



SCHOTT

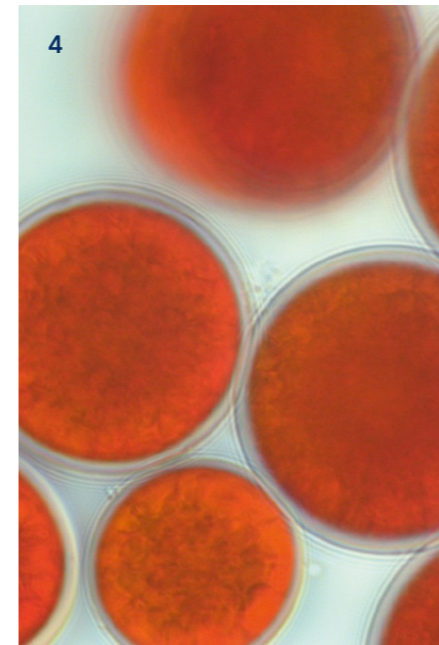
Tubular glass photobioreactors

Enabling efficiency

Where others say no, we say yes.

Because at SCHOTT we believe that shared responsibility can release the energy to achieve the impossible. As a global material technology group, we are constantly exploring unique and innovative ways to make a difference for businesses and people. Being a foundation company, SCHOTT has anchored responsibility, scientific research, society and the environment deeply in its DNA. Represented in over 30 countries by 17,400 employees, we are a highly skilled partner for many high-tech industries. Whatever challenges the future might hold, we can't wait to come up with innovative solutions and turn visions into reality.

With a production capacity of round about 230,000 tons and production sites in Europe, South America and Asia, SCHOTT Tubing is one of the world's leading manufacturers of glass tubes, rods and profiles. More than 60 different glass types are produced in a large variety of dimensional and cosmetic specifications based on a standardized production process and a global quality assurance system. SCHOTT Tubing provides customized products and services for international growth markets such as pharmaceuticals and electronics as well as industrial and environmental engineering.

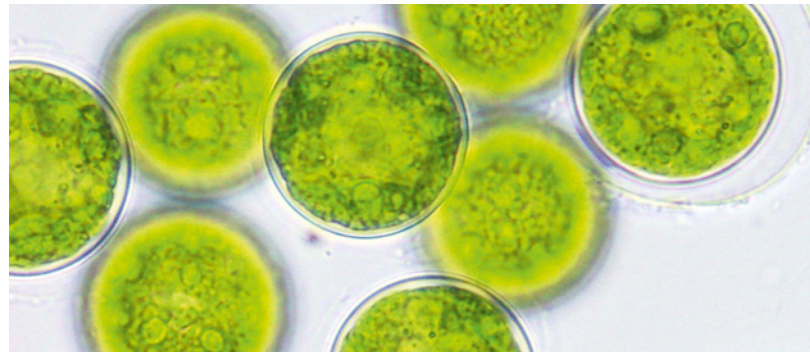


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Algae production systems

Common photosynthetic algae cultivation systems are either open ponds or photobioreactors (PBRs).

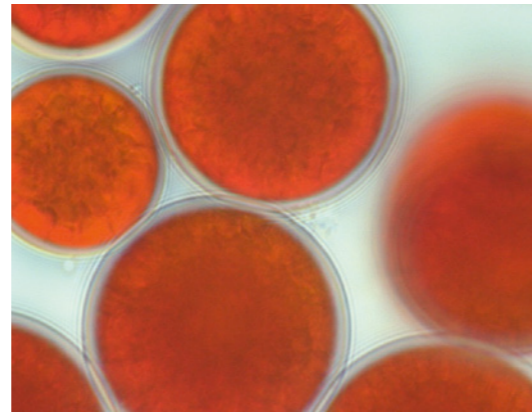


Open ponds

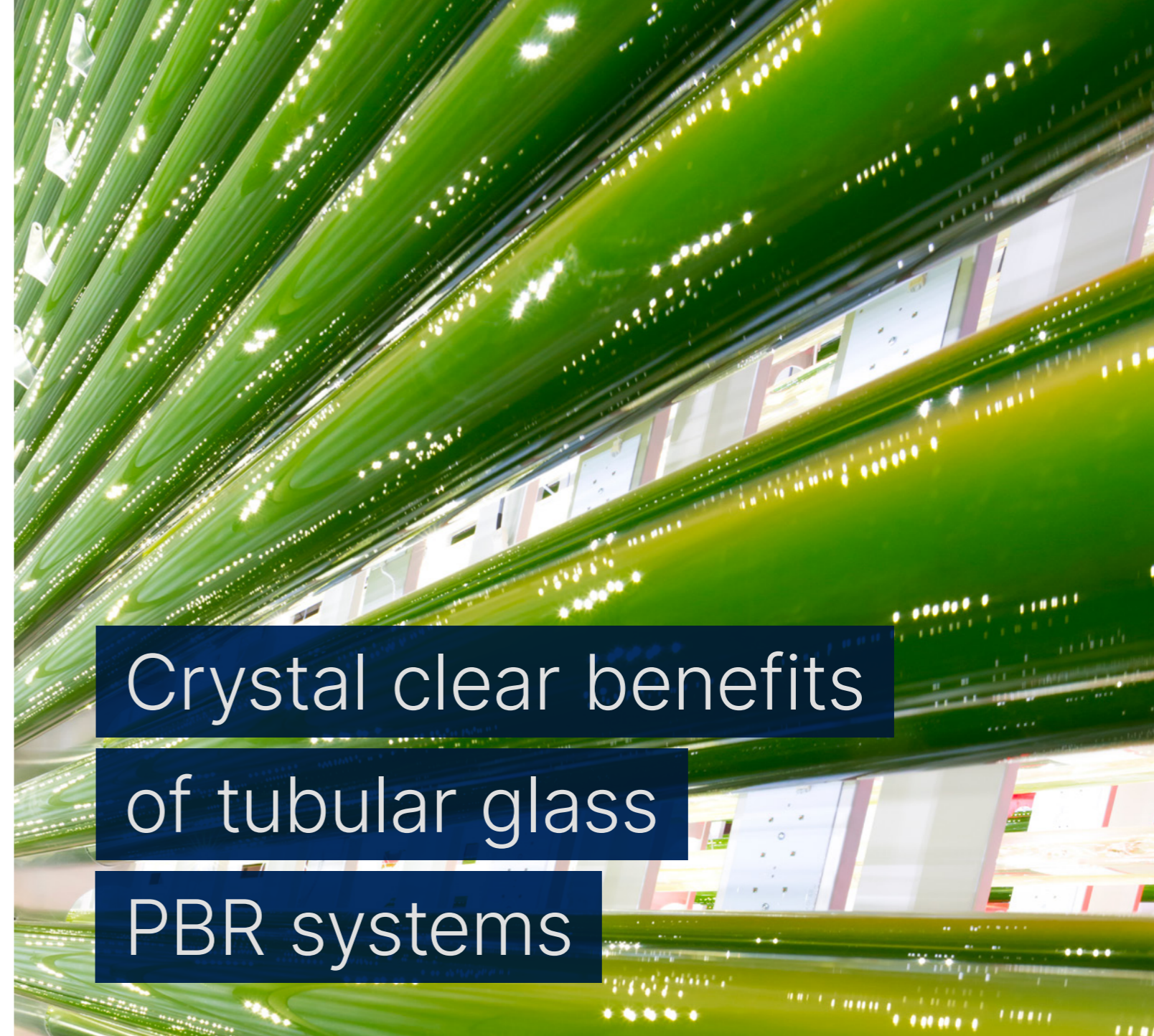
Open ponds are typically built in circular or raceway configurations. The water is kept in motion, for example by paddle wheels. Open ponds are seemingly inexpensive and easy to build. However, poor light utilization, danger of contamination and high water evaporation are the main challenges, which lead to low biomass output per area and large water uptake. Some difficulties can be overcome by rooftops however this increases the costs further.

Photobioreactors

Tubular glass Photobioreactors (PBRs) with long lifetimes and easy cleanability, are very well suited for the highly reproducible cultivation of algae resulting in the highest possible growth rates. As such, tubular glass PBRs are best suited to provide biosecurity for high quality and high value products derived from algae.



Upper photo
Haematococcus pluvialis, green phase
Lower photo
Haematococcus pluvialis, red phase
Right
© Algalif Iceland ehf.



Crystal clear benefits

of tubular glass

PBR systems



Biosecure

protection against bio-contamination and culture crashes



Cost efficient

little maintenance and low total cost of ownership



Resistant

against chemicals, corrosion, sagging, scratches, UV-light



Productive

80 – 160 l/m² photoactive volume, PBR height up to 6 m



Durable

lifetime of 50 years and more, stable light transmission T > 95 % (air – glass – water)



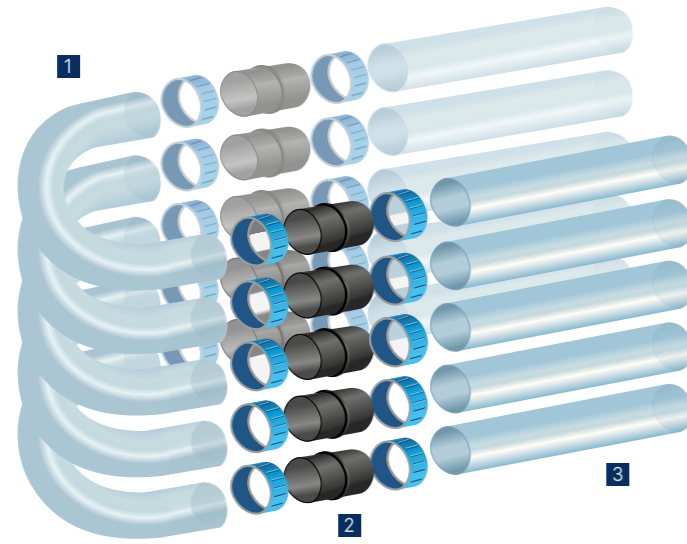
Food safe

food and pharma grade

Overview

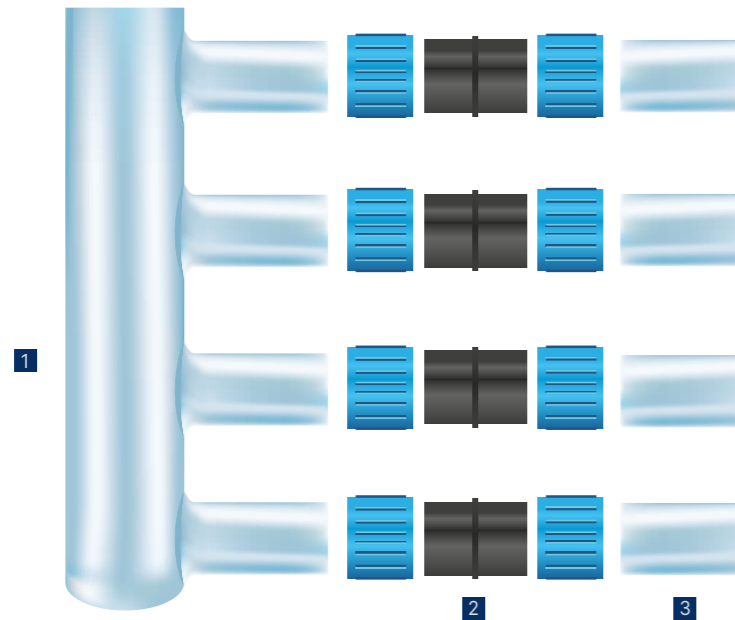
Helical system

- 1 U-bend
- 2 Coupling
- 3 Tubing



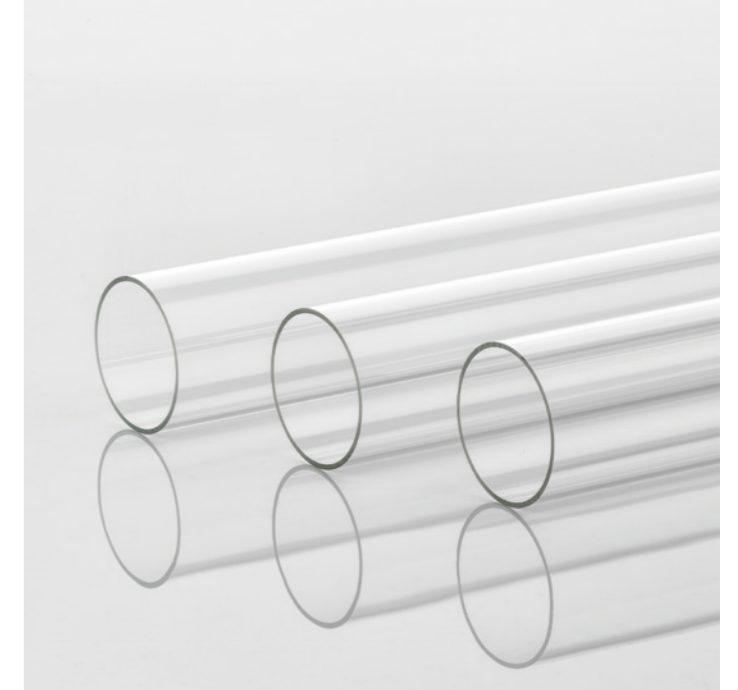
Fence system

- 1 Manifold
- 2 Coupling
- 3 Tubing



horizontal or vertical orientation

Borosilicate glass tubing



Item no.	Joint outside diameter [mm] [in]	Joint wall thickness [mm] [in]	Tube length [m] [ft]	Volume per tube [l] [gal]	Package type*	Package content Number of tubes Weight approx. [kg] approx. [lb]
1535285			1.4	2.79	carton	9 8.3
			4.6	0.74	pallet	180 166 366
1522883	54 ± 0.65 2.13 ± 0.03	1.8 ± 0.18 0.07 ± 0.01	2.5	4.99	carton	12 19.7 43.5
			8.2	1.32	pallet	144 236.4 522
1523124			5.5	10.97	wooden box	56 202.6 430.8
1534297			18	2.90	pallet	238 861.2 1898.6
1500383			1.4	4.04	carton	9 12.2 26.9
			4.6	1.07	pallet	180 244 538
1511901	65 ± 0.65 2.56 ± 0.03	2.2 ± 0.18 0.09 ± 0.01	2.5	7.21	carton	9 21.8 48.0
			8.2	1.90	pallet	108 261.6 576
1459938			5.5	15.86	wooden box	36 191.6 422.3
1534302			18	4.19	pallet	165 877.9 1935.5

*for explanation regarding package type please see page 12

Other dimensions upon request.

Glass tubing for algae cultivation must be stored in dry conditions in closed buildings. For storing pallets and wooden boxes with glass tubing, the floor must be level and horizontal and have a load-bearing capacity of 1,000 kg/m². Do not stack more than 3 pallets on top of each other.

Product range

Borosilicate glass U-bends



Product range

Borosilicate glass manifolds



Helical system



© Algalif Iceland ehf.

Fence system



Manifolds and couplings, fence system. © Jongerius ecoduna GmbH

Manifolds are placed at the tops or at the ends of tubular PBR fences and function as U-bends and in- and outlets.

- Biosecure and food safe, full glass solution
- Available with closed ends or with flange
- Outside diameter of arms: 54 mm or 65 mm for use with standard couplings
- Number of arms, distance between arms, total length etc. are customized with a minimum order quantity of 25 pieces

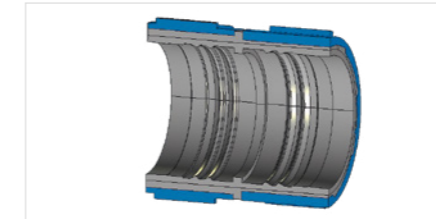
Item no.	Joint outside diameter [mm] [in]	Joint wall thickness [mm] [in]	Joint U-bend width [mm] [in]	Approx. U-bend height [mm] [in]	Straight side length [mm] [in]	Volume per bend (approx.) [l] [gal]	Package type	Package content Number of tubes
1534644	54 ± 0.65 2.13 ± 0.02	2.5 ± 0.20 0.10 ± 0.01	234 ± 2.00 9.21 ± 0.08	200 7.87	> 45 > 1.77	0.85 0.22	carton pallet	33 396
1436672	65 ± 0.65 2.56 ± 0.03	2.8 ± 0.20 0.11 ± 0.01	245 ± 2.00 9.65 ± 0.08	200 7.87	> 45 > 1.77	1.2 0.32	carton pallet	21 252

Glass U-bends for algae cultivation must be stored in dry conditions in closed buildings.

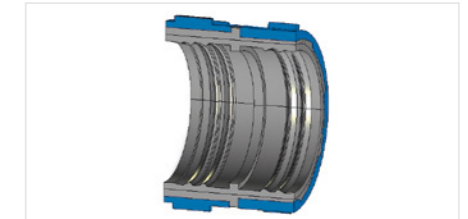
Description*	Package	Package content	Minimum order quantity (MOQ)
Manifolds 10 arms closed 54 mm			25
Manifolds 5 arms flange 54 mm			25
Manifolds 8 arms closed 65 mm			25
Manifolds 4 arms flange 65 mm			25
Manifolds 6 arms open 65 mm	carton pallet	2 36	1 pallet

* closed: both ends closed; flange: one side closed and one side flange; open: both sides flange
Glass manifolds for algae cultivation must be stored in dry conditions in closed buildings.

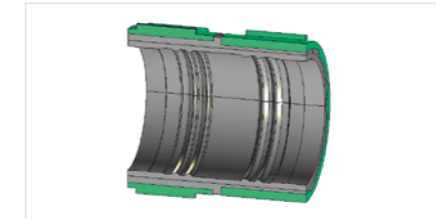
Couplings



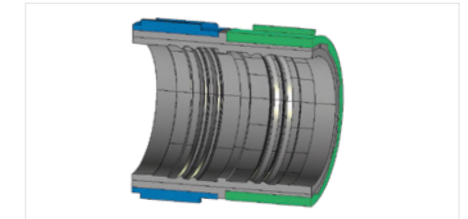
1 Standard, length 80 mm
Partition wall to assure glass separation and smooth transition (torque wrench 40Nm needed)



2 Standard slim, length 45 mm
(torque wrench 25Nm needed)



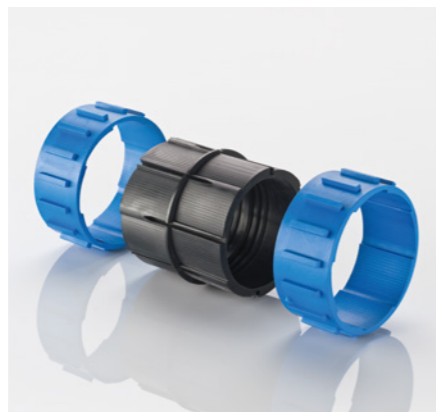
3 Maintenance, length 80 mm
Allows easy exchange of tubes, no partition wall



4 Adapter, length 80 mm
Allows connection to periphery tubes with 2.5 in outer diameter



SCHOTT tool kit



Detached parts of standard coupling



Detached parts of standard slim coupling

Item no.	Outside diameter glass tube [mm] [in]	Package Number of couplings	Description	Package Weight approx. [kg] approx. [lb]
1530116	54 2.13	24 960	1 Standard	6.9 15.3 277.7 612.2
1581056		24 1824	2 Standard slim	3.0 7.0 226.2 530.8
1463260	65 2.56	24 960	1 Standard	6.1 13.4 219.4 483.7
1581035		24 1824	2 Standard slim	3.2 6.6 240.8 498.6

Toolbox 54
Standard with torque wrench 40Nm for closing of coupling and tools for opening

Toolbox 54
Slim with torque wrench 25Nm for closing of coupling and tools for opening

Toolbox 65
Standard with torque wrench 40Nm for closing of coupling and tools for opening

Toolbox 65
Slim with torque wrench 25Nm for closing of coupling and tools for opening



Specially developed for tubular photobioreactors:

The couplings are designed for SCHOTT glass tubes with plain tube ends according to the product range shown in this brochure.

- Proven lifetime > 10 years*
- 3 bar pressure resistance
- UV-resistance
- Regular cleaning cycles with various chemicals
- Fast installation allowing for reduced built up time of the reactor
- Easy to disassemble and re-use allowing for fast modification or extension of a reactor system
- Easy handling with pre-assembled devices and a special tool kit including a torque wrench (Standard couplings: 40 Nm, Slim couplings 25 Nm)
- Food grade

*installed in PBR systems since 2014

Additional equipment

Item no.	Outside diameter glass tube [mm] [in]	Package Number of couplings	Description	Package Weight approx. [kg] approx. [lb]
1530120	54 2.13	4 576	3 Maintenance kit (no partition wall)	0.9 2.0
1530105	65 2.56	4 576	3 Maintenance kit (no partition wall)	1.0 2.2
1534828	65 2.56	4 576	4 Adapter	1.0 2.2

Couplings for algae cultivation must be stored in dry conditions in closed buildings.

Packaging



Bags

- Couplings



Cartons

- Tubes, up to 2.5 m length
- U-bends
- Couplings
- Manifolds



Wooden boxes and special pallets

- Tubes, 5.5 m length
- Smaller quantities

i All products from SCHOTT for algae cultivation must be stored in **dry conditions in closed buildings**. For storing pallets and wooden boxes with glass tubing, the floor must be level and horizontal and have a load-bearing capacity of 1,000 kg/m². **Do not stack more than 3 pallets on top of each other.**

Borosilicate glass properties

DURAN® glass tubing

	Metric	US
Coefficient of mean linear thermal expansion α acc. to DIN ISO 7991	$3.3 \cdot 10^{-6} \text{ K}^{-1}$ (20 °C; 300 °C)	$3.3 \cdot 10^{-6} \text{ K}^{-1}$ (68 °F; 572 °F)
Transformation temperature T_g	525 °C	977 °F
Density ρ at 25 °C	$2.23 \text{ g} \cdot \text{cm}^{-3}$	$139.2 \text{ lb} \cdot \text{ft}^{-3}$
Modulus of elasticity E (Young's modulus)	$63 \cdot 10^3 \text{ N} \cdot \text{mm}^{-2}$	$91 \cdot 10^5 \text{ lb} \cdot \text{in}^{-2}$ (psi)
Poisson's ratio μ	0.20	0.20
Thermal conductivity λ_w at 90 °C	$1.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$	$0.69 \text{ Btu} \cdot \text{hr}^{-1} \cdot \text{ft}^{-1} \cdot \text{°F}^{-1}$
Refractive index ($\lambda = 587.6 \text{ nm}$) n_d	1.473	1.473
Stress-optical coefficient (DIN 52 314) K	$4.0 \cdot 10^{-6} \text{ mm}^2 \cdot \text{N}^{-1}$	$4.0 \cdot 10^{-6} \text{ mm}^2 \cdot \text{N}^{-1}$

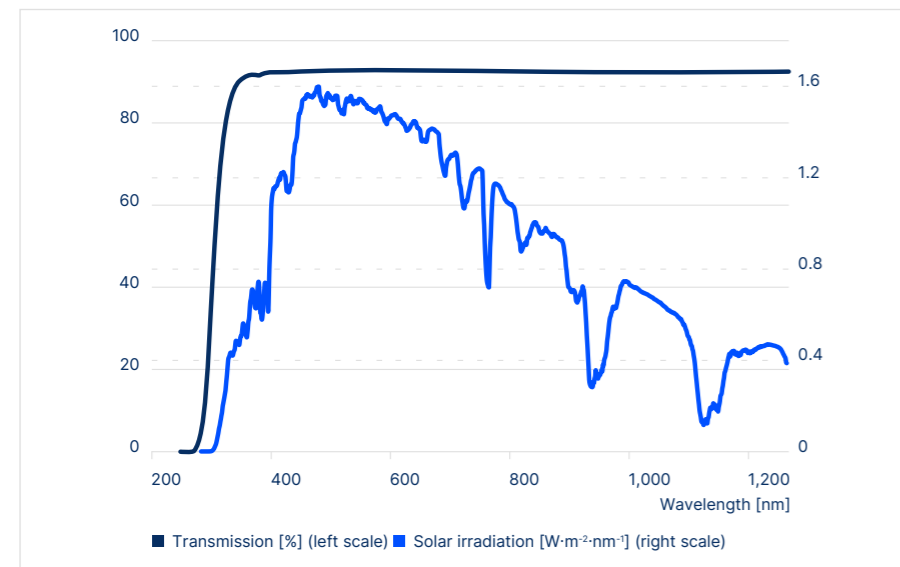
Chemical composition				Chemical resistance	
SiO ₂	B ₂ O ₃	Na ₂ O + K ₂ O	Al ₂ O ₃	Hydrolytic class (DIN ISO 719)	HGB 1
81	13	4	2	Acid class (DIN 12116)	Class S 1
main components in approx. weight %				Alkali class (DIN ISO 695)	Class A 2

DURAN® is a registered trademark of DWK Life Sciences GmbH.

Borosilicate glass properties

DURAN® glass tubing

Transmission



Transmission of DURAN® glass (d = 2.2 mm) in configuration air/glass/air. DURAN® is a registered trademark of DWK Life Sciences GmbH.

Note
When the glass tube is filled with water, the transmission increases from about 92% to 95.6% due to reduced reflection losses at the inner glass/water interface.

Pressure resistance of tubing made of borosilicate glass *

The following formulas apply to stress free, pristine tubing and cylindrical hollow bodies with a circular profile, uniform wall thickness with open ends, free from thermal load, under internal positive pressure.

Estimation of the minimum wall thickness (WT)

$$WT = \frac{OD \cdot p}{140 \text{ bar} + p}$$

$$\frac{K}{S} = 70 \text{ bar}$$

Estimation of the maximum pressure resistance (p)

$$p = \frac{WT \cdot 140 \text{ bar}}{OD - WT}$$

OD = Outside Diameter in [mm]
WT = Wall Thickness in [mm]
p = Pressure Resistance in [bar]

Other points to be considered:

- AD 2000-leaflet N 4, edition 2000-10: Pressure vessels made of glass, with encl. 1, edition 2000-10: evaluation of faults in walls of glass pressure containers
- AD 2000-leaflet B 1, edition 2000-10: cylindrical and spherical shells under internal pressure overload

According to DIN EN 1595: "Pressure equipment made from borosilicate glass 3.3 – general rules for design, manufacture and testing", DURAN® approved material and may be used for the construction of pressure equipment.

*typical values under standard conditions

Permissible load referring to standard DIN EN 1595: "Pressure equipment made from borosilicate glass 3.3 – general rules for design, manufacture and testing"

Pressure drop in tubular photobioreactors

Pressure loss *

In general, the pressure drop can be calculated for any velocity using the following formula.

$$\Delta p = \zeta \cdot \frac{\rho}{2} \cdot u^2$$

Δp : pressure loss
 ζ : pressure loss number (zeta)
 ρ : algae culture density
 u : linear velocity of algae culture

$u = 0,7 \text{ m/s}$	ζ	$\Delta p \text{ [Pa]}$
Round tube (D = 65 mm, WT = 2.2 mm, L = 5.5 m)	1.96	480
U-bend (D = 65 mm, WT = 2.8 mm)	0.252	62

Pressure drop of a tube and a U-bend at the given velocity, u. D is the outer diameter, WT the wall thickness. The algae culture's density was approximated with $\rho = 1 \text{ g/cm}^3$.

*typical values under standard conditions

Electrical power

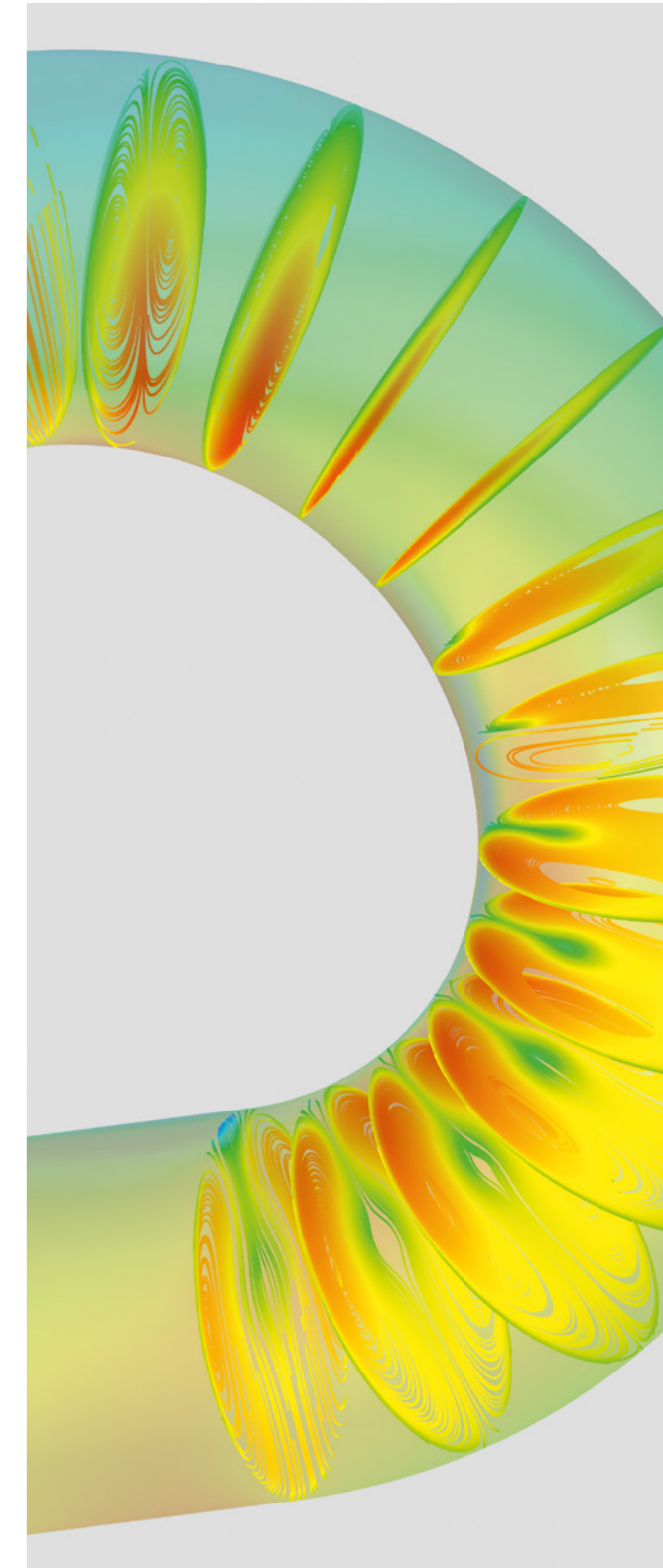
The electrical power of the pumps, P_{el} , scales with the pressure drop and the volume flow, Q:

$$P_{el} = \frac{\Delta p \cdot Q}{\eta_p}$$

P_{el} : electrical power
 Δp : sum of pressure loss in Pa
 Q : volume flow rate in m^3/s
 η_p : pump efficiency at operating point ($0 < \eta_p < 1$)

Research done in cooperation with: Institute of Fluid Dynamics, LSTM, Technical Faculty, University Erlangen-Nuremberg, Germany

Figure:
Dean-vortex appearance in an U-bend – computer simulation (ANSYS® CFX® 14.5.7)



Features and benefits

Tubular glass photobioreactors versus open ponds



Tubular photobioreactor



Open pond

Contamination

- Very low risk of contamination compared to open ponds, where other microorganisms or insects have easy access
- No limitation regarding the algae species that can be grown, also due to effective blocking against competing organisms

Productivity

- Higher productivity in terms of mass per area and day
- Significantly higher volumetric productivity

Algae concentration at harvest

- Notably higher concentration in terms of mass per liter
- More efficient harvesting procedure

Water loss

- No evaporation within PBR system compared to open ponds, which can lose significant water amounts, resulting in salinization
- Water loss is limited to external factors, such as the cooling process

Biomass quality

- Biomass quality is highly reproducible due to excellent process control of tubular PBR systems
- High value products or high quality inoculum can be produced with optimum reliability

Production flexibility

- Easy cleanability allowing for defined initial status any time, thus switching algae species is possible and secure

Borosilicate glass versus polymer materials

Light transmission

- Excellent light transmission (see page 14 for details)
- No solarization or browning effect
- No UV-protective additive or coating necessary to secure material properties

Fire protection

- Glass does not burn or give off toxic fumes

Leaching

- Glass is a chemically highly resistant material. With plastic tubing, depending on the polymer type, monomers or oligomers of hazardous substances such as Bisphenol molecules can be leached into the algae culture.

Cleaning

- Mechanical stability allows continuous in-line cleaning with pipe pigs or sponges
- Chemical stability allows cleaning in place (CIP)
- Lower material and maintenance costs compared to quality polymer tubes

Thermal stability

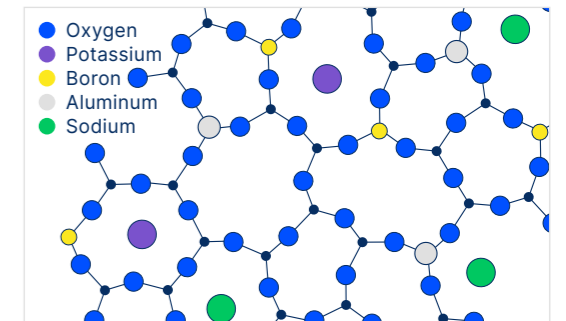
- No need for expansion loops due to low thermal expansion; Example: For 5.5 m long tubes and a temperature increase of 20 °C / 36 °F the expansion of Borosilicate glass is only 0.36 mm / 0.01" while polymers expand from 3.3–8.8 mm / 0.13"–0.35" depending on polymer type.

Cost saving

- Glass components can last fifty years and longer
- Reduced number of rack poles. High mechanical stability allows increased support distances without significant sagging of tubes (see picture on right)

Sagging

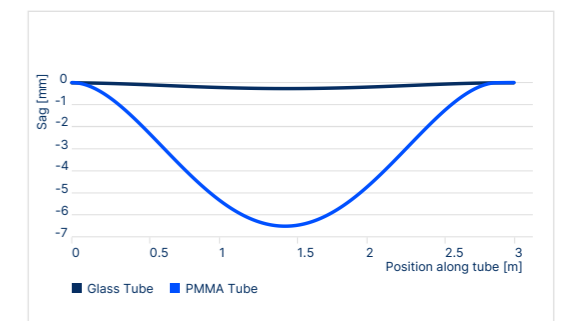
- No permanent deformation of glass tubes in contrast to polymer tubes



Borosilicate glass



Polymer



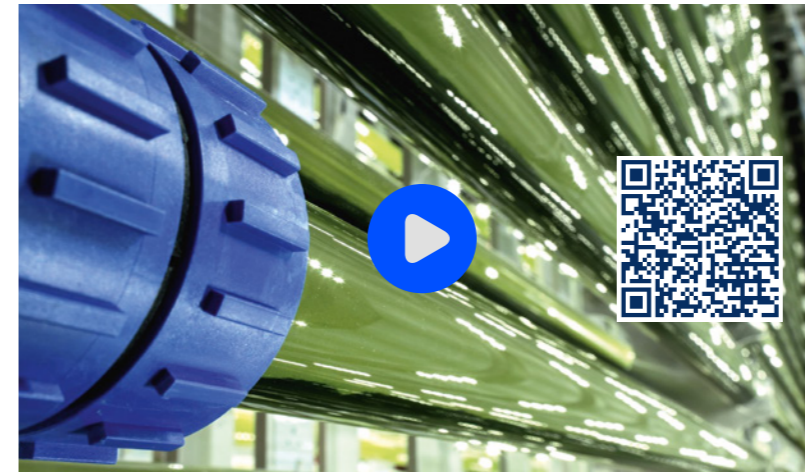
Sagging of water filled tubes
(outer diameter 65 mm, wall thickness 2.2 mm, length 2.75 m).
The sag of the glass and polymer tubes is 0.5 mm and 6.6 mm, respectively. The polymer tube would need to be supported every 1.5 m for the same sag as the glass tube.

References of tubular glass photobioreactors

SCHOTT has formed alliances and partnerships all over the world. This allows us to provide complete tubular photobioreactors according to your needs.

Please contact us for further details.

- 1 © Algalif Iceland ehf., Iceland
- 2 © Varicon Aqua Solutions Ltd., UK, Phyco-Flow PBR at OP Bio, Japan
- 3 © A4F-Algae for Future, Portugal
- 4 © Algatechnologies Ltd., Israel
- 5 © Lgem AlgaeHUB®, Netherlands
- 6 © ROHTO, Japan



Technical performance specification

Detailed information on permissible faults, definition of faults, testing methods and testing units are available upon request. Reduced tolerances are also available upon request. Regarding quality issues the relevant "Technical performance specification" (TPS) for the application apply to all sales and are binding unless separate written agreements with respect to specification have been agreed upon.

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