.6	1.1
Sulfate	mmol/l	0.55	1.25	1.45	1.15	3.35	1.15
Chloride	mmol/l	0.90	5.4	1.5	0.79	2.5	1.7
Nitrate	mmol/l	0.18	0.18	0.02	0.01	0.29	0.29
Oxygen	mg/l	4.8	6.2	10.8	8.5	3.0	3.9

1) The water contains 3.6 mg/l phosphate (P_2O_5), 10 % being polyphosphate

Table 32: Test water analyses used in the investigation of the corrosion behavior of zinc-coated steel pipes in cold water [88]

The degradation of zinc coatings in hot-dip galvanized 3/4" steel pipes at a constant flow rate of 1.4 m/min was monitored in tap water with the aid of metallographic microsection studies [89]. According to these, the pure zinc layer had the task of allowing transition to a pitting-free, long-acting, protective layer.

As already indicated in [89], aging of the surface coatings occurs as the test duration increases, this being associated with a decrease in the corrosion rate which is not detected in short-term studies.

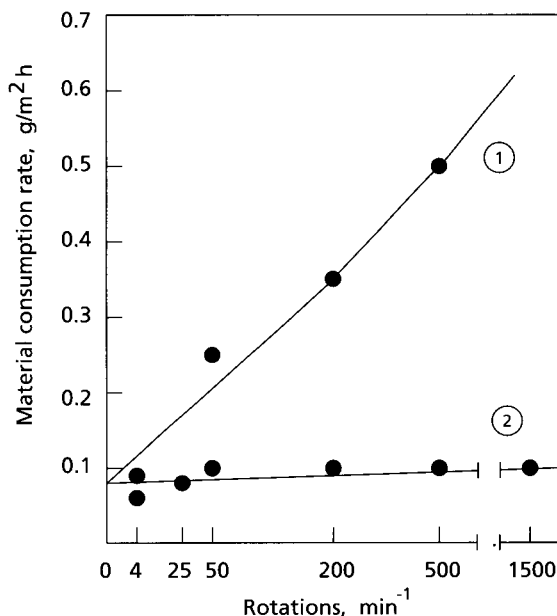


Figure 21: Material consumption rate of hot-dip galvanized disks as a function of the rotational velocity and the zinc content of the water (tap water, pH approx. 7.1) [90]

Zn²⁺ content <0.05 mg/l, pH 7.10–7.20

Zn²⁺ content 25–26 mg/l, pH 7.05–7.15

By means of the long-term studies described in [91], it was possible to describe the nature, build-up and time course of the corrosion-protecting action of surface coatings in more detail. Long-term studies lasting 18 and 28 months were carried out on 1/2" steel pipes hot-dip galvanized to comply with the standard in Berlin tap water (Table 33) using the test parameters described in Table 34.

From the abundance of experimental results, the pH dependence of the corrosion behavior of hot-dip galvanised steel pipes also found in all other studies will be discussed first using the example of the time-dependence of the material consumption per unit area shown in Figures 22 and 23. While the weight loss tends to rise significantly initially, but then to a lesser degree at pH 7 and 2 mg/l O₂, it increases linearly with respect to time at pH 6.9 and 0.5 mg/l O₂. The integral material consumption rate depends on the flow rate. However, this dependence becomes negligibly

low over a prolonged test duration (see Figure 24). According to Figure 25, the pH dependence of the integral material consumption rate also decreases with respect to time, but is still distinctly pronounced after 18 months. It also decreases with time largely independently of the O_2 content (Figure 26). Metallographic studies have shown a virtually complete removal of the entire zinc layer after only 13 months in acidified water (pH 6.9). In the other types of water, the iron/zinc alloy phase was retained in a uniform layer even after 28 months. The Zn, Fe and Ca contents of the surface layers shown in Table 35 indicate that the primary layers firmly adhering on the metal side consist of zinc corrosion products. The loose secondary layers which form on the water side on or from the primary layers have zinc contents which decrease and iron and calcium contents which increase with respect to time.

Measurable variable	Measured value	Units
pH of sample (284.4–286 K (11.4 – 13 °C))	7.35 to 7.45	
Electrical conductivity at 293 K (20 °C)	53.2 to 55.0	mS/m
Acid capacity, pH 8.2	–0.36 to 0.21	mol/m ³
Acid capacity, pH 4.3	3.67 to 3.74	mol/m ³
Total alkaline earths	2.43 to 2.90	mol/m ³
Calcium (Ca ²⁺)	2.20 to 2.51	mol/m ³
Magnesium (Mg ²⁺)	0.23 to 0.39	mol/m ³
Chloride	1.03 to 1.20	mol/ m ³
Sulfate	0.94 to 0.97	mol/m ³
Nitrate	0.03 to 0.096	mol/m ³
Total silicon	approx. 350	mmol/m ³

Table 33: Data obtained from Berlin tap water during the test period [91]

No.	x	y	z
	pH	Oxygen content	Flow rate
		mg/l	m/s
1	7.9	8	0.3
2	7.4	2	0.1
3	6.9	0.5	0.03

Table 34: Test conditions [91]

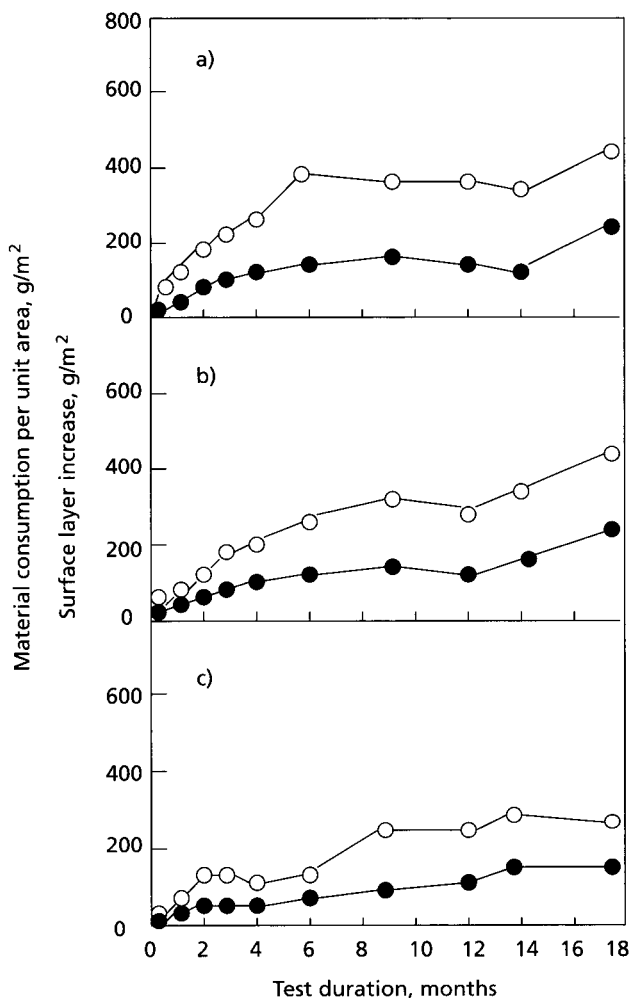


Figure 22: Material consumption per unit area (○) and surface layer increase (●) on zinc-coated steel pipes in Berlin tap water (pH 7.9, 2 mg/l oxygen) as a function of the test duration and the flow rate a) 0.3, b) 0.1 and c) 0.03 m/s [91]

Overall, it can be demonstrated from the experimental results that zinc layers are degraded too rapidly in acidic water with a low oxygen content, so that local corrosive attack with the consequence of premature rupture of the pipe wall occurs. In Berlin water, carbonation of the zinc hydroxide layer and incorporation of compounds of calcium, silicon and phosphate take place, surface layers which provide good protection being formed in the long term. The experiments with non-galvanized steel in Duisburg tap water already described [55] gave the results shown in Figure 13 with varying pH, O₂ content and flow rate.

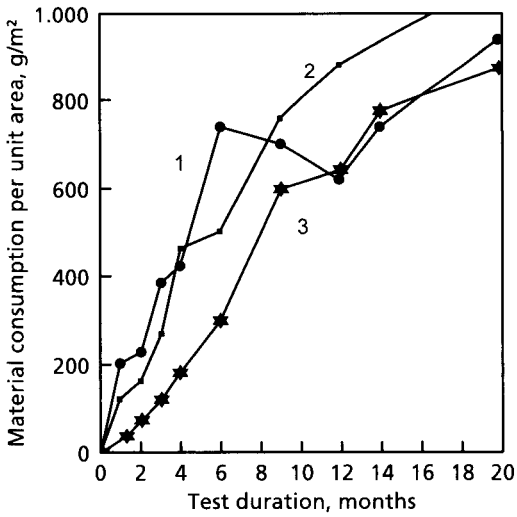


Figure 23: Material consumption per unit area as a function of the test duration with various flow rates, pH 6.9, oxygen content 0.5 mg/l [91]

- ① 0.3 m/s
- ② 0.1 m/s
- ③ 0.03 m/s

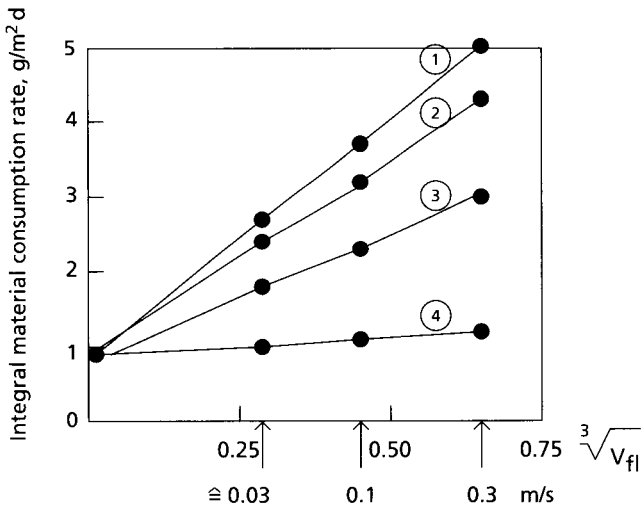


Figure 24: Integral material consumption rate as a function of $\sqrt[3]{V_f}$ after different test durations, pH 7.4, oxygen content 2 mg/l at various flow rates [91]

- ① 0.5 months
- ② 2 months
- ③ 6 months
- ④ 18 months

Field tests on hot-dip galvanized steel pipes and pipe connections lasting five years are described in [92]. The data on the nature of the materials, the test duration and the operating conditions are summarized in Table 36.

The water parameters are the same as those already described in Table 9. The dependence of the homogeneity of surface layers on the water quality could be seen from metallographic studies. Water samples having relatively large neutral salt contents gave significantly less homogeneous surface layers in pipes through which the water flowed intermittently. The experimental results for smooth lengths of pipes have been assessed in [93], the evaluation being based on the material consumption per unit area $m_1(100 \text{ d})$, $m_1(1000 \text{ d extrapolated})$, $m_2(1000 \text{ d})$ and $\Delta m = (m_1(1000 \text{ d}) - m_2(1000 \text{ d}))$. Hot-dip galvanized steel pipes can be classified into three groups according to Figure 27:

- Group 1: $m_1(100 \text{ d}) > 300 \text{ g/m}^2$ and $\Delta m(1000 \text{ d}) < 100 \text{ g/m}^2$. No protective surface layers are formed, e.g. water sample 05 according to Table 9, severe risk of corrosion.
- Group 2: $m_1(100 \text{ d}) > 100 \text{ g/m}^2$; $\Delta m(1000 \text{ d})$ increases linearly with $m_1(100 \text{ d})$. As the removal of zinc increases, surface layers rich in iron oxide are formed initially, turning into protective layers of rust; e.g. water samples 01, 03, 04, 08, 10 and 11, local corrosive attack cannot be excluded in water which is often stationary [87].
- Group 3: $m_1(100 \text{ d}) \leq 100 \text{ g/m}^2$ and $\Delta m(1000 \text{ d}) < 100 \text{ g/m}^2$. After 5 years, metallic zinc is still present on the pipes, good corrosion resistance; e.g. water sample 02 (pH increased by NaOH metering to pH 8), no influence on the reduction in the humic acid content in water samples 06 and 07; water sample 09 has a high pH of 9.2.

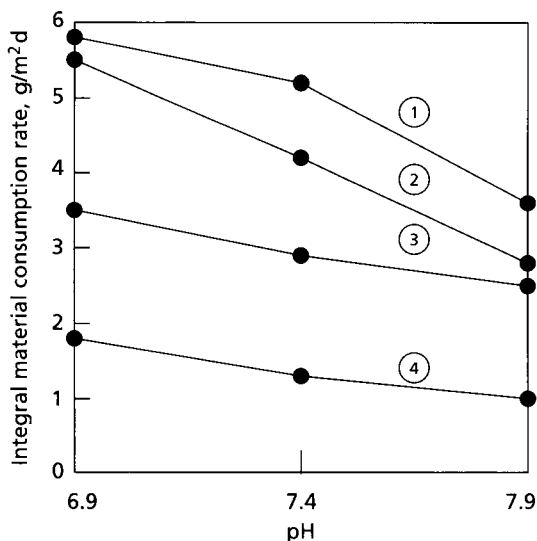


Figure 25: Integral material consumption rate as a function of the pH after various test durations, oxygen content 8 mg/l, flow rate 0.3 m/s [91]

① 0.5 months ② 2 months ③ 6 months ④ 18 months

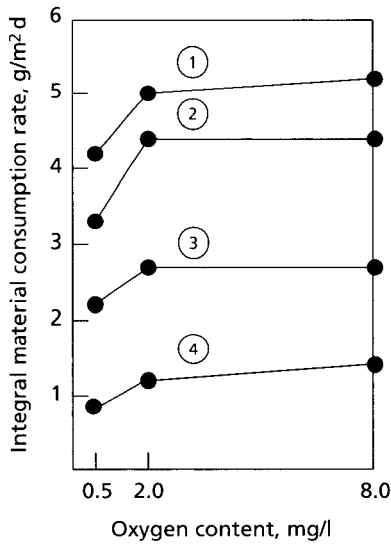


Figure 26: Integral material consumption rate as a function of the oxygen content after various test durations, pH 7.4, flow rate 0.3 m/s [91]

① 0.5 months

② 2 months

③ 6 months

④ 18 months

Unit	Layer	Zn content, %				Fe content, %				Ca content, %			
		4	9	13	28	4	9	13	28	4	9	13	28
122	primary layer	59	58	61	54	1	1	1.5	5	0.3	0.5	0.7	1.2
	secondary layer	36	19	25	8	2.5	7	9	17	9	20	13	21
222	primary layer	–	58	57	56	–	0.9	1	4	–	0.2	0.2	0.3
	total layer	59	–	–	–	1.5	–	–	–	0.2	–	–	–
	secondary layer	–	38	44	37	–	4.0	4	10	–	0.9	1.6	0.9
322	primary layer	54	70	60	–	1	5	6	–	0.1	0.2	0.3	–
	total layer	–	–	–	9	–	–	–	39	–	–	–	1.0
	secondary layer	43	38	39	–	3	9	7	–	0.7	1.1	1.0	–
332	total layer	(72)*	12	4.5	1.9	(11)*	25	37	41	(0.1)*	0.9	1.1	0.9

* metallic Fe/Zn particles

Table 35: Time dependence of Zn, Fe and Ca contents (%) in various surface layers [91]

Steel pipes:	Welded, stretch-reduced ND 20					
	Chemical composition, %					
	C	Si	Mn	P	S	Al
	0.1	0.03	0.50	0.03	0.02	0.01
Hot-dip galvanizing:	a) According to DIN EN 10240, 586 g/m ² , 81 µm zinc layer					
	Chemical composition, %					
	Al	Pb	Cd	Cu	Sn	
	0.04	0.55	0.057	0.024	0.059	
	b) According to Group B, DIN EN 12502-3, 200 µm zinc-iron alloy phase					
	c) According to Group C, DIN EN 12502-3, blown out with pressurized air, 1130 g/m ² , 157 µm					
Operating conditions:	a) Constant flow, 0.5 m/s					
	b) Intermittent operation					
	– downtime 12 h					
	– 12 h, 12'' pro h flow					
Test duration:	4.5 to 5.5 years					

*test duration in d

Table 36: Test conditions [92]

Overall, a clear dependence of the corrosion rate on the carbonic acid concentration ($K_{B8.2}$) was found in these experiments:

- Group 1: $K_{B8.2} = 1.5$ without polyphosphate addition
- Group 2: $K_{B8.2} = 0.27$ to 1.5, water sample 04 demonstrates the favorable influence of the polyphosphate addition
- Group 3: $K_{B8.2} = 0.05$ to 0.06

It should also be noted that no influence of the neutral salt content was found in these experiments.

The marked influence of the CO_2 concentration can also be seen from experiments with galvanized steel pipes carried out under the experimental conditions described in [60]. The results of these experiments reveal, in addition to group 2 with $K_{B8.2} = 0.93$, the significant risk of corrosion in soft water containing carbonic acid ($K_{A4.3} = 0.48$). The water samples in group 3 ($K_{B8.2} = 0.05$ and 0.14) are formed by the deacidification measures described.

The evaluation [94] of the experiments [91] according to the data in [93] showed substantial agreement with the results of the experiments [93] for a test duration of 18 months.

Investigation of the long-term behavior in the experiments described in [91] was continued on 9 specimens for up to 10 years [94, 95]. The oxygen content was kept constant at 6 to 8 g/m³ and the pH and flow rate were varied. The clear dependence

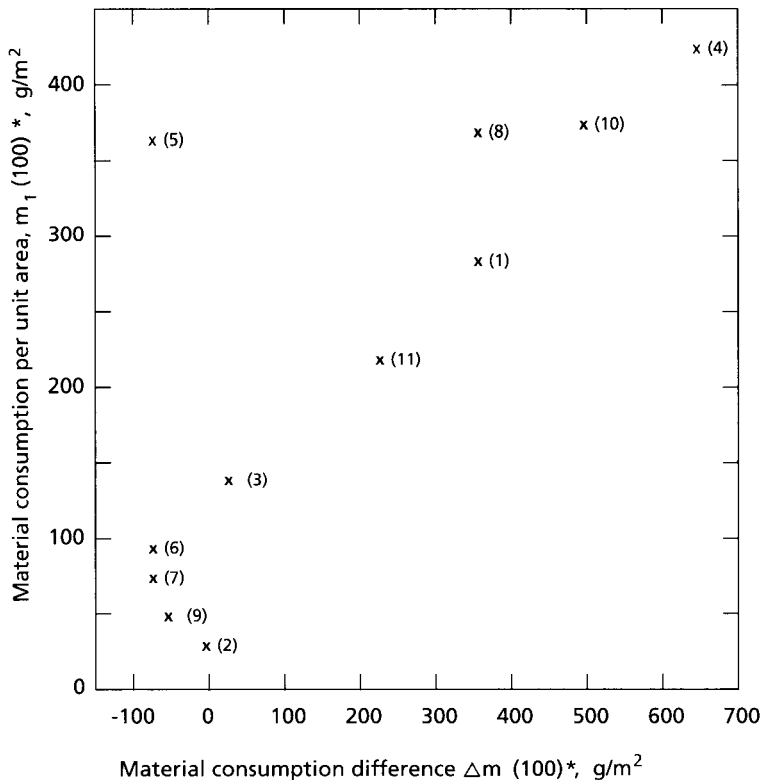


Figure 27: Relationship between the material consumption per unit area $m_1(100)^*$ and the material consumption difference $= (m_1(1000)^* - m_2(1000)^*)$ – the figures correspond to the water according to [93]

of the material consumption per unit area at a flow rate of 0.3 m/s is shown in Figure 28.

The influence of the pH and flow rate can be seen by comparing the residual zinc layers after 2.5 and 10 years with the aid of micrographs (see Figure 29). At pH 7.5 and 8.0 and flow rates of 0.1 and 0.3 m/s, residual zinc layers 25 to 40 μm thick are present even after 10 years, while after 10 years at pH 7.5 and a flow rate of 0.3 m/s, the residual zinc layer still present after 2.5 years has been removed completely. At a low pH (7.0) and a low flow rate (0.03 m/s), a zinc layer is no longer present after 2.5 years; but the corrosive attack on the steel progressed further for up to 10 years. Microprobe studies show the increasing incorporation on the water side of compounds due to the calcium, silicon (silicate) and phosphorus (phosphate) contents of the water. The finding that the surface layers provide a protective action under the experimental conditions described only as long as zinc is present is important. If zinc is no longer present, rust spots are formed and wide pitting corrosion occurs.

The diagram in Figure 30 reflects the material consumption/time relationship with the original zinc layer. Curve ① applies to an increased pH and low flow rate; it

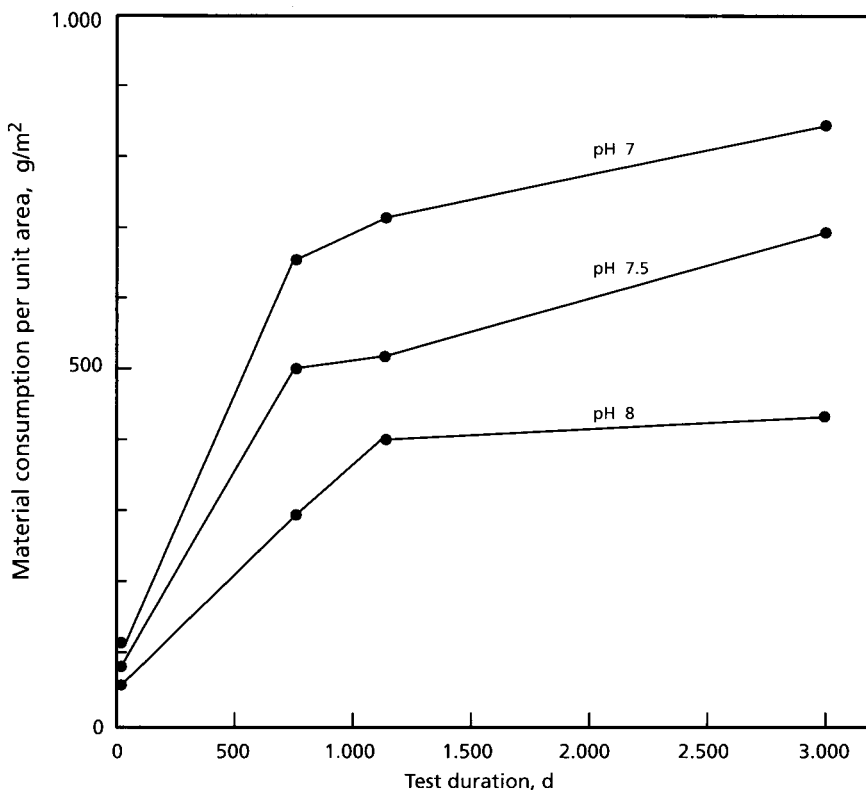


Figure 28: Relationship between the material consumption per unit area of hot-dip galvanised steel pipes in flowing water and the test duration (oxygen content 8 mg/l, flow rate 0.3 m/s) at various water pHs [94]

indicates residual layers of zinc after 10 years. At a low pH and higher flow rate, the zinc layer has been removed after about 2 years and corrosive attack starts on the steel (Curve ②). While Curves ① and ② apply to an initial oxygen content of 6 to 8 mg/l, Curve ③ is typical of pH 7.0 and $c(\text{O}_2)$ of 0.5 mg/l. Mathematical analysis of the material consumption/time curves plotted showed a good fit on these curves when the logarithmic function

$$(m/g \times m^{-2}) = (a/g \times m^{-2}) \ln ((b/a^{-1})(t/a) + 1))$$

was taken as the basis. The exponential function chosen in previous publications

$$(m/g \times m^{-2}) = (a/g \times m^{-2} \times a^{-1})(t/a)^b$$

does not lead – as Figure 31 shows – to a description of the actual relationships. Some characteristic values of the logarithmic function are summarized in Table 37 [95].

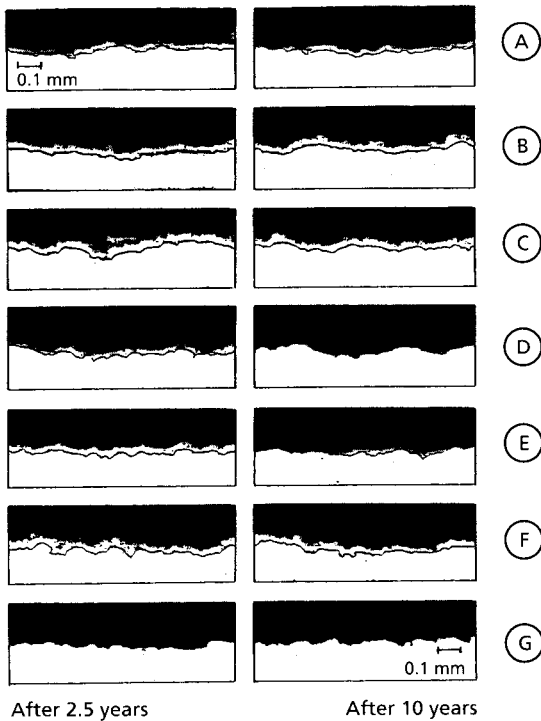


Figure 29: Comparison of the residual zinc layer on zinc-coated pipes after different service times in various waters [95]

- A) pH 8, oxygen content 6–8 g/m³, flow rate 0.3 m/s
- B) as A) but 0.1 m/s
- C) as A) but 0.03 m/s
- D) as A) but pH 7.5
- E) as D) but 0.1 m/s
- F) as D) but 0.03 m/s
- G) pH 7, oxygen content 6–8 g/m³, flow rate 0.03 m/s

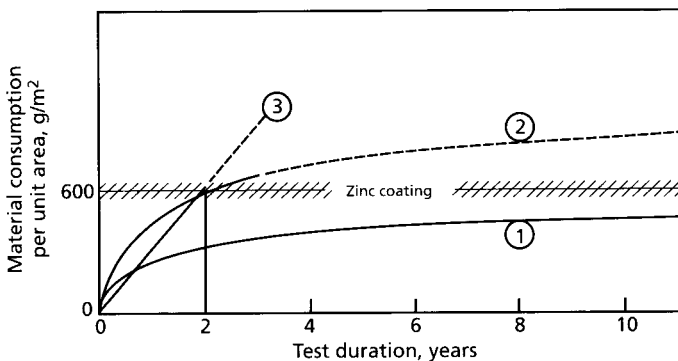


Figure 30: Typical material consumption per unit area curves for zinc in tap water in relation to the original zinc layer as a function of time [95]

- ① Increased pH and low flow rate
- ② Low pH and high flow rate
- ③ Low pH and low oxygen content

When evaluating the results of field and laboratory studies, it should be remembered that a higher water throughput has been used in these – in comparison with conditions in domestic installations. However, a higher water throughput causes higher corrosion rates in domestic installations than a lower throughput.

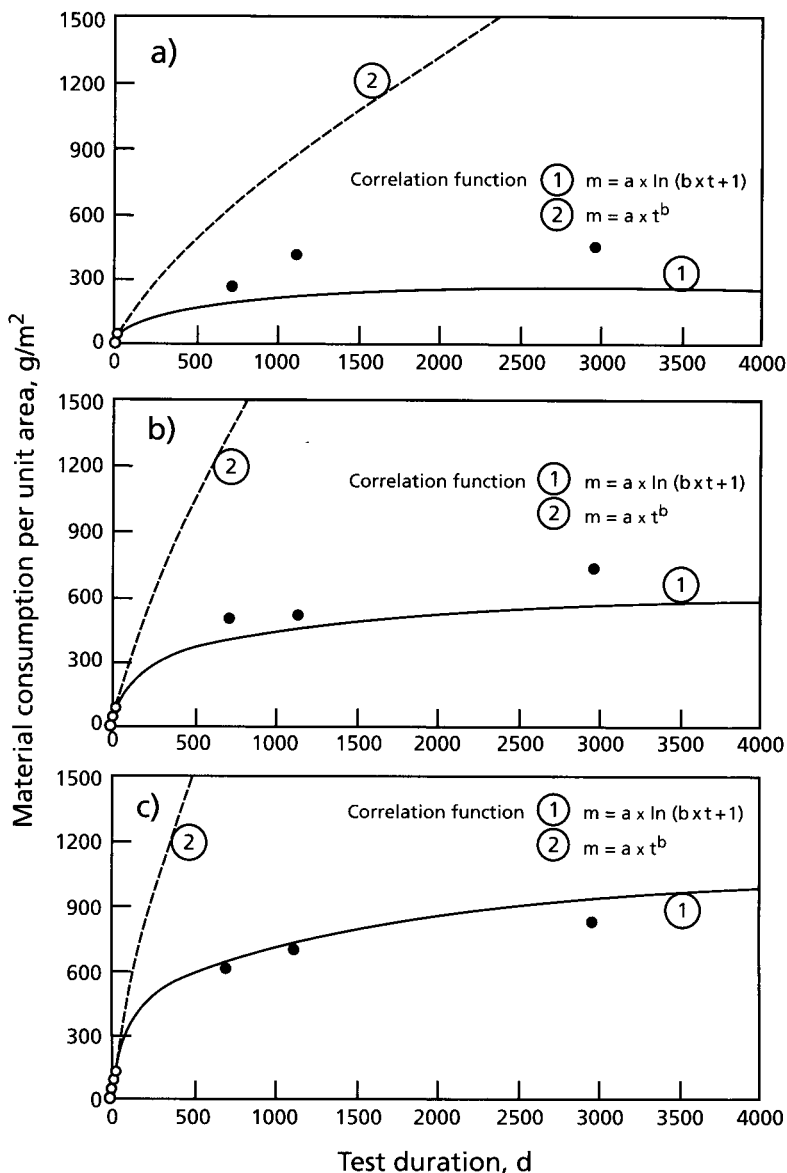


Figure 31: Correlation functions ① and ② at different tap water pHs (oxygen content 6–8 g/m^3 , flow rate 0.3 m^3/s) with regard only to short-term values ($t_{\max} = 28$ d) [95]

- a) pH 8
- b) pH 7.5
- c) pH 7

Experiments were carried out for 2.5 years under the conditions listed in Table 38 to study the influence of the nitrate content in drinking water [96]. A good surface layer was formed in pipes with galvanizing which complies with the standard according to DIN EN 10240, regardless of the nitrate content. Selective corrosion in the form of zinc tricklings was found in water with a high nitrate content of 1.26 mol/m^3 in pipes blown out with air, corresponding to group A, and in pipes with an intergrown FeZn alloy layer, group B, according to [87]. Severe corrosive attack occurred in pipes from group B in the same water.

Test conditions	$a/\text{m}^{-2} \text{ a}^{-1}$	b/a^{-1}
pH 8.0 $\text{O}_2 = 6 - 8 \text{ mg/l}$ $v = 0.3 \text{ m/s}$	103.7	0.0267
pH 7.5 $\text{O}_2 = 6 - 8 \text{ mg/l}$ $v = 0.3 \text{ m/s}$	155.0	0.0303
pH 7.0 $\text{O}_2 = 6 - 8 \text{ mg/l}$ $v = 0.3 \text{ m/s}$	180.3	0.0382

Table 37: Characteristic values of the logarithmic function [95]

The occurrence of zinc tricklings in pipes from group A was detected in a study lasting 9 years, while this was not the case in pipes galvanized according to the standard [97].

Steel pipes:	ND 20 according to DIN EN 10240
Hot-dip galvanizing:	a) according to DIN EN 10240 b) according to Group B, DIN 12502-3 c) according to Group C, DIN 12502-3
Operating conditions:	a) constant flow 0.5 and 1.5 m/s b) intermittent flow 120 min/d throughput 0.25 m/s
Test duration:	2.5 years

Table 38: Test conditions according to [96]

In the experiments already described [52], the pH dependence found elsewhere, that is to say the decrease in removal of zinc as the pH rises, was also confirmed – as Figure 32 shows.

It can be seen from Figure 33 that under the given experimental conditions, the iron corrosion which starts after removal of the zinc layer results in the same iron contents in the surface layers as in the experiments with unalloyed steel pipes.

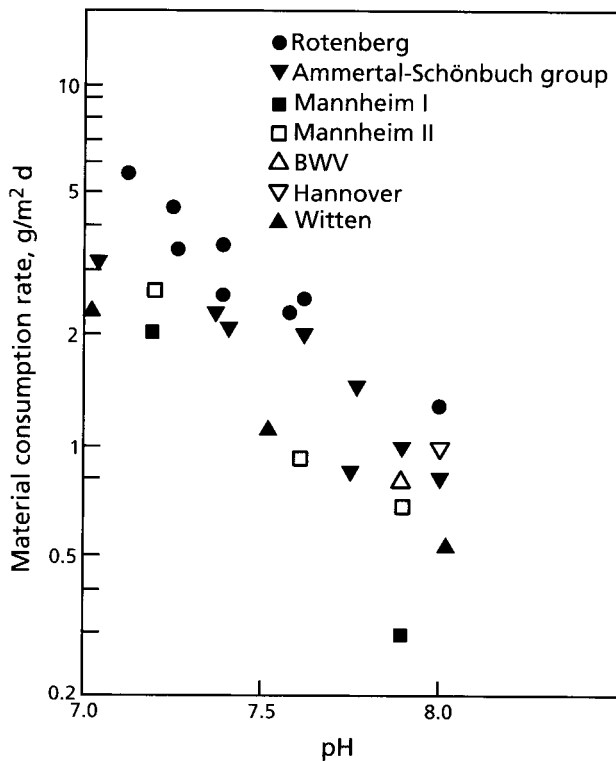


Figure 32: Influence of pH on the material consumption rate of zinc in 26 different water qualities (flow rate 0.5 m/s) [52]

	Measured value	Units
pH	7.8–8.0	
m value	2.5	mol/m ³
Ca ²⁺	1.1	mol/m ³
Cl ⁻	0.13	mol/m ³
SO ₄ ²⁻	0.3	mol/m ³
PO ₄ ³⁻	3–3.5 × 10 ⁻³	mol/m ³
org. C	1.1–1.3	mg/l

Table 39: Partial analysis of Lake Constance water – Sipplingen waterworks [98]

No clear adverse influence of ozone and chlorine treatment was found in experiments in water from Lake Constance (Table 39) over a test duration of five and a half years [98]. According to Figure 34, the material consumption rate of the zinc layer per unit area averaged for the period between 500 and 2000 days is about 0.1 g/m² d.

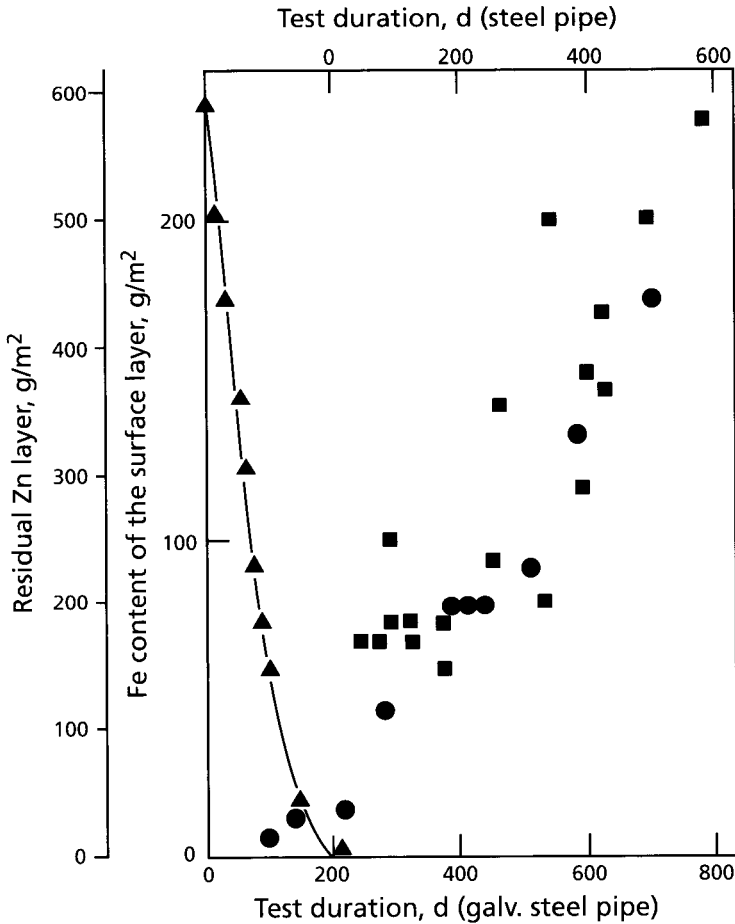


Figure 33: Comparison of the iron content in the surface layer of steel pipes after removal of the zinc layer (pH 7.2, flow rate 1.5 m/s) [52]

▲ residual zinc layer; ● iron content in the surface layer of the zinc-coated steel pipes; ■ iron content in the surface layer of the unalloyed steel pipes (2 test lines)

The reduction in corrosive attack by increasing the pH found in all the experiments is confirmed by studies in Switzerland [99]. By increasing the pH of Zürich lakewater by only 0.3 units (Table 40), a large reduction could be achieved in the material consumption per unit area (Figure 35). In Dübendorf groundwater (Table 40), the material consumption is higher – because of the noticeably lower pH of 7.1 compared with Zürich lakewater – and increases sharply with time (Figure 36).

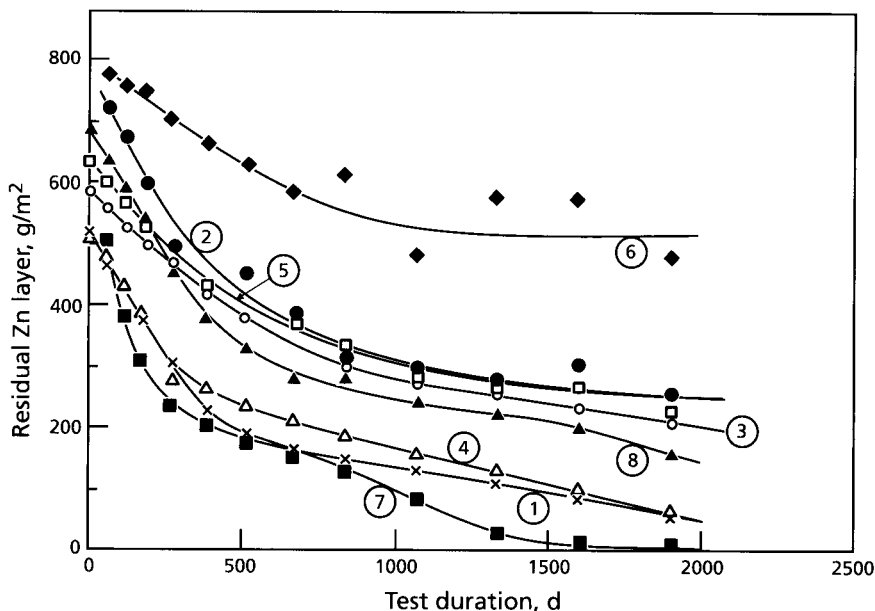


Figure 34: Material consumption rate per unit area of the residual zinc layer as a function of time during different water treatment steps using Lake Constance water and under various flow conditions [98]

- ① Untreated water 1.5 m/s
- ② Untreated water 0.5 m/s
- ③ Untreated water 0.5 m/s intermittent
- ④ Untreated water, ozonized 1.5 m/s
- ⑤ Untreated water, ozonized 0.5 m/s
- ⑥ Untreated water, ozonized 0.5 m/s intermittent
- ⑦ Untreated water, ozonized and chlorinated 1.5 m/s
- ⑧ Untreated water, ozonized and chlorinated 0.5 m/s

The corrosion behavior of pipe connections in cold drinking water was also investigated in the field tests according to [92]. Table 41 provides information on the corrosive attack found with the aid of rating figures. Non-galvanized threads of malleable cast iron fittings are severely attacked in comparison with galvanized threads. Pronounced contact corrosion occurred on the non-ferrous metal fittings because of the relatively large non-ferrous metal cathodes. No noticeable contact corrosion was found on the hard solder connections because of the small area of the cathodes.

Measurable variables	Dübendorf groundwater	Zürich lakewater	
	pH 7.1	pH 7.1	pH 8.0
	mol/m ³	mg/l	mol/m ³ mg/l
Acid capacity (K _A 4.3)	5.7	–	2.62 –
Calcium (Ca ²⁺)	2.9	116	1.33 53
Sulfate (SO ₄ ²⁻ *)	0.92	44	0.313 15
Chloride (Cl ⁻)	0.76	27	0.127 4.5
Nitrate (NO ₃ ⁻)	0.32	20	0.054 3.3

*) value refers to half the molecular weight

Table 40: Water analyses according to [99]

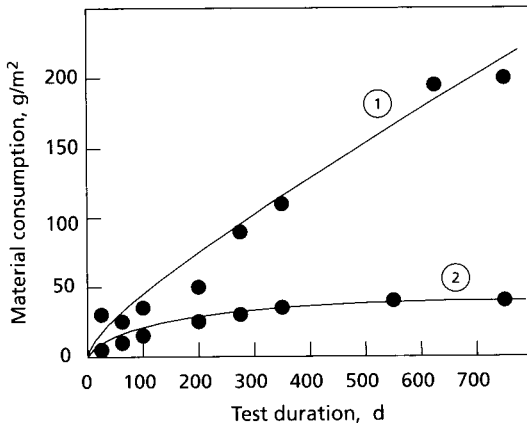


Figure 35: Internal corrosion on zinc-coated steel pipes. Influence of the pH [99]

- ① Zürich lakewater, untreated, pH 7.7
② Zürich lakewater, treated, pH 8.0

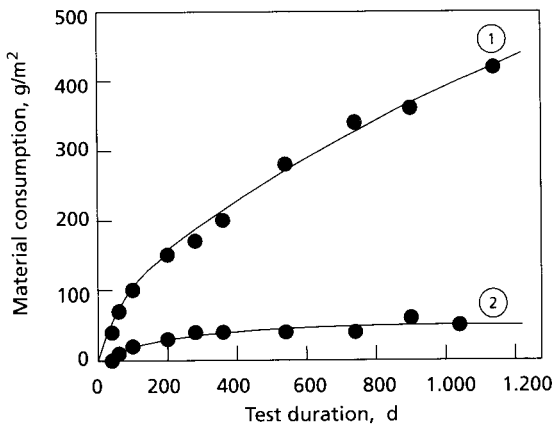


Figure 36: Internal corrosion on zinc-coated steel pipes. Influence of the water quality [99]

- ① Dübendorf groundwater
② Zürich lakewater

Water sample no.	Malleable cast iron fittings				Non-ferrous fittings		Hard solder connection	
	Non-galvanized threads		Galvanized threads		Intermittent	Flowing	Intermittent	Flowing
	Intermittent	Flowing	Intermittent	Flowing				
1	4	5	2	2	4	6	3	4
2	4	2	1	1	4	4	1	1
3	4	4	2	2	6	6	4	5
4	5	5	5	4	5	4	4	4
5	6	6	6	4	6	6	5	5
6	4	4	2	2	2	3	2	4
7	3	4	2	2	3	5	2	3
8	5	4	3	3	6	6	3	4
9	5	4	3	3	6	6	3	4
10	5	4	2	3	5	5	3	4
11	4	5	2	4	4	6	3	4

The figures have the following significance:

1 uniform surface layer, gray

2 uniform surface layer, brown

3 non-uniform surface layer, white/gray

4 non-uniform surface layer, brown

5 pronounced local corrosion, countless tiny rust spots

6 pronounced local corrosion, fewer but larger rust spots

Table 41: Evaluation of the corrosion on fittings in different waters [92]

The increased occurrence of corrosion damage to hot-dip galvanized steel pipes in heated drinking water (hot water) in mixed installations had already been attributed early on to the influence of copper ions.

Experiments were carried out in Berlin tap water (Table 42) with various pHs and copper ions of various origins to study the laws which apply [100].

Table 43 contains the test conditions. It can be seen from the corrosion results summarized in Table 44 that shallow pitting corrosion occurs already in water of pH 7.4 at a copper ion content of 0.1 mg/l. This form of corrosion also occurs in acidified water of pH 6.5 without copper ions; but is significantly increased by the latter, and is also found in the vertically arranged pipes. Copper ions only influence shallow pit corrosion if the zinc layer has been removed locally and the steel surface is exposed. Typical points of local attack were found at the three-phase boundary of air/pipe surface/water. According to the experimental results, as long as no steel surfaces are exposed, copper which has been deposited, e.g. on new hot-dip galvanized surfaces, cannot induce local corrosion. However, if copper ions are constantly arriving at the inner surfaces of the pipes, pitting corrosion is induced.

Measurable variables	Measured value	Units
Sampling temperature	284.4 – 287.6 (11.4 – 14.6)	K (°C)
pH, electrometric	7.35 – 7.45	
Electrical conductivity at 293 K (20 °C)	530 – 610	μS/cm
m value	3.53 – 3.74	mmol/l
p value	–0.22 to –0.3	mmol/l
Calcium (Ca ²⁺)	88.2 – 101	mg/l
Magnesium (Mg ²⁺)	5.73 – 9.47	mg/l
Sulfate (SO ₄ ²⁻)	68.3 – 115.5	mg/l
Chloride (Cl ⁻)	27.4 – 52.5	mg/l
Nitrate (NO ₃ ⁻)	< 2	mg/l
Iron (Fe ²⁺)	< 0.05	mg/l
Manganese (Mn ²⁺)	n.d.	
Copper (Cu ²⁺)	< 0.05	mg/l
Zinc (Zn ²⁺)	< 0.05	mg/l
Silicic acid as SiO ₂	15 – 20	mg/l
Phosphate	n.d.	

n.d. not detectable

Table 42: Fluctuation in measured values from Berlin tap water in a period of two years [100]

In [101], microprobe studies on the distribution of the elements in the surface layers of the pipes in the experiments [100] demonstrated areas of chloride and sulfate concentration at the metal/surface layer phase boundary. This gives the surface layers semi-conductor properties, leading to partial separation of regions at which anodic and cathodic part reactions proceed. As the concentration of copper ions increases, the cathodic part current is increased, so that pitting corrosion is intensified at the anodic regions.

Experiments in two different types of water (Table 45) at temperatures of 285 to 346 K (12 to 73 °C) under a constant water flow revealed, with the aid of rest potential measurements, the existence of a critical potential range for the occurrence of pitting [102]. By comparative studies on pure zinc and hot-dip galvanised steel pipes – as can be seen from Figures 37 and 38 – a potential shift in the noble direction was also found on pure zinc as the temperature increases, and not only on hot-dip galvanised steel pipes. The critical potential range for pitting corrosion on zinc, which depends on the water quality, lies coincidentally in the rest potential range of steel and is not to be attributed to a potential shift of zinc in the noble direction with respect to steel (potential reversal). A reduction in the potential shift in the noble direction and therefore the suppression of pitting corrosion was found, depending on the water quality, on addition of monomeric phosphates.

Unit no.	Test conditions
Unit 1:	tap water, pH 7.35 to 7.45 (measured at sampling temperature)
Unit 2:	tap water, pH 7.35 to 7.45. In the flask 20 sheets of CuNi20Fe-F30 with a total surface area of 2000 cm ² were placed. Dimensions of a single sheet 50 × 100 × 1.5 mm
Unit 3:	tap water, pH 7.35 to 7.45. In the flask 20 sheets of SF-Cu (CW024A) with a total surface area of 2000 cm ² were placed. Dimensions of a single sheet 50 × 100 × 1 mm
Unit 4:	tap water, pH 7.35 to 7.45, ascending pipe at the front internally copper-plated
Unit 5:	tap water acidified with CO ₂ , pH 6.45 to 6.55
Unit 6:	tap water, pH 6.45 to 6.55, flask with 20 sheets of CuNi20Fe, total surface area = 2000 cm ²
Unit 7:	tap water, pH 6.45 to 6.55, flask with 20 sheets of SF-Cu, total surface area = 2000 cm ²
Unit 8:	tap water, pH 6.45 to 6.55, ascending pipe at the front internally copper-plated
Unit 9:	tap water, pH 6.45 to 6.55, copper concentration = 0.1 mg/l Cu ²⁺
Unit 10:	tap water, pH 6.45 to 6.55, copper concentration = 0.3 mg/l Cu ²⁺
Unit 11:	tap water, pH 7.35 to 7.45, copper concentration = 0.1 mg/l Cu ²⁺
Unit 12:	tap water, pH 7.35 to 7.45, copper concentration = 0.3 mg/l Cu ²⁺

Table 43: Test conditions used in the investigation of the corrosion resistance of hot-dip galvanised steel pipes in mixed installations [100]

Unit	Operating conditions (see also Table 43)	Horizontal pipes			Vertical pipes
		Test duration, months			
		4	9	13	13
1	tap water pH 7.4	–	–	–	–
2	pH 7.4 flowing over CuNi20Fe	–	–	–	–
3	pH 7.4 flowing over SF-Cu	–	+	+	–

– no shallow pit corrosion

+ shallow pit corrosion

++ extensive shallow pit corrosion

Table 44: Corrosion behavior of pipes under the test conditions mentioned in Table 43 [100]

Table 44: Continued

Unit	Operating conditions (see also Table 43)	Horizontal pipes		Vertical pipes	
		Test duration, months			
		4	9	13	13
4	pH 7.4 copper-plated ascending pipe	–	–	–	–
11	pH 7.4 0.1 mg/l Cu ²⁺	–	–	+	–
12	pH 7.4 0.3 mg/l Cu ²⁺	–	+	++	–
5	tap water + CO ₂ + air pH 6.5	–	+	+	+
			negligible	negligible	negligible
6	pH 6.5 flowing over CuNi20Fe	–	+	++	++
7	pH 6.5 flowing over SF-Cu	+	+	++	+
8	pH 6.5 copper-plated ascending pipe	–	+	+	+
			negligible	negligible	negligible
9	pH 6.5 0.1 mg/l Cu ²⁺	–	+	++	+
					negligible
10	pH 6.5 0.3 mg/l Cu ²⁺	–	+	++	+

– no shallow pit corrosion

+ shallow pit corrosion

++ extensive shallow pit corrosion

Table 44: Corrosion behavior of pipes under the test conditions mentioned in Table 43 [100]

Studies have been carried out in Berlin tap water (Table 46) under the experimental conditions shown in Table 47 to investigate the influence of phosphates and/or silicates on the pitting corrosion induced by copper ions [103]. X-ray scanning photographs have shown the formation of a primary layer of zinc reaction products and a secondary layer of inhibitors and calcium. The latter develops into corrosion-inhibiting protective layers in the course of time, the protective function of these being improved by inhibitors. The effectiveness of inhibition of general corrosion is given by the following sequence:

o-phosphate – silicate – silicate/phosphate – o/p-phosphate and p-phosphate. The mixture silicate/phosphate is the best as regards inhibition of local corrosive attack, while o-phosphate shows the lowest inhibition. All the other inhibitors can be classified in between. Although most of the inhibitors studied reduce the incidence of pits, the pit depth and therefore probability of damage are not substantially reduced. The inhibitor mixture silicate and phosphate prevents pitting on hot-dip galvanised steel pipes under the given experimental conditions, which can be applied to hot water circulation systems.

Measurable variables	Dortmund	Ewersbach	Units
pH at 293 K (20 °C)	6.90	6.65	
Electrical conductivity at 293 K (20 °C)	29.0	16.0	mS/m
Base capacity up to pH 8.2 at 293 K (20 °C)	0.48	0.50	mol/m ³
Acid capacity up to pH 4.3 at 293 K (20 °C)	1.60	1.43	mol/m ³
Calcium (Ca ²⁺)	1.2	0.66	mol/m ³
Magnesium (Mg ²⁺)	0.20	0.36	mol/m ³
Sulfate (SO ₄ ²⁻)	0.55	0.22	mol/m ³
Chloride (Cl ⁻)	0.45	0.31	mol/m ³
Nitrate (NO ₃ ⁻)	0.18	0.056	mol/m ³
Oxygen (O ₂)	4.8	8.7	g/m ³

Table 45: Parameters used for test waters [102]

Measurable variables	Measured value	Units
Electrical conductivity at 293 K (20 °C)	50–62	mS/m
pH at 284 – 287 K (11 – 14 °C)	7.3–7.5	
Base capacity up to pH 8.2	0.33–0.44	mol/m ³
Acid capacity up to pH 4.3	3.9–4.0	mol/m ³
Total alkaline earths (hardness)	2.4–2.94	mol/m ³
Nitrate (NO ₃ ⁻)	0.05–0.1	mol/m ³
Chloride (Cl ⁻)	1.36–1.88	mol/m ³
Sulfate (SO ₄ ²⁻)	0.7–1.32	mol/m ³
Total phosphorus as P ₂ O ₃	< 0.2	mg/l
Total silicon as SiO ₂	18–22.2	mg/l

Table 46: Analysis of Berlin tap water in a period of two years [103]

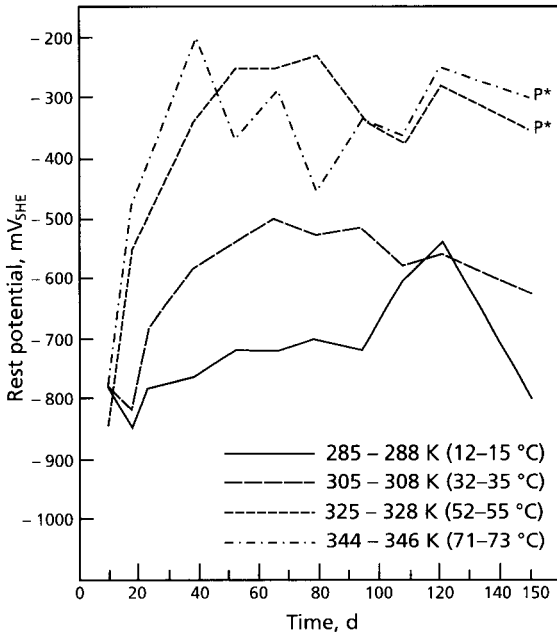


Figure 37: Rest potential/time curves for zinc in Ewersbach tap water as a function of water temperature [102]

P*: pitting corrosion

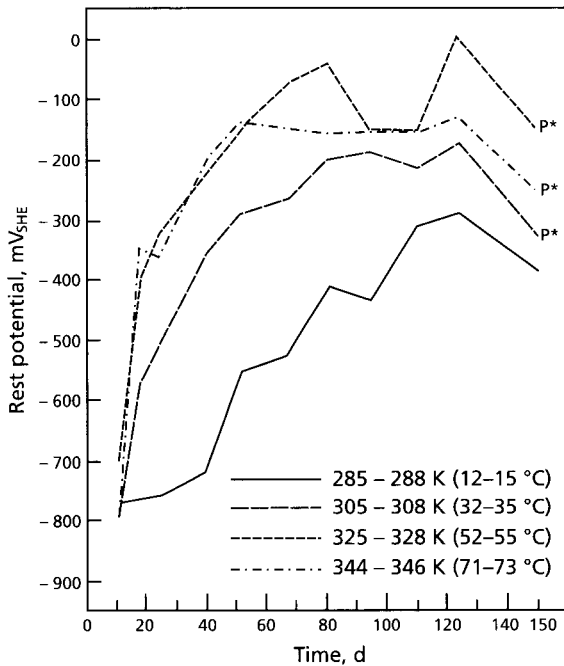


Figure 38: Rest potential/time curves for hot-dip galvanized steel in Ewersbach tap water as a function of the water temperature [102]

P*: pitting corrosion

Unit no.	Test conditions
0	tap water without additions
1	tap water flowing over copper sheet, no additions
2	tap water flowing over copper sheet + 5 mg/l P_2O_5 as trisodium monophosphate ¹⁾
3	tap water flowing over copper sheet + 5 mg/l P_2O_5 as trisodium monophosphate ²⁾
4	tap water flowing over copper sheet + 5 mg/l P_2O_5 as sodium hexametaphosphate ³⁾
5	tap water flowing over copper sheet + 5 mg/l P_2O_5 as combination of disodium monophosphate and sodium tripolyphosphate ⁴⁾
6	tap water flowing over copper sheet + 20 mg/l SiO_2 as sodium waterglass 40/42° Bé ⁵⁾
7	tap water flowing over copper sheet + 20 mg/l SiO_2 as sodium waterglass 58/60° Bé ⁶⁾
8	tap water flowing over copper sheet + (mg/l) 4 P_2O_5 + 22 SiO_2 as a combination of sodium waterglass and sodium tripolyphosphate ⁷⁾

All chemicals used are commercial products.

1) trisodium monophosphate, technically pure with a P_2O_5 content of 49.9 %

2) sodium tripolyphosphate, technically pure with 55.9 % P_2O_5

3) sodium hexametaphosphate (trade name) also Graham's salt, a long-chain polyphosphate with a chain length in the middle of 25 – 30 (10), P_2O_5 content 68.7 %

4) a mixture of 70 % sodium tripolyphosphate and 30 % disodium monophosphate, total P_2O_5 content = 62.5 %

5) sodium silicate with a molar ratio $SiO_2 : Na_2O = 3.42$; $D = 1.4 \text{ g/cm}^3$, total solids content = 38.0 %

6) sodium silicate, molar ratio $SiO_2 : Na_2O = 2.09$; $D = 1.71 \text{ g/cm}^3$, total solids content = 54.5 %

7) a mixture of 45.9 % SiO_2 as sodium silicate and 8.3 % P_2O_5 as sodium tripolyphosphate (Ferrosil® 160)

Table 47: Test conditions used in the investigation of the effect of phosphates and silicates on copper ion-induced pitting corrosion on zinc-coated pipes [103]

Attempts were made under conditions close to those in practice to clarify whether modified zinc layers have a better corrosion resistance than standard galvanization [104]. Inhibition by pure o-phosphate and a long-chain polyphosphate was also investigated. The electrolytic water treatment process proven in practice (called the electrolysis process for short) was included in the studies. The experimental conditions can be seen from Figure 39, and Table 48 contains the water analysis.

The best corrosion protection is achieved by the electrolysis process, as can be seen, for example, by comparing the material consumption per unit area on the five materials investigated in accordance with Figures 40 and 41. From the current density/potential curves plotted, it was found that the protective action by the electrolysis process is based on inhibition of the cathodic part reaction. This is evidently caused by incorporation of aluminium hydroxide into the surface layers which form. This has the effect of a significantly lower conductivity of the surface layer compared with the surface layers otherwise formed from zinc oxide. The studies also showed that the modified zinc layers tested, without the electrolysis method, show a distinctly poorer corrosion behavior than standard galvanization according to DIN EN 10240.

Measurable variables	Measured value	Units
pH	6.76	
Electrical conductivity at 293 K (20 °C)	37 ¹⁾	mS/m
Base capacity up to pH 8.2	0.43 ²⁾	mol/m ³
Acid capacity up to pH 4.3	1.75 (4.9° d)	mol/m ³
Calcium Ca ²⁺	1.45 (9.6° d)	mol/m ³
Magnesium Mg ²⁺	0.27 (9.6° d)	mol/m ³
Sodium Na ⁺	0.91 (21) ³⁾	mol/m ³
Sulfate SO ₄ ²⁻	0.55 (53) ³⁾	mol/m ³
Chloride Cl ⁻	1.16 (41) ³⁾	mol/m ³
Nitrate NO ₃ ⁻	0.35 (22) ³⁾	mol/m ³
Silicate SiO ₂	5.4	mg/l
Phosphate PO ₄ ³⁻	0.35	mg/l
Oxygen O ₂	7.4	g/m ³
KMnO ₄ consumption	5.4	mg/l

1) $\triangleq$ 370 μ S/cm

2) $\triangleq$ 19 mg/l CO₂

3) $\triangleq$ mg/l

Table 48: Water analysis [104]

The advantageous formation of surface layers found in [104] due to the incorporation of Al₂O₃ is confirmed by the chemical composition of the protective layer shown in Table 49 [105]. On hot-dip galvanised steel pipes in particular, protective layers are formed similar to those found by investigating installed, hot-dip galvanized control lines for more than 10 years [106].

Studies were carried out in cold and hot water in Denmark to investigate the influence of the quality of hot-dip galvanised steel pipes [107]. The water analysis is summarized in Table 50 and the test conditions in Table 51. The origin of the steel pipes investigated, the thickness of the zinc layer and data on the structure of the zinc layers are contained in Table 52. The result found was a tendency towards increased corrosion at low thicknesses in the absence of pure zinc. The most severe corrosion was observed on pipes from Hungary with the lowest coating thickness of 50 μ m. Corrosive attack three times more severe than in cold water was found in circulating hot water or in hot water with intermittent operation.

The matter of reduction of nitrate to nitrite is discussed in respect of hygiene conditions when hot-dip galvanised steel pipes are used in domestic installations. The conditions which lead to nitrate reduction – especially in respect of the limit for nitrite of 0.1 mg/l stated in Table 1 – are discussed in [108, 109, 110]. The conditions can be described with the aid of Figure 42 as follows:

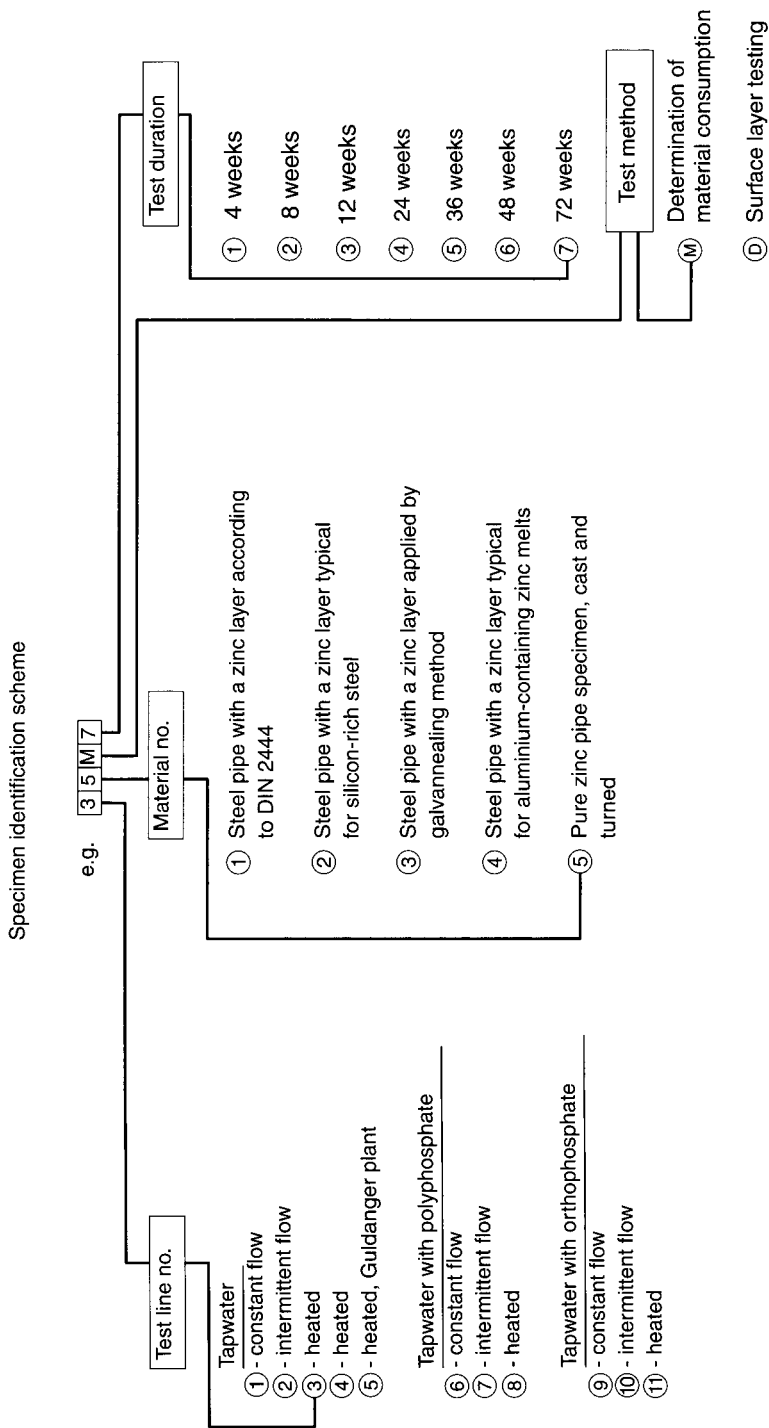


Figure 39: Specimen identification scheme and overview of the test conditions [104]

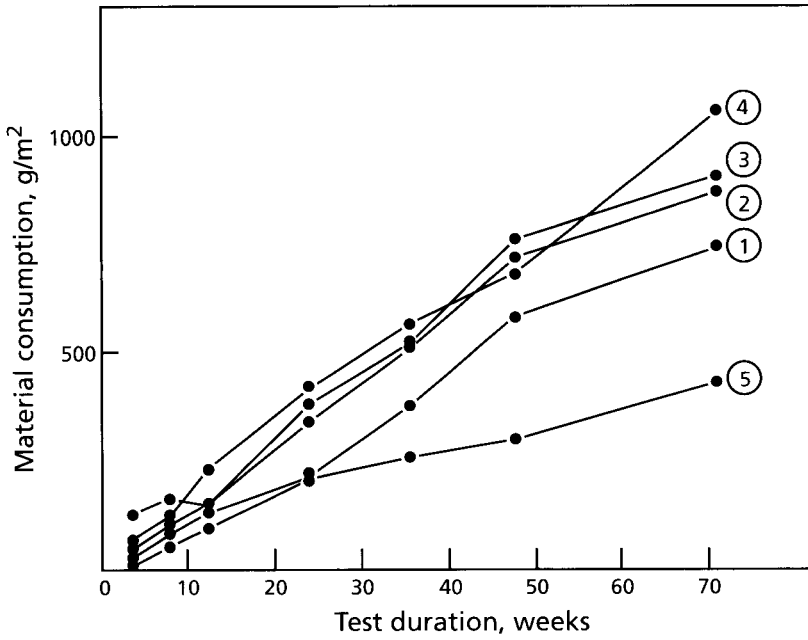


Figure 40: Material consumption in test line no. 4, see Figure 39 (Materials ①, ②, ③, ④ and ⑤ according to Figure 39) [104]

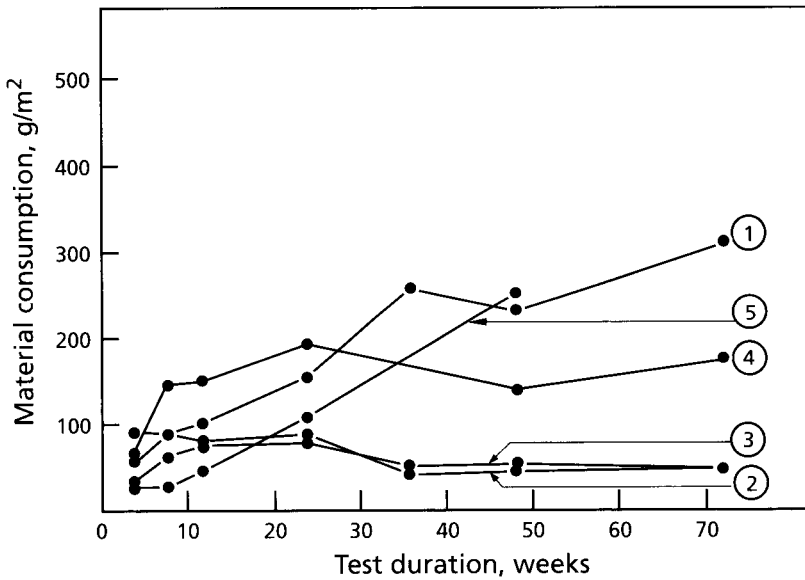


Figure 41: Material consumption in test line no. 5, see Figure 39 (Materials ①, ②, ③, ④ and ⑤ according to Figure 39) [104]

- The reduction to nitrite clearly depends on the flow conditions and the age of the hot-dip galvanized steel pipes installed.
- $c(\text{NO}_2^-) > 0.1 \text{ mg/l}$ occurs in stagnant water overnight (16 h) and over the weekend (64 h), compared with the daily average (daytime water).
- As the age of the installation increases, nitrite values lower than 0.1 mg/l are obtained even after prolonged stagnation times.

Chemical composition, %						
	Fe_2O_3	Al_2O_3	CaO	ZnO	CO_2	SiO_2
Hot water outflow						
Scaling	52.3	17.6	4.8	0.68	4.65	2.0
Sand-blasted	54.0	21.5	2.3	1.04	2.86	2.2
Pickled	55.4	25.4	3.9	0.76	3.53	2.3
Zinc-coated	12.8	30.5	trace	43.0	6.52	3.4
Circulation						
Scaling	65.0	4.2	4.1	0.8	3.85	2.5
Sand-blasted	66.4	4.6	1.1	1.08	2.43	2.2
Pickled	67.4	3.9	3.1	0.72	2.89	2.4
Zinc-coated	23.2	20.1	trace	42.0	4.29	4.4

Table 49: Chemical composition of the protective layers [105]

Measurable variables	Measured value	Units
pH	7.25	
Electrical conductivity	75	mS/m^3
$K_A 4.3$	5.4	mol/m^3
$c(\text{Ca}^{2+})$	3.2	mol/m^3
$c(\text{SO}_4^{2-})$	0.98	mol/m^3
$c(\text{Cl}^-)$	0.93	mol/m^3
$c(\text{NO}_3^-)$	0.10	mol/m^3
$c(\text{Na}^+)$	0.48	mol/m^3
$c(\text{Mn}^{2+})$	< 0.2	mmol/m^3
$c(\text{SiO}_2)$	0.33	mol/m^3
$c(\text{PO}_4^{3-})$	0.00	mol/m^3

Table 50: Water analysis according to [107]

	Temperature K (°C)	Operation
Cold water	298–301 (25–28)	$v = 1.2$ m/s, constant
Hot water	338 (65)	$v = 0.3$ m/s, circulation
Hot water	338 (65)	$v = 1.2$ m/s, intermittent 25 L/3 h, tapping for 1 min

Table 51: Test conditions according to [107]

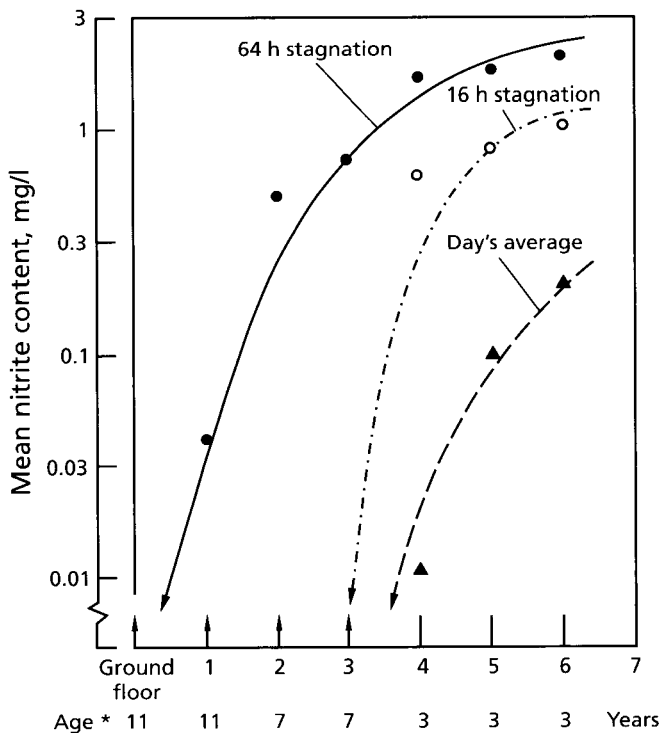


Figure 42: Mean nitrite content in daily water samples and stagnant samples overnight (16 h) and over the weekend (64 h) as a function of the test site (floor level) and service life of the installation [108, 109]

The oxygen content in drinking water is another parameter which influences nitrate reduction. As can be seen from Figure 43, nitrite formation decreases as the oxygen content increases. At oxygen contents of about 6 mg/l and a pH of about 7.5 usually present in drinking water, the nitrite content is less than 0.1 mg/l.

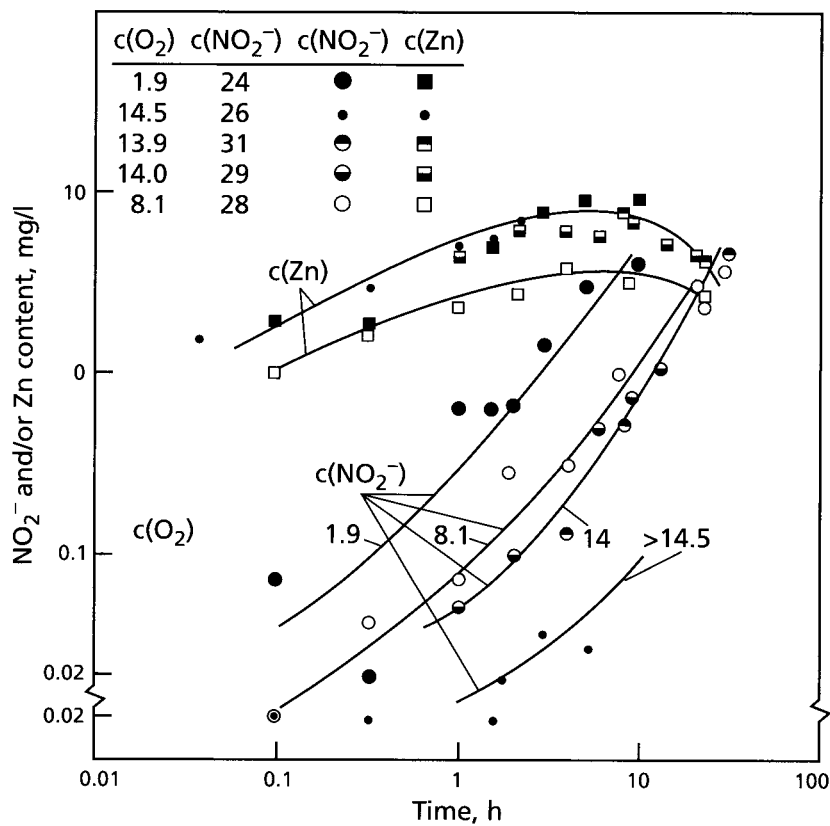


Figure 43: Effect of O_2 content on nitrite reduction [109]

Country of origin	Type	Inside coating analysis, %		Inside coating thickness, μm			Outside coating, μm	Comments on the structure and appearance of the zinc coating
		Pb	Cd	max.	min.	mean		
Germany Mannesmann	welded	1.14	0.097	110	70	90	75	smooth, regular, pure zinc all over
Germany Mannesmann	welded			250 120	70 60	150 85		fairly smooth, regular, pure zinc all over
Germany Mannesmann	welded	0.52	0.039	140 150	60 60	95 100	75	smooth, regular, pure zinc all over
Germany Mannesmann	seamless	0.95	0.114				80	slight roughnesses, otherwise regular, no metallographic examination
Germany Maximilians Hütte	seamless	0.50	0.021	90	60	75	85	smooth, regular, only iron-zinc alloy and no pure zinc layer since the steel is killed steel (Si: 0.37 %)
Hungary	seamless	0.64	0.055	60	50	50	95	smooth, longitudinal scratches produced by mechanical removal of excess zinc. Iron-zinc alloy only, no pure zinc layer since the steel is killed steel (Si: 0.31%)
Sweden	welded heavy seam	0.44	0.003	130	50	85	55	very irregular, zinc foam and heavy thickening at some places

Table 52: Examination of steel pipes in delivery state [107]

Table 52: Continued

Country of origin	Type	Inside coating analysis, %		Inside coating thickness, μm			Outside coating, μm		Comments on the structure and appearance of the zinc coating
		Pb	Cd	max.	min.	mean		mean	
Russia	welded			140	40	100			irregular, varying thickness of coating, layer of pure zinc all over
Russia	welded visible seam	0.80	0.002	210	60	125		60	highly varying thickening at some places, layer of pure zinc all over
		0.78	0.002	390	100	235			
Russia	welded visible seam	0.38	0.002	210	60	120		50	smooth, regular, at some places slight thickening, layer of pure zinc all over
		0.37	0.002						
Unknown	welded			630	80	260		165	very rough, large areas without pure zinc
				280	140	170			
Great Britain	welded	0.50	0.005	220	60	110		90	fairly regular, at some places slight thickening, layer of pure zinc all over
				200	100	150			
Austria	welded	0.83	0.001						slightly rough, small irregularities, no metallographic examination
India	welded heavy seam	0.71	0.005	330	70	150		75	very irregular, formed zinc, heavy thickenings
		0.71	0.006	480	30	220			
France/Belgium Valey	welded			400	55	70 - 80		80	smooth, regular, thickening longitudinally, pure zinc all over
France/Belgium Valey	welded, faintly visible seam			120	40	60		70	smooth, regular, thickening longitudinally, pure zinc all over

Table 52: Examination of steel pipes in delivery state [107]

B

Non-metallic inorganic materials

B 1 Asbestos

Asbestos by itself is of no significance for the drinking water supply, in contrast to , which will be discussed in this section. Pipes made of asbestos cement are used for long-distance and distribution lines.

[111] contains data on observations on the inside surfaces of pieces of pipe exposed to water for several years. These observations are summarized in Table 53. Column b in the table also states whether the inside surfaces had been painted – chiefly with bitumen paint. It can be seen from the water parameters listed in columns d, e and f that the inner surfaces were exposed to soft, lime-dissolving water.

The coating of bitumen paint has become brittle in some cases and has small blisters. The underlying asbestos cement pipe wall has not been attacked – apart from one case.

The use of asbestos cement pipes without a coat of paint is recommended in [111] where the following water parameters exist:

- $\text{pH} > 6.0$,
- $K_A4.3 > 1.8$,
- lime-dissolving $\text{CO}_2 < 5 \text{ mg/l}$ in soft water and
- $c(\text{SO}_4^{2-}) < 1000 \text{ mg/l}$.

It should be pointed out that if asbestos cement pipes are used, possible attack by the soil on the outer surfaces and the mechanical strength of the pipes must be taken into account.

Pipe dimensions	Inner coating	Operating duration	Water parameters			Observations after disassembly
			$K_{A4.3}$		Lime aggressive	
ND		Years	pH	mol/m ³	CO ₂ mg/l	
a	b	c	d	e	f	g
100	not	23	7.1	2.18	19.6	carbonated on the surface
80	present	23	6.9	1.04	20.0	n.C. ¹⁾
100		11	6.4	0.61	12.0	n.C. ¹⁾ , protective phosphate layer as a result of phosphate metering (3 g/m ³)
100	present	20	5.8	–	26.2	n.C. ¹⁾
200		26	–	0.25	22.5	n.C. ¹⁾
80		24	5.4	1.50	26.4	blistering of bitumen coating, bitumen embrittled, traces of corrosion, max. depth 2 mm
150		5	6.9	0.78	11.0	blistering in bitumen coating
100		27	–	0.21	15.4	bitumen coating embrittled, extensive blistering
80		20	6.0	–	24 to 70	corrosion areas where coating damaged
100		29	4.0	0.39	9.0	n.C. ¹⁾
175		17	6.6	0.16	6.6	n.C. ¹⁾

1) n.C. no corrosion on the inner surface

Table 53: Operating conditions and observations on the inner surfaces of pipes made of asbestos cement after several years' exposure [111]

B 4 Binders for building materials (e.g. mortar and concrete)

Of these materials, cement mortar is successfully used worldwide for lining water pipes made of cast iron and steel. The main areas of use are long-distance and distribution lines for drinking and untreated water.

To achieve an optimum corrosion protection, a cement mortar lining (called CM lining below) should have the densest possible structure. This means that only small amounts of water pass through the CM layer to the inside surface of the pipe by diffusion, submicroscopically thin passive layers forming on the iron surface as a result of the alkaline reaction of the mortar. The total current density/potential

curves shown in Figure 44 are representative examples of the passive behavior of unalloyed ferrous materials in an alkaline medium [112].

Comparative studies on cast iron pipes with and without a CM lining showed the protective action of the CM lining after exposure to water of the quality shown in Table 54 for 5 and 20 years [63]. The formation of rust nodules, together with corrosive attack on the pipe wall, occurred on the cast iron pipes with a dip-tar coating. The cast iron pipes with a CM lining showed neither corrosive attack nor the formation of rust nodules.

The corrosion protection properties of a CM lining also exist without adhesion, as must be required, for example, for layers of organic lining. The CM lining lies close to the pipe wall and forms a self-supporting body [113]. While elastic deformations of cast iron and steel pipes do not lead to damage of the CM layer, cracks and flaking may occur under plastic deformation, which is also unacceptable for other reasons.

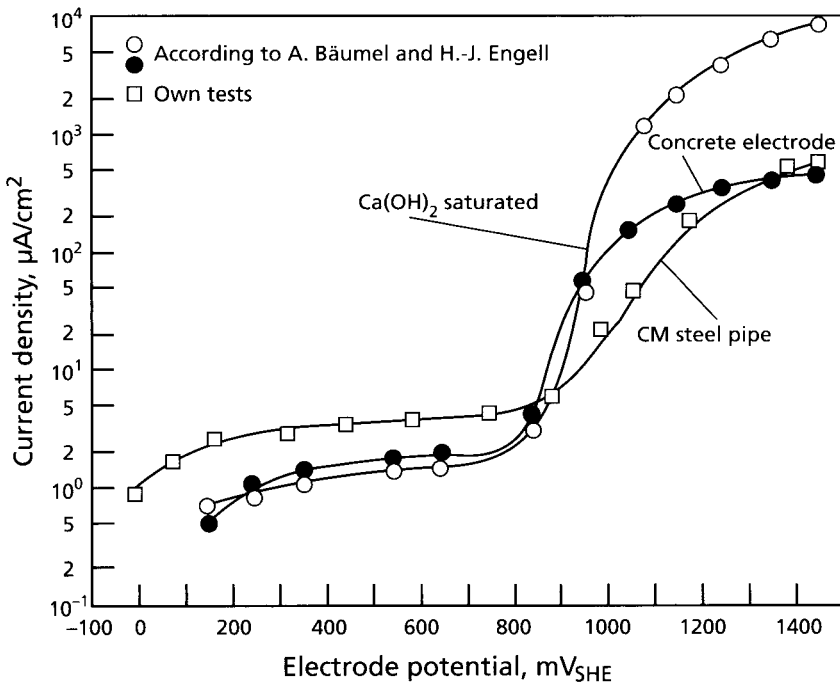


Figure 44: Current density/potential curves for steel in concrete, mortar and alkali solution [112]

The resistance of cement mortar depends on the following influencing parameters:

- The water quality, and here lime-dissolving water should be mentioned in particular, since this can lead to decalcification (leaching out of CaO) of the CM layers.

- As a result of decalcification, sand removal from the CM layer may occur under the following conditions:
 - turbulent flow
 - pigging of the pipe
 - if the pipe is out of use and the CM layer dries out.
- Decalcification and sand removal depend on the type of cement used, the production and structure of the CM lining and the density of the CM layer.
- Sulfate- and magnesium-rich water can lead to damage by internal breaking up of the CM layers. Experience to date has shown that this is generally of minor importance in the case of drinking water. If cements which are resistant to sulfate are used, there is in any case no danger from water containing sulfate.
- CM layers can become carbonated throughout, depending on the conditions.
- If the chloride contents are very high, chlorides may reach the inner iron surfaces.

If cracks occur, especially continuous cracks, there must be corrosion protection of the exposed pipe wall.

CM linings for drinking water pipes must comply with hygiene requirements and be resistant to organism growth. An unacceptable increase in the pH which may occur in individual cases (alkalization of drinking water) and chlorine consumption must also be taken into account.

The influencing parameters and aspects listed are dealt with in detail below.

Decalcification and sand removal

Studies in lime-dissolving drinking water (Table 55) on cast iron and steel pipes lined with cement mortar by the rotational centrifugal method (Method 1 according to [114]) revealed decalcification in the top part of the layer down to a depth of about 2 mm after 6.5 to 12 years (see Figure 45) [115].

Service life years	Water quality	Cast iron pipes	
		with CM lining	with tar coating
5	pH 7.2 to 8.5 $K_A 4.3 = 1.2$ to 2.5 mol/m^3 total hardness 8.0 to 23.8°dH $K_B 8.2 = 0.03$ to 0.3 mol/m^3	smooth inner surface no rust nodules no corrosion	occasional rust nodule formation, 2 to 3 mm in thickness
20	pH 6.5 to 7.0 $K_A 4.3 = 0.89$ to 1.78 mol/m^3 total hardness 6 to 10°dH lime aggressive CO_2 20 mg/l	smooth inner surface no rust nodules no corrosion	adhering layer of rust nodules up to 15 mm in thickness, max. pitting depth in pipe wall 2.5 mm

Table 54: Long-term studies on cast iron pipes with and without a CM lining [63]

Measured variables	Measured value	Units
pH	6.4–6.9	
K _A 4.3	1.2–2.0	mol/m ³
K _B 8.2	0.14–0.62	mol/m ³
Sulfate (SO ₄ ²⁻)	0.35–0.70	mol/m ³
Electrical conductivity	248–386	μS/cm
Fe, total	9	mmol/m ³
Mn, total	17	mmol/m ³

Table 55: Water quality of drinking water used in studies on CM-lined cast iron and steel pipes [114]

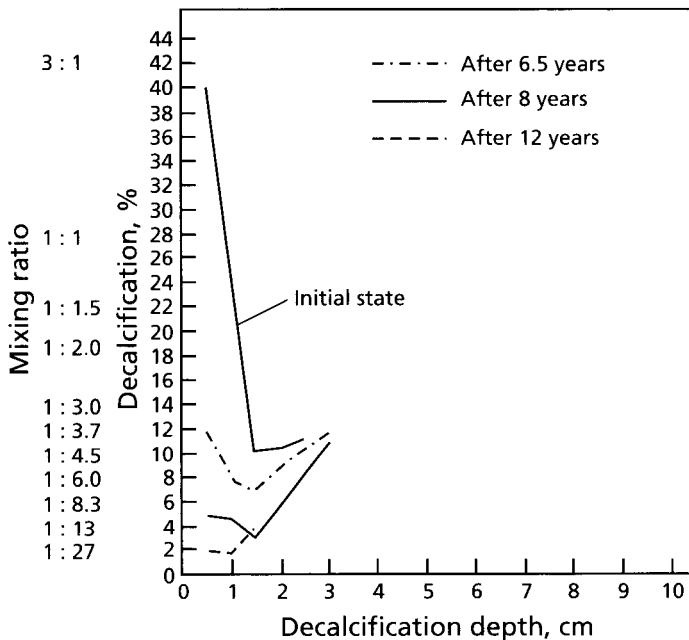


Figure 45: Decalcification of fabricated cement mortar linings (ND 100) in Dortmund tap water after various service times [115]

Decalcification leads to the possibility of sand removal from the uppermost decalcified layers, although this was not described in these studies. As well as choosing a suitable type of cement, additives and grain composition, it is suggested that richer mixing ratios (1:1) are more favorable in respect of decalcification than less rich mixtures (1:2), as shown, for example, by Figure 46. Figure 46 shows, however, that the absolute amount of decalcification is significantly greater at a ratio of 1:1 than at 1:2.

The decalcification in equilibrium water and lime-dissolving water (Table 56) was investigated, amongst other things, in studies in practice [116]. These studies were carried out with steel pipes which had a cement mortar lining which can be characterized as follows:

- sulfate-resistant Portland cement
- mixing ratio 1 : 1.5
- maximum grain size of the sand 1 mm
- water-cement ratio 0.3 after centrifugation
- lining thickness 4 mm

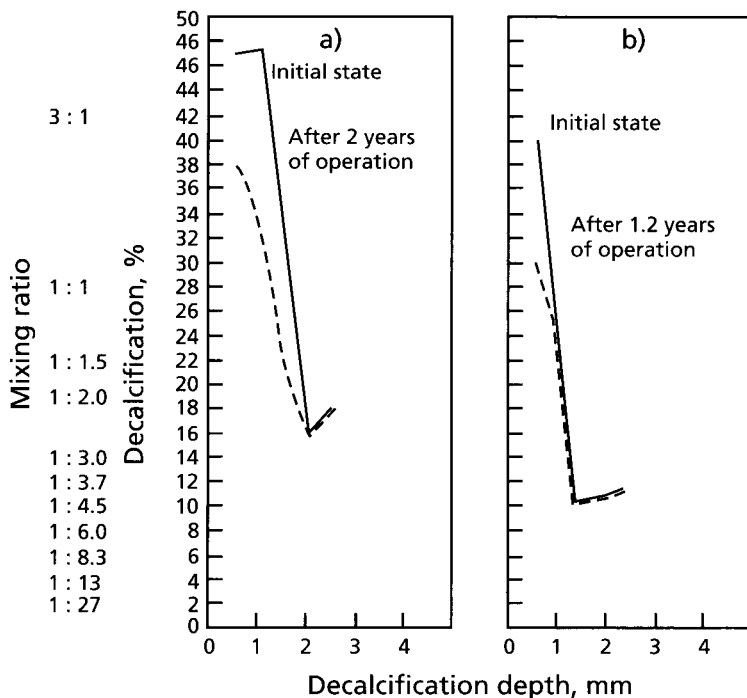


Figure 46: Decalcification as a function of the mixing ratio in fabricated cement mortar linings (ND 100) (layer analyses) [115]

a) mixed 1 : 1

b) mixed 1 : 2

Chemical analysis of the main constituents of the fine layer and the main layer showed that the calcium content in the fine layer (columns 10 and 12) is greatly reduced by the carbonic acid dissolved in the water ($K_B 8.2$) due to the formation of soluble calcium bicarbonate, which is washed away by the water flow. In contrast, the composition of the main layer (column 11 and 13) still remained unchanged. The decalcification depth determined by chemical analysis could be confirmed with a satisfactory accuracy by scratching the surface with a steel needle (column 14).

No.	pH	Water quality				Saturation index	Nominal diameter Flow rate Service life	Composition of the cement mortar layer				Decalcification depth
		K _{5.4.3}	K _{8.2}	Q _c	SO ₄ ²⁻			delivery state				
								mm ³ /m ³				fine layer
4	8.9	0.64	0.0	0.64	0.34	-0.1	ND 300 v = 1 m/s 2 years	sand SiO ₂ (silicate) CaO CO ₂	37-44	65-76	38-40	65
									11-16	2-7	11-13	5
									21-35	10-15	21-24	15
									10	2-6	9-10	4
5	5.9	0.36	0.95	1.31	0.81	-2.8	ND 100 v = 1 m/s 13 months	sand SiO ₂ (silicate) CaO CO ₂	65-76	30-39	70-73	~1
									2-7	21-22	3-5	
									10-15	8-10	13-14	
									2-6	0	2-6	
6	6.6	1.0	0.75	1.75	1.18	-1.8	ND 500 v = 0.3 m/s 3 years	sand SiO ₂ (silicate) CaO CO ₂	65-76	84-80	65-75	~1
									2-7	5-7	2-5	
									10-15	3-4	10-12	
									2-6	0	3	

Table 56: Decalcification of cement mortar-lined steel pipes [116]

CM samples taken from two service lines (Table 57, No. 1 and 2) [117] were decalcified down to a depth of 1.5 and 2.4 mm after 6 and 11 years by the acidified drinking water and the untreated water respectively (Table 57, see under “Softened Layer”).

A long-term study [117] over 12 years in flowing, acidified drinking water (Table 57, No. 3) showed the dependence of decalcification on time plotted as a graph in Figure 47. The parabolic time law plotted in Figure 47 is typical of rate-determining transport through a reaction layer.

In another series of experiments (Table 57, No. 4), the drinking water flowing through was adjusted to various constant pHs by addition of sulfuric acid. The decalcification rate (Table 57, see “Observations”) clearly depends on the carbon dioxide content ($c(\text{CO}_2)$).

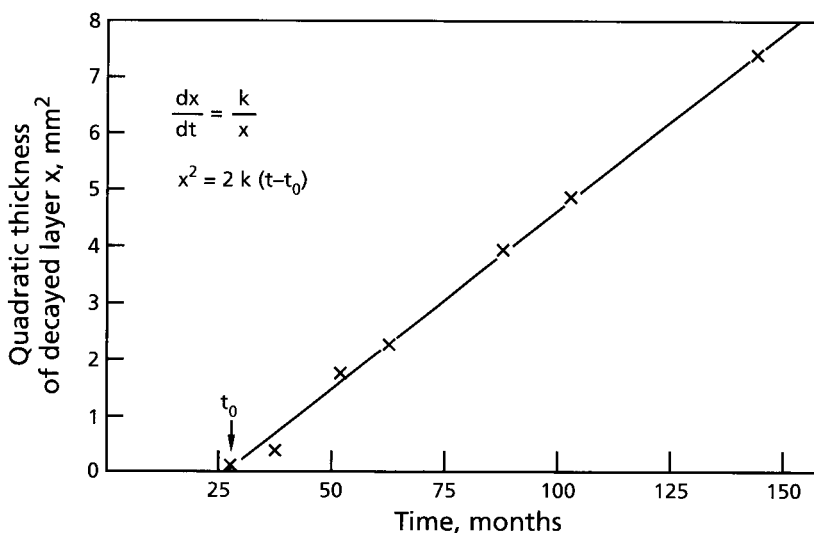


Figure 47: Time dependence of decalcification [117]

The decalcification was also investigated by chemical analysis of the decalcified (fragile) and main (stable) layers. The analytical values listed in Table 58 show that the decrease in the CaO value is pronounced in the topmost layer. While the main layers in experiments no. 1 and 2 are virtually unchanged in composition, they show marked changes as a result of water sample no. 3 of high carbonic acid content after 12 years.

The decalcification and dealkalization of mortar specimens produced by the centrifugal method and by trowelling were studied in a further series of experiments [117] under the experimental conditions shown in Table 59. According to the results of the studies summarized in Table 60, no significant influence on decalcification and dealkalization was found. Nevertheless, even these experiments showed that although the plastic dispersions added did not substantially influence decalcification, they caused the decalcified layers to have a firm consistency. This is of advantage in view of possible sand removal.

Type of mortar, nominal diameter	Medium	$c(\text{Ca}^{++})$		Q_c	$c(\text{CO}_2)$	pH	Test duration	Softened layer		Dealkalized layer	Observations
		mol/m^3	mol/m^3					mm	mm		
1. centrifuged BFC, $v^* = 2.5$ ND 1000	drinking water	1.2	2.1	0.48	6.9	3–6	1.5	n.d.	1 m/s		
	centrifuged PC, $v^* = 2.5$ ND 200	1.2	2.1	0.48	6.9	6	1.5	n.d.	1 m/s		
2. centrifuged PC, $v^* = 2.5$ ND 500	untreated water	1.3	2.0	0.7	6.8	10	2.4	n.d.	–		
						11	n.d.	3.5			
3. centrifuged PC, H 30 $v^* = 1.5$ ND 100	drinking water + H_2SO_4	2.2	3.4	1.4	6.5	12	2.7	4	Fig. 47		
4. centrifuged PC, $v^* = 2.5$ ND 100	drinking water + H_2SO_4	2.2	2.2–3.5	2.0–2.7	5	3	3	n.d.	0.9 mm/a (35 mpy)		
		2.2	2.7–3.9	1.5–2.0	6	3	2.5	n.d.	0.8 mm/a (31 mpy)		
		2.2	4.0–4.2	0.2–0.3	7	3	0	n.d.	0.0 mm/a (0 mpy)		
		2.2	3.7–4.1	2.7–3.7	5	1.4	2.2	n.d.	1.5 mm/a (59 mpy)		
		2.2	3.6–4.2	1.7–2.7	6	1.4	1.6	n.d.	1.1 mm/a (43 mpy)		
		2.2	3.9–4.1	0.2–0.4	7	1.4	0	n.d.	0.0 mm/a (0 mpy)		

* v = mixing ratio
n.d. not determined

Table 57: Behavior of cement mortar in flowing, acidified drinking water [117]

Sample specimen	Content, %			
	CaO	Al ₂ O ₃	SiO ₂ + Sand	Fe ₂ O ₃
1. Initial state (BFC)	13	3	80	< 0.5
after 3 years, fragile layer	3.4	3.7	85	4
Initial state (PC)	15	1.7	78	2
after 6 years, fragile layer	4.3	5	78	5.1
stable layer	15	1.4	73	2
2. Initial state (PC)	11	–	81	1.3
after 10 years, fragile layer	1.7		87	2.4
stable layer	9.1		78	
3. Initial state (PC)	17	4	71	
after 12 years, fragile layer	1	4	89	
stable layer	6.1	3.3	80	

Table 58: Composition of the CM layers before and after attack by acidified drinking water [117]

Type of cement:	Portland cement (PC)
Mixing ratio:	2.5
Type of sand:	sand H 30
	grain 0.2 to 1 mm;
	sand grain 0.2 to 3.0 mm
Additions:	plastic dispersion, mixed polymers M 1 or M 2, 10 or 7 % (percent by mass) in respect of cement water-repelling agents (heavy metal soaps)
Specimen production:	centrifugal method trowelling without compression
Flow rate in circulation:	30 m/min
pH adjustment by means of HCl addition	

Table 59: Data from tests in flowing, acidified drinking water [117]

Time-accelerated laboratory studies were carried out under the conditions in Table 61 according to [118] to investigate decalcification and sand removal. The influence of the cement base (Table 62), the mixing ratio, the compaction and the plastic additives was investigated. Table 63 gives a summary of characteristic data for the specimens studied.

Type of mortar	Medium	$c(\text{Ca}^{2+})$		Q_c	$c(\text{CO}_2)$	pH	Test duration		Softened layer		Dealkalized layer		Observations
		mol/m^3	mol/m^3		mol/m^3		months	mm	mm	mm	mm		
a) centrifuged PC; 0.2–3 mm	drinking water + CO_2 + HCl	2.1	23.5	19.2	5.6	14	1.5	1.5	1.5				attack on fine layer
b) as a) abraded fine layer	as a)					14	n.d.	n.d.	3–4				softening of main layer not measurable
c) filler v = 2.5; H 30	as a)					14	1.8	1.8	4–4.5				
d) as c) + M 1 (mixed polymer)	as a)					14	1.2	1.2	2.5–3				
e) as c) + M 2	as a)					14	1.4	1.4	3.5–4				
f) filler v = 2.5; 0.2 – 3 mm	as a)					14	n.d.	n.d.	2–2.5				
g) as f) + M 1	as a)					14	n.d.	n.d.	2–2.5				
h) as f) + M 2	as a)					14	n.d.	n.d.	1.5–2.0				
i) centrifuged PC; 0.2 – 3 mm	drinking water + HCl	2.5	4.5	3.9	5.5	16	n.d.	n.d.	1.2–1.4				
j) as i) + soaps	as i)					16	n.d.	n.d.	1.5–2.2				several specimens

n.d. = not determined

Table 60: Behavior of cement mortar in flowing, acidified drinking water [117]

The dependence of the decalcification rate E ($\text{g}/\text{m}^2 \text{ d}$) on time plotted in Figure 48 shows the validity of the parabolic law mentioned in [117]. The virtually identical decalcification properties of specimens of Portland cement (PC) and blast furnace cement (BFC) can also be seen. Aluminous cement (AC) shows somewhat better properties. The relative decalcification rates $E' = E/\% \text{ CaO}$ plotted in Table 64 are between about 0.1 and $0.2 \text{ g}/\text{m}^2 \text{ d}^1/\%$, that is to say the decalcification is largely independent of the parameters of the mortar composition.

Solution:	0.1 mol/l CH_3COOH + 0.1 mol/l NaCH_3COO (acetate buffer)
pH:	4.5
Temperature:	room temperature
Test duration:	196 d
Change in solution:	twice a week in the first 4 weeks, then once a week
Analytical test:	CaO at various times
After disassembly and drying:	crack formation observed
Sand removal:	surface layers brushed clean with nylon brushes, amount of sand removed weighed, references to sand-free surface

Table 61: Data from laboratory tests [118]

Substance	Composition, %		
	CaO	$\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{TiO}_2$	SiO_2
Portland cement 45 HS	64.4	10.8	19.7
Blast furnace cement 350 L	46.9	17.1	21.4
Aluminous cement	38.3	61.2	3.8
EFA filler	1.7	14.2	12.5

Table 62: Composition of cements and EFA fillers in [118]

Designation	Type of cement	Mixing ratio $\nu^{1)}$	Filler ratio $x^{2)}$	Plastic ratio $k^{3)}$	Water value in cement $w^{4)}$	Additions/ observations
Test line I (stamped prisms)						
PI/1	AC	1.8	0	0	0.31	–
PI/2	AC	2.5			0.37	–
PI/3	PC	1.8	0	0	0.40	
PI/4–11	PC	2.5	0.1–1.0	0	0.28/0.35	–
PI/12–35	PC	1.0–3.0	0	0–0.4	0.20/0.50	acrylic resin
PI/36–58	PC	1.0–3.0	0.1	0–0.4	0.20/0.50	acrylic resin
PI/59–81	PC	1.0–3.0	0.18	0–0.4	0.20/0.50	acrylic resin
Test line II (stamped prisms)						
PII/1–4	PC	2–5	0	0	0.3–0.6	28 d water
PII/5–8	PC	2–5	0	0	0.3–0.6	vaporized
PII/9–12	BFC	1.5/2.5	0	0	0.31/0.35	
PII/13–16	AC	1.5/2.5	0	0	0.31/0.35	
PII/17–20	AC	1.8	0	0.035/0.14	0.31/0.35	acrylic resin
PII/21	PC, coarse	0	0	0	0.26	pure cement
PII/22	PC, fine	0	0	0	0.35	(normal)
PII/23	BFC	0	0	0	0.34	pure cement
PII/24	AC	0	0	0	0.22	pure cement
Test line III (centrifuged lining ND 100)						
RI/1	PC	2.5	0.1	0	0.42	
RI/2	PC	2.5	0.1	0.01	0.33	liquefier
RI/3	PC	1.5	0	0	0.40	
RI/4	PC	3.0	0	0	0.50	
RI/5	BFC	2.0	0	0	0.32	
RI/6	AC	2.0	0	0	0.37	
RI/7	PC	2.5	0.1	0.05	0.33	acrylic resin
RI/8	PC	2.5	0.1	0.10	0.32	acrylic resin
RI/9	PC	2.5	0.1	0.05	0.32	propionate
RI/10	PC	2.5	0.1	0.10	0.32	propionate

PC = Portland cement, BFC = blast furnace cement, AC = aluminous cement

1) sand/cement + filler

2) filler/cement

3) plastic/cement + filler

4) mixing water + dispersion water/cement + filler

Table 63: Characteristic values of specimens from [118]

Table 63: Continued

Designation	Type of cement	Mixing ratio $\nu^{1)}$	Filler ratio $x^{2)}$	Plastic ratio $k^{3)}$	Water value in cement $w^{4)}$	Additions/ observations
Test line III (centrifuged lining ND 100)						
Test line IV (industrial pipe linings)						
RII/1-3	PC	~ 1.5				like Centriline
RII/4-6	PC	~ 1.0				like Centriline
RII/7, 8	PC	2.5	0	0.10		centrifuged, acrylic resin

PC = Portland cement, BFC = blast furnace cement, AC = aluminous cement

1) sand/cement + filler

2) filler/cement

3) plastic/cement + filler

4) mixing water + dispersion water/cement + filler

Table 63: Characteristic values of specimens from [118]

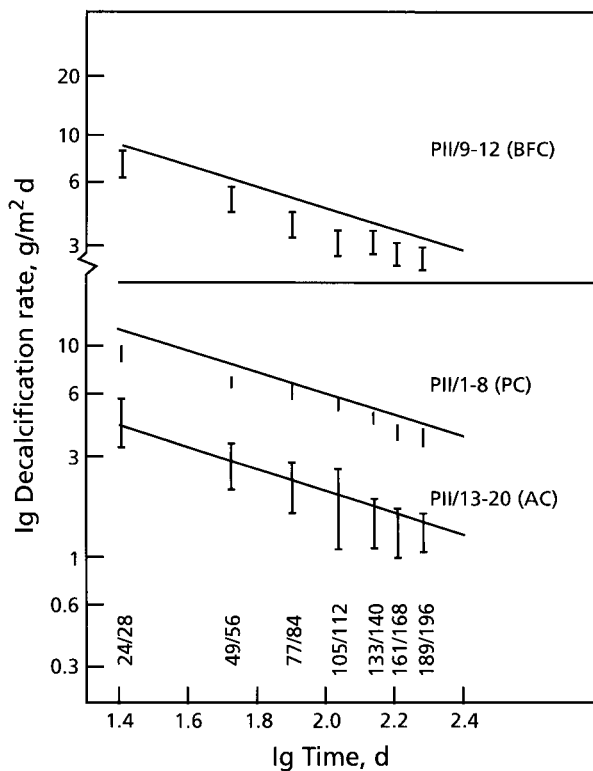


Figure 48: Decalcification of mortar specimens with time (see Tables 63 and 64) [118]

As was already found in the studies in [117], sand removal (g/m^2) can be improved by about 3 powers of ten by plastic additives, especially in the case of PC. The dependence of sand removal A or relative sand removal $A' = A/\%$ sand on the content of plastics in the mortar plotted in Figure 49 clearly shows this relationship and the substantial lack of dependence on the mixing ratio. The values determined for the relative sand removal are summarized in Table 65.

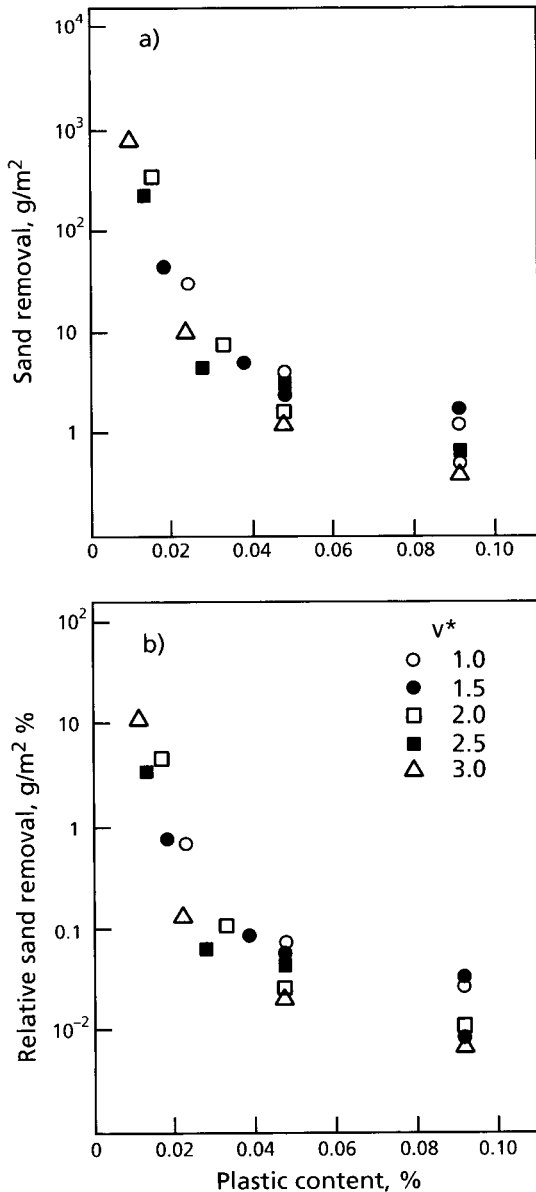


Figure 49: Effect of the plastic content of Portland cement specimens on sand removal and relative sand removal (relative sand removal = sand removal/% sand) [118]

v^* : mixing ratio

Specimen	Type of cement*	$E'; \text{g/m}^2 \text{ d} \%$	Observations
PI/3–81	PC	0.10–0.20	equation (7)
PII/1–8	PC	0.19–0.22	
PII/21, 22	PC	0.16–0.18	pure cements
RI/1–4, 7–10	PC	0.16–0.21	centrifuged
RII/1–3	PC	0.17	in situ ($v = 1.5$)
RII/4–6	PC	0.21	in situ ($v = 1.0$)
RII/7, 8	PC	0.16	centrifuged, acrylic resin
PII/9–12	BFC	0.14–0.19	
PII/23	BFC	0.12	pure cement
RI/5	BFC	0.14	centrifuged
PI/1, 2	AC	0.06–0.09	
PII/13–20	AC	0.07–0.09	no plastic influence
PII/24	AC	0.09	pure cement
RI/6	AC	0.12	centrifuged

* PC = Portland cement, BFC = blast furnace cement, AC = aluminous cement

Table 64: Relative decalcification rates E' [118]

The findings which have been described so far and usually obtained in laboratory experiments are the starting basis for the field tests described in [119–121] with a constant water flow rate of about 1 m/s.

According to the parameters of the water analyzed which are summarized in Table 66, two types of equilibrium water and lime-dissolving and soft water were investigated. Table 67 provides information on the nature and production of the CM linings, which were used in all the types of water (normal program). In a special program, the CM linings produced by the centrifugal method (Table 68) were – apart from one exception – tested in Dortmund water (Table 66, Samples 1 and 2).

The sand abrasion was used as a criterion of the resistance of CM layers by determination of the abraded material. In addition to the sand component, which is essential for the evaluation, deposits of Fe_2O_3 and MnO_2 which essentially originated from the water were found in the abraded material.

Figure 50 is a graph of the means of all the specimens in the normal program (Table 67) in the two types of Dortmund water (Samples 1 and 2). Figures 51 and 52 show the influence of the type of cement, the production method (methods I and II) and the flow rate for PC II in the water sample 2 for the normal program.

<i>Specimen</i>	<i>Type of cement</i>	<i>A'; g/m² %</i>	<i>Observations</i>
PI/3–81	PC	21–42	influence of v (see Table 63)
PII/1–8	PC	23–31	treatment, w (see Table 63)
RI/1–4	PC	12–21	(error due to separation possible)
RII/1–3	PC	20–24	in situ (v = 1.5)
RII/4–6	PC	27–28	in situ (v = 1.0)
PII/9–12	BFC	8–17	influence of v
RI/5	BFC	5	centrifuged
PI/1, 2	AC	6–9	
PII/13–18	AC	1.4–3.1	influence of v
RI/6	AC	0.7	centrifuged
With plastic addition			
PI/12–81	PC, acrylic resin	0.01–15.7	
RI/7, 8	PC, acrylic resin	0.3–5	separated by centrifugation
RI/9, 10	PC, propionate	1.3–1	separated by centrifugation
RII/7, 8	PC, acrylic resin	0.3–0.6	separated by centrifugation
PII/17–20	AC, acrylic resin	0.01–1	

PC = Portland cement, BFC = blast furnace cement, AC = aluminous cement

Table 65: Relative sand removal A' of plastic-free and plastic-containing mortar [118]

<i>Water parameters</i>	<i>Samples</i>					
	1	2	3	4	5	6
pH	7.76	6.75	6.60	9.11	4.67	6.10
K _A 4.3, mol/m ³	2.0	1.6	1.8	0.73	0.03	0.06
c(CO ₂), g/m ³	2.9	20.4	75.8	< 0.01	1.8	6.3
Excess CO ₂ , g/m ³	1.6	19.5	71.3	< 0.01	1.8	6.3
Saturation index	– 0.34	– 1.4	– 1.4	± 0.03	< – 4	< – 3
c(Ca ²⁺), g/m ³	46	47	77	16.7	1.4	1.8
c(Al), g/m ³	0.006	0.01	0.15	0.02	0.65	0.10
c(Fe), g/m ³	0.01	0.04	14.7	0.002	0.33	0.10
c(Mn), g/m ³	0.006	0.006	1.1	0.002	0.27	0.05
c(O ₂), g/m ³	6.5	8.0	< 0.1	11.5	10	11
KMnO ₄ consumption, g/m ³	4.4	3.6	34	6	15.6	– 7

Table 66: Water parameters in [121]

No.	Abbreviation	Method ¹⁾	Cement ²⁾	$v^3)$	$k^4)$	Observations
1	2.5	I	PC	2.5	0	normal lining
2	2.5 compressed	I	PC	2.5	0.01	compressed (liquefier)
3	1.5	I	PC	1.5	0	too rich
4	3.0	I	PC	3.0	0	too lean
5	BFC	I	BFC	2.0	0	
6	AC	I	AC	2.0	0	
7	5 A	I	PC	2.5	0.05	acrylic resin
8	10 A	I	PC	2.5	0.10	acrylic resin
9	5 K	I	PC	2.5	0.06	propionate + liquefier
10	10 K	I	PC	2.5	0.11	propionate + liquefier
11	1.5 II	II	PC	1.5	–	normal lining
12	1.0 II	II	PC	1.0	–	(richer)

1) I centrifugal method, II spinning method

2) PC = Portland cement, BFC = blast furnace cement, AC = aluminous cement

3) mixing ratio: v = sand/cement

4) plastic content: k = plastic/cement

Table 67: Mortar lining (normal program) in [121]

No.	Abbreviation	Method ¹⁾	Cement ²⁾	$v^3)$	Observations
23	PC II	II	PC	1.0	(rotating)
24	PC II	II	PC	2.1	(rotating)
25	PC II	II	PC	1.8	(stationary)
26	PC II	II	PC	1.1	(stationary)
27	BFC I	I	BFC	1.5	(cast pipes)
28	PC Col 1	II	PC	0	colloidal cement, up to 3 mm
29	PC Col 2	II	PC	0	colloidal cement, up to 1.5 mm
30	PC II	II	PC	1.1	
31	PC II	II	PC	1.7	rotating (separated)
32	PC II	II	PC	1.0	with plastic
33	PC II	II	PC	1.0	
34	BFC II	II	BFC	0.9	
35	BFC II	II	BFC	1.5	

1) I centrifugal method, II spinning method

2) PC = Portland cement, BFC = blast furnace cement

3) mixing ratio: v = sand/cement based on analytical findings

Table 68: Mortar lining (special program) in [121]

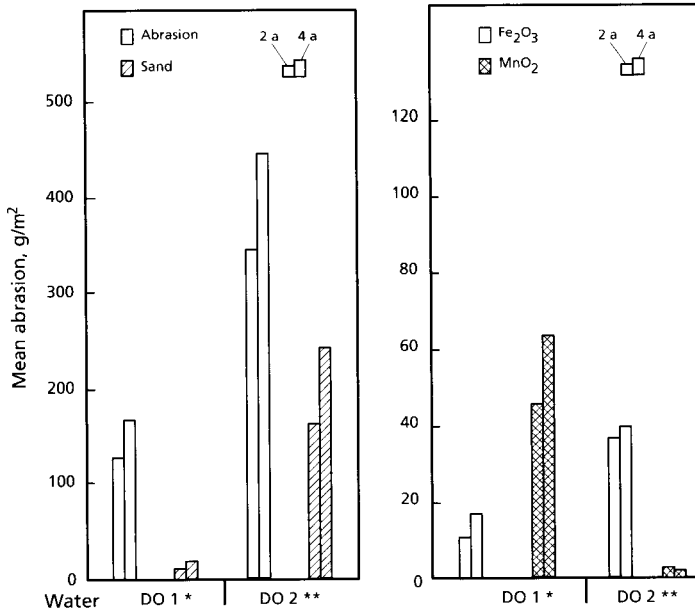


Figure 50: Mean abrasion for sand, Fe_2O_3 and MnO_2 ; 2 and 4 year specimens [121]
* see Table 66

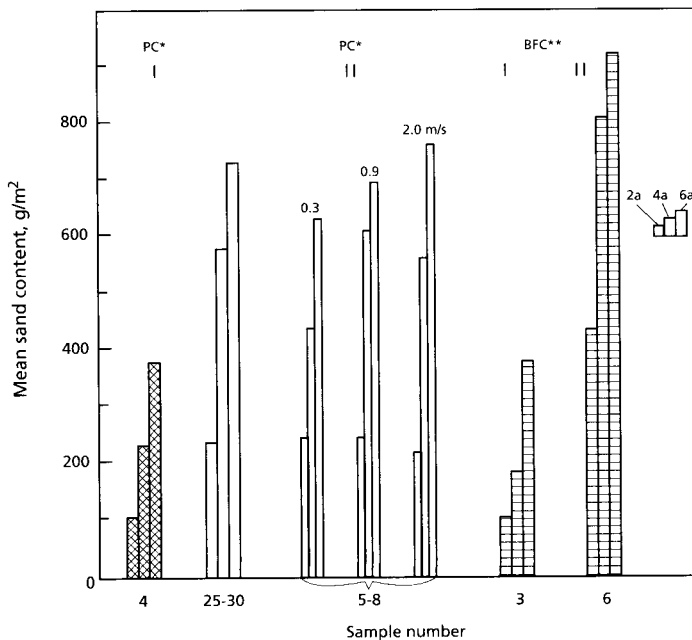


Figure 51: Mean sand content in the water sample 2 (see Table 66); 2, 4 and 6 year specimens [121]

* Portland cement

** Blast furnace cement

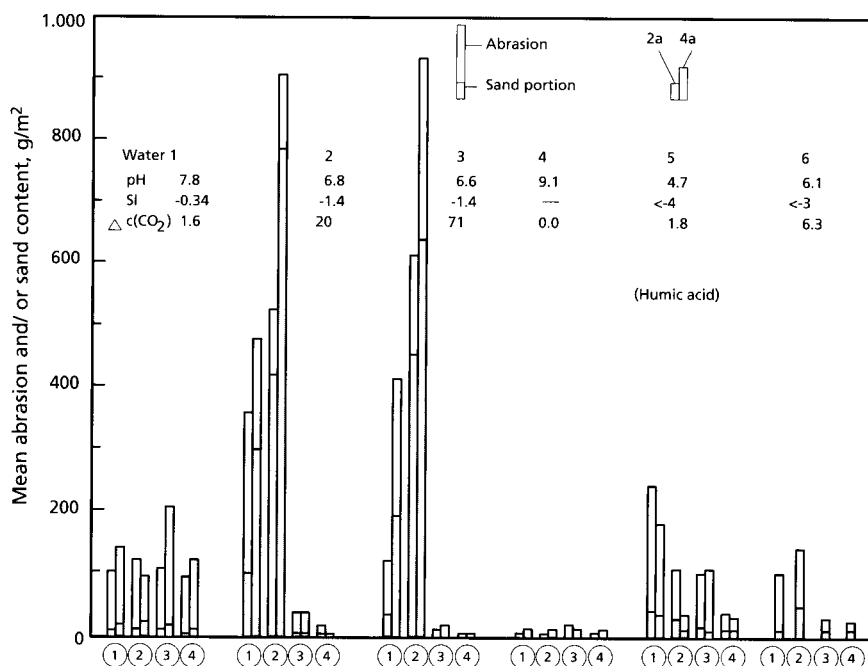


Figure 52: Mean values for abrasion and sand content, 2 and 4 year specimens, normal program [121]

- ① Portland cement, method 1
- ② Portland cement, method 2
- ③ Aluminous cement
- ④ Portland cement with 10% acrylic resin

The following conclusions in respect of sand abrasion can be drawn from the results of the studies:

- The severest sand abrasion occurs in water of high CO_2 content, and increases with time; the pH and saturation index SI by themselves are not significant criteria.
- CM linings which have been produced by the centrifugal method, method I, are superior to those which have been produced by the spinning method, method II, according to [114].
- There is no substantial difference between PC and BFC; AC mortar and PC mortar with 10 % added acrylic resin give low to very low sand abrasion values in all types of water.
- No influence of the flow rate or mixing ratio is detectable.
- In lime-dissolving waters, the mortar attacked remains on the pipe wall and does not migrate into the water; however, there is a tendency towards sand abrasion here after the pipelines have been put out of service, especially if the CM lining dries out.

- Rust forms in thin CM layers (specimens 12, 28 and 29 Table 67 and 68) in lime-dissolving water.

The results reported are the basis for establishing possible applications of CM linings listed in DIN 2880. Table 69 summarizes, by way of probability conclusions, the data obtained from [114] on the application range of cement mortar grades listed in Table 70.

$Q_c > 0.25 \text{ mol/m}^3$
$c(\text{Ca}^{2+}) > 0.02 \text{ mol/m}^3$
$\text{pH} > 7.8$
$7.0 \leq \text{pH} \leq 7.8, \text{SI} \geq -0.3$
$7.0 \leq \text{pH} \leq 7.8, \text{SI} < 0.3, \Delta c(\text{CO}_2) \leq 0.25 \text{ mol/m}^3$
$\text{pH} < 7.0, \text{SI} \geq -0.1$
$\text{pH} < 7.0, \text{SI} < -0.1, \Delta c(\text{CO}_2) \leq 0.25 \text{ mol/m}^3$
$\Delta c(\text{CO}_2) = c(\text{CO}_2) (1 - 10 \text{ SI})$
$\Delta c(\text{CO}_2)$ is excess CO_2

Table 69: Application range of N, S and V cement mortar grades according to DIN 2614 [114]
SI is the saturation index according to DIN EN ISO 7887

Type of cement addition	Cement mortar grades*)		
	Centrifugal method	Spinning method	Manual method
	(Method I)	(Method II)	Method III)
Cement according to DIN 1164-10, except HS cements, no addition	I-N	II-N	III-N
HS cements according to DIN 1164-10, no addition	I-S	II-S	III-S
Aluminous cement according to BS 4550-6 no addition	I-T	II-T	III-T**)
Cement according to DIN 1164-10, cement liquefier (CL)	I-V	II-V	III-V
Cement according to DIN 1164-10, plastic dispersion	I-K	II-K	III-K

*) see Table 69 for the application range

**) for mortar used in repairs plastic dispersion is generally added: III-TK

Table 70: Cement mortar grades according to DIN 2614 [114]

In addition, it should be pointed out that studies in 1930 already showed that de-calcified and completely carbonated CM layers do not lose their corrosion protection in the wet state [122]. The reason for this behavior lies in the low diffusion of oxygen through wet CM layers.

Cracks and gaps

As well as the resistance of the CM layer, the corrosion behavior of exposed iron surfaces in the region of cracks and gaps in CM linings must be taken into account. Iron surfaces covered by mortar can act as cathodes and thus provide an anodic danger to exposed crevice surfaces.

It was shown in laboratory experiments [116] that anodic cell currents occur in neutral drinking water up to gap widths of 16 mm, but drop to negligibly low values after about 100 days (Figure 53). This drop is partly due to the formation of corrosion products in the gaps. However, the consumption of the oxygen originally present in the CM layers has a considerable influence [123]. The amount of oxygen reaching the iron surface by diffusion through the wet CM layer is so low in proportion that the cathodic action can be ignored after some time.

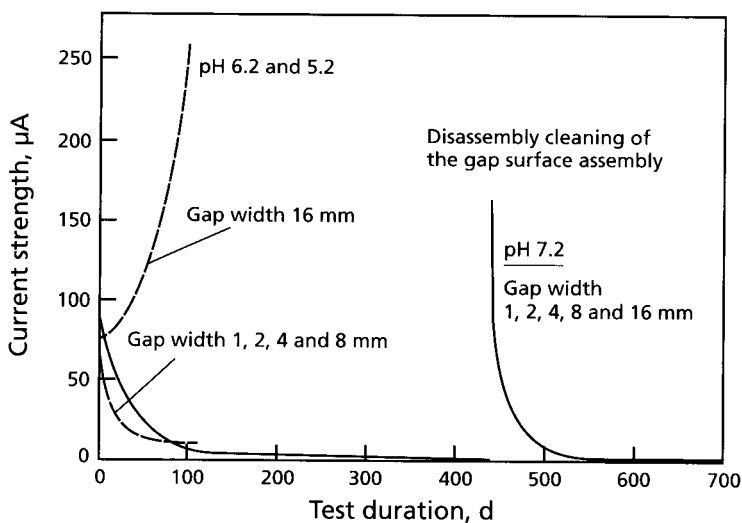


Figure 53: Cell currents in gap studies according to [116]

In the above-mentioned experiments in practice, only mild general corrosion at a corrosion rate of 50 µm/a occurred in the soft water sample no. 4 containing no CO₂ at a gap width of 20 mm. The soft water sample no. 5 with a high carbonic acid content showed no corrosive attack at gaps 2 mm wide, which can be attributed to the oxygen consumption. On the other hand, pitting (0.2 mm/a; 7.8 mpy) occurred in gaps of 8 and 16 mm width in this water, these evidently being due not to cell formation, but to self-corrosion (Table 71) [116].

Water no. according to table 56	Nominal diameter operating conditions test duration	Gap width, mm	Observations
4	ND 300 $v = 1 \text{ m/s}$ 2 years	20	uniform general corrosion $\sim 0.05 \text{ mm/a}$ (2 mpy)
5	ND 100 $v = 1 \text{ m/s}$ 13 months	2.8 and 16	at 2 mm no measurable corrosion; isolated pitting at 8 and 16 mm $\sim 0.2 \text{ mm/a}$ (8 mpy)

Table 71: Field tests on gaps in the CM layer [116]

Laboratory experiments [124] in static water show that the duration of crack healing depends on crack width and the Q_c value (see Figure 54). Data on the tensile strength of healed, cracked mortar samples (Table 72) show that healing leads to remarkably high tensile strengths in the case of “cracks which have closed up” in water which is not too soft [117].

On the basis of the results reported, continuous cracks of up to 1.5 mm are approved for drinking water in DIN 2614 [114].

Hygiene requirements

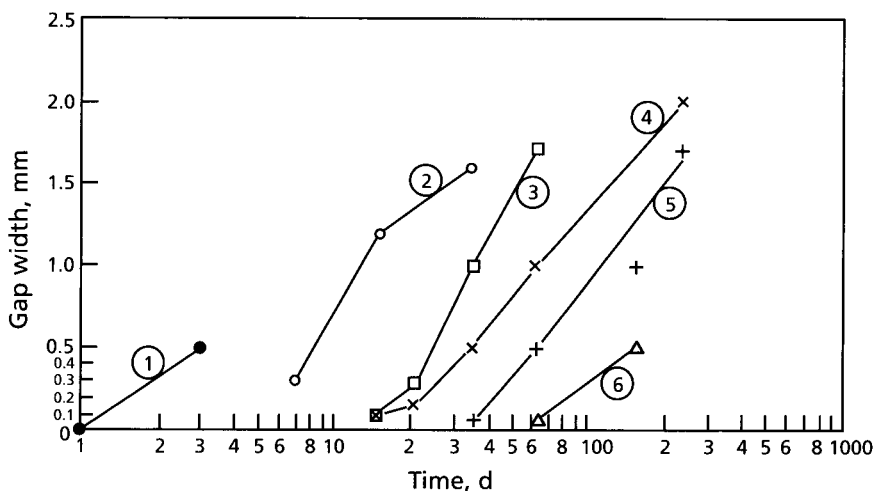
The microbiological behavior of CM linings containing organic additives must be tested in accordance with [11]. According to [125], no general, macroscopically perceptible organism growth has yet been found.

Water parameters	Gap width mm	Duration of exposure months	Tensile strength N/cm^2
Drinking water $Q_c = 5.5 \text{ mol/m}^3$ $c(\text{Ca}^{2+}) = 3.5 \text{ mol/m}^3$	0 ¹⁾	1	5
	0	3	14
	0	6	22
	0.2	6	6
	0.5	6	3
	1.0	6	0
Drinking water $Q_c = 5.5 \text{ mol/m}^3$ $c(\text{Ca}^{2+}) = 3.5 \text{ mol/m}^3$ $c(\text{Mg}^{2+}) = 0.08 \text{ mol/m}^3$	0	1	44

1) with gap widths of 0 mm the fissures were close together

Table 72: Tensile strength of healed mortar specimens (blast furnace cement with 0.2 to 3 mm sand, mixing ratio: $v = 3$, kept at 25°C in a week flow of water varying in composition) [117]

Extensive studies to determine chlorine consumption in accordance with the test specifications of the KTW recommendations [12] are described in [126]. The chlorine consumption depends on several influencing parameters, such as, for example, chlorine concentration, volume/surface ratio and type of cement. Figure 55 shows this dependence on the test duration for various types of cement and $R = 40$.



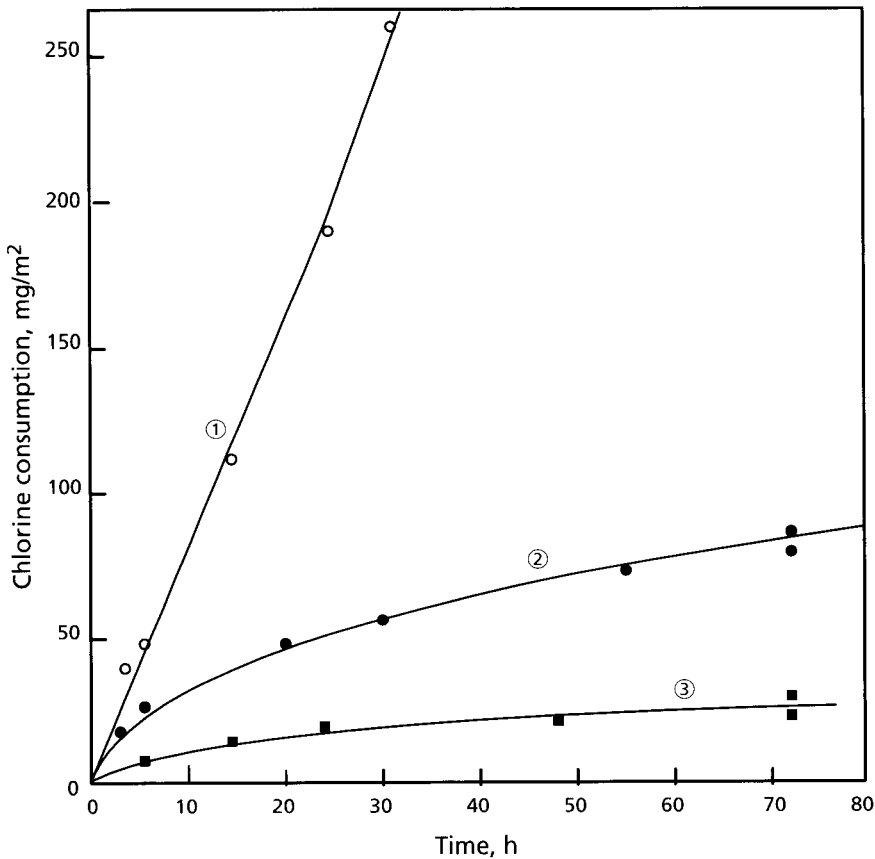


Figure 55: Time dependence of chlorine consumption, $R = 40$ cm [126]

- ① Blast furnace cement
- ② Aluminous cement
- ③ Portland cement

CM lining of buried cast iron and steel pipes

The rules listed in [128] must be observed for this type of lining. Practical experiences are reported in [129, 130], the physiological harmlessness of the additives being referred to, amongst other things. By addition of acrylic resin to the cement mortar, it was possible to produce a CM lining by the centrifugal method which allowed early exposure to water, which is desirable operationally [130]. The pH could be reduced to 7.2 within a short time by frequent rinsing (see Figure 57). Using a mobile chlorine metering unit, it was possible to achieve perfect bacteriological results.

Curve	Water	pH	$K_A 4.3 \text{ mol/l}^3$	$K_A 8.2 \text{ mol/l}^3$	$Q_c \text{ mol/l}^3$	$c(\text{Ca}^{2+}) \text{ g/m}^3$
①	A	9.2	1.00	0.13	0.87	5
②	B	9.2	0.44	0.11	0.33	10
③	water B (pretreatment 7 cycles water A)					

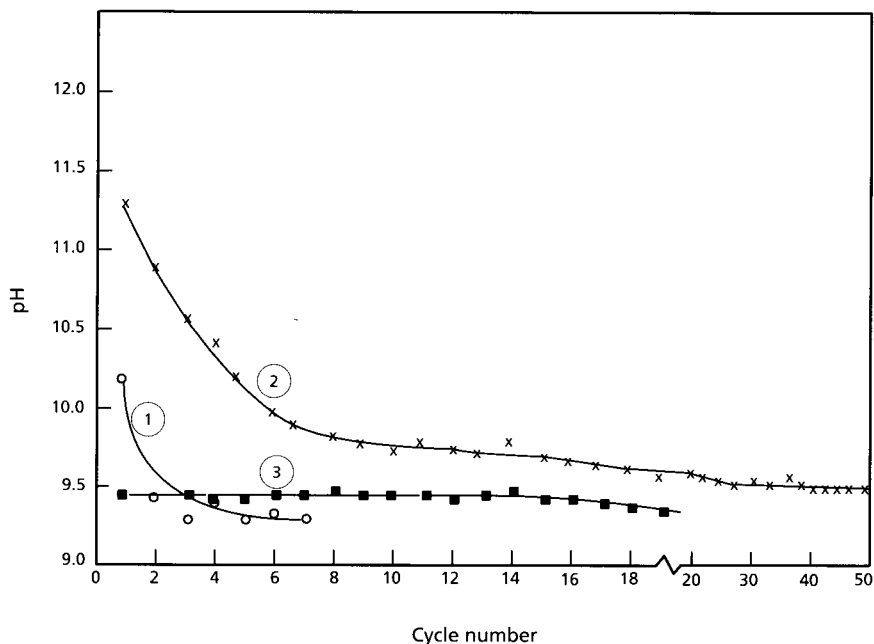


Figure 56: pH after one contact cycle of two waters with different Q_c values (test line 1), $R = 40 \text{ cm}$ [127]

Concrete is used in combination with loose steel reinforcement as reinforced concrete pressure pipes for long-distance water pipelines. The resistance of this steel/concrete composite depends both on the quality of the concrete and on the concrete covering of the steel reinforcement [131]. The dimensions of these pipes are described in detail in [132].

The composite of prestressed steel/concrete is used as prestressed concrete pipes for long-distance water pipelines which are operated under high pressure [133]. Test methods are described in [134] for avoiding corrosive attack on the prestressed steel.

A comprehensive compilation of the various designs of pipes made of steel/concrete composite materials is contained in [135].

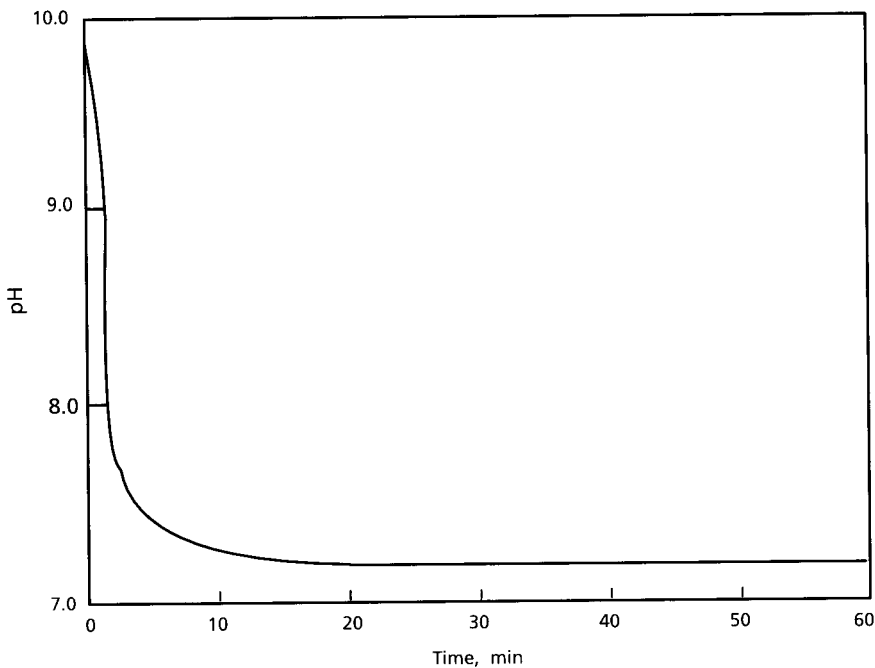


Figure 57: pH change as a function of the rinsing time [130]

B 8 Enamel

Enamel is used for lining water heaters made of unalloyed steel and fittings and shaped pieces of cast iron. Enamelling leads to the formation of composite enamel/ferrous material, the glass and iron interlocking mechanically. Ion exchange also takes place between the iron and enamel-like oxides, leading to internal bonds between the two materials [136]. These bonds cause such a good adhesion that there is no migration underneath, starting from defects in the enamel coating, such as exists, for example, in organic coatings. By defects is to be understood pores which penetrate down to the ferrous material.

Some properties relevant to corrosion have been obtained from various publications and summarized in Table 73.

Good steel enamelling must have the maximum possible resistance to fish-scaling [137, 138]. The weight loss of a corrosion-resistant enamel layer in various corrosive media was investigated in an autoclave experiment, tap water resulting in the lowest corrosion (see Figure 58).

Properties	Values	Literature
Water vapor permeability	$< 10^{-9}$ g/cm h Torr	[136]
Oxygen permeability	$< 10^{-11}$ cm ³ /s cm Torr	[136]
Surface volume resistance	10^{10} to 10^{13} Ω m ²	[139]
Electrical breakdown potential	> 1.5 kV/mm	[139]
Linear coefficient of expansion	10×10^{-6}	[139]

Table 73: Corrosion properties of enamel coatings

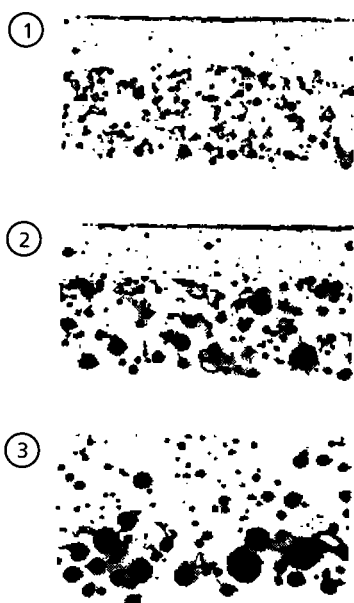


Figure 58: Different enamel structures (30° diagonal cut in the enamelled sheet) [138]

- ① Underdeveloped enamel structure
- ② Well-developed enamel structure
- ③ Enamel structure too coarse

When enamelling the inside of water heaters, the presence of defects must be remembered. At a metallic conduction join to the enamelled tank wall, e.g. with heating inserts of copper or stainless steel, these large-area cathodes can lead to locally severe corrosive attack at small defects [140].

Reliable protection of the inside walls of the tanks of water heaters by combining the internal enamelling with cathodic protection – noting the requirement specified in [141, 142] – is economically possible because of the small area of defects on enamelling and the constant high coating resistance.

In tanks with heating inserts, these must be separated electrically from the tank wall in the case of cathodic protection, since otherwise the protection potential is not reached in all places (Figure 59). Examples of practical implementation of electrical separation and information on the use of potential-controlled inert anodes are contained in [143].

Testing of the release of lead and cadmium from the enamelling in accordance with the KTW recommendations is proposed in [142] in respect of physiological harmlessness. Not more than $0.3 \text{ mg/m}^2 \text{ d}$ lead and $0.03 \text{ mg/m}^2 \text{ d}$ cadmium may be released into the cold water during testing.

The internal enamelling of fittings and shaped pieces of nodular cast iron serves to protect the substrate material from corrosion and to maintain good hydraulic properties. Enamelling of shut-off fittings guarantees their functioning, which is otherwise in doubt due to the formation of corrosion products (encrustations) in the sealing region of the closing body. Materials according to DIN EN 1563 [144] are used for fittings and those according to DIN EN 545 [145] are used for shaped pieces. Construction of the components in a manner suitable for enamelling is an essential prerequisite for fully effective corrosion protection [146].

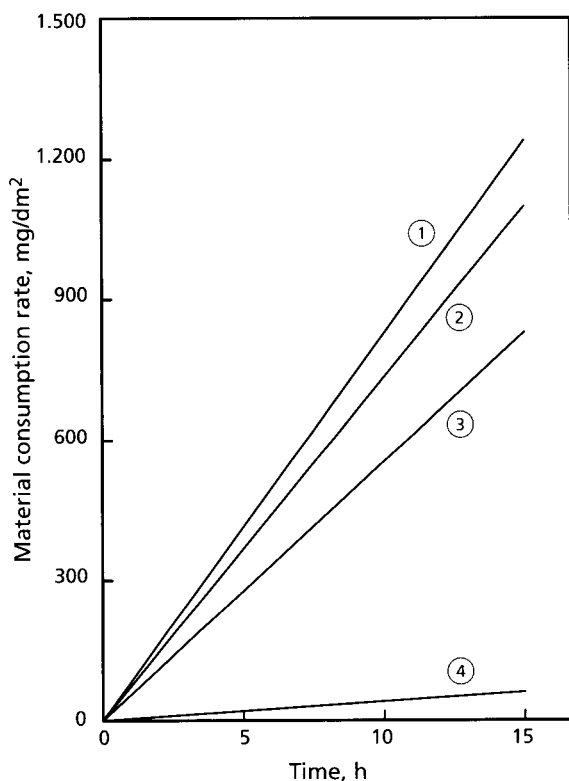


Figure 59: Material consumption on an enamel coating in the autoclave at 428 K (155 °C) [138]

- ① 400 ppm sodium hydrogen carbonate
- ② Chemically softened water
- ③ Distilled water
- ④ Tap water

C

Organic Materials

C 2 Bituminous compositions (bitumen, asphalt, pitch)

Until the sixties, steel pipes for long-distance and distribution lines for water supplies were lined with residual asphalt. Linings based on coal tar pitches were not used for drinking water pipes – because of impairment of the smell and taste of the drinking water. Bitumen lining has been replaced for more than about 35 years by the cement mortar lining described in Section B 4.

Bitumen lining is used in special cases, where the properties of the residual asphalt material according to DIN 30673 [147] should be noted. Coal tar pitch can no longer be used (for environmental reasons [147]).

The thin bitumen lining used for transportation and storage protection [148] has led to difficulties (local penetration) in some types of drinking water and is therefore no longer included in [147].

Where filled bitumen is used for internal linings, the type of filler is of importance – as can clearly be seen from Figure 60 [149]. The use of gypsum as a filler, for example, must be excluded, since the water uptake is unacceptably high and leads to premature failure of the bitumen lining.

To avoid blistering in the lining, a pressure of 0.2 MPa may not be exceeded in the test for tightness to compressed air. The gas diffusing in leads to blistering when the pressure is released; blisters can also be formed in the same way in water of very high CO₂ content of > 1000 mg/l [150].

If pipes are taken out of service, they must be prevented from drying out to avoid cracking in the bitumen lining [151].

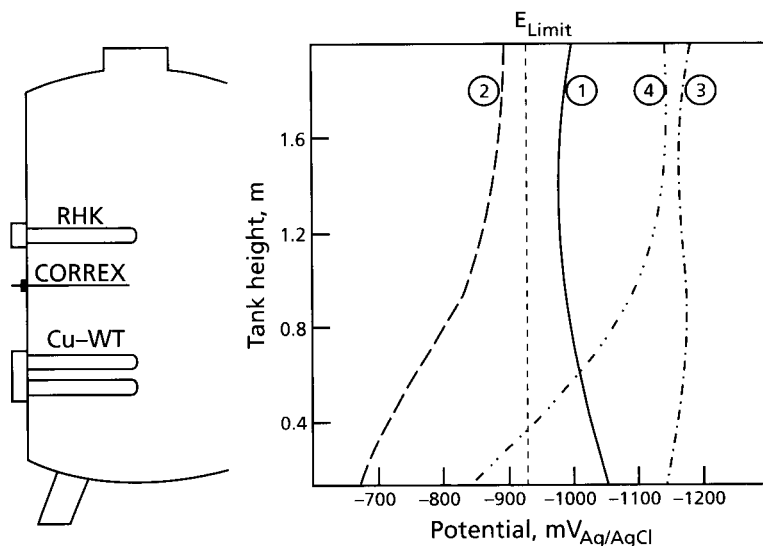


Figure 60: Course of the potential in a 250 l heat pump storage tank, reference potential = $-1350 \text{ mV (E}_{\text{Ag/AgCl}})$ [143]

a) conductivity: $130 \mu\text{S/cm}$, $293 \text{ K (20}^\circ\text{C)}$, ① Cu-WT isolated, $i = 16.2 \text{ mA}$, ② Cu-WT not isolated, $i = 30.2 \text{ mA}$, $T = 333 \text{ K (60}^\circ\text{C)}$

b) conductivity: $1040 \mu\text{S/cm}$, $293 \text{ K (20}^\circ\text{C)}$, ③ Cu-WT isolated, $i = 36.8 \text{ mA}$, ④ Cu-WT not isolated, $i = 107 \text{ mA}$, $T = 323 \text{ K (50}^\circ\text{C)}$

C 7 Polyolefins and their copolymers

C 8 Polyvinyl chloride and its copolymers

Of these groups of materials, pipes made of LDPE (flexible polyethylene), HDPE (rigid polyethylene), rigid PVC (rigid polyvinyl chloride) and VPE (crosslinked HDPE) are widely used as distribution lines, and especially as domestic connecting pipelines [13, 14]. The properties of these pipes (called plastic pipes below) are summarized in Table 74. The plastics listed are resistant to drinking water without limitation [152]. The chlorine dissolved in the water also has no adverse influence on the creep strength (Figure 61), as testing at $353 \text{ K (80}^\circ\text{C)}$ shows. The plastic pipes must comply with the KTW recommendations [15] to maintain the hygiene requirement. The microbiological harmlessness must, moreover, be demonstrated in accordance with [14].

If plastic pipes are laid in contaminated soils, organic substances and gases may reach the drinking water by diffusion through the plastic and under some circumstances have an adverse influence on water quality. The diffusion of methyl bromide, which is used for disinfection in market gardens, may be mentioned as an example (see Figure 62).

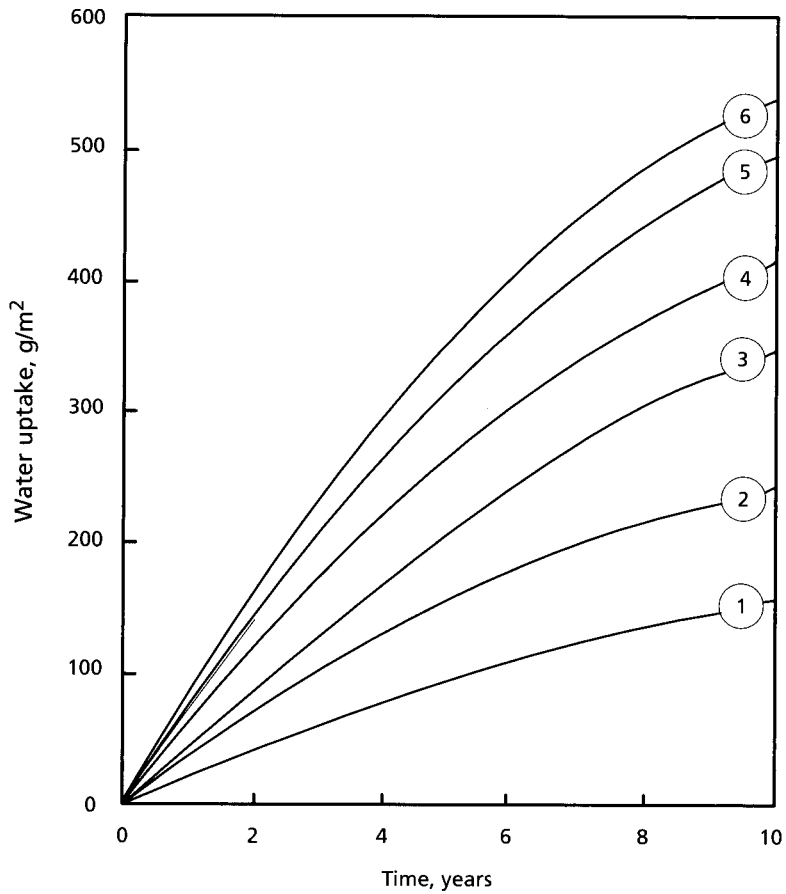


Figure 61: Water uptake by mixtures of 70 % blown bitumen 115/15 and 30 % filler in tap water [149]

- ① Pure bitumen
- ② With ground slate addition
- ③ With fine asbestos addition
- ④ With cement addition
- ⑤ With limestone powder addition
- ⑥ With gypsum addition

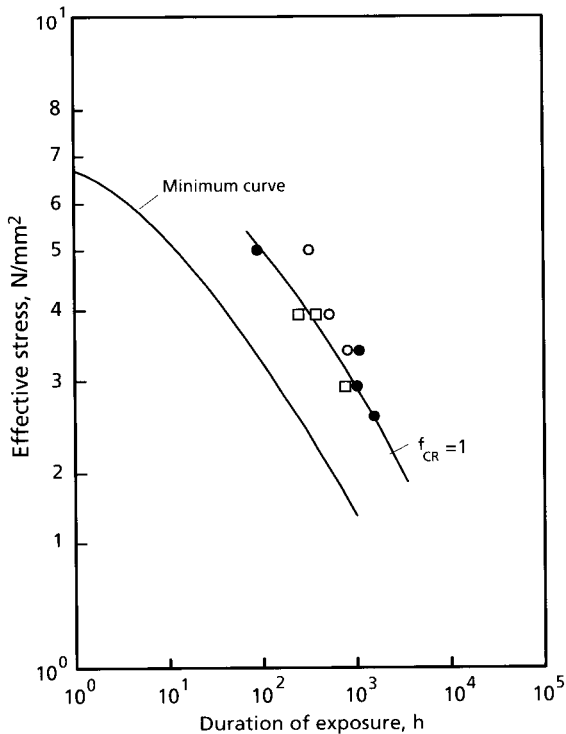


Figure 62: Creep strength of HDPE pipes (Hostalen® GM 5010) under the influence of water and chlorine dissolved in water at 358 K (85°C) [152]

- Water
- Chlorine dissolved in water
- Chlorine dissolved in water (butt-welded pipes)

Table 75 provides information on the specific gas permeability. According to [152], if plastic pipes are laid in contaminated soils, it is advisable to provide them with a diffusion barrier, e.g. an aluminium casing, or to insert them in protective pipes.

Properties	Units	Test method	Rigid PVC	LDPE	HDPE
Density	g/cm ³		≈ 1.4	≈ 0.93	≈ 0.94
Mechanical properties					
Yield stress	N/mm ²	DIN EN ISO 527	55	11	18
Elongation at yield stress	%	DIN EN ISO 527	5	20	
Elongation at break	%	DIN EN ISO 527	20	1000	700
Bending strength limit	N/mm ²	DIN EN ISO 178	95	21	23
Elastic modulus	N/mm ²	DIN EN ISO 604	3000	200	≈ 700

Table 74: Material properties of plastic pipes [152]

Table 74: Continued

Properties	Units	Test method	Rigid PVC	LDPE	HDPE
Impact strength when notched (296 K (23 °C), 50% relative humidity)	kJ/m ²	DIN EN ISO 179	4	– not broken –	
Impact strength (296 K (23 °C), 50% relative humidity)	kJ/m ²	DIN EN ISO 179	– not broken –		
Thermal properties					
Crystallite melting point	K		–	383	397 – 405
Thermoforming resistance according to Vicat, Method B	K	DIN EN ISO 75	353	303	331
Linear coefficient of expansion	K ⁻¹	DIN ISO 7991	0.8×10^{-4}	2×10^{-4}	2×10^{-4}
Thermal conductivity	W/mK	DIN 52612	0.15	0.34	0.41
Water uptake	mg/4d	DIN EN ISO 62	1		
Electrical properties					
Specific volume resistance	Ω cm	DIN IEC 60167	$> 10^{16}$	$> 10^{17}$	$> 10^{18}$
Surface resistance	Ω	DIN IEC 60167	$> 10^{12}$	$> 10^{12}$	$> 10^{14}$

Table 74: Material properties of plastic pipes [152]

Material	Specific gas permeability in dm³ mm/m² a bar						
	Air	N₂	O₂	H₂	CO₂	CH₄	C₂H₄
PVC	0.4	0.1	1.2	29	2.4		
HDPE	12	7.2	24	84	96	19	31
LDPE	24	19	62	180	240	72	120

Table 75: Specific gas permeability of plastics [152]

Controlled quality assurance is a prerequisite for the good resistance of plastic pipes and is described in detail in DVGW worksheets W 320 [153] and W 531 [154].

If pipes made of rigid PVC are used in buildings, W 328 [155] must be noted. According to [156], the burning properties of these pipes present the main problem.

D

Materials with special properties

D 1 Coatings and linings

Lining steel pipes for domestic installations with plastic has not found acceptance in practice. This is due to the fact that pipes with diameters of less than 50 mm cannot be lined [157]. Adhesion difficulties, moreover, occur in practice at steel pipe/fitting transitions when the pipes are disconnected.

In contrast, drinking water tanks are often lined. The plastics used here must comply both with corrosion and hygiene requirements [158]. Initial tests in this respect were carried out on 30 different epoxy resin varnishes [159].

Internal lining of pressurized tanks in waterworks (cold water) with thermoplastics, thermosets and elastomers is described comprehensively in [160], possible blistering as a result of solvent retention being pointed out, amongst other things.

Hot water tanks can be lined with plastics based on phenolic resins or epoxy resins as a stove enamel [161]. According to [162], however, studies have shown objections since the coating resistance r_u falls from initially very high values to values of about $10^3 \Omega \text{dm}^2 = 10 \Omega \text{m}^2$ after a relatively short time (see Figure 63).

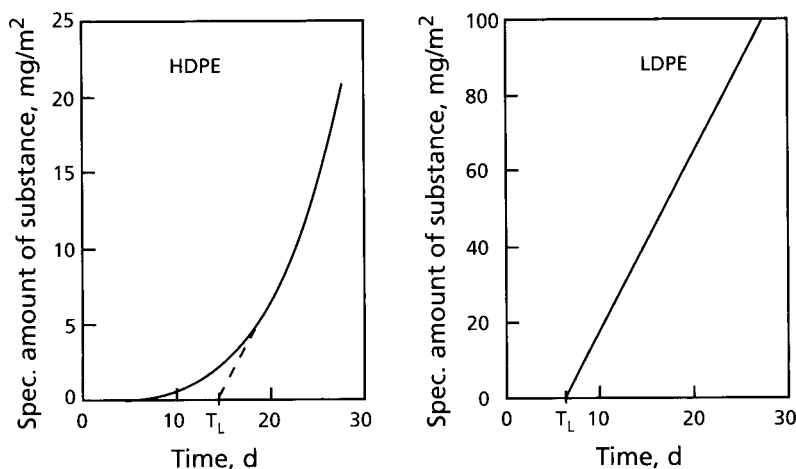


Figure 63: Diffusion of methyl bromide through LDPE and HDPE pipes [152]

Coated steel surfaces of $r_u < 10^5 \Omega \text{ m}^2$ can act as large-area cathodes which lead to intense anodic dissolution processes on the steel at small defects in the coating [163]. If cathodic corrosion protection is used, this cell formation can be avoided, but it must then be ensured that no severe blistering due to electroosmosis occurs.

D 5 Natural and synthetic elastomers

The connections on pipes made of ductile cast iron are sealed with rubber. Sealing rings made of natural rubber are preferably used here in pipes for drinking water supply lines.

Rubber has a chemical resistance to all types of drinking water. To achieve a long-term sealing effect, some properties are subject to requirements, these being summarized in Table 76 in accordance with DIN 28617 [164]. As well as mechanical properties such as hardness, tensile strength, elongation at break, compression set and stress relaxation, the aging properties must be taken into account [165].

Testing for ozone resistance should ensure that no cracks occur from the UV radiation of the sun (light-induced cracks) during exposure of the rings. To prevent substances which can migrate from the rubber rings into the drinking water from having an adverse influence on the water, these rings must comply with the conditions of the KTW recommendations [166].

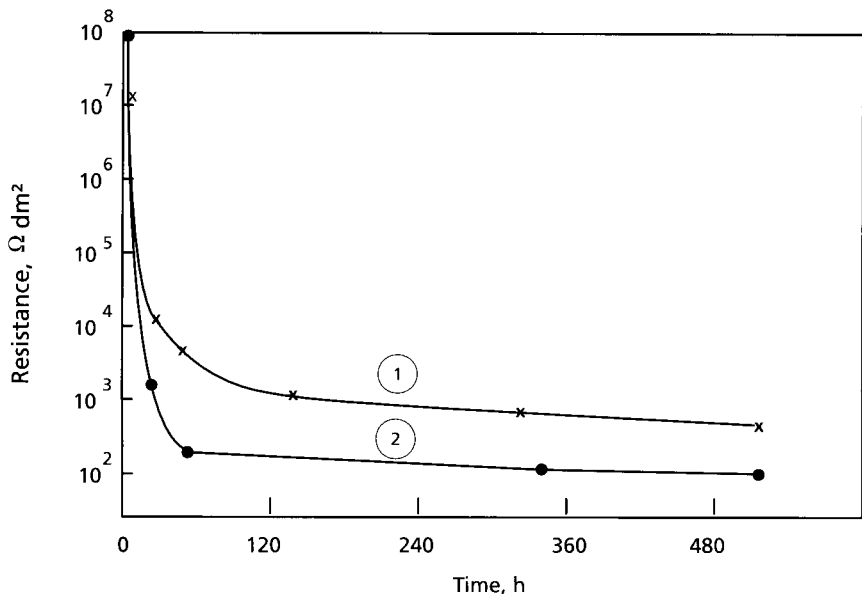


Bild 64: Resistance/time curves of a hot water-resistant stove enamel; exposure conditions: fully demineralized water at 363 K (90 °C) [162]

① With direct current

② Without direct current

If sealing rings made of synthetic rubber (e.g. with protective caps) are used for certain applications, they must be tested appropriately in accordance with DIN 3535-1 [167]. According to [168], synthetic rubbers based on styrene/butadiene rubber, nitrile rubber, polychloroprene rubber and EPDM rubber or blends of these materials are used (Figure 64).

Pipelines made of asbestos cement and reinforced concrete pipes also have connections sealed with rubber. The sealing rings used comply with DIN 4060 [169], which deals with prevention of roots growing through, as well as the material properties [162].

Properties	Units	Requirements		
		Soft mixture		Hard mixture
		Screwed fitting	Conduit glands and socket joints	
Hardness	shore-A	50 ± 5	55 ± 5	85 ± 5
Tensile strength	N/mm ²	≥ 17		≥ 10
Elongation after fracture	%	≥ 500		≥ 160
Compression set				
	at 263 K (-10 °C)	%	≤ 20	≤ 50
	at 296 K (23 °C)	%	≤ 7	≤ 20
	at 343 K (70 °C)	%	≤ 30	≤ 40
Stress relaxation	%	≤ 20		–
Ozone resistance	cracks	maximally step 1		maximally step 2
Properties after ageing				
	change in hardness	shore-A	≤ 6	≤ 6
	change in tensile strength	%	≤ 25	≤ 25
	change in elongation after fracture	%	≤ 25	≤ 40
Properties after cold test				
	change in hardness	shore-A	≤ 6	≤ 10

Table 76: Properties of rubber sealing rings used on ductile cast iron pipes according to DIN 28617 [178]

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Waste Water (Municipal)

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	Page		Page
Survey Table	140	B 5	Acid-resistant building materials and binders (putties) 198
Introduction	142	B 6	Glass 199
A Metallic materials	156	B 7	Quartz materials and quartz glass 199
A 2 Aluminium	156	B 8	Enamel 200
A 3 Aluminium alloys	156	B 9	Porcelain 202
A 14 Unalloyed steels and cast steel	158	B 10	Stoneware 202
A 15 Unalloyed cast iron	160		
A 18 Ferritic chromium steels with more than 12% chromium	165	C Organic materials	205
A 19 Ferritic-austenitic steels with more than 12% chromium	165	C 2	Bituminous compositions (bitumen, asphalt, pitch) 205
A 20 Austenitic CrNi steels	165	C 7	Polyolefins and their copolymers 205
A 21 Austenitic CrNiMo(N) steels	165	C 8	Polyvinyl chloride and its copolymers 205
A 22 Austenitic CrNiMoCu(N) steels	165	C 11	Acrylic resins 208
A 33 Lead and lead alloys	170	C 14	Polyesters 209
A 39 Zinc, cadmium and their alloys	170		
B Non-metallic inorganic materials	172	D Materials with special properties	211
B 1 Fibre concrete (asbestos)	172	D 1	Coatings and linings 211
B 2 Natural rock	174	D 2	Seals and packings 214
B 4 Binders for building materials (e.g. mortar and concrete)	174	D 5	Natural and synthetic elastomers 214
		Bibliography	219

Survey Table

The evaluation of the corrosion behavior of the individual materials is based on practical experience and conditions described in the text. Only those materials have been taken into account which usually come into contact with waste water.

Material Type No.	Behavior*	Material Type No.	Behavior*
A	Metallic materials	B5	Acid-resistant building materials and binders (putties) +
A2	Aluminium + to –	B6	Glass + to –
A3	Aluminium alloys + to –	B7	Quartz ware and quartz glass + to –
A14	Unalloyed and low-alloy steels/ cast steel ⊕ to –	B8	Enamel +
A15	Unalloyed cast iron and low-alloy cast iron + to –	B9	Porcelain +
A18	Ferritic chromium steels with more than 12% chromium + to –	B10	Stoneware +
A19	Ferritic-austenitic steels with more than 12% chromium + to –	C	Organic materials
A20	Austenitic CrNi steels + to –	C2	Bituminous compositions (bitumen, asphalt, pitch) –
A21	Austenitic CrNiMo(N) steels + to –	C7	Polyolefins and their copolymers +
A22	Austenitic CrNiMoCu(N)-steels + to –	C8	Polyvinyl chloride and its copolymers +
A33	Lead and lead alloys + to –	C11	Acrylic resins +
A 39	Zinc, cadmium and their alloys + to –	C14	Polyesters +
B	Non-metallic inorganic materials	D	Materials with special properties
B1	Asbestos (substitute materials) + to –	D1	Coatings and linings + to –
B2	Natural rock –	D2	Seals and packings +
B4	Binders for building materials (e.g. concrete, mortar) + to ⊕		

* + resistant ⊕ fairly resistant – not resistant

Warranty disclaimer

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Even for the correct selection of materials and correct processing, corrosive attack cannot be excluded in a corrosion system as it may be caused by previously unknown critical conditions and influencing factors or subsequently modified operating conditions.

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Introduction

Waste water is defined as drainage water which has been changed by utilisation and all that which flows into a sewerage system [1].

Types of waste water include:

- sanitary sewage
- storm water
- infiltrating water
- combined water
- cooling water.

The behavior of materials in waste water systems is influenced by the composition of the water, the construction and the operating conditions, such as the temperature and flow rate.

In selecting materials it must be taken into account that e.g. in the case of operating faults, there may be unintentional release of harmful substances in different amounts and concentrations into the sewerage system.

Construction components of estate drainage systems within buildings, such as pipes, fittings and pipe couplings for the connection, transporting and collection pipelines must be suitable for a maximum waste water temperature of 368 K (95 °C) at an ambient temperature of 283 K (10 °C). The corresponding usability is checked in a system test under cyclic and continuous loading conditions [2].

For underground waste water sewers and pipelines, the pipes, fittings and pipe connections must be suitable for diameters

up to ND 350 for water temperatures of 318 K (45 °C)

up to ND 400 for water temperatures of 308 K (35 °C)

at an ambient temperature of 283 K (10 °C) [3]. If process waste water has a higher temperature, then it must be cooled before it is discharged into the public waste water system.

In the case of plastic pipes, for example, the waste water temperature is decisive for the choice of material and its service life. For other materials, an increased attack of the material must be assumed at higher temperatures.

In components installed underground, particularly gravity-flow sewers, the temperature of both the waste water and the air space has a marked influence on the

biogenic corrosion reactions occurring on the sewer walls above the level of the water.

To maintain aerobic conditions and to avoid the formation of deposits, the flow conditions (flow rate and gradient) are particularly important in waste water pipelines. Therefore, for the different types of pipes used for estate drainage, minimum gradients which depend on the individual nominal diameter are specified in [4].

Behavior of materials

During transport of mixtures of water and solids, as is usual in waste water sewers and pipelines, abrasion occurs in the region of the bottom of the pipe as a result of the action of the solids in the waste water. This abrasion depends on the

- pipe material
- pipe diameter
- flow rate
- density, grain size and strength of the material.

Particularly in steep and bent sections, abrasion must be expected. Very different testing procedures have been proposed to determine the abrasion behavior, e.g. Böhm's disk, sand-blast test, and the Bauch test. The most widely used test is the so-called Darmstadt procedure of Kirschmer [5].

Table 1 gives values of the abrasion of various types of pipes after 400,000 stress cycles.

Type of pipe	Abrasion after 400,000 stress cycles, mm
Concrete pipe from various manufacturers and in various qualities	0.25 x 2.00
Stoneware, medium quality	0.40 x 0.60
Stoneware, best quality	0.20 x 0.30
Stoneware, poor quality	up to 2.40
Asbestos cement	0.20 x 8.50
Various types of coatings	0.50 x 1.50
Glass fibre-reinforced plastic, according to type and position of reinforcement	0.75 x 2.40
PVC	0.55 x 0.80
Polymer concrete	0.30 x 0.50
Plexiglas® (only for comparison)	0.20 x 1.00
Pitch-coated-fibre pipes	no. of stress cycles not attained

Table 1: Abrasion after 400,000 stress cycles for various types of pipes [6]

In spite of careful planning and execution, maintenance of the pipelines cannot be avoided. It is not always possible to select the cross-section and the gradient of the pipes so that the flow rates are always sufficient under the changing flow conditions to avoid the formation of deposits and their subsequent removal by cleaning.

Nowadays, high-pressure flushing is used almost exclusively for the cleaning of waste water pipelines. This cleaning process serves to remove any deposits and blockages and is also a preparatory measure for pipeline inspections and, if necessary, for repairs.

Corrosion behavior

In waste water installations, the components are loaded by the waste water on the inside (e.g. pipes) as well as on the outside (e.g. air-inlet pipes, scrapers). The functioning of metallic pipes is influenced by local attack (dimple and pitting corrosion). Uniform surface corrosion generally plays a secondary role. A site particularly susceptible to local corrosion is the area close to an electrically conducting contact of different metals (contact corrosion).

A macroelement arises if metals with different corrosion potentials are in metallic and electrolytic contact with one another. Therefore, the following protective measures are recommended:

- use of materials with similar corrosion potentials
- galvanic separation of the structures with differing corrosion potentials or
- cathodic protection.

This can be realised most simply in new installations by galvanic separation using insulating intermediate layers, insulating flanges or insulating components [7].

Many metals are susceptible to microbiologically induced corrosion. Damage has been observed of unalloyed steels as well as high-alloy CrNi steels. Damage is also known for copper and copper alloys as well as aluminium. Titanium is less susceptible to microbiologically induced corrosion; however, it offers favorable conditions for biofouling [8].

Biogenic sulfuric acid corrosion (BSAC) in partially filled sewer pipelines made of concrete is described in detail in Section B 4.

Corrosive attack of plastics is possible as a result of high concentrations of solvents in the waste water (chlorinated hydrocarbons). The risk of the migration of plasticizers in plastics must be taken into account. Stress cracking must also be expected for plastics.

Summary of the behavior of materials

According to [9], waste water installations can be classified into the following main areas:

Area 1:

- estate drainage

- sanitary equipment
- domestic sanitary sewage and storm water without commercial and industrial sewage.

Area 2:

- waste water discharge from estates into waste water treatment plants.
This includes gravity-flow and forced-flow pipelines as well as special facilities, e.g. pumping and lifting plants, storm water storage basins, storm water overflows.

Area 3:

- mostly concrete basins, steel tanks, equipment and connecting pipelines.

For each of these three areas there are a number of materials that can be used for the components. Tables 2 and 3 provide information on the range of application of various materials. Further information for the selection of materials as well as criteria for the choice of the method to use for remediation and rebuilding of sewers are given in [10] and [11].

Table 4 shows an evaluation scheme for the different materials used in sewers [11]. Both the chemical and mechanical stresses as well as constructive requirements are weighted according to practical values.

A summary of the service life of facilities and installations in waste water treatment plants is given in Tables 5 and 6 [12, 13].

Area of application	Material
Area 1	
Estate drainage	
Sanitary equipment, e.g.	
bath tubs	steel and cast iron, plastics (e.g. PMMA)
drains	stainless steel
wash-basins	porcelain
sinks	fireclay
pressure flushers	brass
Domestic sewage and storm water drainage in buildings, e.g.	
drains in cellars, roofs and floors	cast iron
pipelines	hard PVC
Facilities used for estate drainage, e.g.	
basins and lifting plants	concrete, reinforced concrete, steel with coatings

Table 2: Use of materials for equipment and pipelines for estate drainage [9]

Area of application	Material
Area 2	
Pipelines from estate drainage to waste water treatment plants	
gravity-flow sewers and pipelines	brickwork in-situ concrete concrete, reinforced concrete, pre-stressed concrete, fibre concrete stoneware plastics, PVC, PE, FRP ductile cast iron with cement mortar lining steel with cement mortar lining
forced-flow pipelines	ductile cast iron with cement mortar lining steel with cement mortar lining reinforced concrete, pre-stressed concrete plastics, PVC, PE, FRP
Special facilities	concrete facilities made of coated iron materials
Area 3	
Waste water treatment plants	coated and uncoated concrete coated and uncoated metallic materials pipelines made of materials listed under Area 2

Table 3: Use of materials for pipelines between estate drainage and waste water treatment plants as well as the waste water treatment plants themselves [9]

Pipe material		Resistance to chemical loading*	Resistance towards mechanical loading			Connections to house and road drains	Total score
			Abrasion cleaning equipment	Settling, earth movement, traffic stress	Transport, installation, compaction		
Weighting, %		30	20	30	10	10	100
Stoneware pipes	open construction				6	8	740
	propulsion	10	9	4	6	7	730
	burst lining				4	6	700
HDPE pipes	open construction				8	8	810
	sewage/roll-down	9	9	6	8	5	760
	relining				9	5	770
	burst lining				7	5	780
FRP pipes	open construction				9	7	800
	propulsion	9	8	7	8	5	780
	relining				8	5	780
Ductile cast iron	open construction	8	8	10	9	8	870
PVC pipes	open construction				8	7	710
	propulsion	8	7	6	8	6	700
	rib-loc etc.				7	4	670
Polymer concrete pipes	open construction				9	8	830
	propulsion	8	9	8	9	6	810
	burst lining				8	6	800
Concrete/reinforced concrete pipes (FRP)	open construction	7	8	9	9	7	800
In-situ pipes	tube relining	8	7	7	8	5	720
Brickwork	open construction	6	7	5	8	8	630

* loading by e.g. acids, solutions, salts, solvents, vapors, corrosion internal and external etc.

Table 4: Evaluation scheme for different pipe materials used in sewers. Evaluation using scores between 1 (very poor) and 10 (very good) [11]

Plant component – installation	Service life years	Material/specification or commercially available realization	Function, environmental conditions
Canalisation system			
Sewers			
Estate drainage	50 – 60	cement pipe stoneware, fibre cement, plastic	transport of raw waste water
Industrial plants	50 – 60	(applies to estates and industry)	vapors, gases, pH
Local canalisation	50 – 60	SBR, in-situ concrete B35/25	vapors, gases, pH
Shafts	50 – 60	in-situ concrete, prefabricated concrete elements, fibre concrete, cement mortar	vapors, gases, pH
Overflow constructions	50 – 60	in-situ concrete B35/25 + cement mortar	vapors, gases, pH
Stormwater basins	50 – 60	in-situ concrete B35/25 + cement mortar	vapors, gases, pH
Pumping installations	50 – 60	in-situ concrete B35/25 + cement mortar	vapors, gases, pH
		brickwork	atmospheres
		cladding elements	atmospheres
Electromechanical equipment			
Screw pumps	20 – 25	steel, coated	transport of waste water
Centrifugal pumps	15 – 20	cast steel, coated	
Driving motors	12 – 17	starter and protection system according to application	
Electrical installation	20 – 25	(in-house techniques)	
Electrical controls	12 – 17	low-voltage cabinets	dry rooms
Pipelines	20 – 25	steel, galvanised; stainless steel*; plastics	raw waste water
Fittings (sliding valves etc.)	20 – 25	standard commercial	vapors, gases, pH
Shut-off valves	20 – 25	standard commercial	vapors, gases, pH

1) stator rubberised; rotor, stainless steel or rubberised

2) swimming gas holder in the water lute, Neopren® bellows for dry gas tanks or polyamide airbag

3) service life depends on the rotation speed

* increased susceptibility to concrete corrosion in areas ± 0.5 m over the water level, especially for soft drinking water

Recommendation: increase the amount of cement by approx. 25 kg/m^3 in this area

** with internal coating based on tar-pitch and epoxide resins, at least in the gas zones.

Table 5: Service life of facilities and installations in waste water treatment plants [12]

Table 5: Continued

Plant component – installation	Service life years	Material/specification or commercially available realization	Function, environmental conditions
Manhole covers	50 – 60	steel, cast iron	vapors, gases, pH
Access ladders	15 – 20	steel, cast iron	vapors, gases, pH
Handrails	20 – 25	steel, galvanised; stainless steel*	vapors, gases, pH
Gratings, checker plates	20 – 25	steel, galvanised; stainless steel*	vapors, gases, pH
Spillways	20 – 25	steel, galvanised; stainless steel*	vapors, gases, pH
Waste water treatment plants			
Supporting structures			
Raking equipment	25 – 30		raw waste water
Sand – oil trap	25 – 30		raw waste water
Settling tank	25 – 30		raw waste water
Aeration tank*	25 – 30		$\geq 2 \text{ mg/l O}_2$
Percolating filter*	25 – 30		$\geq 10 \text{ mg/l O}_2$
Immersed percolating filter*	25 – 30		
Sedimentation tank*	25 – 30		$\geq 0 \text{ mg/l O}_2$
Sludge stabilisation	25 – 30	in-situ concrete B35/25	$\geq 0 \text{ mg/l O}_2$
Sludge thickener**	25 – 30	cement mortar coatings on the floor and inclined surfaces	
Digestion tank**	25 – 30		anaerobic, pH > 7.0
Sludge collecting tank**	25 – 30	iron covering = 4 cm	anaerobic, pH > 7.0
Return flow reservoir**	25 – 30		septic water
Gas tank (water lute)	25 – 30		

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** with internal coating based on tar-pitch and epoxide resins, at least in the gas zones.

Table 5: Service life of facilities and installations in waste water treatment plants [12]

Table 5: Continued

Plant component – installation	Service life years	Material/specification or commercially available realization	Function, environmental conditions
Filter plant*	25 – 30		$\geq 2 \text{ mg/l O}_2$
Machine house	25 – 30		
Plant building	25 – 30		
Works pipeline	25 – 30		
Gutter	25 – 30		
Mechanical installations			
Screw pumps	20 – 25	steel, coated	waste water transport
Centrifugal pumps	15 – 20	cast steel, coated	transport of waste water
Piston pumps	15 – 20	cast steel, coated	service water and sludge
Eccentric screw pumps ¹⁾	15 – 20	cast steel, coated	
Dosing pumps	15 – 20	stainless steel (> 2% Mo); steel, rubberised etc.	chemicals
Raking machines	20 – 25	steel, coated, stainless steel	raw waste water
Raked material compactor	20 – 25	steel, coated	raw waste water
Raker for sand collector	20 – 25	steel, coated	raw waste water
Sand grader	20 – 25	steel, coated	raw waste water
Paddle	20 – 25	steel, coated	raw waste water
Sludge scraper installation	20 – 25	steel, coated	fresh sludge
Ventilation turbines	20 – 25	steel, coated	raw waste water
Giant rotors	20 – 25	steel, coated, stainless steel	raw waste water
Flocculator	20 – 25	steel, coated	raw waste water

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Recommendation: increase the amount of cement by approx. 25 kg/m^3 in this area

** with internal coating based on tar-pitch and epoxide resins, at least in the gas zones.

Table 5: Service life of facilities and installations in waste water treatment plants [12]

Table 5: Continued

Plant component – installation	Service life years	Material/specification or commercially available realization	Function, environmental conditions
Ventilator and turbocompressor	20 – 25	cast steel	air
Compressors for air	20 – 25	cast steel	air
Compressors for gas	20 – 25	cast steel	sewer gas
Rotary sprinklers	20 – 25	steel, galvanised; stainless steel	raw waste water
Wrapping reel	20 – 25	plastic; steel, coated	raw waste water
Chain raker	20 – 25	steel; plastic	treated waste water
Suction pipe raker	20 – 25	steel, coated	treated waste water + sludge
Sludge sieve	20 – 25	cast steel, coated	fresh sludge
Sludge sanitisation	20 – 25	steel, galvanised; stainless steel	fresh sludge
Screw-type pump	15 – 20	steel, coated	digested sludge
Surface scum breaker	15 – 20	steel, coated	digested sludge
Gas tank ²⁾	15 – 25	steel, coated; plastic	foul gas
Heating furnace	15 – 20	cast steel	gas/oil
Gas motors	15 – 20	cast steel	foul gas
Heat pumps	15 – 20	steel, coated	treated waste water
Thickener-clarification	20 – 25	steel, coated	fresh or digested sludge
Sludge dewatering			
– Centrifuges	15 – 20	steel, partly coated	activated sludge, digested sludge
– Manual sieve presses	20 – 25	steel, partly coated	activated sludge, digested sludge
– Chamber filter presses	20 – 25	steel, partly coated	activated sludge, digested sludge

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Recommendation: increase the amount of cement by approx. 25 kg/m^3 in this area

** with internal coating based on tar-pitch and epoxide resins, at least in the gas zones.

Table 5: Service life of facilities and installations in waste water treatment plants [12]

Table 5: Continued

Plant component – installation	Service life years	Material/specification or commercially available realization	Function, environmental conditions
Flocculant treatment			
– Stirrers	20 – 25	steel	
– Pumps	20 – 25	cast steel, coated	polyelectrolyte
– Tanks	20 – 25	plastic	
Ventilation equipment			
– Ventilators	20 – 25	standard commercial	air
– Air heaters	20 – 25	standard commercial	exhaust gas
Electrical installations			
Driving motors ³⁾	12 – 17	starter and protection system according to application	
Electrical installations	20 – 25	in-house technique	
Electrical controls	12 – 17	low-voltage cabinets	
Technical measuring installations for waste water	10 – 15	flow volumes, temperature, pH, concentration	waste water, sludge, gas, air,
Electronic components	10 – 15	computer installations	atmosphere
Equipment and technical facilities			
Pipelines for			
– Drinking water	20 – 25	steel, galvanized	electrically insulated in waste water, made of stainless steel
– Service water	20 – 25	steel, galvanized; stainless steel; fibre concrete	electrically insulated in waste water, made of stainless steel

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** with internal coating based on tar-pitch and epoxide resins, at least in the gas zones.

Table 5: Service life of facilities and installations in waste water treatment plants [12]

Table 5: Continued

Plant component – installation	Service life years	Material/specification or commercially available realization	Function, environmental conditions
– Waste water, septic water	20 – 25	steel, galvanized; stainless steel; fibre concrete	electrically insulated in waste water, made of stainless steel
– Sludge, sand	20 – 25	steel, galvanized; stainless steel	electrically insulated in waste water, made of stainless steel
– Compressed air	20 – 25	steel, galvanized; stainless steel	electrically insulated in waste water, made of stainless steel
– Sewer gas	20 – 25	plastic; stainless steel (> 2% Mo)	electrically insulated in waste water, made of stainless steel
– Chemical	20 – 25	plastic	electrically insulated in waste water, made of stainless steel
Fittings such as	according to the medium		
– Sluices	20 – 25	cast steel, coated; stainless steel	
– Valves	20 – 25	cast steel, coated; stainless steel	
– Flap traps	20 – 25	cast steel, coated; stainless steel	
Shut-off valves	20 – 25	steel, coated	
Flashback arresters	20 – 25	stainless steel (partly > 2% Mo)	
Steam traps	20 – 25	steel, galvanized; plastic; stainless steel	
Gas hoods and septic tank	20 – 25	steel, coated; stainless steel (> 2% Mo)	

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3) service life depends on the rotation speed

* increased susceptibility to concrete corrosion in areas ± 0.5 m over the water level, especially for soft drinking water

Recommendation: increase the amount of cement by approx. 25 kg/m^3 in this area

** with internal coating based on tar-pitch and epoxide resins, at least in the gas zones.

Table 5: Service life of facilities and installations in waste water treatment plants [12]

Table 5: Continued

Plant component – installation	Service life years	Material/specification or commercially available realization	Function, environmental conditions
Heat exchangers for			
– Water/water	20 – 25	steel	
– Water/sludge	20 – 25	steel	
– Sludge/sludge	20 – 25	steel	
Reaction vessels	20 – 25	steel, galvanised, coated; stainless steel; plastic	
Mixed vessels	20 – 25	stainless steel; plastic	
Storage tanks for			
– Heating oil	20 – 25	steel, coated	
Chemicals (metal salts, caustic solutions, acids)	20 – 25	plastic; steel, raw according to the medium, coated, rubberised	
Manhole covers	20 – 25	steel; cast iron	waste water, sludge, vapors, gases
Access ladders	15 – 20	steel, galvanised; stainless steel	waste water, sludge, vapors, gases
Steel stairs, handrails	20 – 25	steel, galvanised	waste water, sludge, vapors, gases
Gratings, checker plates	20 – 25	steel, galvanised	waste water, sludge, vapors, gases
Spillways	20 – 25	steel, galvanised; stainless steel	waste water, sludge, vapors, gases
Scum boards	20 – 25	steel, galvanised; stainless steel	waste water, sludge, vapors, gases

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3) service life depends on the rotation speed

* increased susceptibility to concrete corrosion in areas ± 0.5 m over the water level, especially for soft drinking water
Recommendation: increase the amount of cement by approx. 25 kg/m^3 in this area

** with internal coating based on tar-pitch and epoxide resins, at least in the gas zones.

Table 5: Service life of facilities and installations in waste water treatment plants [12]

Technical waste water installations	Service life, years
Waste water discharge	
Sewers (except for those made of stoneware and plastic)	50 – 60
Stoneware sewers	80 – 100
Plastic sewers (rigid PVC, rigid PE)	40 – 50
Canalisation shafts	50
Forced-flow pipelines and underwater pipelines	28 – 50
Gravity-flow pipelines	20 – 33
Storm water overflow constructions, storm water basins	
– Constructional part	50 – 70
– Mechanical part: according to the type	5 – 20
Pumps and lifting stations	
– Constructional part	25 – 40
– Mechanical installations:	
Screw pumps	14 – 20
other pumps	8 – 12
Special vehicles (such as those for petrol separators, faeces, high-pressure flushing, sludge suction, road drain cleaners)	7 – 10
Waste water treatment plants (sewage plants)	
Facilities in large plants in separate or compact style (raker facility, sand trap, settling tank, activation tank, sedimentation tank, machine house, pump shafts)	25 – 40
– Mechanical part of the raker installation	10 – 14
– Mechanical part of the sand trap	8 – 12
– Mechanical part of the settling and sedimentation tanks	12 – 20
– Mechanical part of the activation facility with surface ventilator	10 – 20
– Mechanical part of the activation facility with forced ventilation	12 – 20
– Mechanical part of the percolating filter	20 – 25

Table 6: Average service life of hydraulic engineering installations [13]

A

Metallic materials

A 2 Aluminium

A 3 Aluminium alloys

Aluminium and its alloys are used in a wide range of applications in waste water treatment plants, e.g. for toothed barriers, scum boards, gutters, gates, sluices, sludge scrapers and sweepers.

The corrosion behavior, mechanical properties and the construction of components made of aluminium alloys are reported in [14]. The following information is based on this publication, which contains further literature citations.

The choice of material is very important with regards to the corrosion resistance. For example, alloys of copper and zinc are not suitable because their corrosion resistance is not sufficient. Table 7 gives the chemical composition of four aluminium alloys with good to very good resistance [15].

If aluminium components are used then materials with sufficient strength must be used, depending on the mechanical loading to be expected.

Aluminium alloys are generally resistant in municipal waste water treatment plants in which the waste water has a pH between 6 and 8. Corrosive attack may occur up to depths of maximum 0.8 mm by waste waters which contain high amounts of chloride ions and low amounts of heavy metal salts. Heavy metal salts include those of mercury, silver, nickel and copper; they can cause pitting corrosion.

Because of the amphoteric nature of aluminium, its protective oxide film can be destroyed in strongly acidic or strongly alkaline waste waters so that corrosive attack can start. The above parameters can lead to strong corrosive attack, particularly in industrial waste water treatment plants.

In the waste water change-over zone there may be increased surface oxidation to produce matt grey coatings but without significant corrosive attack.

Constructive influences must be taken into account in addition to the composition of the material and the corrosive properties of the waste water. A metallogically conducting connection of Al materials to materials that act as a cathode, e.g. reinforced concrete, copper or brass, must be avoided otherwise the aluminium can be dissolved anodically. Therefore, to avoid the formation of a galvanic cell, it has proved necessary to join aluminium constructions to reinforced concrete by means of plastic dowels. If the aluminium is embedded directly in the concrete, there is no

Designation	Aluminium Association Standards	Chemical composition, %								
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	others
AlMg1	EN AW-5005A AA 5005	3.3315 [†]	0.30	0.45	0.05	0.15	0.7 – 1.1	0.10	0.20	
AlMg3	EN AW-5754 AA 5754	3.3535 [†]	0.40	0.40	0.10	0.50	2.6 – 3.6	0.30	0.20	Mn+Cr 0.10 – 0.6
AlMg2.7Mn	EN AW-5454 AA 5454	3.3537 [†]	0.25	0.40	0.10	0.50 – 1.0	2.4 – 3.0	0.05 – 0.20	0.25	0.20
AlMg4.5Mn	EN AW-5083 AA 5083	3.3547 [†]	0.40	0.40	0.10	0.40 – 1.0	4.0 – 4.9	0.05 – 0.25	0.25	0.15

[†] old DIN-Mat. No.

Table 7: Composition of non-hardenable wrought Al alloys according to DIN EN 573-3 [15]

risk of corrosion in the absence of water. However, if water is always present, then aluminium components must have an organic coating that provides good protection.

Even though a crevice does not always lead to corrosion, crevice corrosion cannot be excluded in the case of a critical width of the gap.

A 14 Unalloyed steels and cast steel

Unalloyed steels without coatings or protective films are widely used for the reinforcement of concrete buildings [16]. Their required mechanical strengths are specified in DIN 1045 [17]. Common designations are “concrete steel I-IV” with minimum yield strengths of 220 to 500 N/mm² (special reinforced concrete) and tensile strengths of 340 to 550 N/mm².

In addition to a circular cross-section (round steel), the reinforcing steels can have special shapes, e.g. twisted, knotted, ribbed, in order to produce a special adhesion effect.

Constructional steel textiles and steel mats used to reinforce concrete consist of steel rods laid at right-angles to one another with various separations and cross-sections. They are joined together by welds which are electrically conducting. These steels, along with the concrete steels of groups II to IV, require a general approval by the highest building supervision office of the relevant federal state (building department approval). This prescribed approval must be taken into account for the use of pre-stressed concrete elements, e.g. round basins or septic towers. The corresponding details are given in the standard DIN 1045 [17].

Mainly steel St 37 is used for steel constructions in the different facilities in waste water treatment plants. This collective term is used for the steels St 37.0 (UNS K02501, DIN Mat. No. 1.0254), St 37-2 (UNS K02401, 1.0037) and St 37-3 (UNS K02501, 1.0116) according to DIN EN 10025 [18].

The electrochemical behavior of the unalloyed steel must be taken into account in steel constructions. Since concrete has a strongly alkaline reaction, sub-microscopic thin films of iron oxides are formed on the surface of the steel. This leads to the unalloyed steel in concrete becoming electrochemically more noble, i.e. it behaves as a practically resistant material. Therefore, it can be used as a cathode in an electrochemical cell [19].

In reinforced concrete basins of waste water treatment plants, there are extensive steel mats which act as cathodes with a large surface area. If these steel mats, which are in the waste water, are in electrical contact with components of unalloyed steel, it is possible that an electrochemical cell is formed by contact corrosion [20].

A metallic conducting connection can be produced during building e.g. by the unintentional contact between the steel reinforcement and an iron bracket. On the other hand, a metallic conducting connection can be produced if all metallic components have to be in electrical contact with each other for reasons of electrical protection against human contact [21]. According to the area rule, coated steel components are strongly susceptible to the anodic dissolution of iron as pitting corrosion, partic-

ularly where there is a small defect in the coating [20]. This susceptibility can be estimated by the ratio of areas of the cathodic surface S_c (steel and concrete) to the anodic surface (S_a) (steel in waste water). For $S_c : S_a = 100 : 1$; pitting corrosion rates in the order of 1 mm/a (40 mpy) can be expected [22].

Contact corrosion is also possible if unalloyed steel is in contact with other materials which also act as cathodes, e.g. stainless steels. The area ratio $S_c : S_a$ is also decisive in this case; however, corrosion only occurs if, e.g. large area cathodes of stainless steel are present. For cathodes with smaller surface areas, e.g. stainless steel screws, contact corrosion is not expected.

As a protective measure against the electrochemical cell formation described above, it is recommended to install a "local cathodic corrosion protection" (see Figure 1) [23, 24].

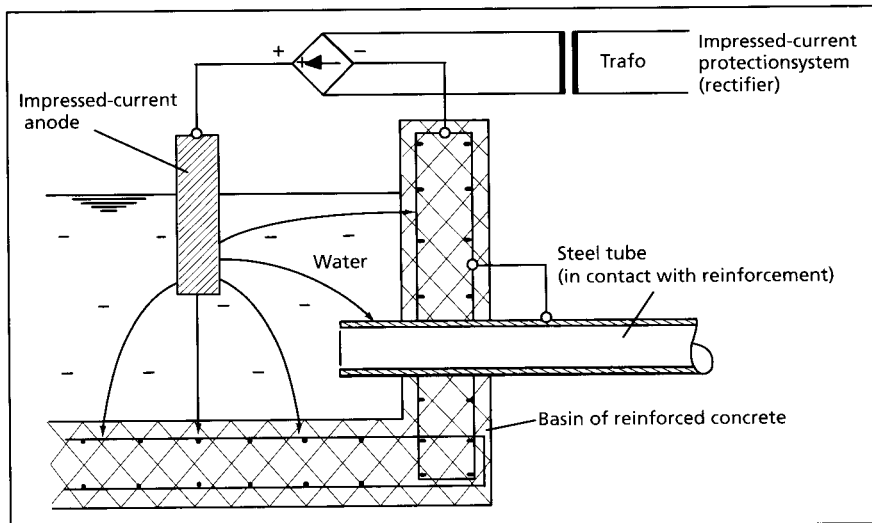


Figure 1: Local cathodic corrosion protection in a clarification basin [23]

If there is a gap between two components of unalloyed steel, then there is a possibility of crevice corrosion. For example, this can be the case for screwed connections. In principle, crevice corrosion is an aeration cell which results from a difference between the oxygen concentration in the crevice (low oxygen content) and that outside the crevice (higher oxygen content). This type of corrosion only occurs at critical crevice widths [25]. If the width of the crevice lies markedly above or below the critical value, there is no corrosive attack. This also explains the practical observation that corrosive attack does not occur in every crevice [22].

Another example for a possible aeration cell occurs with suction scrapers made of unalloyed steel in the clarification basin. In this case, the difference in aeration arises from the oxygen deficiency in the bottom deposit and the relatively high oxygen content in the waste water [26].

A further large application area of unalloyed steels are steel components which are used in connection with protective measures. Protective measures in the form of coatings or films are described in Sections A 39, B 4, B 8 and D 1.

A 15 Unalloyed cast iron

Cast-iron sewer components for the drainage of buildings and estates or for the drainage of traffic areas include the following types of castings: drains for cellars, floors, bathrooms, balconies, rainwater, courtyards, flat roofs as well as cleaning stoppers, cut-off devices against backpressure, sliding gates, waste water pumps, separators for light liquids (petrol traps, heating oil traps), heating oil barriers, fat separators, potato starch separators as well as covers and caps of e.g. courtyard drains, drainage gutters, bridge drains and manhole steps.

Some of these are the so-called BEGU constructions (cast concrete).

Coating of cast-iron sewer components is not necessary for reasons of corrosion protection. A surface treatment, e.g. for optical reasons, is optional for the manufacturer. This statement is now included in a number of standards for cast articles used in sewer systems. Surface treatment is carried out exclusively for cosmetic reasons; in the past, these have been thin coatings. Some castings are also epoxidised or enamelled; see also Sections B 4, B 8 and D 1.

Sanitary equipment, e.g. cast-iron bath tubs, is usually enamelled. Cast-iron drain pipes with sleeveless couplings (SML) and nominal diameters ND 50 to ND 300 in overall lengths of up to 3 m are standardised in DIN 19522, Part 1 [27]. They can be used to replace the previously standard cast-iron drainpipes with sleeves (GA) (which are still common) because since the outer diameters are the same.

Bridge pipelines are usually made of cast-iron drainpipes up to ND 600 and overall lengths of up to 6 m. The pipes consist of cast iron with lamellar graphite inclusions according to DIN EN 1561 (grade at least EN-GJL-150 (0.6015, GG-15), i.e. an iron-carbon alloy whose carbon is finely dispersed in the metallic matrix as lamellae) [28]. This particular microstructure gives the material very high damping properties. Even without special insulation, cast-iron drainpipes are robust, have a long service life and are quiet during operation. Additionally, according to its building material classification A 1 (inflammable), no particular fire-protective wrapping is necessary. Table 8 summarises the properties of the material [28].

For these pipes there is an extensive range of fittings and rubber-sealed couplings with stainless steel joiners made of 1.4510 (cf. UNS S43035) and sealing rings of EPDM (ethylene-propylene-diene rubber). These are resistant to ageing and also resistant to boiling water, see Sections A 18 and D 2. The special principles of construction and inspection from the Deutsches Institut für Bautechnik (German Institute of Building Technology), apply to the pipe couplings.

SML pipes and fittings are supplied with a red-brown ground coat which contains synthetic iron oxide pigments [29]. The ground coat is applied to the inside and outside of the fittings by dipping and to the pipes by spraying. The pipes are coated on the inside with a durable pitch-epoxide resin coating which offers additional protection

Material characteristics and properties	
Density:	approx. 7.2 kg/dm ³
Tensile strength:	≥ 150 N/mm ² for fittings ≥ 180 N/mm ² for pipes
Compressive strength:	approx. 3 to 4 times the value of the tensile strength
Shear strength:	1.1 to 1.6 times the value of the tensile strength
Circular compressive strength/pipe flattening resistance:	≥ 300 N/mm ²
Modulus of elasticity:	8 x 10 ⁴ to 12 x 10 ⁴ N/mm ²
Poisson no.:	~ 0.3
Longitudinal coefficient of expansion:	0.0105 mm/mK (between 273 and 373 K) (0 and 100 °C)
Thermal conductivity:	50–60 W/mK (at 293 K (20 °C))
Thermal resistance, without significant alteration of the mechanical properties:	up to 673 K (400 °C)
Chemical resistance:	pH 2 to 12 for domestic use of the pipeline

Table 8: Material characteristics and properties of cast-iron drainpipes [28]

against chemical and mechanical influences and its smooth surface improves the flow behavior in the pipes.

If necessary, the external ground coat of the pipes and fittings can be covered with commercially available paints and coating systems used for steel constructions.

In agreement with the technical delivery conditions specified in DIN 19522-2, the phosphorus content of the cast iron must lie below 0.9 mass% [29]. Coatings for these pipes and fittings are described in Section D 1.

A special type of sleeveless cast-iron drainpipes are the so-called EML drainpipes which are supplied with a internal enamel coating that is very resistant to acids and alkaline solutions; these are described further in Section B 8.

In general, sealing collars made of EPDM are supplied with the couplings. They can be used between approximately 223 K (–50 °C) and 393 K (120 °C), depending on the medium being carried. These collars are resistant to a wide range of different media and substances under normal conditions.

For special requirements in which the EPDM seals are not resistant, special sealing collars of NBR (based on nitrile rubber) are used. Sealing collars made of fluorinated rubber are also possible; however, they are very expensive.

See Section D 2 for information on the resistance of these sealing elements.

Ductile sewer pipes are standardised in DIN EN 598 for gravity-flow sewers and forced-flow pipelines pressurised up to 6 bar (600 kPa) in the nominal diameters ND 100 to ND 2000 [30]. They are used for combined, sanitary or storm water pipe-

lines in local canalisation systems, in free terrain, in wooded areas, in rivers, on steep slopes and in groundwater-protected areas. The material characteristics are listed in Table 9 [31].

Material characteristics and properties	
Tensile strength:	min. 400 N/mm ²
0.2% yield strength:	min. 300 N/mm ²
Ductile yield:	min. 7%
Bursting strength:	min. 300 N/mm ²
Crushing strength	min. 550 N/mm ²
Longitudinal bending strength	min. 420 N/mm ²
Hardness	max. 250 HB 5/750
Modulus of elasticity:	170 kN/mm ²
Longitudinal elongation	10 ⁻⁵ m/mK
Ductility of the alumina cement mortar lining	≤ 4%

Table 9: Material characteristics and properties of ductile sewer pipes [31]

The pipes are made with the bell-and-spigot coupling system Tyton® in overall lengths of 6 m. They are generally coated on the outside with a spray galvanized coating and top coat according to DIN 30674 Part 3 [30] (see Section A 39) and have an internal lining of aluminous cement mortar according to DIN 2614 (see Section B 4) [32]. The pipes are supplemented with special fittings, such as e.g. tapping saddle pieces 45° or 90° or shaft couplings with Tyton® bell-and-spigot joints to ensure that all the pipeline components are permanently leakproof. This prevents the infiltration of surrounding water into the pipe or leakage of the medium flowing through it into the ground.

To check the suitability of the sewer pipes for their use as a one-pipe system for waste water pipelines in drinking-water protected areas, an expert's report was commissioned [33]. Table 10 summarises the results of this report. Ductile sewer pipes are particularly suitable for the repetitive tests specified in the guidelines [34] with water or air or vacuum tests [35].

The vacuum testing of ductile sewer pipes has been newly developed for this. In contrast to the water overpressure test procedure, this new test method has the advantage that it can be carried out in a few hours, it doesn't require large amounts of test water and the test itself is especially enhanced.

The differential pressure test is used for the vacuum test and is also used to test gas pipelines for leaks. In this test, the leakproofness of the sewer pipeline is compared with the absolute leakproofness of a heat-insulated control bottle (reference vessel). This is carried out with digital differential pressure measuring equipment. The pre-requisite for this is an absolutely leakproof pipe system. Both the pipe material and the couplings must be gastight.

Requirements	Evaluation
Observance of the standards and regulatory works as well as special ordinances	The waste water pipe under examination is made of ductile cast iron and is manufactured according to DIN EN 598. The bell-and-spigot coupling system Tyton® corresponds to DIN 28603.
High safety factor against the expected and calculated, external and internal, static and dynamic loads High reserve safety factor or insensitivity towards not planned or not calculated additional external and internal loads	The high work capacity of ductile iron, the large longitudinal displacement, the experimental uptake of shear loads as well as a water pressure of 10 bar confirm the large safety factor against external and internal loads. For this reason, it is generally sufficient to install Tyton® shaft couplings with simple joints in buildings.
As few pipe connections as possible using long pipes, with a simple and safe assembly.	The pipe overall length is 6 m.
No ports to the pipes. Availability of all necessary accessories (complete system)	There is a complete system available that allows e.g. pressure-sealed shafts with ductile shaft pipes which have ports only in the pipe shafts
External and internal corrosion resistance of the pipe material itself and the sealing material or the external and/or internal corrosion protection	External corrosion protection according to DIN 30674 Part 3 or Part 1, 2 or 5. Internal corrosion protection with cement mortar lining according to DIN 2614 or with a special lining.
Permanently leakproof pipe materials, pipe connections and ports in the shafts with respect to waste water and gases for both internal and external overpressure as well as a vacuum	Ductile cast-iron pipes and their couplings withstand a test pressure of more than 10 bar and thus exceed the pressure of 2.4 bar for pressure-less waste water pipes by several times. Also for special applications in which the pipe coupling must remain permanently leakproof, even in case of bending and longitudinal displacement as well as decentring (areas with ground subsidence etc.) the ductile cast-iron pipe system withstands a test pressure of 10 bar without a pressure drop. Likewise, the system remains gastight for an internal gas overpressure of 1.13 bar and a vacuum of 0.5 bar.
Wear resistance	The wear resistance of the cast-iron pipework was verified using the a "tilted gutter test"

Table 10: Ductile cast-iron pipeline system for the transportation of waste water in drinking-water protection zones II [33]

Table 10: Continued

Requirements	Evaluation
Thermal resistance	The thermal resistance specified in DIN EN 476 of 318 K (45 °C) for nominal diameters up to ND 350 and 308 K (35 °C) for nominal diameters greater than ND 400 was fulfilled by the ductile cast-iron pipe.
Tangential bending ability of the pipe couplings	The tangential bending ability of the pipe coupling system Tyton® was verified according to DIN 4060 and also with a test pressure of 10 bar.
Axial displacement in the pipe couplings	The leakproofness during longitudinal displacement of 80 mm in the pipe coupling was verified in a test using an internal water pressure of 10 bar.
Resistance to plant roots	The resistance to plant roots was verified in a shear test based on DIN 4060.
Permanent compatibility between the materials used in the pipes, fittings, seals and mountings	Permanent compatibility between the materials used in the pipes, fittings and seals was attained by observance of DIN 4060.
Maintenance suitability	Investigations with respect to the influence of high-pressure water sprays on the cement mortar lining of the ductile cast-iron pipes showed that there was no damage caused by commonly used nozzle heads and flushing pressures up to 170 bar.

Table 10: Ductile cast-iron pipeline system for the transportation of waste water in drinking-water protection zones II [33]

The test section must be sealed off from the start and end shafts by sealing cushions. These are inserted into smooth pipes with an internal coating of epoxy resin. The same applies to the sealing of house connection pipelines in inspection shafts as well as road drains with adaptor pipes. After sealing off, the pipeline is evacuated by means of a vacuum pump that works on the principle of the water jet and is connected to a compressor.

In waste water sewers and pipelines in water-protection zone II, leakproof testing must be carried out at certain intervals during operation, at least every five years. Shorter intervals may be necessary, depending on the type and loading of the sewers and pipelines [34].

In water-protection zone III, leakproof tests should be carried out according to need, generally every ten years.

A 18 Ferritic chromium steels with more than 12% chromium**A 19 Ferritic-austenitic steels with more than 12% chromium****A 20 Austenitic CrNi steels****A 21 Austenitic CrNiMo(N) steels****A 22 Austenitic CrNiMoCu(N) steels**

Within the class of stainless steels, ferritic chromium steels as well as austenitic chromium-nickel steels, with and without additional molybdenum, can be used as passivable materials in waste water installations. Table 11 lists the most frequently used chromium-nickel steels, which are also listed in DIN EN 1124-1 [36].

The following considerations must be taken into account if stainless steels are to be used:

- water composition
- processing
- operating conditions.

The materials are primarily selected with regards to the corrosive loading by the waste water, particularly with respect to the amount of chloride ions. These are able to locally penetrate the passivating layer on the stainless steels in very small regions, stabilise anodes and thus lead to pitting. Reference [37] gives information on the maximum permissible chloride content for a waste water with a pH of 7. From the information given in Table 12, it can be seen that the resistance of stainless steels to pitting corrosion increases with increasing molybdenum content. This statement is confirmed, in principle, by the diagram given in Figure 2. The pitting potential U_p on the abscissa is a criterion for the resistance to pitting corrosion, i.e. the more positive this potential is, the more resistant is the stainless steel against pitting corrosion [37]. Pitting corrosion can only occur if the redox potential of the waste water is more positive than the pitting potential.

Designation				Chemical composition, %					Pitting index	Pitting potential U_p, mV
				C	Cr	Ni	Mo	Others		
AISI 304	UNS S30400	1.4301	≤ 0.08	18–20	8–10.5	–	–	–	18	+ 250
AISI 316 L	UNS S31603	1.4435	≤ 0.03	16–18	10–14	2.0–3	–	–	25	+ 600
AISI 316 Ti	UNS S31635	1.4571	≤ 0.08	16–18	10–14	2.0–3	$5 \times C1N \leq Ti \leq 0.5$	–	25	+ 600
AISI 317 LMN	UNS S31726	1.4439	≤ 0.03	17–20	13.5–17.5	4.0–5.0	$N 0.10–0.20$	–	32	+ 1200

Table 11: Stainless steels used in waste water facilities [38]

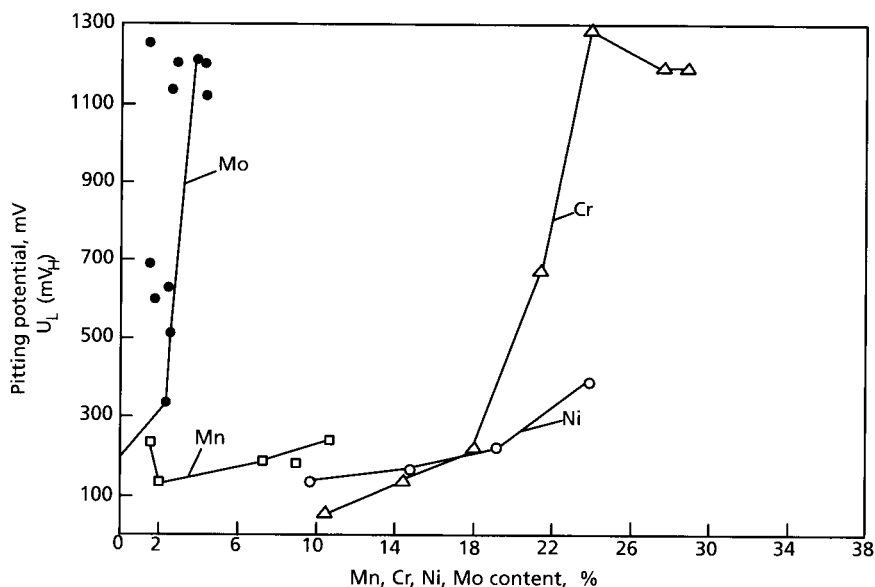


Figure 2: Influence of the alloying elements manganese, chromium, nickel and molybdenum on the pitting potentials of austenitic CrNi steels in 3 % NaCl solution [37]

DIN-Mat. No.	Designation	Chemical composition, %				Resistance at pH 7 max. Cl content, g/l		Temperature K (°C)
		Cr	Ni	Mo	C	Pitting corrosion	Crevice corrosion	
1.4301*	AISI 304*	18	8	–	< 0.07	0.2	0.02	298 (25)
1.4306	AISI 304 L	18	8	–	< 0.03	0.2	0.02	298 (25)
1.4401*	AISI 316*	18	10	2	< 0.07	1	0.2	308 (35)
1.4404	AISI 316 L	18	10	2	< 0.03	1	0.2	308 (35)
1.4436*	AISI 316*	18	12	3	< 0.07	5	1	308 (35)
1.4435	AISI 316 L	18	12	3	< 0.03	5	1	308 (35)
1.4439	AISI 317 LMN	17	13	4.5	< 0.03	10	5	334 (70)
1.4539	AISI 904 L	20	25	4.5	< 0.03	10	5	353 (80)

*Attention: In the sensitised state, these steels have an increased susceptibility to pitting corrosion and a strongly reduced resistance to intergranular stress corrosion cracking

Table 12: Maximum chloride contents for pitting and crevice corrosion of stainless steels [12, 38]

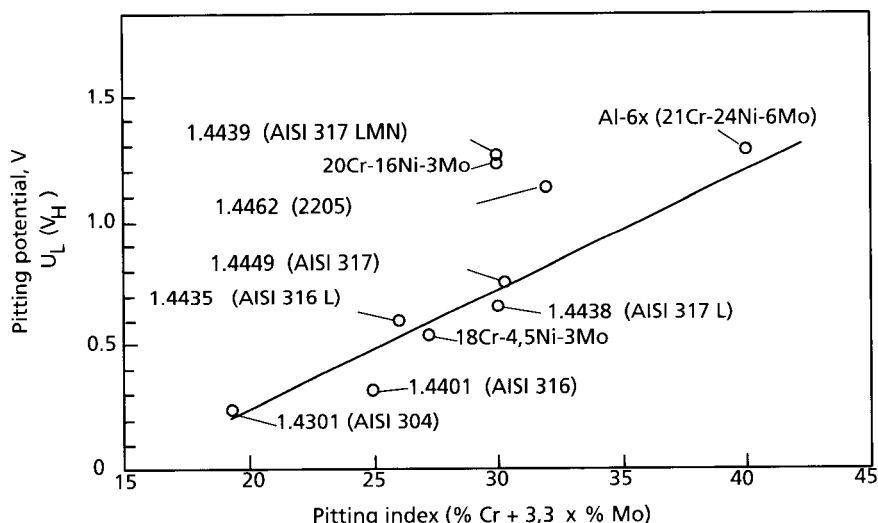


Figure 3: Dependence of the pitting potentials of austenitic CrNi steels in 1 mol/l NaCl solutions on the pitting index (PI) of chromium and molybdenum [37]

Furthermore, it can be seen from Figure 2 that both manganese as well as nickel have very little influence on the pitting potential. The presence of chromium only has a favorable effect on the pitting potential when the steel contains more than 18 mass% Cr. This determination of the influence of chromium and molybdenum was the reason for the introduction of the so-called pitting index ($PI = \% Cr + 3.3 \times \% Mo$). The larger the pitting index is, the more positive is the pitting potential U_p , as can be seen from Figure 3 and the corresponding values in Table 11 [37]. Generally, the N content also is included in the pitting index and is taken into consideration with a factor of 30.

There is a close relationship between crevice corrosion and pitting corrosion. Crevice corrosion only occurs in waste waters that contain chloride ions, and is dependent on the conditions in the crevice. Crevice widths of more than 0.5 mm are generally not critical; however, the crevice depth must also be taken into account [39]. Crevices between stainless steels and insulating materials, e.g. plastics, are particularly susceptible to crevice corrosion. Experience shows that the most important potential for crevice corrosion, the critical potential U_c , is clearly more negative than the pitting potential U_p , as shown in Figure 4 [40]. Thus, for example, for a chloride concentration of 1 g/l, these potentials are $U_c = +0.10$ V and $U_p = +0.45$ V. Crevice corrosion between stainless steel and stainless steel was also observed; however the risk of corrosive attack is only to be expected at very high chloride concentrations [37]. For the use of the materials listed in Table 11, only a very low probability of corrosion is to be expected if there are crevices in the components [41].

In most cases it is sufficient to use steels with 18% Cr, 10–12% Ni and a molybdenum content of 2 to 3%. CrNi steels without additional molybdenum do not exhibit sufficient resistance to crevice corrosion in waste waters with chloride contents of approx. 70 mg/l [7].

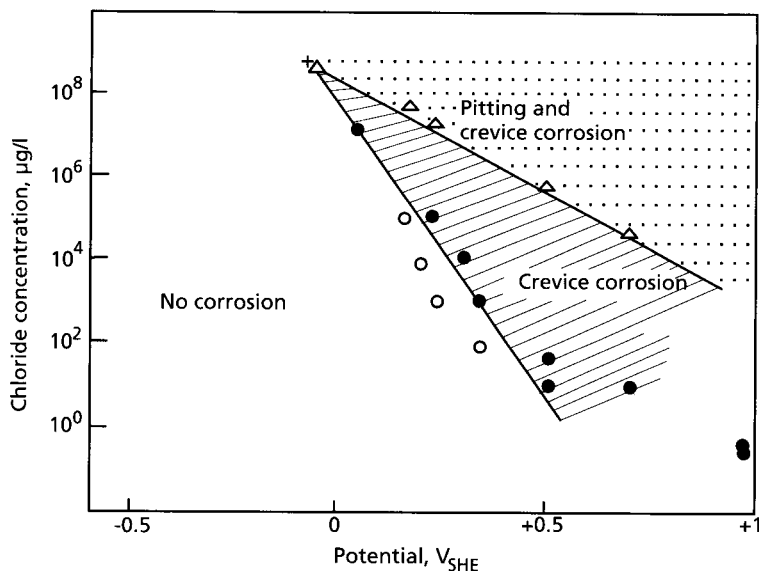


Figure 4: Resistance diagram of steel AISI 304 L (cf. 1.4306, X2CrNi19-11) towards pitting and crevice corrosion in neutral, chloride-containing waters at 298 K (25 °C) [40]

d, s = crevice corrosion potential

n = pitting potential

+ = threshold potential

The data on pitting corrosion assumes that the stainless steel component has a smooth surface. However, if there are deposits or films on these surfaces that remain in place, then there may be a concentration of chloride ions at the sites of these deposits. At these sites, the pitting potential U_p is more negative than the pitting potential outside the deposits. Therefore, in the presence of deposits, pitting corrosion attack can occur even if the chloride content of the waste water is not at a critical level. With respect to the deposits caused by operation, the flow rate of the waste water is of great importance. The greater the flow rate, the less is the likelihood of the formation of deposits and thus also the risk of pitting corrosion. Surfaces with low flow rates can thus be susceptible to corrosion.

Adhering deposits can form at the three-phase boundary air/material/waste water. These deposits lead to the enrichment of chloride ions at this site. Pitting corrosion is not only favored by deposits and films, but also by coarse mechanical damage of the surface, e.g. by scratches or by too coarse grinding.

A further important influential factor for pitting and crevice corrosion is the possible presence of oxidising agents (e.g. ozone) and anions (e.g. hydroxide and sulphate ions) in the waste water. The presence of these substances in the waste water can shift the potentials U_p and U_c in a positive direction. This results in an increased susceptibility towards pitting and crevice corrosion [37, 40].

In the selection of materials, the possibility of intergranular corrosion must also be taken into account. This type of corrosion is selective and is based, for example,

on the precipitation of chromium-rich carbides on the grain boundaries (e.g. by welding). The chromium depletion can lower the corrosion resistance so that the grains disintegrate. This modification of the material is known as sensitisation [39]. Thus, for example, steel no. 1.4301 (Table 11) can be sensitised and, according to [41], the use of this material is not recommended.

Steels can be stabilised against intergranular corrosion e.g. by the use of steels with a low carbon content, as in material no. 1.4435 (Table 11). Another possibility is alloying with titanium or niobium which have a great affinity for carbon and thus prevent the formation of chromium carbides, as in e.g. material 1.4571 (AISI 316 Ti, Table 11).

Steels with 18 % Cr, 10–12 % Ni and carbon contents < 0.03 % or those stabilised with titanium are recommended for welded constructions [7].

Stress corrosion cracking and corrosion fatigue are only rarely observed in waste water installations [42]. These types of corrosion are only to be expected in materials listed in Table 11 only at temperatures above 323 K (50 °C).

Stainless steel components are preferentially joined by welding. During welding, oxide films and scales are produced on the surfaces and they very greatly reduce the resistance towards pitting corrosion [41]. Therefore, inert-gas-shielded arc welding is recommended to prevent the formation of oxide films and scales. It must be ensured that there is a sufficient supply and correct control of the inert gas. For example, during welding at construction sites it must be ensured that the position of the inert gas bell is not disturbed by the wind [43].

The permissibility of the different tarnishes which are produced during welding are discussed in [44]. According to this, straw yellow to dark blue tarnishes are harmless, whilst the lighter tarnishes with a film thickness of up to 50 nm are close to the limit of permissibility. Pitting corrosion must be expected in chloride-containing waste waters for brown to brown-black and particularly black films of macroscopic thickness. It is recommended to remove all tarnishes, regardless of color. The films and layers that lead to corrosion must be removed by shot peening, careful grinding (grain size >100 µm) or by pickling. The components can be treated by the manufacturer in pickling baths of nitric acid/hydrofluoric acid. Pickling pastes must be used at the construction site. The pickling agents must not contain any hydrochloric acid [41].

There are a number of possible welding defects, e.g. drips, root crevices that have not been properly welded, offset edges, open pores, welding splashes, residual slag on the base material and the welds. These defects underline the importance of correct and careful execution of the welding [44].

In the case of rubber-sealed joints, the amount of chlorides that can be extracted by water must not exceed 0.05% otherwise there is a risk of pitting or crevice corrosion. Brazed joints, independent of the braze, are no longer permitted for stainless steels because of attack by knife-line corrosion [41].

Clamped couplings made of stainless steel with elastomer seals are used for sleeveless drainpipes of cast iron and fibre cement. According to the principles of construction and inspection from the Deutsches Institut für Bautechnik (German Institute of Building Technology), the following requirements apply to the materials of

the elements used to clamp cast-iron pipes [45]; the clamping straps/sleeves must be made of stainless steel according to DIN EN 10028-7, which is resistant to intergranular corrosion, even in the welded state. Therefore, in the case of austenitic steels, all grades are permissible, while only the two materials 1.4510 (AISI 439, X3CrTi17) and 1.4511 (X3CrNb17), are permissible in the case of ferritic and martensitic steels. For clamping collars made of stainless steel for fibre cement pipes which are to be welded, only steels may be used that are resistant to intergranular corrosion (1.4510 and 1.4511).

In waste water installations, the mixed construction i.e. the installation of components made of different materials, cannot be avoided. The risk of corrosion in mixed constructions is also discussed in [46].

Stainless steels are electrochemically noble materials in the passive state, i.e. they can form cathodes in electrochemical cells. Information with regard to this is given in Section A 14.

Corrosion damage which has been ascribed to acid attack has recently been observed in stainless steel sludge tanks in waste water treatment plants. The regions where corrosion occurred were in contact with sewer gas. The CrNi steels 18 10–12 with 2–3% molybdenum used here proved to have insufficient resistance. Therefore, the use of more highly alloyed stainless steels with increased resistance to acids is worthwhile in this case [7].

According to [47], thick-walled CrNiMo rolled-steel pumps are to be favored for use as components in waste water installations over those made of plastic or gray cast iron as they are resistant to corrosion and biocorrosion.

A 33 Lead and lead alloys

Lead pipes are used in waste water installations because of the good corrosion resistance of lead and its good processing properties [48].

The range of application of these pipes includes sinks and flushing pipes as connection lines between flushing tanks and basins of a water closet installation. Lead pipes are soldered watertight with rosin or stearin solders that contain at least 40 % soldering tin.

A 39 Zinc, cadmium and their alloys

Zinc is widely used as a coating on unalloyed steel components in waste water installations. The zinc coating is generally applied using the hot-dip galvanisation process [49]. Spray galvanisation and electrogalvanisation only play a secondary role in this range of applications.

Hot-dip galvanised steel components are used in sewer technology as drain gratings, covers and as dirt pans for balconies, roofs and cellars in road and estate drainage. It is also used as buckets for drains in roads [50]. A zinc layer of at least 400 g/m² is required for these components [51].

A large area of application are hot-dip galvanised steel drainpipes and fittings for estate drainage. According to DIN EN 1123-1 [51], these pipes can be used with and without a coating. The hot-dip coating must have a smooth, perfectly adhesive and uniform layer with a minimum amount of 400 g/m^2 on average; the individual value must not be less than 350 g/m^2 .

For waste water with a normal level of aggressiveness, a service life of e.g. 20 years is calculated for a hot-dip galvanised pipeline with a coating thickness of $100 \text{ }\mu\text{m}$ and a 1 mm thick wall of the steel pipe. This is based on a corrosion rate of the hot-dip coating of approx. 5 to $10 \text{ }\mu\text{m/a}$ (without excessive abrasion) and of the steel of $100 \text{ }\mu\text{m/a}$ (without the normal erosion or cavitation loading) [46].

The combination of hot-dip galvanisation and coating is a synergetic system, i.e. the overall protective effect is greater than the sum of the protective effects of the individual components of the system [52]. This system is defined as a duplex system.

For hot-dip galvanised components (holders, supports, handrails etc.) in waste water treatment plants that lie above the level of the waste water, it can be expected that there is an increase in the protective effect by the duplex system by approximately 50 to 200%, i.e. a four-fold protective effect, compared to the protective effect of the individual system components [53].

However, below the level of the water, hot-dip galvanised components are only regarded as resistant in exceptional cases [53]. This behavior is attributed to the numerous waste water parameters [49]. The existing good practical experience is therefore often difficult to transfer to other systems and can only be generalised in a limited manner. This applies e.g. to the good experience with hot-dip galvanised components described in various publications [54–56].

Corrosion damage of hot-dip galvanised components in oxygen-poor waste waters with pH values between approximately 3.5 and 5.0 is reported in [57]. The reason for the damage is attributed to the low oxygen content under the layers of dirt and sewer slime. Because the oxygen content is too low, the conditions for the formation of protective layers of basic zinc carbonates deteriorate.

A coating of hot-dip galvanised components with plastics based on tar pitch or epoxy resins is recommended in [49]. It is expressly stated that the coating thicknesses should lie above 500 to $800 \text{ }\mu\text{m}$. Before the coating is applied to the hot-dip galvanised surfaces they should be treated by means of the irradiation process known as “sweeping” to obtain good adhesion [58]. For the coating of hot-dip galvanised surfaces, only certain plastics can be used whose suitability must be verified according to the AGK Worksheet B 1 [59].

B

Non-metallic inorganic materials

B 1 Fibre concrete (asbestos)

The designation fibre concrete, as a replacement for the building material asbestos cement which is frequently used in many applications in waste water technology, means it is asbestos-free. It should be pointed out here that asbestos is a carcinogenic substance and consequently may no longer be used [60].

Process fibres – specially selected, natural and synthetic organic fibres – are used for filtration, drainage and to reinforce the cement matrix. They allow the embedding of the reinforcing synthetic fibres in the required amount and in the correct position in the cement matrix. Thus the synthetic fibres reinforce the products and serve to increase the tensile strength of the cement matrix and the elasticity of the material.

Synthetic textile fibres made of polyacrylonitrile or polyvinyl alcohol with diameters of approximately 15 µm are used as reinforcing fibres [61]. The fibres are pretreated before the manufacturing of the fibre concrete and subsequently mixed with cement and water. The mixing ratio is approximately 94% cement and 6% fibre mixture.

High-quality Portland cement according to DIN 1164 is used for the manufacture of fibre cement [62]. The strength of the cement is not lessened by the initially large proportion of water in the fibre cement mixture, since the water is eliminated during the manufacturing process. Only the water/cement ratio of the finished wrapped pipe is decisive for the strength. The water/cement ratio of < 0.3 for fibre concrete is extraordinarily favorable.

The replacement of drainpipes for domestic and estate drainage by fibre cement started in 1984. These pipes are standardised according to DIN EN 12763, as sleeveless pipes in nominal diameters ND 50 to ND 300 and overall lengths of 2 and 4 m [63]. The pipes are connected with couplings that consist of clamping sleeves made of stainless steel and elastomer seals (see Sections A 18 to A 22 and D 5). An extensive range of fittings is available for the pipes. The fittings are produced by a spraying process.

Because of the special material properties and the current state of adhesive chemistry, it is possible to manufacture speciality fittings of hardened material by adhesive bonding. An adhesive filler is used for the couplings. This is made of an epoxy resin tailored to the fibre cement.

According to DIN EN 12763, the pipes and fittings must have an internal protective coating (pipe protection) [63]. They can be impregnated on the outside. If the outside of these pipes and fittings are in contact with aggressive waters, soils or gas, a suitable external pipe protection must be specified or used by the manufacturer. The pipes, and particularly their internal protection, are subjected to numerous tests. These are carried out by storage and cyclic loading in various chemical agents, by variation of temperature, storage in hot water, a boiling test and by filling with cold water in dry heat.

The resistance of the internal pipe protection against domestic sewage is tested by cyclic loading with acetic acid buffer solution or sodium hydroxide solution. To evaluate the long-term behavior, the chemical resistance of pipes without pipe protection towards domestic sewage is tested by 28-day storage in a medium given in Table 13. There must be no changes which affect the quality of the product.

Component	Concentration, mg/l
Starch (polysaccharide)	50
Sodium stearate	32
Sodium acetate	56
Glycerine tristearate	15
Urea	13
Ammonium sulphate	70
Proteins	90

Table 13: Media to test the chemical resistance [63]

The resistance towards changing temperatures is tested in a pipeline system which is exactly specified in a DIN standard. Furthermore, the pipes must be tested for their resistance to SO₂ and UV radiation [63]. Resistance to mould fungus must be tested according to DIN EN ISO 846, methods A + B [64].

Pipes and fittings with adhesive joints must be stored according to DIN 50014 [65].

DIN 19850 is valid for sewer pipes made of fibre concrete that are used in combined sewers, sanitary sewers and storm water sewers. Pipes and fittings are standardised in Part 1 [66] and pipe couplings are standardised in Part 2 [67].

Both pipes and fittings must be given an internal protective coating if they are to be used in combined sewers and sanitary sewers. An internal pipe protection is only necessary for storm water sewers in special cases. Pipes and fittings that are in contact with aggressive waters, soils or gases must be manufactured or protected so that they resist these types of attack. The chemical test is the neutralisation of acetic acid carried out on samples cut out of pipes that do not have a protective coating.

B 2 Natural rock

Based on the high level of knowledge of the Romans, the first drainage sewers were built of masonry at the beginning of the 19th century. Initially, natural rock were used for this, particularly in France and Italy.

The best-known example of a drainage sewer in Germany, was built of sandstone in Dresden around 1900, and is described in [68] and [69]. To compensate for unevenness and to attain watertightness, the interior surfaces were covered with a cement facing up to the height of the abutment. The arched ceiling of smaller sewers was made of sewer bricks.

Waste water sewers are still being made of masonry. The ATV worksheet A 139 specifies the use of sewer bricks with cement mortar of the mortar group III (see Section B 5) [70, 71].

B 4 Binders for building materials (e.g. mortar and concrete)

The best-known and most used binder is cement for the production of cement-bonded components. For special applications, plastic binders, e.g. unsaturated polyesters or epoxy resins, are used to make polymer concrete. A more recent development is sulphur concrete in which polymerised sulphur is used as a thermally hardening binder.

These three materials are discussed in the order of their importance and practical application.

Cement concrete

The superordinate designation "cement-bound materials" is decisive for this type of material. Concrete and reinforced concrete are used extensively for components in waste water installations. These materials are divided into two classes, according to the method of manufacture, namely in-situ concrete and prefabricated concrete parts. Table 14 gives a summary of the range of applications of components made by the two methods [72, p. 19].

A series of basic requirements are placed on concrete and reinforced concrete parts according to [72, p. 19]:

- cement according to DIN 1164 [73]. It must be pointed out that the following statements on the corrosion behavior of concrete components refer to those made with Portland cement, Portland slag cement, blast-furnace slag cement or trass concrete. Aluminous cement is not contained in this standard. The corrosion behavior of cement-based linings is described in Section D 1
- permitted agents and additives for concrete
- wear-resistant concrete B II, minimum quality B 35
- concrete coverings of steel reinforcements for in-situ concrete 40 to 50 mm thick, for prefabricated parts ≥ 20 mm.

In-situ concrete
- reinforced concrete sewers of large diameter - special constructions, distributing and connecting installations, basins in waste water treatment plants, storage basins
Prefabricated concrete parts
- concrete pipes and fittings - pressure pipes made of reinforced concrete and pre-stressed concrete - waste water treatment plants made of prefabricated concrete parts - petrol and fat separators - drains - prefabricated shaft components

Table 14: Summary of concrete components according to [72]

Table 15 lists the requirements placed on a water-impermeable concrete according to [74]. The tests according to DIN 1048 are included in this Table [75].

Concrete property/level of attack	Construction site approved for	Water/cement ratio ¹⁾		Additional requirements
Water tightness ²⁾	B II	d	≤ 60 cm	water penetration depth $e_w \leq 50$ mm
		w/c	≤ 0.60	
		d	> 40 cm	
		w/c	≤ 0.70	
Chemical attack: weak ²⁾		w/c	≤ 0.60	water penetration depth $e_w \leq 50$ mm
strong		w/c	≤ 0.50	water penetration depth $e_w \leq 30$ mm
very strong		w/c	≤ 0.50	water penetration depth $e_w \leq 30$ mm and protection of the concrete, e.g. according to the code of practice

1) to take account of the scattering of building site mixtures, the w/c value must be kept approximately 0.05 lower at the building site.

2) B I possible as an exception. Minimum cement content 400 kg/m^3 for grading curves A 16/B 16 or 350 kg/m^3 for grading curves A 32/B 32

Table 15: Watertight concrete as well as concrete with a high resistance to chemical attack [74]

Concrete and reinforced concrete pipes are used in most cases for gravity-flow pipelines as well as forced-flow pipelines. Corrosive attack of concrete parts is divided into three levels of attack: weak, strong and very strong. These are specified in DIN 4030-1 [76] (see Table 16).

The limiting values given in Table 17 can be used to evaluate possible corrosive attack of cement-bonded building materials by municipal waste water. Details of the influence of the sulphate content of the waste water are described in [77].

pH value	Lime-dissolving carbonic acid ¹⁾ (CO ₂), mg/l	Ammonium ions (NH ₄ ⁺) mg/l	Magnesium (Mg ²⁺) mg/l	Sulphate ²⁾ (SO ₄ ²⁻) mg/l
6.5–5.5	15 – 40	15 – 30	300 – 1000	200 – 600
5.5 – 4.5	40 – 100	30 – 60	1000 – 3000	600 – 3000
< 4.5	> 100	> 60	> 3000	> 3000

1) Heyer's marble dissolution test

2) For sulphate concentrations of more than 600 mg/l SO₄²⁻ in water, except seawater, a cement with a higher sulphate resistance must be used (DIN 1164-1, DIN 1045)

Table 16: Limiting values for the evaluation of the level of corrosive attack of concrete by waters with a primarily natural composition [76]

It must be pointed out that the evaluation of a waste water according to Tables 16 and 17 is not possible if biogenic sulfuric acid corrosion is to be expected. In this respect, see the corresponding remark in Table 19.

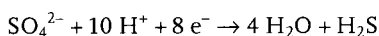
Domestic and municipal waste waters do not attack concrete [78]. Commercial and industrial waste waters that correspond to ATV Worksheet A 115 [79] are to be classified as weakly attacking; in these cases, correctly mixed, processed and post-treated concrete resists this attack without special additional measures. If the limiting values given in Tables 16, 17 and 18 are exceeded, then special measures must be taken.

When fresh waste water, i.e. aerobic, is transported to the waste water treatment process as quickly as possible, then corrosion problems do not occur in partially filled waste water sewers. However, it is known that these conditions are not always fulfilled, i.e. the waste water often becomes anaerobic. In gravity-flow sewers, corrosive attack can occur above the water level; this type of attack is defined as biogenic sulfuric acid corrosion (BSAC) in the literature [80]. Because of the great practical importance of this special type of corrosion, many investigations have been carried out in laboratories and waste water sewers. Extensive reports which contain numerous literature citations are given in [81, 82]. The factors that influence biogenic sulfuric acid corrosion are summarised in [83].

The individual phases of the biogenic sulfuric acid corrosion process are described [84]. These processes are explained in Figures 5 and 6. It must be pointed out that these two illustrations are model representations; however, they are very

useful to explain the processes on the phase boundary between the waste water and the sewer gas/sewer wall.

Fresh waste water forms a layer of sewer slime over a period of time within which microbial sulphate reduction occurs in the anaerobic zone according to the reaction



The hydrogen sulphide produced in this manner diffuses into the aerobic zone and is largely oxidised there. Under these conditions, only negligible amounts of H_2S are left in the waste water and thus also in the sewer gas. From practical experience, it is known that in well-ventilated and rapidly flowing gravity-flow pipelines, the high amount of oxygen in the waste water produces conditions that prevent the risk of corrosion by biogenic sulfuric acid corrosion.

The formation of the layers shown in Figure 5 does not only depend on the oxygen content, but also on the temperature and the amount of organic matter in the waste water. The amount of organic matter in waste water is expressed by the term BOD_5 (biological oxygen demand). According to [85], no sewer slime is formed for $\text{BOD}_5 \leq 50 \text{ mg/l}$, so that no hydrogen sulphide is formed. The H_2S formation is a biological process which is dependent on both the amount of nutrients (BOD_5) as well as the temperature. Taking account of these influencing parameters, the term effective BOD (EBOD) value has been coined, which is expressed by the relationship:

$$\text{EBOD} = \text{BOD}_5 \times 1.07^{(T-20)}$$

According to Table 18, and depending on this value, the flow rate must be higher to prevent the formation of H_2S . However, depending on the flow rate and the length of the sewer, the oxygen content continually decreases and the value drops below 0.1 mg/l , so that the anaerobic zone grows strongly at the expense of the aerobic zone. The intensive microbial sulphate reduction produces a lot of hydrogen sulphide and hydrogen sulphide ions which then enter the waste water and the sewer gas. The processes that take place under primarily anaerobic conditions are represented schematically in Figure 6.

Type of attack	Attack by e.g.	Loading by common municipal waste waters pH: 6.5 to 10	Resistance of the concrete is sufficient when:			
			Limiting values in waste water		Existing concrete property	
			Contents	Loading	Permanent	Short-term
Dissolution by leaching	soft water	none	–	–	–	w/c ≤ 0.50 and water penetration depth of ≤ 3 cm acc. to DIN 1048
Dissolution by acid attack	inorganic acids sulphuric acid hydrochloric acid nitric acid		inorgan. acid	pH > 5.5	pH > 4	
	organic acids		organic acid	pH > 6	pH > 4	
	lime-dissolving carbonic acid	CO ₂ < 15 mg/l	CO ₂	≤ 40 mg/l ¹⁾	≤ 100 mg/l ¹⁾	
Dissolution by exchange reaction	magnesium	Mg ²⁺ < 100 mg/l	Mg ²⁺	≤ 1,000 mg/l		
	ammonium	NH ₄ -N < 100 mg/l	NH ₄ -N	≤ 200 mg/l		
	chloride	Cl ⁻ < 250 mg/l	Cl ⁻	≤ 3,000 mg/l	≤ 10,000 mg/l	
Expanding	sulphate ions	SO ₄ ²⁻ < 250 mg/l	SO ₄ ²⁻	≤ 600 mg/l	≤ 2,000 mg/l	without high sulphate-resistant cement
				≤ 3,000 mg/l		with high sulphate-resistant cement
Loading by frost or by de-icing salts	effect of frost	not direct – addition of moisture				concrete > B 45

1) This attack generally only occurs in storm water sewers which, according to the planning, are also used to carry large amounts of soft water that contain CO₂, e.g. surface water from mountain regions

Table 17: Type and limiting values for corrosive loading by municipal waste water in cement-bonded components in waste water installations [77]

For the subsequent processes, the pH value of the waste water is decisive. In well-ventilated municipal waste water, the pH value lies in neutral to weakly alkaline range, i.e. according to Figure 7, mainly hydrogen sulphide and a little sulphuric acid is present. However, if the pH of the waste water is 6.0, then 90 % of the total amount of dissolved sulphides are present as H_2S . The hydrogen sulphide dissolved in the waste water does not attack the sewer wall. However, in the region of the sewer gas, the hydrogen sulphide is absorbed by the damp sewer walls, particularly in the regions of the water surface and the crown of the sewer.

Flow rate of the waste water m/s	Effective BOD_5 mg/l
0.30	55
0.45	125
0.60	225
0.75	350
0.90	500
1.05	690
1.20	900

Table 18: Required flow rates in the sewer to prevent the formation of hydrogen sulphide [85]

The bacteria of the genus *thiobacillus* oxidise the hydrogen sulphide to sulphuric acid. Some of the H_2S is oxidised to elementary sulphur. The formation of the acid is initiated by the bacteria *thiobacillus thioparus* and *thiobacillus denitrifikans* which are active in a pH range of 4.5 to 8.0. When a pH of 4.5 is attained, the metabolism of these bacteria stops. The bacteria of the species *thiobacillus thiooxidans* then take over the further oxidation of hydrogen sulphide. These bacteria are active between pH 1 and pH 6 (optimum value pH 2 to pH 3) and produce large amounts of sulphuric acid. The processes described above assume a damp sewer wall.

Figure 8 gives an idea of the concentrations of sulphuric acid formed on the sewer wall; these values are based on the investigations carried out by Schremmer [86, 87].

The H_2SO_4 content in the condensed water is essentially independent of the H_2S content of the sewer gas, but clearly dependent on the temperature. Thus, after 12 weeks at temperatures of 291 K (18 °C), sulphuric acid concentrations of 5 to 6 % are obtained. This acid concentration represents a maximum value and was confirmed by investigations in the USA [87].

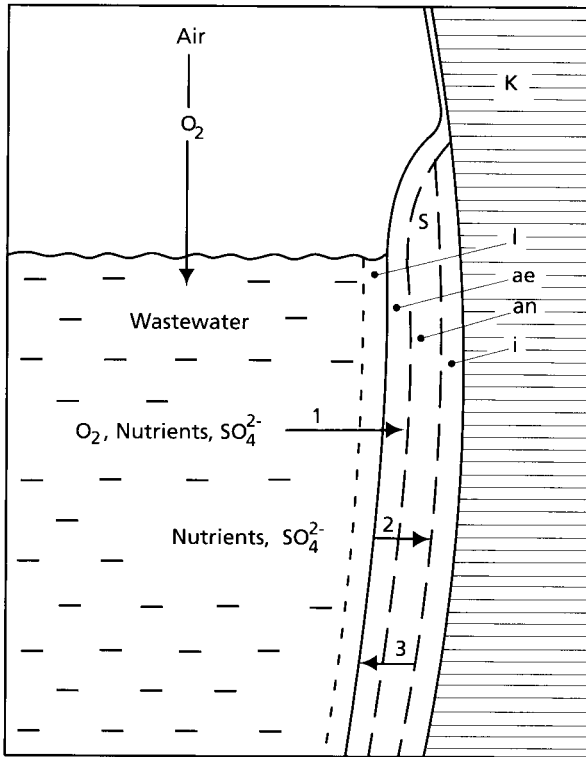


Figure 5: Schematic representation of the basic processes in an aerobic or semi-aerobic gravity-flow pipeline (dissolved oxygen > 0.5 mg/l; traces of hydrogen sulphide and hydrogen sulphide ions) [84]

- K = sewer wall
- l = zone of laminar flow
- s = sewer slime (layer thickness 1–2 mm)
- ae = aerobic zone
- an = sulphate-reducing anaerobic zone
- i = inert anaerobic zone
- 1 = diffusion of dissolved oxygen, sulphate ions, nutrients etc. into the aerobic zone of the sewer slime.
- 2 = diffusion of organic nutrients (hydrogen donors) and sulphate ions into the sulphate reduction zone
- 3 = diffusion of the H_2S or HS^- into the aerobic zone with subsequent microbial oxidation

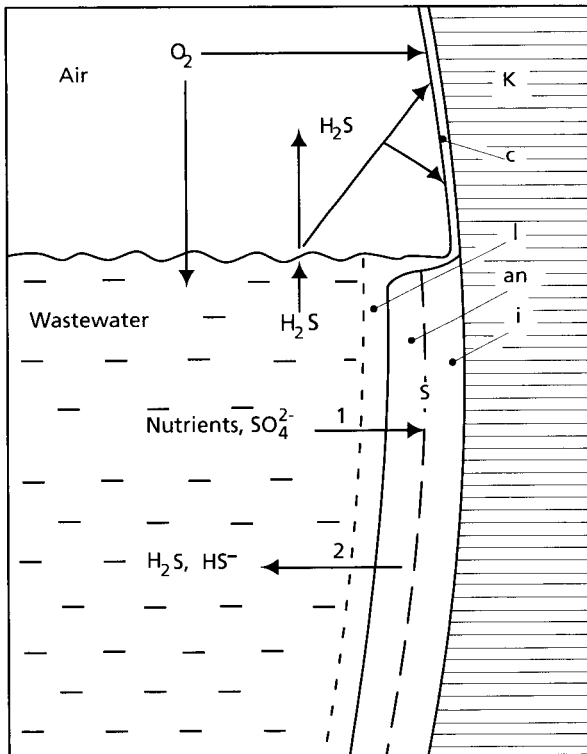


Figure 6: Schematic representation of the basic processes in an anaerobic gravity-flow pipeline (dissolved oxygen < 0.1 mg/l; hydrogen sulphide and hydrogen sulphate ions are present) [84]

K = sewer wall

l = zone of laminar flow

S = sewer slime (layer thickness 1–2 mm)

an = sulphate-reducing anaerobic zone

c = condensed water on the sewer wall (via the H_2S contained in the sewer gas; H_2S is subsequently oxidised to SO_4^{2-} by microbes)

i = inert anaerobic zone

1 = diffusion of organic nutrients (hydrogen donors), sulphate ions etc. into the zone of sulphate reduction.

2 = diffusion of the H_2S or HS^- formed in microbes in the sulphate-reducing zone of the sewer slime into the waste water

pH value of condensed water droplets on the sewer wall	S_2 – the existing or expected sulphide concentration in free cross-section (H_2S), ppm	No. of cells	Level of corrosive attack	Removal rate of the concrete surface per year	Time until remediation measures are necessary in years	Comments
		1)	2)	3)	4)	
14						
13						
12						non-carbonatised concrete
11						
10						
9	8.5					carbonatised concrete
8		0 – 10 ²	weak	loss of sand	> 80	
7						
6.0						
5						
	< 0.5	10 ³ – 10 ⁵	medium	< 0.5	> 40	
3.5						
3	≥ 0.5	10 ⁶ – 10 ⁸	strong	≥ 0.5 mm	> 5	
2						

1) The number of cells refers to *thiobacillus thiooxidans* and gives the number of cells per 1 mg protein in the sewer wall

2) The method chosen here to evaluate the level of attack is not in agreement with DIN 4030

3) The data is estimated and is partly based on experience and partly on laboratory investigations

4) The data is estimated and is based on experience

Table 19: Information on the occurrence of biogenic sulfuric acid corrosion of concrete [88]

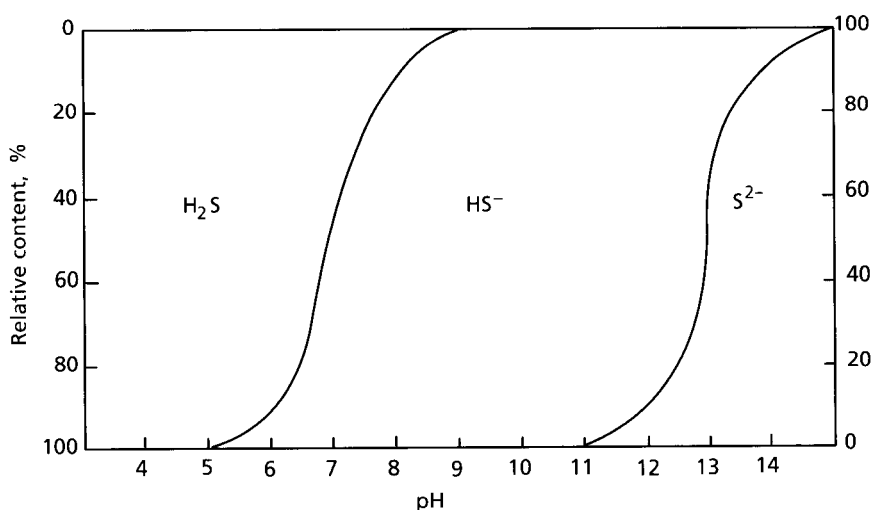


Figure 7: Influence of the pH value on the equilibrium hydrogen sulphide/hydrogen sulphide ion and hydrogen sulphide ion/sulphide ion at 293 K (20°C) water temperature. According to DEV 1975, altered slightly [84]

Even though less sulphuric acid is formed at temperatures of 283 K (10°C) than at 291 K (18°C) (see Figure 8), the H_2SO_4 concentration of 0.5% (pH 1.2) formed at this temperature is so strong that corrosive attack of the sewer walls must be expected. According to the current level of knowledge, H_2S contents of ≤ 0.5 ppm do not lead to the formation of sulphuric acid [87].

The sulphuric acid formed on the sewer wall leads to acid attack of cement-bonded components, and corrosion rates of 3 to 6 mm/a (120 to 240 mpy) can be expected [89]. In addition to acid attack, depending on the C_3A content of the cement and the density of the concrete, it must be expected that voluminous tricalcium aluminate is formed which leads to the disintegration of the concrete.

According to [90], concretes with limestone aggregates only offer advantages in the case of attack by biogenic sulfuric acid corrosion. In the case of other acids that react with limestone to produce soluble corrosion products, quartzite aggregate materials are to be preferred.

Table 19 gives information on biogenic sulfuric acid corrosion and provides a good summary of the processes described above [88].

The explanations given to this point are based on gravity-flow sewers. In forced-flow pipelines, large amounts of hydrogen sulphide are formed during passage, but because of the constant complete filling of the pipeline they remain in the waste water and do not lead to corrosive attack. At the end of forced-flow pipelines, the hydrogen sulphide contained in the waste water can outgas into the atmosphere and can lead to strong corrosive attack of cement-bonded and metallic components (e.g. manhole steps) in partially filled installations, e.g. pump sumps, following the described processes. The results summarised in Table 20 were obtained from detailed investigations in waste water pipeline systems [91, p. 22].

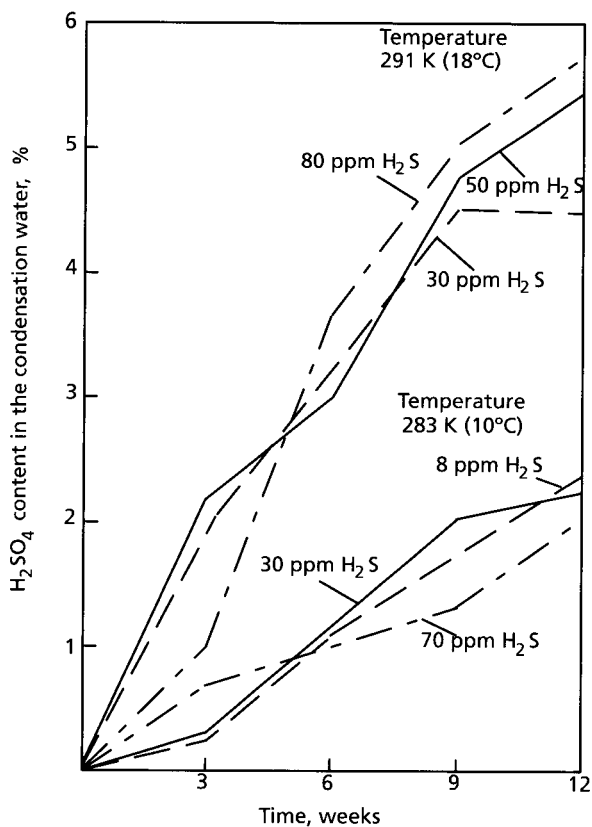


Figure 8: Formation of sulphuric acid (% H_2SO_4) in dependence upon the H_2S content, the temperature and the time [87]

- 5 % H_2SO_4 = pH 0.2
- 0.5 % H_2SO_4 = pH 1.2

In earlier times, especially in countries with a warm climate, **biogenic sulfuric acid corrosion (BSAC)** was often found, this phenomenon is also becoming increasingly common in countries with a more moderate climate. According to [91, p. 89] and on the basis of practical experience, there is a risk of BSAC in the types of waste water treatment facilities listed in Table 21.

In the literature, empirical equations have been proposed for the estimation of the biogenic sulfuric acid corrosion. These are largely based on experience gained in the USA. These equations are individually discussed in detail in [91, p. 111].

Location of investigated site	Operating time years	Partial filling max. η	Waste water		Atmospheric volatile sulphur compounds ppm	Approx. depth of damage mm	Comments
			Temperature K	Max. sulphide content mg/l			
Hamburg Sanitary sewage collector	10	0.20	290.7	3.9	13.7	40	discharge shaft of 2 forced-flow pipelines with flow times day/night = 2.8/8 h; concrete pipe ND 1000 with thin epoxy resin coating
	10	0.13	290.6	5.0	8.3	10	discharge of settled sludge; concrete pipe ND 1500 with thin epoxy resin coating
	10	0.17	291.7	5.6		10	discharge of the overflow from faeces sludge collecting basins; turbulences caused by deflection; concrete pipe ND 1800 with thin epoxy resin coating
	10	0.28	290.3		1.1	10	discharge of a forced-flow pipeline carrying waste water that didn't contain sulphides; very turbulent discharge; outgases from the collected waste water contained sulphides; in-situ concrete pipe ND 1550/2000, uncoated
	10	0.25	290.0	1.3	4.1	10	drop structures in the floor of in-situ concrete pipe ND 1550/2000, uncoated

Table 20: Summary of the investigated corrosion damage in sewer networks [91, p. 22]

Table 20: Continued

Location of investigated site	Operating time years	Partial filling max. η	Waste water		Atmospheric volatile sulphur compounds ppm	Approx. depth of damage mm	Comments
			Temperature K	Max. sulphide content mg/l			
Hamburg Sanitary sewer pipe	45	0.35	291.1	0.5	0.03	10	30 m above the junction of a forced-flow pipeline with flow times day/night = 1/3 h, exposed aggregate concrete-type structure of the surface of the concrete pipe; no indications of corrosion advance
Mannheim Combined sewer, main supply sewer	30	0.13	295.2	1.3	0.7	4	collector ND 3050/2900 made of non-reinforced in-situ concrete B 15 with approx. 30 mm facing; facing partially flaked off; effect of biogenic sulfuric acid corrosion and flaking due to great porosity caused by the capillary absorption of the concrete
Copenhagen Sump of pump work Amarken, combined system	25		287.9	1.5	1.0	12	exposed aggregate concrete-type structure in the pump sump; outgasing due to turbulent discharge into the sump; gradient of floor: 1–2%, even in small pipe diameters

Table 20: Summary of the investigated corrosion damage in sewer networks [91, p. 22]

Table 20: Continued

Location of investigated site	Operating time years	Partial filling max. η	Waste water		Atmospheric volatile sulphur compounds ppm	Approx. depth of damage mm	Comments
			Temperature K	Max. sulphide content mg/l			
Munich Combined sewer	10	0.08	290.2	0.3	1.3	3	sewer made of in-situ concrete with calcareous aggregates ND 2400/1900; faced up to approx. 2/3 height; measuring point lies approx. 3.3 km below a forced-flow pipeline; palm (hand)-sized flaking of facing in the waste water region; pH value of the condensed water approx. 6.0 at the time of investigation (no BSAC)
Frankfurt Airport sanitary sewer	30	0.66	294.8	10.6	23.0	10	discharge shaft of a forced-flow pipeline with flow times day/night = 1.4/4.5 h. Stoneware pipeline made of sewer bricks (soft jointing material); already 1–2 mg/l sulphide in inlet to pumping station
	30	0.66	295.8	2.8	40.1		drop structures in the pipe floor; stoneware pipeline ND 500; concrete shafts replaced by FRP shafts
Hanover Sanitary sewer collector	14	0.3	294.0	5.6	9.5	10	collecting area with several forced-flow pipelines; concrete pipes ND 1000 to ND 1400 with a thin epoxy resin coating; some deposits in the floor region; influenced by waste water from a slaughterhouse (COD up to 2000 mg/l)

Table 20: Summary of the investigated corrosion damage in sewer networks [91, p. 22]

For forced-flow pipelines and very long sewers, the most important calculation equations for the estimation of the biogenic sulfuric acid corrosion (BSAC) in connecting sewers and installations are discussed in [92]; they are briefly discussed below. It is known that outlets of forced-flow pipelines contain large amounts of hydrogen sulphide which, on transition into gravity-flow sewers, lead to strong corrosive attack by BSAC in these pipelines. The following equation can be used for a rough estimation of the hydrogen sulphide formed in forced-flow pipelines:

$$\text{mg S/L} = t/D$$

where t denotes the flow time in minutes, which is calculated from the flow rate v and the length L of the forced-flow pipeline; D is the pipe diameter. The sulphide contents estimated with this equation for $v = 1.7 \text{ m/s}$ and $L = 10 \text{ km}$ for pipe diameters 10 and 100 cm are given in Table 22. The H_2S contents listed in the Table, which were taken from Figure 7, were determined for the pH values 6 and 8 of the waste water. The influence of the pipe diameter can be clearly seen, i.e. much more hydrogen sulphide is formed in the pipelines with a small diameter than in pipelines with a large diameter.

Waste water treatment facilities
Forced-flow pipelines of individual pumping stations and of large forced-flow drainage systems (> 1000 m) which discharge into a gravity-flow sewer
Inter-regional drainage systems with a central waste water treatment plant
Waste water collectors that have been dimensioned for the future and are not working to full capacity
Waste water collectors and waste water sewers with insufficient gradient for the waste water they carry
Drainage system, into which there is constant or intermittent flow of waste water which already contains hydrogen sulphide (e.g. from estate waste water treatment plants, animal husbandries and certain types of commercial and industrial plants).

Table 21: Waste water treatment facilities in which hydrogen sulphide can be formed [89, p. 89]

Taking into account a limiting value of $0.1 \text{ mg H}_2\text{S}$ per liter below which no biogenic sulfuric acid corrosion is to be expected, there is a risk of BSAC only in pipes of large diameter and pH values of 8.

Whilst the conditions in forced-flow pipelines are reasonably clear, this is not the case for gravity-flow sewers. The reason for this lies in the interaction of the following parameters:

- hydraulics (gradient, discharge quantity)
- geometry (sewer slime)
- biology (EBOD).

Flow time <i>t</i> min	Pipe diameter <i>D</i> cm	Sulphide concentration mg/l	pH value	H ₂ S content mg/l
100	10	10	6	9.1
100	100	1	6	0.9
100	10	10	8	0.9
100	100	1	8	0.09

Table 22: Hydrogen sulphide concentrations in forced-flow pipelines of 10 km length and flow rates of 1.7 m/s [92]

The ATV Worksheet A 110 [93] gives the limiting values for the sedimentation-free operation. If the critical flow rates and critical gradients do not drop below the values given in this Table, then there are no deposits, i.e. the probability of H₂S formation is negligible, so that there is no risk of corrosion as a result of biogenic sulfuric acid corrosion. The two critical values are valid for half-filling $h_1/d = 0.5$, as well as for the partially filled state $h_1/d \geq 0.3$. In the partially filled range $0.1 > h/d < 0.3$, the critical flow rate must be taken as approx. 10 % higher.

In the USA, an estimation is carried out using the A/B curves (Figure 9). Above curve A only a negligible amount of H₂S is formed; below curve B several tenths of mg sulphide can occur. In order to carry out estimations using values other than EBOD = 500 mg/l, the gradient of the floor, J_2 , is calculated according to the equation:

$$J_2 = J_1 \cdot \text{EBOD}_2 / \text{EBOD}_1$$

For an estimation of the **biogenic sulfuric acid corrosion**, taking account of the influencing parameters given above, Pomeroy's "Z equation" can be used:

$$Z = \frac{3 \cdot \text{EBOD}}{J^{1/2} \cdot Q^{1/3}} \cdot \frac{U}{b_t}$$

Z	index of dissolved sulphides, which is evaluated according to Table 23
EBOD	effective BOD ₅
J	pipeline gradient, absolute
Q	discharge quantity, l/s
U/b _t	ratio of the wetted surface of the sewer to the width of the surface according to DIN 4263 [94].

In the case of very low gradients and the following partial degrees of filling, an rough estimation can be made:

5% partial filling	$Z = 32 \times \text{EBOD}$
15–50% partial filling	$Z = 16 \times \text{EBOD}$

For Z values up to 5000, the formation of H_2S is not expected. For greater Z values, an additional calculation must be carried out with regards to the influence of the sewer length.

According to [92] the following is valid:

$$\frac{d(S)}{d_t} = 0.32 \cdot 10^{-3} \cdot \text{EBOD} \cdot R^{-1} - 0.64(J \cdot v)^{3/8} \cdot d_m^{-1}$$

$d(S)/d_t$ sulphide formation rate in mg/l h
 R hydraulic radius, m (A/U, DIN 4263)
 J gradient, absolute
 v flow rate, m/s
 d_m average depth, m (A/b₁, DIN 4263).

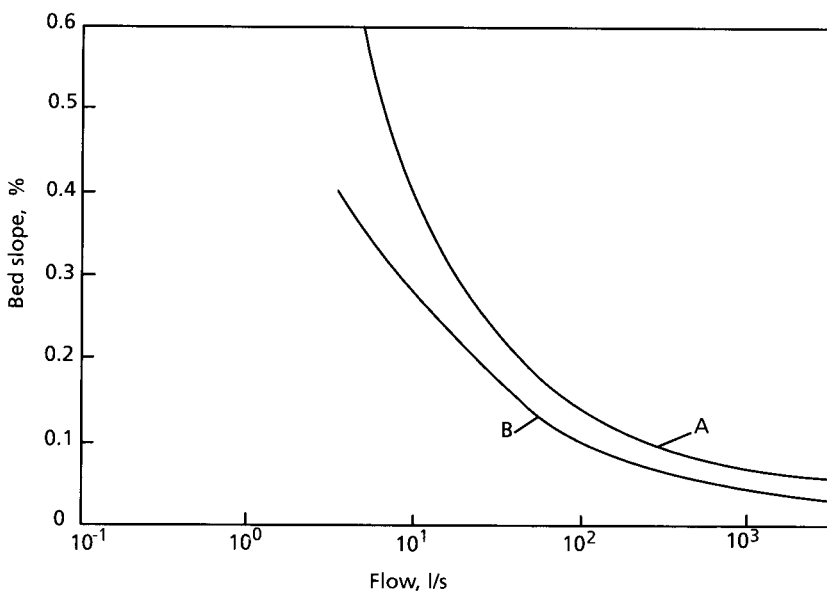


Figure 9: A/B curves for 500 mg/l EBOD [92]

After a certain time, a limiting value $(S)_{\text{lim}}$ is reached at which the sulphide loss by H_2S outgasing equals the formation of sulphide:

$$(S)_{\text{lim}} = \frac{0.5 \cdot 10^{-3} \cdot \text{EBOD}}{(J \cdot v)^{3/8}} \cdot \frac{U}{b_t}$$

Z Value	Expected conditions
< 5000	Hardly any sulphides or only in very low concentrations.
≈ 7500	Max. values of a few tenths mg/l S may occur; slight attack of cement-bonded materials; stronger attack at regions with high turbulence.
≈ 10000	Sulphides can occur in larger concentrations at times, which may also lead to odours. Stronger corrosion, particularly in regions with higher turbulence.
≈ 15000	Sulphide formation and odours more common. Rapidly advancing corrosion of cement-bonded materials.
> 25000	Dissolved sulphides present almost continuously. Smaller concrete pipes can be destroyed within 5 to 10 years.

Table 23: Evaluation of the Z value [92]

The permissible sewer length L for which there is still no biogenic sulfuric acid corrosion (BSAC) is given for $(S)_{\text{lim}} > 1 \text{ mg (S)/l}$ according to the relationship

$$L = v \cdot \Delta t$$

with

$$\Delta t = \left[\frac{d_m}{0.64 \cdot (J \cdot v)^{3/8}} \right] \ln \left[\frac{(S)_{\text{lim}}}{(S)_{\text{lim}}^{-1}} \right]$$

Where Δt is the flow time in hours until the sulphide content in the waste water reaches 1 mg/l.

The H_2S content in waste water is estimated according to these equations. For the determination of the corrosion rate by biogenic sulfuric acid corrosion, the transfer of the hydrogen sulphide dissolved in the waste water into the sewer gas is important. It is calculated with the following equation:

$$O_{\text{sw}} = 0.7 \cdot (J \cdot v)^{3/8} \cdot j \cdot (DS) \cdot (b_t / U)$$

- O_{sw} transfer of H_2S (as S in $\text{g/m}^2 \cdot \text{h}$) from the sewer gas into the pipe wall
 J sewer gradient, absolute
 v flow rate, m/s
 j j factor [92]
 (DS) total amount of dissolved sulphides, mg/l
 b_t width of the water level according to DIN 4263
 U surface of the sewer wall exposed to H_2S according to DIN 4263.

The corrosion rate is calculated with the O_{SW} value as follows:

$$c = 11.5 \cdot k \cdot O_{SW} \cdot 1/A$$

- c average corrosion rate (penetration depth), mm/a
- k correction factor, 0.8
- A alkalinity of the concrete, expressed as CaCO_3 equivalents (0.16 for concrete and reinforced concrete pipes)

As an approximation, the corrosion rate can be estimated for the following degrees of filling from the H_2S content determined in the waste water:

partial filling up to 5%: $c = 0.5 \text{ mg/l H}_2\text{S}$

partial filling 5–50%: $c = 1.0 \text{ mg/l H}_2\text{S}$

The processes described above for biogenic sulfuric acid corrosion refer to concrete installations made of the cements listed in DIN 1164 [73].

In concrete components, the concrete has a load-bearing function. Unprotected, it must withstand the aggressive stressing caused by waste water and by the sewer gas. For conditions of strong attack, the concrete components are given coatings and linings (Section D 1) in order to maintain the leakproofness as well as the load-bearing function. In pipes and fittings of ductile cast iron or steel, the metallic material bears the load. Waste water pipes of ductile cast iron and steel usually receive a cement mortar lining. This lining improves the hydraulic properties of the pipe compared to the unlined pipe and helps to prevent corrosion damage.

Processes to manufacture cement mortar linings as well as their requirements and tests are specified in DIN 2614 [95]. In the explanations to this standard, it is stated that the cement mortar linings are resistant to waste waters that correspond to the ATV Worksheet A 115 [79]. In waste waters which do not fulfil these conditions, cement mortar linings based on aluminous cement or those with cement mortars modified with plastics can be used.

Nowadays, ductile cast iron pipes for the transport of waste water receive a cement mortar lining based on aluminous cement. The resistance of these linings towards biogenic sulfuric acid corrosion was confirmed by field trials and laboratory investigations. According to [96], investigations of concrete waste water sewers made with aluminous cement exhibit good resistance towards BSAC.

Corresponding data is given in Table 24; the pH values measured on the pipe walls indicate biogenic sulfuric acid corrosion [96].

Experiments with cast-iron pipes carrying flowing waste water are reported in [97]. The results showed that these pipes can be used without limitations for waste waters with pH 5 to 9. For normal municipal waste waters, the application range is given as pH 5 to 12. The aluminous cement used in the cement mortar lining corresponds to the British standard BS 915 [98].

According to [96] and [97], the good resistance of the aluminous cement lining is due to the low solubility of the hydrates of the aluminous cement in mineral acids along with the low porosity of this lining.

Location	Service life years	Temperature K (°C)	pH value of the pipe wall
Durban, South Africa	30	¹⁾	2 – 5
Kuala Lumpur, Malaysia	30	307 (34)	4
Cairo, Egypt	10	¹⁾	1 – 2

¹⁾ no data given in the literature; the value is assumed to be 303 K (30 °C)

Table 24: Service life of gravity-flow sewers made with aluminous cement [96]

In a detailed investigation, ductile cast-iron pipes with aluminous cement linings that were made with different cements, were tested by means of simulation tests in a pollution gas cabinet to determine the behavior with respect to biogenic sulfuric acid corrosion (BSAC) [99]. These time-accelerated experiments reflect the correlation between the H₂S concentration and corrosion attack. This was confirmed by comparison with conditions in practice. The conditions of the one-year tests in the pollution gas cupboard were as follows:

- temperature 303 K (30 °C)
- relative humidity $\geq 95\%$
- inoculation with bacteria that product sulphuric acid (thiobacillae)
- sulphuric acid precursors in excess, 10 ppm gaseous H₂S.

The results of the tests with Portland cement and aluminous cement gave the following results:

- both in the experiments with Portland cement as well as with aluminous cement the initial pH value of 6 had dropped to pH 1.0 to 1.3, i.e. sulphuric acid had been produced on the surface of the samples
- the number of thiobacillae cells lay between 10^4 and 10^7 cells/cm² for the Portland cement and the aluminous cement
- the loss of material was very different for the two types of samples: 60 % for Portland cement and 2 to 5 % for aluminous cement.

Figure 10, which shows the dependence between the average number of cells, N, and the loss of material, illustrates the different behavior of the investigated cements. The aluminous cement lining exhibited the best behavior.

According to [99], the aluminous cement lining of ductile cast-iron pipes is stated as being very resistant to strong biogenic sulfuric acid corrosion; this is reflected by the limiting parameters of the range of applications for the aluminous cement lining (Table 25) [77].

Polymer concrete

Polymer concrete is widely used in drainage gutters. The permissible total weight plays a particular role along with the high corrosion resistance. Table 26 contains the results of resistance tests carried out on samples of polyester concrete.

In polymer concrete (thermosetting resin concrete) binders based on unsaturated polyester or epoxy resins are used instead of a cement binder [81, p. 199]. Pipes made of polymer concrete are manufactured with nominal widths from ND 300 to ND 3500 and are either non-reinforced, standard reinforced or pre-stressed. These pipes are primarily used and tested as waste water pipelines in the chemical industry.

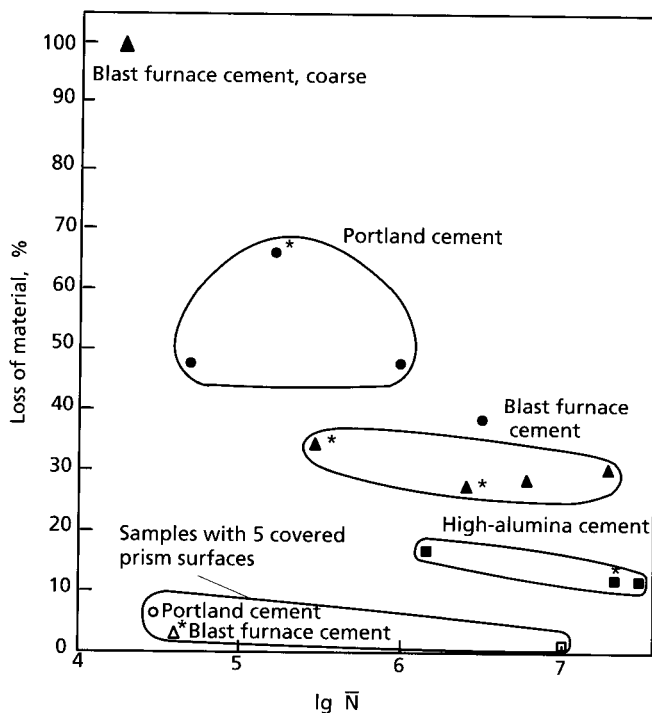


Figure 10: Relationship between the average number of cells N and the loss of material for the 6th sampling (344th day) [99]

* Samples contain acrylic-resin dispersion

The properties and tests of pipes made of polymer concrete for underground gravity-flow and forced-flow pipelines for the drainage of domestic waste waters are described in [100]. The walls of these pipes have the following two-layer structure:

- outer pipe wall, polymer concrete with 90 % quartz sand aggregates, maximum grain diameter 16 mm
- inner pipe wall, 2 mm thick resin coating, proportion of resin ≥ 35 %, of quartz sand ≤ 50 %, of glass fibres 15 %.

Parameter	Type of lining, DIN 2614	
	I-S	I-T
Flowing medium		
pH value	6.5–12	4.5–10
Mg ²⁺ , mg/l	≤ 500	limit of solubility
SO ₄ ²⁻ , mg/l	≤ 3000	limit of solubility
NH ₄ ⁺ , mg/l	≤ 200	≤ 2000
Ca ²⁺ , mg/l	1	0 (rainwater)
Lime dissolving carbonic acid, mg/l	≤ 7	limit of solubility (rainwater)
Sewer gas		
H ₂ S concentration in the free cross-section of the sewer, ppm	< 0.5	≤ 0.5
pH value in the droplets of condensed water on the sewer wall	> 3.5	≥ 1.0

Table 25: Limiting parameters of the range of application of cement mortar linings of ductile cast-iron pipes, steel pipes and fittings, taking DIN 2614 [77] into account

There must be good adhesion between the outer and inner parts of the wall with an adhesive strength of $\geq 22 \text{ N/mm}^2$. These pipes are connected together by push-on couplings made of glass-fibre-reinforced polyester resin.

The tests can be briefly described as follows:

- thickness of the resin-rich inner layer
- grading curve of the quartz sand
- adhesion between the outer and inner parts of the wall: pressure test according to [101]
- wall roughness according to [102]
- temperature behavior according to [103]
- chemical resistance, sulphuric acid pH 1, sodium hydroxide pH 10 [104]
- wear resistance according to [102]
- watertightness according to [102]
- load-bearing capacity according to [105]
- pulsating fatigue strength [106].

The couplings were tested with regards to the glass content, the weight per area (g/m^2) of the glass and the structure of the laminate [107].

Medium	Mass change¹⁾ %	Volume change¹⁾ %	Changes to the sample¹⁾
Tap water	+ 0.67	+ 0.75	none
Lime water, saturated	+ 0.35	+ 0.37	none
Soap solution, 10 g/l	+ 0.72	+ 0.31	slight water-repellent "waxy" surface, fine white soapy deposits in places
Soda solution, 50 g/l	+ 0.20	+ 0.26	isolated attack of aggregate grains with rust-colored discoloration
Synth. detergent solution, 50 g/l	+ 0.42	– 0.18	none
Sodium hydroxide solution, 5 %	+ 1.39	+ 0.03	slight attack, primarily on the fine-grained plastic mixture; surface: slight brown discoloration, grey pores, and slightly softened; hair-cracks in unworked narrow lateral surfaces
Hydrochloric acid, 5 %	– 0.96	+ 0.37	slight attack with dissolution, primarily on fine-grained plastic mixture; surface with grey pores and slightly softened; isolated attack of aggregate grains (rust-colored discoloration); storage medium tinted yellow
Hydrochloric acid, 10 %	– 1.02	+ 0.04	as described for 5% hydrochloric acid, storage medium: yellow
Sulphuric acid, 10 %	+ 0.15	+ 0.48	grey, slightly softened surface; isolated attack of aggregate grains (rust-colored discoloration)
Toluene	+ 0.09	+ 0.48	none
Mineral oil	+ 0.17	+ 0.24	brownish discoloration of the surface by the mineral oil; isolated small specks of rust
Petrol	+ 0.15	– 0.60	brownish discoloration of the surface by petrol, isolated small specks of rust (mostly aggregate grains)

1) These tests were carried out over a period of 28 days at room temperature. For the most part, there were no significant changes in the mass or volumes as well as no significant changes of the samples. Only for storage of the samples in sodium hydroxide and hydrochloric acid there was a somewhat more clear increase or decrease in the mass (changes of approx. 1–1.5%), whereby slight attack – primarily of the fine-grained plastic mixture – occurred. Clear indications of attack or changes of the samples were not observed in any of the storage tests.

Table 26: Resistance of polymer concrete towards various media [89]

Sulphur concrete

Sulphur concrete consists of lime-free, quartzitic aggregates and polymerised sulphur as a thermally hardening binder. Polymeric sulphur is almost pure elementary sulphur which, for example, is treated with dicyclopentadiene as an activator and stabiliser. It confers thermoplastic properties to sulphur concrete as well as high density and resistance to acids and salts.

Sulphur concrete is mixed and poured at a temperature of approximately 398 to 408 K (125 to 135 °C). It is ready for use immediately after cooling, i.e. in minutes to about one hour, depending on the thickness of the workpiece. The shaping, casting and shuttering of sulphur concrete components is carried out in a manner similar to that used to fabricate cast components [108].

Figure 11 shows the design and technical casting structure of a shaft floor made of sulphur concrete.

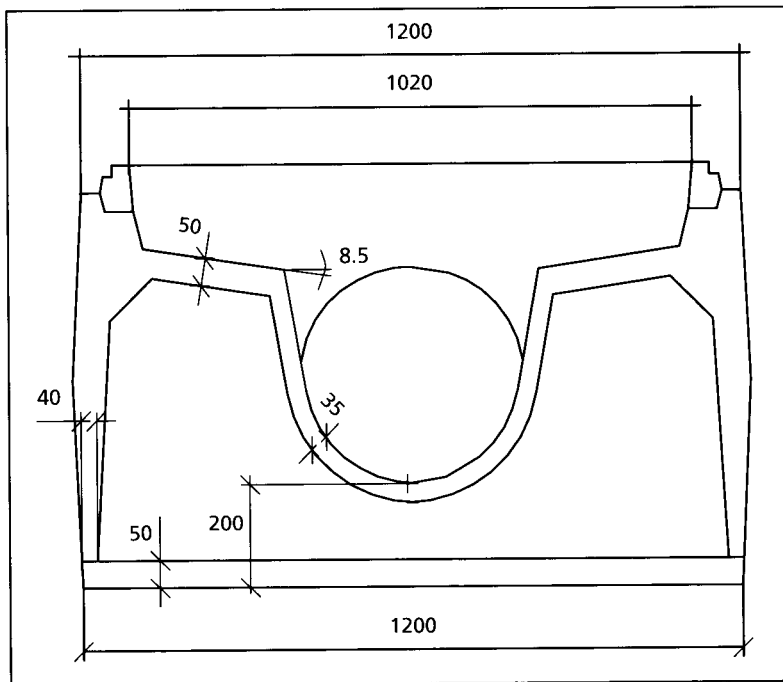


Figure 11: Assembly dimensions and actual dimensions (mm) of a shaft floor [109]

After cooling, i.e. within a few hours, the sulphur concrete has the following properties at 293 K (20 °C):

- compressive strength 50 to 70 MPa
- bending/tensile strength (long-term) 7 to 8 MPa
- water absorption $\leq 0.10\%$

- air content (entrapped air) 3 to 6 %
- thermal coefficient of expansion ≤ 13 to $15 \times 10^{-6} \text{ K}^{-1}$
- modulus of elasticity 40 to 50 GPa
- density 2.3 to 2.5 t/m^3

The chemical resistance for the pH range 1 to 11 is given in [109]. After 6 days in a 30 % hydrochloric acid solution, normal Portland concrete is strongly damaged while sulphur concrete is completely undamaged.

B 5 Acid-resistant building materials and binders (putties)

Sewer bricks are used as acid-resistant materials for buildings and sewers in waste water installations. Sewer bricks are made of loam, clay or argillaceous materials with or without additives and are sintered. They must fulfil certain requirements and may only be designated as sewer bricks when they comply with the minimum or maximum test requirements specified in the above standard. The material used for sewer bricks should be free of inclusions that expand, e.g. lime, as well as damaging materials that cause spalling and blooming in the finished product.

The test for the acid resistance is carried out on granulated brick material with a mixture of 3 parts 10 % sulphuric acid and 1 part 10 % nitric acid (1 h).

The usual egg-shaped cross-section of sewers was used for the first time in 1846 in London and in 1870 in Germany. From the hydraulic point of view, it is particularly advantageous for the drainage of large amounts of strongly fluctuating waste water, e.g. in combined sewers with a small amount of dry-weather flow. Mouth-shaped cross-sections are used when the height is limited and larger amounts of water must be carried. This shape is particularly favorable from the static point of view, as it follows approximately the course of the pressure line [68].

Sewer bricks are widely used in prefabricated shafts. The gutters and tread of the lower parts of the shaft are lined in the works. In older sewers, some of which are older than 100 years, the jointings have been attacked by waste water and destroyed to a large degree, although the sewer bricks are still well-preserved. Nowadays, the joints are filled with particularly sulphate-resistant mortar or plasticised mortars.

If the joints in the masonry of old sewers are not properly remediated in time, then there may be leakages, one or more bricks may fall out of the masonry or even the arched ceiling may collapse. These types of damage and their consequences are intensified by high-pressure flushing, which is the common method used nowadays to clean the sewers [110].

B 6 Glass

B 7 Quartz materials and quartz glass

The use of glass pipes commenced in chemical laboratories and production plants for chemical processes [111–113]; they are now used in waste water pipelines [114–117].

Of the many different types of glass [118], borosilicate glass 3.3 [119] has proved to be particularly advantageous for the above applications on the basis of its properties.

Table 27 gives the limited application range of glass pipes in the drainage of buildings according to the test reports of the Deutsches Institut für Bautechnik (German Institute of Building Technology), Berlin [114]. According to these results, glass pipes are not permitted for installation as a basic underground pipeline or in inaccessible areas of buildings or outdoors.

Range of application
Glass pipes
• service pipeline, connection pipeline • downpipes • gathering line • vent pipe • storm water sewer in buildings

Table 27: Range of application of glass pipes in the drainage of buildings according to DIN 1986, Part 4 [114]

The use of glass pipes in waste water sewers was investigated in research projects in Hamburg and Munich and is described in [116] and [117], respectively. In Münster, waste water has been flowing through a glass sewer (ND 1200) since 1990 and has proved suitable up to now and has even been cleaned using high pressure without damaging the glass or the joints.

During the 3rd International Pipeline Congress in Hamburg, a demonstration construction site was visited in which a 70 m long, egg-profile sewer built of masonry in 1870 was remediated with a lining of corrosion-resistant, precision-made glass fittings [117].

Table 28 lists the material properties of borosilicate glass 3.3 and its composition. The major portion of the alkaline material contained in common glass is replaced by boron trioxide (12–13 % B₂O₃).

The characteristic material property is the extremely low coefficient of linear expansion of $3.3 \pm 0.5 \times 10^{-6} \text{ K}^{-1}$, (from which the designation of the borosilicate glass 3.3 is derived) and this results in the high thermal shock resistance. The linear coefficient of expansion is approximately one third lower than that of common glass; only quartz glass, which has a value of $0.6 \times 10^{-6} \text{ K}^{-1}$, is more favorable. A further prerequisite

Composition:	
SiO ₂	approx. 80%
B ₂ O ₃	approx. 12–13%
Al ₂ O ₃	approx. 2%
Alkaline materials	approx. 4%
Properties:	
Density	2230 kg/m ³
Heat capacity, specific	0.91 kJ/kg · K
Thermal conductivity, average value between 293–473 K	1.3 W/m · K
Longitudinal coefficient of expansion	3.3 x 10 ⁶ /K
Thermal shock resistance	120 K
Permissible stress	
• from tension or bending	K/S = 6 N/mm
• from pressure	K/S = 100 N/mm
Modulus of elasticity	64 kN/mm

Table 28: Composition and properties of borosilicate glass 3.3 [120]

for the use of glass pipes was the development of elastic pipe couplings for the end-flanged pipes and the availability of the corresponding prefabricated lengths and fittings with transitional pieces which can also be used to connect the glass pipes to other materials. Pipe couplings are usually equipped with PTFE seals which provide sufficient corrosion resistance under increased loading conditions.

Borosilicate glass pipes are resistant to almost every substance. Exceptions are hydrofluoric acid, highly concentrated phosphoric acid and caustic solutions of high concentration and temperature. The literature [120] contains test values of different glasses with regards to classifications of hydrolytic, acid and alkaline resistance. Data is given for the chemical resistance of Solidex® glass.

B 8 Enamel

In waste water technology, enamel is used for the corrosion protection of components made of steel and cast iron for the following range of applications:

- sanitary equipment; bath tubs, shower tubs, wash basins [121, 122]
- mountings and fittings.

The most important components of enamel are:

- refractory materials, such as quartz, alumina, zirconia, calcium oxide and titanium dioxide. The amount of quartz is decisive for the degree of chemical resistance
- fluxes, such as borax, boric acid, potash, soda.

Two enamelling processes have become established over the years which are characterised as follows:

- two-layer enamels that consist of a base coat and a top coat; these are used mainly where there is loading by aggressive substances
- one-layer enamels, also known as direct enamels; the enamel layer is applied directly to the material without an intermediate base coat. This type of enamel is used in waste water applications for e.g. in inner linings of mountings and fittings [123].

The enamelling process produces a composite material. During the melting process, the adhesive oxides in the enamel provide a good adhesion between the enamel and the iron-based material as a result of electrochemical processes. This intimate enamel/iron composite prevents undermining of the enamel layer which may start from mechanically damaged sites (defects). This ensures there is no rust formation under the enamel.

Because of the high electrical insulating capacity of the enamel layer, no cathodically active surfaces can form in the vicinity of the defects, this is in contrast to thin organic coatings. Therefore, the formation of a macroelement, which can lead to pitting corrosion, is not possible [124]. However, it must be pointed out that there is a risk of pitting corrosion at defects in the enamel layer if there are external cathodes present with an electrochemically more noble potential and which are in metallic connection with components made of iron-based materials. In the case of mountings, e.g. pushers, this can occur, as shown by a few practical examples of damage, if e.g. spindles of stainless steel are connected with metallic conduction to the housing made of ductile cast-iron.

For the enamel/iron composite, both the composition of a suitable enamel and its correct application as well as the selection of suitable iron-based material is important. In the experiments described in [125] and [126] it was shown that "black enamel" is not a suitable material, since this material does not exhibit long-term resistance. Cast-iron is often used in waste water installations as a material for mountings and fittings. The historical development of this material in these types of applications is reported in [127]. This development has led to spheroidal-graphite cast iron of grade GGG-50 (A 536, 1.7050) [128–130].

The roughness of metallic surfaces after fine machining (e.g. fine turning, grinding, flat-rolling) is much greater than that of enamel surfaces. Neither mineral components in water nor fungus cultures can adhere to the very smooth enamel surfaces formed by the flowing melt. A further advantage of these smooth surfaces is demonstrated by the internal enamelling of mountings with elastomer seals, e.g. in oval pushers or annular valves. The smooth surface of the enamel reduces abrasive

wear of the elastomer seals so that the operating forces of the mountings are markedly reduced.

Testing of the interior enamel of mountings and fittings of spheroidal-graphite cast iron is carried out according to DIN 3475, which also specifies the requirements [131].

B 9 Porcelain

Porcelain is used in waste water installations as sanitary objects. Immediately after drinking water has flowed into the sanitary object, it is designated as waste water. The precautional requirements to be made for hygienic reasons are decisive.

Because of its hard, smooth, non-porous surface, porcelain is a particularly suitable material for sanitary equipment. This also explains the wide use of this material in spite of its great sensitivity to fracture.

Porcelain consists mainly of feldspar and quartz along with kaolin clays, whereby Kaolinit or kaolin is based on aluminium silicate $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$. The composition of the raw materials and the firing temperature determine the properties of the porcelain, particularly its transparency and strength. There are two different types of material: high-melting hard porcelain, with better mechanical properties and temperature shock resistance than the more sensitive tender porcelain. In hard porcelain, the proportion of kaolin is 40 to 55 % (feldspar 15 to 25 %, quartz 20 to 40 %). In tender porcelain, the proportion of kaolin is 20 to 40 % (feldspar 20 to 25 %, quartz 25 to 30 %, whiteware clay 5 to 20 %) [132].

In the principles of construction and inspection from the Deutsches Institut für Bautechnik (German Institute of Building Technology), Berlin, [133] or DIN EN 997 for water closet bowls [134], it is required of the porcelain material, and continually tested, that the water absorption capacity of the fragments is not more than 0.75 %. Because of this and because of the additional glaze, the adherence of materials is prevented.

B 10 Stoneware

In agreement with the information given in [135], stoneware is a widely used material in waste water installations. It is used particularly for pipes and fittings as well as slabs and shells for egg-shaped and mouth-shaped profiles. The latter are joined together to give the corresponding sewer cross-sections. The basic raw material for stoneware is clay; opening materials, e.g. fireclay and water, are added during manufacture. The main components of stoneware clays are clay minerals and quartz sand as well as contaminants, such as organic materials, iron compounds, pyrites, lime etc. These basic materials are fired at a temperature of approximately 1473 K (1200 °C) to give a product with a great chemical resistance.

Stoneware is given a special surface by means of a glaze. The raw materials for the dipping glazes used almost exclusively nowadays are loam, feldspar, lime, dolo-

mite, clay and manganese dioxide. During the firing process, these react to give a silicate which increases the smoothness and wear resistance of stoneware pipes. The smooth surface has a very low roughness which facilitates cleaning and therefore operational maintenance.

The influence of the glaze on the density and corrosion resistance of stoneware is only very slight since the fragments themselves are dense and corrosion resistant. The hardness of the pipe surface is 8 to 9 on Mohs scale, so that there is practically no abrasion by the hard bed load transported by the waste water.

Stoneware resists corrosion by all chemicals, except for hydrofluoric acid – and this acid is rarely encountered in waste water. Stoneware is not attacked by the substances contained in waste water, in groundwater or in the soil.

In the explanations in DIN EN 295-2 [136], it is stated under the materials section that pipes and fittings made of stoneware must be fired to the sintering densification temperature. The glaze mainly consists of a glassy phase (melted phase, amorphous) whose proportion of the total weight should lie between 50 and 70 %. The direct determination of the proportion of the glass phase is not possible experimentally.

Pipes and fittings are classified as resistant to bending, while the connections are classified as flexible. They both have a very high corrosion resistance. Fittings can also be made by joining previously fired pieces. The surfaces of the products can be treated after firing.

The chemical resistance and wear resistance are verified in the standard for stoneware pipes. Testing methods are described for special requirements. This provides important statements for the long-term utilisation of stoneware pipes. An average service of 80 to 100 years is given in [137]. With regards to the damage caused to stoneware pipes during operation as a result of leaks in the couplings and cracks in the shaft of the pipe, other decisive parameters are taken into account in the evaluation of the material for remediation and renewal applications.

Based on the experience, it is proposed that not only the chemical resistance but also the mechanical loading during transport, installation, compaction, subsequent settling, subsidence and traffic loading are equally important in the evaluation of the service life [138].

Basic criticisms are made in [139] concerning the utilisation time of over 50 years on average in waste water drainage systems.

Stoneware pipes are standardised in nominal widths of ND 100 to ND 1200 with overall lengths of 1 to 3 m in 5 load-bearing classes, with and without sleeved couplings [140]. Generally, the sealing elements are integrated into sleeved pipes.

The main areas of application of stoneware pipes include basic pipelines for house and estate drainage as well as sanitary sewers and combined sewers or local sewer networks and in industrial applications that are operated as gravity-flow sewers or pipelines. According to DIN EN 295, Section 1.1 [140] a temporary overpressure is permissible. If the stoneware pipes are to be used for continuous operation in low pressure ranges, then the pressure for the test specified in this standard must be agreed upon by the manufacturer and the customer; whereby the highest value is 600 kPa (0.6 bar).

Special types of stoneware pipes include shafts, double-walled pipes for pipelines in drinking-water protected areas, perforated pipes for sicker pipelines on waste dumps or pipes with processed ends and increased wall thickness for underground pipe tunnelling.

Special test specimens are specified in DIN EN 295-3, [141] which are used to determine the pulsating fatigue strength under cyclic stress as a verification of their suitability for installation under road surfaces with predominantly non-stationary loading and compliance of the required safety factors.

Certain minimum requirements are specified with regards to the strength of adhesive joints of fittings bonded together after firing. According to this standard, after complete hardening of the test specimens, neither the adhesive material nor the adhesive surface of the stoneware components may fracture under a bending tensile stress of 0.5 N/mm^2 . Storage in test liquids is also specified.

Rubber seals are used as joining materials for the pipe couplings. If these are firmly attached to the pipes and fittings, no visible cracks may appear during the ozone test. Furthermore, polyurethane sealing elements and polypropylene sleeve couplings are used, for which special test requirements apply, see Section D 2. To ensure the exchangeability of the components, the dependence on the loading-bearing classes must be taken into account. Furthermore, it is also decisive for the joining system whether the inner diameter of the bell or the outer diameter of the spigot is the decisive reference size. Therefore, in the performance specifications, it is necessary to exactly define and label the loading-bearing class as well as the coupling system [140].

Stoneware pipes are particularly sensitive to fracture by impact loading, as may occur during transportation and dispatch. Therefore, before the pipes are installed they must be checked for possible cracks by means of a sound test. Hair cracks can be visualised with talcum powder. Pipes with very fine cracks that are not visible to the naked eye, are liable to burst at the site of the crack during an internal water pressure test with 15 bar (1500 kPa) [142].

During the conventional method of installation, the pipes must be carefully bedded and covered up. In addition, the storage conditions must be maintained as specified for the design load in the static calculations.

C

Organic materials

C 2 Bituminous compositions (bitumen, asphalt, pitch)

Bitumen and coal-tar pitch do not provide permanent corrosion protection of concrete pipes in waste water systems [143].

C 7 Polyolefins and their copolymers

C 8 Polyvinyl chloride and its copolymers

From the wide range of plastics, a few have proven particularly suitable over the years for use in waste water installations. It is worthwhile to treat the plastics which are used for pipes and fittings together in this section.

Table 29 lists the most important pipe materials and their use in the various areas of waste water technology [144]. Table 30 provides information on the properties of plastic pipes.

The most important material is rigid PVC, followed by high-density polyethylene (HDPE) [145]. A good review of the development of plastic pipes, particularly in waste water technology, is given in [146].

A summary of the quality regulations and DIN standards is given in [145]. The following information on the advantageous properties of rigid PVC for sewer pipes was taken from this report:

- time to rupture: > 50 years
- pulsating fatigue strength: at least 2×10^6 stress cycles
- operating temperature:
 - 318 K (45 °C) for $ND \leq 400$
 - 308 K (30 °C) for $ND \geq 400$
- chemical resistance:
 - sewer pipes made of rigid PVC are resistant towards waste water and all chemicals in this water (see also [147–149])

Pipe material	Connection or supply pipeline	Penstock	Collecting pipeline	Basic pipeline			Ventilation pipeline		Storm water pipeline	
				inaccessible in buildings			underground		indoors	outdoors
rigid PVC normal wall thickness ¹⁾	+	-	-	-	-	-	-	+	+	+
increased wall thickness ¹⁾	-	+	+	+	-	-	-	+	+	+
rigid PVC ¹⁾	-	-	-	+	+	-	+	-	-	-
rigid PVC with corrugated outer pipe ¹⁾	-	-	-	-	-	+	+	-	-	-
rigid PE ²⁾	+	+	+	+	-	-	+	+	+	+
HDPE ²⁾	-	-	-	+	+	+	+	-	-	-
rigid PE with profiled wall ²⁾	-	-	-	-	-	+	-	-	-	-
PVC-C ¹⁾	+	+	+	+	-	-	-	+	+	+
pp ¹⁾	+	+	+	+	+	-	-	+	+	-
ABS/ASA ²⁾	+	+	+	+	-	-	-	+	+	-

+ can be used; - is not to be used

1) hardly inflammable

2) normally inflammable

Table 29: Range of applications of plastic pipes for waste water pipelines [144]

Property	Rigid PVC	Rigid PE	PP	PVC-C	ABS/ASA
Density, g/cm ³	1.4	0.95	0.93	1.55	1.06
Yield stress, N/mm ²	55	23	30	70	45
Elongation at yield stress, %	5	14	16	5	10
Elongation at tear, %	20	800	700	10	20
Limiting bending stress, N/mm ²	95	30	44	–	110
Modulus of elasticity, N/mm ²	3,000	900	1,200	3,000	2,500
Notched impact strength, kJ/m ^{2 1)}	4	no fracture	no fracture	3	15
Impact strength, kJ/m ^{2 1)}	no fracture	no fracture	no fracture	no fracture	no fracture
Crystalline melting point, K	–	503	433	–	–
Heat distortion temperature, K ²⁾	356	338	373	378	373
Linear coefficient of expansion, K ⁻¹	0.8×10^{-4}	2×10^{-4}	1.5×10^{-4}	0.7×10^{-4}	0.9×10^{-4}
Thermal conductivity, W/m · K	0.15	0.42	0.23	0.12	0.15
Specific volume resistance, $\Omega \cdot \text{cm}$	$> 10^{16}$	$> 10^{17}$	$> 10^{18}$	$> 10^{15}$	$> 10^{16}$
Surface resistance, Ω	$> 10^{12}$	$> 10^{12}$	$> 5 \times 10^{13}$	$> 10^{12}$	$> 10^{12}$
Relative electrical constant	3.5	2.35	2.27	–	3.0

1) measured at 296 K (23 °C) and 50% humidity

2) measured with the Vicat procedure B

Table 30: Properties of plastic pipes [144]

- wear behavior:
compared to other materials used in sewers, pipes of rigid PVC always exhibited the smallest values of wear (see Figure 12). (This is also valid for other plastics.) [150, 151]
- hydraulic behavior:
 $K_b = 0.40$ mm for normal sewers of rigid PVC
 $K_b = 0.25$ mm for straight sewers, further information is given in [152]
- leakproofness: requirements, see [153, 154]
- deformation behavior: see [155, 156]

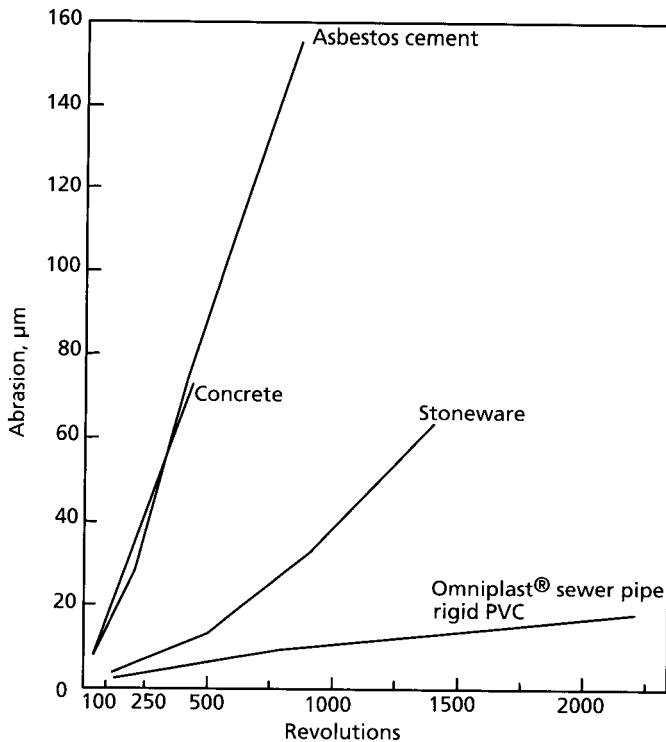


Figure 12: Results of wear experiments using the Wuppertal procedure [145]

Plastics of these material classes are also used for lining concrete pipes and sewer shafts; their application is described in Section D1.

C 11 Acrylic resins

In addition to the traditional materials, sanitary enamel (Section B 8) and sanitary porcelain (Section B 9), the use of acrylic resins in sanitary equipment is now established.

In addition to the general material specifications, there are special requirements regarding the thermal stability, the color fastness against UV radiation and the effect of hot water. An essential part of the tests is aimed at determining the behavior towards domestic cleaning agents and dyes.

Although much experience in the use of polymethylmethacrylate (PMMA) has been gained from other applications, e.g. Plexiglas® roofs and lamps for ceilings or vehicles, with respect to its resistance to light, weather, color fastness and general ageing, extensive special investigations on its suitability and usability were still necessary for its launch onto the market.

Determination of the Mohs hardness, wear and scratch resistance tests as well as the determination of bacterial growth on sanitary objects etc. are reported in [157]. A 20-year outdoor exposure test with Plexiglas® is also described. In addition to the daily measurements of the weather, a xenometer was used to measure the radiation energy to which the samples were exposed. The values measured for Plexiglas® XT with regards to the tensile strength, impact strength, heat distortion resistance and the level of transmission showed a remarkably low deterioration after 20 years of outdoor exposure.

Acrylic glass has a Mohs hardness of 1, while values of 4 to 7 are reported for steel enamel. In addition to the determination of the hardness, extensive tests were carried out to determine the scratch resistance and the wear resistance of these two materials using very different test methods. Results are available for tests carried out after artificially produced wear, after the action of hot detergents and after 20 or 13 years of practical use. In the brand-new state, the surface of Plexiglas® is already more even, smoother and groove-free than that of steel enamel. This is also demonstrated by the measured average roughness of Plexiglas® with $R_a = 0.004 \mu\text{m}$ which is smaller than the value of steel enamel by about a factor of 40. This is intensified when Plexiglas® or enamel is abraded or is rubbed with sand, scouring cleaning agents etc., as in practice.

The harder, and therefore more brittle enamel shows a stronger abrasion than acrylic glass. A R_a value of $0.105 \mu\text{m}$ was measured on a 20-year old Plexiglas® bath tub while a value of $0.45 \mu\text{m}$ was measured on a steel enamel bath tub that had only been used for 8 years. The 20-year old Plexiglas® tub had a smoother surface than that of the brand-new steel-enamel tub. These results that were determined on single test-pieces were confirmed in an investigation of 96 installed acrylic glass bath tubs [158]. These results also explain the particularly advantageous behavior of acrylic glass surfaces with respect to hygiene considerations: they have the lowest surface adherence of bacteria compared to other materials (stainless steel, fireclay, porcelain, steel enamel) [157].

More details of the bacteriological investigations are given in [157].

C 14 Polyesters

Section B 4 describes the use of polyester resins as replacements for cement binders in the manufacture of polymer concrete.

Polyester resins are used in combination with glass-fibre reinforcement under the designation FRP in pipes, fittings and shafts in underground waste water sewers [159]. FRP pipes can be used for gravity-flow pipelines and forced-flow pipelines up to PN 6 with nominal strengths (N/m^2) of SN 2500, SN 5000 and SN 10000. The pipes must have a wall structure which is essentially symmetrical with respect to the mechanical point of view. This means that the distribution of the glass reinforcement and the mechanical behavior both sides of the neutral plane must be equal. The pipes must have an internal lining of resin with a coating thickness of at least 1 mm. This layer may contain a corrosion-resistant filler of up to a maximum of

10 mass%. If this layer contains glass fibres they must be of E-CR glass. An additional UP (unsaturated polyester) resin filling layer is allowed between the resin-rich layer and the barrier layer. The barrier layer, which consists of a mixture of UP-resin and textile fibres, must be 1.5 mm thick for gravity-flow pipelines and 2.0 mm for forced-flow pipelines. The average weight proportion of the glass in the barrier layer should be 25 %. The structural layer must be the next layer; this is made of a mixture of UP-resin, textile glass fibres and a filler. The mass proportions of UP resin, textile glass and filler in the structural layer are dependent on the nominal pressure PN and the nominal stiffness SN. The resin-rich outer layer must have a thickness of at least 0.5 mm.

The structure of the laminate used to connect the individual parts of FRP fittings must be built up of alternating layers of matted fibres and textile layers or with corresponding complex materials, and start with a matted layer; the weights of glass fibres in the mats and textiles must be approximately the same. The laminate must have at least the following strengths:

Longitudinal tensile strength 60 N/mm^2 , adhesive shear strength 3 N/mm^2 .

The mechanical properties must be verified by short-term and long-term tests [160]. The resistance to chemical attack is determined according to DIN EN 1120 with sulphuric acid (pH 1) and sodium hydroxide (pH 10).

The properties of the component specified or determined at room temperature are valid for continuous operating temperatures up to 318 K (45 °C) for $\text{ND} < 400$ or 308 K (35 °C) up to $\text{ND} \geq 400$. Special grades of resins must be used for higher temperatures and pH ranges, so that the operating range can be extended to pH 0.2 to 14 and maximum of 363 K (90 °C) [161].

D

Materials with special properties

D 1 Coatings and linings

The corrosion protection of iron-based materials is carried out by coating with organic materials and films, i.e. with metallic or inorganic materials, preferably with zinc or enamel. In the case of pipelines and tanks, the external protection is a covering and the internal protection is a lining. In waste water technology, these are known as coatings and linings; they protect concrete components which are used extensively.

The coating of concrete components with plastic thermosetting resins is carried out in the works or in-situ. In the case of in-situ coatings, only an internal coating is possible. Sheets, plates or pipe-shaped pieces of thermosetting resins are used for the linings.

Coatings and films used on steel and cast iron

Recommendations for the corrosion protection of waste water installations used for municipal waste water are given in ATV Code of Practice M 263 [162]. The statements contained in this code of practice are based on the fundamental standard DIN EN ISO 12944-1-9. In particular Part 5 refers to coating materials and protective systems [163, 179].

The most important information for the correct corrosion-protection measures in the design of components in waste water installations, which must be taken into account for an effective corrosion protection are as follows:

- consideration of the accessibility for the coating process
- special corrosion protection for those components that are no longer accessible after installation
- corrosion protection of components to be concreted in up to a depth of approximately 5 mm is also necessary
- ensure smooth welded seams, no interruptions and no spot welds
- avoid profiles that open upwards because of the possibility that they can collect water
- avoid contact corrosion with differing metallic materials, either by using insulating intermediate layers or by coating the contact points.

For surface pre-treatment, the standardised level of cleanliness Sa 2 according to DIN EN ISO 12944-4 [164] is to be used. An important practical tip is to only use complete protection systems with the materials from one manufacturer.

According to [165], the internal coatings must exhibit a high level of adhesion, as well as a good resistance towards undermining and formation of blisters. A value of $r_B \geq 10^5 \Omega m^2$ is recommended for the specific resistance of the coating.

The tests listed in Table 31 are specified for waste water pipelines made of steel with a bell-and-spigot coupling, according to [166]. A criticism has been made concerning the minimum value of $10^3 \Omega m^2$ required for the specific resistance of the covering; according to the information given in [165], this is regarded as being too low. Investigations, for example, on the formation of galvanic elements and susceptibility towards blister formation of tar-epoxy resin coatings have shown that the coated steel surfaces can act as cathodes and can thus lead to strong local corrosive attack at defects in the coating [167].

Test	Requirements
Layer thickness	$\geq 100 \mu m$
Resistance of coating	after 30 d: $r_B \geq 10^3 \Omega m^2$
Undermining ¹⁾	after 7 d: rusting beneath the coating $\leq 0.5 mm$
Diffusion of water vapor Inside: 373 K (100 °C) water vapor Outside: $288 \pm 5 K$ ($15 \pm 5 ^\circ C$) water	blistering $\leq m3/g4$ according to DIN 53209
Effect of acids and alkalis: H_2SO_4 , pH 2 NaOH, pH 12	after 7 d: $r_B \geq 10^3 \Omega m^2$

1) salt-spray test according to DIN 50021

Table 31: Test of the plastic coating [166]

Extensive tests for epoxy resin powder coatings are described in a British standard [168]. Table 32 gives a selection of tests which allows a comparison with the test procedures already listed.

In the case of metallic coatings, hot galvanisation is preferred. Section A 39 describes the properties of hot-galvanised coatings, the protective effect of which is increased by a coating (duplex system). Cement mortar linings of steel and cast iron pipes are described in Section B 4.

Test	Requirements
Layer thickness	$\geq 250 \mu\text{m}$
Non-porous surface	1 kV, direct current
Impact resistance	5 J
Adhesion: deionat 363 K (90 °C)	after 7 d: 8 N mm according to DIN EN ISO 4624
Methyl isobutylene test RT, wipe with a white cloth	cloth must remain clean

Table 32: Tests of epoxy resin powder coatings [168]

Coatings and linings of components made of cement-bonded materials

From practical experience, the internal coating of concrete pipes with plastics is regarded as very problematic [169]. Internal coatings with organic materials that are applied in-situ in underground concrete components have led to the spalling of these coatings in very many cases. The reason for this is essentially that the specified safe and perfect bonding (adhesion) between the concrete and the concrete substrate cannot be maintained on a long-term basis. All organic coating materials (although to different extents and depending on the applied thickness) are permeable to water vapor, oxygen and carbon dioxide on a long-term basis. A loosening of the bonding occurs on the phase boundary coating/concrete substrate. If the outer surfaces of the underground concrete components cannot be coated, then there is a risk of the internal coating being forced off by infiltrating groundwater.

As an example of the failure of an internal epoxy resin coating, see the trials undertaken with this coating within the framework of the research project "Demonstrationsobjekt Hamburger Sammlersystem" (Demonstration object, Hamburg's Collection System) [91, p. 178]. During the trials the following conditions were used:

- sandblasting
- drying of the concrete to a residual moisture $\leq 3\%$
- application at 289 K (16 °C) and a relative humidity of 65%
- layer thickness 2.0 mm above the level of the grain tips.

In spite of these carefully carried out measures, spalling and blistering occurred.

A better internal protection of concrete pipes is obtained by lining with the materials listed in Table 33 [143]. A difference is made between partial linings and complete linings. Partial linings applied to the floor of the pipe, i.e. in the wetted area, serve to protect against direct chemical attack by the waste water, while partial lining of the gas cavity should provide protection against biogenic sulfuric acid corrosion. Understandably, complete lining is a general measure for protection against all possible types of corrosive attack.

Lining	Material/execution
Lining of the pipe floor	stoneware shells for pipe floors stoneware half-shells stoneware slabs stoneware slab elements glass-fibre concrete shells for pipe floors BKU profiles (rigid PVC, webbed slabs) prefabricated elements of BKU glass-fibre-reinforced concrete
Partial lining of the gas cavity and complete linings	plasticised PVC, webbed foils rigid PVC, webbed slabs slabs of rigid PVC, PP, HDPE stoneware slab elements composite pipes (complete plastic pipe within a concrete pipe)

Table 33: Linings for partially filled waste water concrete sewers [143]

If non-self-supporting linings (sheets, slabs and pipe-shaped components) are used, then they must be attached to the supporting cross-section (anchoring). In the case of self-supporting linings (e.g. inliner pipes), anchorage is not necessary. Linings must fulfil the following requirements:

- resistance towards acids and microorganisms,
- sufficient wear resistance towards waste water containing solids and sand, stony rubble, suspended matter and
- mechanical resistance towards loading by cleaning equipment.

D 2 Seals and packings

D 5 Natural and synthetic elastomers

The use of clamped couplings for plastic pipes on the building site has not proven useful. For the fabrication of sleeved couplings and similar components, an adhesive bond is still used for pipes made of fibrous concrete, concrete, stoneware and plastic. Cast iron, steel and polyethylene pipes are generally welded, this can be carried out the building site, with the exception of cast-iron pipes. Procedures used to weld polyethylene pipes are heated-tool butt welding and heated-spiral welding with electric welding fittings. Heated-tool butt welding produces a bead on the outside and the inside of the pipes, which presents a certain disadvantage from the hydraulic point of view.

The structure of welding joints and welding defects carried out with the above methods on polyethylene are described in DVS 2206 [170].

A waste water pipeline of ND 300 is reported in [171] in which a partially detached inner welding bead was found. The assembly of bell-and-spigot couplings is, however, simple and rapid. Therefore, it is used for practically all types of pipes. The

clamped couplings of sleeveless pipes made of fibrous concrete, stoneware and cast iron are also quick and simple to assemble.

The most important element of the clamped coupling, and above all for the bell-and-spigot coupling, is the elastic sealing ring which is either a round ring or is profiled and is generally made of synthetic materials for waste water pipes. If the seals are arranged in recesses, then high safety factors towards internal pressure can be attained. In the case of Tyton® sealing rings, which have an additional special arrangement of rigid and non-rigid components, the couplings are safe even up to the bursting point of the pipes. The cross-sectional thickness of the sealing rings is a direct function of the dimensional accuracy of the bell and of the spigot. Therefore, very small sealing ring diameters with very low hardnesses can be used for plastic pipes.

In concrete pipes in which the dimensions that are relevant for the leakproofness are not specified in standards, there are relatively large sealing cross-sections. The correct dimensioning of the sealing rings for different gaps is dealt with in detail in [172] (see Table 34).

Table 35 contains the requirements of the properties specific to the sealing material with dense or cellular structure, depending on the degree of hardness and according to DIN 4060 [173].

Requirements and tests of the pipe couplings are also specified with regards to waterproofness on tangential bending and action of shear loads, ease of assembly, thermal loading and gas-tightness. Instead of complex plant-root penetration tests, it is sufficient nowadays to verify resistance to roots by testing for integrity under shear loading.

Likewise, the test of the chemical resistance by storage in dilute sulphuric acid or dilute sodium hydroxide solutions has been replaced by storage and testing in de-ionised water at 343 K (70 °C).

The use of sealants with volatile liquids or and their interaction with volatile materials based on chlorinated hydrocarbons (CHC) is discussed in DIN 4060. Sealants made of elastomers, which are generally based on SBR, EPDM or NR, have only limited resistance or are not resistant to the long-term effects of direct interaction with volatile liquids (mineral oils, lubricants, fuels) and CHC (such as trichloroethene and tetrachloroethene).

If, in individual cases, the long-term action of these substances is to be expected (particularly for drainage of estates), then correspondingly resistant sealants are required. In the case of volatile liquids, sealants must be used in waste water pipelines up to the volatiles trap. These sealants must comply with additional requirements, e.g. those specified in the principles of construction and inspection from the Deutsches Institut für Bautechnik (German Institute of Building Technology), for elastomer seals with increased resistance towards volatile liquids for use in waste water pipelines.

In the public canalisation system, short-term contact with volatile liquids, e.g. after accidental oil spillages, does not have a negative effect on the sealing function of elastomers. In the case of volatile chlorinated hydrocarbon solvents, the sealing function of the elastomers is only affected if the solvent is in direct contact. The use

<i>W</i>	<i>d_r</i>	<i>d_r = d_r ± t/1.10</i>		<i>Elongation, ε</i>		<i>Δ ε</i>
		<i>max.</i>	<i>min.</i>	<i>max.</i>	<i>min.</i>	
<i>mm</i>	<i>mm</i>	<i>mm</i>		%	%	%
7 ± 1.5	12 + 0.8/-0.4	12.2	11.0	55	23	32
8 ± 1.7	13.5 + 0.8/-0.4	13.6	12.5	54	22	32
9 ± 1.9	15 + 0.8/-0.4	15.1	13.9	54	21	33
10 ± 2.1	17 + 0.8/-0.4	17.0	15.8	55	22	33
12 ± 2.5	20 + 1.2/-0.4	20.2	18.7	53	22	31
14 ± 3.0	23 + 1.2/-0.4	23.1	21.5	52	21	31
16 ± 3.5	27 + 1.2/-0.4	26.9	25.3	54	23	31
18 ± 4.0	30 + 1.2/-0.4	29.8	28.2	53	22	31
20 ± 4.5	33 + 1.6/-0.4	33.0	31.1	53	21	32
22 ± 5.0	36 + 1.6/-0.4	35.9	33.9	53	20	33
24 ± 5.5	40 + 1.6/-0.4	39.7	37.8	53	22	31
26 ± 6.0	43 + 1.6/-0.4	42.5	40.6	53	21	32

Table 34: Dimensioning of the minimum ring thickness for complete utilisation of the permissible dimensional deviations and 10 % pre-stretching [172]

of CHC-resistant sealants is thus limited to special cases in estate drainage; a special resistance verification is required in this case.

Within the public canalisation system, negative effects of CHC on the sealants are not expected. Apart from that, CHC are only slightly miscible with water and belong to the water-hazardous substance class, which according to the new legal regulations, may only be discharged into sewer systems in amounts which do not effect the sealants.

Testing of the bell-and-spigot sealing system Tyton® made of nitrile rubber (NBR) in aqueous solutions saturated with CHC are given in a test report of the Staatliches Materialprüfungsamt Nordrhein-Westfalen (Federal Material Testing Office, North Rhein-Westphalia) [174]. This report gives the results on the changes of the material properties, such as microhardness, tear strength, elongation at tear, compressive set and volume after storage for 7, 28 and 56 days in aqueous solutions saturated with trichloroethane, trichloroethene, tetrachloroethane and dichloromethane. Tap water was used as a control. Additionally, the sealing rings in the pipe couplings were tested by storage for 30, 60 and 90 days in aqueous solutions saturated with trichloroethylene. Both the change of the determined properties of < 1 % as well as the successful leakage test after 90 days storage showed no negative influence of the functional safety of the seals. The Tyton® sealing rings made of nitrile rubber (NBR) were therefore evaluated as resistant towards the action of CHC-saturated water.

Properties	Sealant with dense structure for hardness class (IRHD)				Sealant with cellular structure
	A	B	C	D	
	Nominal hardness				
	≤ 59	60 – 64	65 – 74	≥ 75	
Tear resistance, N/mm ²	10	10	9	acc. ag.	2
Elongation at tear, %	400	300	200	acc. ag.	360
Compressive set, %	20	20	25	acc. ag.	20
Tension set, %	25	25	acc. ag.	acc. ag.	–
Compressive strain relaxation, %					
168 h	15	15	15	acc. ag.	30
10 ⁵ h	25	25	25	acc. ag.	45
Tensile strain relaxation, %					
168 h	15	15	15	acc. ag.	30
10 ⁵ h	25	25	25	acc. ag.	45
Artificial ageing					
a) tear resistance, %	15	15	15	acc. ag.	15
b) elongation at tear, %	25	25	25	acc. ag.	25
Volume change, %	5	5	5	5	5
Ozone resistance (tear level)	0	0	0	0	acc. ag.
Low-temperature behavior (Δ Shore A)	10	10	10	10	–

acc. ag.: according to agreement

Table 35: Requirements of the properties specific to the sealing material [173]

A special test apparatus was built for an additional expert opinion. This was used to test the rotational tangential bending and longitudinal displacement of the Tyton® coupling and to verify the suitability for areas with subsidence [175].

Sealing rings made of polytetrafluoroethylene (PTFE) or fluorinated rubber (FPM) are supplied by manufacturers of stainless steel waste water pipes or of enamelled cast-iron pipes.

The high-temperature resistant and chemical resistant PTFE and FPM sealants are generally used in glass pipes in laboratory waste water pipelines. A particularly high resistance is also exhibited by polyurethane seals, which are used with stone-ware pipes. The creep behavior of filled polyester resin is given in [176] and the relaxation of polyurethane in [177].

In sewer technology, the Penny separating process has established itself as the general method to renovate leaky pipe couplings [178]. A further possibility to renovate sewer pipelines is the use of highly flexible spiral tubes made of chloroprene rubber. These tubes are simply pulled into the sewer [179].

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Waste Water (Industrial)

Authors: E. Heitz, G. Subat/Editor: R. Bender

	Page		Page
Introduction	235	B Non-metallic inorganic materials	283
A Metallic materials	251	B 3 Carbon and graphite	283
A 2 Aluminium	251	B 4 Binders for building materials	285
A 3 Aluminium alloys	251	(e.g. concrete, mortar)	
A 9 Copper-nickel alloys	251	B 5 Acid-resistant building materials	304
A 14 Unalloyed steels and low-alloy	252	and binders (putties)	
steels/cast steel		B 6 Glass	305
A 15 Unalloyed cast iron and low-	256	B 8 Enamel	306
alloy cast iron		B 10 Stoneware	306
A 16 High-alloy cast iron	256	B 14 Other inorganic materials	307
A 16.1 Silicon cast iron	256		
A 17 Ferritic chromium steels with <	260	C Organic materials/plastics	308
13 % Cr		Classification of organic	308
A 18 Ferritic chromium steels with	260	materials	
≥13 % Cr		Damage mechanisms of organic	309
A 19 High-alloy multiphase steels	260	materials	
A 19.1 Ferritic/pearlitic-martensitic	260	Chemical resistance of organic	324
steels		materials used in the treatment	
A 19.2 Ferritic-austenitic steels/duplex	260	of industrial waste waters	
steels		Thermoplastics	326
A 20 Austenitic CrNi steels	262	Duroplasts	332
A 21 Austenitic CrNiMo(N) steels	262	Elastomers	333
A 22 Austenitic CrNiMoCu(N) steels	262	Fibers	334
A 27 Nickel-chromium alloys	277		
A 28 Nickel-chromium-iron alloys	277	D Materials with special properties	335
(without Mo)		D 1 Coatings and linings	335
A 29 Nickel-chromium-molybdenum	277	D 2 Seals and packings	349
alloys		D 3 Composite materials	349
A 30 Nickel-copper alloys	277		
A 37 Tantalum, niobium and their	281	E Materials recommendations	355
alloys			
A 38 Titanium and titanium alloys	281	Bibliography	364
A 39 Zinc, cadmium and their alloys	281	Key to materials compositions	385
		Index of materials	415
		Subject Index	424

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Introduction

Index of the Introduction

V 1 General	<i>V 1.2.1 Gaseous waters</i>
V 2 Description of the processes used for industrial waste water treatment	<i>V 1.2.2 Aqueous pickling baths</i>
<i>V 2.1 Physical processes</i>	<i>V 1.2.3 Waste electroplating baths</i>
<i>V 2.2 Chemical processes</i>	<i>V 1.2.4 Organic wastes from various branches of industry</i>
<i>V 2.3 Thermal processes</i>	<i>V 1.2.5 Landfill leachates</i>
<i>V 2.3 Biological processes</i>	V 1.3 Microbiologically influenced corrosion processes
V 1.1 Storage of substances hazardous to water	<i>V 1.3.1 Microbially influenced corrosion (MIC)</i>
V 1.2 Process waste waters with particular corrosion problems	<i>V 1.3.2 Biogenic sulfuric acid corrosion</i>

Introduction

V1 General

Waste waters are classified according to their source into domestic, commercial, and industrial **waste waters** and contaminated storm water runoff. Liquids that have seeped and have been collected from landfill facilities (leachates, landfill leachates) are also regarded as waste water. If these waste waters are combined, they are known as municipal waste water [1].

In contrast to municipal waste water, the type and concentration of the pollutants in commercial and industrial waste waters can vary greatly, depending on their origin.

V2 Description of the processes used for industrial waste water treatment

Industrial waste waters contain non-recyclable materials from chemical, thermal, and mechanical processes and may contain a wide variety of corrosive agents, depending on their origin. The concentrations of these agents must comply with the legally stipulated values before they can be discharged into **waste water treatment plants** or sewers. This is achieved by means of a wide range of **treatment processes** that are very specific to the particular branch of industry and the respective process engineering.

Although modern processing techniques that have integrated environmental protection aim to minimize waste, they still produce aqueous solutions containing high levels of contaminants that have to be treated chemically, thermally, physically, or biologically.

In the diverse waste water treatment processes, the typically high concentrations of aggressive compounds and the frequently high temperatures necessitate the use of highly corrosion-resistant materials. This means that a design with standard materials is no longer suitable.

A very useful description and assessment of the various methods and their variants that are used in practice for industrial **waste water treatment** are compiled in [2]. A comprehensive evaluation of the physical and chemical methods reported in the specialist literature is given in [3] with a total of 382 references.

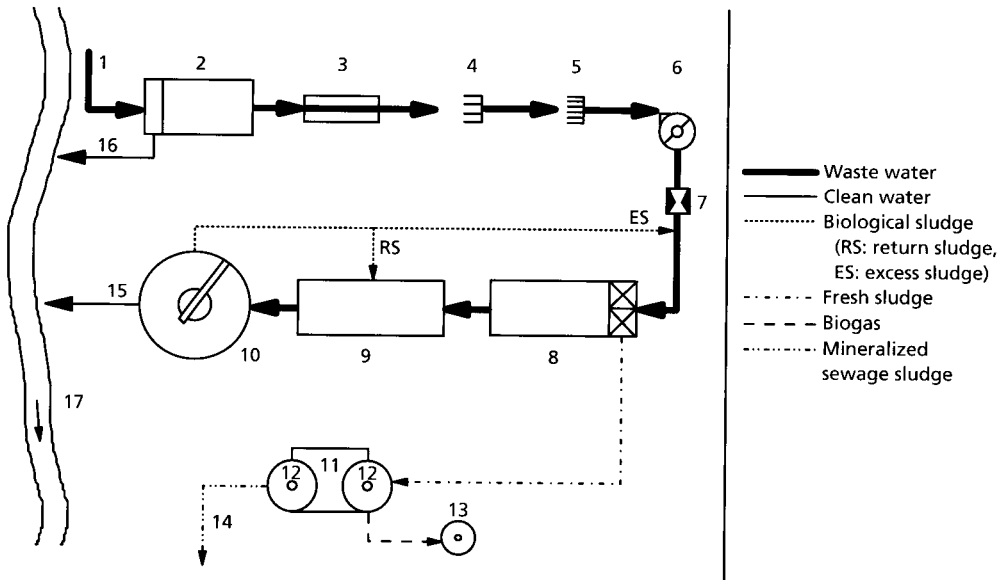


Figure 1: Diagram of a mechanical/biological waste water treatment process (activated sludge process) [8]
 1. Inlet, 2. Rainwater basin, 3. Lifting or pumping station, 4. Coarse screen, 5. Fine screen, 6. Sand trap, 7. Flowmeter, 8. Primary settling tank, 9. Aeration tank, 10. Secondary settling tank, 11. Plant building, 12. Digesters, 13. Gas container, 14. Sludge outlet, 15. Effluent outlet, 16. Storm water overflow, 17. Receiving body of water

Comprehensive overviews and information on the origin and types of waste water produced by the different commercial and industrial facilities as well as the appropriate treatment process are given in [4,5,6].

Reference [7] gives a detailed description of the basic principles for the treatment of industrial waste waters and also discusses the legal aspects, problems regarding environmental protection, and the various technical processes. In addition to an overview on industrial waste waters, evaluation criteria, and the possibilities of reducing or avoiding waste water are also addressed. The chemical, physical, and biological processes for waste water treatment and the elimination of waste water contaminants are described in detail.

Figure 1 shows a diagram with a typical design of a waste water treatment plant, and Table 1 lists the most important plant sections, their functions, equipment, and the frequently used materials [8].

Section	Plant section	Function, description	Mechanical equipment and machinery	Materials
Outdoor facilities	sewer system	collection of waste water in sewers	manhole ladders and covers, gate valves, etc.	concrete, stoneware, fibrous concrete, plastics (PE, PVC, FRP), cast iron, steels
	storm water tank	retention or separation of pollutants in storm water, overflow of the diluted waste water	gate valves, throttles, rinsing devices, emptying pumps	tanks made of in-situ or prefabricated concrete elements, installations made of metals with plastics
	pumping stations	lift the waste water to a higher level	centrifugal pumps with dry or wet locations, spiral pumps	structures made of in-situ or prefabricated concrete elements, installations made of metals with plastics
Mechanical section	screens	removal of bulky materials, paper and textiles	coarse, medium, or fine screens with a mechanical screen-cleaning system	metallic materials, plastics
	sand/grease trap	removal of sand and grease, allows mineral materials to settle and keeps organic materials suspended	aeration equipment or paddle agitator, scrapers, sand pumps	concrete, installations made of metal and plastics
	primary settling tank	removal of materials that float or settle in the sedimentation tank	scraper unit, fresh sludge pumps (compressed air lifter, centrifugal pumps)	concrete, installations made of metal and plastics
Biological/chemical section	aeration tanks, rotating biological contactors, trickling filters	conversion of dissolved organic materials into biomass and CO ₂ by creating ideal living conditions for microorganisms	aeration equipment, biological contactors with drive motors, rotary distributors, or tilting belts	concrete, metallic materials, plastics, stoneware, ceramics

Table 1: Description of a waste water treatment plant with outdoor facilities [8]

Table 1: Continued

Section	Plant section	Function, description	Mechanical equipment and machinery	Materials
Biological/ chemical section	secondary settle- ment	separation of micro-organisms from treated waste water in a secondary settling tank or drum filter	chain, suction or shield scrapers, pumps, drum filters with drive, and filter cleaning systems	concrete, metallic materials, plastics, textiles
	further treatment	to produce effluent with an enhanced quality (phosphate precipitation, nitrification and denitrification, flocculation filtration, etc.)	dosing equipment, agitators, pumps, filters, etc.	concrete, metallic materials, plastics, sand, activated carbon, etc.
Sludge treatment	pasteurization, sterilization	partial sterilization of the fresh sludge by thermal treatment (aerobic or anaerobic)	pumps, storage tanks and treatment tanks, reactors, heat exchangers, etc.	metallic materials, plastics
	anaerobic digestion or sludge aeration	sludge stabilization by partial degradation of digestible organic materials (aerobic or anaerobic), sludge thickening	agitators, recirculating pumps, gas installations, compressors, aeration equipment, etc.	concrete, installations made of metal and plastics
	gas tanks	storage of biogas (methane gas containing CO ₂ and H ₂ S) in wet/dry gas tanks or pressure vessels	gas compressor, gas cleaning (explosion protector)	concrete, metallic materials, plastics
	heating plant or combined heat and power plant	heating of the sludge, heating of the plant building, generation of electrical power	oil or gas heating, combustion engine	metallic materials
	further sludge treatment	dewatering, drying, and incineration of the sludge	belt filters, filter presses, centrifuges, lime-sludge mixers, furnaces, etc.	metallic materials, plastics

Table 1: Description of a waste water treatment plant with outdoor facilities [8]

Table 2 gives the important properties/measurable parameters used for **waste water evaluation** that allow an assessment of the type of contamination with respect to toxicity.

Parameter	Comments on the detrimental effect on plants and animals
Organic parameters	
TOC Total Organic Carbon	possible toxicity, oxygen depletion
COD Chemical Oxygen Demand	possible toxicity, oxygen depletion
BOD Biological Oxygen Demand	oxygen depletion of downstream waters
Oils and fats	detrimental effect on plants and animals
Physical parameters	
TSS Total Suspended Solids	turbidity, can be detrimental
pH	large deviation from neutral can be detrimental
Temperature	excessive temperatures can be detrimental
Miscellaneous parameters	
Coloration	visible contamination, possible toxicity
Odor	perceptible contamination, possible toxicity

Table 2: Parameters for waste water evaluation [2]

V 2.1 Physical processes

Treatment processes based on a physical effect include the following:

- Separation of insoluble contaminants by the effect of gravity (oils, sedimentable solids). The resulting sludges must be subjected to a special treatment in settling tanks, inclined settlers, filter presses for dewatering
- Sedimentation of emulsified oils, greases, and fine-grained solids by means of air floatation; emulsions can be broken up mechanically, if necessary
- Oil separation from emulsions by coalescence. Under certain circumstances, separation is possible using oleophilic synthetic fiber packings. The combination of de-emulsification with ionic polymers and subsequent ultrafiltration allows effective treatment of highly concentrated and stable oil-in-water emulsions that are particularly prevalent in metalworking processes e.g. drilling, milling, or deep-drawing emulsions [9].
- Evaporation processes are used to reduce volumes and are usually aimed at precipitating dissolved materials on cooling, e.g. in waste waters from flue gas desulfurization plants (see Sections A 9, A 20, A 21, A 22, and B 3). The

frequently occurring encrustation can cause problems. This can be avoided by means of a special process [10].

- Filtration is one of the standard processes for the separation of dispersed materials, e.g. oil emulsions in refinery waste waters. Filter materials include glass, porous ceramics, metals, plastics, and sand. Ultrafiltration processes operate with membranes made of cellulose acetate, polyamide, and polysulfone, that allow the separation of dissolved macromolecular materials in the range from 0.1 – 0.001 μm .
- Adsorption processes using activated carbon are used to remove dissolved organic contaminants from waste waters. The fine-grained activated carbon is used for batchwise treatment, whereas granulates are best suited as the packing material in continuous-flow columns that are operated in pairs. While one column is being regenerated, the other is operating as the adsorber. Saturated activated carbon packings are treated with steam to remove the adsorbed materials and reactivate them.
- Stripping with air or steam is used to separate highly volatile contaminants dissolved in water by means of a counterflow process.
- In liquid/liquid extraction, the dissolved organic material being recovered from the waste water is brought into contact with an extraction solvent in which it has low or no solubility. The prerequisite is that the material being extracted has a greater solubility in the extraction solvent than in the waste water. This is usually carried out as a continuous process in packed columns or bubble columns, and it is used e.g. to remove phenols from industrial waste waters. The extraction solvent, e.g. hydrocarbons, toluene, isopropyl ether, butyl acetate, methyl isobutyl ketone, etc. is then regenerated.

V2.2 Chemical processes

Chemical processing is the most frequently used method of treating industrial waste waters. These processes include precipitation, electrolysis, ion exchange, reverse osmosis, as well as chemical oxidation and reduction.

- Precipitation is based on the addition of particular chemicals to the stirred waste water, these may include flocculants. The treated waste water is then fed into settling tanks in which the precipitated substances collect as a sludge on the floor of the tank. The clear effluent exiting the tank is subjected to further treatment or it is discharged into the receiving body of water, depending on whether it contains further contaminants. Because chemical treatments are carried at approximately neutral pH values, the corresponding tanks are generally referred to as neutral tanks in practice. This method, as well as most of those described below, are frequently used in the electroplating industry [11]. Owing to the use of toxic substances and also to the necessity of recovering valuable materials from the rinsing baths, this branch of industry is particularly interested in the consistent use of the most up-to-date

treatment methods to save as much water as possible with the ultimate objective of a waste water-free operation [12].

- Electrolytic methods generally used to deposit metals from waste waters or rinsing baths. This is carried out for reasons of economic viability or because of the legal stipulations that minimum levels for the corresponding metal concentrations in the waste water are not exceeded. However, the metal concentrations in the waste water should not be too low if they are to be treated by electrolysis.
- Ion-exchange processes are less frequently used to treat waste water. They are predominantly used to produce pure water. A certain exception is the above-mentioned electroplating industry. This process is used to recover valuable metals from the rinsing baths or to return essentially pure water back into the water cycle.
- Reverse osmosis, like the ion-exchange process, is used to produce pure water that can be fed back into the cycle. Which of the two processes is the most suitable depends on economic factors. The last two processes could also be assigned to the previous section “Physical processes”.
- Chemical oxidation and reduction is used to remove toxic contaminants in waste waters; this is why the term “detoxification process” is used for the oxidation of cyanide-containing waste waters and for the reduction of waste waters containing Cr(VI). The most frequently used oxidizing agents are solutions of sodium or calcium hypochlorite, hydrogen peroxide, or ozone. The latter two oxidizing agents are also used, above all, to remove organic substances that are difficult to degrade biologically. Particularly for the treatment of cyanide-containing waste waters, a number of chemical, physical, and biological processes have been proposed or are already used in practice [13].
- An interesting combination of processes, namely ozone, biodegradation, and irradiation with ultraviolet light, is used to treat heavily contaminated waste waters. It is described in [14] and some application examples are given. The treatment of waste waters containing high levels of organic contaminants with oxygen is known as “wet-chemical oxidation” and has been used for many years. It is carried out at high temperatures and pressures (see Sections A 20, A 21 and A 22). **Wet-chemical oxidation** with ozone on its own or ozone plus UV light achieves similar effects, even at temperatures of up to 313 K (40 °C) and pressures below 5 bar. It decreases the concentrations of the following contaminants in the waste water, whereby the remaining residual organic materials are then biodegraded:
 - dissolved organic hydrocarbons (TOC)
 - chemical oxygen demand (COD)
 - adsorbable organic halogenated hydrocarbons (AOX)
 - highly volatile hydrochlorocarbons (HCC)
 - polycyclic aromatic hydrocarbons (PAC)
 - pesticides
 - dioxins
 - dyes

V2.3 Thermal processes

- High-pressure/high-temperature **wet oxidation** is carried out in the presence of air at temperatures of up to approx. 603 K (330 °C) and pressures of up to approx. 200 bar. Most of the organic substances in the waste water are stoichiometrically oxidized to carbon dioxide and water. This process can be used for waste waters that are too toxic for biodegradation and which have insufficiently high concentrations of organic substances for incineration. It cannot be used if the inorganic fraction is too high.
- Wet oxidation with supercritical water is carried out between at least 647 K (374 °C) at 225 bar and not more than 913 K (640 °C) at 250 bar. Additional oxidizing agents, such as air, oxygen, or hydrogen peroxide, accelerate the process. In the lower range, the process is similar to the above-mentioned simple wet oxidation. Sulfur, chlorine, and phosphorus fractions are converted into their acids. Organic nitrogen is mostly converted into ammonia above 773 K (500 °C), whereas molecular nitrogen and dinitrogen oxide (N_2O) are formed above 873 K (600 °C). Temperatures of at least 873 K (600 °C) and pressures above 230 bar are necessary for complete conversion in less than one minute. Above 647 K (374 °C) and pressures of 225 bar, water is in a supercritical state and becomes an excellent solvent for organic substances and gases. It transforms organic components into small molecules that are oxidized in supercritical water in the presence of oxygen. A concentration of approx. 10 mass% hydrocarbons produces an autothermic reaction temperature of 903 K (630 °C) [15].
- The pyrolysis of waste waters containing high concentrations of organic substances by spraying them into a flame is carried out at temperatures between 1273 K (1000 °C) and 1973 K (1700 °C). The salt-free waste waters containing high levels of organic substances arising during the production of synthetic Trevira® fibers are evaporated and then combusted in a special furnace at 1173 K (900 °C) [16]. In another process, vapors produced during evaporation are combusted flamelessly by air oxidation [17].

V2.3 Biological processes

Biological waste water treatment is based on the property of particular, mostly aerobic (i.e. active in the presence of oxygen) bacteria strains that are able to completely degrade organic substances contained in waste water to carbon dioxide and water, in the ideal case. This process requires oxygen as well as nutrients, e.g. substances containing nitrogen and phosphorus. The waste water must not contain any toxic substances. Therefore, industrial waste waters must be “detoxified” before they are fed into a biological waste water treatment plant. The detoxification processes are described above under “Chemical processes” (V 2.2). Waste waters suitable for biological treatment or pretreated industrial waste waters are first subjected to settling to remove the sedimentable materials. This waste water is then fed into the activated sludge tank together with the activated sludge from the secondary settling tank

along with oxygen via an aerator. The non-recycled excess sludge is dewatered and disposed of either in a landfill, by wet-chemical oxidation, or by incineration. It can also be biodegraded in so-called digesters by the action of anaerobic organisms under oxygen-free conditions. This produces digester gas (**biogas**) that has a high calorific value. Biological waste water treatment with anaerobic organisms is currently used in large-scale plants in certain branches, e.g. in the food and petrochemical industries. The denitrification of nitrate-rich waste waters is also carried out with this method [18].

V3 Storage of substances hazardous to water

According to § 19 g of the German Water Resources Act, any tanks to be used for the storage of liquids that are hazardous to water must be certified as being suitable – this is currently an official general technical approval – unless these tanks correspond to certain DIN standards that are anchored in construction laws and which can thus be regarded as simple or conventional. Storage tanks are classified as supply tanks (unused liquids) or collecting tanks (used liquids). They must be equipped as stipulated for storage tanks, in particular, by the **Technical Guidelines for Combustible Liquids (TRbF)** [19]. The design and monitoring of the storage tanks is based on a number of criteria, above all, on the verification of the corrosion resistance of the tank material itself or its coating or its lining with respect to long-term exposure to the medium being stored. The basic material and the weld seams of metallic materials that are directly exposed to the media must exhibit a corrosion rate of less than 0.1 mm/a (4 mpy) and must not be expected to exhibit any types of local corrosion. This verification is based on DIN 6601 [20], which uses a so-called positive liquid list in combination with suitable materials. The suitability of liquid/material combinations that are not included in this list must be verified by means of an individual expert assessment [21, 22]. For tanks, collecting equipment, and pipes made of plastics that are used for storage, collection, and transport of liquids that are hazardous to water, an application must be made for a general **technical approval** from the Deutsches Institut für Bautechnik (DIBT, German Institute for Building Technology). The prerequisite for this is a suitability verification for the media listed in the Media Lists II 440 of the DIBT or an individual verification. Individual media lists are available for thermoplastic materials, for FRP laminates, as well as for laminates with a thermoplastic coating. The lists are regularly updated [23]. General technical approvals have already been granted for cylindrical flat-bottomed tanks and collecting equipment made of PP (polypropylene) and PE-HD (high-density polyethylene) with coiled cylinder jackets [24].

A technical approval from the DIBT for concrete and steel containers and collecting tanks lined with coatings, plastic sheeting, and rubber that are to be used for the storage of liquids which are hazardous to water requires a verification of the qualification of the lining or coating materials in accordance with the design and testing regulations for water protection, Part 1 [25].

The technical safety aspects in industrial waste water facilities are discussed in [26]. Topics dealt with include accidents in waste water plants and systems, their causes, and countermeasures. A repeatedly occurring cause of explosions was the enrichment of ignitable gases in the gas-filled headroom over waste water in closed systems.

V4 Process waste waters with particular corrosion problems

Particularly demanding processes with respect to corrosion exposure that are used for **industrial waste water treatment** are described below.

V4.1 Gaseous waters

Gaseous waters are aqueous waste flows that are produced by secondary processing of coal and crude oil. They contain corrosive components, such as ammonia, carbon dioxide, hydrogen sulfide, and hydrogen cyanide, as well as low concentrations of other organic and inorganic impurities. Some of them are extremely corrosive and are treated in coking plants and refineries by multistage distillative separation processes [27, 28].

V4.2 Aqueous pickling baths

Metals are pickled in order to remove scale, rust, oxide layers, or corrosion products during the fabrication of semifinished goods. Pickling is also an essential pretreatment process in nearly all manufacturing branches where there is subsequent surface treatment, such as zinc plating, enameling, painting, anodizing, and electroplating. Pickling is usually carried out after a degreasing step to remove oxidic and other corrosion products as well as inorganic and organic residues from a previous machining process. This also gives the parts a uniform bright metallic finish and an activated surface for a subsequent surface treatment. Pickling can be carried out at ambient temperatures or above.

Waste pickling baths arising from the surface treatment of metals may be based on an inorganic acid, such as hydrochloric acid, sulfuric acid, nitric acid, phosphoric acid, chromic acid, hydrofluoric acid, and mixed acids or on NaOH solutions if it is used to pickle aluminium materials. Such waste waters and the associated rinsing baths are treated by neutralization, whereby the pH values must be tailored to the metals that are present. This produces the corresponding quantities of neutral salts that also have to be disposed of [4, 5]. Aqueous pickling baths are also described in Sheet 3 of the ATV Worksheet H 765 [29].

Examples for the composition of sulfuric and hydrochloric acid-based waste pickling baths from different metal processing plants are given in Table 3 and Table 4 [4].

Plant	Pickled material	H ₂ SO ₄ , free g/l	FeSO ₄ · 7 H ₂ O g/l	Corresponds to Fe g/l	H ₂ SO ₄ total g/l
A	strip steel	37.7	320.0	64.5	151.1
B	sheet metal	16.4	449.0	90.7	175.2
B	wire	22.6	106.0	21.4	59.5
E	rods	3.2	289.0	58.3	105.6
F	pipes	41.0	231.0	46.6	122.9
G	wire	25.3	455.0	91.5	186.2
H	wire	22.6	577.0	116.2	225.8
R	strip steel	24.5	632.0	127.3	248.0
T	strip steel	86.7	537.0	108.3	277.1
V	strip steel	15.4	631.0	127.0	237.5

Table 3: Composition of typical waste pickling baths based on sulfuric acid from metal working [4]

Plant	Pickled material	HCl, free g/l	FeCl ₂ g/l	Corresponds to Fe g/l	HCl total g/l
A	galvanizing plant	69.1	361.9	159.4	276.5
B	galvanizing plant	56.9	185.5	81.8	163.0
L	strip steel	41.3	258.5	114.2	91.0
N	tinplate	27.6	240.0	105.8	164.4
E	wire	90.5	261.0	115.0	238.2

Table 4: Composition of typical waste pickling baths based on hydrochloric acid from metal working [4]

The chemical or electrochemical removal procedures used for **surface treatment** (polishing, burnishing, deburring) or for shaping (countersinking, drilling, etc.) of metals also utilize the dissolving properties of strong acids, bases, or oxidizing salt solutions to remove metal.

Table 5 lists the frequently used solutions for chemical removal of metals [30].

Basic material	Solutions and mixtures of solutions for chemical removal											
	NaOH	NaCN	H ₂ O ₂	HF	HCl	HNO ₃	H ₂ SO ₄	H ₃ PO ₄	CrO ₃	FeCl ₃	Fe(NO ₃) ₃	NH ₄ HF
Mg	XXX											
	XXX											
	XXX											
Al	XXX											
	XXX											
	XXX			XXX	XXX							
	XXX						XXX					
Ti	XXX											
	XXX		XXX									
	XXX			XXX								
	XXX			XXX								
Fe, FeCr	XXX					XXX						
FeCrNi	XXX				XXX							
	XXX					XXX	XXX					
	XXX					XXX	XXX					
Ni, Co	XXX				XXX							
	XXX				XXX		XXX					
Zn	XXX											
	XXX											
Cu											XXX	
Ag	XXX											
												XXX
Au	XXX				XXX							
	XXX	XXX										
Nb, Mo, Ta, W	XXX			XXX								
Be	XXX											
	XXX											
	XXX											

Table 5: Solutions and mixtures of solutions for chemical removal of various metals [30]

V4.3 Waste electroplating baths

Waste waters from electroplating processes are characterized by heavy metal contaminants, complexing agents, such as cyanides, and organic brighteners. They are highly corrosive and are treated by elaborate redox, neutralization, and adsorption processes [4, 5]. Information on waste electroplating baths is given in Sheet 2 of ATV Notice H 765 [31].

V4.4 Organic wastes from various branches of industry

Organic wastes are oxidatively degraded by wet oxidation at high temperatures and pressures with the aid of oxygen-containing water to produce less harmful endproducts. The usual reactor operating temperatures of more than 473 K (200 °C) require high performance criteria for the materials.

V4.5 Landfill leachates

Landfill leachates have a detrimental effect on the environment and are often very corrosive due to the presence of hydrogen sulfide, ammonia, and halogenated hydrocarbons. They require multistage treatment processes. There are particular demands on the processes if halogenated hydrocarbons are present. Table 6 gives typical ranges of some corrosion-relevant parameters of landfill leachates [6].

<i>Parameter</i>	<i>Dimension</i>	<i>Levels</i>
pH value		6.2 – 8.3
Electrical conductivity	μS/cm	2000 – 50000
Organic acids	mg/l	1400 – 6900
AOX	μg/l	260 – 6200
Chlorides	mg/l	300 – 12400
Sulfates	mg/l	25 – 2500
NH ₄ -N	mg/l	15 – 1650

AOX = adsorbable organohalogen compounds

Table 6: Corrosion-relevant leachate parameters [6]

V5 Microbiologically influenced corrosion processes

V5.1 Microbially influenced corrosion (MIC)

Microorganisms are able to attach themselves to surfaces by secreting extracellular polymeric substances (EPS) as a gel-like slime ("biofilm"). They then stabilize themselves as colonies, bind water, generate metabolic products and, if necessary, use

parts of their substrate as nutrients. Such microorganisms can induce and accelerate the corrosion of metals, plastics, and other materials. The corrosion of metals in water and aqueous solutions is an electrochemical interfacial reaction that is influenced by local inhomogeneities, the redox potential, the pH values, the concentration of dissolved salts, and by the further reaction of primary corrosion products. These factors can be affected by microbial activity, particularly by microorganisms in superficial biofilms to allow reactions that would not take place or only at very slow rates if there were no microbial participation [32, 33].

Local corrosion damage due to increased pitting and crevice corrosion in anaerobic zones has been known for a long time on low-alloy steels in seawater and in the oil industry. This damage is attributed to the action of sulfate-reducing bacteria (SRB) [49, 50].

Some types of microorganisms can form organic and inorganic acids that greatly decrease the pH value in biofilms thus resulting in acid attack of the surface. Superficial biofilms can hinder the ingress of oxygen and thus favor the formation of aeration cells.

Reduction and oxidation processes in the biofilm also influence the redox potential on the surface, which may thus significantly differ from that in the actual electrolyte solution. If the redox potential under the biofilm is shifted to more positive values, the pitting corrosion potential can be exceeded in high-alloy stainless steels and pitting corrosion occurs in media in which the redox potential of the free solution lies below the pitting corrosion potential so that pitting corrosion cannot occur without the biofilm.

The presence of microorganisms is also often associated with the formation of deposits of differing thicknesses (biofouling), which not only disturb operations by increasing the resistance to flow and hampering heat transfer, but also by promoting the formation of aeration cells or the enrichment of corrosion-promoting substances in the water.

A comprehensive compilation of examples of microbial damage of metallic, ceramic, and organic materials is given in [33].

V5.2 Biogenic sulfuric acid corrosion

For longer residence times in the waste water, e.g. in facilities used for intermediate storage or in pipelines on the flow line between the point of origin to the treatment plant, bacterial activity may cause changes in the substances contained in the water, particularly sulfur-containing compounds. The resulting volatile sulfur compounds in the gas atmosphere lead to considerable corrosion problems.

The high humidity of the atmosphere in closed waste water treatment plants results in the formation of condensed water droplets or films in which aggressive gases, such as H_2S , SO_2 or CO_2 , can dissolve and become enriched. An important role is played, in particular, by "biogenic sulfuric acid corrosion", i.e. corrosive attack by sulfuric acid formed from biological reactions of sulfates [1, 34–36].

Biogenic sulfuric acid corrosion is primarily induced by biological reduction of sulfate sulfur or other sulfur compounds, e.g. protein compounds, to form sulfides

(H_2S , HS^- , S^{2-}) under anaerobic conditions in the underwater regions. However, more rarely, it can also be formed directly from sulfides in industrial waste waters. The liberated volatile sulfides, e.g. H_2S , can dissolve in the condensate on the pipe walls where they are subsequently oxidized to sulfuric acid by biological reactions with bacteria of the genus *Thiobacillus*. The resulting strongly acidic condensates can attack metallic or cement-bonded building materials.

Figure 2 gives an overview of the various sulfur compounds occurring in waste water [34].

Reduction of sulfates from the waste water also takes place in sewer slime and in deposits. Sewer slime is a film of microorganisms (bacteria and fungi) as well as organic and inorganic materials that adhere to the inner surfaces of waste water facilities. Sulfate, nutrients, oxygen, and organic substrates diffuse out of the waste water into the sewer slime and into the deposits. The reduction of sulfate to sulfide by anaerobic sulfate-reducing bacteria commences after the dissolved oxygen has been consumed, which is already the case after a few tenths of a millimeter in sewer slime. If resulting sulfide diffuses towards the waste water into the upper aerobic layer of the sewer slime or the deposit, it is reoxidized to sulfate before it reaches the waste water. Thus, under such aerobic conditions, sulfate reduction does indeed occur in the lower regions of the sewer slime and deposits; however, the reduced sulfur compounds are reoxidized before they reach the waste water and they cannot enter the sewer atmosphere.

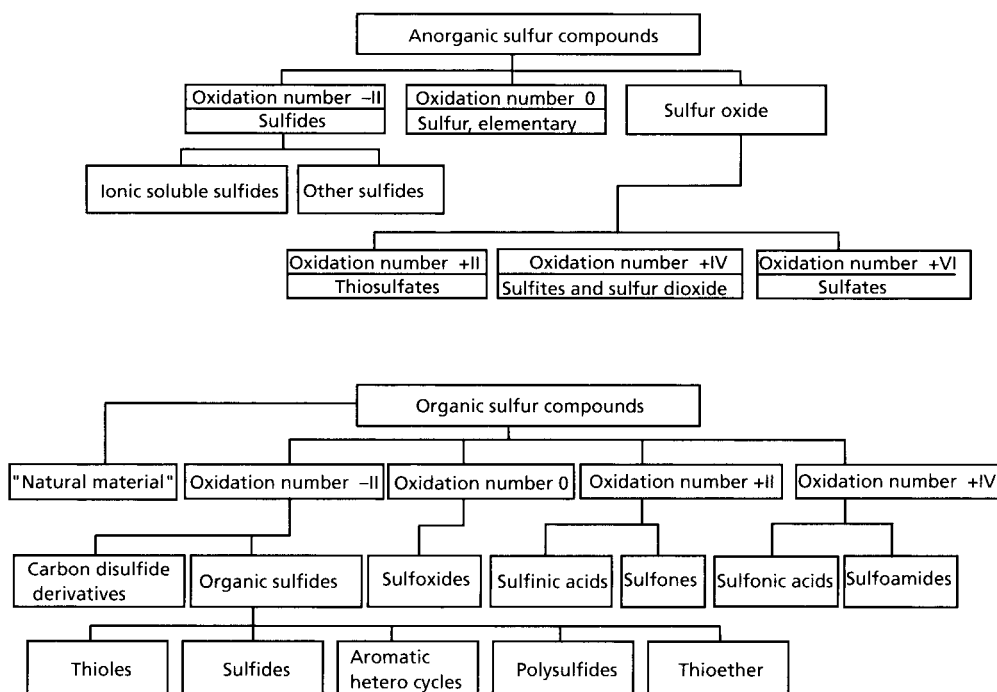


Figure 2: Possible sulfur compounds in waste water [34]

Under anoxic or anaerobic conditions, the sulfate is already reduced in the upper layers of the sewer slime and deposits, and the sulfides thus formed can diffuse into the waste water. Depending on the pH value, an equilibrium between H_2S , HS^- and S^{2-} is established in accordance with Figure 3.

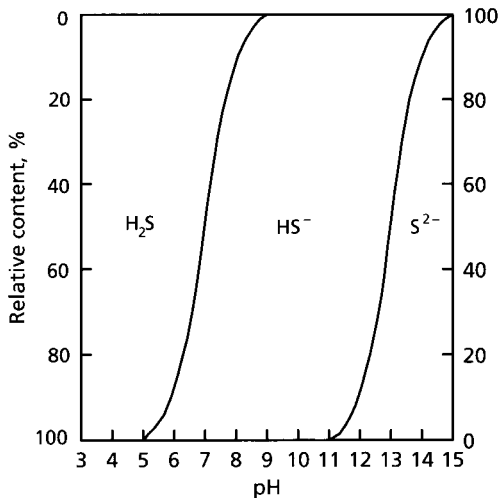


Figure 3: Influence of the pH value on the equilibrium between $\text{H}_2\text{S}/\text{HS}^-$ and $\text{HS}^-/\text{S}^{2-}$ at 293 K (20 °C) in water [35]

When the waste water has a pH value between pH 7 and 8, the fraction of hydrogen sulfide lies between 50 % and 10 %. As the pH value decreases, not only does the proportion of H_2S of the total sulfide content increase, but also the quantity of H_2S that can be released into the sewer atmosphere increases along with the risk of corrosion.

Diffusion or turbulences allow the volatile hydrogen sulfide to enter the sewer atmosphere and then dissolve in the condensate on the inner surface of the sewer wall. This can lead to direct corrosive attack of some metals. *Thiobacillae* oxidize the hydrogen sulfide to elemental sulfur or to sulfuric acid to result in stronger acid attack of the sewer wall.

A

Metallic materials

A 2 Aluminium

A 3 Aluminium alloys

Aluminium and its alloys are generally not resistant to substances that attack their protective oxide layer. These include e.g. acid media with pH values below pH 6 (except for nitric acid), alkaline media with pH values above pH 9 (except for ammonia solutions), and aqueous solutions containing chloride ions. An extensive compilation of the various chemicals and their effect on aluminium (general) is given in [37]. Aluminium has good resistance to hydrogen sulfide-containing atmospheres as found above the water line in many waste water treatment plants due to biogenic sulfate reduction. It has thus proven suitable for components in regions exposed to the atmosphere but which are not in direct contact with the waste water, e.g. for covers in sewage treatment facilities, for ventilation ducts as well as for grids and floor plates in this zone [38].

An aluminium pipeline used to withdraw H_2S above settling tanks was damaged internally by pitting corrosion. This was attributed to the bacteria-mediated conversion of H_2S to sulfuric acid, although some observations indicate otherwise [38].

An aluminium alloy of unspecified composition has been used successfully as a heat exchanger material in low-temperature waste water evaporation plants at temperatures up to approx. 363 K (90 °C) and a salt concentration of approx. 7 % [39].

In the corrosion tests described in Section A 14 (Table 7) in a biological industrial waste water treatment plant, serious pitting corrosion was exhibited by the aluminium samples that were also tested. Therefore, these materials are not suitable for this application.

A 9 Copper-nickel alloys

Copper-nickel alloys can fail if the waste waters contain hydrogen sulfide, sulfides, ammonia or ammonium compounds [39, 40].

Owing to their good resistance to high concentrations of salt solutions, the alloys CuNi30Fe1Mn (CW354H, 2.0882, CuNi 70/30) and CuNi10Fe1Mn (CW352H, 2.0872, CuNi 90/10) are used in seawater and waste water evaporation plants [41].

An evaporator plant made of CuNi30Fe1Mn, which processed waste water from the scrubbers of a waste incineration plant, exhibited stress corrosion cracking after only a short operating time. The reason was found to be mercury entrained in the waste (Hg content of the waste water 10.6 mg/l). The plant was able to continue operating without problems after a mercury precipitation step had been installed upstream of the evaporation unit and the damaged sections had been repaired [42].

In smaller waste water evaporation plants, some of the valves and other fittings are made of partly nickel-plated CuNi alloys [43]. The evaporator and heat exchangers in seawater desalination plants with vapor compression are frequently made of CuNi10Fe1Mn and CuNi30Fe1Mn [44].

A comprehensive tabulated compilation of metallic materials, including copper-nickel alloys, used in seawater desalination plants with multistage flash processes is given in [45]. However, the statements made in [44] and [45] only refer to experiences gained with seawater desalination plants. Therefore, the results have only very limited applicability to waste water because the pH values of seawater are usually neutral to slightly alkaline. Because hot solutions with high chloride contents are produced in the final stage of seawater desalination plants that use evaporation processes, experiences gained with respect to the material's behavior can also be applied to the material behavior in the corresponding plant sections of waste water evaporation plants of flue gas desulfurization plants and waste incineration plants that also have high chloride concentrations, as long as they have comparable pH values.

A 14 Unalloyed steels and low-alloy steels/cast steel

Pipes made of unalloyed and low-alloy steels are frequently used for waste water pipelines, which are usually installed underground. The corrosion rates of these materials in almost neutral waste waters are chiefly determined by the concentration of dissolved oxygen and by its transport to the steel surface. Uniform corrosion rates are usually in the range of 0.1 to 0.2 mm/a (4 to 8 mpy). There may be increased local attack owing to the formation of aeration cells, e.g. underneath deposits, and if there are differing oxygen concentrations in the medium. Without corrosion protection, these steel grades are thus not sufficiently resistant to the flowing medium nor to the gas atmosphere above the level of the liquid. Therefore, pipes made of these steels as well as the frequently used pipes of ductile cast iron can only be used if they have sufficient corrosion protection [1, 8]. Unalloyed steels are not attacked by dry H₂S at room temperature. There have been several reports of heavy corrosion of covers of biological settling tanks after longer operating times [38]. These tanks are exposed to high H₂S concentrations and high humidity levels.

The structural steel St 38 (cf. AISI 1015, 1.0037), gray cast iron, austenitic CrNi steels, aluminium, and polymer materials were tested in the laboratory for their suitability in a waste water treatment plant under simulated operating conditions, such as in collecting tanks for mixed waste water (buffer tanks), in the neutralization stage, in primary biological stage and in the final biological stage. The industrial

waste waters from various points with differing compositions are stored in buffer tanks at an average temperature of 314 K (41 °C). In the neutralization stage, the waste waters at approx. 313 K (40 °C) are adjusted to pH 6-7. In the main biological treatment stage, the mixed water, neutralized or at pH 5, is subjected to bacterial degradation at a temperature between 303 K (30 °C) and 313 K (40 °C) with excess oxygen and strong turbulence from recirculating pumps. This increases the pH value to pH 7-8. The subsequent treatment is carried out in the final biological stage at 303 K (30 °C). The resulting corrosion rates for samples of unalloyed steel and gray cast iron are given in Table 7 [46].

According to these results, St 38 (cf. AISI 1015) or gray cast iron can only be used in the final biological stage under the given conditions. The likewise tested austenitic CrNi steels were resistant under all experimental conditions, whereas all tested aluminium samples exhibited strong pitting corrosion.

Plant	Test duration days	Corrosion rate mm/a (mpy)	
		unalloyed steel St 38 AISI 1015	gray cast iron
Buffer tank	140	2.68 (105.5)	5.90
Neutralization stage		0.76 (29.92)	0.32
Main biological treatment stage	180 to 260	0.89 (35.04)	0.38
Final biological treatment stage	260	0.02 (0.70)	0.02

Table 7: Corrosion rates of unalloyed steel and gray cast iron in plants used for waste water treatment [46]

The corrosion behavior of unalloyed C steel USt 42-2 (1.0040, JIS SS 400), low-alloy steel 34CrMo4 (1.7220, JIS SCM 435) and 36NiCr10 (1.5736, JIS SNC 631), CrNi steel AISI 304 (1.4301, X5CrNi18-10), 13 % chromium steel AISI 403 (1.4000, X6Cr13), 17 % chromium steel AISI 430 (1.4016, X6Cr17), copper Cu-PHC (CW020A, SE-Cu, 2.0070) and a CuZn alloy CuZn40 (CW509L, 2.0360) in contact with ozone-containing water was investigated with respect to ozone, which has been used more frequently in recent years [47]. The chemical composition of the materials is given in Table 8.

The ozone concentration in the deionized water was varied between 0 and 7.1 mg/l, and the corrosion rate was determined in static, fast-flowing, and slow-flowing media (Table 9). The corrosion rate of unalloyed steel USt 42-2 (1.0040) in pure, air-saturated water at room temperature with a very low concentration of dissolved ozone, determined under static conditions and with a slow flow rate, was several times higher than that obtained in ozone-free water. According to the generally accepted evaluation rules, resistance can only be expected for higher flow rates. In practice, however, this favorable behavior is not significant because the investigation showed that the corrosion potential was immediately shifted from the positive

Material	DIN-Mat. No.	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
USt 42-2 (JIS SS 400)	1.0040	0.18	0.05	0.80	0.007	0.005	–	–	–	balance
34CrMo4 (JIS SCM 435)	1.7220	0.34	0.19	0.71	0.012	0.006	–	1.09	0.19	balance
36NiCr10 (JIS SNC 631)	1.5736	0.30	0.32	0.57	0.014	0.006	2.64	0.75	–	balance
AISI 304 X5CrNi18-10	1.4301	0.06	0.40	0.75	0.031	0.004	9.07	18.22	–	balance
AISI 430 X6Cr17	1.4016	0.07	0.52	0.41	0.031	0.007	0.30	16.61	–	balance
AISI 403 X6Cr13	1.4000	0.07	0.36	0.32	0.022	0.002	0.24	12.57	–	balance
		Cu	Zn	Fe	Pb					
CuZn40 (CW509L)	2.0360	61.41	38.57	0.006	0.016					
Cu-PHC (CW020A, SE-Cu)	2.0070	99.95	–	–	–					

Table 8: Composition of the investigated materials (%) [47]

range to the negative range when the ozone feed diminished. Once the corrosion process had started, the potential could not be shifted back into the noble range, even if ozone was added.

From the experience with ozone treatment of cooling waters reported in [48], it can be assumed that a negative influence on the corrosion of low-alloy steels is not expected for ozone concentrations of 0.1 mg/l. However, the use of high-alloy steels is recommended for pipelines carrying ozone-rich water.

Reference [49] describes the influence of sulfate-reducing bacteria on the corrosion of unalloyed steels in detail. Certain prerequisites are linked to the formation of a biofilm. These are essentially the concentrations of dissolved oxygen and dissolved Fe^{2+} ions as well as the physical and chemical properties of the resulting iron sulfides. Locally occurring anaerobic conditions on metal surfaces in industrial waste water systems encourage the formation of biofilms that contain sulfate-reducing bacteria. Even low concentrations of Fe^{2+} ions in the presence of sulfate-reducing bacteria lead to the breakdown of protective layers, and the corrosion rate increases proportionally to the concentration of iron ions (Figure 4). The corrosion rate of unalloyed steels in industrial waste water systems is not directly determined by the activity of sulfate-reducing bacteria, but indirectly by the properties of the adhering Fe^{2+} sulfides produced as corrosion products [49].

Water flow rate	None		Low flow rate, 5 – 10 cm/s		High flow rate, 1.7 m/s	
Ozone concentration, mg/l	2.1	0	2.1	0	2.1	0
Material	Corrosion rate, mm/a (mpy)					
Unalloyed steel	0.18	0.07	0.68	0.11	0.003	0.003
USt 42-2 (1.0040)	(7.09)	(2.76)	(26.77)	(4.33)	(0.12)	(0.12)
Low-alloy steel	0.14	0.05	0.17	0.06	0.01	0.002
34CrMo4 (1.7220)	(5.51)	(1.97)	(6.69)	(2.36)	(0.39)	(0.08)
Low-alloy steel	0.12	0.04	0.15	0.05	0.015	0.001
36NiCr10 (1.5736)	(4.71)	(1.57)	(5.91)	(1.97)	(0.59)	(0.04)
CrNi steel AISI 403 (1.4301, X5CrNi18-10)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	–	–
13 %-Cr steel AISI 304 (1.4000, X6Cr13)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)
17 %-Cr steel AISI 430 (1.4016, X6Cr17)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)
Copper SE-Cu (CW020A, 2.0070)	0.02 (0.79)	0.002 (0.08)	0.02 (0.79)	0.003 (0.12)	0.03 (1.18)	0.004 (0.16)
Brass CuZn40 (CW509L, 2.0360)	0.02 (0.79)	0.003 (0.12)	0.03 (1.18)	0.003 (0.12)	0.05 (1.97)	0.01 (0.39)

Table 9: Corrosion rates of the metals listed in Table 8 in air-saturated water with and without ozone at room temperature and with differing flow rates [47]

Corrosion damage to several components made of low-alloy steels and cast iron in the waste water treatment plant of a petroleum refinery were also caused by the action of sulfate-reducing bacteria. To prevent further damage, the pipelines were either replaced by those made of glass-fiber-reinforced polyester resin or they were lined with sulfate-resistant concrete [50].

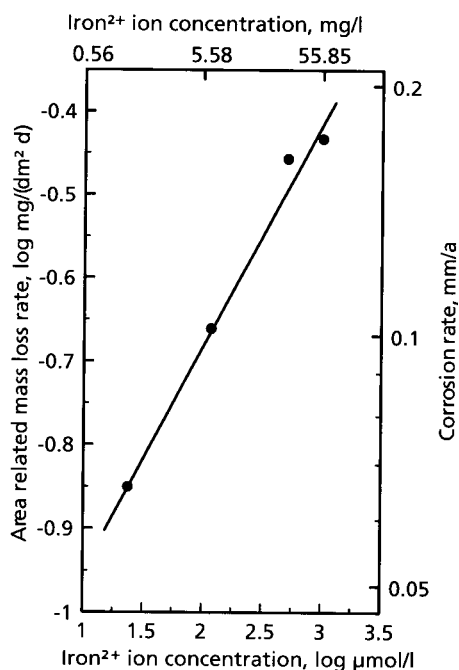


Figure 4: Corrosion rate of unalloyed steels depending on the Fe^{2+} concentration in water and on the presence of sulfate-reducing bacteria [49]

A 15 Unalloyed cast iron and low-alloy cast iron

A 16 High-alloy cast iron

A 16.1 Silicon cast iron

The results of corrosion tests described in Section A 14 that were carried out in a biological industrial waste water treatment plant on samples of gray cast iron are given in Table 7.

These showed, as expected, that unalloyed cast iron behaves similarly to unalloyed steel [46].

Immersed motor pumps made of gray cast iron have been used for many years in waste water applications; however, for reasons of weight and improved corrosion resistance, they have recently been replaced by pumps made of CrNiMo stainless steels [51].

Waste water pumps made of gray cast iron (EN-GJL-250, 0.6025) have surface roughnesses between 12 and 50 μm (R_a , arithmetic mean roughness) and are thus ideal substrates for adhesive biofilms. Biocorrosion is accelerated on these materials, in contrast to polishable spherical graphite cast iron and cast ferrosilicon. Bronze pumps have improved mean roughness values of approx. 10 μm R_a , and pumps

made of cast high-alloy CrNiMo can be polished to values of 5 μm Ra. However, the formation of cavities with a risk of biocorrosion cannot be excluded in this case [52].

Unalloyed cast iron grades (e.g. EN-GJL-250) are mainly recommended for less aggressive waste waters in the pH range of ≥ 6 with low concentrations of abrasive solid particles (less than 1 g/l) [53]. Pipes made of gray cast iron usually have corrosion protection coatings on the inner and outer surfaces [1, 8]. The withdrawn standard DIN 19690 specified a bitumen-based coating for the external corrosion protection. The new DIN EN 598 [54] stipulates that the standard external protection of the pipes must consist of a zinc coating plus top coat as well as an epoxy resin coating in the region of the male ends and the inner surfaces of the sockets. DIN 19690 stipulates a cement-bonded mortar lining for the inner corrosion protection [55].

Hard chromium-molybdenum-alloyed cast iron GX250CrMo15-3 (Norihard® NH 15 3, cf. GX300CrMo15-3, 0.9635) has a predominantly martensitic microstructure with chromium carbide inclusions. It is characterized by a high wear resistance and relatively good toughness. The hardness and abrasion resistance of this material is only superseded by the pure metal oxides and metal carbides (hard metals). However, compared to these materials, it has the advantage that it can be soft-annealed by heat treatment after casting so that it can be machined. It has a corrosion resistance comparable to unalloyed cast iron. However, as a material for submersible pumps, it is superior to the latter material because it has a better resistance to abrasive wear. Under comparable operating conditions, it has a 10- to 15-fold longer service life than gray cast iron and a 5- to 10-fold longer service life than wear-resistant special cast iron. Application areas include the transport of lime milk, sludges in alumina production, sinter waters from steelworks, and ash/water suspensions in power stations [56].

The high-alloy ferritic-austenitic CrNiMo cast steel GX3CrNiMoCuN24-6 based on chromium-nickel-molybdenum-copper with a ferrite/austenite ratio of 50:50 (Noridur® 9.4460, cf. GX2CrNiMoCuN25-6-3-3, 1.4517) is suitable as a pump material owing to its good resistance to simultaneous hydroabrasive wear and chemical attack. Its high chromium and molybdenum contents make it superior to the conventional austenitic CrNi and CrNiMo cast steel grades, particularly if, for example, there are strong fluctuations in the pH value and high chloride concentrations in chemical waste waters that also contain large quantities of abrasive solids [53, 56–59]. Table 10 gives the relevant material data for the various cast materials and Table 11 gives information on their applications [56].

Pipes made of ductile cast iron i.e. cast iron with spheroidal graphite according to DIN EN 1593 [60] are used extensively in communal and industrial waste water disposal systems. The technical terms of delivery DIN EN 598 [54] contain information on the material parameters, on their joints, as well as on the testing and quality control of pipes. Some material parameters are given in Table 12.

Materials	Chemical composition mass%								Mechanical properties (approximate values)					
	C	Si	Mn	P _{max}	S _{max}	Cr	Ni	Mo	Cu	Tensile strength R _m N/mm ²	Yield strength R _{p0.2} N/mm ²	Elongation at failure A ₅ %	Impact toughness A _v DVM J	Hardness HB 30
EN-GJL-250, 0.6025	3.3	1.95	0.7	0.10	0.08					309				180-240
EN-GJS-400-15, 0.7040	3.7	2.2	0.4	0.04	0.01					420	283	24		180-220
Norihard® NH 15 3 cf. GX300CrMo15-3, 0.9635	2.6	0.7	0.6			15		2.6		600				750-1000 ¹⁾
1.4408, CF-8M GX5CrNiMo19-11-2	0.07	2.0	1.5			18.5	10	2.2		440	185	20	68	130-200
Noridur® 9.4460 cf. GX2CrNiMo CuN25-6-3-3, 1.4517	0.04	1.5	1.5			25.5	6.0	2.5	3.0	690	485	25	80	200-260

¹⁾ HV 50

Table 10: Material data for selected pump materials [56]

Materials	Comments on applications
EN-GJL-250, 0.6025	Standard material for waste waters containing chemicals that are not aggressive; without abrasive solids
EN-GJS-400-15, 0.7040	For waste waters containing chemicals that are not aggressive; without abrasive solids when pressurized components are subjected to pressure surges or if there is a risk of frost damage
Norihard® NH 15 3 cf. GX300CrMo15-3, 0.9635	For waste waters containing chemicals that are not aggressive but with large quantities of abrasive solids
1.4408, CF-8M GX5CINiMo19-11-2	For waste waters containing chemicals that are not aggressive up to pH values of ≥ 4.0 and chloride concentrations of < 100 mg/l
Noridur® 9.4460 cf. GX2CrNiMoCuN25-6-3-3, 1.4517	For chemical waste waters with extremely low pH values and high chloride concentrations; also for low concentrations of abrasive solids

Table 11: Comments on applications for selected pump materials [56]

Material parameters	
Tensile strength	$\geq 400 \text{ N/mm}^2$
0.2 % Yield strength	$\geq 300 \text{ N/mm}^2$
Elongation at failure	$\geq 7 \%$ (pipes)
Hardness	$\leq 250 \text{ HB } 5/750$
Modulus of elasticity	170 kN/mm^2
Bursting strength	$\geq 300 \text{ N/mm}^2$
Hoop strength	$\geq 550 \text{ N/mm}^2$
Longitudinal bending strength	$\geq 420 \text{ N/mm}^2$

Table 12: Material data for pipes made of ductile cast iron according to DIN EN 598 [54, 62]

Pipes made of ductile cast iron are supplied with push-in joints according to DIN 28603 [61]. These joints have a sealing ring made of natural or synthetic rubber. The pipes are used in waste water applications with a standard protection consisting of an internal cement mortar lining and an external spray-coating of zinc with an additional bitumen-based coating (see also Section D 1). The cement mortar lining not only provides passive protection because it separates the metal surface from the media, but it also provides active protection by absorbing lime out of the mortar so that the phase on the surface of the metal has a pH value greater than 12 in which the cast iron is virtually passive [62].

- A 17 Ferritic chromium steels with < 13 % Cr
- A 18 Ferritic chromium steels with ≥ 13 % Cr
- A 19 High-alloy multiphase steels
- A 19.1 Ferritic/pearlitic-martensitic steels
- A 19.2 Ferritic-austenitic steels/duplex steels

In a biological sewage treatment plant, components made of ferritic stainless chromium steel AISI 409 (1.4512, X2CrTi12) that were partially immersed in the waste water exhibited strong corrosion, particularly at the weld seams. The incoming industrial waste water contained between 1100 – 3080 mg/l chloride during the observation period. A microbiological analysis also showed high levels of sulfate-reducing bacteria. The selected material with a chromium content of only 12 % was not suitable for this application [63].

Table 9 [47] also gives the results of exposure tests in ozone-containing water for the 13 % chromium steel AISI 403 (1.4000, X6Cr13) and the 17 % chromium steel AISI 430 (1.4016, X6Cr17) (composition in Table 8). Both materials were resistant under the given test conditions. In contrast, the low-alloy chromium steel 34CrMo4 (UNS G41300, 1.7220) is not resistant in ozone-containing water.

Most of the waste waters from oil refinery plants arise from stripping of acidic waste gases that are produced by distillation or gas production. In this process, the H_2S and CO_2 components are absorbed by a counterflow of amine solutions (monoethanolamine (MEA) or diethanolamine (DEA)). The absorption solution is recycled after thermal removal of the acidic gases. The heat exchangers used in this process are subjected to the conditions given as an example in Table 13.

	Untreated water, piping	Treated water, outer wall
H_2S	5,000 ppm	4 ppm
Mercaptans	90 ppm	15 ppm
Thiosulfate	–	25 ppm
Cl^-	10 – 30 ppm	–
pH	7	9 – 11
Temperature	inlet: 303 K (30 °C) outlet: 373 K (100 °C)	inlet: 423 K (150 °C) outlet: 333 K (60 °C)
Pressure	1.0 MPa	1.0 MPa

Table 13: Corrosion conditions in heat exchangers exposed to waste waters from oil refining for components made of ferritic-austenitic steel (duplex steel) UNS S31500 (3RE60, 1.4417) [64, 65]

Heat exchangers made of duplex steel UNS S31500 (18 Cr, 5 Ni, 3 Mo, cf. 3RE60, 1.4417) have been used without problems for more than 10 years. In previous trials, the ferritic 17 % chromium steel AISI 430 (1.4016, X6Cr17) and also the austenitic chromium-nickel-molybdenum steel AISI 316 (1.4401, X5CrNiMo17-12-2) failed

due to stress corrosion cracking less than six months after commissioning. The duplex steel UNS S31500 has been used successfully for almost seven years as a head condenser in a DEA scrubber. The gas in contact with the pipes contained hydrogen sulfide, water, carbon dioxide, ammonia, as well as traces of DEA, oxygen, and acetonitrile. The temperature was 368–378 K (95–105 °C). The outer wall was in contact with brackish water containing 1000 – 1200 ppm Cl⁻ [64, 65].

In general, for the selection of materials to be used in conditions where there is a risk of stress corrosion cracking, it is advisable to short-list duplex steels because these exhibit better resistance than austenitic chromium-nickel steels [66].

Ferritic, austenitic, or ferritic-austenitic cast alloys are used in preference as materials for pumps in scrubber circuits of flue gas desulfurization plants (FGD plants). The chemical compositions of some typical high-alloy pump materials are given in Table 14 [67]. The pumped media are strongly corrosive owing to their low pH values and high salt concentrations on the one hand, and, on the other hand, the entrained solids cause hydroabrasive wear of pump parts, such as impellers or wear plates, that are exposed to fast-flowing media. Table 15 gives the essential parameters to which the material is exposed along with values of a typical FGD scrubbing solution. Furthermore, Sheet 4 of the ATV Notice H 706 discusses waste waters from flue gas scrubbers in detail [68].

Material	Trade name	C	Si	Mn	Cr	Ni	Mo	Cu	other
GX5CrNiMo19-11-2, 1.4408	Norinox®	≤ 0.14	≤ 1.5	≤ 1.5	19.0	11.0	2.3		
EN-GJN-HV 600, 0.9650	Noriloy® NL 25 2	1.7	1.0	1.0	25.0		2.0		
GX3CrNiMoCuN24-6-2-3, 1.4593	Noridur®	≤ 0.04	≤ 1.5	≤ 1.5	25.0	6.0	2.4	3.1	N
GX3CrNiMoCuN24-6-5, 1.4573, AISI 316 Ti	Noriclor® NL 24 6	≤ 0.04	≤ 1.0	≤ 1.0	24.0	6.0	5.0	2.0	N

Table 14: Approximate analysis values of some high-alloy cast steel grades used for pump construction (mass%) [67]

Parameters and contents	Unit	Usual range	Extreme values
pH value		4 – 8	< 1 – 12
Chloride concentration	g/l	5 – 80	100
Sulfate concentration	g/l	1 – 4	6
Nitrate concentration	g/l	0.2 – 1.0	1.5
Other salts	mg/l	< 0.5	
Solids content	mass%	10 – 25	60
Density	g/cm ³	1.02 – 1.15	1.5

Table 15: Essential parameters of scrubbing solutions in flue gas desulfurization plants that operate with the calcium carbonate scrubbing process [67]

Under critical conditions, these materials also exhibit damage due to abrasion or corrosion. For example, in a FGD scrubbing suspension with the following data

- pH value: 3.5 – 5.5
- chloride concentration: approx. 70,000 mg/l
- solids content: > 200 g/l

the wear plate of a pump made of EN-GJN-HV 600 exhibited strong abrasive wear after 8800 operating hours. Noticeably improved service lives were attained under these conditions by the use of GX3CrNiMoCuN24-6-2-3 with a wear plate protected with by a weld-cladding with the hard alloy Stellite® H6 or by a SiC ceramic coating [67].

A 20 Austenitic CrNi steels

A 21 Austenitic CrNiMo(N) steels

A 22 Austenitic CrNiMoCu(N) steels

In addition to ferritic-austenitic steels (duplex steels), austenitic CrNiMo steels can also be used in waste water treatment plants. These steels are sufficiently passive in most waste waters so that uniform surface corrosion can be practically neglected; however, under critical conditions, they can exhibit local corrosive attack in the form of pitting corrosion, crevice corrosion or stress corrosion cracking. The decisive evaluation criteria for their possible application with respect to the media are:

- the chloride concentration
- the pH value
- the temperature
- the redox potential

Pitting corrosion only occurs when the potential of the steel in the medium is more positive than the pitting corrosion potential. For longer exposures, the corrosion potential of the steel shifts in the direction of the redox potential, however, it does not exceed this potential. Pitting corrosion cannot occur if the pitting corrosion potential is more positive than the redox potential of the system. In the inverse case, if the pitting corrosion potential is more negative than the redox potential, there is always a risk of pitting corrosion.

The risk of pitting corrosion thus increases if the pitting corrosion potential is shifted to more negative values, e.g. in the event of

- an increasing chloride concentration
- a decreasing pH value
- a higher temperature

Higher redox potentials, i.e. high concentrations of oxidizing agents, increase the risk of pitting corrosion in that they shift the resting potential of the steel in the direction of the pitting corrosion potential.

The resistance to pitting corrosion increases as the pitting corrosion potential becomes increasingly positive. As the contents of chromium and molybdenum increase, the pitting corrosion potential of stainless steels is shifted to more positive values, i.e. the resistance to pitting corrosion is increased, whereby the effect of molybdenum is approximately three times greater than that of chromium.

This allows the pitting corrosion resistance to be estimated from the composition of the steel. The differing efficiencies of the alloying elements is taken into account in the **pitting index (PI)**.

$$PI = \text{mass\% Cr} + 3.3 \times \text{mass\% Mo}$$

The pitting corrosion resistance of the steels increases as the value of the pitting index increases.

Correctly selected materials made of CrNiMo stainless steels have proven suitable in various components of sewage treatment plants, including aerated and buried sewage sludge and digester gas tanks. The few problematic cases to date have been limited to two types of damage, which, however, are not limited to waste water treatment plants, but are generally applicable:

- spots of extraneous rust due to incomplete final cleaning
- crevice corrosion due to deposits that were not removed by routine cleaning
- processing faults

These problems can be avoided by final checks before commissioning the plant and sufficiently high flow rates during operation.

Table 16 gives a selection of DIN and European standards for stainless steels [69].

DIN 17440 [70]	Stainless steels; Technical terms of delivery for sheets, hot-rolled strip, rolled wire, drawn wires, bars, forgings, and semifinished products
DIN EN 10028-7 [71]	Stainless steels; Technical terms of delivery for cold-rolled strips and split strips as well as sheets cut from them
DIN 17455 [72]	Welded circular tubes made of stainless steels for general quality requirements; Technical terms of delivery
DIN 17456 [73]	Seamless circular tubes made of austenitic stainless steels for general quality requirements; Technical terms of delivery
DIN EN 10217-7 [74]	Welded circular tubes made of austenitic stainless steels for enhanced quality requirements; Technical terms of delivery
DIN 17458 [75]	Seamless circular tubes made of austenitic stainless steels for enhanced quality requirements; Technical terms of delivery
DIN EN 1124-3 [76]	Pipes and fittings of longitudinally welded stainless steel pipes with spigot and socket joints for waste water pipelines – Part 3: System X; Dimensions
SEW 400 [77]	Stainless steels for rolling and forging

Table 16: DIN and DIN EN standards for stainless steels [69]

Table 16: Continued

DIN EN 10088-1 [78]	List of stainless steels, chemical composition and physical properties
DIN EN 10088-2 [79]	Technical terms of delivery for sheet and strip steel for general purposes
DIN EN 10088-3 [80]	Technical terms of delivery for semifinished products, bars, rolled wire, and sections for general purposes
Supplementary DIN EN standards for general purposes are in preparation for wires, forgings, seamless tubes, and welded tubes	
Applicable to pressure vessels:	
DIN EN 10028-7 [71]	Flat products, bars
DIN EN 10225-5 [81]	Forgings
DIN EN standards are being prepared for seamless and welded tubes for pressure vessels.	

Table 16: DIN and DIN EN standards for stainless steels [69]

Nowadays, austenitic steels with chromium contents of 18 %, nickel contents of 10 – 12 % and molybdenum contents of 2 – 3 % are generally used in preference in waste water treatment plants. Steels that do not contain molybdenum are generally not sufficiently crevice corrosion resistant to the chloride concentrations of approx. 70 mg/l that are typical in waste waters. Repeatedly observed corrosion damage of the gas zone in sludge tanks are attributed to the influence of high concentrations of organic acids. Under these conditions, preference should be given to the use of more highly alloyed metallic materials with an enhanced resistance to acids by alloying with copper, e.g. AISI 904 L (X1NiCrMoCuN25-20-5, 1.4539) or UNS N08926 (X1NiCrMoCuN25-20-7, 1.4529) [82]. Table 17 gives the critical values for the chloride ion concentrations in pure, neutral water for a few commercially available steels with respect to avoiding pitting and crevice corrosion. The critical concentrations decrease with decreasing pH values and increasing temperatures [8].

Figure 5 gives an example of a flow diagram of a waste water treatment plant with the essential components. Table 18 gives the associated operating conditions and the behavior of the austenitic steel grades CrNi18-8 (type AISI 304, comparable to 1.4301) and CrNiMo18-8-2 (type AISI 316, comparable to 1.4401, 1.4436) for the respective conditions [83].

The corrosion rates for uniform surface corrosion are always less than 0.002 mm/a (0.08 mpy), so that this type of corrosion can be neglected. However, for molybdenum-free steel grades, there is a risk of crevice corrosion in most cases. Both types of steel are also insensitive to damp gases containing H₂S that occur in some parts of the plant. Damp chlorine vapors, which arise if there is insufficient ventilation in the vicinity of chlorine storage tanks, can also lead to pitting corrosion of the 316-type steels at locations where such vapors can collect.

Alloy	Contents of key alloying components					Max. chloride concentration g/l		Max. temperature K (°C)
	% C	% Cr	% Ni	% Mo	Other	PC	CC	
AISI 304 1.4301 X5CrNi18-10	max. 0.07	18	10	–		0.2	0.02	298 (25)
AISI 304 L 1.4306 X2CrNi19-11	max. 0.03	19	11	–		0.2	0.02	298 (25)
AISI 321 1.4541 X6CrNiTi18-10	max. 0.08	18	10	–	Ti	0.2	0.02	298 (25)
AISI 316 1.4401 X5CrNiMo17-12-2	max. 0.07	17	12	2		1.0	0.2	308 (35)
AISI 316 L 1.4404 X2CrNiMo17-12-2	max. 0.03	17	13	2		1.0	0.2	308 (35)
AISI 316 Ti 1.4571 X6CrNiMoTi17-12-2	max. 0.08	17	12	2	Ti	1.0	0.2	308 (35)
AISI 316 1.4436 X3CrNiMo17-13-3	max. 0.07	17	13	3		5.0	1.0	308 (35)
AISI 316 L 1.4435 X2CrNiMo18-14-3	max. 0.03	18	14	3		5.0	1.0	308 (35)
AISI 317 LMN 1.4439 X2CrNiMoN17-13-5	max. 0.03	17	13	5	N	10.0	5.0	343 (70)
AISI 904 L 1.4539 X1NiCrMoCuN25-20-5	max. 0.03	20	25	5	Cu, N	10.0	5.0	353 (80)
UNS N08926 1.4529 X1NiCrMoCuN25-20-7	max. 0.02	20	25	6	Cu, N	10.0	5.0	353 (80)

PC: pitting corrosion, CC: crevice corrosion

Table 17: Critical concentrations of chloride ions in neutral waters to avoid pitting or crevice corrosion of stainless steels [8]

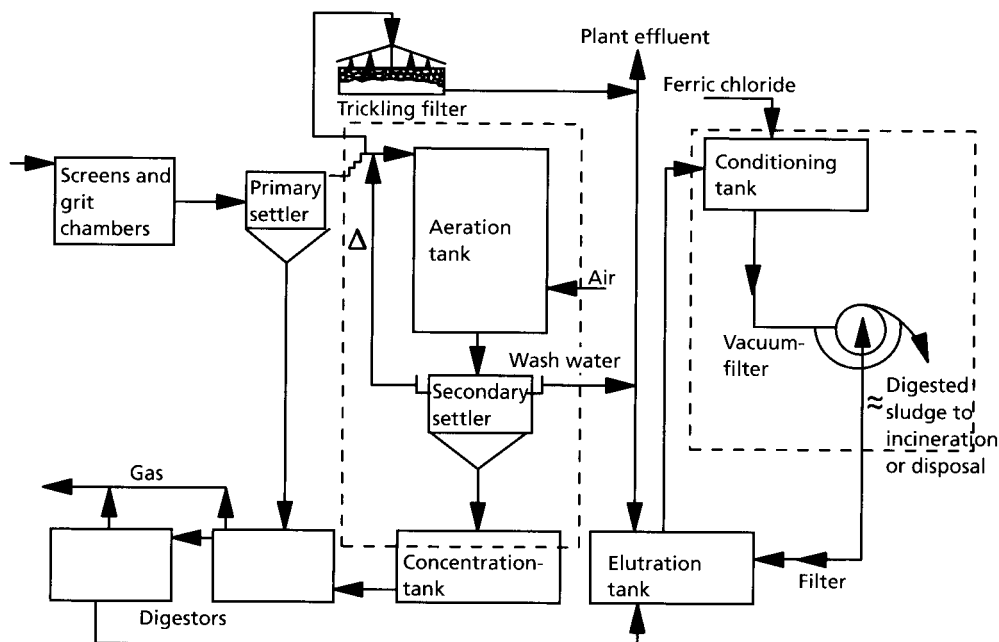


Figure 5: Typical flow diagram of a waste water treatment plant [83]

Austenitic steels are sufficiently corrosion-resistant for chlorine concentrations below 3 mg/l, which usually occur if the waste water is chlorinated. The molybdenum-free grades are susceptible to crevice corrosion if they are in continuous contact with waters with a residual chlorine concentration of 3 – 5 mg/l. Austenitic steels are not suitable in chlorine discharge systems in which the chlorine concentration may reach several hundreds of mg/l.

Iron(III)chloride, which is frequently added as a flocculant to treatment tanks, can lead to pitting corrosion and crevice corrosion of both types of steel.

Wet oxidation is a process to oxidize organic waste materials as an alternative to incineration. It is carried out at high temperatures (up to approx. 603 K (330 °C)) and high pressures (up to approx. 250 bar) in aqueous media. This process is used for the treatment of sewage sludge and industrial waste water. The chloride concentration of the waste water is the decisive criterion for the selection of materials for plant components, such as reactors, heat exchangers, high-pressure pumps, and air compressors. Austenitic CrNiMo stainless steels can be used for chloride-free or low-chloride waste waters containing less than 300 – 400 mg/l chloride. Only special alloys, such as Hastelloy® alloy C-276 (cf. 2.4819, NiMo16Cr15W) or Inconel® alloy 625 (2.4856, NiCr22Mo9Nb) are suitable for chloride concentrations of 1000 mg/l and temperatures of approx. 423 K (200 °C). Titanium has proven suitable at higher concentrations [84] (see also Sections A 29 and A 38).

Plant section ¹⁾	Flow rate	Component	Type 304 ³⁾	Type 316 ³⁾
1		untreated raw water BOD ²⁾ : 175-300 ppm O ₂ : 140 ppm; solids: 220-550 ppm	< 0.002 mm/a (< 0.08 mpy) CC	< 0.002 mm/a (< 0.08 mpy) CC
2	0.6 – 0.9 m/s	70 % waste water 30 % activated sludge + H ₂ S	< 0.002 mm/a (< 0.08 mpy) CC	< 0.002 mm/a (< 0.08 mpy) CC
3	vigorous	70 % waste water 30 % activated sludge	< 0.002 mm/a (< 0.08 mpy) CC	< 0.002 mm/a (< 0.08 mpy) CC
4	weak	activated sludge some outflow	< 0.002 mm/a (< 0.08 mpy) CC	< 0.002 mm/a (< 0.08 mpy) CC
5	fairly high		< 0.002 mm/a (< 0.08 mpy) CC	< 0.002 mm/a (< 0.08 mpy) CC
6	0.3 m/s no aeration	active sludge FeCl ₃ addition (250-300 ppm)	< 0.002 mm/a (< 0.08 mpy) CC + PC	< 0.002 mm/a (< 0.08 mpy) CC
7	0.6 m/s moderate aeration		< 0.002 mm/a (< 0.08 mpy) PC	< 0.002 mm/a (< 0.08 mpy) CC
8	1.2 – 1.5 m/s intensive aeration	high concentrations of chloride and solids possible	< 0.002 mm/a (< 0.08 mpy) CC	< 0.002 mm/a (< 0.08 mpy) CC
9	high aeration		< 0.002 mm/a (< 0.08 mpy) CC	< 0.002 mm/a (< 0.08 mpy) CC

1) Numbering from Figure 5, 2) BOD: Biological Oxygen Demand, 3) Corrosion rate, CC: crevice corrosion, PC: pitting corrosion

Table 18: Operating conditions in the plant sections shown in Figure 5 and corrosion behavior of austenitic CrNi and CrNiMo steels
(temperature range: 293-298 K (20-25 °C); pH range: 7.4 – 7.7) [83]

Reference [85] reports on practical experience with respect to the corrosion behavior of austenitic steels, nickel alloys, and titanium in more than 30 plants used for the wet oxidation of sewage sludge over a period of more than 5 years. It also gives the results of investigations in autoclaves and in a pilot plant under comparable conditions. The investigated materials are given in Table 19. The investigations were carried out in autoclaves on welded U-bending samples and in the pilot plant on pipe samples and on bending samples. The results of these investigations are given in Table 20.

The austenitic steels alloy AISI 304 (1.4301, X5CrNi18-10) and alloy AISI 316 (1.4401, X5CrNiMo17-12-2) were only resistant to stress corrosion cracking in

sludges with chloride concentrations of less than 300 – 400 mg/l and also at temperatures up to 561 K (288 °C). Stress corrosion cracking of steel AISI 316 was already observed after 48 hours of exposure to a chloride concentration of 1000 g/l. For information on the behavior of nickel alloys and titanium in these investigations, see Sections A 27 – A 29 and A 38.

Material		Ni	Fe	Cr	Mo	C _{max.}	Other
Hastelloy® alloy C-276	2.4819 NiMo16Cr15W	balance	5	16	16	0.015	Co _{max.} 2.5, W 3.5
Inconel® alloy 625	2.4856 NiCr22Mo9Nb	balance	max. 5	22	9	0.010	(Nb + Ta) 3.5
Hastelloy® alloy G	2.4618 NiCr22Mo6Cu	balance	20	22	6.5	0.015	Cu 2.0, Co _{max.} 2.5, (Nb + Ta) 2.0
28Cr-4Mo	cf. UNS S44700 29-4	max. 0.15	balance	28	4	0.01	(C + N) _{max.} 0.025
28Cr-4Mo-2Ni	cf. UNS S44800 29-4-2	2	balance	28	4	0.01	(C + N) _{max.} 0.025
Incoloy® 825	2.4858 NiCr21Mo	42	balance	21	3	0.025	Cu 2
Carpenter® 20Cb-3	2.4660 NiCr20CuMo	37	balance	20	2.5	0.05	Cu 3.5, Mn _{max.} 2.0, Nb _{max.} 1.0
Sandvik® 2RN65		24	balance	17.5	4.7	0.02	Mn 1.8
E-Brite® 26-1		max. 0.5	balance	26	1.0	0.06	
Sandvik® 3RE60	1.4417 X2CrNiMoSi19-5	4.7	balance	18.5	2.7	0.03	Si 1.65, Mn _{max.} 2.0
AISI 316	1.4401 X5CrNiMo17-11-2	12	balance	17	2.5	0.08	Mn _{max.} 2.0, Si _{max.} 1.0
AISI 304	1.4301 X5CrNi18-10	9	balance	18		0.08	Mn _{max.} 2.0, Si _{max.} 1.0
Titanium			balance				Ti 99.5

Table 19: Composition (approximate, mean, or maximum % values) of the materials investigated under conditions of wet oxidation of sewage sludge [85]

Material		Autoclave experiments 477 K (204 °C)			Pilot plant 450 K (177 °C)
		Chloride concentration			
		600 mg/l	1000 mg/l	3000 mg/l	1000 mg/l
Titanium		0	0	0	0
Hastelloy® alloy C-276	2.4819 NiMo16Cr15W	0	0	PC	0
Inconel® alloy 625	2.4856 NiCr22Mo9Nb	0	0	PC	0
Hastelloy® alloy G	2.4618 NiCr22Mo6Cu	0	PC; CC	PC;CC	–
28Cr-4Mo	cf. UNS S44700 29-4	0	PC; CC	PC;CC	PC
28Cr-4Mo-2Ni	cf. UNS S44800 29-4-2	0	PC; CC	PC;CC	–
Incoloy® 825	2.4858 NiCr21Mo	PC; CC	PC; CC	PC; CC	PC
Carpenter® 20Cb-3	2.4660 NiCr20CuMo	PC; CC	PC; CC	PC; CC	PC
Sandvik® 2RN65		–	PC;CC;SCC	PC;CC;SCC	PC;SCC
E-Brite® 26-1		PC; CC	PC; CC	PC; CC	PC
Sandvik® 3RE60	1.4417 X2CrNiMoSi19-5	PC; CC	PC;CC;SCC	PC;CC;SCC	PC;SCC
AISI 316	1.4436 X3CrNiMo17-13-3	PC;CC;SCC	PC;CC;SCC	–	PC;CC;SCC

0 = No corrosion, PC = pitting corrosion, CC = crevice corrosion, SCC = stress corrosion cracking

Table 20: Results of corrosion tests of the materials listed in Table 19 [85]

Pipe-in-pipe heat exchangers made of four different alloys were tested in a wet oxidation unit for sewage sludge over a period of 1600 h under the following operating conditions.

Temperature	294-466 K (21-193 °C)
pH	5.1
Chloride concentration	250 – 500 ppm
Sludge composition	
COD (Chemical Oxygen Demand)	26.1 g/l
Total volatile acids	0.6 g/l
NH ₃ , total	0.06 g/l
N, total	0.31 g/l
P, total	0.10 g/l
Solids, total	22.0 g/l
Volatile substances	14.4 g/l
Sulfur, total	0.17 g/l
Alkalinity calculated as CaCO ₃	0.24 g/l
Soluble chlorides	0.51 g/l

Table 21: Experimental conditions in a wet oxidation unit for sewage sludge [86]

The investigated materials were stainless steel AISI 316 L (1.4401, X5CrNiMo17-12-2) and the nickel alloys Incoloy® 825 (2.4858, NiCr21Mo), Hastelloy® alloy G (2.4618, NiCr22Mo6Cu) and Hastelloy® alloy C-276 (DIN-Mat. No. 2.4819, NiMo16Cr15W). The dismantled heat exchangers were examined after completion of the test. Depending on the operating conditions and the alloy, some of them exhibited pitting corrosion as well as crevice corrosion and stress corrosion cracking. All the investigated materials exhibited uniform surface corrosion rates of 0.03-0.06 mm/a (1.18-2.36 mpy). Table 22 gives the limiting temperatures of the materials with respect to local corrosion for these test conditions [86].

Material	Limiting temperature
Alloy 316 L 1.4401, X5CrNiMo17-12-2	366 K (93 °C)
Incoloy® 825 2.4858, NiCr21Mo	395 K (122 °C)
Hastelloy® alloy G 2.4618, NiCr22Mo6Cu	395 K (122 °C)
Hastelloy® alloy C-276 2.4819, NiMo16Cr15W	466 K (193 °C) ¹⁾

¹⁾ Final temperature of the test

Table 22: Limiting temperatures for the occurrence of local corrosion in a wet oxidation unit for sewage sludge [86]

A study was carried out with a large number of individual and mixed waste waters in test plants at pressures of 150 – 200 bar, temperatures of 543-603 K (270-330 °C) and with variations of the chloride, sulfate, and phosphate concentrations, the pH values as well as the COD values (Chemical Oxygen Demand). The following metallic materials were examined in this study with regard to their suitability in wet oxidation plants for industrial waste waters: chromium-nickel-molybdenum steel 1.4571 (X6CrNiMoTi17-12-2), titanium, tantalum and nickel. None of the investigated materials was resistant at acidic pHs. At pH values > 7, titanium and tantalum were resistant, even in the presence of low fluoride concentrations and chloride concentrations of up to 100 g/l [87].

The standard stainless steels of type AISI 300 series (cf. AISI 304, 1.4301, X5CrNi18-10; AISI 321, 1.4541, X6CrNiTi18-10; AISI 316, 1.4401, X5CrNiMo17-12-2; AISI 316 Ti, 1.4571, X6CrNiMoTi17-12-2) exhibited sufficient resistance to damp hydrogen sulfide and to waters containing low concentrations of sulfuric acid. They are used in biological waste water plants for pipelines to extract odorous gases as well as for aeration screens and ladders [38].

The chromium-nickel steel AISI 304 (1.4301, X5CrNi18-10) is resistant to ozone-containing water (Table 9).

Austenitic chromium-nickel steels have proven suitable in all sections (collecting tanks for various industrial waste waters, treatment tanks) in a biological sewage treatment plant [46]. These investigations are described in Section A 14.

References [88] and [89] point out that the oxidic passive layer on stainless steels only develops its full effectiveness if the material has been properly processed. If this work is not carried out properly, it may result in damage at a lower corrosive load than the expected nominal resistance. Table 23 lists the processing steps that can have a negative effect on the corrosion resistance of the materials [88]. Figure 6 shows the influence of **tarnishes**, which may be produced during welding, on the pitting potential of the austenitic steel 1.4571 (AISI 316 Ti, X6CrNiMoTi17-12-2). Tarnishes must be completely removed by pickling with nitric acid/hydrofluoric acid [88].

Reference [90] gives a general discussion of the effect of tarnishing on the pitting corrosion of austenitic steels. With respect to this, the author emphasizes the common practice of removing all tarnishing to prevent any pitting corrosion. It is now considered standard practice to avoid tarnishing. If tarnishing cannot be prevented, the materials must be pickled. If there are places where it is not possible to check for tarnishing and thus its presence cannot be reliably excluded, the materials must be pickled.

It is just as important that the construction has been properly executed for the particular material taking account of the specific strength and elasticity values, careful assembly, as well as parting and joining techniques during assembly [88, 89].

The immersion motor pumps mentioned in Section A 15 and Section A 16 that were made of chromium-nickel-molybdenum steel AISI 316, (1.4401, X5CrNiMo17-12-2) were compared to those made of cast iron. In addition to a better corrosion resistance, the CrNiMo steel pumps also have the advantage of a smooth and poreless surface and can thus be cleaned more easily if used in waste water treatment tanks [51].

Factors influencing corrosion	Production step causing corrosion
Chemical composition	melting welding, weld filler, welding parameters
Microstructure	hot and cold forming, heat treatment
Precipitations • intermetallic phases • nonmetallic compounds	heat treatment welding, welding parameters
Gaps	constructive design flanges, sleeves, seals, weldments
Superficial contaminants • Inclusions of foreign metals • Notches • Oxide layers	mechanical processing and machining; shaping, cutting, grinding, peening, welding
Surface roughness	surface treatment peening, grinding, pickling
State of stress	welding, construction, production, assembly

Table 23: Possible influences of the material during production [88]

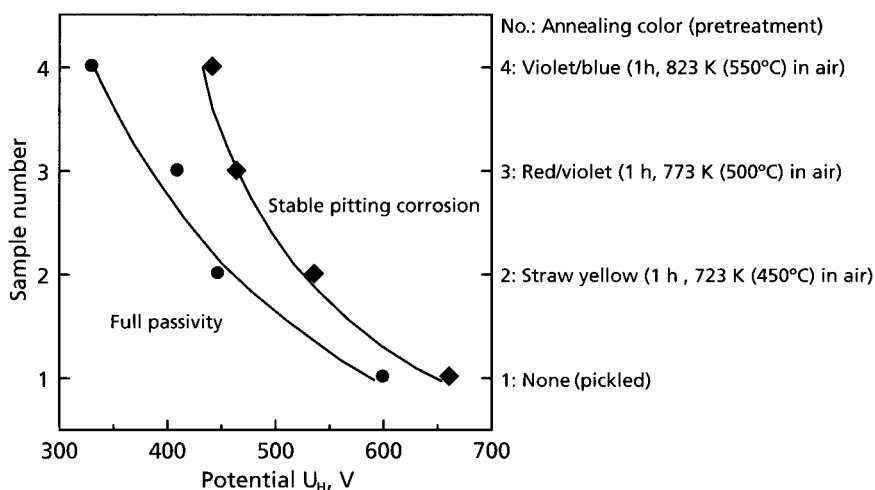


Figure 6: Influence of tarnishing on the pitting corrosion potential of steel 1.4571 (X6CrNiMoTi17-12-2); 0.01 M NaCl, 303 K (30 °C) [88]

CrNiMo pumps made of rolled, thickwalled material that have a poreless and void-less surface have considerable advantages with respect to their susceptibility to biocorrosion owing to their lower roughness, which can be as low as approx. 1 μm Ra after a corresponding surface finishing [91–93].

The austenitic chromium-nickel-molybdenum steel UNS N08904 (1.4539, X1NiCrMoCu25-20-5) has proven suitable as a material for the head cooler of stripper units used in waste water treatment plants of refineries [64]. The operating parameters are summarized in Table 24.

	<i>Inner surface of the pipe</i>	<i>Outer surface of the pipe</i>
Medium	cooling water with 2 % chlorides	stripped acidic water
Temperature	323 K (50 °C)	403 K (130 °C)
Pressure	0.5 MPa	1.0 MPa

Table 24: Operating parameters of UNS N08904 (1.4539, X1NiCrMoCu25-20-5) in a stripping unit [64]

The chromium-nickel-molybdenum steels 1.4571 (AISI 316 Ti, X6CrNiMoTi17-12-2) and particularly 1.4435 (AISI 316 L, X2CrNiMo18-14-3) are resistant to crevice corrosion, which can occur under the operating conditions in a digester if steels with lower alloy contents are used. The importance of the correct constructive design as well as the elimination of welding tarnishes by pickling is discussed [94].

The raw waters produced in waste water treatment plants or seawater desalination plants that operate on the principle of reverse osmosis must also be treated. Suitable materials for the pipelines must have good corrosion resistance to chlorides and other aggressive ingredients in the media as well as good strength properties to be able to withstand the pressures occurring during the reverse osmosis process. The requirements demanded by some of the operating conditions are fulfilled by the austenitic chromium-nickel steel X1NiCrMoCuN25-20-7 (DIN-Mat. No. 1.4529) that contains 6 – 7 % molybdenum [95].

Filters made of stainless steel of grade CrNi18-10 exhibited pitting corrosion due to contact corrosion with the activated carbon that is used for waste water treatment. Activated carbon is electrochemically more noble than steel. Suitable countermeasures include modification of the filter design and more frequent cleaning of the filters. The chemical composition of the steels for the outer and the inner pipes are given in Table 25 [96].

	<i>Outer pipe</i>	<i>Inner pipe</i>
C	0.06	0.06
Si	0.57	0.76
Mn	1.76	1.04
P	0.038	0.030
Cr	18.74	18.38
Ni	11.03	8.51
Mo	0.39	0.13

Table 25: Chemical composition of the corroded pipes [96]

For small evaporator units, e.g. those used to concentrate emulsions for drilling, cutting, grinding and deep-drawing, as well as process solutions and rinsing baths used for surface treatments during electroplating, pickling, anodizing, phosphating, EPS coating and painting, the austenitic chromium-nickel-molybdenum steel 1.4571 (AISI 316 Ti, X6CrNiMoTi17-12-2) is used for components exposed to dirty water and distillates, such as evaporators and heat exchangers [43].

According to the Federal Water Resources Act (Wasserhaushaltsgesetz, 17th BImSchV), from 1996 onwards, all waste waters must be treated, including those from flue gas desulfurization plants (FGD), from the drying of activated sludge, as well as landfill leachates. Because of the higher levels of pollutants, particularly heavy metals in waste waters, the stipulations given in the approvals must be taken into account for the construction of new thermal waste recycling plants. Nowadays, such waste waters are treated in waste water evaporator units. Salt concentrations of up to 60 % may arise that crystallize to give a disposable or a reusable salt as the end product. The very high chloride concentrations and temperatures up to approx. 393 K (120 °C) require a high corrosion resistance of the metallic construction materials in the waste water evaporator units [97]. Stainless steels soon exhibit pitting corrosion, crevice corrosion and stress corrosion cracking, so that preference is given to nickel alloys. An average FDG waste water analysis is given in Table 26 [98]. The samples were analyzed after a two-stage concentration process and after concentration in the thin-film evaporator in the final stage. The waste water is evaporated at almost neutral pH values. The suitability of the metal materials for components in evaporator units are given in Table 27 [98].

Main components	Initial concentration (%)	Concentrated to 1:6 after 2-stage evaporation (%)	Concentrated to 1:8 after the thin-film evaporator (%)
Anions:			
Chloride	4.50	27.00	36.00
Fluoride	0.006	0.036	0.048
Bromide	0.01	0.06	0.08
Iodide	0.005	0.03	0.04
Sulfate	0.14	0.84	1.12
Nitrate	0.10	0.60	0.80
Cations:			
Calcium	1.80	10.80	14.40
Potassium	0.03	0.18	0.24
Sodium	0.18	1.08	1.44
Magnesium	0.40	2.40	3.20
Aluminium	0.015	0.09	0.12
Sum of the heavy metals	0.008	0.05	0.066
Silicic acid	0.015	0.09	0.12
DOC	0.003	0.018	0.02

DOC = dissolved organic carbon

Table 26: Average waste water analysis values from a flue gas desulfurization unit [98]

Material	Standard abbreviations			Composition, approx. values (%)					
	DIN-Mat. No.	Alloy	UNS	Ni	Cr	Fe	Mo	other	
X1NiCrMoCuN25-20-7 (Cronifer® 1925 hMo)	1.4529	926	N08926	25	21	balance	6.5	Cu 0.9; N 0.2	
X1NiCrMoCu32-28-7 (Nicrofer® 3127 hMo)	1.4562	31	N08031	31	27	balance	6.5	Cu 1.2; N 0.2	
NiCr22Mo9Nb (Nicrofer® 6020 hMo)	2.4856	625	N06625	62	22	2	9	Nb 3.5	
NiMo16Cr15W (Nicrofer® 5716 hMoW)	2.4819	C-276	N10276	57	16	6	16	W 3.8	
NiCr23Mo16Al (Nicrofer® 5923 hMo)	2.4605	59	N06059	59	23	1	16	–	

Table 27: Stainless steels and nickel-based alloys for environmental engineering [98]

The materials listed in Table 27 were investigated by simulating laboratory tests under operating conditions and exposure tests in waste water evaporator units of flue gas desulfurization plants and waste incineration plants [99]. It was confirmed that only an approximate resistance can be estimated for the metallic materials in these plant sections. Precise material resistance data can only be determined for actual plants. The mass losses determined for alloy C-276 and alloy 59 after an exposure time of 9 months was only 0.053 mm/a (2.09 mpy) and 0.045 mm/a (1.77 mpy), respectively, with respect to the term of exposure. Therefore, they do not have technical significance. This results in the following proposal for materials for pipelines and tanks of waste water evaporator units of flue gas desulfurization plants

- for the 1st evaporation stage: X1NiCrMoCu32-28-7, 1.4562 (Nicrofer® 3127 hMo, alloy 31)
 - for the 2nd evaporation stage: NiCr23Mo16Al, 2.4605 (Nicrofer® 5923 hMo, alloy 59)
- possibly also: NiMo16Cr15W, 2.4819 (Nicrofer® 5716 hMoW, alloy C-276).

The high-alloy austenitic steel 1.4529 (X1NiCrMoCuN25-20-7) and the nickel alloy Inconel® alloy 625 (NiCr22Mo9Nb, 2.4856) are not sufficiently resistant for the third concentration stage of waste waters from flue gas desulfurization plants using thin-film evaporators. Alloy C-4 (NiMo16Cr16Ti, 2.4610) is not always sufficiently resistant. Laboratory tests indicated that the most resistant material is alloy 59 (NiCr23Mo16Al, 2.4605). However, in this case, the pH value must not drop below pH 5 and the redox potential must not increase into the transpassive dissolution range of this NiCrMo alloy. In addition, the design must avoid crevices as far as possible [97–100].

Austenitic steels for the evaporation of problematic leachates from special waste landfills were not sufficiently resistant to pitting corrosion when exposed to chloride concentrations of up to 6 g/l at the given temperatures [40].

Tanks for vehicles used to recover materials that are hazardous to water and waste media after accidents at sea or on land must be qualified with respect to the resistance of the tank materials. Statements on the resistance of tank materials to hazardous materials are given in the following regulations:

- List from the Bundesanstalt für Materialforschung und -prüfung (BAM, German Federal Institute for Materials Research and Testing): Requirements for tanks used to transport hazardous goods [101]
- Ordinance on the transport of hazardous goods on roads (Gefahrgutverordnung Straße – GGVS) [102]
- DIN 6601 [20]: Resistance of materials of steel tanks against liquids (positive list of liquids), see also under introduction V 3 Storage of substances hazardous to water

On the basis of the evaluated literature data, X1NiCrMoCuN25-20-7 (1.4529, cf. UNS N08926) has been qualified for the transport of more than 1000 media [103].

In a Russian study of construction materials to test for their suitability for industrial waste water plants in which the samples were exposed for 8 h/d with stirring to the waste water media (Table 28), only the steel 06ChN28MDT (22 – 25 % Cr, 26 – 29 % Ni, 2.5 – 3 % Mo, 2.3 – 3.5 % Cu) proved to be resistant in acidic waste water (Medium 1) with a corrosion rate of 0.002 mm/a (0.08 mpy). The steels from Table 29 were also resistant in neutralized waste water (Medium 2) [104].

	Medium 1 acidic waste water	Medium 2 waste water neutralized with NaOH and lime milk
pH	0.95 – 2.7	7.1
Cl ⁻	3.2 – 10.3 g/l	3.7 g/l
NO ₃ ⁻	0.13 g/l	0.05 g/l
NH ₄ ⁺	0.26 g/l	0.08 g/l
SO ₄ ²⁻		7.4 g/l
Br ⁻		0.2 g/l
Nitro compounds	0.008 – 0.300 g/l	
Amino compounds	0.17 – 0.40 g/l	
Phenolic compounds	0.007 – 0.028 g/l	

Table 28: Analysis of the waste water [104]

Grade (Russian)	Analysis	Abbreviation
06ChN28MDT	0.06 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.020 S, 22-25 Cr, 2.5-3.5 Cu, 2.5-3.0 Mo, 26-29 Ni, 0.5-0.9Ti	–
12Ch13	0.09-0.15 C, 0.80 Si, 0.80 Mn, 0.030 P, 0.025 S, 12-14 Cr, 0.30 Cu, 0.60 Ni, 0.20 Ti	1.4006, X12Cr13, AISI 410
08Ch17T	0.08 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.025 S, 16-18 Cr, 0.30 Cu, 0.60 Ni	1.4510, X3CrTi17
15Ch25T	0.15 C, 1.0 Si, 0.80 Mn, 0.035 P, 0.025 S, 24-27 Cr, 0.30 Cu, 1.0 Si	–
08Ch22N6T	0.08 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.025 S, 21-23 Cr, 0.30 Cu, 0.30 Mo, 5.30-6.30 Ni, 0.20 W	–
12Ch18N10T	0.12 C, 0.80 Si, 2.0 Mn, 0.035 P, 0.020 S, 17-19 Cr, 0.30 Cu, 0.50 Mo, 9-11 Ni, 0.20 W	1.4541, AISI 321, X6CrNiTi18-10
08Ch21N6M2T	0.08 C, 0.80 Si, 2.0 Mn, 0.035 P, 0.025 S, 20-22 Cr, 0.30 Cu, 1.80-2.50 Mo, 5.5-6.5 Ni, 0.20-0.40 Ti, 0.20 W	–
10Ch17N13M2T	0.10 C, 0.80 Si, 2.00 Mn, 0.035 P, 0.020 S, 16-18 Cr, 0.30 Cu, 2.00-3.00 Mo, 12-14 Ni, 0.20 W	1.4571, AISI 316 Ti, X6CrNiMoTi17-12-2
06ChN28MDT	0.06 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.020 S, 22-25 Cr, 26-29 Ni; 2.5- 3 Mo; 2.5 – 3.5 Cu, 0.5-0.9 Ti	–

Table 29: List of Russian steel grades that are resistant to neutralized waste water (Medium 2 from Table 28) [104]

A 27 Nickel-chromium alloys

A 28 Nickel-chromium-iron alloys (without Mo)

A 29 Nickel-chromium-molybdenum alloys

A 30 Nickel-copper alloys

Investigations of the suitability of nickel alloys Hastelloy® alloy C-276 (2.4819, NiMo16Cr15W), Incoloy® 825 (2.4858, NiCr21Mo) and Hastelloy® alloy G (2.4618, NiCr22Mo6Cu) as materials for heat exchanger pipes in a wet oxidation unit for sewage sludge are reported in [86] (see Section A 20 – A 22). The experimental conditions in the wet oxidation plant for sewage sludge are given in Table 21. Hastelloy® alloy C-276 was resistant up to the final testing temperature of 466 K (193 °C), Incoloy® 825 and Hastelloy® alloy G were resistant up to 395 K (122 °C).

The evaluations of the behavior of various metallic materials from more than 30 plants used to treat sewage sludges with the wet oxidation process after more than 5 years and supplementary test results showed that Hastelloy® alloy C-276 (2.4819, NiMo16Cr15W) and Inconel® alloy 625 (2.4856, NiCr22Mo9Nb) are resistant under the corresponding operating conditions with up to 1000 mg/l chloride. Both alloys exhibited signs of attack when exposed to 3000 mg/l Cl⁻ ions. Hastelloy®

alloy G can only be used up to approx. 600 mg/l Cl^- . The remaining alloys (see Table 19) exhibited noticeably lower operating limits (Table 20) [85].

Reference [105] summarizes the results of intensified SCC tests of various nickel-based materials under conditions simulating wet oxidation (Table 30). The test solution had the following composition:

- 3,000 ppm acetic acid
- 7,500 ppm oxygen
- 2,500 ppm carbon dioxide
- 1,000 ppm chloride
- 5 ppm fluoride

The test was carried out on C-ring samples at a temperature of 565 K (292 °C) and a pressure of 107 bar. Only Hastelloy® alloy C-276 did not show any stress corrosion cracking and pitting corrosion. The other materials reacted in the following order of decreasing resistance:

Inconel® alloy 625

Hastelloy® alloy G

E-Brite® 26-1

Carpenter® 20Cb-3

Wet oxidation units are used to treat waste waters and sludges that contain contaminants which are difficult to biodegrade and which are frequently produced in the chemical industry. They are treated at temperatures up to 603 K (330 °C) and pressures up to 250 bar. The following materials are proposed for concentrations of 1000 mg/l chloride and temperatures of 573 K (300 °C): nickel-chromium-molybdenum alloys of the Hastelloy®-C group (C-4, NiMo16Cr16Ti, 2.4610; C-276, 2.4819, NiMo16Cr15W; C-22, NiCr21Mo14W, 2.4602) and Inconel® alloy 625 (2.4856, NiCr22Mo9Nb). Titanium has proven suitable for higher chloride concentrations (see Section A 38), whereas Hastelloy® C exhibited considerable pitting corrosion in a waste water containing 80 g/l NaCl at 493 K (220 °C). Comparisons of economic viability have been carried out for processes based on adsorption, biological treatment, and incineration, whose range of applications depend on the COD value (Chemical Oxygen Demand) of the waste water [84].

The desulfurization of flue gases in coal-fired power plants is usually carried out with wet processes. This scrubbing process uses suspensions of lime milk or limestone to remove sulfur dioxide as well as all other water-soluble components in the flue gases, e.g. halogen hydric acids. In the evaporation process used to treat these scrubbing fluids from flue gas desulfurization plants in coal-fired power plants and waste incineration plants, the aqueous phase that has been separated from the solids contains high concentrations of soluble salts, mainly calcium chloride (see Table 26) [98]. Table 31 summarizes results from extensive laboratory investigations in simulated test solutions. These results, which have been confirmed by exposure tests, indicate that only NiCrMo alloys with molybdenum contents greater than 14 % can be used for the highest exposure levels. These include alloy C-22 (DIN-Mat. No. 2.4602, NiCr21Mo14W), alloy C-276 C-276 (DIN-Mat. No. 2.4819, NiMo16Cr15W) and alloy C-4 (DIN-Mat. No. 2.4610, NiMo16Cr16Ti) [100]. Subsequent laboratory

Materials	Alloy	Abbreviation	SCC in the liquid phase <i>fractured samples, tested samples, test duration</i>	Corrosion rate (max.) mm/a (mpy)		Susceptibility to pitting corrosion ¹⁾	
				Vapor phase	Liquid phase	Vapor phase	Liquid phase
	C-276	2.4819, UNS N10276 NiMo16Cr15W	0	0.04 (1.57)	0.04 (1.57)	0	0
	625	2.4856, UNS N06625 NiCr22Mo9Nb	0	0.06 (2.36)	0.6 (23.62)	1	2
	G	2.4618, UNS N06007 NiCr22Mo6Cu	0	0.18 (7.09)	2.1 (82.68)	1	1
	26-1	UNS S44626	3 of 10 in 281 h	0.33 (12.99)	0.71 (27.95)	2	3
	20Cb-3	2.4660, UNS N08020 NiCr20CuMo	0	0.25 (9.84)	2.7 (106.3)	3	4
	20Cb-3 pipe		1 of 10 in 440 h			3	4
	825	2.4858, UNS N08825 NiCr21Mo	1 of 9 in 295 h	0.16 (6.3)	5.2 (204.72)	2	4
	Nitronic® 50	1.3964 X2CrNiMnMoNb21-16-5-3	9 of 10 in 30 h	0.24 (9.45)	3.3 (129.92)	2	3
	Nitronic® 10		8 of 10 in 16 h	0.66 (25.98)	4.5 (177.17)	2	3
	Nitronic® 60	UNS S21800	9 of 10 in 11 h	2.6 (102.36)	5.2 (204.72)	3	1
	Nitronic® 33		9 of 10 in 11 h	1.0 (39.37)	13.4 (527.56)	2	4
	AISI 316 L	1.4404	10 of 10 in 12 h			3	3
	AISI 304 L	1.4306	10 of 10 in 12 h			3	3

1) 0 = none, 1 = slight, 2 = medium, 3 = heavy, 4 = very heavy

Table 30: Results of intensified SCC tests on various nickel-based materials under conditions simulating wet oxidation [105]

Test solution	pH value	Redox potential		Materials					
		mV _{NHE}		UNS N08926 1.4529 X2NiCr-MoCu25-20-6	UNS N06625 2.4856 NiCr22Mo9Nb	UNS N06022 2.4602 NiCr21Mo14W	UNS N10276 2.4819 NiMo16Cr15W	UNS N06455 2.4610 NiMo16Cr16Ti	
500 g/l CaCl ₂ 30 g/l NaCl	9.4	445	pitting	pitting	pitting	pitting	pitting	pitting	pitting
200 g/l CaCl ₂ 30 g/l NaCl	8.7	525	pitting	pitting	pitting	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl	3.0 ¹⁾	635	pitting	pitting	pitting	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 100 mg/l Fe ³⁺	3.0 ¹⁾	615	pitting	pitting	pitting	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 1000 mg/l Fe ³⁺	1.4	855	pitting	pitting	passive	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 1000 mg/l Fe ³⁺ SO ₂ saturated	< 1	335	pitting	pitting	passive	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 100 mg/l F ⁻	3.0 ¹⁾	665	pitting	pitting	pitting	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 1000 mg/l F ⁻	3.0 ¹⁾	635	pitting	pitting	pitting	passive	passive	passive	passive

1) pH adjusted with HCl

Table 31: Results of electrochemical corrosion tests (holding time 48 h) with polarization of the materials to the redox potential of the aerated test solution at 353 K (80 °C) [100]

investigations of alloy 59 (DIN-Mat. No. 2.4605; NiCr23Mo16Al) showed it to be the most resistant material. However, it must be ensured that the pH value does not drop below pH 5, if possible, and that the redox potential cannot increase into the transpassive dissolution range. Crevices must be avoided [97, 98, 100].

Because of their lack of susceptibility to chloride-induced stress corrosion cracking, nickel-copper alloys are used in seawater desalination plants as pipes for evaporators or heat exchangers. An evaporator made of alloy 400 (NiCu 30 Fe, 2.4360) exhibited a corrosion rate of > 0.01 mm/a (> 0.4 mpy) after an exposure time of 225 days to a CaCl_2 concentration of up to 35 % and a temperature of 433 K (160 °C). The corrosion rate was 0.07 mm/a (2.76 mpy) for a NaCl solution saturated with water vapor and air at 366 K (93 °C) [106]; see also [45].

Alloy 400 (NiCu 30 Fe, 2.4360) was used in three stages of the evaporator/crystallization unit for waste water from the absorption fluid of a flue gas desulfurization plant at 364 K (91 °C) and a pH value of 8 – 10. A corrosion rate of 0.04 mm/a (1.57 mpy) was measured after an operating time of 4 years. The alloy was used because the previously fitted rubber-coated steel components required frequent repairs [107].

A 37 Tantalum, niobium and their alloys

A 38 Titanium and titanium alloys

A 39 Zinc, cadmium and their alloys

Autoclave investigations of the wet oxidation of industrial waste waters containing halogens carried out at a temperature of 593 K (320 °C) and a pressure of 200 bar showed that titanium and tantalum are resistant at pH > 7 and chloride concentrations of up to 100 g/l, even in the presence of low fluoride concentrations. These materials also exhibited corrosion in acidic solutions [87]. At higher fluoride concentrations, titanium and tantalum are no longer sufficiently resistant [40]. The protective oxide layer on both titanium and tantalum is rapidly attacked by the alkalis NaOH and KOH as well as by aqueous solutions that contain low concentrations of free hydrofluoric acid, i.e. also by acidic, fluoride-containing waters, so that these materials can no longer be used in these media. Titanium alloyed with 0.2 % palladium was tested in a waste water produced during the manufacture of cellulose reaction products that contained 80 g/l NaCl. It did not exhibit any corrosion up to 573 K (300 °C), even if the oxygen partial pressure that is required to maintain the passivation was lacking at times. Tantalum exhibits embrittlement at 573 K (300 °C) with cracking [84]. Titanium, tantalum and niobium are generally susceptible to embrittlement due to the absorption of gases such as hydrogen, oxygen and nitrogen. These gases already diffuse into the materials as individual atoms at room temperature and especially at higher temperatures. They are then incorporated into the interstices of the metal lattice or they form metalloids. Tantalum, in particular, is very sensitive to hydrogen embrittlement, whereby hydrogen can also be produced on the surface of the metal by corrosion reactions. This must always be taken into account if this material is used.

In the investigations described in Sections A 20 – A 22, titanium also proved to be corrosion-resistant under the conditions prevailing in sewage sludge treatment by wet oxidation with chloride concentrations of approx. 3 g/l at 477 K (204 °C) [40, 85, Table 19]. These results are supported by the excellent corrosion resistance in Japanese wet oxidation units that operate under comparable conditions [85].

Zinc is discussed in Section D 1 Coatings and linings.

B**Non-metallic inorganic materials****B 3 Carbon and graphite**

The use of graphite in components of chemical engineering equipment and in evaporator units for aggressive waste waters is currently standard practice. Graphite is used for apparatus components, particularly for waste waters from flue gas desulfurization plants, dilute acids and landfill leachates. Its most important properties with respect to these areas of application are its excellent chemical resistance and good thermal conductivity [108], which make this material particularly interesting for heat exchangers [109–111]. The open pores in molded graphite, which are caused by the production method, can be closed by impregnating it with synthetic resins if the material must be completely impermeable. Graphites impregnated with a synthetic resin (DIABON® NS 1 and DIABON® NS 2) to make them impermeable to gases and liquids are used in tubular heat exchangers of waste water evaporator units. However, impregnation with a synthetic resin lowers the material's resistance to both acidic and alkaline oxidizing media, to organic solvents and also lowers its operational temperature limits. However, these limitations do not usually play a role if the material is used in heat exchangers of waste water evaporator units. The limiting operating temperatures of 450–470 K (177–197 °C) are low enough and there are no oxidizing media. The material is resistant to hydrochloric acid, hydrofluoric acid and salt solutions in all concentrations and pH values. Carbon fiber-reinforced pipes (DIABON® HF) have better mechanical properties and also have a higher bursting pressure. This is necessary if high-pressure water is used for cleaning and removing incrustations. DIABON® F is a graphite with a fluorinated polymer binder that allows the manufacture of pressed components, e.g. heat exchanger plates. DIABON® F has a higher thermal conductivity than e.g. the metallic materials titanium, Hastelloy® and Incoloy®. Taking account of the smallest possible plate thickness, the heat transfer coefficients are comparable with those of metallic materials (Table 32). However, its maximum operating temperature of 413 K (140 °C) is lower than that of metallic materials [112].

Many years of operating experience have been gained with the use of graphite and metallic materials in evaporator units used to treat waste water from flue gas desulfurization plants and landfill leachates. The advantages of graphite include its complete inertness, e.g. for the evaporation of leachates containing high chloride

	Thermal conductivity, $W/(K\ m)$	Plate thickness, mm	Heat transfer coefficient k for $\alpha_i=\alpha_a=6000$ $W/(K\ m^2)$
Cu (pure)	393	0.6	2986
Steel (0.2 % C)	50	0.7	2879
Titanium	16	0.6	2697
Hastelloy® C	12	0.6	2609
Plastic (PVC)	0.17	1.5	109
DIABON® F 100	20	2.3	2230

Table 32: Thermal properties of various materials used for plate-type heat exchangers [110]

concentrations in the presence of fluoride ions, which can lead to unpredictable types of corrosion, even in highly alloyed metallic materials. From the point of view of operational reliability, the use of carbon fiber-reinforced graphite tubes in heat exchangers is advantageous because they remain impermeable to liquids, even at non-permissible overpressures and steam hammering up to a differential pressure of approx. 2 – 5 bar [113].

References [114] and [115] report on operating experience gained with the hitherto largest evaporator unit for waste water from the flue gas desulfurization unit of a power station in Berlin (Germany). Figure 7 shows the flow diagram of the FGD unit [114].

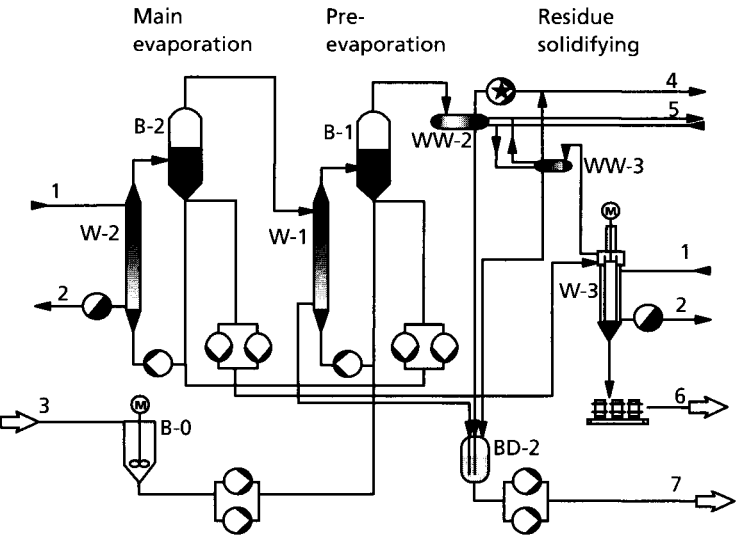


Figure 7: Evaporator unit for waste water from a flue gas desulfurization plant [114]
 B-O Untreated water tank, W-1/2 Recirculation evaporator, B-1/2 Evaporation vessel, WW-2/3 Con-
 denser, BD-2 Distillation tank, W-3 Thin-film evaporator
 1: Steam, 2: Condensate, 3: Waste water, 4: Exhaust gas, 5: Cooling water, 6: Salts, 7: Distilled
 water

The main problems concerning the evaporation of waste waters containing salts are: incrustation, foaming, outgassing, corrosion and wear due to abrasion. These problems were solved in the evaporator units of this power station that has been operating fully automatically for more than one year. At the time the report was written, the evaporation ratio was maintained at 1 : 17; i.e. this means that more than 90 % of the untreated water was recovered as a recyclable distillate. With the downstream thin-film evaporators, it is possible to recover more than 95 % of the waste water produced by FGD. Graphite heat exchangers have been used successfully in recirculation evaporators whose pipes were reinforced with graphite fibers. Rubber-coatings on steel and special metallic materials were used for the remaining equipment and pipelines [115].

The problems caused by chlorinated hydrocarbons that have to be removed from the waste water arise where the waste water originated, e.g. during regeneration of activated carbon absorbers with steam or during cleaning or degreasing steps. The solubilities of the chlorinated hydrocarbons in the waste water usually lie above the statutory limiting values so that the waste water must be scrubbed. This is carried out in stripper columns in which the waste water passes through in counterflow to a forced air flow. The solvent-enriched air is then fed through activated carbon beds. The steam/solvent mixture produced during regeneration of the activated carbon with superheated steam is passed through a graphite heat exchanger in which it is cooled from 403 to 303 K (130 °C to 30 °C) so that it condenses. The aggressive condensate contains water, chlorinated hydrocarbons and HCl. Here too, graphite is a good cost-effective solution owing to the combination of complete chemical resistance and good thermal conductivity [116].

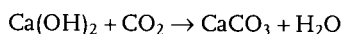
B 4 Binders for building materials (e.g. concrete, mortar)

The most frequently used building material is concrete, which consists of the hardened binder cement, otherwise known as **hardened cement paste**, and mineral aggregate materials. It is inevitable that the hardened cement paste has a microporous structure containing submicroscopic capillary pores that depend on the **water/cement ratio**. Water and dissolved salts can penetrate the concrete structure through these pores. The porous microstructure of concrete has a decisive influence on its chemical resistance. To increase the frost resistance, approx. 5 volume% of air pores are generated in the concrete. These pores serve as expansion spaces during frost-induced dilation and crystallization pressure. Concrete structures may have steel reinforcements that absorb tensile forces. Such reinforced concrete structures are extensively used in waste water treatment systems, particularly in biological sewage treatment plants, e.g. as collecting tanks. Depending on the aggressiveness of the waste water to be stored or treated, it may not be necessary to protect the surface with coatings or linings. The resistance properties of concrete are determined by its physical structure as well as by its chemical composition. Table 33 lists the types of pores and their proportions that arise during concrete hardening [117].

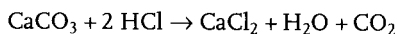
Designation	Hydration pores		Air pores	
– scientific	Gel pores (GP)	Capillary pores (CP)	Compaction pores	Artificial air pores
– technical	fillable pores		unfillable pores	
Origin	during hydration of the cement		during processing of the concrete	by air-entraining additives
Water absorption	can be filled at normal storage in water		cannot be filled at normal storage in water	
Diameter (mm)	$2 - 4 \times 10^6$	$10^5 - 10^3$	$10^2 - \text{several mm}$	$10^2 - 1$
Content in concrete	6	W/C = 0.5 : 3.4	Standard concrete: 1 – 2	Air-entrained concrete: approx. 5
Cement = 300 kg/m ³		W/C = 0.6 : 6.4		
Complete hydration (vol%)		W/C = 0.7 : 9.4		

Table 33: The various types of cavities in concrete [117]

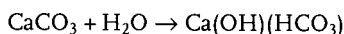
The hardened cement paste of the concrete consists of hydrated calcium silicates and calcium aluminates as well as up to approx. 30 mass% of calcium hydroxide. Calcium hydroxide reacts with CO₂ in the air to produce a calcium carbonate layer on the surface (**carbonation**):



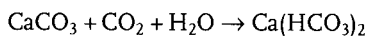
This carbonate layer is attacked by acidic waters, e.g. according to the reaction



and by soft water, according to the hydrolysis reaction



and by waters containing carbonic acid



to form the readily soluble calcium hydrogen carbonate.

Figure 8 shows which of the three last-named reactions take place preferentially depending on the pH value and the CO₂ partial pressure.

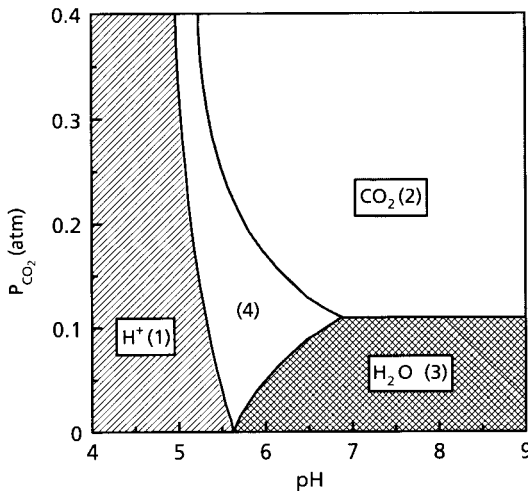


Figure 8: Ranges of the individual reactions of calcium carbonate dissolution (according to Grauer) [8]

Range (1): predominantly acidic

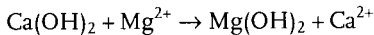
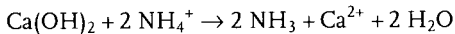
Range (2): predominantly carbonic acid

Range (3): hydrolysis

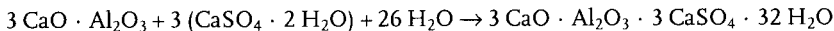
Range (4): more than one reaction participating in calcium carbonate dissolution

At pH values below pH 6, acidic attack is predominant, whereas the reaction with carbonic acid is predominant at pH values greater than pH 6.5 and at CO₂ partial pressures above 0.1 bar.

Waters containing ammonium and magnesium ions can also attack concrete because these ions react with calcium hydroxide:



Sulfate-containing waters can react with the aluminates in the hardened cement paste to form trisulfates, such as ettringite, which contain large quantities of water of crystallization:



The formation of these voluminous reaction products causes expansion phenomena that result in damage due to swelling and softening of the concrete. This can be counteracted by the use of Portland cement, which has a high sulfate resistance (HS cement).

Figure 9 shows the various causes of corrosion in cement-bonded construction materials and the resulting types of corrosion and associated phenomena [34].

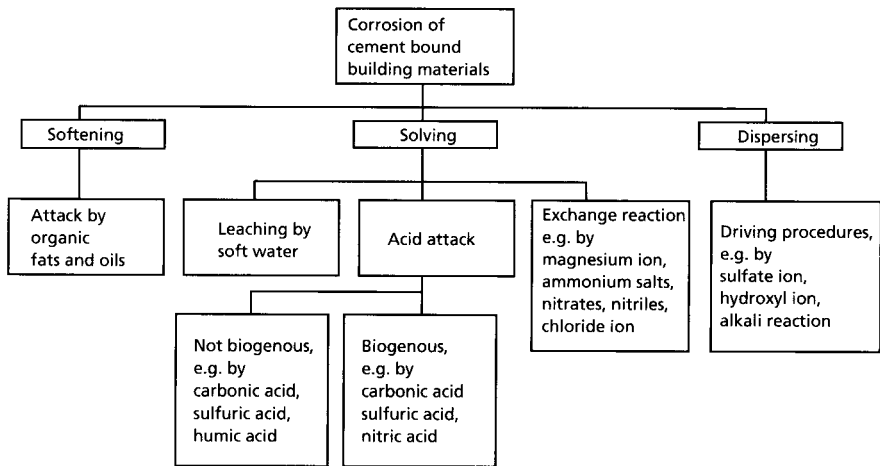


Figure 9: Types of corrosion in cement-bonded construction materials [34]

Concrete property/ level of attack		Requirements for the construction site	Water/ cement ratio	Additional requirements
Water impermeability		construction site for concrete group B II ¹⁾	$d \leq 40 \text{ cm}$ $w/c \leq 0.60$	penetration depth of water $e_w \leq 50 \text{ mm}$
Chemical attack	weak		$w/c \leq 0.60$	penetration depth of water $e_w \leq 50 \text{ mm}$
	heavy		$w/c \leq 0.50$	penetration depth of water $e_w \leq 30 \text{ mm}$
	very heavy		$w/c \leq 0.50$	penetration depth of water $e_w \leq 30 \text{ mm}$ and protection of the concrete, e.g. acc. to the information sheet

1) B: Concrete of concrete group B; Concrete B is an abbreviation for concrete of strength class B 35 and higher and also for a concrete with particular properties, such as water impermeability and the high resistance to chemical attack mentioned here

Table 34: Performance criteria for waterproof concrete according to DIN 1045 and concrete with a high resistance to chemical attack [118]

Concrete components that come into contact with waste water require a water-proof concrete in accordance with DIN 1045-1 [118]. The performance criteria of this standard are summarized in Table 34. Table 35 contains the limiting values to evaluate the level of attack by waters according to DIN 4030-1 [119]. In addition to the requirement for water impermeability, a “high resistance to chemical attack” corresponding to the above-listed chemical reactions (Table 34) and “high resistance to frost or to frost and de-icing salt” (Table 36, DIN 1045 [118]) must be taken into account for the construction of concrete structures for waste water facilities.

Investigation	Level of attack		
	weak attack	heavy attack	very heavy attack
pH value	6.5 – 5.5	< 5.5 – 4.5	< 4.5
Calcium carbonate-dissolving carbonic acid (CO ₂)	mg/l 15 – 40	> 40 – 100	> 100
Ammonium (NH ₄ ⁺)	mg/l 15 – 30	> 30 – 60	> 60
Magnesium (Mg ²⁺)	mg/l 300 – 1000	> 1000 – 3000	> 3000
Sulfate (SO ₄ ²⁻) ¹⁾	mg/l 200 – 600	> 600 – 3000	> 3000

1) For sulfate concentrations above 600 mg/l SO₄²⁻, except for seawater, a cement with a high sulfate resistance (HS) must be used.

Table 35: Limiting values according to DIN 4030-1 for the evaluation of the level of attack by waters [119]

Concrete property	Requirements for the construction site	Water/cement ratio	Additional requirements
High frost resistance	Construction site for concrete group B II ¹⁾	w/c ≤ 0.60	Frost-resistant aggregates; e _w ≤ 50 mm
		for solid structural elements w/c ≤ 0.70	Frost-resistant aggregates; e _w ≤ 50 mm; average air pore content for
High frost and deicing salt resistance	Construction site for concrete group B II ¹⁾	w/c ≤ 0.60 for flowing concrete w/c ≤ 0.50; if there is heavy exposure to frost and de-icing salt w/c ≤ 0.50 advisable	8 mm max. grain size ≥ 5.0 vol% 16 mm max. grain size ≥ 4.0 vol.% 32 mm max. grain size ≥ 3.5 vol.% 63 mm max. grain size ≥ 3.0 vol.

¹⁾ B II: Concrete of concrete group B II; Concrete B II is an abbreviation for concrete of strength class B 35 and higher and also for a concrete with particular properties, such as the high frost resistance and the high frost and de-icing salt resistance mentioned here

Table 36: Requirements for concrete with a high frost resistance or high frost and de-icing salt resistance according to DIN 1045 [118]

Reference [1] gives the limiting values for the exposure of concrete structural elements to communal waste waters. These values deviate from the information given in Table 35 because, compared to the stipulations in DIN 4030-1, high flow rates of the waste water and the mechanical effects of frequent cleaning operations on the surface of the concrete must be taken into account. Table 37 gives the limiting values for continuous exposure and Table 38 gives the corresponding values for special cases with an intermittent or short-term exposure.

Attack by	Common values in communal waste water	Sufficient resistance of the concrete for	
		Limiting value in waste water	Compliance with the following requirement for concrete
Inorganic and organic acids	pH value 6.5 – 10	pH value ≥ 6.5	
Calcium carbonate-dissolving carbonic acid (CO_2)	< 10 mg/l	≤ 15 mg/l	$w/c \leq 0.50^{1)}$ and penetration depth of water
Magnesium (Mg^{2+})	< 100 mg/l	≤ 1000 mg/l	(DIN 1048) ≤ 3 cm
Ammonium – nitrogen ($\text{NH}_4 - \text{N}$)	< 100 mg/l	≤ 300 mg/l	
Sulfate (SO_4^{2-})	< 250 mg/l	≤ 600 mg/l	as above without HS cement
		< 3000 mg/l	as above with HS cement

1) Lower w/c values and the use of concrete with a special composition considerably improves the chemical resistance of the concrete.

Table 37: Limiting values for continuous exposure of concrete to communal waste water [1]

[1] gives a good summary of the requirements to be taken into account in planning as well as information for the construction of concrete structures and structural elements in the waste water sector. It is also important that the chosen thickness of the **concrete cover** over the steel reinforcement is thick enough. Table 39 [120] gives the values for the concrete cover that differ from those in DIN 1045 [118] based on experience gained in Hamburg [121].

If the concrete cover is thick enough, the alkaline pH value, which results from the high proportion of calcium hydroxide in the hardened cement paste, ensures reliable corrosion protection of the steel reinforcement in the concrete due to the formation of a passive layer. However, corrosive attack of the reinforcement can occur under the following conditions:

- the steel can be directly attacked if the chloride concentration in the concrete exceeds approx. 0.4 %

- if the concrete cover is not thick enough, carbonation due to CO_2 in the air can penetrate until it reaches the surface of the steel; the associated reduction of the pH value leads to loss of the passivation
- if the concrete is not sufficiently impermeable, or there is increased porosity or cracks, then moisture, oxygen and chlorides can diffuse into the concrete

The voluminous corrosion products formed on the steel can cause spalling of the concrete layers close to the surface and critically diminish the load-bearing capacity of the steel reinforcement in prestressed concrete.

Concrete and reinforced concrete pipes have been used extensively since the beginning of the 20th century for the discharge of waste water into the sewage system in addition to those made of stoneware. From the corrosion point of view, biogenic sulfuric acid is probably the greatest problem because the increased volumes of the resulting calcium sulfate crystals and other reaction products make the concrete

Attack by	Resistance of concrete is sufficient if the following limiting values are observed		
	by the waste water		by the concrete
	intermittent exposure ¹⁾	short-term exposure ²⁾	
Inorganic acids (e.g. H_2SO_4 , HCl , HNO_3)	pH value: ≥ 5.5	pH value: ≥ 4	w/c ≤ 0.50 ³⁾ and penetration depth of water (DIN 1048) ≤ 3 cm
Organic acids	pH value ≥ 6	pH value ≥ 4	
Calcium carbonate- dissolving carbonic acid (CO_2)	≤ 25 mg/l	≤ 100 mg/l	
Magnesium (Mg^{2+})	≤ 3000 mg/l	no limitation	
Ammonium – nitrogen ($\text{NH}_4 - \text{N}$)	≤ 1000 mg/l		
Sulfate (SO_4^{2-})	≤ 1000 mg/l		as above without HS cement
	≤ 5000 mg/l		as above with HS cement

1) Maximum exposure time of up to one year per ten years

2) Unplanned operating conditions, maximum exposure time of one hour per week

3) Lower w/c values and the use of concrete with a special composition considerably improves the chemical resistance of the concrete.

Table 38: Limiting values for intermittent or short-term exposure of concrete to communal waste water [1]

Cast-in-place concrete¹⁾		Prefabricated parts	
without corrosion protection	with corrosion protection	without corrosion protection	with corrosion protection
5 cm	4 cm	3 cm	2 cm

1) Cast-in-place concrete: concrete that is installed as fresh concrete in structures that are already in their final position and left to harden.

Table 39: Recommended concrete cover over the steel reinforcement [120]

surface friable. Independent of the biogenic sulfuric acid produced via the intermediate product hydrogen sulfide in communal waste water pipelines, industrial waste waters may have high sulfate concentrations (Table 40) [122, 123].

According to DIN 4030-1 [119], if the sulfate concentration exceeds 600 mg/l SO_4^{2-} , the cement to be used for the concrete must have a high sulfate resistance as specified by DIN 1164-10 [124]. Iron-containing Portland blast-furnace cement or blast furnace cement are regarded as sulfate-resistant cements. High-alumina cement has proven particularly resistant to biogenic sulfuric acid corrosion [120].

On the basis of results from a research project on the collecting system in Hamburg [121] and contrary to the information given in DIN 4030-1 [119], a proposal has been made to define the degree of attack with respect to the pH value in the condensed water droplets on the sewer walls, the sulfide concentration in the headspace of the sewer and the number of *Thiobacillae* per 1 mg protein present on the sewer wall [120, 121, Table 41].

Branch of industry	Maximum sulfate concentration mg/l
Glass industry	60,000
Anodizing workshops	14,000
Rechargeable battery factories	5,000
Chemical industry	100,000
Electroplating with cyanide detoxification chromate reduction	2,000
Wire drawing works	6,000
Electropolishing works	8,000

Table 40: Measured sulfate concentrations in industrial waste waters [122]

Table 40: Continued

Branch of industry	Maximum sulfate concentration mg/l
Photographic waste water Fixing bath	150,000
Surface treatment works Pickling plant Nickel electroplating Hard chromium	54,000
Landfill leachates (incineration residues)	11,000
Ore digestion	50,000

Table 40: Measured sulfate concentrations in industrial waste waters [122]

During the research project, corrosion was found in sewage and mixed water sewers for the waste water values given in Table 41 that are characteristic for mixtures of communal and industrial waste waters.

pH Range	7 – 8
Biochemical oxygen demand over 5 days (BOD 5)	100 – 450 mg/l
Chemical oxygen demand (COD)	300 – 800 mg/l
Concentration of microorganisms	$10^{10} - 10^{12}$ cells/l
Oxygen concentration	2 – 6 mg/l
Protein concentration	100 – 500 mg/l
Sulfate concentration	50 – 250 mg/l
Temperature	281-295 K (8-22 °C) depending on the season

Table 41: Waste water values that lead to corrosion in sewage and mixed water sewers [121]

All cement-bonded construction materials used in waste water sewers can be affected by biogenic sulfuric acid corrosion (see V 5.2 Biogenic sulfuric acid corrosion). These include pipes made of solid concrete or reinforced concrete as well as pipes reinforced with fibers or asbestos cement and cement mortar coatings. Although **cement mortar coatings** are also classified into Section D 1 Coatings and linings, their corrosion properties with respect to waste water are discussed here.

In addition to the proteins contained in waste water that can be degraded to volatile sulfur compounds, the reduction of sulfates under anaerobic conditions can also lead to the formation of hydrogen sulfide.

Anaerobic conditions in sewers can be prevented by

- increasing the flow rate
- aeration in different stages
- addition of oxygen

If the flow rate drops below a certain minimum value, deposits can form on the sewer floor that ultimately decrease the flow rate due to increased roughness of the walls and also decrease the flow cross-section. On the basis of the results of a study of a series of sewers for a mixed waste water (communal with some industrial waste water), Table 42 gives the **minimum flow rate** and the minimum downward gradients, depending on the sewer diameter, that must be observed to avoid critical deposits [121].

Sewer diameter mm	Minimum flow rate v_c m/s	Minimum downward gradient I_{min} ‰
300	0.56	1.51
500	0.76	1.40
1000	1.123	1.26
1500	1.39	1.19
2000	1.62	1.14
3000	2.03	1.08

Table 42: Flow conditions to avoid deposits in mixed sewers and storm water sewers [121]

The mechanisms of formation and corrosive effects of biofilms on the materials used in waste water engineering are described in [125].

Cast iron pipes with varying diameters and steel pipes for sewers usually have a cement mortar lining for effective protection from corrosive attack (see Section A 15). The good corrosion protection effect of the mortar lining is based on the one hand on the pH value > 8 of the pore solution, which passivates the surface of the iron, and on the other hand, the high rotation speed of the centrifugal coater forces out the mixing water (w/c value approx. 0.3) to give a compacted mortar structure that hinders oxygen diffusion to the surface of the metal.

Table 43 summarizes the limits for the pH values and the concentrations of substances in the water for components lined with cement mortar [1].

Medium – Parameter	Type of lining acc. to DIN 2614	
	I – S (BFC or Portland cement)	I – T (HAC)
Water	limiting values	
pH value	6.5 – 12	4.5 – 10
Mg ²⁺	≤ 1000 mg/l	limit of solubility
SO ₄ ²⁻	≤ 3000 mg/l	limit of solubility
NH ⁴⁺	≤ 200 mg/l	≤ 2000 mg/l
Ca ²⁺	≥ 1 mg/l	≥ 0 mg/l (storm water)
Calcium carbonate-dissolving carbonic acid	≥ 7 mg/l	limit of solubility
Sewer atmospheres		
H ₂ S concentration as a measure of the BSAC ¹⁾	< 0.5 ppm	0.5 – 10 ppm

¹⁾ BSAC = Biogenic sulfuric acid corrosion

Table 43: Limiting operating parameters for continuous exposure of cement mortar linings in ductile cast iron pipes, steel pipes and fittings [1]

Cement mortar for pipe linings is made of fine-grained quartz sand (max. grain size 1.4 mm) and standard Portland blast furnace cement. The water/cement ratio should be max. 0.35 – 0.4 to lower the shrinkage tendency. The coating thicknesses for popular pipe diameters are given in Table 44.

Nominal width group	Nominal diameter (ND)	Coating thickness, mm		
		average	minimum value	maximum value
I	80 – 300	3	1.5	7
II	350 – 600	5	2.5	9
III	700 – 1200	6	3.0	11
IV	1200 – 2000	9	4.0	17

Table 44: Coating thicknesses for cement mortar linings [126]

The compressive strength of freshly applied mortar after 28 days was 70.9 – 101.3 MPa with a bending strength greater than 10 MPa. The fresh cement mortar lining has only a low adhesion to the metal and its pore volume of approx. 10 % means that it is not impermeable. The first time the lining comes into contact with water, the capillarity transports the water to the surface of the metal where iron hydrates are formed. These hydrates, together with the calcium hydroxide of the har-

dened cement paste, form a well-adhering layer and also close the pores. Experience has shown that this provides reliable and long-lasting corrosion protection if the limiting values according to DIN 4030-1 [119] of chemicals that attack concrete are not continuously exceeded in the waste water (see Table 35). However, special sulfate-resistant cements used for the cement mortar lining of industrial sewers made of ductile cast iron withstood continuous exposure to 3000 mg/l sulfate and short-term pH values of 4.5 without damage [126, 127]. To achieve this, the male and female ends of the pipes had to be sealed with a layer of epoxy-tar grout.

Owing to the initial porosity, a newly coated pipeline first appears to be leaking in water absorption tests with increasing pressure. Figure 10 shows the quantities of topped-up water every 24 h in dependence upon the applied pressure. In this case, the quantity of topped-up water decreases to approx. 3 % of the initial value after 2 x 24 h. Therefore, it can be assumed that the absorption of water is definitely complete after approx. 20 days.

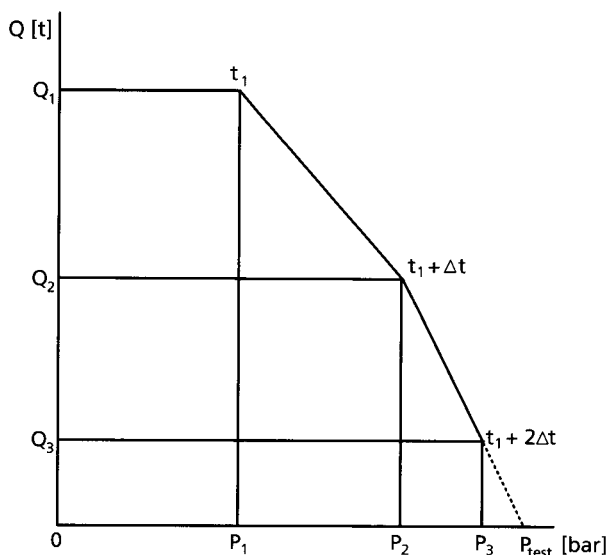


Figure 10: Absorption of water by cement mortar during pressure tests [126]

DIN 1164-10 [124] specifies the cement grades to be used for structures made of concrete and reinforced concrete

- Portland cement (PC)
- Portland blast furnace cement (PBFC)
- Blast furnace cement (BFC)
- Trass cement (TC)

High-alumina cement (HAC) is produced by fusing limestone and bauxite together. Its main components are thus CaO and Al_2O_3 in molar ratios 1 : 1, 1 : 2 and 12 : 7 ($\text{CaO} : \text{Al}_2\text{O}_3$). Numerous studies have indicated that a limiting water/cement ratio

of 0.4 ensures that the compressive strength of the concrete does not drop below 40 MPa during the reaction of the calcium oxide/aluminium hydrates with water [127]. High-alumina cement has a low porosity and exhibits good resistance to industrial waste waters, seawater, and sulfates.

Immersion tests of mortar prisms of high-alumina cement and blast furnace cement containing 74 % granulated slag in a H_2SO_4 solution of pH 3, which was renewed daily, showed that the HAC sample was noticeably more resistant (Figure 11).

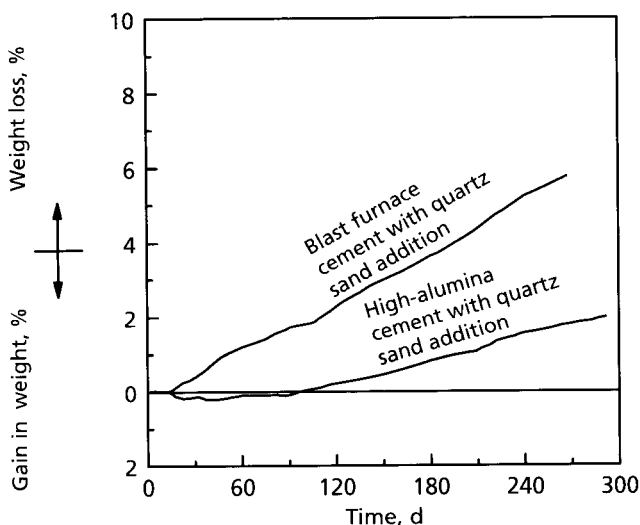


Figure 11: Mass change/time curves of cement mortar prisms in dilute H_2SO_4 (pH = 3)
HOZ = blast furnace cement with quartz aggregates, TSZ = high-alumina cement with quartz aggregates [127]

Solutions of sodium hydroxide with pH values of pH 14 and pH 13 attacked very rapidly at first. There was a mass loss of 2 – 3 % after 20 d, which had stabilized after 400 d to approx. 9 % at pH 14 and 5 % at pH 13 [127]. The results obtained in NaOH solutions of pH 11 are given in Figure 12.

High-alumina cement coatings on pipe segments were tested with respect to the effects of biogenic sulfuric acid. These coatings were tested at 303 K (30 °C) and a relative humidity > 95 % in sodium thiosulfate solutions, which are a precursor of biogenic sulfuric acid and which had been inoculated with bacteria that produce sulfuric acid. During the 300 d of exposure, the pH value on the surface of the mortar dropped to pH 2.3. A visual inspection did not reveal any signs of damage. The high-alumina cement mortar thus proved suitable under these experimental conditions [127].

The influence of the type of cement on the behavior of cement mortar coatings in an atmosphere that simulated the conditions in sewers was investigated with the following types of cement:

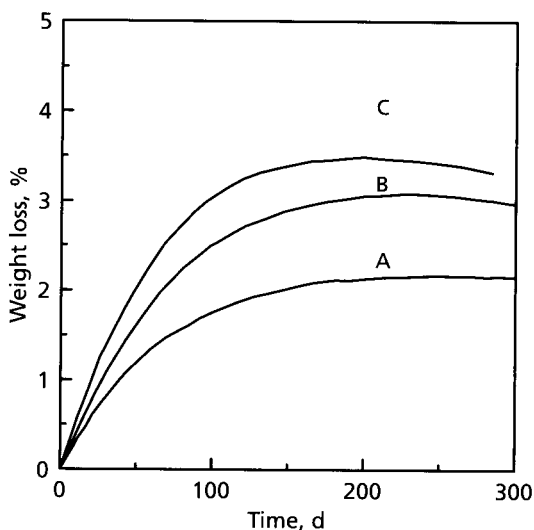


Figure 12: Mass loss/time curves of high-alumina cement-mortar prisms in NaOH solution, pH 11 [127]

A: 1 day at 293 K (20 °C) in damp air, then 27 days under water at 293 K (20 °C)

B: Hardened for 1 day in damp air at 293 K (20 °C), then 13 days under water at 293 K (20 °C) and 14 days under water at 311 K (38 °C)

C: Hardened for 5 days under water at 311 K (38 °C)

- Blast furnace cement (70 % slag sand)
- Portland blast furnace cement (80 % slag sand)
- High-alumina cement
- Portland cement

The horizontally arranged pipe sections (450 mm) were filled to approx. 1/3 with waste water. Air containing 100 ppm H_2S was pumped with a flow rate of 400 l/h through their interconnected headspaces. Experience has shown that this H_2S concentration leads to very high attack by bacteriogenic sulfuric acid. The lower regions of the samples were placed in a water bath at 310 K (37 °C). The upper region was cooled so that condensed water formed. After a test period of two years, all the tested types of mortar, with the exception of the high-alumina cement mortar, were friable at the water level and slightly above it. Table 45 gives an overview on the penetration depth of the damage in the region of the water level for the investigated types of mortar.

The behavior of high-alumina cement coatings was tested in a salt solution containing various anions and cations as well as urea and organic surfactants. This salt solution should simulate an extremely aggressive waste water. Its pH was adjusted to values of pH 2, pH 4, and pH 5 in three separate pipelines. The flow rate was 0.2 m/s at room temperature and the waste water volume per test rig was approx. 150 l. The results after operating periods of 4.5 years and 9 years are summarized in Table 46.

No.	Cement type	Corrosion depth at the water level
1	Blast furnace cement	1.7 – 2 mm
2	Portland blast furnace cement	2.4 – 2.7 mm
3	High-alumina cement	0.6 mm (removal of the cement grout)
8	Portland cement PZ 400	1.9 – 2.3 mm

Table 45: Corrosion depth of various cement mortar linings after a two year test period [127]

pH	After 4.5 years	After 9 years
2	the lining was softened down to the iron substrate	The lining was softened down to the iron substrate. The upper layers are partly dislodged.
4	the slurry and fine sand layer has softened to a depth of approx. 2 mm	Cement slurry is friable. Parts of the uppermost layer have dislodged, approx. 2 mm softening underneath.
5	the slurry and fine sand layer has softened to a depth of approx. 2 mm	Surface softened to a depth of approx. 1 mm. (Better test result than after 4.5 years; probably due to rehardening after a short-term drying period.)

Table 46: Corrosion of high-alumina cement mortar coatings in extremely aggressive artificial waste waters [127]

All the described tests show that linings for cast iron pipes based on high-alumina cement can be used without reservations for industrial waste waters in a pH range between pH 5 and pH 9.

Pipes based on asbestos cement have also been used successfully for many years in the waste water sector. However, owing to the carcinogenic effect of asbestos fibers, this material is now only used in exceptional cases. Much effort has been put over many years into replacing asbestos in cement-bonded pipes by other inorganic and organic materials, e.g. glass fibers, mineral wool, or synthetic fibers. Reference [128] discusses asbestos-free fiber cement pipes containing reinforcing fibers based on polyvinyl alcohol (PVAL). An approval certificate in accordance with § 19 of the Federal Water Resources Act has been issued by the Institut für Bautechnik (Institute for Building Technology).

Table 47 gives the limiting values defined according to DIN 4030-1 [119] for the level of attack on concrete compared to the applicable standard values for fiber cement [129].

The impermeability of the concrete sewers with respect to liquid organic pollutants, particularly chlorinated hydrocarbons (HCC), which may be present in industrial waste waters, has been the topic of much discussion in the past owing to sensitized environmental awareness. It is estimated that approx. 2%, i.e. 6,000 t, of approx. 300,000 t HCC produced annually in Germany, pass into the waste water [130]. The limiting value for the discharge of highly volatile HCC into waste waters in Germany is currently 0.5 mg/l. Figure 13 shows the results of penetration tests with methylene chloride into concrete.

		Level of attack for concrete DIN 4030-1			Limiting values for fiber cement ¹⁾	
		Weak attack	Heavy attack	Very heavy attack	Without pipe protection	With standard pipe protection
pH value		6.5 – 5.5	< 5.5 – 4.5	< 4.5	> 6	> 5
Calcium carbonate-dissolving carbonic acid (CO ₂)	mg/l	15 – 40	> 40 – 100	> 100	< 10	< 20
Ammonium (NH ₄ ⁺)	mg/l	15 – 30	> 30 – 60	> 60	< 80	< 120
Magnesium (Mg ²⁺)	mg/l	300 – 1000	> 1000 – 3000	> 3000	< 2000	< 3000
Sulfate (SO ₄ ²⁻) ²⁾	mg/l	200 – 600	> 600 – 3000	> 3000	< 500	< 800

1) The data given for fiber cement are approximate values that must be checked for each individual case.

2) For sulfate concentrations above 600 mg/l SO₄²⁻, except for seawater, a cement with a high sulfate resistance (HS) must be used.

Table 47: Comparison of the limiting values for the level of attack of concrete according to DIN 4030-1 ([119], see also Table 35) and fiber cement with and without a coating [129]

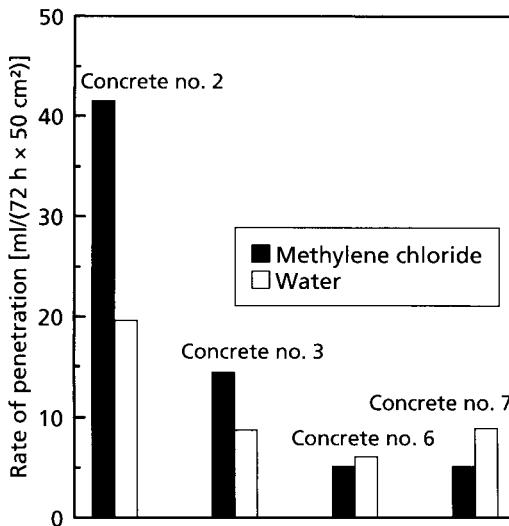


Figure 13: Penetration of water and methylene chloride into concrete of differing compositions with and without additives [131]

Concrete no. 2: W/C = 0.58, without additive

Concrete no. 3: W/C = 0.50, without additive

Concrete no. 6: W/C = 0.52, with swellable plastic additive

Concrete no. 7: W/C = 0.50, with soluble plastic additive

Investigations to elucidate the relationships and properties that influence the penetration ability of HCC and some other organic liquids were carried out at the research institute of the cement industry. Particular attention was paid to the behavior of dichloromethane (methylene chloride) with respect to concrete. The experimental results showed that the correctly prepared standard concretes with a water/cement ratio of ≤ 0.50 exhibited a high penetration resistance to dichloromethane. After 72 h, the uptake of CH_2Cl_2 was only approx. 2 l/m^2 . The impermeability can be increased even further by plastic additives that swell when they come into contact with penetrating solvents and thus exert a barrier effect.

The penetration of organic liquids, similar to that of water, follows a $\sqrt{t}$ law. This also applies to gaseous CH_2Cl_2 . Furthermore, it was also proved that the incorporated plastic additives can seal bending cracks in the concrete with crack widths of up to 0.1 mm as long as there is still an uncracked pressure zone a few cm wide in the concrete part [131]. The testing methods and equipment are described in [131–134].

The penetration behavior of organic liquids is generally determined by the quality of the concrete, by the physical properties of the liquid and by interactions between the concrete and the liquid, whereby the physical parameters of the liquid, namely surface tension and viscosity, are decisive [135]. All described effects only apply to dry concrete.

Because the impermeability of the cement matrix is the decisive factor with regard to the penetration of liquids into concrete, the most effective measure to improve this impermeability is to reduce the water/cement ratio. For example, a W/C value of 0.50 halves the amount of penetrating liquid compared to a concrete with a W/C value of 0.60. The addition of silica fume noticeably reduces the penetration of liquids for a given W/C value. The optimum addition of 10 % of the cement fraction reduced the quantity of penetrating liquid by approx. 70 %. The impermeability increasing effect of silica fume was independent of the penetrating liquid. Low quantities of organic polymers considerably increased the penetration resistance of the concrete even further. The addition of 2 mass% polystyrene or 5 mass% styrene-butadiene together with 10 mass% silica fume produce extremely impervious concretes [136].

In waste water facilities, the steel parts immersed in the waste water form the anode of a **galvanic cell** if they are in electrically conducting contact with the reinforcing steel of the concrete tank. If no protective measures are implemented, this can lead to corrosion of the steel parts. Table 48 gives the results of a damage survey carried out in 1989 in Switzerland. The evaluation of the reasons for this damage revealed that more than 60 % of all damage was caused by the formation of such a **macrocell** between steel components and the reinforcement in reinforced concrete constructions [137].

Cause of damage	Share of damage
Unsuitable material (self-corrosion of the material)	27 %
Macrocells due to contact corrosion	61 %
Processing deficiencies	7 %
Mechanical loading with corrosion	5 %

Table 48 a): Overview of corrosion damage in waste water treatment plants, ordered according to cause of damage [137]

Affected treatment section	Share of damage
Mechanical treatment	18 %
Biological treatment	58 %
Sludge treatment	22 %
Further treatment	2 %

Table 48 b): Overview of corrosion damage in waste water treatment plants, ordered according to the treatment sections [137]

Affected materials	Share of damage
Galvanized steel	35 %
Coated steel	41 %
Stainless steel	6 %
Concrete	10 %
Aluminium	6 %
Copper-based materials	2 %

Table 48 c): Overview of corrosion damage in waste water treatment plants, ordered according to the type of material [137]

Such a cell always arises when various metallic components that have different corrosion potentials are connected so that they are both electrically and electrolytically conducting. The metallically conducting connection can also lie outside the corrosion medium. In the case of the concrete tanks and immersed steel parts, the metallic contact is generally established via equipotential bonding if the tank reinforcement is the ground or via unintentional contacts, particularly anchoring systems. Figure 14 shows, as an example, the voltages and the corrosion processes taking place [8, 137].

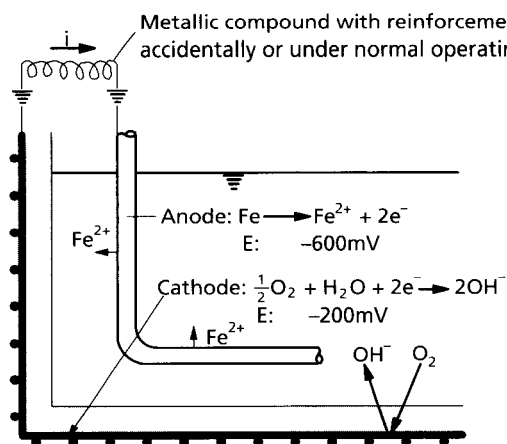


Figure 14: Cell formation for a contact between the reinforcing steel of a concrete tank and the steel parts immersed in the tank [8, 137]

The corrosion potential of steel in aerated waste water is frequently $U_{\text{Cu}/\text{CuSO}_4} = -600 \text{ mV}$, whereas that of the reinforcing steel in the alkaline environment of the concrete has a potential of approx. $U_{\text{Cu}/\text{CuSO}_4} = -200 \text{ mV}$. Because of this difference in potentials, if both parts are short-circuited, the current resulting in the galvanic cell flows and causes the corrosion reactions described above. The anodic reaction of metal dissolution always takes place on the component with the more negative corrosion potential. The entire surface of the reinforcement is available for the cathodic reaction of the oxygen reduction. This greatly increases the anodic metal dissolution on the comparatively small anode surfaces (for steel parts, a corrosion current of 1 mA leads to an annual mass loss of approx. 10 g iron).

Table 49 gives practical examples of such cases of damage along with the corrosion currents flowing in the cell and the resulting mass losses [137].

Possible countermeasures include electrical isolation, installation of galvanic anodes (active anodes, sacrificial anodes) as close as possible to the immersed steel parts, or an electrically isolating, resistant lining of the entire concrete tank. A high silicon cast iron ($14.5\% \text{ Si} + 4.5\% \text{ Cr}$) has proven suitable as an anode for **cathodic protection**. These cathodic protective systems should generate a protective potential in the voltage range between $-0.85 V_{\text{Cu}/\text{CuSO}_4}$ and $-1.11 V_{\text{Cu}/\text{CuSO}_4}$, measured 1 cm away from the steel constructions being protected. Examples and types of design for cathodic protection of concrete tanks in waste water facilities are described in [8]. For coated steel constructions, there is a risk of particularly rapid corrosion at defects, such as cracks or bubbles [138].

Prefabricated parts of polymer concrete containing a vinyl ester polymer or a furan resin polymer have proven suitable for components in facilities for chemical waste waters or as tank linings [139].

Corroded component (anode)	Contact component (cathode)	Corrosion medium	Corrosion current <i>I</i> mA	Mass loss g/year
Water pipeline (cast iron)	reinforcement of foundation	soil	50 – 300	500 – 3000
Scraper shield (coated steel)	tank reinforcement	waste water	30 – 65	300 – 650
Frame (cast iron)	tank reinforcement	waste water	15 – 50	150 – 500
Submersible pump (coated steel)	tank reinforcement	waste water, sludge	6 – 10	60 – 100
Drum filter (steel)	tank reinforcement	waste water	80	800
Rotating disc filter (steel)	tank reinforcement	waste water	145	1450
Sliding/gate valves (cast iron)	stainless steel pipeline	waste water, sludge, service water	0.1 – 10	1 – 100

Table 49: Corrosion currents caused by macrocells and the resulting corrosion rates of various components in waste water treatment plants [137]

B 5 Acid-resistant building materials and binders (putties)

In waste water facilities, there is a risk of microbiological attack of unprotected concrete. Thin protective coatings have not proven suitable for long-term use. Thick-layer systems based on reactive resins exhibit better behavior if they have been correctly formulated and applied without defects. Experience has shown that their disadvantage is the risk of detachment from the substrate by moisture underneath the coating coming from the concrete itself.

Good results were obtained by the use of a protective system consisting of an elastic foil glued to the concrete substrate and a top layer based on an acid-cured potassium waterglass. Under practical conditions, the coating did not exhibit any signs of microbially induced attack and has long-lasting resistance to acidic media [140]. Section D 1 Coatings and linings discusses the currently popular acid-resistant binders for putties and coatings.

Plastic linings have proven suitable as corrosion protection in waste waters in which there is a risk of concrete corrosion. These are preferentially made of the thermoplastic PE-HD (high density polyethylene) or, for communal waste waters, also PVC [141].

B 6 Glass

On account of its combination of good properties, glass, particularly that based on **borosilicate**, has been used successfully for many years in the chemical industry as an apparatus material or for pipelines. Its positive properties include:

- good corrosion and temperature resistance
- dimensional stability with respect to temperature changes
- smooth, poreless surface
- aging resistance

This material is being used more and more frequently in waste water engineering for pipelines and apparatus. The material properties of borosilicate glass 3.3, which is manufactured under various brand names, are specified in DIN ISO 3585 [142]. The suffix 3.3 refers to the thermal longitudinal expansion coefficient of $3.25 \times 10^{-6} \text{ K}^{-1}$, which is the lowest of all known types of technical glass [143].

The outstanding material properties of borosilicate glass are due to its composition, namely approx. 81 % SiO_2 and 13 % B_2O_3 . This material is only corroded by media containing free hydrofluoric acid, concentrated phosphoric acid and strongly alkaline media [143]. An overview of borosilicate glass 3.3, equipment made from it, and their applications in plants used to treat corrosive process waters and to separate organic components is given in [144].

Borosilicate glass has also proven suitable for concentrating spent bath solutions from electroplating works using recirculating evaporators. The only problematic baths are those containing high concentrations of free fluorides as well as cyanide-containing baths with very high pH values [145].

The borosilicate glass DURAN® has good resistance to warm, strongly alkaline media. The uniform surface corrosion of the glass was 1 mm after 25 years, which corresponds to 0.04 mm/a (1.57 mpy), under the following conditions:

- Application: laboratory waste water pipeline
- Medium: NaOH solution
- Concentration: 1 mol/l (pH 14)
- Temperature: 332 K (59 °C)
- Operating time: 8 h/d (= approx. 2.000 h/a)

Pipeline systems with branches and connections must have sealing materials that exhibit the same chemical and thermal resistance as the glass pipe. The temperature-dependent expansion must not lead to any leakages, even after several years of operation. The BORESIST® pipeline system uses PTFE as the sealing material. It has been used successfully for more than 20 years [146–148]. The waste water from plants of the chemical and pharmaceutical industries may contain residual organic compounds. Such waste waters usually contain mixtures of organic solvents, mineral acids and other components at temperatures up to approx. 353 K (80 °C). The above-mentioned glass pipeline systems have proven suitable for transporting waste waters to the works waste water treatment plant or – depending on the concentration of the impurities – to a biological sewage treatment plant.

Organic materials dissolved in the waste water can be recovered by a waste water treatment based on an extraction process. This process, including the associated stripper column and recovery of the pure water, can be implemented in a glass construction for various application cases [149–152]. For the associated process engineering, see reference [116].

A borosilicate glass pipe was initially used in the heat exchanger (from 453 K (180 °C) to 388 K (115 °C)) in a waste incineration plant. This pipe already exhibited damage on the raw gas side due to HF attack after approximately half a year [42].

Reference [153] proposes that glass is used as tiles for the lining of concrete structures exposed to waste waters. These structures include discharge channels in a waste water treatment plant, sewer pipe linings and collecting tanks. Advantages include good chemical resistance and the smooth surface, which increases the flow rate in the sewers and decreases the cleaning work because there are fewer deposits. The TRANSPLUS® system consists of large-format glass tiles that are usually 8 mm thick and can be supplied in flat or curved shapes. They are glued onto the concrete substrate with a polymer cement-based adhesive. The joints are sealed with a jointing material selected according to the expected loads [153].

B 8 Enamel

This group of materials is discussed under D 3 Composites.

B 10 Stoneware

Stoneware is one of the oldest and most important pipe materials for sewers. In addition to the pipes themselves, a complete system of shaped pieces is available as accessories. The internal diameter of the pipes lies in the range ND 200 – 1200 (mm), the length of the individual pipes are e.g. 2.0 m and 2.5 m. Pipes to be used in waste water applications are glazed on both surfaces. They are manufactured from clay with additional fireclay as an opening material. The glaze consists of a mixture of loam, clay, lime, dolomite, quartz and metal oxides. This mixture is finely ground and then applied as an aqueous suspension during shaping by pressing or it is applied to the pressed body after it has dried. After the glaze has dried, the coated bodies are fired at temperatures up to 1523 K (1250 °C). The clay mixture fuses and the glaze melts so that it is irreversibly bonded to the clay body. The fired material, stoneware, consists of glass, quartz and mullite. The basic standard for stoneware in waste water applications is incorporated in DIN EN 295-1 to 3 [154]. It specifies the requirements, quality control and tests for stoneware pipes, shaped pieces and pipe connections. The specifications are to be updated in the works standard WN 295 [155]. The most important properties for stoneware materials in waste water applications are:

- Chemical resistance: stoneware is resistant to all substances that occur in waste waters, with the exception of waste waters containing hydrofluoric acid.
- Mechanical properties: very high wear resistance, high hardness
- Good flow properties due to the low wall roughness
- Temperature resistance

Special applications of stoneware used for waste waters arising from industrial and commercial applications include:

- Waste waters from automotive repair workshops that are contaminated by gasoline and other solvents
- Waste waters containing mineral acids from wire drawing plants, zinc coating plants, metalworking industry
- Organic acids from dairies and cheese-makers
- Various types of aggressive waste waters from the chemical and pharmaceutical industries as well as those from plants processing textiles and leather

Bowls and flat tiles made of stoneware have also proven suitable for lining concrete sewers and shafts in especially loaded zones.

The proportion of stoneware pipes in sewers is approx. 48 % [55].

B 14 Other inorganic materials

The beds of screw conveyors in settling tanks are subject to wear by the solids entrained in the waste water. This gradually diminishes the throughput of the screw. This effect can be avoided by a lining made of tiles of fused basalt ABRESIST® [156].

C

Organic materials/plastics

There are two areas of application for organic materials:

- The treatment of industrial waste waters before they are discharged into waste water treatment plants.
- The waste water treatment plants themselves.

Both applications differ considerably with respect to their loading profiles. In contrast to the treatment of industrial waste waters, in which a large number of chemicals may be present under various operating conditions, in waste water treatment plants, the loads must be within the permissible limiting concentrations and limiting operating conditions. The resistance behavior of individual plastics and groups of plastics are discussed below in accordance with this differentiation.

In general, the damage mechanisms of organic materials are completely different to those of metallic materials, and the resistance data together with the corresponding theoretical explanations were only available from the end of the 1970s to a sufficient degree [157]. Because the damage mechanisms are not only due to the surrounding media, but are also due to irreversible structural changes resulting from the physical effects of the media, the term "**aging**" is used in addition to the term "corrosion". On the other hand, plastics have been used successfully for more than 50 years to construct pipelines, equipment and tanks, and their use has been continuously accompanied by standards and the appropriate rules and regulations, even though the basic damage mechanisms were not understood in detail.

Plastics are differentiated into thermoplastics, duroplasts, elastomers and thermoeLASTOMERS on the basis of certain mechanical properties and their temperature-dependence [158]. This classification is based on their molecular structure, which leads to differing resistance behavior under the various conditions of exposure.

Classification of organic materials

Thermoplastics

Thermoplastics, such as polyolefins, polyvinyl chloride, polystyrene, polyamides, etc. are hard to rubbery-soft materials at room temperature. They can be plastically

deformed, even at moderate temperatures, and exhibit flow properties. They are amorphous to partially crystalline. In amorphous thermoplastics, the linear or branched macromolecules are only crosslinked by physical bonds. They form random tangled bundles which align into a certain order in the partially crystalline state. Their crystallinity is decisive for the mechanical properties, particularly for their brittleness.

Duroplasts

Duroplasts include e.g. epoxy resins, phenol-formaldehyde resins. Duroplasts have a high degree of chemical crosslinking and have a high strength. They do not become viscous on heating, but decompose instead. Their structure arises from chemical crosslinking reactions of reactive components during molding.

Elastomers

Elastomers, such as natural rubber, synthetic rubber, silicone rubber, consist of stretchable macromolecules with only a few crosslinkages. Their rubber-elastic domain covers a large temperature range up to the decomposition temperature and there is no viscous state.

Thermoelastomers

Thermoelastomers are an intermediate between thermoplastics and elastomers. Examples of these are blends of crystalline polypropylene and amorphous polymers.

In order to obtain certain properties for utilization and processing, specific chemical substances are added to the polymer materials. The most important of these are stabilizers, light stabilizers and additives (e.g. plasticizers, dyes, abrasion-resistant fillers). In addition to the structure of the basic material, they can also be important for the chemical resistance.

To simplify dealings with plastics, it is customary to use abbreviations. These are summarized in Table 50.

With respect to this, see Table 62. In addition, reference [160] contains a detailed list of trade names.

Damage mechanisms of organic materials

The present understanding of the aging behavior and the chemical resistance, including the individual mechanisms, of thermoplastics are given in reference [159] and for duroplasts and elastomers in reference [157, 160].

The main topics discussed below are the chemical resistance and the resulting **swelling** as well as **stress cracking**, **chemical degradation** and **attack by microorganisms**. Resistance to atmospheric effects, photooxidation and ionizing radiation play only a secondary role in the present deliberations. The corresponding data are given in [157, 159]; they are not discussed in detail here.

Abbreviation	Chemical structure
ABS	Acrylonitrile-butadiene-styrene copolymer
BS	Butadiene-styrene copolymer
CR	Chloroprene rubber
E-P	Ethylene-propylene copolymer
E-TFE	Ethylene-tetrafluoroethylene copolymer
EP	Epoxy resin
EP-GF	Epoxy resin, glass fiber-reinforced
EPDM	Ethylene-propylene-diene rubber
FPM	Fluorinated rubber
MBS	Methylmethacrylate-butadiene-styrene copolymer
NBR	Acrylonitrile-butadiene rubber
NR	Natural rubber
PA 6	Polyamide, homopolycondensate made of ϵ -caprolactam
PA 66	Polyamide, homopolycondensate of hexamethylenediamine and adipic acid
PAN	Polyacrylonitrile
PB	Polybutene – 1
PBT	Polybutylene-terephthalate copolymer
PC	Polycarbonate
PE	Polyethylene
PE-C	Chlorinated polyethylene
PE-HD	Polyethylene, high density ($> 0.940 \text{ g/cm}^3$)
PE-LD	Polyethylene, low density ($< 0.930 \text{ g/cm}^3$)
PE-LLD	Polyethylene, low density ($0.918 - 0.935 \text{ g/cm}^3$) and linear structure
PE-VLD	Polyethylene very low density
PET	Polyethylene terephthalate
PF	Phenol-formaldehyde resin
PF-GF	Phenol-formaldehyde resin, glass fibre-reinforced
PI	Polyimide
PIB	Polyisobutylene

Table 50: Abbreviations and chemical structure of important plastics [157, 159, 160]

Table 50: Continued

Abbreviation	Chemical structure
PMMA	Polymethylmethacrylate
POM	Polyacetal, polyoxymethylene
PP	Polypropylene
PPS	Polyphenylene sulfide
PPSU	Polyphenylene sulfone
PS	Polystyrene
PSU	Polysulfone
PTFE	Polytetrafluoroethylene
PUR	Polyurethane
PVAC	Polyvinyl acetate
PVAL	Polyvinyl alcohol
PVC	Polyvinyl chloride
PVC-C	Chlorinated polyvinyl chloride
PVC-P	Soft (plasticized) polyvinyl chloride
PVC-U	Hard (unplasticized) polyvinyl chloride
PVDF	Polyvinylidene fluoride
SB	Styrene-butadiene copolymer
SAN	Styrene-acryl copolymer
SBR	Styrene/butadiene rubber
SBS	Styrene-butadiene-styrene block copolymer
SI	Silicones
TPE-A	Thermoplastic elastomers (polyetheramide grades)
TPE-O/V	Thermoplastic elastomers (polyolefin grades)
TPE-U (TPU)	Thermoplastic elastomers (polyurethane grades)
UP	Unsaturated polyester resins
UP-GF	Unsaturated polyester resins, glass fiber-reinforced
VE	Vinyl ester

Table 50: Abbreviations and chemical structure of important plastics [157, 159, 160]

For an evaluation of the chemical resistance, it is convenient to divide processes into two basic types:

- physically acting media with reversible changes in the properties of the material, e.g. by swelling
- chemically acting media with irreversible changes as a result of the cleavage of chemical bonds.

It is not only the type of polymer material that is important, but manufacturing and processing factors must also be taken into account. These include poor plastification, inhomogeneous distribution of additives, microscopic and macroscopic defects, high and inhomogeneous residual stresses, as well as rough surfaces or even those with pores and microcracks [161].

Swellability and stress cracking

During swelling the solvent molecules enter the material by diffusing into the interstitial spaces between the tangled molecules. This pushes the molecular chains apart, which reduces the cohesion and thus the mechanical strength. In general, these processes are reversible since the solvent can be removed by effusion from the polymer to give the original structures.

If the swelling process takes place under tensile stress or elongation which lies under the yield strength in a short-time test, stress cracks can occur as an additional complication. Such cracks, which may only arise after a long period, are caused by residual stresses as the result of incorrect processing, external mechanical loading, or a combination of both types of stress. Exposure to particular chemicals can greatly decrease the time until cracks start to form [161].

Furthermore, a high degree of swelling can lead to dissolution of the material, which is also an irreversible type of damage.

The old chemist's rule applies to the swellability of a polymer in solvents: "**A material will dissolve in a solvent of similar structure**". This means that the ability of a polymer to absorb solvent molecules is greatest when the chemical structures of the two materials are most similar. However, this is only a rough approximation. Further evaluation factors, such as polarity of the solvent, solubility parameters and cohesion energies of the material and the media must also be taken into account [157]. In extreme cases, very polar solvents, e.g. halogenated hydrocarbons, even in concentrations in the ppm range, can cause swelling in many plastics.

Pure diffusion (**permeation**) through plastics plays a role in all media with a finite vapor pressure. The gases are able to diffuse through the material to different extents and exit on the other side. If the material is a coating on unalloyed steel within which there is a temperature gradient, liquid may condense on the boundary surface between the two materials to result in blisters that destroy the adhesion. This permeation effect is particularly marked for gases with a small molecule size, e.g. HCl and HF. Concentrated hydrochloric acid and hydrofluoric acid with high partial pressures of these gases exhibit this permeation effect.

Swelling, stress crack formation, and permeation are temperature-dependent. These effects are generally intensified as the temperature increases.

Table 51 gives some relationships between the structure and the swellability. For example, polyethylene is a saturated, nonpolar hydrocarbon in which strongly polar water or aqueous solutions lead to a very low level of swelling because the material and the medium have very different chemical structures. Epoxy resins with polar C-O and C-N bonds, on the other hand, exhibit strong swelling in contact with similarly structured esters and ketones ("a material will dissolve in a solvent of similar structure"). Polyvinyl chloride, which is polar due to its Cl bonds, is only slightly attacked by nonpolar gasoline, but it is very strongly attacked by polar acetone. Halogenated hydrocarbons have a special status: they are able to diffuse into nearly every organic material, with the exception of phenol-formaldehyde resins.

Polymer material	Structure	Solvent	Structure	Swellability
Polyethylene	saturated HC, nonpolar	water	O-H bond, polar	very low
		benzene	aromat. HC	strong
		halogenated HC	C-Cl bond	very strong
Polyvinyl chloride	Cl-containing satd. HC, polar	gasoline	satd. HC, nonpolar	very low
		acetone	satd. HC with O-C bond, polar	strong
Epoxy resins	HC with C-O and C-N bonds, polar, three-dimensional	alcohols	HC with C-OH groups, polar	low
		esters and ketones	HC with C-O bond	strong

HC = hydrocarbon, satd. = saturated

Table 51: Swellability of selected polymer materials and structure of the solvents at room temperature (for further data, see [157])

Chemical degradation (corrosion)

The chemical resistance of organic materials depends on its structure and composition (including additives and fillers), on the type and composition of the medium to which it is exposed, and on the exposure conditions (temperature, mechanical loading).

The chemical reactions of macromolecular substances follow the same rules as for low molecular-weight organic compounds. The reaction rates and the resulting changes in properties are, however, very different. This depends on the fact that the

attacking medium attacks only the surface (of duroplasts) or must first diffuse into the material in order to attack the macromolecules (of thermoplastics and elastomers). The resulting processes inside the material are also very different. The decisive factor is the type and number of reactive groups on the macromolecule that can react with the attacking medium.

For example, it is known from general organic chemistry that hydrocarbons are not very reactive. Similarly, high-molecular weight compounds, whose macromolecules are formed of hydrocarbon chains, are not very reactive. Thus, polyethylene and polypropylene are very resistant to attack by acids, bases, salts and weak oxidizing agents in aqueous solutions. The resistance is considerably increased if the hydrogen atoms in the macromolecule are replaced partially or completely by fluorine which shields the carbon atoms from chemical attack. An example of this is polytetrafluoroethylene (PTFE).

If the hydrocarbon chain contains OH groups, as in the case of polyvinyl alcohol (PVAL), these provide sites that can be attacked in aqueous solutions and this leads to corrosion. If the carbon atoms are partly replaced by oxygen or nitrogen, then attack occurs here and the chains are cleaved. Correspondingly, such compounds are readily attacked by hydrolytically active media (aqueous acids and bases) with the result that polyamides, polyurethanes and polyesters have little chemical resistance to these media [159].

Similar to swelling processes, mechanical tensile stresses or vibrational loads lead to stress cracks, whereby the simultaneous exposure to chemicals may accelerate these processes.

Table 52 and Table 53 a and b summarize the chemical resistances ordered according to the type of material and the type of medium, respectively [157, 160 – 162]. Table 52 takes account of the susceptibility to stress cracking, if known, because most of the data are based on exposure tests without mechanical loading.

Table 53 a and b shows a pronounced temperature-dependence of the chemical resistance of some plastics. It is thus not possible to state that plastics have a general temperature resistance in chemical media as they do in air.

Microbiological degradation (microbiological corrosion)

Both the basic polymer as well as additives and fillers in plastics can be degraded by microorganisms (bacteria, algae, fungi, lichens). The prerequisites for this are the presence of water or sufficient moisture, optimum temperature conditions, and the presence of organic material that the microorganisms can degrade.

There is a risk of **microbial corrosion** in facilities that contain water, such as in the treatment and conditioning of water, evaporation and cooling units and in heat recovery. In the purely chemical process steps of industrial waste water treatment, the microbiological degradation of plastics is not important; however, such processes are always associated with water-filled circuits used to control the heat balance. In the actual waste water treatment plants, no damage of the plastics by microbiological degradation is expected if the materials correspond to the standard and regulations.

Plastic	Resistance to					
	Water	Salt solutions	Acids	Bases	Oxidizing agents	Solvents
PE	1	1	1	1	2 – 3	1 – 2, S
PP	1	1	1	1	3	1 – 2, S
PS	1	1	1	1	2 – 3	3, S
SAN	1	1	2	1	3	3, S
ABS	1	1	2	1	3	3, S
SBR	1	1	2	1	3	3, S
PTFE	1	1	1	1	1	1
PVDF	1	1	1	3	2	2
PVC-U	1	1	1	1	2	1 – 3
PVC-P	1	1	2	2	2 – 3	3
PMMA	2	1	2	2	2 – 3	3, S
PAN	1	2 – 3	2 – 3	2 – 3	2 – 3	1 – 2
POM	1	1	3	2	3	1 – 3
PSU	1	1	2 – 3	2	3	1 – 3
PA	2	2	3, S	2	3	1 – 3, S
PC	1	1	2 – 3	3	3	2 – 3, S
PET	1	1	2	3	3	1 – 3, S
EP	1	1	3	1	2 – 3	1 – 3
PF	1	1	1	2 – 3	3	1 – 3
NR	1	1	1	1	3	2 – 3
NBR	1	1	1	1	2	1 – 3
EPDM	1	1	1	1	3	1 – 3
FPM	1	1	1	1	1	1

1: Very good resistance, 2: Average resistance, 3: Low resistance, S: Susceptible to stress cracking

Table 52: Chemical resistance ordered according to the type of material [157, 159, 162]

Temperature, K (°C)	Thermoplastics													
	PVC-U		PVC-C		PE-HD		PP		PVDF					
	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (80)	333 (60)	353 (80)	373 (100)	393 (120)
1. Aqueous inorganic acids														
hydrochloric acid, 20 %	+	0	+	+	+	+	+	+	0	+	+	+	+	+
hydrofluoric acid, 38 %	+	0			+		+	+		+	+	+	+	+
phosphoric acid, 85 %	+	+	+	+	+	0	+	+	0	+	+	+	+	+
sulfuric acid, 98 %	+	0	+	+	-	-	-	-	-	-	-			
sulfuric acid, 70 %	+	+	+	+	+	0	0	0	+	+	+	+	0	0
2. Aqueous inorganic oxidizing acids														
nitric acid, 20 %	+	+	+	+	+	+	0	-	+	+	+	+	+	+
nitric acid, 10 %	+	+	+	+	+	+	+	0	+	+	+	+	+	+
perchloric acid, 10 %	+				+	+	+	+	+	+	+	+	+	+
aqua regia	+	0	+	+	-	-	-		+					
chromic acid, 10 %	+	0	+	+	+	+	+		+	+	+	+		
3. Aqueous organic acids														
acetic acid, 10 %	+	+			+	+	+	+	+	+	+	+	+	+
citric acid, 10 %	+	+	+	+	+	+	+	+	+	+	+	+	+	+
4. Concentrated organic acids														
glacial acetic acid	0	-			+	0	+	0	+				+	

+: resistant, 0: limited resistance, -: not resistant

Table 53 a: Chemical resistance of thermoplastics at various temperatures ordered according to the type of medium [161]

Table 53 a: Continued

Thermoplastics																	
Temperature, K (°C)		PVC-U			PVC-C			PE-HD			PP			PVDF			
		293 (20)	333 (60)	333 (20)	293 (20)	333 (60)	333 (20)	293 (20)	333 (60)	333 (20)	293 (20)	333 (60)	333 (20)	293 (20)	333 (60)	373 (100)	393 (120)
5. Aqueous alkalis	potassium hydroxide solution, 50 %	+	+	+	+	+	+	+	+	+	+	+	+	0			
	NaOH solution, 40 %	+	+	+	+	+	+	+	+	+	+	+	+	0	—		
	ammonia solution, 30 %	+	+	+	+	+	+	+	+	+	+	+	+	+			
6. Amines	ethylene diamine	0	—		+	+	+	+	+	+	+	+	+	+	+	0	
	aniline	—		—		—	+	+	+	+	+	+	+	+	0		
	pyridine	—		—		—	+	+	0	0	0	+	+	+	0		
7. Aliphatic com- pounds	gasoline	+			+	+	+	0	0	—	—	+	+	+	+	+	+
	benzene	—		—		—	0	0	—	0	—	+	+	0	0	+	+
8. Aromatic com- pounds	toluene	—		—		—	0	0	—	0	—	+	+	0	0		
	methanol	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+
9. Alcohols	ethanol	+	+	+	+	+	+	+	0	+	+	+	+	+	+	+	+

+: resistant, 0: limited resistance, –: not resistant

Table 53 a: Chemical resistance of thermoplastics at various temperatures ordered according to the type of medium [161]

Table 53 a: Continued

Temperature, K (°C)	Thermoplastics															
	PVC-U			PVC-C			PE-HD			PP			PVDF			
	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (60)	293 (20)	333 (60)	373 (100)	393 (120)
10. Ketones																
acetone	—	—	—	—	+	+	+	+	+	+	+	+	+	—	—	—
methyl ethyl ketone	—	—	—	—	+	+	+	+	+	+	+	+	+	—	—	—
11. Esters																
butyl acetate	—	—	—	—	+	+	+	+	+	+	+	+	+	+	+	+
12. Ethers																
di-isopropyl ether	—	—	—	—	+	+	+	+	+	+	+	+	+	+	+	+
13. Halogenated hydrocarbon																
carbon tetrachloride	—	—	—	—	0	—	—	—	—	—	—	—	+	+	+	+
trichloroethylene	—	—	—	—	0	—	—	0	0	0	+	+	+	+	+	+
chlorobenzene	—	—	—	—	0	0	+	+	+	+	+	+	+	0	—	—
14. Other																
water	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
sodium chloride solution	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
copper sulfate solution, 10 %	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
potassium carbonate solution, 10 %	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
P-3 solution, 1 %	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
sodium hypochlorite	+	+	+	+	+	+	—	—	—	—	+	+	+	+	+	+
hydrogen peroxide, 30 %	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

+: resistant, o: limited resistance, -: not resistant

Table 53 a: Chemical resistance of thermoplastics at various temperatures ordered according to the type of medium [161]

Duroplasts														
Temperature, K (°C)	UP					VE					EP			
	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	373 (100)	393 (120)
1. Aqueous inorganic acids														
hydrochloric acid, 20 %	+	o		-			+	+	+	+	+	+	+	+
hydrofluoric acid, 38 %	-			-						+	+	+	+	+
phosphoric acid, 85 %	+	+	+	+	+	+	+	+	+	+	+	+	+	+
sulfuric acid, 98 %	-			-						+	-			
sulfuric acid, 70 %	+			+						+	+	+	+	+
2. Aqueous inorganic oxidizing acids														
nitric acid, 20 %	+	-		+	-		+	o	o	+	o	o	-	-
nitric acid, 10 %	+	+	-	+	+	-	+	+	+	+	+	+	+	-
perchloric acid, 10 %	+			-						+				
aqua regia	-			-						-				
chromic acid, 10 %	+	+	+	+	+	+	+	+	+	+	+	-		
3. Aqueous organic acids														
acetic acid, 10 %	+	+					+	+	+	+	+	+	+	+
citric acid, 10 %	+	+	+	+	+	+	+	+	+	+	+	+	+	+
4. Concentrated organic acids														
glacial acetic acid	-						+			+	-			

+: resistant, o: limited resistance, -: not resistant

Table 53 b: Chemical resistance of duroplasts at various temperatures ordered according to the type of medium [161]

Table 53 b: Continued

		Duroplasts											
		UP				VE				EP			
Temperature, K (°C)		293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)
5. Aqueous alkalis	potassium hydroxide solution, 50 %	0			+	+		+	+	+	+	+	+
	NaOH solution, 40 %	0			+			+	+	+	+	+	+
	ammonia solution, 30 %							+	+	+			
6. Amines	ethylene diamine	0						0	–				
	aniline	–			+	–		+	0	0			
	pyridine	–			–			0	–				
7. Aliphatic com- pounds	gasoline	+	+		–			+	+	+	+	+	+
8. Aromatic com- pounds	benzene	–			–			+	0				
	toluene	–			–			+	+	+	+	+	+
9. Alcohols	methanol	–			–			+	+	+			
	ethanol	–			–			+	+	+			
10. Ketones	acetone	–			–			0	–				
	methyl ethyl ketone	–			–			0	0	–			

+: resistant, 0: limited resistance, –: not resistant

Table 53 b: Chemical resistance of duroplasts at various temperatures ordered according to the type of medium [161]

Table 53 b: Continued

Duroplasts													
Temperature, K (°C)	UP				VE				EP				
	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	293 (20)	333 (60)	353 (80)	373 (100) (120)
11. Esters	+			-						+	o	o	-
12. Ethers	-			-						+	o		
13. Halogenated hydrocarbon	+			+						+	+	+	+
	-			-						+	+	+	
	+			-						+	+	+	o
14. Other	+	+		+	+	+	+	+	+	+	+	+	+
	+	+		+	+	+	+	+	+	+	+	+	+
	+	+		+	+	+	+	+	+	+	+	+	+
	+	+		+	+	+	+	+	+	+	+	+	+
	+	+		+	+	+	+	+	+	+	+	+	+
	+	+		+	+	+	+	+	+	+	+	+	+
	+			+	+	+	+	+	+	+	+	+	+
	+			+	+	+	+	+	+	+	+	+	+
	+			+	+	+	+	+	+	+	+	+	+

+: resistant, o: limited resistance, -: not resistant

Table 53 b: Chemical resistance of duroplasts at various temperatures ordered according to the type of medium [161]

The following mechanisms have been determined for microbial degradation [33, 163]:

- Direct attack of the basic polymer and/or additives by the use of these compounds as a source of carbon and/or nitrogen. For example, the PE plasticizer dibutyl adipate can be cleaved into its educts adipic acid and butanol. This reduces the pH and thus enhances the ambient conditions.
- Indirect attack by metabolic products of the microorganisms without the organic material being used as a source of nutrients. Metabolic products include enzymes, acids and pigments. Examples include acid corrosion of plastic optical lenses, discoloration of shower curtains and the red discoloration of milk bottles by dye-producing bacteria.
- Surface contamination by the growth of fungi on the surfaces of components, especially in the tropics, and bacterial infestation of the seals of cooling equipment.

The microbial degradability of some materials is described below [33, 157]:

Polyethylene

- Polyethylene is resistant to microbial attack. Long-term tests showed that grades with a molecular weight > 10.000 are completely resistant. Superficial growth of molds does not alter the mechanical properties. Polypropylene (PP) behaves similarly.

Polyvinyl chloride

- The basic polymer is resistant. Mass losses from polymers containing plasticizers are due to microbial degradation of the plasticizer, whereby its type and proportion are decisive. Microbial growth often leads to permanent discolorations.

Polystyrene

- This polymer is regarded as being very resistant; however, fungal hyphae can grow into the material through the surface cracks.

Polyamides

- Bacteria are able to cleave the peptide groups to produce compounds containing carbonyl and amino groups, whereby the resistance depends on the type of monomers. PA 6 (Nylon® 6) is more resistant than PA 66. Fungal growth on the surface can lead to discolorations and degradation.

Polyesters

- Their resistance depends on the acidic monomers used. Adipic acid esters, sebacic acid esters and azealic acid esters are attacked by extracellular hydrolases produced by the molds. Phthalic acid esters are relatively resistant.

Polyurethanes

- Polyester urethanes are significantly more susceptible to attack than polyether urethanes on account of their chemical structure. Fungal growth can lead to discolorations and cracks that are due to the action of esterases produced by the microorganisms.

Fluoropolymerisates

- This group is absolutely resistant to microbiological corrosion.

High-temperature thermoplastics

- There is no data available on high-temperature thermoplastics containing sulfur.

Epoxy resins, phenol-formaldehyde resins and urea-formaldehyde resins

- These materials are very resistant; however, in the presence of organic fillers, such as wood dust, cellulose, cotton and other susceptible components, these additives may be strongly attacked by molds which makes the material as a whole unserviceable.

Natural and synthetic rubber

- Natural rubber is very readily attacked by microorganisms and numerous types of bacteria. Their resistance depends on the rubber compound. Butadiene-styrene rubber and butyl rubber are resistant unless they are not contaminated by materials that serve as nutrients for microorganisms.

Silicone elastomers

- Silicone elastomers are susceptible to combined attack of yeasts and bacteria [164].

The microbial degradation of organic multilayer systems and coatings follow similar mechanisms [165]. Depending on the substances they contain, these materials are all susceptible to differing speeds of microbial attack. Microbial attack must be taken into account for some of the coating systems described in Section D1, although the unambiguous proof of microbial damage can be difficult [166].

Although microbial corrosion of plastics must be avoided from the point of view of the material's resistance, they should be biodegradable for environmental reasons. In order to take account of both of these aspects, national and international standards have been developed for test methods. The most important of these are summarized in Table 54.

Standard	Title of the standard
ASTM G21-96	Standard Practice for Determining Resistance of Synthetic Polymeric Materials to Fungi
ASTM G29-96	Standard Practice for Determining Algal Resistance of Plastic Films
DIN EN ISO 846	Plastics – Evaluation of the action of microorganisms on plastics

Table 54: Standardized test methods to determine the resistance of plastics to microbial attack [33]

There are many measures that can be taken to protect plastics against microbial attack [163]:

- The microbial degradability of plastic additives should be tested in advance using the test methods described above (prescreening).
- Optimization of the compounding recipe allows the biological recyclability of plastics to be reduced even further.
- Addition of microbiocides to inhibit biocorrosion is very effective [33, 163, 167]; however, the corresponding environmental problems must be taken into account.
- The surface of the plastic must be protected from organic contaminants that promote microbial attack.
- Special constructive and process engineering measures can be taken with respect to the operation of pumps and other equipment [33, 93]. These include the avoidance of constrictions and dead spaces as well as the use of smooth surfaces.

Further information on protective measures for layers and coatings is given in [165]. These materials are described in Section D1.

Chemical resistance of organic materials used in the treatment of industrial waste waters

Because the corrosive load of correctly operated waste water facilities is low on account of the low permissible concentrations of pollutants and the ban on noncompliant discharge, the standard materials used in these facilities, PVC-U, PE-HD, PP and UP-GF (glass fiber-reinforced plastics based on unsaturated polyester resins) present no problems with respect to corrosion [8, 168].

However, there is an increased corrosive load in the process steps before the waste water is discharged. The analysis of conventional treatment processes indi-

cates a series of typically aggressive media that are important with respect to the corrosion of organic materials and which must be taken into account in the design of the facilities. The most important aggressive media are summarized in Table 55 with respect to some treatment processes.

Branch of industry	Aggressive media	Critical process steps
Chemical industry	acids, bases, solvents (halog. HC), heavy metals, ammonium, nitrate, sulfate, oxidizing agents, fats and oils	neutralization, oxidation
Mineral oil processing	hydrocarbons, hydrogen sulfide, sulfite, sulfate, heavy metals, mineral oil, halog. HC	rectification, absorption, neutralization, detoxification
Iron and steel producing industry and metalworking industry	acids, bases, sulfate, fluoride, chromate, nitrate, oxidizing agents, heavy metals	neutralization, metal deposition, complex decomposition by oxidation, chromate reduction
Paint industry	solvents, scrubbing solutions, peak loads due to the COD (Chemical Oxygen Demand)	separation of solvents, neutralization
Fertilizer industry	acids, bases, conc. chloride solutions, ammonium, nitrate, sulfate, heavy metals	neutralization, evaporation
Glass industry	hydrofluoric acid, sulfuric acid, heavy metals	neutralization, lime treatment, deposition of metals
Textile industry	bases, acids, chlorine, sulfite, sulfate, surfactants, chromate, halog. HC	neutralization, elimination of chlorine and tensides
Rechargeable batteries and the battery industry	acids, bases, heavy metals (Pb, Cd, Hg, Zn)	neutralization, deposition of heavy metals
Food industry	bases, acids, fats, oil, ammonium, sand, hydrogen sulfide	cleaning, sterilization, separation of solids

Table 55: Branches of industry with typically aggressive media and critical processing steps

From the point of view of corrosiveness, the elimination of cyanide, chromate and nitrite are problematic due to the necessary oxidizing agents (hydrogen peroxide and ozone) and reducing agents (sulfur dioxide). Details of the use of these processes in the metalworking industry are given in [5], those from the other branches of industry are given in [4, 6].

The organic materials used for the treatment of industrial waste waters are discussed below according to the type of polymer, namely thermoplastics, duroplasts, elastomers. With respect to the temperature resistance, it must be stated that different values are reported for the upper permissible temperature limits for continuous

exposure. Therefore, the lowest published values are given in the interests of a conservative approach.

Thermoplastics

Polyolefins and their copolymers

Polyolefins, with their main representatives PE, PP, PB, are completely resistant at room temperature to chemicals such as aqueous solution of acids, bases and salts. Solvents, such as alcohols, aliphatic hydrocarbons, gasoline, esters and ketones, all have differing effects, as shown in Table 56. Aliphatic, aromatic and chlorinated HC all diffuse readily into the materials and cause swelling and stress cracking [160].

	PE-LD	PE-HD	PP	PB
Alcohols	+ S	+ S	+	+
Esters, ketones	–	–, S	–	–
Aliphatics, gasoline, aromatics	–, S	–, S	–	–
Formic acid, 100%	+ S	+	+	+
Acetic acid, 100%	–, S	–, S	–	–

+: resistant, –: not resistant, S: susceptible to stress cracking

Table 56: Resistance of polyolefins to organic solvents [157, 160]

The strong temperature dependence of the thermal and thermal-oxidative degradation of polyolefins, which can be counteracted by adding stabilizers, is also observed for the action of chemicals. As in nearly all chemical reactions, the reaction rate considerably increases as the temperature rises, whereby there may be large differences depending on the reaction mechanism. The upper limiting temperatures for use (without mechanical loading) are tabulated in [162].

Apart from the temperature, another decisive factor is mechanical stress in the material. Because simple immersion tests do not take this parameter into account and bending tests are not sufficient, a defined testing method, the **internal pressure test of the creep rupture strength** of pipes, has been developed that indicates the influence of mechanical stress on the service life of materials with respect to the action of chemicals and temperature [169, 170]. This test is specified in the standards BS-ISO 8584-1 [171] and ISO 8584-2 [172].

Figure 15 shows the decisive effects of temperature and mechanical stress on the chemical resistance (expressed as the creep rupture strength) of PE-HD pipes. According to this, the service life is decreased by three orders of magnitude for a temperature increase from 313 K (40 °C) to 353 K (80 °C); it decreases by one order of magnitude if the stress is increased by a factor of 2. The influence of chemicals is

expressed as the **resistance factor f** (service life in the medium / service life in water) and lies between $f = 0.25$ (353 K (80 °C)) and $f = 0.07$ (313 K (40 °C)). Further data and references on resistance factors are cited in [157, 169, 170]. Numerous further chemicals and media used in chemical engineering are given in [170, 173] along with values for particular waste waters (Table 57). However, there is no such data for the majority of the corrosive loads discussed below. Depending on the application case, the corresponding suitability tests must therefore be carried out.

Medium	Comment	Test stress, N/mm^2	Resistance factor f_{CR0} for PE-HD at 353 K (80 °C)
Waste water from a cellulose factory	mixture of inorganic and organic substances	4 – 2	0.95
Waste water from a synthetic fiber factory	mixture of inorganic and organic substances	4 – 2	0.75
Waste water from a whey processing plant	mixture of inorganic and organic substances	4 – 2	0.73
Various detergents	mixture of inorganic and organic substances	4 – 3	0.6 – 1
Water containing 2 % wetting agent	mixture of inorganic and organic substances	4 – 2	0.6

Table 57: Resistance factors f_{CR0} for PE-HD (Hostalen® GM 5010) at 353 K (80 °C) in various waste waters [170, 173]

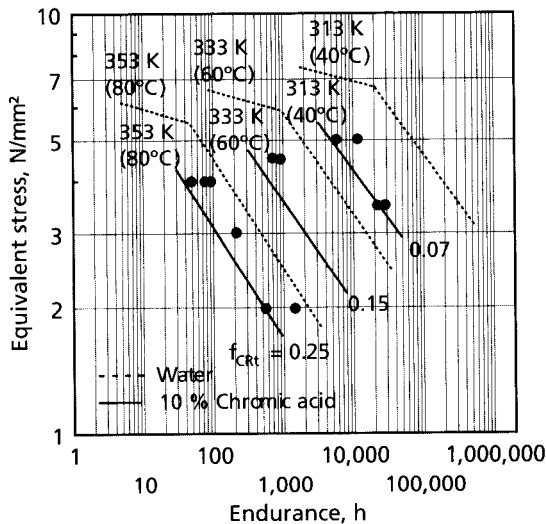


Figure 15: Creep rupture strength of PE-HD-pipes exposed to water and 10% chromic acid with resistance factors [169]

Polyethylene (PE)

The chemical resistance of polyethylene decreases as the density increases (PE-LD and PE-HD), whereas the resistance to stress cracking decreases slightly. All PE grades cannot be used in strong acids (HCl, HF), oxidizing acids (HNO₃, H₂SO₄, H₂CrO₄), in gaseous and liquid chlorine, and in hypochlorite solutions (stress cracking) [157].

The latest data on the swelling and diffusion susceptibility of PE-VLD with respect to organic media in the temperature range between 298 to 348 K (25 to 75 °C) are given in [174]. The swellability decreases in the following order: aromatic HC – chlorinated HC – ketones. These data are important for the sealing of landfills (use of so-called geomembranes). Experience gained with PE-HD geomembranes with respect to the attack of leachates is reported in [175]. The chemical composition of leachates is given in Table 6 in the Introduction.

Pressurized pipes made of PE-HD have been used successfully for many years for the gas and water supply. The guaranteed service life is 50 years, although 80 years are expected [159]. PE-HD is used extensively as a standard material in waste water facilities, which is documented in standards as well as in the corresponding rules and regulations [8].

Ethylene-vinyl acetate copolymer

This material is interesting because as the vinyl acetate content decreases, the chemical resistance decreases; however, the resistance to stress cracking increases [159].

Polypropylene (PP)

Its chemical resistance is comparable to that of PE. Because of the differing structure (tertiary H atom), its resistance to oxidizing agents (H₂O₂, nitric and chromic acids) is less than that of PE. Compared to PE, however, PP is much less susceptible to stress cracking. Its resistance to organic solvents is comparable to that of PE. One of the advantages of PP compared to PE is the higher load capacity for continuous operation at higher temperatures: 363 K instead of 333 K (90 °C instead of 60 °C) in general, or 373 K instead of 353 K (100 °C instead of 80 °C) in the absence of mechanical loads.

A good application example is the use of PP in a plant to treat waste water containing chlorinated hydrocarbons and traces of HCl. In this plant, the pure gas pipelines, stripper pumps and droplet separators, that were operated at temperatures between 293 and 358 K (20 and 85 °C), were made of PP, whereas a phenol-formaldehyde resin coating or graphite was necessary for the extreme demands in the stripper column (403 K (130 °C)) [116]. An overview of the materials used in the various sections of the plant is given in Table 58.

Plant section	Loading	Materials
Stripper reservoir	293 K (20 °C), HCC in water	Steel, coated with furan resin
Stripper	293 K (20 °C), HCC in water	Phenol resin duroplast
Stripper pumps	293 K (20 °C), HCC in water, gaseous HCC	Polypropylene
Droplet separator after the stripper, pipeline after the stripper, packing in the stripper	293 K (20 °C), HCC in water, gaseous HCC	Polypropylene
Heater for stripping air	293 K (20 °C), HCC in water, gaseous HCC	Stainless steels
Clean gas pipeline	293-358 K (20-85 °C), traces of HCl, damp	Polypropylene
Adsorption vessel	403 K (130 °C), condensing steam, condensing HCC, HCl	Phenol resin duroplast
Cooler/condenser	403 K (130 °C), condensing steam, condensing HCC, HCl	Graphite
Regenerate pipeline	403 K (130 °C), condensing steam, condensing HCC, HCl	PVDF (solid)
Safety valve	403 K (130 °C), condensing steam, condensing HCC, HCl	PTFE/glass
Process air dampers, dry blower dampers	403 K (130 °C), condensing steam, condensing HCC, HCl	Phenol resin duroplast
Regenerate dampers	403 K (130 °C), condensing steam, condensing HCC, HCl	Steel/PTFE jacketed
Steam dampers	water vapor, 403 K (130 °C)	Steel/PTFE jacketed
Solvent separator	303 K (30 °C), condensed HCC, HCl	Phenol resin duroplast
Solvent pump	condensed HCC	Stainless steel

HCC: Chlorinated hydrocarbons

Table 58: Materials for a stripper unit used to remove chlorinated hydrocarbons [116]

Information on improvements in application engineering for the use of block copolymers and random copolymers with PE is given in [176, 177].

Polybutene (PB)

The chemical resistance corresponds to that of PE and PP. Concentrated inorganic acids, such as chromic, hydrofluoric, nitric and hydrochloric acids, aqua regia as well as oxidizing agents, such as hypochlorite and ozone, can trigger stress cracking. Its sensitivity to solvents corresponds to that of the other polyolefins.

Polyvinyl chloride (PVC)

Extensive experience has been gained with internal pressure tests of the creep rupture strength of these oldest thermoplastic materials that have been used since 1938 for pressurized water pipes. These tests predict a service life of well over 100 years in water supply systems [178]. Just as much data is available on their thermooxidative and photooxidative resistance and on their improvement with stabilizers [159]. Hard or unplasticized PVC (PVC-U) is a standard material in waste water facilities. Its use is regulated with standards [8].

PVC-U is resistant up to 333 K (60 °C) to water, aqueous solutions of inorganic acids, bases and salts, as well as to fats, oils, aliphatic hydrocarbons, gasoline and detergents. It is not resistant to aromatic and chlorinated hydrocarbons, ketones, esters, stain removers and strong oxidizing agents, such as chlorine and ozone. Surprisingly, it is not attacked by hypochlorite solutions [157].

Stress cracking of PVC-U occurs at a low level in polar solvents, such as methanol, ethanol, ethyl acetate, fluorinated hydrocarbons and in specific solvents for PVC as well as their vapors. PVC-P (soft or plasticized PVC) is not susceptible to stress cracking.

The type of plasticizer and its concentration in the PVC-P is of great importance. The behavior depends upon whether the chemicals act as extraction agents for the plasticizer. Monomeric plasticizers are particularly susceptible to media with a similar structure (cf. the principle of "a material will dissolve in a solvent of similar structure"). However, polyester plasticizers are resistant to extraction by aliphatic hydrocarbons [159].

Fluoropolymerisates

Fluoropolymerisates are one of the most chemically resistant groups of organic materials. Their thermooxidative and photooxidative resistance is excellent. A summarizing overview of the physical properties, chemical resistance and application engineering of this group of materials is given in [179, 180].

Polytetrafluoroethylene (PTFE)

PTFE has no thermoplastic properties and must therefore be processed by means of pressure sintering, powder extrusion and paste extrusion. It decomposes above 573 K (400 °C); its service temperature lies between 73 and 523 K (–200 and +250 °C). Close to the upper limiting temperatures, the formation of traces of hydrogen fluoride may cause problems with fluoride-sensitive materials if they are in contact with PTFE. For example, PTFE seals in equipment made of titanium promote corrosion on the contact surfaces of this material at high temperatures.

PTFE is resistant to nearly all chemicals. Only a few special media are exceptions to this rule: alkali metal melts, fluorine, chlorine trifluoride. This material has a high resistance to stress cracking [159]. PTFE is susceptible to permeation by gaseous HCl and HF, and this has to be taken into account if the material is exposed to extreme conditions.

The creep strength of PTFE is low ("cold flow"), which must be taken into consideration in apparatus engineering. Its main fields of application are thus linings of vessels and pipelines in which metallic materials act as the mechanical support [181, 182]. Examples for the use of PTFE as a lining material are given in Section D 1 Coatings and linings.

Polyvinylidene fluoride (PVDF)

In contrast to PTFE, this material can be processed thermoplastically and can be welded and adhesively bonded. It can be used as an alternative to PTFE in many cases. Its resistance properties lie between those of PTFE and polyolefins. Its service temperatures lie between 213 and 413 K (– 60 and + 140 °C). It has excellent chemical resistance. Exceptions are some organic solvents (dioxan, acetone, cyclohexanone) and some others only at elevated temperatures (amines, butyl acetate, acetic acid) [157]. PVDF is not resistant to highly concentrated alkalis. The good chemical resistance of PVDF is proved by its use in heat exchangers of flue gas desulfurization plants.

In spite of its good chemical resistance, PVDF can also exhibit stress cracking. This occurred in damaged PVDF linings of transportation tanks for 31 % hydrogen peroxide. These tanks were made of stainless austenitic steel 1.4571 (AISI 316 Ti, X6CrNiMoTi17-12-2) and were used for road transport at temperatures between 313 and 253 K (+ 40 and – 20 °C). Stress cracks were observed in the vicinity of the weld seams of the PVDF sheets. These cracks were attributed to incorrect welding procedures (overheating) when the lining was installed.

High-temperature thermoplastics

Polyphenylene sulfide (PPS)

This material, which can only be processed by injection molding, is becoming increasingly important, particularly in combination with reinforcing fibers of glass or carbon. The thermooxidative and photooxidative resistance as well as the chemical resistance are excellent. The maximum operating temperatures are relatively high: 533 K (260 °C) for short-term exposures and 411 K (138 °C) for long-term exposures or 493 K (220 °C) if fiber-reinforced.

Its chemical resistance is comparable to that of the fluoropolymerisates. It is only attacked by chlorosulfonic acid, concentrated nitric acid and by polar solvents above 453 K (180 °C). It does not exhibit stress cracking.

Styrene polymerisates, polyamides, polyoxymethylenes, polycarbonates and polyurethanes

The chemical resistance of these thermoplastics is limited, i.e. medium to low. They have little importance with respect to the selection of materials for the treatment of industrial waste waters and are therefore not discussed individually here. Resistance data are given in [157, 159, 160].

Duroplasts

Epoxy resins

Cured epoxy resins have a good chemical resistance. Their resistance depends on the type of the curing agent as well as on the type and concentration of fillers. Comprehensive investigations relating to the surface protection of biotowers for waste water treatment are reported in [200]. For a detailed resistance table see [157].

Phenol-formaldehyde resins

The chemical resistance of this group of materials corresponds to that of the epoxy resins. The resistance to aromatic, aliphatic and chlorinated HC is remarkable because it cannot be matched by the thermoplastics, with the exception of the fluorinated polymers. Phenol-formaldehyde resins play an important role in plants used to separate chlorinated hydrocarbon from aqueous media (see Table 58). On the other hand, they should not be exposed to oxidizing acids, bases, esters and ketones. Table 59 gives some data on the resistance of these materials. Reference [157] contains further data.

Medium	Resistance
Acids, not oxidizing	+
Acids, oxidizing	–
Salt solutions	+
Water	+
Bases, not oxidizing	–
Bases, oxidizing	–
Aliphatic hydrocarbons	+
Aromatic hydrocarbons	+
Chlorinated hydrocarbons	+
Alcohols	o
Esters, ketones	o
Oils, fats	+

+ resistant, o limited resistance, – not resistant

Table 59: Chemical resistance of phenol-formaldehyde resins [183]

Furan resins

Furan resins, in contrast to phenol-formaldehyde resins, are more resistant to alkalis and solvents if they have been thermally cured. Comprehensive resistance data are given in [157].

Polyester resins

Glass fiber-reinforced unsaturated polyester resins (UP-GF) are widely used in the construction of waste water treatment facilities. Uses and application engineering are discussed in Section D 3. Some information on failure mechanisms is given below.

The chemical resistance depends on the composition of the polyester resin, the composition and the type of monomer, the composition of the glass, the structure of the laminate (for layers), the ratio between the fractions of resin and glass as well as on the processing. The weak point of the polyester resins is the ester group, which is prone to cleavage by hydrolytic agents. On the other hand, the polar character of the ester group confers good resistance to nonpolar solvents, such as aliphatic hydrocarbons. The so-called chemically resistant UP resin has a significantly better corrosion resistance compared to standard resins and is only attacked by acetone, ethyl acetate, benzene, halogenated HC, nitric acid and sulfuric acid [160]. Further resistance data of UP-GF are given in [157].

The damage is usually caused by diffusion of the medium into the composite along the hydrophilic glass fibers. This diminishes the bonding between the resin and the glass and, in some cases, this leads to chemical degradation of the resin. This is detrimental to the mechanical properties. Therefore, the glass fibers must not protrude freely out of the composite. They must be covered by a chemically resistant layer of resin, a so-called chemical-resistant coating.

The temperature resistance of the composite depends on the resin used. Table 71 contains some data on UP materials. The combination with glass fibers increases the temperature resistance by 10 to 15 K (10 to 15 °C).

Elastomers*Synthetic and natural rubber**Natural and synthetic elastomers*

The resistance of rubber to aggressive media depends on the type of rubber used, on the type and quantity of fillers and on the level of vulcanization.

Rubber from natural rubber, butadiene-styrene rubber, chloroprene rubber, butyl rubber

All rubber grades exhibit good resistance to aqueous acids, bases and salt solutions. They are chemically attacked by oxidizing agents and organic solvents, except for

alcohols. They are widely used as rubber coatings on steel. The hard rubber grades with a closely crosslinked structure and tough vulcanizates based on natural rubber, styrene-butadiene rubber and acrylonitrile-butadiene rubber have a better chemical and thermal resistance compared to the more loosely crosslinked and flexible soft rubber grades [182]. Reference [182] also provides extensive information on their application engineering.

Fibers

Organic fibers are used particularly in wet filtration. Fibrous materials include duroplastic and thermoplastic polymers, e.g. those based on polyamide, polyester, polyethylene and fluoropolymerisates. The temperature and chemical resistance of various types of fibers is given in Table 60. The limits of thermal resistance are relatively high.

Type of fiber	Temperature resistance	Resistance to acids	Resistance to bases	Resistance to organic solvents
Polypropylene	373 K (100 °C)	+	+	soluble in chlorinated hydrocarbons
Polyamide 6 (Perlon®)	393 to 403 K (120 to 130 °C)	–	+	+ except for phenol
Polyamide 6.6 (Nylon®)	403 to 413 K (130 to 140 °C)	–	+	+ except for phenol
Polyester	393 K (120 °C)	+ except for conc. sulfuric acid	o for dilute cold alkaline solutions	+ except for phenol
Polyester PBTP	373 to 393 K (100 to 120 °C)	+	test at higher concentrations	test required
Polyacrylonitrile	413 to 423 K (140 to 150 °C)	+	o for dilute cold alkaline solutions	+
Low pressure polyethylene	353 to 373 K (80 to 100 °C)	+	+	+ at room temperature, swells in chlorinated hydrocarbons
Polyvinylidene fluoride PVDF	383 to 393 K (110 to 120 °C)	+	+	+
Polytetrafluoroethylene PTFE	513 to 533 K (240 to 260 °C)	+	+	+
Cotton	383 to 423 K (110 to 150 °C)	–	o	+ to o

+: resistant, o: limited resistance, –: not resistant

Table 60: Resistance of various fibers used for wet filtration [184]

D

Materials with special properties

D 1 Coatings and linings

Cement mortar coatings are discussed in Section B 4 Binders for building materials (e.g. concrete, mortar).

Reactive resin coatings and linings are also used in waste water engineering for internal protection of plant components made of concrete and steel against attack by aggressive aqueous media.

According to [185], the coatings are subdivided into

- thin coatings with a thickness of up to 1 mm
- thick coatings with a thickness of 1 mm to 5 mm
- fiber-reinforced layers (laminates) with a thickness of 2 mm to 6 mm.

Thin coatings should not be used in vessels with continuous exposure to liquids.

Linings can be made of semifinished products in the form of sheets, panels, and other shapes made of thermoplastics and elastomers. These can be subdivided into

- adhesively bonded, i.e. the lining adheres over its entire surface, thickness 1.5 mm to 5 mm
- mechanically anchored linings, thickness 2.5 mm to 10 mm
- loose linings.

The following standards apply to steel constructions:

- Organic coatings for metallic components, DIN EN 14879-2 [186]
- Coating materials – corrosion protection of steel structures by coating systems –, DIN EN ISO 12944-1 and DIN EN ISO 12944-2 (follow-up documents of DIN 55928-1), DIN EN ISO 12944-3 (replaced DIN 55928-2), DIN EN ISO 12944-8 (replaced DIN 55928-3), DIN EN ISO 12944-4 (replaced DIN 55928-4), DIN EN ISO 12944-5 (replaced DIN 55928-5), DIN EN ISO 12944-7 (replaced DIN 55928-6), DIN EN ISO 12944-7, and DIN EN ISO 12944-8 (replaced DIN 55928-7), DIN 55928-8 and DIN 55928-9 [187]
- Chemical apparatus engineering – coatings and linings made of organic materials. Metallic substrates and semifinished products – requirements for the metal surfaces, DIN 28053 [188]
- Linings made of organic materials, DIN 28055-1 [189]

Of the solvent-free, cold-curing thick coatings used to protect concrete and steel structures, epoxy resins (EP) and vinyl ester resins (VE) should be on the short list. Unsaturated polyester resins as chemically resistant types of binders have been largely supplanted by the even more chemically and thermally resistant vinyl ester resins. Polyurethane (PUR) and polymethacrylate resins (PMMA) are hardly ever used as tank coatings. Blends of EP and PUR resins with coal tar, which is used to make the material more flexible and cheaper, are no longer used for occupational safety reasons (Class 2 carcinogen according to Appendix I of the Hazardous Substances Ordinance). EP/tar and some PUR/tar coating systems were frequently used in the past to protect concrete structures in the waste water sector. For information on the material properties, see [190, 191].

The characteristic material properties of the thermoplastics and duroplasts used in waste water engineering are evaluated in [192, 193].

A list of coating systems based on epoxy resins, including some blended with tar and other resins, that are used for sewers in various countries is given in [194].

Reactive resin coatings used in a large-scale trial in the collecting system of the city of Hamburg did not prove suitable [120, 121]. The reason for the observed blistering and partial detachment are assumed to be osmotic phenomena. Diffusion of water vapor through the coating with subsequent condensation on the rear side of the coating due to the large temperature gradient between the warm and damp inner surface of the pipe and the cold concrete body may also have played a significant role. The factors influencing this effect must be critically evaluated before synthetic resin coatings are used.

A settling tank, made of lined structural steel, and the downstream overflow tank of a biological sewage plant used to treat the waste waters from a paper factory exhibited heavy corrosion after an operating period of four years, even though a highly resistant synthetic resin coating (no further details given) was used. The damage was so extensive that it was decided to construct the new tank and its installed components entirely of high-density polyethylene (PE-HD) and polypropylene (PP) [195].

Practical experience, properties, processing criteria and development trends with epoxy resin systems, in particular, used for surface protection of sewer pipelines made of concrete and asbestos cement is reported in [196]. Some of the information given is no longer quite up-to-date; however, it does point out the correct trend of using the two-component hot-spray process for thick, solvent-free coatings of epoxy resin/amine curing agent systems in waste water treatment plants.

In an extensive test program, corrosion protection systems based on reactive resin coating systems were investigated as coatings (Table 61) and linings (Table 62) in waste water treatment plants [197]. The sample surfaces were directly applied to the steel construction of the reactors in the waste water facilities or were installed as suspended samples of coated steel sheets in particularly endangered zones in the activated sludge and secondary settlement zones. The important pretreatment of the surface of the steel substrate, which is essential for the long-term behavior of the coatings and linings, was included in the investigations for the most important systems. After preliminary investigations, it was decided to pickle the sheets and then

blast them. The surface quality essentially corresponded to Sa 3 (according to DIN EN ISO 12944-4 [187]). Details of the pretreatment procedure and the test method for the influence on the adhesive properties are given in [198].

The test times for the sample fields and suspended samples in the different treatment stages of five waste water treatment plants was between four and six months. After withdrawal of the samples or cleaning of the test fields, changes that had occurred in the corrosion protection system were compared to the initial state. In addition to the registration of visible changes, such as detachments from the substrate and blistering, discolorations as well as the level of rusting underneath the coating, the pull-off strength according to DIN EN ISO 4624 [199] of the coatings and linings was determined along with the change in the surface hardness (Shore A) of rubber coatings. A total of 145 suspended samples and test fields were evaluated.

Results of the investigations in waste water treatment plants

Rubber coatings are particularly at high risk in waste waters containing organic substances. A pronounced reduction of the surface hardness was found in the following order: secondary settlement, aqueous activated sludge phase, crude waste water, organic activated sludge phase. CR rubber coatings, in particular, exhibited serious damage in crude waste waters and in waste waters of the activation stage in the form of detachments from the substrate over large areas and small gas-filled bubbles in the rubber sheets themselves. Five months after the first inspection, the latter had grown to large gas-filled bubbles within the sheet or between the steel surface and the sheet. The coating systems F (EP/tar) and G (here isophthalic acid/polyester resin) were also attacked comparatively rapidly. The tar components from system F and the binder from system G had dissolved to leave a framework of EP resin (system F) or mineral flakes (system G) that no longer exhibited sufficient strength. The values of the measured adhesive strength were correspondingly very low. Of all the corrosion protection systems tested in the field trials, the hot spray-coated epoxy resin system E exhibited the best behavior. The only change it showed was a superficial discoloration; however, this also occurred in all the other systems. There were no signs of attack initiated from the surface. The coating remained glossy and there was no rusting underneath it. The elasticity was sufficient to prevent damage to the coating during the possible deformations of the steel vessels under actual operating conditions. In addition to the reactors made of sheet steel, the above-described EP coating has proven suitable for sewers and tanks made of concrete. Further details on this system with respect to the coating method on concrete surfaces in waste water treatment plants are described in [200]. A reference list for application examples of the system on steel and concrete surfaces used in waste water treatment is given in [201]. Technical material datasheets on the two individual components and their processing guidelines can be obtained from the respective manufacturer [202].

Code letter	Type of system	Thickness, mm	Remarks
A, C, D	epoxy resin, solvent-based, isocyanate curing agent, multilayer, with zinc dust primer	0.33	several versions
E	epoxy resin, solvent-free, amine curing agent, single layer, application by 2K hot spraying, pigment: graphite	1	–
F	epoxy resin/tar mixture, multilayer, no primer. Pigment: Fe ₂ O ₃	0.4 – 0.6	–
G	different types of resin bases, multilayer, filler: mineral flakes	1.2 – 1.5	various manufacturers, polyester, phenol and epoxy resins

Table 61: Coatings evaluated in a field trial in a waste water treatment plant [197]

Code letter	Type of system	Thickness, mm	Remarks
H	chloroprene rubber (CR), self-vulcanizing	4	different mixtures
K, S	chloroprene rubber (CR), self-vulcanizing		comparable with H, different recipe
J, R	butyl rubber (IIR), completely vulcanized		various manufacturers
U	laminate linings based on EP, UP and VE resins, multilayer	2 – 3	various manufacturers and combinations

Table 62: Linings evaluated in field trials in a waste water treatment plant [197]

Table 63 gives an overview of the organic materials used for the linings.

Concrete is an inhomogeneous building material. Owing to its method of manufacture, it has lower strength values on the surface compared to its core. The near-surface layers have a negative effect on the adhesion of an applied coating and must therefore be removed. The best way to do this is by shot peening with granular abrasive media. This removes the cement grout and formwork release agents, opens the pores and hair cracks, and exposes the aggregates. The measured pull-off strength should be at least 1.5 N/mm². This produces a rough surface with a good grip that has to be subsequently leveled with a filling compound. Cement-based filling compounds refined with a thermoplastic dispersion or fine filling compounds, which are generally based on a solvent-free epoxy resin, are particularly suitable for this. Of all the binders that harden well without elevated temperatures, the epoxy resin

Abbreviation	Chemical name	Trade name (not binding)
Thermoplastics		
PVC	polyvinyl chloride	Hostalit [®] , Vestolit [®] , Trovidur [®]
PE	polyethylene	Hostalen [®] , Vestolen [®]
PP	polypropylene	Hostalen [®] PP, Trovidur [®] PP
PA	polyamide	Rilsan [®] A, Grilamid [®]
PVDF	polyvinylidene fluoride	Kynar [®] , Solef [®] , Forafion [®]
FEP	tetrafluoroethylene/hexa-fluoropropylene	Teflon [®] FEP, Neoflon [®] , Hostafion [®] FEP
PTFE	polytetrafluoroethylene	Hostafion [®] , Teflon [®]
E-CFTE	ethylene/chlorotrifluoroethylene	Halar [®]
PFA	perfluoroalkoxy polymers	Teflon [®] PFA, Hostafion [®] PFA
ETFE	ethylene/tetrafluoroethylene	Hostafion [®] ET, Tefzel [®] , Afion [®]
PCTFE	polychlorotrifluoroethylene	Halon [®] , Kel-F [®] , Voltaf [®]
Duroplasts (reinforced or filled)		
UP	unsaturated polyester resins	Alpolit [®] UP, Palatal
EP	epoxy resins	Beckopox, Araldit [®]
FN	furan resins	QuaCorr [®]
PF	phenol-formaldehyde resins	Genakor [®] , Bornumharz, Vetrodur-N, Asplit
PUR	polyurethane resin	Permatex [®]
Elastomers		
IR	polyisoprene	Natsyn [®] , Cariflex [®] IR
SBR	styrene/butadiene rubber	Buna Hüls, Cariflex [®] S
NBR	acrylonitrile-butadiene rubber	Perbunan [®] N, Baypren [®] , Buna
IIR	isobutylene-isoprene rubber	Genakor, butyl rubber
CR	chloroprene rubber	Baypren [®] , Neopren [®]
CSM	chlorosulfonated polyethylene	Hypalon [®] , Baypren [®]
FPM	fluorinated rubber	Viton [®] , Fluorel [®] , Kalrez [®]
SI	silicone rubber	
NR	(natural rubber)	Smoked sheets, First Latex Crepe

Table 63: Linings evaluated in field trials in a waste water treatment plant [161]

systems exhibit the most favorable properties. They have the best adhesion on both steel and on concrete, they also have the lowest tendency of all systems with respect to shrinkage during curing. They can thus be applied as a thick layer in a single application. This only applies to solvent-free EP systems. They are resistant to continuous exposure to a wide range of warm salt solutions, basic media and weak inorganic acids. They are not resistant to continuous exposure to low concentrations of organic acids and high concentrations of mineral acids. The desired properties of the coating can be obtained by formulating the mixtures as a combination of several curing systems and resin types. A disadvantage of the chemically resistant formulations is the generally relatively high viscosity of the mixture that hampers the incorporation of fillers and its processing. Furthermore, adhesion problems may occur if cured coatings have to be recoated.

These problems do not occur with the 2-component hot-spray process in which the two components are heated to 353 K (80 °C) in separate chambers and then applied to a previously primed surface by airless spraying via a mixer unit. The temperature-related reduction of the viscosity allows more viscous components and resin/hardener adducts to be used along with platelet-shaped fillers that act as diffusion barriers. Depending on the viscosity, coatings with a thickness of up to 1.5 mm can be applied in one go. This process has also proven suitable in the waste water treatment sector for coatings on steel as well as on concrete substrates [203].

The concrete/wall transitions in round vessels and additionally the wall/wall transitions in rectangular concrete tanks with cyclic temperature loading should be bridged by a laminate coating because this is where cracks occur in practice. If the temperature of the medium lies above approx. 343 K (70 °C), a steel should be chosen as the construction material, regardless of the heat deflection temperature of the synthetic resin binder [204].

If the material is exposed to very acidic and oxidizing waste waters, preference should be given to vinyl ester resins, and in many cases bisphenol-A polyester resins as well in the form of laminates applied of the entire surface to be coated. A multilayer process is required owing to the relatively high shrinkage tendency during hardening that would lead to cracking of a single-layer coating. Excess styrene is also required. The series of layers that make up the structure of laminates, in the order given below, is described in DIN EN 14879-2 along with the corresponding processing information [205].

- Primer/bond coat, thicker than 50 µm
- Intermediate coat, approx. 1 mm
- Reinforcement layer with one or more layers of a semifinished product, generally consisting of glass fibers, with a thickness between 1.5 mm and 4 mm
- Top layer with a thickness of 0.2 mm to 2 mm
- Sealing layer with a thickness of 0.2 mm to 0.4 mm

The glass fiber inlays are used to bridge any cracks up to approx. 0.2 mm in the underlying concrete structures. Laminate-coated steel vessels can absorb deformation forces without cracking better than coatings without fibers.

Coating systems that contain thin, disk-shaped glass flakes are used to protect concrete and steel vessels in waste water treatment plants [206]. Flakeline® 232, a

mineral flake-filled vinyl ester resin coating, was used to line steel collecting tanks for industrial waste waters of differing compositions in a large chemical plant. It was applied by airless spraying [207].

Reference [208] reports on the increased use of internally coated cast iron pipes with polyurethane (PUR) in waste water applications. The thickness of the lining is between 1.2 mm and 1.5 mm. It is applied to the pipes by centrifugal coating. The advantages of this material are its chemical resistance, its resistance to bacterial infestation, its wear resistance and its smooth surface. The latter property ensures good hydraulic conditions and also prevents the formation of incrustations. Cast iron shut-off valves powder-coated with Nylon® have proven resistant to the action of abrasive solids [209].

Pipes made of ductile cast iron or cast iron with spheroidal graphite have also been used for a long time for the disposal of industrial waste waters. They are standardized up to a diameter of 2000 mm (ND 2000). In this sector, the pipes are usually lined with a coating of cement mortar. The concrete mortar coating is resistant to waste waters with a pH value between 5.5 and 12, or to $\text{pH} \geq 4.5$ for short-term exposure. The standard external protection of the pipes is a sprayed zinc coating of at least 130 g/m^2 . A bitumen-based coating approximately $70 \text{ }\mu\text{m}$ thick is applied on top of this. The combination of cast skin, zinc layer and bituminous layer is more effective than the sum of the individual effects. It offers protection against aggressive soils with a code number of approximately -10 according to the DVGW Worksheet GW 9 [62].

In a comparative investigation of cement mortar coatings made of four different cement grades under practical conditions in sewers, the best behavior was exhibited by high-alumina cement (for details, see [127]).

The good corrosion protective effect of cement mortar coatings on cast iron pipes is based on the following processes: The fresh coating has a pore volume of 10 % – 12 % and is thus not impermeable. In addition, the adhesion is low. The first time the material comes into contact with water, the water penetrates up to the cast iron wall of the pipe where it reacts with the hardened cement paste to form calcium hydroxide with the pipe wall to form iron hydrates that are then incorporated into the mortar layer. This increases the adhesion to the surface of the cast iron on the one hand and on the other, it clogs the pores in the concrete thus making it impermeable to water. At the same time, oxygen can no longer diffuse into the material so that the initial corrosive attack is also completely prevented. In practice, correctly processed mortar linings made of sulfate-resistant cements (e.g. trass cement) in cast iron sewers can withstand continuous exposure to industrial waste waters containing $3000 \text{ mg SO}_4^{2-}/\text{l}$ without damage [126].

Ductile cast iron sewers coated with PE filled with quartz sand proved suitable in the USA. Therefore, several kilometers of pipes with quartz-filled PE have been laid as trial sections in North Rhine-Westphalia since the mid-1980s. At the time of publication, checks of the system showed good results [210].

To test the wear resistance of sewer linings according to DIN EN 295-3 [211], a defined quantity of gravel and water are filled into a pipe that has been cut in half lengthways and then fitted to a tilting device that rocks it back and forth. Of course,

this test does not allow any direct conclusions to be drawn on the individual wear loading in practice; however, within certain limits, it can be used as a comparative method to test the wear behavior of different types of coating materials. Figure 16 shows the results for different pipe materials and lining materials.

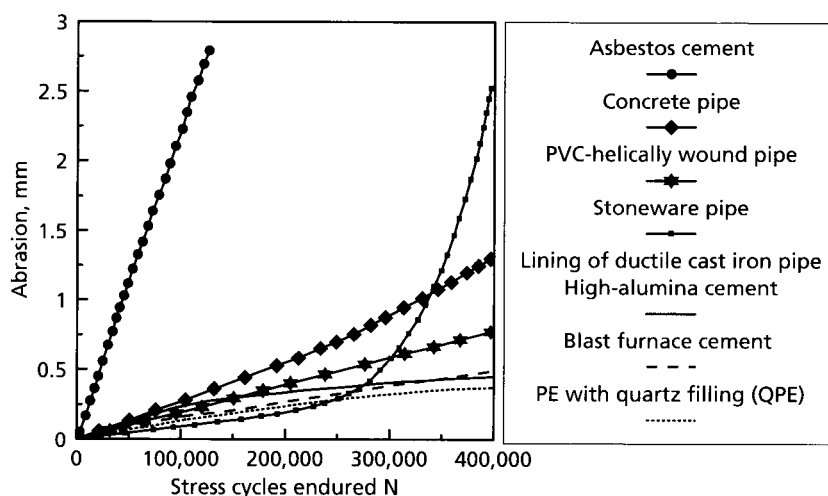


Figure 16: Wear values according to DIN EN 295-3 [211] of asbestos cement, concrete, PVC-rising pipes, stoneware pipes and ductile cast iron pipes with coatings made of high-alumina cement (TSZ), blast furnace cement (HOZ) and quartz-filled PE (QPE) [210]

The best results were obtained with the coated, ductile cast iron pipes, the worst results were obtained for the pipes made of asbestos cement and stoneware.

A cement/polymer mixture has been proposed as a coating material for sewer pipes to protect them against aggressive industrial waste waters [212] (Table 64). This mortar mixture should be less expensive than one based on high-alumina cement. It offers good corrosion protection against waste waters that contain mineral oil products and salts.

Components	Mass%
Portland cement M 400	29.93 %
Sand	65.79 %
Gypsum hemihydrate	0.44 %
Aluminium sulfate	0.55 %
Furfuryl alcohol	2.19 % or 25 % of the mixing water
Aniline hydrochloride	0.33 % or 15 % of the weight of furfuryl alcohol
Water	8.77 %

Table 64: Cement/polymer-mixture to coat concrete-sewer pipes [212]

This mortar mixture should be less expensive than one based on high-alumina cement. It offers good corrosion protection against waste waters that contain mineral oil products and salts [212].

The most commonly used method of coating steel parts with a metal layer is hot-dip galvanizing. For this, the steel part is given a suitable surface treatment and is then dipped into a zinc melt. A zinc-iron alloy is formed first and a zinc layer then grows on top. This produces a uniform, poreless and firmly adhering corrosion protection coating. The good corrosion behavior of zinc coatings is essentially determined by the dense and firmly adhering top layers produced in air. The thickness of the zinc coating is

- 50 μm to 150 μm for individually galvanized parts
- more than 60 μm for galvanized pipes
- 10 μm to 70 μm for strip galvanizing

Examples for the use of hot-dip galvanized components for waste water engineering are described in [213, 214].

For the use of galvanized steel parts in sewage treatment plants, a differentiation is made between the above-water zone and the zone in contact with the waste water. Much positive long-term experience has been made with galvanized components in the above-water zone, e.g. for brackets, supports, handrails, etc. An additional coating of the zinc layer is recommended (the so-called duplex process) [215]. An assessment of the corrosion protection effect in the zone in contact with the water is primarily based on the understanding of the chemical and physical criteria of the waste water and the type of processing during treatment. The following limiting values of the waste water must be observed for the use of hot-dip galvanized components without a coating:

- pH value 6.5 to 9.0 (temporarily 6.0 to 9.5).
- Chloride ion concentrations up to 300 mg/l (temporarily up to 1000 mg/l)
- The effects of other neutral salts are regarded as secondary; the electrical conductivity should not exceed 100 mS/cm.
- Maximum copper ion concentration of 0.064 mg/l. If the Cu concentration in the water exceeds this value, there is a risk of copper-induced corrosion

One of the mechanically anchored types of linings (see DIN 28052-4 [216]) for concrete basins, sewers, manholes, etc. is a frequently used process that has proven suitable in the waste water sector: thermoplastic sheets with anchoring elements attached to the rear side in the form of studs or webs are used as lost formwork. When the concrete is cast, this produces a fixed attachment at specific points between the liner and the concrete structure. The sheets and shaped pieces are mostly made of PE-HD and PP as well as PVC-U and PVDF. They are commercially available from several manufacturers in different dimensions [217–221], see also [38].

The chemical resistance properties of the grades of thermoplastics used for this provide a long-lasting corrosion protection of concrete structures for every type of application case in the waste water zone (see also Section C and Table 71, [268]).

In contrast to a lining that is adhesively bonded to the entire surface of the substrate, the advantage of this lining method is that the ingress of water from the concrete side does not cause any damage. Even a groundwater pressure equivalent to a water column of approx. 6 m does not have a negative effect [217]. It can also be used for relaying sewers with a thermoplastic lining that has been concreted in or for sewer remediation using the relining method.

For the reliable sealing of landfills to protect the groundwater from leachates containing pollutants, large sheets with a thickness of 2 mm to 4 mm made of medium-density polyethylene (PE-MD) are used in order to obtain the necessary flexibility (Figure 17). Further properties required for this type of application are the lowest possible permeation values for the pollutants present in the landfills as well as resistance to microorganisms and gnawing rodents. These membranes are used to cover contaminated sites as well as for the bottom liner of new landfills [222–226].

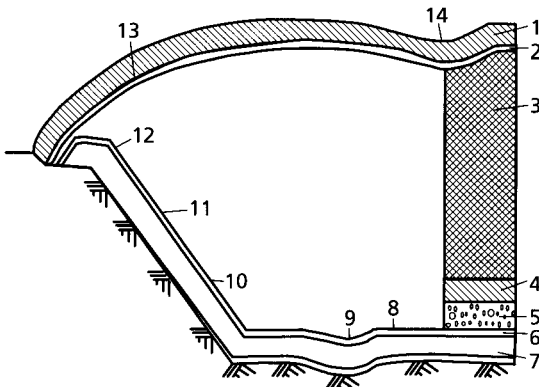


Figure 17: Layout of landfills and mechanical loading of landfill sealing membranes [222]

1: Cover, 2: Sealing liner of PE, 3: Waste, 4: Protective layer, 5: Drainage layer, 6: Base liner of PE, 7: Supporting layer, 8: Compression load and point loads, 9: Tensile stresses due to a settlement basin, 10: Shear stresses due to waste decomposition, 11: Tensile stresses due to temperature changes, 12: Tensile stresses due to dead weight, 13: Shear stresses due to water flowing downhill, 14: Tensile stresses due to a settlement basin

The leachates formed in the landfill must be collected by the sealing membranes and fed through drainage pipelines to shafts. They must then be treated in waste water facilities. PE-HD is suitable for the membranes, pipes and shafts [227]. The chemical resistance of PE-HD and PE-MD in this field can be divided into four groups:

- 1. Aqueous solutions of strongly oxidizing substances (e.g. nitric acid > 25 %; sulfuric acid > 80 %, sodium hypochlorite). These substances do not usually occur in landfill leachates. PE is not resistant to this group of media.
- 2. Aqueous solutions of non-oxidizing acids, bases, salts

- 3. Aqueous solutions of wetting agents (e.g. detergents)
- 4. Organic substances that can swell (degradation products from the waste, hydrocarbons from special and industrial waste, landfill gases)

The effect of these substances on the short-term properties of PE (yield stress, ultimate elongation, impact toughness) and on the creep strength is shown in Figure 18 [222, 228]. Quantitative values for the lowering of the resistance under simultaneous exposure to chemicals and mechanical loading are given as resistance factors. These are dependent on the temperature and the medium. They are given e.g. in [169, 170, 173].

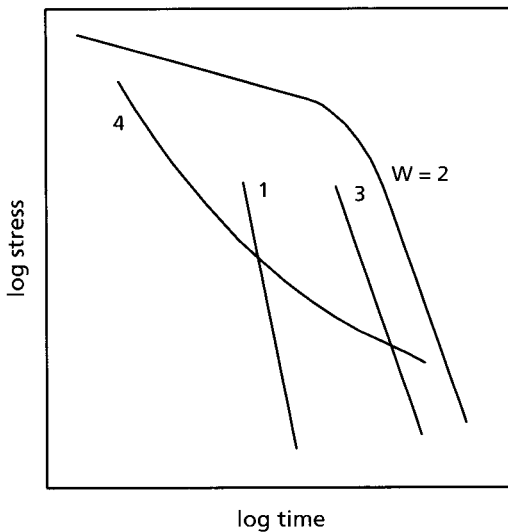


Figure 18: Creep curves of PE-HD-pipes exposed to chemical substances [228]

W: Water, 1 – 4: Groups of chemical substances

Group 1: Aqueous solutions of strongly oxidizing substances (e.g. nitric acid > 25 %; sulfuric acid > 80 %, sodium hypochlorite)

Group 2: Aqueous solutions of non-oxidizing acids, bases, salts

Group 3: Aqueous solutions of wetting agents (e.g. detergents)

Group 4: Organic substances that can swell (degradation products from the waste, hydrocarbons from special and industrial waste, landfill gases)

The oxidative damage of the material by substances of Group 1 leads to a reduction of the ultimate elongation and the impact toughness (curve 1), which would make PE-HD unsuitable for this (long-term) application. PE is resistant to most of the substances in Group 2. The creep curve is the same as that for water (curve 2). The substances of Group 3 do not change the short-term properties. For longer exposure times, the creep curve drops a little earlier, approximately parallel to the water curve. Some of the substances in Group 4 cause different degrees of swelling, whereas others have an insignificant swelling effect. Swelling lowers the yield stress (curve 4). Organic substances that cause swelling are only produced in low quanti-

ties in landfills for domestic waste. In contrast, landfills for special wastes and industrial wastes may produce large quantities of such materials, e.g. hydrocarbons.

Sheets of rubber and thermoplastics adhesively bonded over the entire surface of the concrete or steel substrate with a thickness of 3 mm to 4 mm have been used for many years in the waste water sector for linings of basins, e.g. for neutralization and detoxification of waste waters or for rinsing baths in electroplating [192, 193]. Sheet thicknesses less than 2 mm or greater than 5 mm are only used in special cases. The currently favored polymers for linings are [229]:

- NR: Natural rubber, polyisoprene
- IR: Synthetic polyisoprene
- SBR: Styrene-butadiene copolymer
- NBR: Butadiene-acrylonitrile copolymer
- IIR: Isobutylene-isoprene copolymer
- CR: Polychlorobutadiene
- CSM: Chlorosulfonated polyethylene

If a stronger mechanical loading is expected, for example during scraping of the sludge deposits, additional acid-resistant tiles made of suitable synthetic resin grouts are laid on top of the adhesively bonded sheets. Types of rubber linings for steel basins are usually hard and soft rubber grades that are vulcanized in autoclaves. They are based on crosslinked natural rubber mixtures (NR and NR/SBR, IIR/PVC). Self-vulcanizing grades are rarely used. In concrete tanks, of course, only cold-processable, i.e. self-vulcanizing or prevulcanized or completely vulcanized grades are used. They are based on chloroprene (CR), butyl or halogenated butyl (IIR, CIIR, BIIR), chlorosulfonated PE (CSM) and butyl/PVC (IIR/PVC) two-layer sheets. They are known as on-site rubber linings or field linings. Detailed resistance lists depending on the service temperature for the various types of rubber linings are given in [230–233].

The described types of rubber linings are fully chemically resistant in the waste water treatment tanks in the acidic and the alkaline ranges at temperatures between approx. 333 and 373 K (60 and 100 °C). However, special grades should be used in strongly oxidizing, acidic solutions (containing nitric and chromic acid) and in oxidizing, alkaline solutions (containing hypochlorites). For example, Vulkodurit® WBC (IIR/PVC) is a soft rubber grade for steel tanks that is vulcanized in an autoclave. It is resistant to chromic acid rinsing baths up to approx. 5 % H_2CrO_4 at 353 K (80 °C) and in 50 % chromic acid at 333 K (60 °C). It is also resistant to chlorine bleaching solutions as well as solutions containing HNO_3/HF that are used as pickling baths for stainless steels at temperatures up to approx. 353 K (80 °C) [230]. If the waste waters contain dissolved or emulsified oils (e.g. fuel oil) or other hydrocarbons (e.g. gasoline, benzene), a lining based on nitrile rubber (NBR) is advisable. All other types of rubber linings exhibit differing degrees of swelling in this type of waste water. In this respect, attention must also be paid to the behavior of CR and IIR soft rubber grades in waste water treatment plants if they are in contact with organic substances in the crude waste water and in the activated sludge tank [197].

Thermoplastic liners that can be processed on the building site or in the workshop are usually based on polyisobutylene (PIB) and more rarely on soft PVC (PVC-P). Liners based on PIB (acid-resistant membrane Rhepanol® O.R.G.) have been used successfully in acid-resistant engineering for many years. They have very good resistance, particularly to mineral acids (H_2SO_4 , HCl , HNO_3), up to high concentrations. They are not suitable if they are in contact with oils as well as aliphatic and aromatic hydrocarbons. This material was resistant in simulated waste waters containing benzene 0.6 g/l, toluene 0.5 g/l, xylene 0.2 g/l, i.e. a total of 1.3 g/l of aromatic contaminants; however, it was not resistant in a simulated waste water containing chloroform 9.3 g/l, methylene chloride 17.0 g/l, 1,1,1-trichloroethane 1.3 g/l and trichloroethylene 1.1 g/l [234].

Liners made of soft PVC (PVC-P) are resistant to chromic acid solutions of up to 40% at 338 K (65 °C) and to oily waters; however, they are not resistant in contact with aromatic or aliphatic solvents [235].

Description and reasons for various cases of damage:

The PTFE lining of a steel pipe bend exhibited condensate-filled blisters after two years of exposure to acidic waste waters containing organic components at temperatures between 403 and 453 K (130 and 180 °C). The pipe was not thermally insulated. The reason for the blistering was attributed to the diffusion of water vapor through the PTFE followed by condensation between the temperature dropped below the dew point [236].

A GRP vessel with a lining made of polyvinylidene fluoride (PVDF) had been used as a waste water reservoir for a column sump. The bonding between the GRP vessel and the PVDF lining was to be effected by a textile on the rear surface of the PVDF panel. Stress cracking appeared at various places in the PVDF and there were localized detachments of the textile from the PVDF panel. This detachment was attributed to differing thermal coefficients of expansion between the lining and the vessel, made of composite, at elevated temperatures, and the formation of stress cracks by the stresses resulting from deformations of the PVDF panel in conjunction with the action of hypochlorite. It is recommended that parts exposed to the action of such chemicals should be given a heat treatment after forming and welding [237].

Linings of PVC and synthetic elastomers (CR, IIR) did not prove suitable in the crude waste water of a dye production plant. This applies to the liquid phases as well as to the vapor phase above the level of the water. The pH value fluctuated between pH 1 and pH 13. The COD value (Chemical Oxygen Demand) was 2.2 g/l [238].

Remediation techniques for damaged sewers are classified into open methods using trenches and trenchless techniques. Methods have been specially developed for trenchless relining of sewers that do not have accessible interiors. Reference [239] gives a compilation of the current standard trenchless relining methods, including the coating methods. These methods are divided into pipe relining, hose relining and coating processes. A good example of a pipe lining process is the TROLINING® system [221]. A studded liner made of PE-HD is cut to fit the pipe. This liner is pulled into the sewer under repair and then pressed against the sewer wall. The space between sewer wall and the PE-HD liner formed by the studs is filled with a

special injection grout without an applied pressure. This grout has a high setting. Relining with prefabricated pipes is usually carried out using the pipe-jacking method. Fiber cement pipes for pipe-jacking installation of sewers with inaccessible interiors (microtunneling) are suitable for sewer lines with a small diameter [240].

The hose relining process uses a fiberglass textile or synthetic fiber nonwoven as a flexible hose that is made to fit the dimensions of the pipe section to be repaired (Figure 19). The fiber hose is impregnated with a suitable resin/hardener mixture that is resistant to the expected waste water after hardening. The impregnated hose is attached with an airtight joint to an auxiliary pipe which is then pressed into the defect sewer via a shaft by means of compressed air. This turns the hose inside out. The hose impregnated with the synthetic resin/hardener mixture is thus pressed against the sewer wall and is hardened by superheated steam or by UV irradiation. Synthetic resins used for this are primarily unsaturated polyester (UP) and epoxy resins (EP) [241, 242]. Comparative experiments for types of resins that are suitable for this process based on vinyl ester, epoxide and isophthalic acid/polyester showed that the two types of vinyl ester resin Derakane®, flexibilized and unflexibilized, were superior with respect to the tested criteria of the creep modulus and the chemical resistance [243].

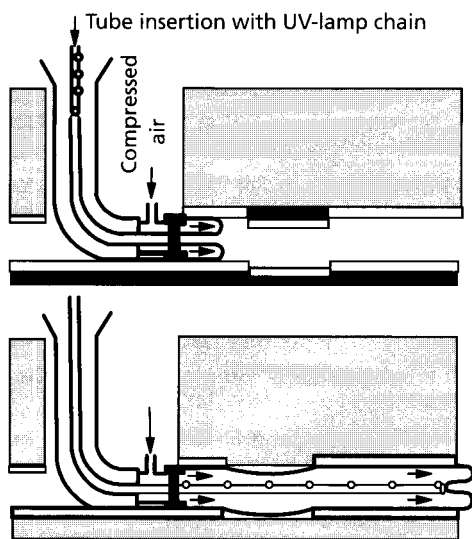


Figure 19: Relining processes using flexible synthetic resin/hardener-impregnated hoses with subsequent UV curing [241]

Plastic linings have proven suitable as corrosion protection in waste waters in which there is a risk of concrete corrosion. These are usually made of the thermoplastic PE-HD (high-density polyethylene). Its chemical resistance is given in Appendix 1 of DIN 8075 [244]. PE-HD is also approved for landfill construction to protect structures, the ground and groundwater from highly aggressive leachates. PVC can be used as an alternative lining material for communal waste waters [141].

D 2 Seals and packings

All materials are suitable for seals and packings as long as they are resistant to the intended chemical and thermal loads and also have the necessary mechanical properties with respect to their sealing function, e.g. sufficient flexibility and compressive creep strength. Possible suitable materials for industrial waste waters include reinforced elastomers and thermoplastics as well as materials based on graphite.

D 3 Composite materials

Composites consist of different materials that are firmly bonded together so that particular useful properties of the individual components can be combined. This bonding can be achieved in different ways. The incorporation of finely divided hard materials into a metallic matrix produces hard materials with a high wear resistance (hard metals). Fiber-reinforced composites consist of a metallic or organic matrix in which wires or fibers made of glass, carbon, plastics or metals are embedded. This usually improves the mechanical properties, such as the tensile strength (e.g. GRP components). Laminated composites are combinations of flat foils, sheets or layers of different metallic, polymeric or inorganic materials. From the point of view of corrosion protection, economic considerations are also important, such as for cladded sheet steel whose exposed surface is made of an expensive alloy or metal.

Enameled steel, which is a composite, is also used in the waste water sector, e.g. in settling tanks, thickeners, flocculation tanks, activated sludge tanks, collecting tanks for landfill leachates, etc. [245]. Enamels consist of a glass matrix, mostly alkali borosilicate, which contains colored inorganic pigments. So-called chemical-resistant enamels are resistant in a wide pH range [246]. In neutral waters, the resistance depends on the type and concentration of the dissolved substance. For example, hydrogen carbonates and phosphates promote corrosion, whereas Al ions inhibit it. Enamels are strongly attacked by acidic waters containing fluorides as well as by strongly alkaline solutions, particularly at elevated temperatures. The usual coating thickness is generally 280 μm to 380 μm . This ensures that the modulus of elasticity of the steel/enamel composite corresponds to the uncoated steel [246].

Pipes, tanks and other apparatus parts made of glass fiber-reinforced duromers (GRP) have been used successfully for many years to convey or store corrosive aqueous media because they combine good chemical resistance with mechanical stability, low weight and economic viability [247–249]. The resin matrix is usually a polyester or vinyl ester resin reinforced with glass fibers, mostly as filament windings. The surface of the component that is in contact with the medium must be a glass-fiber-free resin layer (chemical-resistant coating) because experience has shown that corrosive attack is initiated via the glass fibers. Pipes manufactured by centrifugal coating have an intrinsically uniform, smooth, fiber-free resin surface [250].

Particularly at elevated media temperatures, the thermoplastic liners, most made of PVC-U, PE or PP, in special cases also PVDF, but rarely the significantly more expensive fluorinated thermoplastics (ECTFE, FEP), are used which are firmly

bonded to the GRP body by overlaminating. Owing to their good overall properties, GRP pipes, in particular, are used extensively in waste water engineering [251].

The specific resistance features of the most important thermoplastic liners are given in Table 71 (E Materials recommendations) [268]. The thermoplastic liner/GRP composite also offers the advantage for pipelines of a low susceptibility to wear on account of the smooth inner surface. Reference [252] describes comparative wear measurements using the sand slurry test. The wear resistance of the thermoplastic PP is 35 % better than the antiwear coating of pure vinyl ester resin (Table 65) [252].

The significantly better wear resistances of the thermoplastics are one of the reasons for their successful use in composite pipelines for abrasive loading by flowing liquids containing solid particles, e.g. in flue gas treatment plants.

Material	Wear relative units	
	323 K (50 °C)	343 K (70 °C)
PP	1.0	0.7
UP-GRP	3.2	2.9
VE-GRP	3.1	2.9
VE pure resin	1.6	1.7
VE antiwear coating	—	1.1

Table 65: Wear in the sand-slurry test of PP-liners and substrates [252]

The low thermal conductivity of organic materials means that plastic pipes do not generally require thermal insulation. The greater thermal expansion compared to steel pipes must be taken into account using compensation joints during installation. Reinforcement with glass fibers in the reactive resin layer leads to a considerably reduced thermal expansion compared to the thermoplastics and the nonreinforced duroplasts. The differing expansion between the thermoplastic liner and the GRP substrate leads to axial shear stresses on the boundary surfaces of the composite at elevated temperatures. This can cause detachments in extreme cases. The adhesion in the composite between the textile pressed into the thermoplastic liner and the GRP layer is normally sufficient.

The characteristic properties for the most frequently used resin binders for the GRP substrate are given in Table 66.

Reactive resin	Properties	Price relative units
UP resins		
Phthalic acid/standard glycols	widely used for medium temperature ranges, resistant to acidic media	1.0
Isophthalic acid/neopentyl glycol	good chemical resistance, good adhesion	2.0
Het acid/neopentyl glycol	high chemical resistance, increased heat deflection temperature	2.5
Terephthalic acid/standard glycols	high heat deflection temperature	1.8
Terephthalic acid/neopentyl glycol	high chemical resistance, high heat deflection temperature	1.8
VE resins		
Bisphenol A [®]	very high chemical resistance, high ultimate elongation, increased heat deflection temperature	1.8
Novolak [®]	very high chemical resistance, also towards solvents, high heat deflection temperature	2.3

Table 66: VE and UP-resin systems for laminates [252]

Some application examples for GRP/thermoplastic composite pipes used in the industrial waste water sector are given in Table 67.

In many cases, however, an additional lining with a thermoplastic is not absolutely necessary. If such a decision is to be made, the chemical, thermal and mechanical loads during operation must be clarified and then the suitable type of resin selected. It is advisable to use vinyl ester resins (VE) because they have the best overall properties of all the resin systems under these operating conditions.

GRP pipe systems made of vinyl ester resin Derakane[®] 411-45 have been used successfully without a thermoplastic liner in facilities to treat industrial waste water (Table 68) [253, 254].

Composite	Loading	Pipe diameter, mm
PE-GRP	chemical industry waste water, 323 K (50 °C), 6 bar	250
PE-GRP	chemical industry waste water collecting main	150 – 200
PE-GRP	chemical industry waste water, 323 K (50 °C), 6 bar	50 – 400
PP-GRP	hydrochloric acid 5 %, heavy metal sludge, 343 K (70 °C)	100
PE-GRP	biological waste water, 323 K (50 °C)	50 – 250
PVC-GRP	diverse waste waters (HCl, H ₂ SO ₄ , NaOH), 313 K (40 °C)	25 – 400
PP-GRP	chemical industry waste waters containing HCC, 313 K (40 °C), 6 – 10 bar	50 – 150
PP-GRP	diverse chemical industry waste waters, 313 K (40 °C), 6 – 10 bar	50 – 800
PP-GRP	waste water collecting main for FGD waste waters and other waste waters, 323-343 K (50 – 70 °C), 16 bar	100

Table 67: Application examples for composite pipe systems in the industrial waste water sector [252]

Loading	Dimensions	Location
Waste water from sulfuric acid production containing 5 % H ₂ SO ₄ and 90 g/l Na ₂ SiF ₆ , pressure: 0.15 MPa	D = 600 mm L = 1.3 km	Spain
Acidic mixed waste waters at high ambient temperatures and low flow rates, test pressure: 2 MPa	D = 300 – 600 mm L = 30 km	Abu Dhabi (UAE)
Acidic mixed waste waters at high ambient temperatures and low flow rates	D = 150 – 500 mm L = 15 km	Abu Dhabi (UAE)

Table 68: Resistance of GRP pipe systems without a thermoplastic liner and produced according to the fiber winding process using the acid-resistant glass fiber grade E – CR in industrial waste waters [253, 254].

A GRP tank made of wound glass fibers (diameter 9.1 m, height 7.3 m) was made from several segments in the workshop and assembled on site. It was used for the neutralization of industrial waste waters with a pH range between pH 1 and pH 12. It did not have a thermoplastic lining. The pipeline system consisted of a PE-GRP composite [255].

Ten GRP tanks with a capacity of 113.5 m³, exposed to industrial waste water containing NaOH, were given a chemical-resistant coating based on a non-identified type of resin reinforced with a PETP fiber nonwoven. The generally employed glass fiber nonwoven could not be used owing to the very alkaline medium. The remaining tanks, that were used for acidic waste waters, had a glass fiber nonwoven in the chemical-resistant coating [256].

Shafts to collect leachates from landfills (see Section D 1 Coatings and linings) were also made of GRP filled with quartz sand [257].

Prefabricated GRP sheets made with the VE resin Derakane® 470 were used for the remediation of a heavily corroded concrete collection tank for hot sludge in a large sewage treatment plant. The sheets were mechanically anchored to the damaged concrete surfaces so that the substrate did not need to be pretreated [258].

Prefabricated polymer concrete parts have been used successfully for many years in waste water applications where cement-based concrete is no longer sufficiently resistant. In a sewage treatment plant, damaged channels made of concrete, aluminium grade 57S (EN AW-6063, Al Mg0,7Si) and stainless steel AISI 316 (DIN-Mat. No. 1.4401, X5CrNiMo17-12-2) were replaced by channels made of polymer concrete. Polymer concrete consists of a reactive resin/curing agent mixture and a mineral aggregate filler. This is processed by machines into shaped pieces. UP (unsaturated polyester) is generally used as the resin binder in the waste water sector. The term “polymer concrete” is used because the formal binder phase, cement paste, has been replaced by a synthetic resin [259].

Glass fiber-reinforced thermoplastics exhibit a noticeably better mechanical stability at elevated temperatures than the same grade without reinforcement. Glass fiber-reinforced PP is used as a casing material for chemical dosing pumps employed in waste water treatment [260].

Because of their high heat deflection temperature and chemical resistance (Table 59), particularly to acids and chlorinated hydrocarbons at elevated temperatures, glass fiber-reinforced phenol resin materials (PF) are often the only economically viable solution, e.g. in regenerating plants for waste pickling baths and in plants used to recover chlorinated hydrocarbons from waste water [116]. In the latter plants, the adsorbers containing activated carbon are made of phenol resin composites. They have an external layer of epoxy resin/GRP laminate. The interior of the adsorbers is subjected to frequent temperature changes from room temperature to 403 K (130 °C) and is exposed to water vapor and solvents. The components have a diameter of up to 3 m and a length of up to 4.5 m [261]. Pipelines and the associated shaped pieces for waste water applications that are made of phenol resin materials, have nominal widths between 25 mm and 1000 mm. These parts are produced by kneading phenol resin/formaldehyde filled with short glass fibers until it is homogeneous. This mixture is then cured by polycondensation in pressurized autoclaves at approx. 413 K (140 °C). Pipes containing short fibers mixtures are produced by applying the mixture to a rotating steel mandrel followed by rolling to the required pipe wall thickness. For pipes containing long fibers, a carbon-fiber nonwoven is wound onto a layer of the resin mixture to a defined thickness. This is covered by a layer of wet textile prepreg and finally by a glass roving wound on top of it [261, 183]. The mechanical and thermal properties are given in Table 69 and Table 70.

Properties		Standard	Phenol resin materials	GRP laminates¹⁾
Tensile strength	N/mm ²	DIN EN ISO 527-1, DIN EN ISO 527-2 [262]	15 – 25	100 – 180
Ultimate elongation	%	DIN EN ISO 527-1, DIN EN ISO 527-2 [262]	0.2 – 0.5	2.5 – 3.5
Bending strength	N/mm ²	DIN EN ISO 178/A1 [263]	30 – 50	120 – 200
Tensile modulus of elasticity	N/mm ²	DIN EN ISO 527-1, DIN EN ISO 527-2 [262]	4000 – 8000	8000 – 12000
Bending modulus of elasticity	N/mm ²	DIN EN ISO 178/A1 [263]	4000 – 8000	7000 – 11000
Compressive strength	N/mm ²	DIN EN ISO 604 [264]	100 – 140	130 – 200
Ball indentation hardness	N/mm ²	DIN EN ISO 2039-1 [265]	100 – 170	120 – 170
Impact toughness	kJ/mm ²	DIN EN ISO 179-1/A1 [266]	3.5 – 5	270 – 330
Composite phenol resin material/GRP				
Pull-off strength	N/mm ²	DIN EN 582 [267]	6 – 10	

1) Glass content 35 – 45 mass%; structure: alternative layers of mat and textiles

Table 69: Mechanical properties of short fiber-reinforced phenol resin materials and GRP laminates [261, 183]

Property		Phenol resin materials	GRP laminates¹⁾
Heat deflection temperature under load (Martens)	K (°C)	418-438 K (145-165 °C)	373-398 K (100-125 °C ¹⁾)
Linear coefficient of thermal expansion at 293 K (20 °C)	1/K	15 – 20 × 10 ⁻⁶	20 – 25 × 10 ⁻⁶
Thermal conductivity	W/(m K)	0.4 – 0.5	0.23 – 0.28

1) With respect to the nonreinforced resin

Table 70: Thermal properties of short fiber-reinforced phenol resin materials and GRP laminates [261]

E

Materials recommendations

Warranty Disclaimer

This book has been compiled from literature data with the greatest possible care and attention. The statements made only provide general descriptions and information.

Even for the correct selection of materials and correct processing, corrosive attack cannot be excluded in a corrosion system as it may be caused by previously unknown critical conditions and influencing factors or subsequently modified operating conditions.

No guarantee can be given for the chemical stability of the plant or equipment. Therefore, the given information and recommendations do not include any statements, from which warranty claims can be derived with respect to DECHEMA e. V. or its employees or the authors.

The DECHEMA e. V. is liable to the customer, irrespective of the legal grounds, for intentional or grossly negligent damage caused by their legal representatives or vicarious agents.

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A**Metallic materials****A 2 Aluminium****A 3 Aluminium alloys**

Aluminium materials should be used in areas that only have contact with the atmosphere. The best behavior can be expected from AlMn and AlMgMn alloys. If the materials come into direct contact with the waters, uniform surface corrosion can be expected if the pH value is in the alkaline or acidic ranges. Therefore, damage can also be expected if the materials are in contact with alkaline building materials, such as cement mortar and concrete. There is a risk of pitting and crevice corrosion in neutral waters containing chloride ions. There is also a risk of pitting corrosion in the presence of droplets of condensed water that are enriched by gaseous components of the waste waters.

A 9 Copper-nickel alloys

Of the copper-nickel alloys, the alloys CuNi30Fe1Mn (CW354H, 2.0882) and CuNi10Fe1Mn (CW325H, 2.0872) are virtually resistant to hot salt solutions with high chloride concentrations. Therefore, they are also used for various structural components in waste water evaporator units.

A 14 Unalloyed and low-alloy steels/cast steel

The corrosion rates of these materials in almost neutral waste waters are chiefly determined by the concentration of oxygen and by its transport to the surface of the material. However, in addition to uniform surface attack, which must be taken into account by increasing the wall thickness, there may be increased local attack in the form of shallow pit corrosion and pitting corrosion due to the formation of aeration cells. The use of unalloyed and low-alloy steels as well as cast iron and cast steel is generally not recommended if there are no additional corrosion protection measures, e.g. with coatings, linings or cathodic protection.

In air-saturated deionized water with low ozone concentrations and at room temperature, unalloyed steel exhibits a corrosion rate that is several times higher than that in ozone-free water. This must be taken into account, if appropriate, in waste water treatment processes that use ozone.

A 15 Unalloyed cast iron and low-alloy cast iron**A 16 High-alloy cast iron****A 16.1 Silicon cast iron**

Unalloyed cast iron (gray cast iron) exhibits similar behavior to unalloyed steel in waste water treatment plants. Waste water pumps made of gray cast iron (GG 22, GG 25, 0.6025) have a rough surface that is an ideal substrate for adhesive biofilms that can cause biocorrosion. Biocorrosion cannot be completely excluded on polished cast parts containing spheroidal graphite and silicon as well as on high-alloy CrNiMo cast pumps. The corrosion properties of hard chromium-molybdenum cast iron GX250CrMo15-3 (cf. GX300CrMo15-3, 0.9635) are comparable to those of unalloyed cast iron; however, the former is a superior material for immersion pumps owing to its better resistance to abrasive wear. Ferritic-austenitic CrNiMo cast steel GX3CrNiMoCuN24-6 (cf. DIN-Mat. No. 1.4517) is a superior pump material compared to other cast materials, particularly if the pumped medium is a chemical waste water containing chloride and large quantities of abrasive solids and also has a widely fluctuating pH value.

A 17 Ferritic chromium steels with < 13 % Cr**A 18 Ferritic chromium steels with $\geq$ 13 % Cr****A 19 High-alloy multiphase steels**

Although ferritic chromium steels exposed to chloride-containing waters exhibit good resistance to chloride-induced stress corrosion cracking, they are rarely used owing to the problems associated with their processing. Ferritic-austenitic steels have proven suitable in waste water facilities because of their good resistance to pitting and stress corrosion cracking, even under critical conditions.

A 20 Austenitic CrNi steels**A 21 Austenitic CrNiMo(N) steels****A 22 Austenitic CrNiMoCu(N) steels**

The molybdenum-free austenitic steels are already susceptible to crevice corrosion at chloride concentrations greater than approx. 20 mg/l and to pitting corrosion at concentrations above approx. 200 mg/l. Austenitic steels containing 18 % Cr, 10 – 12 % Ni and 2 – 3 % Mo have proven suitable in waste water treatment plants and are frequently used. They have sufficient resistance to pitting corrosion at moderate temperatures (up to approx. 308 K (35 °C)) in neutral to weakly acidic waters and chloride concentrations up to approx. 1000 mg/l. However, they may already exhibit crevice corrosion at chloride concentrations above 200 mg/l. At higher temperatures, higher chloride concentrations and lower pH values, as in e.g. evaporator units for waste waters from flue gas desulfurization units, sewage sludge drying and for landfill leachates, steels containing high Mo contents must be used. These

include 1.4439 (AISI 317 LMN, X2CrNiMoN17-13-5), 1.4539 (AISI 904 L, X1NiCr-MoCuN25-20-5), 1.4529 (UNS N08926, X1NiCrMoCuN25-20-7) and 1.4562 (UNS N08031, X1NiCrMoCu32-28-7). Nickel-based alloys should be used in strongly acidic solutions and in solutions with a high redox potential.

Stainless steels must be processed and machined correctly so as not to interfere with the homogeneous formation of the protective oxide layer. The surface finish has a significant influence on the corrosion resistance. The greatest resistance is attained with a clean and metallicly bright surface that is also free of cracks and crevice-like phenomena. This is particularly important if the parts are welded. Tarnishing and other surface defects, such as weld splashes and slag residues, undercuts, incomplete welding of the root and pores as well as metal abrasion, deposits and extraneous rust must be carefully removed. Crevices and stresses must also be avoided in the design.

A 27 Nickel-chromium alloys

A 28 Nickel-chromium-iron alloys (without Mo)

A 29 Nickel-chromium-molybdenum alloys

A 30 Nickel-copper alloys

Nickel-based alloys of the Hastelloy® group (alloy C-4, NiMo16Cr16Ti, 2.4610, alloy C-276, NiMo16Cr15W, 2.4819) and Inconel® 625 (NiCr22Mo9Nb, 2.4856) have proven resistant to chloride concentrations of approx. 1000 mg/l and temperatures of approx. 573 K (300 °C) in wet oxidation units for sewage sludge and waste water.

NiCrMo alloys with high molybdenum contents can be used in waste water evaporator units of FGD plants. Their resistance decreases in the following order: 59 (NiCr23Mo16Al, 2.4605), alloy C-22 (NiCr21Mo14W, 2.4602) and alloy C-276 (NiMo16Cr15W, 2.4819).

The nickel-copper Monel® 400 (NiCu 30 Fe, 2.4360) can be used in evaporator/crystallization units for FGD waste waters at 363 K (90 °C) and pH values from pH 8 – 10. It exhibits a corrosion rate of 0.04 mm/a.

A 37 Tantalum, niobium and their alloys

A 38 Titanium and titanium alloys

A 39 Zinc, cadmium and their alloys

Titanium and tantalum are suitable for use in industrial waste waters with high chloride concentrations (only for low fluoride concentrations) at temperatures up to 593 K (320 °C) and pH values > 7. Preference should be given to titanium if the chloride concentration exceeds 1 g/l. This material also exhibits corrosion in strongly acidic ranges as well as in NaOH and KOH solutions.

Zinc is discussed in Section D 1 Coatings and linings.

B**Nonmetallic inorganic materials****B 3 Carbon and graphite**

Parts made of graphite can be used as components of evaporator units, particularly in heat exchangers, for aggressive waste waters from FGD and landfills owing to their excellent resistance and good thermal conductivity.

B 4 Binders for building materials (e.g. concrete, mortar)

Concrete structures are used extensively in waste water treatment, particularly in biological sewage treatment plants, e.g. as collecting and treatment tanks and sewers. Additional surface protection is unnecessary in many cases if the waste water is not very aggressive.

The concrete parts used in the waste water applications must comply with the stipulations given in DIN 1045 with regard to water impermeability, high resistance to chemical attack, and high frost or high frost and de-icing salt resistance. For parts made of reinforced concrete, the thickness of the concrete covering over the steel reinforcement must be sufficiently thick to prevent corrosion of the reinforced steel.

According to DIN 4030-1, a concrete with a high sulfate resistance must be used for waste waters with sulfate concentrations above 400 mg/l SO_4^{2-} . Portland blast furnace cement or blast furnace cement are suitable binders for these concretes.

Problems with biogenic sulfuric acid corrosion can occur in fiber and asbestos cement pipes as well as in cement mortar linings. Sewer pipes made of cast iron and steel are generally protected against corrosion with a cement mortar coating, which is usually a high-alumina cement that is resistant in the pH range between pH 5 and pH 9.

B 5 Acid-resistant building materials and binders (putties)

Because unprotected concrete is subject to chemical, physicochemical or microbiological corrosion in waste water facilities, in certain cases, e.g. in neutralization or detoxification tanks, it may be necessary to use acid-resistant building materials to protect the surfaces. Thick coatings of reactive resins or linings with acid-resistant sheets in synthetic putty beds or acid-resistant membranes are generally used for this. Thin protective coatings have not proven suitable for long-term use. Coatings and linings used in the industrial waste water sector are described under Section D 1 Coatings and linings.

B 6 Glass

In waste water engineering, glass, particularly borosilicate glass is being used increasingly as a material for pipelines and other parts of equipment. These materials are only attacked by waste waters that contain free hydrofluoric acid or have very high pH values.

B 8 Enamel

This group of materials is discussed under D 3 Composites.

B 10 Stoneware

Pipes made of stoneware that are used extensively for sewers are glazed on both sides. Stoneware is resistant to all substances contained in waste waters, with the exception of free hydrofluoric acid. The resulting pipelines exhibit good flow properties owing to the smooth surface.

C**Organic materials/plastics**

The following selection of the most important materials for the individual application areas are given in Table 71 ordered according to the chemical load and maximum permissible operating temperature. The selection of materials is mainly based on the treatment of industrial waste waters that has to be carried out before they are discharged into waste water facilities operated in accordance with the pertaining standards. The standardized materials permitted under normal waste water conditions, PVC-U, PE-HD, PP and UP-GF are also given in Table 71.

The listed maximum permissible operating temperatures refer to thermal-oxidative loads by air. These values can change drastically if the materials are in contact with chemicals. This applies in general to thermoplastics, duroplasts and particularly to firmly bonded thermoplastic linings on steel, which, according to a conservative evaluation should not be exposed to temperatures above 323 K (50 °C) [161].

In summary, it must be stated that the temperature resistance is closely related to the mechanical load and the chemical resistance. The given values are therefore maximum values that may be considerably lower depending on the conditions. Only data from creep rupture tests with exposure to chemicals, such as the internal pressure test of the creep rupture strength give reliable information.

Material	Chemical resistance (positive list)	Temperature limit (continuous operation)
Semifinished products, pipes, vessels, apparatus, pumps		
PE-HD	suitable: aqueous solutions of acids, bases, salts; organic solvents that are miscible with water, fats and oils	333 K (60 °C)
PP	similar behavior to PE-HD	363 K (90 °C)
PVC-U	suitable: aqueous solutions of acids, bases, salts; organic solvents that are miscible with water, fats, oils, gasoline	333 K (60 °C)
PVC-C	as for PVC-U	353 K (80 °C)
PVDF	suitable: aqueous solutions of acids and salts; alcohols, aliphatic and aromatic HC, fats and oils, fuels	413 K (140 °C)
UP-GF	see UP	
Coatings, linings		
NR, SBR, NBR, CR	suitable: aqueous solutions of acids, bases, salts; alcohols	353 K (80 °C)
PF	suitable: aqueous solutions of acids, bases, salts; aliphatic, aromatic, chlorinated HC	depends on the medium; up to 403 K (130 °C)
EP, UP	suitable: aqueous solutions of acids, bases, salts; alcohols	depending on the medium and type of resin; up to 373 K (100 °C)
PVDF, PTFE	can be used for extreme operating conditions	413/523 K (140 °C/250 °C)
Seals		
NBR	suitable: aqueous solutions of acids, bases, salts; oils, gasoline	363 K (90 °C)
EPDM	suitable: aqueous solutions of acids, bases, salts; alcohols, ketones	363 K (90 °C)
FPM, PTFE	can be used with nearly all chemicals	413/523 K (140 °C/250 °C)

Table 71: Organic materials for various applications under chemical and temperature loading [157, 159 – 162, 268]

One of the most important advantages for the use of pipes made of thermoplastics is that they can be connected simply and reliably. PE, PP and PVDF are joined together by heated-tool welding. PVC materials are joined with special PVC-based adhesives. The chemical and thermal properties of the sealing materials are important for detachable connections. These are also given in Table 71.

Detailed information on the application engineering of plastics in apparatus and plant engineering are summarized in [161].

Further information on the materials recommendations for organic materials are given in Sections D 1 and D 3.

D

Materials with special properties

D 1 Coatings and linings

Reactive resin coatings and linings are also used in waste water engineering for internal protection of plant components made of concrete and steel against attack by aggressive aqueous media. Only thick solvent-free coatings with a thickness of 1 – 5 mm or glass fiber-reinforced coatings (laminates) with a coating thickness of 2 – 6 mm are suitable for this. Epoxy resin/hardener systems are nearly always used as the resin binder. Preference should be given to vinyl ester resin/hardener systems if the medium contains strongly oxidizing components. For epoxy resin systems, in particular, there are numerous variants with differing properties, e.g. with respect to their resistance and their flexibility. However, cold-cured epoxy resin coating systems do not generally have long-lasting resistance to organic acids, strong mineral acids, strongly oxidizing acids and alkaline media.

The correct pretreatment of the substrate is essential for the durability of the coatings. This applies to concrete as well as to steel structures. The corresponding standards and guidelines must be observed for this.

Linings based on elastomeric or thermoplastic membranes used for the protection of waste water treatment tanks made of concrete have already been discussed in Section C. Lining materials are generally made of rubber coatings based on chloroprene or butyl rubber, which are resistant to all contaminants in waste water, with the exception of strongly oxidizing substances, organic solvents as well as dissolved and emulsified mineral oils. They are glued to the substrate with special contact adhesives. The thickness of the rubber coatings is usually 2 mm or 3 mm.

Epoxy resin coatings applied by hot spraying have proven suitable in all stages of waste water treatment, both on steel and on concrete substrates.

Base liners and the surface seals of landfills that are used to protect the groundwater from polluted leachates are generally made of medium-density polyethylene (PE-MD) membranes, 2 – 4 mm thick. They have the appropriate properties for this application, such as resistance to the pollutants in the media, to microorganisms, to gnawing rodents and also have low permeation values.

An additional synthetic resin coating is recommended for hot-dip galvanized steel parts installed above the level of the water. The limits to be observed for continuous exposure contact of the materials with the waste water are generally a pH value be-

tween pH 6.5 and pH 9.0 and a chloride ion concentration up to 300 mg/l. The material must also have a sufficient thickness (at least 150 μm).

Information on the resistance behavior of cement mortar coatings on cast iron and steel pipes used for sewers is given in Section B 4.

D 2 Seals and packings

Information on the resistance behavior of elastomers and thermoplastics as well as those based on graphite that are used as seals and packing materials are given in Sections B 3 and C, respectively.

D 3 Composites

Enameled steel, which is a composite, is used extensively in the waste water sector, e.g. for collecting and treatment tanks. The chemical-resistant enamels used here consist of a matrix based on an alkali borosilicate glass that is resistant in a wide pH range. The enamel is strongly attacked by acidic waters containing fluorides as well as by strong alkalis at elevated temperatures.

Pipes and tanks made of glass fiber-reinforced duroplasts have been used for many years in the waste water sector. A glass-free layer of resin is applied to the surface in contact with the medium. The resin matrix is generally made of cold-curing vinyl ester resins and polyester resins with the appropriate curing system. Information on their resistance is given in Sections C and D 1. In the event of elevated media temperatures, the surface that is in contact with the medium is overlaminated with a so-called thermoplastic liner and a resin/hardener mixture. Panels or pipes of PE, PP, PVC-U are generally used for this, or in special cases, fluorothermoplastics, such as PVDF.

Owing to their high heat deflection temperature in conjunction with their high resistance, particularly to strong acids and chlorinated hydrocarbons at temperatures around 403 K (130 °C), glass fiber-reinforced phenol resin materials are frequently used e.g. in regenerating units for waste pickling baths and facilities to recover chlorinated hydrocarbons. They are not resistant to oxidizing acids or to oxidizing and non-oxidizing bases. They have limited resistance to alcohols, esters and ketones.

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BSB Behälter Systembau GmbH, Hamburg
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(Plastics – Determination of compressive properties) (in German)
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(Plastics – Determination of hardness – Part 1: Ball indentation method) (in German)
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(Plastics – Determination of Charpy impact properties – Part 1: Non-instrumented impact test) (in German)
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zugfestigkeit
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adhesive strength) (in German)
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Georg Fischer AG, Schaffhausen

Key to materials compositions

Table 1: Chemical compositions of alloys according to German and other standards

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
0.6015	EN-JL1020	–	A 48 (25B)
0.6025	EN-JL1040	–	A 48 (40B)
0.6655	GGL-NiCuCr 15 6 2	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-13.5-17.5Ni-1.0-2.5Cr-5.5-7.5Cu	A 436 Type 1
0.6656	GGL-NiCuCr 15 6 3	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-13.5-17.5Ni-2.5-3.5Cr-5.5-7.5Cu	A 436 Type 1b
0.6660	GGL-NiCr 20 2	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-18.0-22.0Ni-1.0-2.5Cr	A 436 Type 2
0.6661	GGL-NiCr 20 3	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-18.0-22.0Ni-2.5-3.5Cr	A 436 Type 2b
0.6667	GGL-NiSiCr 20 5 3	Fe-≤2.5C-3.5-5.5Si-0.5-1.5Mn-1.5-4.5Cr-18.0-22.0Ni	
0.6676	GGL-NiCr 30 3	Fe-max. 2.5C-1.0-2.8Si-0.5-0.8Mn-2.5-3.5Cr-28.0-32.0Ni	A 436 Type 3
0.6680	GGL-NiSiCr 30 5 5	Fe-≤2.5C-5.0-6.0Si-0.5-1.5Mn-4.5-5.5Cr-29.0-32.0Ni	A 436 Type 4
0.7040	EN-JS1030	–	A 536 (60-40-18)
0.7660	EN-GJSA-XNiCr20-2	Fe-≤3.0C-1.5-3.0Si-0.5-1.5Mn-≤0.080P-1.0-3.5Cr-≤0.50Cu-18.0-22.0Ni	A 439 Type D-2
0.7661	GGG-NiCr 20 3	Fe-≤3.0C-1.5-3.0Si-0.5-1.5Mn-≤0.080P-2.5-3.5Cr-18.0-22.0Ni	A 439 Type D-2B
0.7665	GGG-NiSiCr 20 5 2	Fe-≤3.0C-4.5-5.5Si-0.5-1.5Mn-≤0.080P-1.0-2.5Cr-18.0-22.0Ni	A 439 Type D-2C
0.7670	EN-GJSA-XNi22	Fe-≤3.0C-1.0-3.0Si-1.5-2.5Mn-≤0.080P-≤0.5Cr-≤0.5Cu-21.0-24.0Ni	A 439 Type D-2C
0.7680	EN-GJSA-XNiSiCr30-5-5	Fe-≤2.6C-5.0-6.0Si-0.5-1.5Mn-≤0.080P-4.5-5.5Cr-≤0.5Cu-28.0-32.0Ni	A 439 Type D-4

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
0.9625	EN-GJN-HV550	Fe-≤3.0-3.6C-≤0.080Si-≤0.080Mn-≤0.1P-≤0.1S-1.5-3.0Cr-≤0.5Mo-3.0-5.5Ni	A 532 (1A NiCr-HC)
0.9635	EN-JN3029	Fe-max. 1.8-2.4C-1.0Si-0.5-1.5Mn-0.08P-0.08S-14.0-18.0Cr-3.0Mo-2.0Ni	A 532
0.9640	EN-GJN-HV600(XCr14)	Fe-≤1.8-2.4C-≤1.0Si-≤0.5-1.5Mn-≤0.080P-≤0.080S-14.0-18.0Cr-≤3.0Mo-≤2.0Ni	A 532
0.9650	EN-JN3049	Fe-max. 2.4-3.2C-1.0Si-0.5-1.5Mn-0.08P-0.08S-23.0-28.0Cr-3.0Mo-2.0Ni	A 532
1.0037	St 37-2; S235JR	Fe-≤0.17C-≤0.3Si-≤1.4Mn-≤0.045P-≤0.045S-≤0.009N	A 283; SAE 1015
1.0038	RSt 37-2	Fe-≤0.17C-≤1.4Mn-≤0.045P-≤0.045S-≤0.009N	UNS K02502
1.0040	USt 42-2	Fe-≤0.25C-≤0.2-0.5Mn-≤0.05P-≤0.05S-≤0.007N	
1.0050	E295; St 50-2	Fe-≤0.045P-≤0.045S-≤0.009N	
1.0116	S235J2G3	Fe-max. 0.17C-1.4Mn-0.035P-0.035S	UNS K02001
1.0204	UQSt 36	Fe-≤0.14C-≤0.25-0.50Mn-≤0.040P-0.040S	SAE 1008
1.0254	P235TR1	Fe-max. 0.16C-0.35Si-1.2Mn-0.025P-0.020S-0.30Cr-0.30Cu-0.08Mo-0.010Nb-0.30Ni-0.04Ti-0.02V	UNS K02501
1.0256	St 44.0	Fe-≤0.21C-≤0.55Si-≤1.60Mn-≤0.040P-≤0.040S-≤0.009N	A 106
1.0301	C10	Fe-≤0.07-0.13C-≤0.4Si-≤0.3-0.6Mn-≤0.045P-≤0.045S	AISI 1010
1.0305	St 35.8	Fe-≤0.17C-≤0.10-0.35Si-≤0.40-0.80Mn-≤0.040P-≤0.040S	UNS K01200
1.0308	St 35	Fe-≤0.17C-≤0.35Si-0.4Mn-≤0.05P-≤0.05S-≤0.007N	SAE 1010
1.0309	DX55D	Fe-≤0.16C-0.17-0.40Si-0.35-0.65Mn-≤0.05P-≤0.050S-≤0.30Cr-≤0.30Ni-≤0.30Cu	UNS K02501
1.0330	St 2; St 12	Fe-≤0.12C-≤0.60Mn-≤0.045P-≤0.045S	A 366 (C)
1.0333	USt 3; USt 13	Fe-≤0.08C-≤0.007N	
1.0336	USt 4	Fe-≤0.09C-≤0.25-0.50Mn-≤0.030P-≤0.030S-≤0.007N	
1.0345	P235GH; H I	Fe-≤0.16C-≤0.35Si-≤0.40-1.20Mn-≤0.030P-≤0.025S-0.02Al-≤0.30Cr-≤0.30Cu-≤0.08Mo-≤0.010Nb-≤0.30Ni-≤0.03Ti-≤0.02V	A 285; A 414
1.0375	TH57; T 57	Fe-≤0.1C-Traces Si-0.25-0.45Mn-≤0.04P-≤0.04S-0.007N	
1.3964	X2CrNiMnMoNNb21-16-5-3	Fe-max. 0.03C-1.0Si-4.0-6.0Mn-0.025P-0.010S-20.0-21.5Cr-3.0-3.5Mo-0.2-0.35N-0.25Nb-15.0-17.0Ni	NITRONIC 50 (Spec)

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.0401	C 15	Fe-≤0.12-0.18C-≤0.40Si-≤0.3-0.6Mn-≤0.045P-≤0.045S	SAE 1015
1.0402	C 22	Fe-≤0.17-0.24C-≤0.4Si-≤0.4-0.7Mn-≤0.045P-≤0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1020
1.0405	St 45.8	Fe-≤0.21C-≤0.10-0.35Si-≤0.40-1.20Mn-≤0.040P-≤0.040S	A 106
1.0408	St 45	Fe-≤0.25C-≤0.035Si-0.40Mn-≤0.050P-≤0.050S	A 108; SAE 1020
1.0414	C20D; D 20-2	Fe-≤0.18-0.23C-≤0.30Si-≤0.3-0.6Mn-≤0.035P-≤0.035S-≤0.01Al-≤0.2Cr-≤0.3Cu-≤0.05Mo-≤0.25Ni	UNS G10200; SAE 1020
1.0425	P265GH; H II	Fe-≤0.20C-≤0.4Si-≤0.5-1.4Mn-≤0.030P-≤0.025S-0.02Al-≤0.3Cr-≤0.3Cu-≤0.08Mo-≤0.01Nb-≤0.3Ni-≤0.03Ti-≤0.02V	UNS K01701
1.0426	P280GH	Fe-≤0.08-0.20C-≤0.4Si-≤0.9-1.5Mn-≤0.025P-≤0.015S-≤0.30Cr	A 662 (A)
1.0473	P355GH	Fe-≤0.1-0.22C-≤0.6Si-≤1.0-1.7Mn-≤0.03P-≤0.025S-≤0.30Cr-≤0.3Cu-≤0.08Mo-≤0.3Ni	A 299
1.0481	17 Mn 4	Fe-≤0.08-0.20C-≤0.4Si-≤0.90-1.50Mn-≤0.030P-≤0.025S-0.02Al-≤0.30Cr-≤0.30Cu-≤0.08Mo-≤0.010Nb-≤0.3Ni-≤0.03Ti-≤0.02V	A 414, 515
1.0501	C 35	Fe-≤0.32-0.39C-≤0.4Si-≤0.5-0.8Mn-≤0.045P-≤0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1035
1.0503	C 45	Fe-≤0.42-0.50C-≤0.4Si-≤0.5-0.8Mn-≤0.045P-≤0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	AISI 1045
1.0505	StE 315	Fe-≤0.18C-≤0.45Si-≤0.70-1.50Mn-≤0.035P-≤0.030S-≤0.30Cr-0.020Al-≤0.20Cu-≤0.020N-≤0.03Nb-≤0.08Mo-0.30Ni	A 573
1.0528	C 30	Fe-≤0.27-0.34C-≤0.4Si-≤0.5-0.8Mn-≤0.045P-0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1030
1.0545	S355N	Fe-≤0.20C-≤0.50Si-≤0.90-1.65Mn-≤0.035P-0.030S-0.02Al-≤0.30Cr-≤0.35Cu-≤0.10Mo-≤0.015N-≤0.050Nb-≤0.50Ni-≤0.03Ti-≤0.12V	UNS K12709
1.0562	StE 355	Fe-≤0.20C-≤0.50Si-≤0.90-1.70Mn-≤0.03P-≤0.025S-0.02Al-≤0.30Cu-≤0.30Cr-≤0.08Mo-≤0.02N-≤0.05Nb-≤0.50Ni-0.03Ti	A 633 (C)
1.0564	N-80	Fe-≤0.030P-≤0.030S	—
1.0570	St 52-3	Fe-≤0.20C-≤0.55Si-≤1.60Mn-≤0.035P-≤0.035S	SAE 1024
1.0605	C 75	Fe-≤0.7-0.8C-≤0.15-0.35Si-≤0.6-0.8Mn-≤0.045P-≤0.045S	SAE 1074

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.0616	C86D	Fe-≤0.83-0.88C-≤0.10-0.30Si- ≤0.50-0.80Mn-≤0.035P-≤0.035S-≤0.01Al- ≤0.15Cr-≤0.25Cu-≤0.05Mo-≤0.20Ni	SAE 1086
1.0619	GP240GH	Fe-≤0.18-0.23C-≤0.60Si-≤0.50-1.20Mn- ≤0.03P-≤0.02S	A 216
1.0670	P-105	Fe-≤0.70C-≤0.03-0.30Si-1.0Mn-≤0.04P- ≤0.04S-≤0.007N	—
1.0912	46Mn7	Fe-≤0.42-0.50C-≤0.15-0.35Si-≤1.6-1.9Mn- ≤0.05P-≤0.05S-≤0.007N	SAE 1345
1.1104	EStE 285	Fe-≤0.16C-≤0.4Si-≤0.5-1.5Mn-≤0.025P- ≤0.015S-0.02Al-≤0.30Cr-≤0.30Cu-≤0.02N- ≤0.5Ni	P275NL2
1.1106	P355NL2	Fe-≤0.18C-≤0.5Si-≤0.9-1.7Mn-≤0.025P- ≤0.015S-≤0.3Cr-≤0.3Cu-≤0.3Mo-0.5Ni- ≤0.02N	A 707
1.1121	C10E	Fe-≤0.07-0.13C-≤0.40Si-≤0.30-0.60Mn- ≤0.035P-≤0.035S	SAE 1010
1.1127	36Mn6	Fe-≤0.34-0.42C-≤0.15-0.35Si-≤1.4-1.65Mn- ≤0.035P-≤0.035S	
1.1151	Ck 22	Fe-≤0.17-0.24C-≤0.4Si-≤0.4-0.7Mn- ≤0.035P-≤0.035S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1023
1.1186	C40E	Fe-≤0.37-0.44C-≤0.4Si-≤0.5-0.8Mn- ≤0.035P-≤0.035S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1040
1.1191	C45E; Ck 45	Fe-≤0.42-0.50C-≤0.4Si-≤0.50-0.80Mn- ≤0.035P-≤0.035S-≤0.40Cr-≤0.10Mo-≤0.4Ni	SAE 1045
1.1520	C70U	Fe-≤0.65-0.74C-≤0.10-0.30Si-≤0.10-0.35Mn- ≤0.030P-≤0.030S	
1.1525	C80U	Fe-≤0.75-0.85C-≤0.10-0.25Si- ≤0.10-0.25Mn-≤0.020P-≤0.020S	SAE W 108
1.1545	C105U	Fe-≤1.0-1.1C-≤0.10-0.25Si-≤0.10-0.25Mn- ≤0.020P-≤0.020S	SAE W 110
1.2365	32CrMoV12-28	Fe-≤0.28-0.35C-≤0.10-0.40Si- ≤0.15-0.45Mn-≤0.030P-≤0.030S- ≤2.70-3.20Cr-≤2.60-3.00Mo-≤0.40-0.70V	AISI H 10
1.2787	X23CrNi17	Fe-≤0.10-0.25C-≤1.00Si-≤1.00Mn-≤0.035P- ≤0.035S-≤15.5-18.0Cr-≤1.0-2.5Ni	
1.3355	HS 18-0-1	Fe-≤0.70-0.78C-≤0.45Si-≤0.4Mn-≤0.030P- ≤0.030S-≤3.8-4.5Cr-≤1.0-1.2V-≤17.5-18.5W	A 600
1.3505	100Cr6	Fe-≤0.93-1.05C-≤0.15-0.35Si- ≤0.25-0.45Mn-≤0.025P-≤0.015S-≤0.05Al- ≤1.35-1.60Cr-≤0.30Cu-≤0.10Mo	SAE 52100; A 29

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.3728	AlNiCo 9/5	Fe-≤11.0-13.0Al-5.0Co-2.0-4.0Cu-≤57.0Fe-21.0-28.0Ni-≤1.0Ti	
1.3813	X40MnCrN19	Fe-≤0.30-0.50C-≤0.80Si-≤17.0-19.0Mn-≤0.10P-≤0.030S-≤3.0-5.0Cr-≤0.08-0.12N	
1.3974	X2CrNiMnMoNb23-17-6-3	Fe-≤0.30C-≤1.0Si-≤4.5-6.5Mn-≤0.025P-≤0.010S-≤21.0-24.5Cr-≤2.8-3.4Mo-≤0.3-0.5N-≤0.1-0.3Nb-≤15.5-18.0Ni	—
1.3981	NiCo 29 18; (X3NiCo29-18)	Fe-≤0.050C-≤0.30Si-≤0.50Mn-≤17.0-18.0Co-≤28.0-30.0Ni	UNS K94610
1.4000	X6Cr13	Fe-≤0.08C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤12.0-14.0Cr	AISI 403, 410S
1.4002	X6CrAl13	Fe-≤0.08C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤0.10-0.3Al-≤12-14Cr	AISI 405
1.4003	X2CrNi12; X 2 Cr 11	Fe-≤0.03C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤10.5-12.5Cr-≤0.03N-≤0.3-1.0Ni	UNS S40977
1.4005	X12CrS13	Fe-≤0.08-0.15C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.15-0.35S-≤12.0-14.0Cr-≤0.6Mo	AISI 416
1.4006	X12Cr13	Fe-≤0.08-0.15C-≤1.00Si-≤1.5Mn-≤0.04P-≤0.015S-≤11.0-13.5Cr-≤0.75Ni	AISI 410
1.4008	GX7CrNiMo12-1	Fe-≤0.10C-1.0Si-1.0Mn-≤0.035P-≤0.025S-12.0-13.5Cr-0.20-0.50Mo-1.0-2.0Ni	UNS J91150
1.4016	X6Cr17	Fe-≤0.08C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤16.0-18.0Cr	AISI 430
1.4021	X20Cr13	Fe-≤0.16-0.25C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤12.0-14.0Cr	AISI 420
1.4024	X15Cr13	Fe-≤0.12-0.17C-≤1.0Si-≤1.0Mn-≤0.045P-≤0.03S-≤12.0-14.0Cr	SAE 420
1.4028	X30Cr13	Fe-≤0.26-0.35C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤12.0-14.0Cr	A 743 UNS J91153
1.4031	X39Cr13	Fe-≤0.36-0.42C-≤1.00Si-≤1.00Mn-≤0.04P-≤0.015S-≤12.5-14.5Cr	UNS S42080
1.4034	X46Cr13	Fe-≤0.43-0.5C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤12.5-14.5Cr	
1.4057	X17CrNi16-2	Fe-≤0.12-0.22C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤15.0-17.0Cr-≤1.5-2.5Ni	AISI 431
1.4085	GX70Cr29	Fe-≤0.50-0.90C-2.0Si-1.0Mn-≤0.045P-≤0.030S-27.0-30.0Cr	
1.4104	X14CrMoS17	Fe-≤0.10-0.17C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.15-0.35S-≤15.5-17.5Cr-≤0.2-0.6Mo	AISI 430 F
1.4110	X55CrMo14	Fe-≤0.48-0.60C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤13.0-15.0Cr-≤0.5-0.8Mo-≤0.15V	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4112	X90CrMoV18	Fe-≤0.85-0.95C-≤1.0Si-≤1.0Mn-≤0.04P- ≤0.015S-≤17.0-19.0Cr-≤0.9-1.3Mo-≤0.07- 0.12V	AISI 440 B
1.4113	X6CrMo17-1	Fe-≤0.80C-≤1.0Si-≤1.00Mn-≤0.04P- ≤0.03S-≤16.0-18.0Cr-≤0.90-1.40Mo	AISI 434
1.4116	X50CrMoV15	Fe-≤0.45-0.55C-1.0Si-1.0Mn-≤0.040P- ≤0.015S-14.0-15.0Cr-0.5-0.8Mo-0.10-0.20V	
1.4117	X38CrMoV15	Fe-≤0.35-0.40C-1.0Si-1.0Mn-≤0.045P- ≤0.030S-14.0-15.0Cr-0.4-0.6Mo-0.10-0.15V	
1.4120	X20CrMo13	Fe-≤0.17-0.22C-≤1.0Si-≤1.0Mn-≤0.04P- ≤0.015S-≤12-14Cr-≤0.9-1.3Mo-≤1.0Ni	
1.4122	X39CrMo17-1; GX35CrMo17	Fe-≤0.33-0.45C-≤1.0Si-≤1.5Mn-≤0.04P- ≤0.015S-≤15.5-17.5Cr-≤0.8-1.3Mo-≤1.0Ni	
1.4125	X105CrMo17	Fe-≤0.95-1.20C-1.0Si-1.0Mn-≤0.040P- ≤0.015S-16.0-18.0Cr-0.4-0.8Mo	AISI 617
1.4126	X 110 CrMo 13	Fe-≤1.05-1.15C-≤1.0Si-≤1.0Mn-≤0.040P- ≤0.030S- ≤17.0-18.0Cr-≤0.8-1.0Mo	
1.4131	X 1 CrMo 26 1	Fe-≤0.010C-≤0.40Si-≤0.40Mn-≤0.020P- ≤0.020S-≤0.015N-≤25.0-27.5Cr-≤0.75- 1.50Mo-≤0.50Ni	
1.4133		Fe-≤0.01C-1.0Si-1.0Mn-≤0.030P-≤0.030S- 26.0-30.0Cr-1.7-2.3Mo-0.010N	
1.4136	GX70CrMo29-2	Fe-≤0.50-0.90C-2.0Si-1.0Mn-≤0.045P- ≤0.030S-27.0-30.0Cr-2.0-2.5Mo	
1.4138	GX120CrMo29-2	Fe-≤0.90-1.30C-2.0Si-1.0Mn-≤0.045P- ≤0.030S-27.0-30.0Cr-2.0-2.5Mo	
1.4300	X 12 CrNi 18 8	Fe-≤0.12C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S- ≤17.0-19.0Cr-≤8.0-10.0Ni	
1.4301	X5CrNi18-10	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S≤17-19.5Cr-≤0.11N-≤8.0-10.5Ni	AISI 304
1.4302	X5CrNi19-9	Fe-≤0.05C-≤1.40Si-≤1.90Mn-≤0.025P- ≤0.015S-≤18.2-19.8Cr-≤8.70-10.30Ni	UNS S30888
1.4303	X4CrNi18-12	Fe-≤0.06C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17-19Cr-≤0.11N-≤11.0-13.0Ni	AISI 305/308
1.4304	X5CrNi18-12E	Fe-≤0.12C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S- ≤17-19Cr-≤8.0-10.0Ni	
1.4305	X8CrNiS18-9	Fe-≤0.10C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.15- 0.35S-≤17-19Cr-≤1.0Cu-≤0.11N-≤8.0-10.0Ni	AISI 303
1.4306	X2CrNi19-11	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤18-20Cr-≤0.11N-≤10.0-12.0Ni	AISI 304 L
1.4307	X2CrNi18-9	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S- ≤17.5-19.5Cr-≤0.11N-≤8.0-10.0Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4308	GX5CrNi19-10	Fe-≤0.07C-≤1.5Si-≤1.5Mn-≤0.04P-≤0.030S- ≤18.0-20.0Cr-≤8.0-11.0Ni	SAE 304 H
1.4310	X10CrNi18-8	Fe-≤0.05-0.15C-≤2.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.0-19.0Cr-≤0.8Mo-≤0.11N≤6.0- 9.5Ni	AISI 301
1.4311	X2CrNi18-10	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.5Cr-≤8.5-11.5Ni-≤0.12- 0.22N	AISI 304 LN
1.4312	GX10CrNi18-8	Fe-≤0.12C-≤2.0Si-≤1.5Mn-≤0.045P-≤0.03S- ≤17.0-19.5Cr-≤8.0-10.0Ni	A 743
1.4313	X3CrNiMo13-4	Fe-≤0.05C-≤0.7Si-≤1.5Mn-≤0.04P- ≤0.015S-≤12.0-14.0Cr-≤0.3-0.7Mo-≤0.02N- ≤3.5-4.5Ni	UNS J91540
1.4315	X5CrNi19-9	Fe-≤0.06C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.03S- ≤18.0-20.0Cr-≤0.12-0.22N≤8.0-11.0Ni	
1.4318	X2CrNi18-7	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S- ≤16.5-18.5Cr-≤0.1-0.2N≤6.0-8.0Ni	
1.4330	X 2 CrNi 25 20	Fe-≤0.03C-≤1.0Si-≤1.5Mn-≤0.045P-≤0.035S- ≤18.0-22.0Cr-≤23.0-27.0Ni	
1.4335	X1CrNi25-21	Fe-≤0.02C-≤0.25Si-≤2.0Mn-≤0.025P- ≤0.010S-≤24.0-26.0Cr-≤0.20Mo-≤0.110N- ≤20.0-22.0Ni	
1.4340	GX40CrNi27-4	Fe-≤0.30-0.50C-≤2.00Si-≤1.50Mn- ≤0.045P-≤0.030S-≤26.0-28.0Cr-≤3.5-5.5Ni	A 743
1.4361	X1CrNiSi18-15-4	Fe-≤0.015C-≤3.70-4.50Si-≤2.00Mn- ≤0.025P-≤0.010S-≤16.5-18.5Cr-≤0.20Mo- ≤0.110N-≤14.0-16.0Ni	A 336
1.4362	X2CrNi23-4	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.035P- ≤0.015S-≤22.0-24.0Cr-≤0.10-0.60Cu- ≤0.10-0.60Mo-≤0.050-0.200N-≤3.5-5.5Ni	
1.4371	X2CrMnNi17-7-5	Fe-≤0.30C-≤1.0Si-≤6.0-8.0Mn-≤0.045P- ≤0.015S-≤16.0-17.0Cr-≤0.15-0.20N- ≤3.5-5.5Ni	AISI 202
1.4401	X5CrNiMo17-12-2	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤0.110N-≤10.0-13.0Ni	AISI 316
1.4404	X2CrNiMo17-12-2; X2CrNiMo17-13-2	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo-≤10.0- 13.0Ni≤0.110N	AISI 316 L
1.4405	X 5 CrNiMo 16 5; GX4CrNiMo16-5-1	Fe-≤0.07C-≤1.0Si-≤1.0Mn-≤0.035P- ≤0.025S-≤15.0-16.5Cr-≤0.5-2.0Mo-≤4.5- 6.0Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4406	X2CrNiMoN17-12-2	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤0.12-0.22N-≤10.0-12.0Ni	AISI 316 LN
1.4408	GX5CrNiMo19-11-2	Fe-≤0.07C-≤1.50Si-≤1.50Mn-≤0.04P- ≤0.030S-≤18.0-20.0Cr-≤2.0-2.5Mo- ≤9.0-12.0Ni	CF-8M
1.4410	X2CrNiMoN25-7-4	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.035P- 0.015S-≤24.0-26.0Cr-≤3.0-4.5Mo- ≤0.200-0.350N-≤6.0-8.0Ni	2507; A 182
1.4417	GX2CrNiMoN25-7-3	Fe-≤0.03C-≤1.0Si-≤1.5Mn-≤0.030P- ≤0.020S-≤24.0-26.0Cr-≤1.0Cu-≤3.0-4.0Mo- ≤0.150-0.250N-≤6.0-8.5Ni-≤1.0W	3RE60; A 789
1.4418	X4CrNiMo16-5-1	Fe-≤0.06C-≤0.7Si-≤1.5Mn-≤0.040P- ≤0.015S-≤15.0-17.0Cr-≤0.8-1.5Mo-≤0.020N- ≤4.0-6.0Ni	
1.4427	X12CrNiMoS18-11	Fe-≤0.12C-≤1.0Si-≤2.0Mn-≤0.06P- ≤0.15-0.35S-≤16.5-18.5Cr-≤2-2.5Mo- ≤10.5-13.5Ni	
1.4429	X2CrNiMoN17-13-3	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.5-3.0Mo- ≤11.0-14.0Ni-≤0.12-0.22N	AISI 316 LN
1.4435	X2CrNiMo18-14-3	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.0Cr-≤2.5-3.0Mo-≤0.110N- ≤12.5-15.0Ni	AISI 316 L
1.4436	X5CrNiMo17-13-3	Fe-≤0.05C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.5-3.0Mo-≤0.110N- ≤10.5-13.0Ni	AISI 316
1.4438	X2CrNiMo18-15-4	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.5-19.5Cr-≤3.0-4.0Mo-≤0.110N- ≤13.0-16.0Ni	AISI 317 L
1.4439	X2CrNiMoN17-13-5	Fe-≤0.030C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤4.00-5.00Mo- ≤12.5-14.5Ni-≤0.12-0.22N	
1.4442	X2CrNiMoN18-15-4	Fe-≤0.03C-1.0Si-2.0Mn-≤0.025P-≤0.010S- 17.0-18.5Cr-3.7-4.2Mo-0.1-0.2N-14.0-16.0Ni	AISI 317 LN
1.4447	X5CrNiMo18-13	Fe-≤0.06C-1.5Si-2.0Mn-≤0.025P-≤0.020S- 17.0-19.0Cr-4.0-5.0Mo-12.5-15.5Ni	
1.4449	X3CrNiMo18-12-3	Fe-≤0.035C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤17.0-18.2Cr-≤1.0Cu- ≤2.25-2.75Mo-≤0.08N-≤11.5-12.5Ni	AISI 317
1.4460	X3CrNiMoN27-5-2	Fe-≤0.05C-≤1.0Si-≤2.0Mn-≤0.035P- ≤0.015S-≤25.0-28.0Cr-≤1.3-2.0Mo- ≤0.05-0.2N-≤4.5-6.5Ni	AISI 329

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4462	X2CrNiMoN22-5-3	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.035P- ≤0.015S-≤21.0-23.0Cr-≤2.50-3.50Mo- ≤4.50-6.50Ni-≤0.1-0.22N	2205; A 182
1.4463	GX6CrNiMo24-8-2	Fe-≤0.07C-1.5Si-1.5Mn-≤0.045P-≤0.030S- 23.0-25.0Cr-2.0-2.5Mo-7.0-8.5Ni	
1.4465	X1CrNiMoN25-25-2	Fe-≤0.02C-≤0.70Si-≤2.0Mn-≤0.020P- ≤0.015S-≤24.0-26.0Cr-≤2.0-2.5Mo- ≤22.0-25.0Ni-≤0.08-0.16N	AISI 310 MoLN
1.4466	X1CrNiMoN25-22-2	Fe-≤0.02C-≤0.7Si-≤2.0Mn-≤0.025P- ≤0.010S-≤24.0-26.0Cr-≤2.0-2.5Mo- ≤21.0-23.0Ni-≤0.1-0.16N	
1.4469	GX2CrNiMoN26-7-4	Fe-≤0.03C-1.0Si-1.0Mn-≤0.035P-≤0.025S- 25.0-27.0Cr-≤1.30Cu-3.0-5.0Mo-0.12-0.22N- 6.0-8.0Ni	UNS J93404
1.4467	X2CrMnNiMoN26-5-4	Fe-≤0.03C-≤0.8Si-≤4.0-6.0Mn-≤0.03P- ≤0.015S-≤24.5-26.5Cr-≤2.0-3.0Mo- ≤0.3-0.45N-≤3.5-4.5Ni	
1.4492	X 8 CrNiMoN 17 5	Fe-≤0.07-0.11C-≤0.5Si-≤0.5-1.25Mn-≤0.04P- ≤0.03S-≤16.0-17.0Cr-≤2.5-3.25Mo- ≤4.0-5.0Ni	
1.4500	GX7NiCrMoCuNb25-20	Fe-≤0.08C-≤1.50Si-≤2.0Mn-≤0.045P- ≤0.03S-≤19.0-21.0Cr-≤1.5-2.5Cu- ≤2.5-3.5Mo-≤24.0-26.0Ni	A 351
1.4501	X2CrNiMoCuWN25-7-4	Fe-≤0.03C-≤1.0Si-≤1.0Mn-≤0.035P- ≤0.015S-≤24.0-26.0Cr-≤0.5-1.0Cu- ≤3.0-4.0Mo-≤0.2-0.3N-≤6.0-8.0Ni-≤0.5-1.0W	UNS S32760
1.4503	X3NiCrCuMoTi27-23	Fe-≤0.04C-0.75Si-0.75Mn-≤0.030P-≤0.015S- 22.0-24.0Cr-2.5-3.5Cu-2.5-3.0Mo-26.0- 28.0Ni-0.4-0.7Ti	
1.4505	X4NiCrMoCuNb20-18-2	Fe-≤0.05C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤19.0-21.0Ni-≤1.8-2.2Cu	
1.4506	X5NiCrMoCuTi20-18	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S- ≤16.5-18.5Cr-≤2.0-2.5Mo-≤19.0-21.0Ni- ≤1.8-2.2Cu	
1.4507	X2CrNiMoCuN25-6-3	Fe-≤0.03C-≤0.7Si-≤2.0Mn-≤0.035P- ≤0.015S-≤24.0-26.0Cr-≤1.0-2.5Cu- ≤0.15-0.30N-≤5.5-7.5Ni-≤2.7-4.0Mo	UNS S43940
1.4509	X2CrTiNb18	Fe-≤0.03C-≤1.0Si-≤1.0Mn-≤0.040P- ≤0.015S-≤17.5-18.5Cr-≤0.10-0.60Ti	
1.4510	X3CrTi17	Fe-≤0.05C-≤1.0Si-≤1.0Mn-≤0.040P- ≤0.015S-≤16.0-18.0Cr	AISI 430 Ti

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4511	X3CrNb17	Fe-≤0.05C-≤1.0Si-≤1.0Mn-≤0.040P- ≤0.015S-≤16.0-18.0Cr	
1.4512	X2CrTi12	Fe-≤0.03C-≤1.0Si-≤1.0Mn-≤0.040P- ≤0.015S-≤10.5-12.5Cr	AISI 409
1.4515	GX2CrNiMoCuN26-6-3	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.030P- ≤0.020S-≤0.12-0.25N-≤24.5-26.5Cr- ≤2.5-3.5Mo-≤5.5-7.0Ni-≤0.8-1.3Cu	
1.4517	GX2CrNiMoCuN25-6-3-3	Fe-max. 0.03C-1.0Si-1.5Mn-0.035P- 0.025S-24.5-26.5Cr-2.75-3.50Cu-2.50- 3.50Mo-0.12-0.22N-5.0-7.0Ni	UNS J93372
1.4520	X2CrTi17	Fe-≤0.025C-≤0.5Si-≤0.5Mn-≤0.04P- ≤0.015S-≤16.0-18.0Cr-≤0.015N-≤0.3-0.6Ti	
1.4521	X2CrMoTi18-2	Fe-≤0.025C-≤1.0Si-≤0.040P-≤0.015S- ≤1.0Mn-≤17.0-20.0Cr-≤1.8-2.5Mo-≤0.030N	AISI 444
1.4522	X2CrMoNb18-2	Fe-≤0.025C-≤1.0Si-≤1.0Mn-≤0.040P- ≤0.015S-≤17.0-19.0Cr-≤1.8-2.3Mo-≤0.25Ni	AISI 443
1.4523	X2CrMoTiS18-2	Fe-≤0.03C-≤1.0Si-≤0.5Mn-≤0.040P- ≤0.15-0.35S-≤17.5-19.0Cr-≤2.0-2.5Mo- ≤0.30-0.80Ti	
1.4528	X105CrCoMo18-2	Fe-≤1.0-1.1C-≤1.0Si-≤1.0Mn-≤0.045P- ≤0.030S-≤16.5-18.5Cr-≤1.0-1.5Mo- ≤0.30-0.80Ti-≤1.3-1.8Co-≤0.07-0.12V	
1.4529	X1NiCrMoCuN25-20-7	Fe-≤0.02C-≤0.50Si-≤1.00Mn-≤0.030P- ≤0.010S-≤19.0-21.0Cr-≤6.0-7.0Mo- ≤0.5-1.5Cu-≤0.15-0.25N-≤24.0-26.0Ni	A 249; ASTM N08926
1.4530	X1CrNiMoAlTi12-9	Fe-≤0.015C-0.10Si-0.10Mn-≤0.020P- 0.6-1.0Al-11.0-12.5Cr-1.5-2.5Mo- 8.5-10.5Ni-0.25-0.40Ti	
1.4539	X1NiCrMoCu25-20-5	Fe-≤0.02C-≤0.70Si-≤2.0Mn-≤0.030P- ≤0.010S-≤19.0-21.0Cr-≤4.0-5.0Mo- ≤24.0-26.0Ni-≤1.2-2.0Cu-≤0.150N	AISI 904 L
1.4540		Fe-≤0.06C-1.0Si-1.0Mn-15.0-17.0Cr- 2.5-4.0Cu-0.050N-0.15-0.40Nb-3.5-5.0Ni	UNS J92130
1.4541	X6CrNiTi18-10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.0Cr-≤9.0-12.0Ni	AISI 321
1.4542	X5CrNiCuNb16-4	Fe-≤0.07C-≤0.70Si-≤1.5Mn-≤0.040P- ≤0.015S-≤15.0-17.0Cr-≤3.0-5.0Ni- ≤3.0-5.0Cu-≤0.60Mo	AISI 630; 17-4 PH
1.4544	X 10 CrNiMnTi 18 10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.035P- ≤0.025S-≤17.0-19.0Cr-≤9.0-11.5Ni	SAE 321 UNS J92630
1.4546	X5CrNiNb18-10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.030S-≤17.0-19.0Cr-≤9.0-11.5Ni	SAE 347

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4547	X1CrNiMoCuN20-18-7	Fe-≤0.02C-≤0.70Si-≤1.0Mn-≤0.030P- ≤0.010S-≤19.5-20.5Cr-≤0.5-1.0Cu- ≤6.00-7.00Mo-≤0.18-0.25N-≤17.5-18.5Ni	254 SMO; A 182
1.4548	X5CrNiCuNb17-4-4	Fe-≤0.07C-≤1.0Si-≤1.0Mn-≤0.025P- ≤0.025S-≤15.0-17.5Cr-≤3.0-5.0Cu- ≤0.15-0.45Nb-≤3.00-5.00Ni	17-4 PH; AISI 630
1.4550	X6CrNiNb18-10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.0Cr-≤9.0-12.0Ni	AISI 347
1.4558	X2NiCrAlTi32-20	Fe-≤0.03C-≤0.70Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.15-0.45Al-≤20.0-23.0Cr- ≤32.0-35.0Ni	
1.4561	X1CrNiMoTi18-13-2	Fe-≤0.02C-≤0.50Si-≤2.0Mn-≤0.035P- ≤0.015S-≤17.0-18.5Cr-≤2.0-2.5Mo- ≤11.5-13.5Ni-≤0.4-0.6Ti	
1.4562	X1NiCrMoCu32-28-7	Fe-≤0.015C-≤0.30Si-≤2.0Mn-≤0.020P- ≤0.010S-≤26.0-28.0Cr-≤1.0-1.4Cu- ≤6.0-7.0Mo-≤0.15-0.25N-≤30.0-32.0Ni	Alloy 31
1.4563	X1NiCrMoCu31-27-4	Fe-≤0.02C-≤0.70Si-≤2.0Mn-≤0.030P- ≤0.010S-≤26.0-28.0Cr-≤3.0-4.0Mo- ≤30.0-32.0Ni-≤0.70-1.5Cu-≤0.11N	B 668
1.4565	X2CrNiMnMoNbN25-18-5-4	Fe-≤0.03C-≤1.0Si-≤3.5-6.5Mn-≤0.030P- ≤0.015S-≤23.0-26.0Cr-≤3.0-5.0Mo- ≤0.3-0.5N-≤0.15Nb-≤16.0-19.0Ni	UNS S34565
1.4568	X7CrNiAl17-7	Fe-≤0.09C-≤0.70Si-≤1.0Mn-≤0.040P- 0.015S-≤16.0-18.0Cr-≤6.5-7.80Ni- ≤0.70-1.5Al	17-7 PH; AISI 631
1.4571	X6CrNiMoTi17-12-2	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- 0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤10.5-13.5Ni	AISI 316 Ti
1.4573	GX3CrNiMoCuN24-6-5	Fe-≤0.40C-≤1.0Si-≤1.0Mn-≤0.030P- ≤0.020S-≤22.0-25.0Cr-≤1.5-2.5Cu- ≤4.5-6.0Mo-≤0.15-0.25N-≤4.5-6.5Ni	AISI 316 Ti
1.4575	X1CrNiMoNb28-4-2	Fe-≤0.015C-≤1.0Si-≤1.0Mn-≤0.025P- ≤0.015S-≤26.0-30.0Cr-≤1.8-2.5Mo- ≤0.035N-≤3.0-4.5Ni	25-4-4; A 176
1.4577	X3CrNiMoTi25-25	Fe-≤0.04C-≤0.50Si-≤2.0Mn-≤0.030P- ≤0.015S-≤24.0-26.0Cr-≤2.0-2.5Mo- ≤24.0-26.0Ni	
1.4580	X6CrNiMoNb17-12-2	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤10.5-13.5Ni	AISI 316 Cb UNS J92971

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4583	X10CrNiMoNb18-12	Fe-≤0.10C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.030S-≤16.5-18.5Cr-≤2.5-3.0Mo- ≤12.0-14.5Ni	318 (Spec)
1.4585	X6CrNiMoNb17-12-2; G-X 10 CrNiMoNb 18 10	Fe-≤0.080C-≤1.50Si-≤2.0Mn-≤0.045P- ≤0.030S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤19.0-21.0Ni-≤1.8-2.4Cu	
1.4586	X5NiCrMoCuNb22-18	Fe-≤0.07C-1.0Si-2.0Mn-≤0.045P-≤0.030S- 16.5-18.5Cr-1.5-2.0Cu-3.0-3.5Mo- 21.5-23.5Ni	
1.4589	X5CrNiMoTi15-2	Fe-≤0.080C-≤1.0Si-≤1.0Mn-≤0.045P- ≤0.030S-≤13.0-15.5Cr-≤0.2-1.2Mo- ≤1.0-2.5Ni-≤0.3-0.5Ti	UNS S42035
1.4591	X1CrNiMoCuN33-32-1	Fe-≤0.015C-≤0.5Si-≤2.0Mn-≤0.020P- ≤0.010S-≤31.0-35.0Cr-≤0.3-1.2Cu- ≤0.5-2.0Mo-≤0.35-0.6N-≤30.0-33.0Ni	
1.4592	X2CrMoTi29-4	Fe-≤0.025C-1.0Si-1.0Mn-≤0.030P-≤0.010S- 28.0-30.0Cr-3.5-4.5Mo-0.045N	
1.4593	GX3CrNiMoCuN24-6-2-3	Fe-≤0.04C-1.5Si-1.5Mn-≤0.030P-≤0.020S- 23.0-26.0Cr-2.75-3.5Cu-2.0-3.0Mo-0.1-0.2N- 5.0-8.0Ni	
1.4652	X1CrNiMoCuN24-22-8	Fe-≤0.02C-≤0.5Si-≤2.0-4.0Mn-≤0.03P- ≤0.005S-≤23.0-25.0Cr-≤0.3-0.6Cu- ≤7.0-8.0Mo-≤0.45-0.55N-≤21.0-23.0Ni	
1.4712	X10CrSi6	Fe-≤0.12C-≤2.00-2.50Si-≤1.00Mn-≤0.045P- ≤0.030S-≤5.50-6.50Cr	
1.4713	X10CrAlSi7	Fe-≤0.12C-≤0.50-1.00Si-≤1.00Mn-≤0.040P- ≤0.015S-≤0.5-1.0Al-≤6.00-8.00Cr	
1.4720	X7CrTi12	Fe-≤0.08C-1.0Si-1.0Mn-≤0.040P-≤0.030S- 10.5-12.5Cr	AISI 409
1.4722	X 10 CrSi 13	Fe-≤0.12C-≤1.90-2.40Si-≤1.00Mn-≤0.045P- ≤0.030S-≤12.0-14.0Cr	
1.4724	X10CrAlSi13	Fe-≤0.12C-≤0.70-1.40Si-≤1.00Mn-≤0.040P- ≤0.015S-≤0.70-1.20Al-≤12.0-14.0Cr	
1.4749	X18CrN28	Fe-0.15-0.20C-1.0Si-1.0Mn-≤0.040P- ≤0.015S-26.0-29.0Cr-0.15-0.25N	
1.4762	X10CrAlSi25	Fe-≤0.12C-≤0.70-1.40Si-≤1.00Mn-≤0.040P- ≤0.015S-≤1.20-1.70Al-≤23.0-26.0Cr	AISI 446
1.4776	GX40CrSi28	Fe-0.30-0.50C-1.0-2.5Si-1.0Mn-≤0.040P- ≤0.030S-27.0-30.0Cr-0.50Mo-1.0Ni	UNS J92605
1.4777	GX130CrSi29	Fe-1.20-1.40C-1.0-2.5Si-0.5-1.0Mn-≤0.035P- ≤0.030S-27.0-30.0Cr-0.50Mo-1.0Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4828	X15CrNiSi20-12	Fe-≤0.20C-≤1.50-2.50Si-≤2.0Mn-≤0.045P- ≤0.015S-≤19.0-21.0Cr-≤0.11N-≤11.0-13.0Ni	AISI 309
1.4829	X12CrNi22-12	Fe-≤0.14C-0.90-1.90Si-1.90Mn-≤0.025P- ≤0.015S-20.8-23.2Cr-10.2-12.8Ni	UNS S30980
1.4833	X12CrNi23-14	Fe-≤0.15C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤22.0-24.0Cr-≤0.11N-≤12.0-14.0Ni	AISI 309 S
1.4835	X9CrNiSiNCe21-11-2	Fe-≤0.05-0.12C-≤1.4-2.5Si-≤1.0Mn- ≤0.045P-≤0.015S-≤0.030-0.080Ce- ≤20.0-22.0Cr-≤0.12-0.20N-≤10.0-12.0Ni	253 MA; A 182
1.4841	X15CrNiSi25-20	Fe-≤0.20C-≤1.50-2.50Si-≤2.00Mn- ≤0.045P-≤0.015S-≤24.0-26.0Cr-≤0.11N- ≤19.0-22.0Ni	3RE60; AISI 310; AISI 314
1.4845	X12CrNi25-21	Fe-≤0.15C-≤1.50Si-≤2.00Mn-≤0.045P- ≤0.015S-≤24.0-26.0Cr-≤0.11N- ≤19.0-22.0Ni	AISI 310 S
1.4848	GX40CrNiSi25-20	Fe-≤0.30-0.50C-≤1.00-2.50Si-≤1.50Mn- ≤0.035P-≤0.030S-≤24.0-26.0Cr- ≤19.0-21.0Ni	A 297 (HK)
1.4856	GX40NiCrSiNbTi35-25	Fe-≤0.35-0.45C-≤1.00-1.50Si-≤0.5-1.50Mn- ≤0.035P-≤0.030S-≤23.0-27.0Cr- ≤0.9-1.5Nb-≤33.0-37.0Ni-≤0.10-0.25Ti	
1.4857	GX40NiCrSi35-25	Fe-≤0.30-0.50C-≤1.00-2.50Si-≤1.50Mn- ≤0.035P-≤0.030S-≤24.0-26.0Cr- ≤34.0-36.0Ni	A 297 (HP)
1.4864	X12NiCrSi36-16	Fe-≤0.15C-≤1.0-2.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤15.0-17.0Cr-≤0.11N-≤33.0-37.0Ni	AISI 330
1.4876	X10NiCrAlTi32-20	Fe-≤0.12C-≤1.00Si-≤2.00Mn-≤0.030P- ≤0.015S-≤19.0-23.0Cr-≤30.0-34.0Ni- ≤0.15-0.60Al-≤0.15-0.60Ti	B 163; Alloy 800
1.4878	X12CrNiTi18-9	Fe-≤0.10C-≤1.0Si-≤2.0Mn-≤0.045P-0.015S- ≤17.0-19.0Cr-≤9.0-12.0Ni	
1.4903	X10CrMoVNb9-1	Fe-≤0.08-0.12C-≤0.20-0.50Si- ≤0.30-0.60Mn-≤0.020P-≤0.010S- ≤0.04Al-≤8.0-9.5Cr-≤0.85-1.05Mo- ≤0.030-0.070N-≤0.06-0.1Nb-≤0.4Ni- ≤0.18-0.25V	A 182
1.4913	X19CrMoNbVN11-1	Fe-0.17-0.23C-0.50Si-0.40-0.90Mn-≤0.025P- ≤0.015S-≤0.02Al-≤0.0015B-10.0-11.5Cr- 0.5-0.8Mo-0.05-0.1N-0.25-0.55Nb- 0.20-0.60Ni-0.10-0.30V	
1.4919	X6CrNiMo17-13	Fe-≤0.04-0.08C-≤0.75Si-≤2.0Mn-≤0.035P- ≤0.015S-≤0.0015-0.0050B-≤16.0-18.0Cr- ≤2.0-2.5Mo-≤0.11N-≤12.0-14.0Ni	AISI 316 H

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.4922	X20CrMoV12-1	Fe-≤0.17-0.23C-≤0.50Si-≤1.00Mn-≤0.030P- ≤0.030S-≤10.0-12.5Cr-≤0.80-1.20Mo- ≤0.30-0.80Ni-≤0.25-0.35V	
1.4947		Fe-≤0.07C-0.50-1.2Si-1.5-2.0Mn-≤0.035P- ≤0.025S-22.0-23.0Cr-≤0.3Cu-≤0.75Mo- 9.5-10.5Ni	UNS J93001
1.4948	X6CrNi18-11	Fe-≤0.04-0.08C-≤0.75Si-≤2.0Mn-≤0.035P- ≤0.015S-≤17.0-19.0Cr-≤10.0-12.0Ni	AISI 304 H
1.4961	X8CrNiNb16-13	Fe-≤0.04-0.1C-≤0.3-0.6Si-≤1.5Mn-≤0.035P- ≤0.015S-≤15.0-17.0Cr-≤12.0-14.0Ni	
1.4981	X8CrNiMoNb16-16	Fe-≤0.04-0.10C-≤0.30-0.60Si-≤1.50Mn- ≤0.035P-≤0.015S-≤15.5-17.5Cr- ≤1.60-2.00Mo-≤15.5-17.5Ni	
1.4986	X8CrNiMoBNb16-16	Fe-≤0.04-0.1C-≤0.3-0.6Si-≤1.5Mn-≤0.045P- ≤0.030S-≤0.05-0.1B-≤15.5-17.5Cr- ≤1.6-2.0Mo-≤15.5-17.5Ni	
1.4988	X8CrNiMoVNb16-13	Fe-≤0.04-0.1C-≤0.3-0.6Si-≤1.5Mn-≤0.035P- ≤0.015S-≤15.5-17.5Cr-≤1.1-1.5Mo- ≤12.5-14.5Ni-≤0.60-0.85V-≤0.06-0.14N	
1.5122	37MnSi5	Fe-≤0.33-0.41C-≤1.1-1.4Si-≤1.1-1.4Mn- ≤0.035P-≤0.035S	
1.5415	15 Mo 3	Fe-≤0.12-0.2C-≤0.35Si-≤0.4-0.9Mn- ≤0.030P-≤0.025S-≤0.30Cr-≤0.30Cu- ≤0.25-0.35Mo-≤0.30Ni	A 204 (A)
1.5511	35B2	Fe-≤0.32-0.39C-≤0.4Si-≤0.5-0.8Mn- ≤0.035P-≤0.035S-≤0.02Al-≤0.0008-0.005B	
1.5662	X8Ni9	Fe-≤0.10C-0.35Si-0.30-0.80Mn-≤0.020P- ≤0.010S-≤0.10Mo-8.5-10.0Ni-0.05V	UNS K71340
1.5736	36NiCr10	Fe-max. 0.32-0.40C-0.15-0.35Si- 0.40-0.80Mn-0.035P-0.035S-0.55-0.95Cr- 2.25-2.75Ni	SAE 3435
1.6511	36CrNiMo4	Fe-≤0.32-0.40C-≤0.4Si-≤0.5-0.8Mn- ≤0.035P-≤0.035S-≤0.9-1.2Cr-≤0.15-0.3Mo- ≤0.9-1.2Ni	SAE 9840
1.6545	30NiCrMo2-2	Fe-≤0.27-0.34C-≤0.15-0.4Si-≤0.7-1.0Mn- ≤0.035P-≤0.035S-≤0.4-0.6Cr-≤0.15-0.3Mo- ≤0.4-0.7Ni	SAE 8630
1.6565	40NiCrMo6	Fe-0.35-0.45C-≤0.15-0.35Si-≤0.50-0.70Mn- ≤0.035P-≤0.035S-≤0.90-1.4Cr-≤0.20-0.30Mo- ≤1.4-1.7Ni	SAE 4340
1.6580	30CrNiMo8	Fe-≤0.26-0.34C-≤0.4Si-≤0.3-0.6Mn-≤0.035P- ≤0.035S-≤1.8-2.2Cr-≤0.3-0.5Mo-≤1.8-2.2Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.6582	34CrNiMo6	Fe-≤0.3-0.38C-≤0.4Si-≤0.5-0.8Mn-≤0.035P-≤0.035S-≤1.3-1.7Cr-≤0.15-0.3Mo-≤1.3-1.7Ni	
1.6751	22NiMoCr3-7	Fe-≤0.17-0.25C-≤0.35Si-≤0.5-1.0Mn-≤0.02P-≤0.02S-≤0.05Al-≤0.3-0.5Cr-≤0.18Cu-≤0.5-0.8Mo-≤0.6-1.2Ni-≤0.03V	A 508
1.6900	X 12 CrNi 18 9	Fe-≤0.12C-≤1.00Si-≤2.00Mn-≤0.045P-≤0.030S-≤17.00-19.00Cr-≤0.5Mo-≤8.00-10.00Ni	UNS J92801
1.6903	X 10 CrNiTi 18 10	Fe-≤0.10C-≤1.00Si-≤2.00Mn-≤0.045P-≤0.030S-≤17.0-19.0Cr-≤0.5Mo-≤10.0-12.0Ni	
1.6906	X 5 CrNi 18 10	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S-≤17.0-19.0Cr-≤0.50Mo-≤9.0-11.5Ni	
1.6957	26NiCrMoV14-5	Fe-≤0.22-0.32C-≤0.3Si-≤0.15-0.40Mn-≤0.015P-≤0.018S-≤1.2-1.8Cr-≤0.25-0.45Mo-≤3.4-4.0Ni-≤0.05-0.15V	A 470 (9)
1.7033	34Cr4	Fe-≤0.3-0.37C-≤0.4Si-≤0.6-0.9Mn-≤0.035P-≤0.035S-≤0.9-1.2Cr	UNS G51320
1.7035	41Cr4	Fe-≤0.38-0.45C-≤0.4Si-≤0.6-0.9Mn-≤0.035P-≤0.035S-≤0.9-1.2Cr	SAE 5140; UNS H51400
1.7218	25CrMo4	Fe-≤0.22-0.29C-≤0.40Si-≤0.60-0.90Mn-≤0.035P-≤0.035S-≤0.90-1.20Cr-≤0.15-0.30Mo	SAE 4130
1.7219	26CrMo4	Fe-≤0.22-0.29C-≤0.35Si-≤0.5-0.8Mn-≤0.03P-≤0.025S-≤0.9-1.2Cr-≤0.15-0.30Mo	A 372
1.7220	34CrMo4	Fe-≤0.3-0.37C-≤0.4Si-≤0.6-0.9Mn-≤0.035P-≤0.035S-≤0.9-1.2Cr-≤0.15-0.30Mo	SAE 4130
1.7259	26CrMo7	Fe-≤0.22-0.30C-≤0.15-0.35Si-≤0.50-0.70Mn-≤0.035P-≤0.035S-≤1.50-1.80Cr-≤0.20-0.25Mo	
1.7273	24CrMo10	Fe-≤0.20-0.28C-≤0.15-0.35Si-≤0.50-0.80Mn-≤0.035P-≤0.035S-≤2.30-2.60Cr-≤0.20-0.30Mo-≤0.80Ni	
1.7276	10CrMo11	Fe-≤0.08-0.12C-≤0.15-0.35Si-≤0.30-0.50Mn-≤0.035P-≤0.035S-≤2.70-3.00Cr-≤0.20-0.30Mo	
1.7281	16CrMo9-3	Fe-≤0.12-0.20C-≤0.15-0.35Si-≤0.30-0.50Mn-≤0.035P-≤0.035S-≤2.00-2.50Cr-≤0.30-0.40Mo	
1.7335	13CrMo4-4	Fe-≤0.08-0.18C-≤0.35Si-≤0.4-1.0Mn-≤0.030P-≤0.025S-≤0.7-1.15Cr-≤0.3Cu-≤0.4-0.6Mo	A 182

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.7357	G17CrMo5-5	Fe- ≤ 0.15 - 0.20 C- ≤ 0.60 Si- ≤ 0.50 - 1.0 Mn- ≤ 0.020 P- ≤ 0.020 S- ≤ 1.00 - 1.50 Cr- ≤ 0.45 - 0.65 Mo	A 217; UNS J11872
1.7362	X12CrMo5	Fe- ≤ 0.08 - 0.15 C- ≤ 0.50 Si- ≤ 0.30 - 0.60 Mn- ≤ 0.025 P- ≤ 0.020 S- ≤ 4.00 - 6.00 Cr- ≤ 0.45 - 0.65 Mo	AISI 501
1.7375	12CrMo9-10	Fe- ≤ 0.10 - 0.15 C- ≤ 0.30 Si- ≤ 0.30 - 0.80 Mn- ≤ 0.015 P- ≤ 0.010 S- ≤ 0.01 - 0.04 Al- ≤ 2.00 - 2.50 Cr- ≤ 0.20 Cu- ≤ 0.9 - 1.10 Mo- ≤ 0.012 N- ≤ 0.30 Ni	UNS K21590
1.7380	10CrMo9-10	Fe- ≤ 0.08 - 0.14 C- ≤ 0.50 Si- ≤ 0.40 - 0.80 Mn- ≤ 0.030 P- ≤ 0.025 S- ≤ 2.00 - 2.50 Cr- ≤ 0.30 Cu- ≤ 0.90 - 1.10 Mo	A 182 (F22); UNS J21890
1.7383	11CrMo9-10	Fe- ≤ 0.08 - 0.15 C- ≤ 0.50 Si- ≤ 0.40 - 0.80 Mn- ≤ 0.030 P- ≤ 0.025 S- ≤ 2.00 - 2.50 Cr- ≤ 0.30 Cu- ≤ 0.90 - 1.10 Mo	
1.7386	X12CrMo9-1	Fe- ≤ 0.07 - 0.15 C- ≤ 0.25 - 1.0 Si- ≤ 0.30 - 0.60 Mn- ≤ 0.025 P- ≤ 0.020 S- ≤ 8.0 - 10.0 Cr- ≤ 0.90 - 1.1 Mo	AISI 504; UNS S50488
1.7715	14MoV6-3	Fe- ≤ 0.1 - 0.18 C- ≤ 0.1 - 0.35 Si- ≤ 0.4 - 0.7 Mn- ≤ 0.035 P- ≤ 0.035 S- ≤ 0.3 - 0.6 Cr- ≤ 0.5 - 0.7 Mo- ≤ 0.22 - 0.32 V	UNS K11591
1.7766	17CrMoV10	Fe- ≤ 0.15 - 0.20 C- ≤ 0.15 - 0.35 Si- ≤ 0.30 - 0.50 Mn- ≤ 0.035 P- ≤ 0.035 S- ≤ 2.70 - 3.00 Cr- ≤ 0.20 - 0.30 Mo- ≤ 0.10 - 0.20 V	
1.7779	20CrMoV13-5	Fe- ≤ 0.17 - 0.23 C- ≤ 0.15 - 0.35 Si- ≤ 0.30 - 0.50 Mn- ≤ 0.025 P- ≤ 0.020 S- ≤ 3.00 - 3.30 Cr- ≤ 0.50 - 0.60 Mo- ≤ 0.45 - 0.55 V	
1.7783	X41CrMoV5-1	Fe- ≤ 0.38 - 0.43 C- ≤ 0.80 - 1.0 Si- ≤ 0.20 - 0.40 Mn- ≤ 0.015 P- ≤ 0.010 S- ≤ 4.75 - 5.25 Cr- ≤ 1.2 - 1.4 Mo- ≤ 0.40 - 0.60 V	AISI 610
1.8070	21CrMoV5-11	Fe- ≤ 0.17 - 0.25 C- ≤ 0.30 - 0.60 Si- ≤ 0.30 - 0.60 Mn- ≤ 0.035 P- ≤ 0.035 S- ≤ 1.20 - 1.50 Cr- ≤ 1.00 - 1.20 Mo- ≤ 0.60 Ni- ≤ 0.25 - 0.35 V	
1.8075	10CrSiMoV7	Fe- ≤ 0.12 C- ≤ 0.9 - 1.2 Si- ≤ 0.35 - 0.75 Mn- ≤ 0.035 P- ≤ 0.035 S- ≤ 1.6 - 2 Cr- ≤ 0.25 - 0.35 Mo- ≤ 0.25 - 0.35 V	
1.8905	StE 460	Fe- ≤ 0.20 C- ≤ 0.60 Si- ≤ 1.00 - 1.70 Mn- ≤ 0.030 P- ≤ 0.025 S- ≤ 0.02 Al- ≤ 0.30 Cr- ≤ 0.70 Cu- ≤ 0.10 Mo- ≤ 0.025 N- ≤ 0.050 Nb- ≤ 0.80 Ni- ≤ 0.03 Ti- ≤ 0.20 V	A 225 (C), A 633 (E)
1.8907	StE 500	Fe- ≤ 0.21 C- ≤ 0.1 - 0.6 Si- ≤ 1.0 - 1.7 Mn- ≤ 0.035 P- ≤ 0.03 S- ≤ 0.02 Al- ≤ 0.30 Cr- ≤ 0.70 Cu- ≤ 0.10 Mo- ≤ 0.020 N- ≤ 0.05 Nb- ≤ 1.0 Ni- ≤ 0.2 Ti- ≤ 0.22 V	6386 B; UNS K02001

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
1.8912	S420NL	Fe- $\leq 0.2\text{C}$ - $\leq 0.6\text{Si}$ - $\leq 1.0\text{-}1.7\text{Mn}$ - $\leq 0.03\text{P}$ - $\leq 0.025\text{S}$ - $\leq 0.02\text{Al}$ - $\leq 0.3\text{Cr}$ - $\leq 0.7\text{Cu}$ - $\leq 0.1\text{Mo}$ - $\leq 0.025\text{N}$ - $\leq 0.050\text{Nb}$ - $\leq 0.8\text{Ni}$ - $\leq 0.03\text{Ti}$ - $\leq 0.2\text{V}$	A 737; UNS K02002
1.8935	WstE 460; P460NH	Fe- $\leq 0.20\text{C}$ - $\leq 0.60\text{Si}$ - $\leq 1.0\text{-}1.70\text{Mn}$ - $\leq 0.030\text{P}$ - $\leq 0.025\text{S}$ - $\leq 0.02\text{Al}$ - $\leq 0.30\text{Cr}$ - $\leq 0.70\text{Cu}$ - $\leq 0.10\text{Mo}$ - $\leq 0.025\text{N}$ - $\leq 0.050\text{Nb}$ - $\leq 0.8\text{Ni}$ - $\leq 0.03\text{Ti}$ - $\leq 0.2\text{V}$	A 350; UNS K02900
1.8961	S235J2W	Fe- $\leq 0.13\text{C}$ - $\leq 0.4\text{Si}$ - $\leq 0.2\text{-}0.6\text{Mn}$ - $\leq 0.040\text{P}$ - $\leq 0.035\text{S}$ - $\leq 0.02\text{Al}$ - $\leq 0.4\text{-}0.8\text{Cr}$ - $\leq 0.25\text{-}0.55\text{Cu}$ - $\leq 0.015\text{-}0.060\text{Nb}$ - $\leq 0.65\text{Ni}$ - $\leq 0.02\text{-}0.10\text{Ti}$ - $\leq 0.02\text{-}0.10\text{V}$	
1.8962	9CrNiCuP3-2-4	Fe- $\leq 0.12\text{C}$ - $\leq 0.25\text{-}0.75\text{Si}$ - $\leq 0.2\text{-}0.5\text{Mn}$ - $\leq 0.07\text{-}0.15\text{P}$ - $\leq 0.035\text{S}$ - $\leq 0.5\text{-}1.25\text{Cr}$ - $\leq 0.25\text{-}0.55\text{Cu}$ - $\leq 0.65\text{Ni}$	A 242; UNS K11430
1.8963	S355J2G1W	Fe- $\leq 0.16\text{C}$ - $\leq 0.50\text{Si}$ - $\leq 0.50\text{-}1.5\text{Mn}$ - $\leq 0.035\text{P}$ - $\leq 0.035\text{S}$ - $\leq 0.02\text{Al}$ - $\leq 0.40\text{-}0.80\text{Cr}$ - $\leq 0.25\text{-}0.55\text{Cu}$ - $\leq 0.3\text{Mo}$ - $\leq 0.015\text{-}0.060\text{Nb}$ - $\leq 0.65\text{Ni}$ - $\leq 0.02\text{-}0.10\text{Ti}$ - $\leq 0.02\text{-}0.12\text{V}$ - $\leq 0.15\text{Zr}$	A 588 (A)
1.8977	L485MB	Fe- $\leq 0.16\text{C}$ - $\leq 0.45\text{Si}$ - $\leq 1.70\text{Mn}$ - $\leq 0.025\text{P}$ - $\leq 0.020\text{S}$ - $\leq 0.015\text{-}0.06\text{Al}$ - $\leq 0.30\text{Cr}$ - $\leq 0.25\text{Cu}$ - $\leq 0.10\text{Mo}$ - $\leq 0.012\text{N}$ - $\leq 0.06\text{Nb}$ - $\leq 0.30\text{Ni}$ - $\leq 0.06\text{Ti}$ - $\leq 0.10\text{V}$	API 5LX70
2.4060	Ni 99,6	$\leq 99.60\text{Ni}$ - $\leq 0.08\text{C}$ - $\leq 0.15\text{Si}$ - $\leq 0.35\text{Mn}$ - $\leq 0.005\text{S}$ - $\leq 0.15\text{Cu}$ - $\leq 0.25\text{Fe}$ - $\leq 0.15\text{Mg}$ - $\leq 0.10\text{Ti}$	UNS N02200
2.4061	LC-Ni 99,6	Fe- $\leq 0.02\text{C}$ - $\leq 0.15\text{Si}$ - $\leq 0.35\text{Mn}$ - $\leq 0.005\text{S}$ - $\leq 0.15\text{Cu}$ - $\leq 0.25\text{Fe}$ - $\leq 0.15\text{Mg}$ - $\leq 99.6\text{Ni}$ - $\leq 0.10\text{Ti}$	UNS N02201
2.4066	Ni 99,2; S-Ni 99,2	$\leq 99.20\text{Ni}$ - $\leq 0.10\text{C}$ - $\leq 0.25\text{Si}$ - $\leq 0.35\text{Mn}$ - $\leq 0.005\text{S}$ - $\leq 0.25\text{Cu}$ - $\leq 0.40\text{Fe}$ - $\leq 0.15\text{Mg}$ - $\leq 0.10\text{Ti}$	UNS N02200
2.4068	LC-Ni 99	$\leq 99.0\text{Ni}$ - $\leq 0.02\text{C}$ - $\leq 0.25\text{Si}$ - $\leq 0.35\text{Mn}$ - $\leq 0.005\text{S}$ - $\leq 0.25\text{Cu}$ - $\leq 0.40\text{Fe}$ - $\leq 0.15\text{Mg}$ - $\leq 0.10\text{Ti}$	UNS N02201
2.4360	NiCu 30 Fe	$\leq 63.0\text{Ni}$ - $\leq 0.15\text{C}$ - $\leq 0.50\text{Si}$ - $\leq 2.0\text{Mn}$ - $\leq 0.020\text{S}$ - $\leq 0.5\text{Al}$ - $\leq 28.0\text{-}34.0\text{Cu}$ - $\leq 1.0\text{-}2.5\text{Fe}$ - $\leq 0.3\text{Ti}$	UNS N04400
2.4366	EL-NiCu 30 Mn	$\leq 62.0\text{Ni}$ - $\leq 0.15\text{C}$ - $\leq 1.0\text{Si}$ - $\leq 1.0\text{-}4.0\text{Mn}$ - $\leq 0.030\text{P}$ - $\leq 0.015\text{S}$ - $\leq 0.5\text{Al}$ - $\leq 27.0\text{-}34.0\text{Cu}$ - $\leq 0.5\text{-}2.5\text{Fe}$ - $\leq 1.0\text{Nb}$ - $\leq 1.0\text{Ti}$	B 127-98
2.4368	G-NiCu 30Si4	Fe- $\leq 0.25\text{C}$ - $3.5\text{-}4.5\text{Si}$ - $0.5\text{-}1.5\text{Mn}$ - $27.0\text{-}31.0\text{Cu}$ - $1.0\text{-}2.5\text{Fe}$ - $60.0\text{-}68.0\text{Ni}$	UNS N10665
2.4375	NiCu 30 Al	Ni- $\leq 0.20\text{C}$ - $\leq 0.50\text{Si}$ - $\leq 1.5\text{Mn}$ - $\leq 0.015\text{S}$ - $\leq 2.2\text{-}3.5\text{Al}$ - $\leq 27.0\text{-}34.0\text{Cu}$ - $\leq 0.5\text{-}2.0\text{Fe}$ - $\leq 63.0\text{Ni}$ - $\leq 0.3\text{-}1.0\text{Ti}$	UNS N05500

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
2.4600	NiMo29Cr	Ni≤0.01C≤0.1Si≤3.0Mn≤0.025P≤0.015S- ≤0.1-0.5Al≤3.0Co≤0.5-3.0Cr≤0.5Cu- ≤1.0-6.0Fe≤26.0-32.0Mo≤0.4Nb- ≤0.2Ti≤0.2V≤3.0W	
2.4602	NiCr21Mo14W	Ni≤0.01C≤0.08Si≤0.5Mn≤0.025P- ≤0.010S≤2.5Co≤20.0-22.5Cr≤2.0-6.0Fe- ≤12.5-14.5Mo≤0.35V≤2.5-3.5W	UNS N06022
2.4603	NiCr30FeMo	Ni≤0.03C≤0.08Si≤2.0Mn≤0.04P- ≤0.02S≤5.0Co≤28.0-31.5Cr≤1.0-2.4Cu- 13.0-17.0Fe≤4.0-6.0Mo≤0.3-1.5Nb- ≤1.5-4.0W	UNS N06002
2.4605	NiCr23Mo16Al	Ni≤0.01C≤0.10Si≤0.5Mn≤0.025P- ≤0.015S≤0.1-0.4Al≤0.3Co≤22.0-24.0Cr- ≤0.5Cu≤1.5Fe≤15.0-16.5Mo	UNS N06059
2.4606	NiCr21Mo16W	Ni≤0.01C≤0.08Si≤0.75Mn≤0.025P- ≤0.015S≤0.5Al≤1.0Co≤19.0-23.0Cr- ≤2.0Fe≤15.0-17.0Mo≤0.02-0.25Ti≤0.2V- ≤3.0-4.0W	UNS N06686
2.4607	SG-NiCr23Mo16	Ni≤0.015C≤0.08Si≤0.50Mn≤0.02P- ≤0.015S≤0.1-0.4Al≤0.3Co≤22.0-24.0Cr- ≤1.5Fe≤15.0-16.5Mo	UNS N06059
2.4610	NiMo16Cr16Ti	Ni≤0.01C≤0.08Si≤1.0Mn≤0.025P- ≤0.015S≤2.0Co≤14.0-18.0Cr≤0.5Cu- ≤3.0Fe≤14.0-18.0Mo≤0.7Ti	UNS N06455
2.4615	SG-NiMo27	Fe≤0.02C≤0.10Si≤1.0Mn≤0.015S- ≤1.0Cr≤2.0Fe-26.0-30.0Mo-64.0Ni	UNS N10665
2.4617	NiMo28	Ni≤0.01C≤0.08Si≤1.0Mn≤0.025P- ≤0.015S≤1.0Co≤1.0Cr≤0.5Cu≤2.0Fe- ≤26.0-30.0Mo	UNS N10665
2.4618	NiCr22Mo6Cu	Ni≤0.05C≤1.0Si≤1.0-2.0Mn≤0.025P- ≤0.015S≤2.5Co≤21.0-23.5Cr≤1.5-2.5Cu- ≤18.0-21.0Fe≤5.5-7.5Mo≤1.75-2.5Nb- ≤1.0W	UNS N06007
2.4619	NiCr22Mo7Cu	Ni≤0.015C≤1.0Si≤1.0Mn≤0.025P- ≤0.015S≤5.0Co≤21.0-23.5Cr≤1.5-2.5Cu- ≤18.0-21.0Fe≤6.0-8.0Mo≤0.5Nb≤1.5W	UNS N06985
2.4631	NiCr20TiAl	Ni≤0.04-0.10C≤1.0Si≤1.0Mn≤0.03P- ≤0.015S≤1.0-1.8Al≤0.008B≤2.0Co- ≤18.0-21.0Cr≤0.2Cu≤1.5Fe≤1.8-2.7Ti	UNS N07080
2.4641	NiCr21Mo6Cu	Fe≤0.025C≤0.50Si≤1.0Mn≤0.025P- ≤0.015S≤0.2Al≤1.0Co-20.0-23.0Cr- 1.5-3.0Cu-5.5-7.0Mo-39.0-46.0Ni-0.6-1.0Ti	UNS N08042

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
2.4642	NiCr29Fe	≤58.0Ni-≤0.05C-≤0.5Si-≤0.5Mn-≤0.020P- ≤0.015S-≤0.5Al-≤27.0-31.0Cr-≤0.5Cu- ≤7.0-11.0Fe-≤0.5Ti	UNS N06690
2.4650	NiCo20Cr20MoTi	Ni-≤0.04-0.08C-≤0.4Si-≤0.6Mn-≤0.007S- ≤0.3-0.6Al-≤0.005B-≤19.0-21.0Co- ≤19.0-21.0Cr-≤0.2Cu-≤0.7Fe-≤5.6-6.1Mo- ≤1.9-2.4Ti	UNS N07263
2.4652	EL-NiCr26Mo	≤37.0-42.0Ni-≤0.03C-≤0.7Si-≤1.0-3.0Mn- ≤0.015S-≤0.1Al-≤23.0-27.0Cr-≤1.5-3.0Cu- ≤30.0Fe-≤3.5-7.5Mo-≤37.0-42.00Ni-≤1.0Ti	UNS S32654
2.4660	NiCr20CuMo	≤32.0-38.0Ni-≤0.07C-≤1.0Si-≤2.0Mn- ≤0.025P-≤0.015S-≤19.0-21.0Cr-≤3.0-4.0Cu- ≤2.0-3.0Mo	UNS N08020
2.4662	NiCr13Mo6Ti3	Fe-0.02-0.06C-≤0.40Si-≤0.50Mn-≤0.020P- ≤0.020S-≤0.35Al-0.01-0.02B-≤1.0Co- 11.0-14.0Cr-≤0.04Cu-5.0-6.5Mo-40.0-45.0Ni- 2.8-3.1Ti	UNS N09901
2.4663	NiCr23Co12Mo	Ni-≤0.05-0.10C-≤0.2Si-≤0.2Mn-≤0.01P- ≤0.01S-≤0.7-1.4Al-≤0.006B-≤11.0-14.0Co- ≤20.0-23.0Cr-≤0.5Cu-≤2.0Fe-≤8.5-10.0Mo- ≤0.2-0.6Ti	UNS N06617
2.4667	SG-NiCr19NbMoTi	Fe-≤0.08C-≤0.40Si-≤0.40Mn-≤0.015S- 0.2-0.8Al-≤0.006B-17.0-21.0Cr-≤0.30Cu- ≤22.0Fe-2.8-3.3Mo-4.8-5.5Nb-50.0Ni- 0.60-1.20Ti	
2.4668	NiCr19Fe19Nb5Mo3	Fe-0.02-0.08C-≤0.35Si-≤0.35Mn-≤0.015P- ≤0.015S-0.3-0.7Al-0.006B-≤1.0Co-17.0- 21.0Cr-≤0.30Cu-2.8-3.3Mo-4.7-5.5Nb-50.0- 55.0Ni-0.60-1.20Ti	UNS N07718
2.4669	NiCr15Fe7TiAl; NiCr15Fe7Ti2Al	Ni-≤0.08C-≤0.5Si-≤1.0Mn-≤0.02P-≤0.015S- ≤0.4-1.0Al-≤1.0Co-≤14.0-17.0Cr-≤0.5Cu- ≤5.0-9.0Fe-≤0.7-1.2Nb-≤2.25-2.75Ti	UNS N07750
2.4675	NiCr23Mo16Cu	Ni-≤0.01C-≤0.08Si-≤0.5Mn-≤0.025P- ≤0.015S-≤0.5Al-≤2.0Co-≤22.0-24.0Cr- ≤1.3-1.9Cu-≤3.0Fe-≤15.0-17.0Mo	
2.4681	CoCr26Ni9Mo5W	Ni-≤1.0C-≤1.0Si-≤1.5Mn-≤23.5-27.5Cr- ≤1.0-3.0Fe-≤4.0-6.0Mo-≤0.12N-≤7.0-11.0Ni- ≤1.0-3.0W	
2.4800	S-NiMo 30	-≤60.0Ni-≤0.05C-≤1.0Si-≤1.0Mn-≤0.045P- ≤0.025S-≤2.5Co-≤1.0Cr-≤4.0-7.0Fe- ≤26.0-30.0Mo-≤0.2-0.4V	UNS N10001

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
2.4810	NiMo 30	≤62.0Ni-≤0.05C-≤0.5Si-≤1.0Mn-≤0.030P- ≤0.015S-≤2.5Co-≤1.0Cr-≤0.5Cu-≤4.0-7.0Fe- ≤26.0-30.0Mo-≤0.6V	UNS N10001
2.4811		Fe-≤0.03C-≤0.05Si-≤0.80Mn-≤0.030P- ≤0.015S-19.0-21.0Cr-≤0.50Cu-≤2.5Fe- 14.0-17.0Mo-58.0Ni-0.35V	
2.4816	NiCr15Fe	≤72.0Ni-≤0.05-0.1C-≤0.5Si-≤1.0Mn- ≤0.020P-≤0.015S-≤0.3Al-≤0.0060B-≤1.0Co- ≤14.0-17.0Cr-≤0.5Cu-≤6.0-10.0Fe-≤0.3Ti	UNS N06600
2.4817	LC-NiCr15Fe	≤72.0Ni-≤0.025C-≤0.50Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤0.0060B-≤1.0Co- ≤14.0-17.0-≤0.5Cu-≤6.0-10.0Fe-≤0.3Ti	
2.4819	NiMo16Cr15W	Ni-≤0.01C-≤0.08Si-≤1.0Mn-≤0.025P- ≤0.015S-≤2.5Co-≤14.5-16.5Cr-≤0.5Cu- ≤4.0-7.0Fe-≤15.0-17.0Mo-≤0.35V-≤3.0-4.5W	UNS N10276
2.4831	SG-NiCr21Mo9Nb	Fe-≤0.10C-≤0.50Si-≤0.50Mn-≤0.015S- ≤0.4Al-20.0-23.0Cr-≤0.50Cu-≤5.0Fe- 8.0-10.0Mo-3.0-4.5Nb-60.0Ni-≤0.40Ti	UNS N06625
2.4856	NiCr22Mo9Nb	Ni-≤0.03-0.10C-≤0.5Si-≤0.5Mn-≤0.020P- ≤0.015S-≤0.4Al-≤1.0Co-≤20.0-23.0Cr- ≤0.5Cu-≤5.0Fe-≤8.0-10.0Mo-≤3.15-4.15Nb- ≤0.4Ti	UNS N06625
2.4858	NiCr21Mo	≤38.0-46.0Ni-≤0.025C-≤0.50Si-≤1.0Mn- ≤0.025P-≤0.015S-≤0.20Al-≤1.0Co- ≤19.5-23.5Cr-≤1.5-3.0Cu-≤2.5-3.5Mo- ≤0.6-1.2Ti	B 163 UNS N08825
2.4869	NiCr80-20	Fe-≤0.15C-0.50-2.0Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤1.0Co-19.0-21.0Cr- ≤0.50Cu-≤1.0Fe-75.0Ni	UNS N06003
2.4882		Fe-≤0.12C-0.50-2.0Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤1.0Co-19.0-21.0Cr- ≤0.50Cu-≤1.0Fe-75.0Ni	UNS N10001
2.4883		Fe-≤0.03C-≤0.50Si-≤1.0Mn-≤2.50Co- 15.50-17.50Cr-≤7.0Fe-16.0-18.0Mo	UNS N10002
2.4886	SG-NiMo16Cr16W; UP-NiMo16Cr16W	≤50.0Ni-≤0.02C-≤0.08Si-≤1.0Mn-≤0.015S- ≤14.5-16.5Cr-≤4.0-7.0Fe-≤15.0-17.0Mo- ≤0.4V-≤3-4.5W	UNS N10276
2.4887	EL-NiMo15Cr15W	≤50.0Ni-≤0.02C-≤0.20Si-≤1.0Mn-≤0.015S- ≤14.5-16.5Cr-≤4.0-7.0Fe-≤15.0-17.0Mo- ≤0.4V-≤3-4.5W	
2.4951	NiCr20Ti	Ni-≤0.08-0.15C-≤1.0Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤0.0060B-≤5.0Co- ≤18.0-21.0Cr-≤0.5Cu-≤5.0Fe-≤0.2-0.6Ti	UNS N06075

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	AISI/SAE/ASTM/UNS
2.4964	CoCr20W15Ni	≤ 9.0 - 11.0 Ni- ≤ 0.05 - 0.15 C- ≤ 0.4 Si- ≤ 2.0 Mn- ≤ 0.020 P- ≤ 0.015 S- ≤ 19.0 - 21.0 Cr- ≤ 3.0 Fe- ≤ 9.0 - 11.0 Ni- ≤ 14.0 - 16.0 W	UNS R30605
2.4999	MP35N	35.0 Ni- ≤ 0.01 C- ≤ 20.0 Cr- ≤ 9.5 Mo	

Table 2: Chemical compositions of different American, CIS, Bulgarian and other steels

Steel	Materials Compositions, Percent in Weight	Note
000Ch16N13M2	Fe-≤0.07C-≤1.0Si-≤2.0Mn-16.5-18.5Cr-2-2.5Mo-10-13Ni-≤0.045P-≤0.015S-≤0.11N	CIS, formerly USSR, identical with AISI 316
000Ch16N13M3	Fe-≤0.07C-≤1.0Si-≤2.0Mn-16.5-18.5Cr-2-2.5Mo-10-13Ni-≤0.045P-≤0.015S-≤0.11N	CIS, formerly USSR, identical with AISI 316
000Ch16N16M4	Fe-≤0.07C-≤1.0Si-≤2.0Mn-16.5-18.5Cr-2-2.5Mo-10-13Ni-≤0.045P-≤0.015S-≤0.11N	CIS, formerly USSR, identical with AISI 316
000Ch18N10	Fe-≤0.03C-≤0.8Si-≤2.0Mn-17-19Cr-≤0.3Mo-9-11Ni	CIS, formerly USSR/Bulg.
000Ch18N11	Fe-≤0.03C-≤1.0Si-≤2.0Mn-18-20Cr-10-12Ni-≤0.045P-≤0.015S-≤0.11N	Bulg., comparable with 1.4306
000Ch20N20	Fe-≤0.03C-≤18.57Cr-≤19.40Ni-≤0.71Mn-≤0.26Si	CIS, formerly USSR
000Ch21N10M2	Fe-≤0.02C-≤19.8Cr-≤10.5Ni-≤2.1Mo	CIS, formerly USSR
000Ch21N21M4B	Fe-≤0.03C-≤20-22Cr-20-21Ni-3.4-3.7Mo-≤0.6Mn-≤0.6Si-≤0.03P-≤0.02S-0.45-0.8Nb	CIS, formerly USSR
000Ch21N6M2	Fe-≤0.036C-≤21.1Cr-6.5Ni-2.4Mo	CIS, formerly USSR
005Ch25B	Fe-0.005C-0.007N-25Cr	CIS, formerly USSR
00Ch18G8N2T	Fe-≤0.08C-≤0.8Si-7-9Mn-17-19Cr-≤0.3Mo-1.8-2.8Ni-≤0.2W-≤0.3Cu-≤0.2Ti-0.2-0.5Al	CIS, formerly USSR
00Ch18N10	Fe-≤0.015C-≤0.7Si-≤1.7Mn-≤17.3Cr-≤10.4Ni	CIS, formerly USSR
02Ch12N10S5	Fe-0.02C-12Cr-10Ni-5Si, Nb-stabilized	CIS, formerly USSR
02Ch12N10S5B	Fe-0.02C-12Cr-10Ni-5Si, Nb-stabilized	CIS, formerly USSR
02Ch12N10S5T	Fe-0.02C-12Cr-10Ni-5Si, Nb-stabilized	CIS, formerly USSR
02Ch17NS6	Fe-0.02C-4-6.5Si-0.43-0.52Mn-16.3-18Cr-10.5-18.2Ni-0.005-0.008S-0.012-0.014P-	CIS, formerly USSR
02Ch8N22S6	Fe-≤0.02C-≤5.4-6.7Si-0.6Mn-≤0.030P-≤0.020S-7.5-10Cr-0.3Mo-21-23Ni-≤0.2Ti-≤0.20W	CIS, formerly USSR
02Ch8N22S6B	Fe-0.02C-8Cr-122Ni-6Si, Nb-stabilized	CIS, formerly USSR
02Ch8N22T	Fe-0.02C-8Cr-122Ni-6Si, Ti-stabilized	CIS, formerly USSR
03Ch16N15M3	Fe-≤0.03C-15.0-17.0Cr-14.0-16.0Ni-2.5-3.0Mo-Ti	CIS, formerly USSR
03Ch18N11	Fe-0.03C-≤0.80Si-≤0.70-2.0Mn-≤0.035P-0.020S-17.0-19.0Cr-≤0.10Mo-10.5-12.5Ni-≤0.20W-0.30Cu-≤0.50Ti	CIS, formerly USSR, comparable with DIN-Mat.No. 1.4306
03Ch18N14	Fe-0.03C-18Cr-14Ni	CIS, formerly USSR
03Ch21N21M4GB	Fe-≤0.03C-≤0.60Si-1.8-2.5Mn-≤0.030P-≤0.020S-20-22Cr-3.4-3.7Mo-20-22Ni-≤0.2W-≤0.3Cu-≤0.2Ti, Nb 15 x C-0.80	CIS, formerly USSR
03Ch23N6	Fe-≤0.03C-≤0.40Si-1.0-2.0Mn-≤0.035P-≤0.020S-22-24Cr-≤5.3-6.3Ni	CIS, formerly USSR
03Ch25	Fe-about 0.03C-25Cr-0.6Ni	CIS, formerly USSR
03ChN28MDT	Fe-≤0.03C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.020S-22.0-25.0Cr-2.5-3.0Mo-26.0-29.0Ni-0.50-0.90Ti-2.5-3.5Cu	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
04Ch18N10	Fe-≤0.04C-≤0.8Si-≤2.0Mn-17-19Cr-≤0.030P- ≤0.02S-≤0.3Mo-9-11Ni-≤0.2W-≤0.3Cu-≤0.2Ti	CIS, formerly USSR
04Ch18N10T	Fe-≤0.04C-≤0.8Si-≤2.0Mn-17-19Cr-≤0.3Mo-9-11Ni- ≤0.2W-≤0.3Cu-≤0.2Ti	CIS, formerly USSR
05Ch16N15M3	Fe-0.05C-16Cr-15Ni-3Mo	CIS, formerly USSR
06Ch17G15NAB	Fe-0.05C-18.36Cr-16.5Mn-1.6Ni-0.31Nb-8.12Si- 0.01Ce-0.017P-0.014S	CIS, formerly USSR
06Ch23N28M3D3T	Fe-≤0.06C-≤0.8Si-≤2.0Mn-22-25Cr-≤2.4-3Mo- 26-29Ni-0.5-0.9Ti-2.5-3.5Cu	CIS, formerly USSR/Bulg.
06Ch28MDT	Fe-≤0.06C-≤0.8Si-≤0.80Mn-22.0-25.0Cr-2.5-3.0Mo- 26.0-29.0Ni-0.50-0.90Ti-2.5-3.5Cu	CIS, formerly USSR
06ChN28MDT	Fe-≤0.06C-≤0.8Si-≤0.8Mn-≤0.035P-≤0.02S-22-25Cr- 2.5-3.0Mo-26-29Ni-0.5-0.9Ti-2.5-3.5Cu	CIS, formerly USSR
06ChN40B	Fe-0.055C-17.01Cr-39.04Ni-1.99Mn-0.50Nb-0.60Si- 0.013S-0.022P	CIS, formerly USSR
07Ch13AG20	Fe-≤0.07C-≤0.60Si-≤19-22Mn-≤0.035P-≤0.025S- ≤0.0030B-≤0.1Ca-≤0.1Ce-12.-14.8Cr- ≤0.30Cu≤0.1Mg-≤0.30Mo≤0.08-0.18N-≤1.0Ni- ≤0.20W≤0.20Ti	CIS, formerly USSR
07Ch16N4B	Fe-0.05-0.10C-≤0.60Si-≤0.2-0.5Mn-≤0.025P-≤0.020S- 15.16.5Cr-≤0.30Cu-≤0.30Mo-0.2-0.4Nb-3.5-4.5Ni- ≤0.20W	CIS, formerly USSR
07Ch17G15NAB	Fe-0.05C-18.4Cr-16.5Mn-1.6Ni-0.01Ce-0.005B- 0.32N	CIS, formerly USSR
07Ch17G17DAMB	Fe-0.06C-17.6Cr-15.2Mn-0.43Mo-0.3Nb-0.005B- 0.38N	CIS, formerly USSR
08Ch17N15M3B	Fe-≤0.08C-16.0-18.0Cr-14.0-16.0Ni-3.0-4.0Mo-Ti	CIS, formerly USSR
08Ch17N15M3T	Fe-≤0.08C-≤0.80Si-≤2.0Mn-≤0.35P-≤0.020S- 16.0-18.0Cr-3.00-4.00Mo-14.0-16.0Ni-≤0.20W-0.30Cu- 0.30-0.60Ti	CIS, formerly USSR
08Ch17N5M3	Fe-0.06C-0.10C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.020S- 16.0-17.5Cr-3.0-3.5Mo-4.5-5.5Ni-≤0.20W-≤0.30Cu- ≤0.20Ti	CIS, formerly USSR
08Ch17T	Fe-≤0.08C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.025S- 16.0-18.0Cr-≤0.6Ni-≤0.30Cu	CIS, formerly USSR
08Ch18G8N2M2T	Fe-0.08C-18.2Cr-3.42Ni-8.9Mn-2.32Mo-0.22Ti	CIS, formerly USSR
08Ch18G8N2T	Fe-≤0.08C-≤0.80Si-7.0-9.0Mn-≤0.035P-17.0-19.0Cr- ≤0.30Mo-1.80-2.80Ni-≤0.30Cu-≤0.035P-≤0.025S- ≤0.20-0.50Ti-≤0.20W	CIS, formerly USSR
08Ch18N10	Fe-≤0.08C-≤0.8Si-≤2.0Mn-≤0.035P-≤0.020S-17-19Cr- 0.3Mo-9.0-11.0Ni-≤0.2W-≤0.3Cu	CIS, formerly USSR
08Ch18N10T	Fe-≤0.08C-≤0.8Si-≤2.0Mn-≤0.035P-≤0.020S-17-19Cr- 0.5Mo-9.0-11.0Ni-0.5Ti-≤0.2W-≤0.3Cu	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
08Ch21N6M2T	Fe-≤0.08C-≤0.8Si-≤0.8Mn-≤0.035P-≤0.025S-20-22Cr-1.8-2.5Mo-5.5-6.5Ni-0.2-0.4Ti-≤0.2W-≤0.3Cu	CIS, formerly USSR
08Ch22N6M2T	Fe-≤0.08C-≤0.80Si-≤0.80Mn-20.0-22.0Cr-1.80-2.50Mo-5.50-6.50Ni-≤50.20W-≤0.30Cu-≤0.035P-≤0.025S-0.20-0.40Ti	CIS, formerly USSR
08Ch22N6T	Fe-≤0.08C-≤0.8Si-≤0.8Mn-≤0.035P-≤0.025S-21-23Cr-≤0.3Mo-5.3-6.3Ni-≤0.2W-≤0.3Cu, 5x% C max. 0.65Ti	CIS, formerly USSR
08ChP	Fe-0.25Cr-0.25Ni-0.25Mo	CIS, formerly USSR
09Ch16N15M3B	Fe-≤0.09C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.020S-15.0-17.0Cr-≤0.30Cu-2.5-3.0Mo-0.6-0.9Nb-14.0-16.0Ni-≤0.20Ti-≤0.20W	CIS, formerly USSR
09G2S	Fe-≤0.12C-0.5-0.8Si-1.3-1.7Mn-≤0.035P-≤0.035S-≤0.3Cr-≤0.3Ni-≤0.3Cu	Bulg.
0Ch17N16M3T	Fe-≤0.080C-≤0.8Si-≤2.00Mn-16.0-18.0Cr-3.00-4.00Mo-14.0-16.0Ni-≤0.035P-≤0.025S-0.30-0.60Ti	CIS, formerly USSR
0Ch18G8N3M2T	Fe-about 18 Cr-8Mn-3Ni-2Mo, Ti	CIS, formerly USSR
0Ch18N10T	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S-17-19Cr-9-12Ni, Ti 5xC-0.70	CIS, formerly USSR/Bulg.
0Ch18N12B	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S-17-19Cr-≤9.0-12Ni, Nb 10xC-1.00	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.4550
0Ch20N14S2	Fe- about 20Cr-14Ni-2Si	CIS, formerly USSR
0Ch21N5T	Fe-≤0.08Cr-21Cr-5Ni, Ti	CIS, formerly USSR s. text HNO3
0Ch23N18	Fe-≤0.20C-≤1.00Si-1.50Mn-22.0-25.0Cr-≤0.30Mo-17.0-20.0Ni-≤0.035P-≤0.025S	CIS, formerly USSR
0Ch23N28M3D3T	Fe-≤0.06C-≤0.8Si-≤2Mn-22-25Cr-2.4-3Mo-26-29Ni-0.5-0.9Ti-2.5-3.5Cu	CIS, formerly USSR/Bulg.
0Ch25T	Fe-≤0.01C-25Cr, Ti-stabilized	CIS, formerly USSR
0H17N12M2T	Fe-≤0.05C-≤1.0Si-≤2.0Mn-16-18Cr-2-3Mo-11-14Ni-≤0.045P-≤0.030S, Ti 5xC-0.60	Poland
10Ch13 (1Ch13)	Fe-0.08-0.15C-≤1.0Si-≤1.5Mn-≤0.040P-≤0.015S-11.5-13.5Cr-≤0.75Ni	CIS, formerly USSR/Bulg.
10Ch14AG15	Fe-≤0.10C-≤0.80Si-14.5-16.5Mn-≤0.045P-≤0.030S-13.0-15.0Cr-≤0.60Ni-≤0.60Cu-≤0.20Ti-0.15-0.25N	CIS, formerly USSR
10Ch14G14N4T	Fe-≤0.10C-≤0.80Si-13.0-15.0Mn-13.0-15.0Cr-≤0.30Mo-2.80-4.50Ni-≤0.20W-≤0.30Cu-≤0.035P-≤0.020S-5x% C max. 0.60Ti	CIS, formerly USSR
10Ch17	Fe-0.10C-17Cr	CIS, formerly USSR
10Ch17N13M2T	Fe-≤0.10C-≤0.80Si-≤2.0Mn-≤0.035P-≤0.020S-16.0-18.0Cr-≤0.30Cu-2.0-3.0Mo-12.0-14.0Ni-≤0.20W, Ti>5x% C	USA, comparable with DIN-Mat. No. 1.4571

Steel	Materials Compositions, Percent in Weight	Note
10Ch17N13M3T	Fe-≤0.10C-≤0.80Si-≤2.0Mn-≤0.035P-≤0.020S- 16.0-18.0Cr-≤0.30Cu-3.0-4.0Mo-12.0-14.0Ni- ≤0.20W-≤0.7Ti	USA, comparable with DIN-Mat. No. 1.4573
10Ch18N10M2T	Fe-≤0.10C-18Cr-10Ni-2Mo, Ti stabilized	CIS, formerly USSR
10Ch18N10T	Fe-≤0.10C-≤0.80Si-≤1.0-2.0Mn-≤0.035P-≤0.020S- ≤17.0-19.0Cr-≤10.0-11.0Ni	CIS, formerly USSR/Bulg.
10Ch18N9T(Ch18N9T)	Fe-0.08C-1.0Si-≤2Mn-≤0.045P-≤0.015S-17-19Cr- ≤0.3Mo-9-12Ni-Ti5xC-0.70	CIS, formerly USSR/Bulg.
12Ch13G18D	Fe-0.12C-13Cr-18Mn-Cu	CIS, formerly USSR
12Ch17G9AN4	Fe-≤0.12C-≤0.80Si-8.0-10.5Mn-≤0.035P-≤0.020S- 16.0-18.0Cr-≤0.30Mo-3.5-4.5Ni-≤0.20W-≤0.30Cu- ≤0.20Ti-0.15-0.25N	CIS, formerly USSR
12Ch18N10T	Fe-≤0.12C-≤0.8Si-≤2.0Mn-≤0.025P-≤0.020S- 17.0-19.0Cr-≤0.30Cu-≤0.50Mo-9.0-11.0Ni-≤0.20W- ≤0.70Ti	CIS, formerly USSR; comparable with DIN-Mat. No. 1.4878
12Ch18N9T	Fe-≤0.12C-≤0.80Si-≤2.0Mn-≤0.035P-≤0.020S- 17.0-19.0Cr-≤0.50Mo-8.0-9.5Ni-≤0.20W-≤0.30Cu- Ti = 5x % C	CIS, formerly USSR
12Ch21N5T	Fe-0.09-0.14C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.025S- 20.0-22.0Cr-≤0.30Mo-4.80-5.80Ni-≤0.20W-≤0.30Cu- 0.25-0.50Ti-≤0.08Al	CIS, formerly USSR
12Ch2M1	Fe-0.12C-2Cr-1Mo	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.7380, A 182, F 22, B.S. 1501-622
12Ch2N4A	Fe-0.09-0.15C-0.17-0.37Si-0.30-0.60Mn-≤0.025P- ≤0.025S-1.25-1.65Cr-3.25-3.65Ni-≤0.30Cu-≤0.15Mo- ≤0.03Ti-≤0.05V-≤0.12W	CIS, formerly USSR
12ChN2	Fe-0.09-0.16C-0.17-0.37Si-0.30-0.60Mn-≤0.035P- ≤0.035S-0.60-0.90Cr-1.50-1.90Ni-≤0.30Cu-≤0.15Mo- ≤0.03Ti-≤0.05V-≤0.20W	CIS, formerly USSR/Bulg.
13-4-1	Fe-0.043C-12.7Cr-3.9Ni-1.5Mo-0.68Mn-0.39Si- 0.009P-0.013S-0.030N	CIS, formerly USSR
14Ch17N2	Fe-≤0.11-0.17C-≤0.80Si-≤0.80Mn-16.0-18.0Cr- ≤0.30Mo-1.50-2.50Ni-≤0.20W-≤0.30Cu-≤0.030P- ≤0.025S-≤0.20Ti	CIS, formerly USSR
15Ch17N2	Fe-0.13C-0.49Si-0.52Mn-17.17Cr-1.75Ni-0.012P- 0.09S	CIS, formerly USSR
15Ch25T	Fe-≤0.15C-≤1.00Si-≤0.80Mn-≤0.035P-≤0.025S- 24.0-27.0Cr-≤0.30Cu-≤1.00Ni-0.09Ti	CIS, formerly USSR
15Ch28	Fe-≤0.15C-≤1.00Si-≤0.80Mn-27.0-30.0Cr-0.60Ni- ≤0.30Cu-≤0.035P-≤0.025S-≤1.0Ni-≤0.20Ti	CIS, formerly USSR
15Ch2M2FBS	Fe-about 0.15C-2Cr-2Mo-V-Nb-Si	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
15Ch5M	Fe-≤0.15C-≤0.50Si-≤0.50Mn-4.50-6.00Cr-0.40-0.60Mo-≤0.60Ni-≤0.03Ti-≤0.030P-≤0.025S-≤0.20Cu-≤0.05V-≤0.30W	CIS, formerly USSR
16GS	Fe-≤0.12-0.18C-≤0.40-0.70Si-0.90-1.20Mn-≤0.30Cr-≤0.30Ni-≤0.30Cu-≤0.035P-≤0.040S-≤0.05Al-≤0.08As-≤0.012N-≤0.03Ti	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.0481, A 414, A 515, A 516
18/8-CrNi-steel	Fe-≤0.12C-1.0Si-≤2.0Mn-≤0.045P-≤0.030S-≤17.0-19.0Cr≤8.0-10.0Ni	—
1815-LCSi	Fe-0.006C-18.3Cr-15.1Ni-1.5Mn-4.1Si-0.005S-0.010P-0.010N	UNS S30600, comparable with DIN-Mat. No. 1.4361
18-18-2	Fe-≤0.08C-1.5-2.5Si-≤2.0Mn-≤0.030P-≤0.030S-17.0-19.0Cr-17.5-18.5Ni	USA
18G2A	Fe-≤0.20C-≤0.50Si-≤0.9-1.7Mn-≤0.025P-≤0.020S-≤0.0200Al-≤0.30Cr-≤0.50Ni-≤0.30Cu-≤0.08Mo-≤0.020N-≤0.050Nb-≤0.03Ti-≤0.1V	Poland
20Ch13 (2Ch13)	Fe-0.16-0.25C-≤0.8Si-≤0.8Mn-12-14Cr-≤0.6Ni-≤0.030P-≤0.025S-≤0.30Cu-≤0.20Ti	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.4021, AISI 420, 420 S 29
20Ch23N18	Fe-≤0.2C-≤1.0Si-≤2.0Mn-22-25Cr-≤0.3Mo-17-20Ni-≤0.2W-≤0.3Cu-≤0.2Ti-≤0.035P-≤0.025S	CIS, formerly USSR
20Ch2G2SR	Fe-0.16-0.26C-0.75-1.55Si-1.4-1.8Mn-≤0.040P-≤0.040S-1.4-1.8Cr-≤0.30Ni-≤0.30Cu-0.02-0.08Ti-0.015-0.050Al-0.001-0.007B	CIS, formerly USSR
2320	Fe-≤0.08-1.0Si-1.0Mn-≤0.040P-≤0.030S-16.0-18.0Cr-≤1.0Ni	Sweden, comparable with DIN-Mat. No. 1.4016; AISI 430, 10Ch17T
23Ch2G2T	Fe-0.19-0.26C-0.40-0.70Si-1.4-1.7Mn-≤0.045P-≤0.045S-1.35-1.70Cr-≤0.30Ni-≤0.30Cu-0.02-0.08Ti-0.015-0.05Al	CIS, formerly USSR
36NChTju	Fe-≤0.05C-≤0.3-0.7Si-≤0.8-1.2Mn-≤0.020P-≤0.020S-11.5-13Cr-35-37Ni-0.9-1.2Al-2.7-3.2Ti	CIS, formerly USSR
40Ch13	Fe-0.36-0.45C-≤0.80Si-≤0.80Mn-≤0.030P-≤0.025S-12.0-14.0Cr-≤0.30Cu-≤0.60Ni-≤0.20Ti	CIS, formerly USSR, comparable with DIN-Mat. No. 1.4031
45 G2	Fe-0.41-0.49C-0.17-0.37Si-1.4-1.8Mn-0.035P-≤0.035S-≤0.30Cr-≤0.30Cu-≤0.15Mo-≤0.30Ni-≤0.03Ti-≤0.05V-≤0.20W	CIS, formerly USSR, comparable with DIN-Mat. No. 1.0912
50Ch	Fe-0.46-0.54C-0.17-0.37Si-0.50-0.80Mn-≤0.035P-≤0.035S-0.80-1.10Cr-≤0.30Ni-≤0.30Cu-≤0.15Mo-≤0.03Ti-≤0.05V-≤0.20W	CIS, formerly USSR
70G	Fe-0.67-0.75C-0.17-0.37Si-0.90-1.20Mn-≤0.035P-≤0.035S-≤0.25Cr-≤0.25Ni-≤0.20Cu	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
80S	Fe-0.74-0.82C-0.60-1.10Si-0.50-0.90Mn-≤0.040P-≤0.045S-≤0.30Cr-≤0.30Ni-≤0.30Cu-0.015-0.040Ti	CIS, formerly USSR
AISI 1008	Fe-0.10C-0.30-0.50Mn-≤0.030P-≤0.050S	USA, comparable with DIN-Mat. No. 1.0204
AISI 1018	Fe-0.15-0.20C-0.60-0.90Mn-≤0.030P-≤0.050S	USA
AISI C-1018	Fe-0.20C-0.25Si-0.58Mn-0.16Cr-0.04Mo-0.012-0.014P-0.02S	USA
ASTM A-159	Fe-3.1-3.4C-1.9-2.3Si-0.6-0.9Mn-0.15S-0.15P	USA
ASTM A-516 Gr. 70	Fe-0.27C-0.13-0.45Si-0.79-1.30Mn-≤0.035P-≤0.040S	USA, comparable with DIN-Mat. No. 1.0050 and No. 1.0481
ASTM XM-27	Fe-≤0.01C-≤0.40Si-≤0.40Mn-≤0.020P-≤0.020S-25.0-27.5Cr-≤0.20Cu-≤0.75-1.50Mo-≤0.015N-≤0.050-0.2Nb-0.50Ni, Ni+Cu≤0.50	USA, comparable with AISI XM-27
C 1204	Fe-0.20C-0.35Si-0.50Mn-0.050P-0.050S-0.30Cr	Yugoslavia, comparable with DIN-Mat. No. 1.0425, B.S. 1501 Gr. 161-400, 164-350, 164-400; 16 K
C 90	Fe-0.85-0.94C-≤0.35Si-≤0.35Mn-≤0.03P-≤0.03S	Italy
Carpenter 20 Cb-3	Fe-≤0.06C-≤1.00Si-≤2.00Mn-19.0-21.0Cr-2.0-3.0Mo-32.5-35Ni-3.0-4.0Cu-≤0.035P-≤0.035S	USA
Ch12M	Fe-1.45-1.65C-0.15-0.35Si-0.15-0.4Mn-11-12.5Cr-0.4-0.6Mo-≤0.35Ni-15-0.3V-≤0.2W-≤0.3Cu-≤0.03Ti	CIS, formerly USSR
Ch14N40SB	Fe-0.034C-4.0Si-0.05Mn-14.4Cr-38.9Ni-0.63Nb	CIS, formerly USSR
Ch15T	Fe-≤0.1C-≤0.8Si-≤0.8Mn-14-16Cr-≤0.3Mo-≤0.6Ni, 5x%C≤Ti≤0.8	CIS, formerly USSR/Bulg.
Ch17	Fe-≤0.08C-≤1Si-≤1Mn-≤0.040P-≤0.015S-16.0-18.0Cr	Bulg., comparable with DIN-Mat. No. 1.4016, AISI 430, 12Ch17T, X6Cr17
Ch17N12M3T	Fe-≤0.12C-≤1.5Si-≤2.0Mn-16-19Cr-3-4Mo-11-13Ni-0.3-0.6Ti	CIS, formerly USSR/Bulg.
Ch17N18M2T	Fe-0.09C-0.6Si-1.4Mn-16.9Cr-1.9Mo-12.3Ni, Ti stab. (p.a.)	CIS, formerly USSR/Bulg.
Ch17N2	Fe-17Cr-2Ni	CIS, formerly USSR
Ch17T	Fe-≤0.05C-≤1Si-≤1Mn-≤0.040P-≤0.015S-16.0-18.0Cr, Ti4x(C+N)+0.15-0.80	Bulg., comparable with DIN-Mat. No. 1.4510, 08Ch17T, X3CrTi17
Ch18AG14	Fe-18Cr-14Mg-0.5N	
Ch18N9T	Fe-≤0.08C-≤1Si-≤2Mn-≤0.045P-≤0.015S-	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.4541, X6CrNiTi18-10
Ch18N10T	17.0-19.0Cr-9.0-12.0Ni, Ti 5xC-0.70	
Ch18N10	Fe-0.08C-18.4Cr-10.2Ni-1.08Mn-0.3Si-0.005P-0.014S-0.005N	

Steel	Materials Compositions, Percent in Weight	Note
Ch18N12M2T	Fe- $\leq 0.15\text{C}$ - $\leq 5.15\text{Si}$ - $\leq 2\text{Mn}$ - $17\text{-}19\text{Cr}$ - $2\text{-}2.5\text{Mo}$ - $11\text{-}13\text{Ni}$, $4\text{x}\%\text{C}\leq\text{Ti}\leq 0.8$	CIS, formerly USSR/Bulg.
Ch18N12T	Fe- 0.08C - 1.0Si - $\leq 2.0\text{Mn}$ - $\leq 0.045\text{P}$ - $17.0\text{-}19.0\text{Cr}$ - $9.0\text{-}12.0\text{Ni}$ - $\text{Ti} = 5\text{x}\%\text{C}\geq 0.70$	CIS, formerly USSR/Bulg.
Ch18N14	Fe- 0.035C - 18.8Cr - 14.6Ni - 0.35Mn - 0.75Si - 0.005P - 0.03S - 0.004N	
Ch18N40T	Fe- $< 0.08\text{C}$ - $< 1.0\text{Si}$ - $< 2.0\text{Mn}$ - $< 0.045\text{P}$ - $< 0.015\text{S}$ - $17\text{-}19\text{Cr}$ - $9\text{-}12\text{Ni}$ - $< 0.7\text{Ti}$	Comparable with DIN-Mat. No. 1.4541, AISI 321
Ch20N20	Fe- $0.004\text{-}0.015\text{C}$ - $19.4\text{-}21.8\text{Cr}$ - $19.3\text{-}20.8\text{Ni}$ - $0.05\text{-}5.40\text{Si}$ - $0.002\text{-}0.1\text{P}$	CIS, formerly USSR/Bulg
Ch22N5	Fe- 0.07C - 21.54Cr - 5.73Ni	CIS, formerly USSR
Ch23N18	Fe- $\leq 0.20\text{C}$ - $\leq 1.00\text{Si}$ - $\leq 1.50\text{Mn}$ - $22.0\text{-}25.0\text{Cr}$ - $\leq 0.30\text{Mo}$ - $17.0\text{-}20.0\text{Ni}$ - $\leq 0.035\text{P}$ - $\leq 0.025\text{S}$	CIS, formerly USSR/Bulg.
Ch23N27M2T	Fe- 27Ni - 23Cr - 2Mo - Ti	CIS, formerly USSR/Bulg.
Ch23N28M3D3T	Fe- 28Ni - 23Cr - 3Mo - 3Cu - Ti	CIS, formerly USSR
Ch25T	Fe- $\leq 0.15\text{C}$ - $\leq 1.00\text{Si}$ - $\leq 0.80\text{Mn}$ - $24.0\text{-}27.0\text{Cr}$ - $\leq 0.30\text{Mo}$ - $\leq 0.60\text{Ni}$ - $\leq 0.035\text{P}$ - $\leq 0.025\text{S}$ - $5\text{x}\%\text{C}\leq\text{Ti}\leq 0.9$	CIS, formerly USSR/Bulg.
Ch28N18	Fe- 0.16C - 1.7Mn - 1.1Si - 22.6Cr - 18Ni - 0.4Ti (p.a.)	CIS, formerly USSR/Bulg.
ChN28MDT	Fe- $0.03\text{-}0.046\text{C}$ - $22.2\text{-}23.5\text{Cr}$ - $26.55\text{-}27.88\text{Ni}$ - $2.55\text{-}3.06\text{Mo}$ - $2.68\text{-}3.38\text{Cu}$ - $0.54\text{-}0.76\text{Ti}$ - $0.15\text{-}0.30\text{Mn}$ - $0.39\text{-}0.69\text{Si}$ - $0.021\text{-}0.43\text{P}$ - $0.008\text{-}0.017\text{S}$	CIS, formerly USS
ChN40B	Fe- 0.032C - 18.2Cr - 40.4Ni - 0.08Si - 0.05Mn - 0.49Nb	CIS, formerly USSR
ChN40S	Fe- 0.031C - 20.0Cr - 38.9Ni - 4.2Si - 0.05Mn - 0.13Nb	CIS, formerly USSR
ChN40SB	Fe- 0.04C - 18.8Cr - 39.4Ni - 4.3Si - 0.06Mn - 0.63Nb	CIS, formerly USSR
ChN58W	Ni- 0.03C - $14.5\text{-}16.5\text{Cr}$ - $15\text{-}17\text{Mo}$ - $3.0\text{-}4.5\text{W}$ - 1.5Fe - 1.0Mn - $< 0.12\text{Si}$ - 0.02S - 0.025P	CIS, formerly USSR
ChN60V	Fe- $0.01\text{-}0.02\text{C}$ - 0.09N - $\text{max.} 0.05\text{Zr}$ - 0.1Ti - 0.015Ce - $\text{max.} 1.7\text{Nb}$ - $\text{max.} 0.009\text{B}$	CIS, formerly USSR
ChN77TJuR	Fe- $\leq 0.07\text{C}$ - $\leq 0.60\text{Si}$ - $\leq 0.40\text{Mn}$ - $\leq 0.015\text{P}$ - $\leq 0.007\text{S}$ - $0.6\text{-}1.0\text{Al}$ - $\leq 0.01\text{B}$ - $\leq 0.02\text{Ce}$ - $19.0\text{-}22.0\text{Cr}$ - $\leq 1.0\text{Fe}$ - $\leq 0.001\text{Pb}$ - $2.4\text{-}2.8\text{Ti}$	CIS, formerly USSR
FC 20	Fe- 3.92C - 1.12Si - 0.63Mn - 0.072P - 0.012S	Japan
JS 700	Fe- 0.04C - $\leq 1.0\text{Si}$ - $\leq 2.0\text{Mn}$ - $\leq 0.040\text{P}$ - $\leq 0.030\text{S}$ - $19\text{-}23\text{Cr}$ - $4.3\text{-}5.0\text{Mo}$ - $24\text{-}26\text{Ni}$, $\text{Nb}\geq 8\text{x}\%\text{C}\leq 0.40$	USA
OZL-17u	Fe- 0.04C - 0.32Si - 1.5Mn - 23.2Cr - 0.2Mo - 29.4Ni - 0.01P - 0.01S - 0.1Ti	CIS, formerly USSR
S35C	Fe- $0.32\text{-}0.38\text{C}$ - $0.15\text{-}0.35\text{Si}$ - $0.60\text{-}0.90\text{Mn}$ - $\leq 0.030\text{P}$ - $\leq 0.035\text{S}$ - $\leq 0.20\text{Cr}$ - $\leq 0.30\text{Cu}$ - $\leq 0.20\text{Ni}$	Japan, comparable with DIN-Mat. No. 1.0501
SIS 2333	Fe- $\leq 0.05\text{C}$ - 1.0Si - 2.0Mn - $\leq 0.045\text{P}$ - $\leq 0.030\text{S}$ - $17.0\text{-}19.0\text{Cr}$ - $8.0\text{-}11.0\text{Ni}$	Sweden, comparable with DIN-Mat. No. 1.4303; AISI 304, 03Ch18N11
SKH 2	Fe- $0.73\text{-}0.83\text{C}$ - 0.45Si - 0.40Mn - $\leq 0.030\text{P}$ - $\leq 0.030\text{S}$ - $3.8\text{-}4.5\text{Cr}$ - $\leq 0.25\text{Cu}$ - $17.0\text{-}19.0\text{W}$ - $1.0\text{-}1.2\text{V}$	Japan, comparable with DIN 1.3355

Steel	Materials Compositions, Percent in Weight	Note
SKH-4A	Fe-0.80C-0.29Si-0.31Mn-4.16Cr-17.64W-9.3Co-1.1V	Japan
SKH-9	Fe-0.85C-0.16Si-0.31Mn-4.14Cr-4.97Mo-6.03W-1.88V	Japan
SS41	Fe-≤0.050P-≤0.050S	Japan, comparable with DIN-Mat. No. 1.0040
St 38b-2	Fe-0.12-0.20C-0.17-0.37Si-0.40-0.65Mn-≤0.045P-≤0.050S-Cr+Cu+Ni≤0.70	Germany, formerly GDR, comparable with DIN-Mat. No. 1.0038, BS 4360-40C and A 570 Gr. 36
St35b-2	Fe-≤0.16C-0.17-0.40Si-0.35-0.65Mn-≤0.30Cr-≤0.30Ni-≤0.30Cu-0.050P-0.050S	Germany, formerly GDR, comparable with DIN-Mat. No. 1.0309
St35hb	Fe-≤0.18C-≤0.17Si-0.35-0.65Mn-0.050P-0.050S	Germany, formerly GDR
St38	Fe-≤0.20C-≤0.080-≤0.060S	Germany, formerly GDR, comparable with DIN-Mat. No. 1.0037
St5	Fe-≤0.045P-≤0.045S-≤0.009N	Poland, comparable with DIN-Mat. No. 1.0050
SUS 304	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S-18.0-20.0Cr-8-10.5Ni	Japan, comparable with DIN-Mat. No. 1.4301
SUS 430	Fe-≤0.12C-≤0.75Si-≤1.00Mn-16.0-18.0Cr-≤0.60Ni-≤0.040P-≤0.030S	Japan, comparable with DIN-Mat. No. 1.4016, AISI 430, 430 S 15, 12Ch17
Sv-08	Fe-≤0.10C-≤0.03Si-0.35-0.60Mn-≤0.040P-≤0.040S-≤0.015Cr-≤0.30Ni-≤0.01Al	CIS, formerly USSR
TsL-17	Fe-0.1C-5Cr-1Mo	CIS, formerly USSR
TsL-9	Fe-0.07C-1.00Si-2.3Mn-24.1Cr-12.9Ni-1.1Nb-0.03P-0.02S	CIS, formerly USSR
U10A	Fe-0.96-1.03C-0.17-0.33Si-0.17-0.28Mn-≤0.025P-≤0.018S-≤0.20Cr-≤0.20Ni-≤0.20Cu	CIS, formerly USSR, comparable with DIN-Mat.No. 1.1545, AISI W 1 10
U7A	Fe-0.65-0.75C-0.10-0.30Si-0.10-0.40Mn-≤0.030P-≤0.030S	CIS, formerly USSR, comparable with DIN-Mat. No. 1.1520
U8A	Fe-0.75-0.85C-0.10-0.30Si-0.10-0.40Mn-≤0.030P-≤0.030S	CIS, formerly USSR, comparable with DIN-Mat. No. 1.1525
X5CrNiMoCuTi18-18	Fe-≤0.07C-≤0.80Si-≤2.0Mn-≤0.045P-≤0.030S-16.5-18.5Cr-2.0-2.5Mo-19.0-21.0Ni-1.8-2.2Cu-Ti≥7x%C	Germany, formerly GDR, comparable with DIN-Mat. No. 1.4506
X8CrNiTi18-10	Fe-≤0.10C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S-17.0-19.0Cr-9.0-12.0Ni-Ti≥5 x C≤0.80	Germany, formerly GDR, comparable with DIN-Mat. No. 1.4541

Index of materials

o

06ChN28MDT 276–277
 08Ch17T 277
 08Ch21N6M2T 277
 08Ch22N6T 277
 0.6015 160
 0.6025 256, 258–259, 357
 0.7040 258–259
 0.9635 257–259, 357
 0.9650 261

1

1.0037 158, 252
 1.0038 38, 41–43
 1.0040 253–255
 1.0116 158
 1.0254 158
 1.3964 279
 1.4000 253–255, 260
 1.4006 277
 1.4016 253–255, 260
 1.4301 49–52, 54–55, 165–166, 167,
 253–255, 264–265, 267–268, 271
 1.4306 49, 166, 168, 265, 279
 1.4401 49, 54, 166, 167, 260, 264–265,
 267–268, 270–271, 353
 1.4404 49, 166, 265, 279
 1.4408 258–259, 261
 1.4417 260, 268–269
 1.4435 49, 165–166, 167, 273
 1.4436 49, 166, 264, 269
 1.4438 167
 1.4439 49, 165–166, 167, 265, 358
 1.4449 167
 1.4462 49, 167
 1.4510 49–50, 160, 170, 277
 1.4511 170
 1.4512 50, 260
 1.4517 257–259, 357

1.4521 49–50
 1.4529 264, 273, 275–276, 358
 1.4539 49, 166, 264–265, 273, 358
 1.4541 49, 265, 271, 277
 1.4550 51
 1.4558 55
 1.4562 275, 358
 1.4571 49, 51, 54–55, 165, 169, 265,
 271–274, 277, 331
 1.4573 261
 1.4593 261
 1.5736 253–255
 1.7050 201
 1.7220 253–255, 260
 10Ch17N13M2T 277
 12Ch13 277
 12Ch18N10T 277
 15Ch25T 277
 1015 252–253

2

2.0040 27
 2.0060 27
 2.0065 27
 2.0070 27, 253–255
 2.0076 27
 2.0090 27
 2.0290.01 31
 2.0340.02 31
 2.0340.05 31
 2.0360 253–255
 2.0401 31
 2.0402 31
 2.0872 251, 356
 2.0882 251, 356
 2.4360 281, 358
 2.4602 278, 358
 2.4605 275, 281, 358
 2.4610 275, 278, 358

2.4618 268–270, 277, 279
 2.4660 268–269, 279
 2.4819 266, 268–270, 275, 277–279, 358
 2.4856 266, 268–269, 275, 277–279, 358
 2.4858 268–270, 277, 279
 20Cb-3 279
 26-1 279
 28Cr-4Mo 268–269
 28Cr-4Mo-2Ni 268–269
 29-4 268–269
 29-4-2 268–269
 2205 167

3

3.3315 157
 3.3535 157
 3.3537 157
 3.3547 157
 3RE60 260
 31 275
 34CrMo4 253–255, 260
 36NiCr10 253–255
 316 49, 54, 166–167, 260, 264, 264–265,
 267, 267–269, 271, 353
 304 49, 50, 52, 54–55, 165–167, 253–255,
 264–265, 267, 267–268, 271
 304 L 49, 166, 168, 265, 279
 316 L 49, 165–167, 265, 270, 273, 279
 316 Ti 49, 51, 54–55, 165, 169, 261, 265,
 271, 273–274, 277, 331
 317 167
 317 L 167
 317 LMN 49, 165–167, 265, 358
 321 49, 265, 271, 277
 348 51

4

400 281
 403 253–255, 260
 409 50, 260
 410 277
 430 253–255, 260
 430 Ti 50
 439 49, 170
 444 49, 50

5

59 275, 281, 358

6

625 269, 275, 279

8

825 279

9

904 L 49, 166, 264–265, 358
 926 275

a

A 536 201
 AA 1050 21–22
 AA 5005 157
 AA 5049 21
 AA 5083 157
 AA 5454 157
 AA 5754 157
 AA 6003 17, 20
 AA 6060 21
 AA 7072 21, 23
 ABRESIST® 307
 ABS 207, 310, 315
 acrylic glass 209
 acrylic resins 208
 acrylonitrile-butadiene rubber 310, 334,
 339
 acrylonitrile-butadiene-styrene
 copolymer 310
 adipic acid esters 323
 Aflon® 339
 AISI 304 49, 50, 52, 54–55, 165–166, 167,
 253–255, 264–265, 267, 267–268, 271
 AISI 304 L 49, 166, 168, 265, 279
 AISI 316 49, 54, 166, 167, 260, 264–265,
 267, 267–269, 271, 353
 AISI 316 L 49, 165–166, 167, 265, 270,
 273, 279
 AISI 316 Ti 49, 51, 54–55, 165, 169, 261,
 265, 271, 273–274, 277, 331
 AISI 317 167
 AISI 317 L 167
 AISI 317 LMN 49, 165–166, 167, 265, 358
 AISI 321 49, 265, 271, 277
 AISI 348 51
 AISI 403 253–255, 260
 AISI 409 50, 260
 AISI 410 277
 AISI 430 253–255, 260
 AISI 430 Ti 50
 AISI 439 49, 170
 AISI 444 49, 50
 AISI 904 L 49, 166, 264–265, 358
 AISI 1015 252–253
 AL-6X 167
 Al 99.5 21–22
 alkali borosilicate glass 363
 alloy 31 275
 alloy 59 275, 281
 alloy 316 L 270

alloy 400 281
 alloy 625 275
 alloy 926 275
 alloy C-4 275, 278, 358
 alloy C-22 278, 358
 alloy C-276 275, 278, 358
 AlMg1 157
 AlMg2.7Mn 157
 AlMg2Mn0.8 21
 AlMg3 157
 AlMg4.5Mn 157
 AlMgMn 15–18
 AlMgSi0.5 21
 AlMgSi0.8 17, 20
 AlMn 21
 Alpolit® UP 339
 Aluflex-Spezial® solution 16
 aluminium 15, 17, 144, 156, 251, 356
 aluminium alloys 15, 156, 251, 356
 aluminium-magnesium-manganese alloy 15
 aluminium materials 356
 aluminous cement 100, 101–102, 104–106, 108–109, 113, 174, 192–193
 AlZn1 21, 23
 Araldit® 339
 ASA 207
 asbestos 89, 172
 asbestos cement 89–90, 293, 299, 336, 342, 359
 asphalt 118
 Asplit 339
 austenitic CrNiMoCu(N) steels 48, 165, 262, 357
 austenitic CrNiMo(N) steels 165, 260, 262, 273–274, 357
 austenitic CrNi steels 165, 252–253, 257, 261–262, 273, 357
 azealic acid esters 323

b

Baypren® 339
 Beckopox 339
 BFC 296
 BIIR 346
 binders 304, 359
 Bisphenol A® 351
 bitumen 118, 120, 205
 black enamel 201
 blast furnace cement 100, 104–106, 107, 113, 292, 296, 297, 298–299, 342, 359
 blast-furnace slag cement 174
 BORESIST® 305
 Bornumharz 339

borosilicate glass 199, 305, 305–306, 360
 brass 17, 145, 156, 255
 brickwork 146, 148
 BS 310
 Buna 339
 Buna Hüls 339
 butadiene-acrylonitrile copolymer 346
 butadiene-styrene copolymer 310
 butadiene-styrene rubber 323, 333
 butyl rubber 323, 333, 338–339, 362

c

C-4 275, 278, 358
 C-22 278, 358
 C-276 275, 278–279, 358
 cadmium 56, 170, 358
 carbon 283, 353, 359
 Cariflex® IR 339
 Cariflex® S 339
 Carpenter® 20Cb-3 268–269, 278
 cast concrete 160
 cast ferrosilicon 256
 cast iron 11, 13, 145, 149, 160, 192, 201, 214, 215, 252, 255–257, 259, 271, 294, 296, 299, 303, 341, 341–342, 356–357, 359, 363
 cast steel 148, 150, 158, 252, 257, 261, 356, 356–357
 cathodes 170
 CC491K 31
 CC750S 31
 CC754S 31
 cellulose 323
 cellulose acetate 240
 cement 285–286, 289–292, 296–297, 299, 300–301, 338, 341–342, 342, 353
 cement-bound materials 13
 cemented materials 9
 cement grout 338
 cement mortar 12, 90, 92, 97, 99, 109, 148, 174, 259, 293–294, 295, 341, 356, 359
 cement mortar coatings 341
 cement paste 286
 CF-8M 258–259
 chlorinated hydrocarbons 215
 chloroprene 346, 362
 chloroprene rubber 310, 333, 338–339
 CIIR 346
 cladding elements 148
 clay 198
 coal tar 336
 coal tar pitch 47, 205
 coatings and linings 335, 362

- composite materials 349
- composites 363
- concrete 11, 90, 145–146, 174, 176, 214, 237–238, 243, 285–293, 288–289, 296–297, 299–301, 302, 303–304, 306–307, 335–337, 338, 340–344, 346, 348, 353, 356, 359, 362
- concrete structures 289
- copper 17, 20, 25, 144, 156, 255
- copper alloys 144
- copper-nickel alloys 251, 252, 356
- cotton 323, 334
- CR 310, 338–339, 346–347, 352, 361
- Cronifer® 1925 hMo 275
- CR rubber coatings 337
- CSM 339, 346
- CuNi10Fe1Mn 251–252, 356
- CuNi20Fe 76
- CuNi30Fe1Mn 251–252, 356
- CuNi 70/30 251
- CuNi 90/10 251
- CuNi alloys 252
- Cu-PHC 253–254
- CuSn5Zn5Pb5-C 31
- CuZn33Pb2-C 31
- CuZn39Pb1Al-C 31
- CuZn39Pb3 31
- CuZn40 253–255
- CuZn40Pb2 31
- CW004A 27
- CW005A 27
- CW008A 27
- CW020A 27, 253–255
- CW021A 27
- CW023A 27
- CW024A 26–27, 76
- CW325H 356
- CW352H 251
- CW354H 251, 356
- CW509L 253–255
- CW614N 31
- CW617N 31

- d**
- Derakane® 348
- Derakane® 411-45 351
- Derakane® 470 353
- Diabon® 283
- Diabon® F 283
- Diabon® F 100 284
- Diabon® HF 283
- Diabon® NS1 283
- Diabon® NS2 283
- ductile cast iron 47, 146, 163, 192, 341

- duplex steels 260, 262
- Duran® 305
- duroplast® 309, 314, 325, 332, 360

- e**
- E-Brite® 26-1 268–269, 278
- ECR glass 210
- ECTFE 339, 349
- E-Cu57 27
- E-Cu58 27
- EFA filler 100
- elastomer 309, 314, 325, 333
- enamel 115, 200–201, 209, 211, 306, 349, 360, 363
- EN AW-5005A 157
- EN AW-5083 157
- EN AW-5454 157
- EN AW-5754 157
- EN AW-6063 353
- EN-GJL-150 160
- EN-GJL-250 256–259
- EN-GJN-HV 600 261–262
- EN-GJS-400-15 258–259
- EP 310, 315, 319–321, 336–340, 348, 361
- EPDM 160–161, 215, 310, 315, 361
- EPDM rubber 125
- EP-GF 310
- epoxide 348
- epoxy resins 309, 310, 313, 323, 332, 336, 337–338, 339, 348, 353, 362
- epoxy-tar 296
- ETFE 310, 339
- ethylene/chlorotrifluoroethylene 339
- ethylene-propylene copolymer 310
- ethylene-propylene-diene rubber 160, 310
- ethylene/tetrafluoroethylene 339
- ethylene-tetrafluoroethylene copolymer 310
- ethylene-vinyl acetate copolymer 328

- f**
- FEP 339, 349
- ferritic-austenitic cast alloys 261
- ferritic-austenitic steels 165, 260, 262, 357
- ferritic chromium steels 48, 165, 260, 357
- ferritic/pearlitic-martensitic steels 260
- ferritic stainless chromium steel 260
- fiber cement 299–300, 348
- fibers 334
- fibre cement 148, 172
- fibre concrete 146, 172–173
- fibrous concrete 214–215, 237
- fireclay 145, 202
- First Latex Crepe 339

Flakeline® 232 340
 flexible polyethylene 119
 Fluorel® 339
 fluorinated rubber 161, 217, 310, 339
 fluoropolymerisates 323, 330, 331, 334
 FN 339
 Foraflon® 339
 FPM 217, 310, 315, 339, 361
 FRP 146, 209, 237, 243
 furan resins 303, 329, 333, 339
 fused basalt 307

g

G 279
 G41300 260
 galvanized steel 37, 302, 343, 362
 G-CuSn5ZnPb 31
 G-CuZn33Pb 31
 GD-CuZn37Pb 31
 GD-Ms60 31
 Genakor® 339
 GG-15 160
 GG 22 357
 GG 25 357
 GGG-50 201
 GK-CuZn37Pb 31
 GK-Ms60 31
 glass 199, 240, 305–306, 329, 333, 349, 360
 glass-fibre reinforced plastic 143
 glass-fibre-reinforced polyester resin 195
 glass flakes 340
 G-Ms65 31
 graphite 283–285, 329, 338, 349, 359, 363
 gray cast iron 12, 47, 170, 252–253, 256–257, 357
 Grilamid® 339
 GRP 347, 349–354
 GX250CrMo15-3 257, 357
 GX2CrNiMoCuN25-6-3-3 257, 258, 259
 GX300CrMo15-3 257–259, 357
 GX3CrNiMoCuN24-6 257, 357
 GX3CrNiMoCuN24-6-2-3 261–262
 GX3CrNiMoCuN24-6-5 261
 GX5CrNiMo19-11-2 258–259
 GX5CrNiMo19-11-2 261

h

Halar® 339
 Halon® 339
 hardened cement paste 341
 hard PVC 145
 hard rubber 334
 Hastelloy® 283

Hastelloy® alloy C-276 266, 268–270, 277–278
 Hastelloy® alloy G 268–270, 277–278
 Hastelloy® C 278, 284
 HDPE 119, 205–206, 214
 high-alloy cast iron 256, 357
 high-alumina cement 292, 297, 297–299, 342
 high-density polyethylene 205
 high-grade aluminium 21
 high-temperature thermoplastics 323, 331
 Hostaflon® 339
 Hostaflon® ET 339
 Hostaflon® FEP 339
 Hostaflon® PFA 339
 Hostalen® 339
 Hostalen® GM 5010 121, 327
 Hostalen® PP 339
 Hostalit® 339
 HS cement 287
 Hypalon® 339

i

IIR 338–339, 346–347
 Incoloy® 283
 Incoloy® 825 268–270, 277
 Inconel® 625 358
 Inconel® alloy 269
 Inconel® alloy 625 266, 268, 275, 277–278
 in-situ concrete 146, 148, 174
 IR 339, 346
 isobutylene-isoprene copolymer 346
 isobutylene-isoprene rubber 339
 isophthalic acid/polyester resin 337

k

K02401 158
 K02501 158
 K02502 38, 41–42
 Kalrez® 339
 Kel-F® 339
 killed steel 87
 Kynar® 339

l

L-Ag 40 Cd 52, 54
 LDPE 119
 lead 170
 lead alloys 170
 limestone 183
 loam 198
 low-alloy cast iron 357
 low-alloy steels 252, 356

m

MBS 310
 methylmethacrylate-butadiene-styrene
 copolymer 310
 microbiological corrosion 323
 Monel® 400 358
 mortar 90, 174, 259, 285, 294–295,
 297–298, 335, 341–343
 Ms 58 31
 multiphase steels 260, 357

n

N06059 275
 N06625 275
 N08031 275, 358
 N08904 49, 273
 N08926 264, 275, 358
 N10276 275
 Natsyn® 339
 natural rock 174
 natural rubber 309, 310, 323, 333–334,
 339, 346
 NBR 161, 216, 310, 315, 339, 346, 361
 Neoflon® 339
 Neopren® 339
 nickel-chromium alloys 277, 358
 nickel-chromium-iron alloys 277, 358
 nickel-chromium-molybdenum alloys 277,
 358
 nickel-copper alloys 277, 358
 NiCr20CuMo 268–269, 279
 NiCr21Mo 268–270, 277, 279
 NiCr21Mo14W 278, 280, 358
 NiCr22Mo6Cu 268–270, 277, 279
 NiCr22Mo9Nb 266, 268–269, 275,
 277–280, 358
 NiCr23Mo16Al 275, 281, 358
 Nicrofer® 3127 hMo 275
 Nicrofer® 5716 hMoW 275
 Nicrofer® 5923 hMo 275
 Nicrofer® 6020 hMo 275
 NiCu 30 Fe 281, 358
 NiMo16Cr15W 266, 268–270, 275,
 277–280, 358
 NiMo16Cr16Ti 275, 278, 280, 358
 niobium 281, 358
 nitrile rubber 125, 216, 346
 Nitronic® 10 279
 Nitronic® 33 279
 Nitronic® 50 279
 Nitronic® 60 279
 Noriclor® NL 24 6 261
 Noridur® 261
 Noridur® 9.4460 257–259

Norihard® NH 15 3 257, 258, 259
 Noriloy® NL 25 2 261
 Norinox® 261
 Novolak® 351
 NR 215, 310, 315, 339, 346, 361
 NR/SBR 346
 Nylon® 334, 341
 Nylon® 6 322

o

OF-Cu 27

p

PA 315, 339
 PA 6 310, 322
 PA 66 310, 322
 Palatal 339
 PAN 310, 315
 PB 310, 326, 329
 PBFC 296
 PBT 310
 PC 296, 310, 315
 PCTFE 339
 PE 146, 237, 310, 315, 322, 326, 328–329,
 339, 341–342, 344–346, 349, 361, 363
 PE-C 310
 PE-GRP 352
 PE-HD 243, 304, 310, 316–318, 324,
 326–328, 336, 343–345, 347–348,
 360–361
 PE-LD 310, 326, 328
 PE-LLD 310
 PE-MD 344, 362
 Perbunan® N 339
 perfluoroalkoxy polymers 339
 Perlon® 334
 Permatex® 339
 PET 310, 315
 PE-VLD 310, 328
 PF 310, 315, 339, 353, 361
 PFA 339
 PF-GF 310
 phenol-formaldehyde resins 309, 310, 313,
 323, 328, 332, 332–333, 339, 353
 phenol resins 329, 353–354, 363
 phthalic acid ester 323
 PI 310
 PIB 310, 347
 pitch 118
 plasticised PVC 214
 plastics 205
 plastic thermosetting resins 211
 Plexiglas® 143, 208–209
 Plexiglas® XT 209

- PMMA 145, 208, 311, 315, 336
 polyacetal 311
 polyacrylonitrile 172, 310, 334
 polyamide 240, 308, 310, 314, 322, 331, 334, 339
 polyamide 6 334
 polyamide 6.6 334
 polybutene 310, 329
 polybutylene-terephthalate copolymer 310
 polycarbonate 310, 331
 polychlorobutadiene 346
 polychloroprene rubber 125
 polychlorotrifluoroethylene 339
 polyester 209, 314, 323, 334, 338, 348–349, 353
 polyester PBTP 334
 polyester resins 255, 324, 333, 339–340, 363
 polyester urethane 323
 polyetheramide 311
 polyether urethanes 323
 polyethylene 214, 243, 304, 310, 313, 313–314, 322, 328, 334, 336, 339, 344, 346, 348, 362
 polyethylene terephthalate 310
 polyimide 310
 polyisobutylene 310, 347
 polyisoprene 339, 346
 polymer concrete 143, 194, 303, 353
 polymethacrylate resins 336
 polymethylmethacrylate 208, 311
 polyolefins 205, 308, 326, 329, 331
 polyoxymethylene 311, 331
 polyphenylene sulfide 311, 331
 polyphenylene sulfone 311
 polypropylene 243, 309, 311, 314, 322, 329, 334, 336, 339
 polystyrene 301, 308, 311, 322
 polysulfone 240, 311
 polytetrafluoroethylene 217, 311, 314, 330, 334, 339
 polyurethane 311, 314, 323, 331, 336, 339, 341
 polyurethane grades 311
 polyvinyl acetate 311
 polyvinyl alcohol 172, 299, 311, 314
 polyvinyl chloride 205, 308, 311, 313, 322, 330, 339
 polyvinylidene fluoride 311, 331, 334, 339, 347
 POM 311, 315
 porcelain 145, 202
 Portland blast furnace cement 295–296, 298–299, 359
 Portland cement 94, 98, 100–108, 113, 172, 174, 193, 287, 298–299, 342
 Portland concrete 198
 Portland slag cement 174
 PP 207, 214, 243, 311, 315–318, 322, 324, 326, 328–329, 336, 339, 343, 349–350, 353, 360–361, 363
 PPS 311, 331
 PPSU 311
 prefabricated concrete parts 174
 pre-stressed concrete 146
 PS 311, 315
 PSU 311, 315
 PTFE 200, 217, 305, 311, 314–315, 329–331, 334, 339, 347, 361
 PUR 311, 336, 339, 341
 pure zinc 75, 81, 87–88
 putties 198
 PVAC 311
 PVAL 299, 311, 314
 PVC 143, 146, 214, 237, 284, 304, 311, 330, 339, 342, 346–348, 361
 PVC-C 206–207, 311, 316–318, 361
 PVC-P 311, 315, 330, 347
 PVC-U 311, 315–318, 324, 330, 343, 349, 360–361, 363
 PVDF 311, 315–318, 329, 331, 334, 339, 343, 347, 349, 361, 363
- q**
 Quacorr® 339
 quartz glass 199
 quartz material 199
- r**
 red brass 29
 reinforced concrete 13, 145–146, 156, 176
 resins 209
 Rhepanol® O.R.G. 347
 rigid PE 155, 206, 207
 rigid polyethylene 119
 rigid polyvinyl chloride 119
 rigid PVC 119, 155, 205–206, 207, 214
 Rilsan® A 339
 RSt 37–2 38, 41–43
 rubber 243, 323, 333, 337, 346
 rubber coatings 285, 337
 rubber linings 346
- s**
 S30400 49, 52, 54–55, 165
 S30403 49
 S31500 260–261
 S31600 49, 54

- S31603 49, 165
 - S31635 49, 54–55, 165
 - S31726 49, 165
 - S31803 49
 - S32100 49
 - S43035 49, 160
 - S44400 49
 - S44700 268–269
 - S44800 268–269
 - SAN 311, 315
 - sandstone 174
 - Sandvik® 2RN65 268–269
 - Sandvik® 3RE60 268–269
 - sanitary enamel 208
 - sanitary porcelain 208
 - SB 311
 - SBR 215, 311, 315, 339, 346, 361
 - SBS 311
 - SCM 435 (JIS) 253–254
 - seals and packings 363
 - sebacic acid esters 323
 - SE-Cu 27, 253, 255
 - sewer bricks 174, 198
 - SF-Cu 26–27, 76
 - SI 311, 339
 - silicon cast iron 256, 357
 - silicone 323
 - silicone rubber 309, 339
 - silicones 311
 - smoked sheets 339
 - SNC 631 (JIS) 253–254
 - soft rubber 334, 346
 - Solef® 339
 - Solidex® glass 200
 - special reinforced concrete 158
 - SS 400 (JIS) 253–254
 - St 37.0 158
 - St 37–2 158
 - St 37–3 158
 - St 38 252–253
 - stainless austenitic steels 331
 - stainless steel 10, 145, 150, 159, 165, 167, 169, 169–170, 248, 256, 263, 263–265, 271, 273, 275, 302, 304, 329, 358
 - steel 13, 145, 149–150, 214
 - Stellite® 262
 - stoneware 143, 146, 148, 187, 202, 202–203, 214–215, 237, 291, 306, 306–307, 342, 360
 - stove enamel 123
 - styrene-acryl copolymer 311
 - styrene-butadiene 301
 - styrene-butadiene copolymer 311, 346
 - styrene/butadiene rubber 125
 - styrene-butadiene rubber 311, 334, 339
 - styrene-butadiene-styrene block copolymer 311
 - styrene polymerisates 331
 - sulfate-resistant cements 296, 341
 - sulfate-resistant concrete 255
 - sulphur concrete 174, 197, 198
 - SW-Cu 27
 - synthetic fibres 172
 - synthetic rubber 125, 309, 323
 - synthetic textile fibres 172
- t**
- tantalum 271, 281, 358
 - tar 336–338
 - TC 296
 - Teflon® 339
 - Teflon® FEP 339
 - Teflon® PFA 339
 - Tefzel® 339
 - tetrafluoroethylene/
hexafluoropropylene 339
 - thermoelastomers 309
 - thermoplastic elastomers 311
 - thermoplastics 308, 309, 314, 325, 326, 360
 - thermosetting resin concrete 194
 - titanium 144, 266, 267–268, 268–269, 271, 278, 281–283, 284, 330, 358
 - titanium alloys 281, 358
 - TPE-A 311
 - TPE-O/V 311
 - TPE-U 311
 - TPU 311
 - trass cement 296
 - trass concrete 174
 - Trevira® fibers 242
 - Trovidur® 339
 - Trovidur® PP 339
 - Tyton® 215–216
- u**
- unalloyed cast 47
 - unalloyed cast iron 160, 357
 - unalloyed iron 17
 - unalloyed steel 11
 - unalloyed steels 158–159, 160, 252
 - unsaturated polyester resins 311, 336
 - UNS N06007 279
 - UNS N06022 280
 - UNS N06455 280
 - UNS N06625 279–280
 - UNS N08020 279
 - UNS N08825 279

UNS N08926 265, 276, 280
 UNS N10276 279–280
 UNS S21800 279
 UNS S44626 279
 UP 311, 319–321, 333, 338–339, 348, 351,
 353, 361
 UP-GF 311, 324, 333, 360–361
 UP-GRP 350
 urea-formaldehyde resins 323
 USt 42-2 253–255

V

VE 311, 319–321, 336, 338, 350–351, 353
 VE-GRP 350
 Vestolen® 339
 Vestolit® 339
 Vetrodur-N 339
 vinyl ester resins 336, 340, 350, 351, 363
 vinyl esters 303, 311, 336, 341, 348–349,
 362
 Viton® 339
 Voltalef® 339
 VPE 119

W

wood dust 323

X

X12Cr13 277
 X1NiCrMoCu25-20-5 49, 273
 X1NiCrMoCu32-28-7 275, 358

X1NiCrMoCuN25-20-5 264–265, 358
 X1NiCrMoCuN25-20-7 264–265, 273,
 275–276, 358
 X2CrMoTi18-2 49
 X2CrNi19-11 49, 168, 265
 X2CrNiMnMoNNb21-16-5-3 279
 X2CrNiMo17-12-2 49, 265
 X2CrNiMo18-14-3 49, 265, 273
 X2CrNiMoN17-13-5 49, 265, 358
 X2CrNiMoN22-5-3 49
 X2CrNiMoSi19-5 268–269
 X2CrTi12 260
 X2NiCrAlTi32-20 55
 X2NiCrMoCu25-20-6 280
 X3CrNb17 170
 X3CrNiMo17-13-3 49, 265, 269
 X3CrTi17 49, 170, 277
 X5CrNi18-10 49, 253–255, 265, 267–268,
 271
 X5CrNiMo17-11-2 268
 X5CrNiMo17-12-2 49, 260, 265, 267,
 270–271, 353
 X6Cr13 253–255, 260
 X6Cr17 253–255, 260
 X6CrNiMoTi17-12-2 49, 265, 271–274,
 277, 331
 X6CrNiTi18-10 49, 265, 271, 277

Z

zinc 17, 56, 65, 69–70, 87–88, 170, 211,
 358

Subject index

a

abrasion 143, 257, 262, 285, 341, 350
 abrasive wear 357
 ABS 206
 access ladders 149
 acid capacity 44
 activated carbon 273
 activated sludge tanks 349
 activated surface 244
 active anodes 303
 additives 309
 adhering deposits 168
 adsorption processes 240, 247
 aeration 237–238, 267
 aeration cells 248, 252, 356
 aeration tank 149, 236
 aerobic 242
 aging **308**
 air/material/waste water 168
 algae 314
 aliphatic hydrocarbons 332
 alkali metal melts 330
 alkaline waste water 156
 Alodine® 1200 16
 Alodine® 401 16
 alumina cement mortar lining 162
 aluminium association standards 157
 aluminous cement lining 192–193
 ammonia 244, 247, 251, 261
 amount of chloride ions 165
 anaerobic 243, 248–249, 294
 anaerobic conditions 254
 anaerobic sulfate-reducing bacteria 249
 animal husbandries 188
 annealing residue 18
 anode 301
 anode surfaces 303
 anodizing 274
 anodizing workshops 292

anoxic 250
 aqua regia 329
 aromatic hydrocarbons 332
 ASA 206
 asbestos cement pipes 89
 atmosphere 248, 297, 356
 atmospheric effects 309
 attack by microorganisms **309**
 ATV Worksheet 244

b

bacteria 11, 179, 242, 249, 297, 314
 bacterial activity 248
 bacterial degradation 253
 bacteriogenic sulfuric acid 298
 basins 145
 bath tubs 145, 160, 200, 209
 battery industry 325
 Bauch test 143
 bell-and-spigot coupling 212
 bell-and-spigot coupling system 163
 biochemical oxygen demand 293
 biocorrosion 170, 256, 357
 biodegradable 324
 biofilms **247**, 254, 256, 294
 biofouling 144, 248
 biogas **243**
 biogenic sulfate reduction 251
 biogenic sulfuric acid 292–293, 297
 biogenic sulfuric acid corrosion 144,
 176–177, 182–184, **184**, 188–189, **189**,
 191–193, 213, **248**, 295, 359
 biological industrial 256
 biological industrial waste water treatment
 plant 251
 biological oxygen demand 177, 239, 267
 biological reactions 248
 biological settling tanks 252
 biological sewage plants 336

biological sewage treatment plants 260,
271, 285, 305, 359
biological stage 253
biological waste water plants 271
biological waste water treatment 236, **242**
biomass 237
bitumen lining 11, 118
BOD 177, 293
borosilicate **305**
borosilicate glass pipes 200
bottom deposit 159
brazed joints 169
bridge pipelines 160
BSAC 144, 176, **184**, 188, 191–193
buffer tanks 253
burnishing 245

c

calcium carbonate 286
calcium hydrogen carbonate 286
calcium hydroxide 286, 290, 295
canalisation system 148
capillary pores 285
carbon dioxide 9, 244
carbonation **286**, 291
cast-iron drainpipes 160–161
cast-iron pipes 91, 214
cathode 158–159
cathodic corrosion protection 11
cathodic protection 144, **303**, 356
cell 303
cell formation 303
cellulose factory 327
cement concrete 174
cement industry 301
cement mortar 296
cement mortar coatings **293**, 297, 335,
363
cement mortar linings 9, 91–93, 108–113,
118, 146, 163–164, 192, 212, 259, 294,
295, 296, 299, 359
cement-bonded components 183
cement-bonded materials 213
cement-bonded mortar lining 257
cement-bound materials 174
centrifugal pumps 148, 150
chain raker 151
chemical degradation **309**
chemical industry 325
chemical load 360
chemical oxygen demand 239, 241,
270–271, 278, 293, 325, 347
chemical-resistant coating 333

chloride 274
chloride-containing waste waters 169
chlorinated hydrocarbons 285, 299, 329,
332, 353
chlorine bleaching solutions 346
chlorine treatment 70
clamped couplings 170
clamping collars 170
clamping sleeves 172
clarification basin 159
clarification plant see waste water treatment
plant 144
cleaning stoppers 160
coated steel components 158
coating process 211
coatings 211
COD 293, 347
cold water pipes 48
collars 161
collecting tanks 306, 349
combined sewers 173, 198, 203
concrete 156, 158
concrete basins 145, 158
concrete buildings 158
concrete cover **290**, 292
concrete mortar coating 341
concrete pipes 143, 205, 213
concrete sewers 299
concrete tanks 302
constructional steel textiles 158
contact corrosion 144, 273, 302
contact corrosion (in waste water) 159
contaminated soils 119, 121
corrosion fatigue (in waste water) 169
corrosion potential 253, 262, 302–303
corrosion rate 243, 256
crevice corrosion 48, 54–55
crevice corrosion (in waste
water) 158–159, 167–169, 248,
262–267, 269–270, 273–274, 356–357
crevice corrosion resistant 264
critical crevice width 159
critical pitting potential (in drinking
water) 27
crude oil 244

d

dealkalization 96
deburring 245
decalcification 94, 96, 102, 110
deposits 249, 252, 263, 294, 306, 358
dezincification 29
dibutyl adipate 322

dichloromethane 216
 differential pressure test 162
 diffusion 250, 294
 digestion tank 149
 dipping glazes 202
 dirt pans 170
 disinfection 119
 distillation 260, 284
 distilled water 117
 distribution lines 32
 dip-tar coating 91
 domestic installations 10, 12, 14, 25, 32,
 48, 51–52, 54, 56, 68, 81
 domestic sewage 145, 173
 dosing pumps 150
 drain gratings 170
 drainage 160
 drainage sewer 174
 drainpipes 160, 172
 drains 160, 175
 drinking water distribution 10
 drinking water hygiene 54
 drinking water installation 10
 drinking water lines 25
 drinking water plants 11
 drinking water tanks 8, 123
 drinking water transport 10
 drum filter 304
 drying of activated sludge 274
 dry-weather flow 198
 ductile cast-iron pipes 163–164, 193
 ductile sewer pipes 162
 DVGW Worksheet 341

e

EBOD 177, 190
 eccentric screw pumps 150
 effective BOD 177
 elastic sealing ring 215
 elastomer seals 169, 201
 electrical installation 148
 electrochemical cell 158–159
 electrogalvanisation 170
 electroplating 244, 274
 electroplating industry 241
 electroplating process 247
 electroplating works 305
 electropolishing works 292
 EML drainpipes 161
 enameling 244
 enamelled cast-iron pipes 217
 enamelling processes 201
 EPDM seals 161

epoxy resin coating 213
 epoxy resin powder coatings 212–213
 erosion corrosion 28
 estate drainage 148
 evaporation 242, 274–275
 evaporation processes 239, 278
 evaporator 281
 evaporator units 274, 283, 284, 285, 357,
 359
 ewer atmosphere 295
 exhaust steam residue 18
 extraneous rust 263, 358

f

fat separators 160
 Federal Water Resources Act 274, 299
 fertilizer industry 325
 fiber-reinforced composites 349
 fibers 293, 299, 359
 fibre cement pipes 170
 filter 238, 240, 273
 filter plant 150
 filtration 240
 final biological stage 252
 final biological treatment stage 253
 fish-scaling 115
 fittings 115, 148, 173, 201–202, 209
 fixing bath 293
 flap traps 153
 flocculant treatment 152
 flocculation tanks 349
 flocculator 150
 flow rate 8, 168, 253, 255, 263
 flue gas desulfurization plants 239, 252,
 261, 274–275, 278, 281, 283–284, 331
 flue gas desulfurization units 274, 357
 flue gas scrubbers 261
 flue gas treatment plants 350
 flue gases 278
 fluoride 281, 305, 349, 363
 fluoride concentration 271, 358
 fluoride ions 284
 flushing pipes 170
 food industry 325
 forced-flow pipelines 146, 161, 176, 183,
 185, 187–188, 189, 209–210
 frame 304
 FRP fittings 210
 FRP pipes 209
 fungi 314

g

galvanic anodes 303
 galvanic cell 156, **301**
 gas atmosphere 248, 252
 gas bubbles 55
 gas container 236
 gas pipelines 162, 328, 329
 gas tank 149, 151
 gaseous waters 244
 gates 156
 gathering line 199
 Gefahrgutverordnung 276
 giant rotors 150
 glass fiber grade 352
 glass fiber inlays 340
 glass fibers 349–350
 glass industry 292, 325
 glass pipes 199
 glass reinforcement 209
 glass sewer 199
 glass-fibre concrete shells 214
 gratings 149
 gravity-flow pipelines 176–177, 209–210
 gravity-flow sewers 142, 146, 161, 176, 183, 188, 193, 203
 gray cast iron pipes 47
 green chromating layer 16
 groundwater 71, 73, 203
 groundwater-protected areas 162
 gutters 150, 156

h

halogenated hydrocarbons 241, 247
 hard solder 52
 hard solder connection 74
 hardened cement paste **285**, 287, 295
 heat exchanger pipes 10
 heat exchanger plates 283
 heat treatment state 54
 heavy metal salts 156
 high-alumina cement mortar coatings 299
 hot water pipes 48
 hot water tanks 48
 hot-aluminized steel pipes 23
 hot-dip coating 171
 hot-dip galvanisation 171
 hot-dip galvanisation process 170
 hot-dip galvanised components 171
 hot-dip galvanised pipeline 171
 hot-dip galvanised steel pipes 58, 62, 66, 75–76, 78, 81
 hot-galvanised coatings 212
 human consumption 6, 9

hydroabrasive wear 257, 261
 hydrocarbons 240–242, 345–347
 hydrochlorocarbons 241
 hydrofluoric acid 281
 hydrogen cyanide 244
 hydrogen sulfide 244, 247, 250–251, 261, 271, 292, 294
 hygiene requirements 111, 119, 123
 hypochlorite solutions 330

i

impregnation with a synthetic resin 283
 industrial waste water 156
 industrial waste water treatment **244**
 industrial waste water treatment plants 156
 inert-gas-shielded arc welding 169
 insulating materials 167
 intercrystalline corrosion 48, 54
 intergranular corrosion (in waste water) 168, 170
 intergranular stress corrosion cracking (in waste water) 166
 internal pressure test of the creep rupture strength **326**, 360
 ion-exchange processes 241
 ionizing radiation 309
 iron bracket 158
 iron sulfides 254
 in-situ concrete 175

k

knife-line corrosion 52, 54, 169
 knotted steel 158

l

lakewater 71, 73
 lamellar graphite inclusions 160
 landfill leachates 235, 247, 274, 283, 293, 344, 349, 357
 landfills 328
 leachates 235, 275, 328, 344, 348, 362
 lead pipes 170
 leakproofness 162
 lichens 314
 lifting plants 145
 lifting stations 155
 light stabilizers 309
 lime water 196
 linear coefficient of expansion 116
 liner 347
 lining materials 342

linings 211, 243, 285, 306–307, 335–336,
338–339, 343, 346–347, 351
liquid/liquid extraction 240
local canalisation 148
local canalisation systems 162
local cathodic corrosion protection 159

m

macrocells 301, 304
macroelement 144
main biological treatment stage 253
malleable cast iron fittings 74
market garden 119
masonry 199
maximum permissible chloride
content 165
metal abrasion 358
metallic contact 302
metalworking industry 325
MIC 247
microbial activity 248
microbial attack 322, 324
microbial corrosion 314
microbial slime 11
microbial sulphate reduction 177
microbially influenced corrosion 247
microbiocides 324
microbiological attack 304
microbiological corrosion 314, 359
microbiological degradation 314
microbiological harmlessness 119
microbiologically induced corrosion 144
microorganisms 214, 247, 248–249, 362
mineral oil processing 325
minimum flow rate 294
Mohs hardness 209
Mohs scale 203
molecular structure 308
mortar linings 341
mountings 201
municipal waste water 156

n

neutral salt content 36, 40
neutralization 244, 352
neutralization processes 247
neutralization stage 253
non-ferrous fittings 74
non-metallic seal 54
non-self-supporting linings 214

o

oil industry 248
oil refinery 260
oil refining 260
one-layer enamel 201
ore digestion 293
organic coating 158
osmosis 240, 273
overflow constructions 148
oxygen 9
oxygen permeability 116
ozone 241, 253–255, 260, 271, 356
ozone test 204
ozone treatment 70
ozone-free water 356

p

paddle 150
paint industry 325
passivation 281, 291
passive 262
passive layer 271, 290
penetration resistance 301
percolating filter 149
permeation 312
petrol and fat separators 175
petrol separators 155
phosphating 274
photographic waste water 293
photooxidation 309
pickled 244
pickling 169, 271, 273–274
pickling baths 169, 244
pickling pastes 169
pipe couplings 160, 216
pipelines 32, 148
pipes 173, 202, 209
piston pumps 150
pitch-epoxide resin coating 160
pitting 165
pitting corrosion (in drinking water) 27,
29, 40, 55, 75, 77
pitting corrosion (in waste water) 156,
159, 165–166, 168–169, 201, 248, 251,
253, 262, 264–265, 267, 269–270,
273–275, 278, 356–357
pitting corrosion potential 248, 262, 272
pitting corrosion resistance 263
pitting index 165, 167, 263
pitting potential 271
plastic dowels 156
plastic lining 348
plastic pipes 8, 142, 207, 214

plastic sewers 155
 plates 211
 polarization 280
 polishing 245
 polyurethane seals 217
 Pomeroy's Z equation 189
 pore volume 295
 pores 296
 potato starch separators 160
 prefabricated concrete parts 175
 pressed fittings 54
 pressure flushers 145
 pressure vessels 264
 pressurized tanks 123
 prestressed concrete 291
 primary biological stage 252
 process fibres 172
 protective film 158
 PTFE seals 200
 public canalisation system 215–216
 public waste water system 142
 pump material 257–259, 261, 357
 pump sumps 183
 pumping installations 148
 purification plant *see* waste water treatment
 plant 144
 pushers 201

r

raking equipment 149
 raw waste water 148–150
 redox potential 248, 262, 280, 281, 358
 redox processes 247
 regenerate dampers 329
 reinforced concrete sewers 175
 reinforcement 158, 301
 reinforcing steel 158, 301, 303
 repassivable pitting 28
 resistance factor *f* **327**
 resistance of the concrete 290
 reverse osmosis 273
 ribbed steel 158
 rinsing baths 244
 risk of pitting corrosion 356
 road drain cleaners 155
 roots 215
 rotary sprinklers 151
 rotating disc filter 304
 rotational centrifugal method 92
 round steel 158
 rubber coatings 334, 362
 rubber linings 346
 rubber sealing rings 125

rubber seals 204
 rubber-sealed joints 169
 rust nodules 91
 rusty water 11, 36, 40, 45

s

sacrificial anodes 303
 safety valve 329
 sand abrasion 108
 sand removal 105
 sand slurry test 350
 sanitary equipment 160, 200, 202
 sanitary objects 202
 sanitary sewage collector 185
 sanitary sewer pipe 186
 sanitary sewers 173, 203
 saturation index 9, 45, 108
 scraper shield 304
 screw pumps 148, 150, 155
 scum boards 156
 sealants 215, 217
 sealing collars 161
 sealing cushions 164
 sealing rings 125, 216–217
 seals 349
 seawater desalination plant 252, 273, 281
 sedimentation tank 149
 semiconductor 26
 separators for light liquids 160
 septic water 153
 service water 152
 settling tanks 149, 240, 336, 349
 sewage sludge 263, 266–270, 277, 358
 sewage sludge drying 357
 sewage sludge treatment 282
 sewage treatment plant *see* waste water
 treatment plant 144
 sewer atmosphere 249–250
 sewer bricks 198
 sewer gas 153, 170, 177, 179, 191–192,
 195
 sewer linings 341
 sewer pipe linings 306
 sewer pipelines 162, 336
 sewer pipes 162, 173, 205, 359
 sewer slime 171, 249
 sewer systems 160
 sewer technology 170
 sewer wall 195
 sewers 155, 294, 296, 341, 344, 347
 shaft couplings 162
 shafts 148, 209
 shallow pit corrosion 74, 76–77, 356

- sheets 211
 - shells 202
 - shot peening 169
 - shower tubs 200
 - shut-off valves 148, 153
 - silver hard solder 52
 - sinks 170
 - slabs 202
 - sleeveless cast-iron drainpipes 161
 - sleeveless drainpipes 169
 - sliding gates 160
 - sliding/gate valves 304
 - sludge 153
 - sludge deposits 346
 - sludge dewatering 151
 - sludge scrapers 156
 - sludge stabilisation 149
 - sludge tanks 170, 264
 - sludge thickener 149
 - sluices 153, 156
 - soap solution 196
 - soda solution 196
 - solder 54, 55
 - solder fittings 52
 - solders 52
 - solvent pump 329
 - spherical graphite 256
 - spheroidal graphite 257, 341, 357
 - spillways 149
 - spray galvanisation 170
 - SRB 248
 - stabilizers 309
 - stainless steel screws 159
 - stainless steels 55, 274
 - steam dampers 329
 - steel constructions 161
 - steel mats 158
 - steel pipes 11, 32
 - steel reinforcement 158, 285, 290, 292, 359
 - steel tanks 145
 - steep slopes 162
 - stoneware half-shells 214
 - stoneware pipeline 187
 - stoneware pipes 203–204, 217
 - stoneware sewers 155
 - stoneware shells 214
 - storm water drainage 145
 - storm water pipeline 206
 - storm water sewers 173, 178, 199
 - stormwater basins 148
 - stray current 8
 - stress corrosion cracking (in waste water) 169, 252, 261–262, 268–270, 274, 278, 281, 357
 - stress cracking 309, 326, 328, 330–331
 - stress cracks 312, 314
 - stripper pumps 328–329
 - submersible pump 304
 - suction scrapers 159
 - sulfate concentrations 292–293
 - sulfate reduction 249
 - sulfate resistance 287, 292
 - sulfate-reducing bacteria 248, 254–256, 260
 - sulfate-resistant cements 296, 341
 - sulfate-resistant concrete 255
 - sulfide 248, 251
 - sulphur concrete 197
 - superficial contaminants 272
 - surface 244, 247, 271, 286, 306, 338
 - surface finishing 272
 - surface hardness 337
 - surface protection 336
 - surface quality 337
 - surface roughness 256, 272
 - surface treatment 244, 245, 272, 274
 - susceptibility to biocorrosion 272
 - susceptibility to pitting corrosion 279
 - susceptibility to wear 350
 - sweepers 156
 - swellability 312
 - swelling 309, 326
 - synthetic fiber factory 327
 - synthetic fibres 172
 - synthetic textile fibres 172
- t**
- tank 238, 243
 - tank reinforcement 302
 - tap water 42, 52, 57–60, 67–68, 74, 76–80, 93, 115, 117, 120, 196
 - tapping saddle pieces 162
 - tar-epoxy resin coatings 212
 - tarnishes 169, 271, 273
 - tarnishing 272
 - technical approval 243
 - Technical Guidelines for Combustible Liquids 243
 - tetrachloroethane 216
 - textile fibres 210
 - textile industry 325
 - thermal-oxidative loads 360
 - thickeners 349
 - Thiobacillus 179, 193

Thiobacillus 249–250, 292
 Thiobacillus denitrifikans 179
 Thiobacillus thiooxidans 179
 Thiobacillus thioparus 179
 thiosulfate solutions 297
 toothed barriers 156
 total organic carbon 239
 traffic areas 160
 transpassive 281
 transpassive dissolution 275
 trass cement 341
 treatment processes 235
 trichloroethene 216
 TROLINING® 347
 twisted steel 158
 two-layer enamel 201
 Tyton® 162–164
 Tyton® coupling 217
 Tyton® sealing rings 216

u

underground pipeline 199
 underground waste water sewers 142, 209

v

valves 153
 vent pipe 199
 ventilation equipment 152
 Veroxal® coatings 15
 Veroxal® layer 16
 volatile liquids 215

w

wash basins 145, 200
 waste electroplating baths 247
 waste incineration plant 252, 275, 306
 waste pickling baths 244, 353
 waste water collectors 188
 waste water discharge 155
 waste water drainage systems 203
 waste water evaluation 239
 waste water evaporation plants 251–252
 waste water evaporator units 274–275, 356, 358
 waste water facilities 165, 289
 waste water installations 165, 169–170, 198, 202, 205, 211
 waste water pipeline systems 183
 waste water pipelines 143, 163, 194, 199, 215, 252, 263, 292

waste water pumps 160, 256, 357
 waste water sewers 164, 174
 waste water technology 172, 200, 205
 waste water temperature 142
 waste water treatment 235, 253, 273
 waste water treatment facilities 188
 waste water treatment plants 145–146, 149, 156, 158, 170–171, 188, 235, 236–238, 256, 262, 264, 273, 302, 304, 306, 308, 338–339
 waste waters with chloride 167
 water heaters 115–116
 water heating systems 51
 water pipeline 304
 water pipes 25
 water quality 9
 Water Resources Act 243
 water supply 328
 water tanks 11, 123
 water vapor permeability 116
 water/cement ratio 285, 288, 295, 301
 water-hazardous substance class 216
 watertight concrete 175
 waterworks 123
 wear 257, 262, 285, 307, 350
 wear resistance 307, 341, 349
 wear values 342
 weld seam corrosion 51
 welding 169
 welding defects 169
 well water 15, 17–18, 20
 wet filtration 334
 wet oxidation 242, 247, 266–267, 268–270, 279, 281–282
 wet oxidation units 277, 278, 358
 wet-chemical oxidation 241
 whey processing plant 327
 wide pitting 35
 wide pitting corrosion 65
 wire drawing works 292
 wrapping reel 151

y

yellow chromating layer 16

z

zinc coating 56–58, 170, 341
 zinc layer 58, 60, 65–66, 71–72, 81
 zinc plating 244
 zinc removal rate 57

The DECHEMA Corrosion Handbook provides a comprehensive collection of knowledge which is unique both in scope as well as content. Corrosion data and the chemical resistance of all technically important metallic, non-metallic, inorganic and organic materials in contact with aggressive media are covered, constituting the prime information source worldwide for the selection of materials for equipment in which corrosive media are handled or processed. Furthermore, methods of corrosion protection and prevention are also described.

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