Tubular Glass Photobioreactors

Bringing Light to Algae
SCHOTT is an international technology group with more than 130 years of experience in the areas of specialty glasses and materials and advanced technologies. With our high-quality products and intelligent solutions, we contribute to our customers’ success and make SCHOTT part of everyone’s life.

With a production capacity of more than 140,000 tons and production sites in Europe, South America and Asia, SCHOTT’s business segment Tubing is one of the world’s leading manufacturers of glass tubes, rods and profiles. Approximately 60 glass types are produced in large external diameters and a variety of lengths based on site-overlapping strategies in development, production and quality assurance. 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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Product Range

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Helical System

Fence System

U-Bend

Coupling

Round or Oval Tubing

Manifold
# Product Range

**Borosilicate Glass Tubing**

**DURAN®**

<table>
<thead>
<tr>
<th>Joint Outside Diameter</th>
<th>Joint Wall Thickness</th>
<th>Tube Length</th>
<th>Package Type*</th>
<th>Package Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>in</td>
<td>mm</td>
<td>in</td>
<td>m</td>
</tr>
<tr>
<td>54 ± 1.0</td>
<td>2.13 ± 0.04</td>
<td>1.8</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>2.2</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.5</td>
<td>2.2</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4</td>
<td>55.1</td>
<td>9</td>
</tr>
<tr>
<td>65 ± 1.0</td>
<td>2.56 ± 0.04</td>
<td>2.2</td>
<td>0.09</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>2.2</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.5</td>
<td>2.2</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>165</td>
</tr>
<tr>
<td>300 ± 3.8</td>
<td>11.81 ± 0.15</td>
<td>5.0</td>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.0</td>
<td>157.5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

* for explanation regarding package type please see page 22

Other dimensions and quantities available upon request.
Product Range
Borosilicate Glass Tubing
CONTURAX®

Oval tubes with round ends on both sides

<table>
<thead>
<tr>
<th>Round Section</th>
<th>Oval Section</th>
<th>Tube length Total</th>
<th>Package Type</th>
<th>Package Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Outside Diameter</td>
<td>Joint Wall Thickness</td>
<td>Approx. Height</td>
<td>Approx. Width</td>
<td>Approx. Wall Thickness</td>
</tr>
<tr>
<td>mm</td>
<td>mm</td>
<td>in</td>
<td>mm</td>
<td>in</td>
</tr>
<tr>
<td>65 ± 1.0</td>
<td>2.56 ± 0.04</td>
<td>2.2 ± 0.3</td>
<td>0.09 ± 0.01</td>
<td>41</td>
</tr>
<tr>
<td>96</td>
<td>510.8</td>
<td>1126.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Oval glass tubes can improve algae production regarding various aspects such as
• Improved growth rate due to better light utilization
• Higher yields due to illumination uniformity
• Customizable mounting angle according to local light conditions
• Easy installation: all oval tubes have a short section of round ends allowing coupling with regular connection systems

Other dimensions as well as configurations in the oval section (aspect ratio) available upon request.
## Product Range

**Borosilicate Glass U-Bends**

**DURAN®**

<table>
<thead>
<tr>
<th>Joint Outside Diameter (mm)</th>
<th>Joint Wall Thickness (mm)</th>
<th>Joint U-Bend Width (mm)</th>
<th>Approx. U-Bend Height (mm)</th>
<th>Straight Side Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54 ± 1.0</td>
<td>2.13 ± 0.04</td>
<td>234 ± 2.0</td>
<td>200</td>
<td>&gt; 45</td>
</tr>
<tr>
<td>65 ± 1.0</td>
<td>2.56 ± 0.04</td>
<td>245 ± 2.0</td>
<td>200</td>
<td>&gt; 45</td>
</tr>
</tbody>
</table>

Other shapes and dimensions available upon request.
Product Range
Borosilicate Glass Manifolds
DURAN®

The manifolds are designed for the use in photobioreactor fences, i.e. to be used instead of U-Bends, or simply as in- and outlet.
• Full glass solution
• Available with closed ends or with flange.
• Outside diameter of arms:
  54 mm or 65 mm
  → standard couplings usable
• Number of arms, distance between arms, total length etc. are customized with a minimum order quantity of 25 pieces
## Product Range
### Couplings

<table>
<thead>
<tr>
<th>Outside Diameter Tube on Side 1</th>
<th>Outside Diameter Tube on Side 2</th>
<th>Package</th>
<th>Description</th>
<th>Package</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm in</td>
<td>mm in</td>
<td>Number of Couplings</td>
<td>Weight approx. kg</td>
<td>Weight approx. lb</td>
</tr>
<tr>
<td>54 2.13</td>
<td>54 2.13</td>
<td>30 Bag Standard (1)</td>
<td>6.9</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,200 Pallet Standard</td>
<td>277.7</td>
<td>612.2</td>
</tr>
<tr>
<td>65 2.56</td>
<td>65 2.56</td>
<td>25 Bag Standard</td>
<td>6.1</td>
<td>13.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900 Pallet Standard</td>
<td>219.4</td>
<td>483.7</td>
</tr>
</tbody>
</table>

### Toolbox
- Toolbox 54 with torque wrench for closing of coupling and with tools for opening
- Toolbox 65 with torque wrench for closing of coupling and with tools for opening

### Additional Equipment

<table>
<thead>
<tr>
<th>Outside Diameter Tube on Side 1</th>
<th>Outside Diameter Tube on Side 2</th>
<th>Package</th>
<th>Description</th>
<th>Package</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm in</td>
<td>mm in</td>
<td>Number of Couplings</td>
<td>Weight approx. kg</td>
<td>Weight approx. lb</td>
</tr>
<tr>
<td>54 2.13</td>
<td>54 2.13</td>
<td>4 Carton Maintenance kit (no partition wall) (2)</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>65 2.56</td>
<td>65 2.56</td>
<td>4 Carton Maintenance kit (no partition wall)</td>
<td>1.0</td>
<td>2.2</td>
</tr>
<tr>
<td>65 2.56</td>
<td>63.5 2.50</td>
<td>4 Carton Adapter (3)</td>
<td>1.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>
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. 

- Successfully tested for 10 years lifetime regarding
  - 3 bar pressure resistance
  - UV-resistance
  - Regular cleaning cycles with various chemicals
- Fast installation allows reduced built-up time of the reactor
- Easy to disassemble and re-use allowing fast modification or extension of a reactor system
- Easy handling with pre-assembled devices and a special tool kit including a torque wrench

(1) Standard
With partition wall to assure glass separation and smooth transition

(2) Maintenance kit
Allows easy exchange of tubes, no partition wall

(3) Adapter
Allows connection to pheriphery tubes with 2.5 inch outer dimension

More information available upon request.
Light Management

Optimum Light Input for the Highest Growth Rates of Algae

Various systems for individual use
Make use of the advantages of individual light management and guide light directly to where it’s needed: from optimal external illumination to systems within the algae cultivation system.

Efficient reactor system design
Individual light management utilizing small diameter light guides enable optimal algae growth conditions anywhere.

Optimal growth of algae
Light guides transmit only light, not heat; thus avoiding temperature levels that are detrimental to algae development.

Light and humidity – no problem when using artificial light
Fiber optic light guides transmit only light, not electricity – therefore they can be easily used in wet environments.

Light intensity and color temperature
Easy adjustment of light intensity and color temperature to the special requirements of varying algae strains.

Natural sunlight
It is also possible to bundle natural sunlight and guide it directly to the algae.

Our Lighting and Imaging Business Unit is a global leader when it comes to developing and manufacturing innovative glass fiber optic technologies and state-of-the-art LED lighting solutions.
Complete Tubular Photobioreactors

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

Photo courtesy of Heliae Inc.

Photo courtesy of Varicon Aqua Solutions Ltd
Common Photosynthetic Algae Cultivation Systems are either Open Ponds or Closed Photobioreactors.

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

**Closed system**
Closed systems are dominated by tubular and flat-plate reactors. Other options are bags, coils or domes. Flat plate systems have received a lot of attention due to their large illuminated surface area, but the technology suffers from heating problems and a strong tendency to build up biofilm formations on the inner walls. Tubular systems on the other hand reduce these drawbacks while maintaining the advantages of optimal light input and high productivity.

Therefore, closed, tubular glass 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 bio-security for high quality inoculum used in open ponds.
Features and Benefits of Closed Tubular Photobioreactors versus Open Ponds

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

**Productivity**
- Significantly higher productivity in terms of mass per area and day
- More efficient use of land

**Algae concentration at harvest**
- Significantly higher in terms of mass per liter
- More efficient harvesting procedure

**Water loss**
- No evaporation within closed system compared to open ponds, which can lose significant water amounts, resulting in salt precipitation hazard
- Water loss is limited to external factors, such as cooling processes, use of green houses, tube diameter, target temperature etc.

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

**Production flexibility**
- Easy cleanability allows defined initial status any time, thus switching algae species is possible and secure

**Use of GMO* for improved production process**
- GMO is possible in closed reactor design whereas open ponds are very limited

* GMO = Genetically Modified Organism
Features and Benefits of Borosilicate Glass versus Polymer Materials

Light transmission
- Excellent light transmission (see page 19 for details)
- No solarization or browning effect
- No UV-protective additive or coating necessary to secure material properties
- Lifetime of Borosilicate glass tubing >20 years

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 continous in-line cleaning with polymer pellets
- Chemical stability allows cleaning with regular common chemical cleaning agents
- 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
- No need for tube replacement over the normal lifetime of the algae production plant
- Reduced number of racks due to high mechanical stability, which allows increased tube support distances without sagging of tubes
  Example: double distance compared to PMMA (for details see below)
- Reduced number of connections due to standard tube length of 5.5 m

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

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 8.6 mm, respectively. The polymer tube would need to be supported every 1.5 m for the same sag as the glass tube (support every 2.75 m).
# Borosilicate Glass Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Metric</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of mean linear thermal expansion $\alpha$ acc. to DIN ISO 7991</td>
<td>$3.3 \cdot 10^{-6}$ K$^{-1}$ (20°C; 300°C)</td>
<td>$3.3 \cdot 10^{-6}$ K$^{-1}$ (68°F; 572°F)</td>
</tr>
<tr>
<td>Transformation temperature $T_g$</td>
<td>525°C</td>
<td>977°F</td>
</tr>
<tr>
<td>Density $\rho$ at 25°C</td>
<td>2.23 g cm$^{-3}$</td>
<td>139.2 lb ft$^{-3}$</td>
</tr>
<tr>
<td>Modulus of elasticity $E$ (Young’s modulus)</td>
<td>$63 \cdot 10^3$ N mm$^{-2}$</td>
<td>$91 \cdot 10^3$ lb in$^{-2}$ (psi)</td>
</tr>
<tr>
<td>Poisson’s ratio $\mu$</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Thermal conductivity $\lambda_v$ at 90°C</td>
<td>1.2 W m$^{-1}$ K$^{-1}$</td>
<td>0.69 Btu hr$^{-1}$ ft$^{-1}$ °F$^{-1}$</td>
</tr>
<tr>
<td>Refractive index ($\lambda = 587.6$ nm) $n_v$</td>
<td>1.473</td>
<td>1.473</td>
</tr>
<tr>
<td>Stress-optical coefficient (DIN 52 314) $K$</td>
<td>$4.0 \cdot 10^{-6}$ mm$^2$ N$^{-1}$</td>
<td>$4.0 \cdot 10^{-6}$ mm$^2$ N$^{-1}$</td>
</tr>
</tbody>
</table>

## Chemical Composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Metric</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>B$_2$O$_3$</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Na$_2$O + K$_2$O</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Main components in approx. weight %

## Chemical Resistance

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Metric</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrolytic Class (DIN ISO 719)</td>
<td>HGB 1</td>
<td></td>
</tr>
<tr>
<td>Acid Class (DIN 12116)</td>
<td>Class S 1</td>
<td></td>
</tr>
<tr>
<td>Alkali Class (DIN ISO 695)</td>
<td>Class A 2</td>
<td></td>
</tr>
</tbody>
</table>
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 and external negative pressure.

Estimation of the maximum pressure resistance (p)

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

Estimation of the minimum wall thickness (WT)

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

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® is an approved material and may be used for the construction of pressure equipment.
Fluid Mechanical Properties

For the construction of a tubular photobioreactor the expected pressure loss in the system and other fluid mechanical properties can be simulated numerically for a given tube geometry, velocity and temperature. This allows an optimal pump design.

In the following, the impact of the components with an outer diameter OD of 65 mm and a wall thickness of 2.2 mm for the tubes and 2.8 mm for the U-Bend is shown. The velocity of the algae culture in the round tube or oval section corresponds to the value $u_p = 0.7 \text{ m/s}$ ($\equiv Q = 2.02 \times 10^{-3} \text{ m}^3/\text{s}$) and the density to $\rho = 993 \text{ kg/m}^3$.

<table>
<thead>
<tr>
<th>For $u_p = 0.7 \text{ m/s}$</th>
<th>$Q$ in $10^{-3} \text{ m}^3/\text{s}$</th>
<th>$\Delta \rho$ in Pa</th>
<th>$\zeta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round Tube (L = 5.5 m)</td>
<td>2.02</td>
<td>451</td>
<td>1.84</td>
</tr>
<tr>
<td>Oval Tube (L = 5.5 m)</td>
<td>1.67</td>
<td>506</td>
<td>2.88</td>
</tr>
<tr>
<td>U-Bend</td>
<td>2.02</td>
<td>74.5</td>
<td>0.305</td>
</tr>
<tr>
<td>Steel Tube (L = 5.5 m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k = 0.2 \text{ mm}$</td>
<td>2.02</td>
<td>656</td>
<td>2.68</td>
</tr>
<tr>
<td>$k = 0.02 \text{ mm}$</td>
<td></td>
<td>505</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Pressure loss

$\Delta \rho = \zeta \cdot \frac{8\rho}{d^4\pi^2} \cdot Q^2$

- $\Delta \rho$: Pressure loss in Pa
- $\zeta$: Pressure loss number
- $\rho$: Density in kg/m$^3$
- $Q$: Volume flow rate m$^3$/s
- $u_p$: Process velocity in m/s
- $d$: Inner tube diameter in m

round tube: $Q = \frac{d^4\pi}{4} \cdot u_p$

oval tube: $Q = \frac{d^4\pi}{4} \cdot 0.82 \cdot u_p$

Dean-vortex appearance in an U-Bend – computer simulation (ANSYS®CFX® 14.5.7)
The pressure loss numbers $\zeta$ for the U-Bends and oval tubes change slightly with the volume flow rate $Q$.

As the flow elements are arranged in series, each component contribute as an additive element to the global pressure loss $\Delta p_{\text{pv-}}$ of the reactor.

The U-Bends of SCHOTT show small values for $\zeta$ compared to literature indicating a smoother flow guidance and thus a low contribution on the total required electrical power of the photobioreactor.

**Electrical Power**

$$P_d = \frac{\Delta p_{\text{pv-}} \cdot Q}{\eta_p} \ [\text{W}]$$

- $P_d$: Electrical power
- $\Delta p_{\text{pv-}}$: Sum of pressure loss in Pa
- $Q$: Volume flow rate in m$^3$/s
- $\eta_p$: Pump efficiency at operating point ($\eta_p < 1$)

The investigated oval tubes of SCHOTT with their elevated light absorption need only an electrical power compared to the one of conventional round tubes with the same process velocity.

Thus a higher productivity of the photobioreactor can be achieved at similar operational energy costs.

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

**Cartons**
- Tubes, up to 2.5 m length, low quantities
- U-Bends
- Couplings
- Manifolds
- Light management products

**Pallets**
- Tubes, any size, medium and large quantities

**Wooden boxes**
- Tubes, 4 m length or larger
Technical Terms of Supply

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 Terms of Supply” 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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DURAN® is a registered trademark of the Duran Group GmbH.
We thank our customers and partners for their kind assistance in providing product samples and photos.

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