Tubular Glass Photobioreactors
Let’s bring light to algae.
SCHOTT is a leading international technology group in the areas of specialty glass and glass-ceramics. With more than 130 years of outstanding development, materials and technology expertise we offer a broad portfolio of high-quality products and intelligent solutions that contribute to our customers’ success.

With a production capacity of more than 140,000 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.
Contents

4 Algae Production Systems
5 Crystal Clear Benefits
7 Product Range
   Borosilicate Glass Tubing
   Borosilicate Glass U- and J-Bends
   Couplings
   Borosilicate Glass Manifolds
15 Packaging
16 Borosilicate Glass Properties
18 Closed Tubular Photobioreactors versus Open Ponds
19 Borosilicate Glass versus Polymer Materials
20 Pressure Drop in Tubular Photobioreactors
22 References of Glass Tubular Photobioreactors (PBRs)
23 Technical Terms of Supply
Algae Production Systems

Common photosynthetic algae cultivation systems are either open ponds or closed 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.

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 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 bio-security for high quality inoculum used in open ponds.
Crystal Clear Benefits of Closed Tubular Glass PBR Systems

**Bio-Secure**
protection against bio-contamination and culture crashes

**Productive**
80 - 160 l/m² photoactive volume, PBR height up to 6m

**Cost Efficient**
little maintenance and low total cost of ownership

**Durable**
sustainable light transmission
T > 95 % (air-glass-water), lifetime of 50 years and more

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

**Food Safe**
food and pharma grade
Product Range

Overview

Helical System

1. U- or J-Bend
2. Coupling
3. Tubing

Fence System

1. Manifold
2. Coupling
3. Tubing

horizontal or vertical orientation
# Product Range
## Borosilicate Glass Tubing
### DURAN®

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Joint Outside Diameter</th>
<th>Joint Wall Thickness</th>
<th>Tube Length</th>
<th>Volume per tube</th>
<th>Package Type*</th>
<th>Package Content</th>
<th>Number of Tubes</th>
<th>Weight approx. kg</th>
<th>Weight approx. lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1535285</td>
<td>54 ± 0.54 (2.13 ± 0.02)</td>
<td>1.8 ± 0.12 (0.07 ± 0.01)</td>
<td>1.4 (4.6)</td>
<td>2.79 (0.74)</td>
<td>carton</td>
<td>9</td>
<td>8.3</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pallet</td>
<td>180</td>
<td>166</td>
<td>366</td>
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<td>1522883</td>
<td>54 ± 0.54 (2.13 ± 0.02)</td>
<td>1.8 ± 0.12 (0.07 ± 0.01)</td>
<td>2.5 (8.2)</td>
<td>4.99 (1.32)</td>
<td>carton</td>
<td>12</td>
<td>19.7</td>
<td>43.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pallet</td>
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<td></td>
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<td>1523124</td>
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<td></td>
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<td>430.8</td>
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<td>1534297</td>
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<td>pallet</td>
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<td>1500383</td>
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<td></td>
<td></td>
<td></td>
<td>carton</td>
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<td>12.2</td>
<td>26.9</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pallet</td>
<td>180</td>
<td>244</td>
<td>538</td>
<td></td>
</tr>
<tr>
<td>1511901</td>
<td>65 ± 0.65 (2.56 ± 0.03)</td>
<td>2.2 ± 0.18 (0.09 ± 0.01)</td>
<td>2.5 (8.2)</td>
<td>7.21 (1.90)</td>
<td>carton</td>
<td>9</td>
<td>21.8</td>
<td>48.0</td>
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<td></td>
<td></td>
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<td>191.6</td>
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</tr>
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<td>165</td>
<td>877.9</td>
<td>1935.5</td>
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<tr>
<td>1535280</td>
<td>300 ± 3.8 (11.81 ± 0.15)</td>
<td>5.0 ± 0.8 (0.20 ± 0.03)</td>
<td>1.3 (4.3)</td>
<td>85.87 (22.68)</td>
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<td></td>
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<td></td>
<td>pallet</td>
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<td>80.6</td>
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<td>1534764</td>
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<td>pallet</td>
<td>6</td>
<td>247.9</td>
<td>546.5</td>
<td></td>
</tr>
</tbody>
</table>

* for explanation regarding package type please see page 15
Product Range
Borosilicate Glass U- and J-Bends
DURAN®

Helical System

Bend Types are used for the following applications
- **U-Bend**: for gaps between tubes of typically 65 mm/2.56 in or more
- **U-Bend long**: used in combination with J- and U-Bends
- **J-Bend**: for smaller gaps down to 40 mm/1.57 in (couplings are shifted in every second row)
### U-Bend

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Joint Outside Diameter</th>
<th>Joint Wall Thickness</th>
<th>Joint U-Bend Width</th>
<th>Approx. U-Bend Height</th>
<th>Straight Side Length</th>
<th>Volume per Bend (approx.)</th>
<th>Package Type</th>
<th>Package Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1534644</td>
<td>54 ± 0.54 2.13 ± 0.02</td>
<td>2.5 ± 0.2 0.10 ± 0.01</td>
<td>234 ± 2.0 9.21 ± 0.08</td>
<td>200  7.87</td>
<td>&gt; 45  1.77</td>
<td>0.85 0.22</td>
<td>carton</td>
<td>34</td>
</tr>
<tr>
<td>1436672</td>
<td>65 ± 0.65 2.56 ± 0.03</td>
<td>2.8 ± 0.2 0.11 ± 0.01</td>
<td>245 ± 2.0 9.65 ± 0.08</td>
<td>200  7.87</td>
<td>&gt; 45  1.77</td>
<td>1.2 0.32</td>
<td>carton</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pallet</td>
<td>544</td>
</tr>
</tbody>
</table>

### U-Bend long

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Joint Outside Diameter</th>
<th>Joint Wall Thickness</th>
<th>Joint U-Bend Width</th>
<th>Approx. U-Bend Height</th>
<th>Straight Side Length</th>
<th>Volume per Bend (approx.)</th>
<th>Package Type</th>
<th>Package Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1551070</td>
<td>65 ± 0.65 2.56 ± 0.03</td>
<td>2.8 ± 0.2 0.11 ± 0.01</td>
<td>245 ± 2.0 9.65 ± 0.08</td>
<td>300 11.81</td>
<td>&gt; 145 5.71</td>
<td>1.8 0.48</td>
<td>carton</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pallet</td>
<td>189</td>
</tr>
</tbody>
</table>

### J-Bend

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Joint Outside Diameter</th>
<th>Joint Wall Thickness</th>
<th>Joint U-Bend Width</th>
<th>Approx. U-Bend Height</th>
<th>Straight Side Length short leg long leg</th>
<th>Volume per Bend (approx.)</th>
<th>Package Type</th>
<th>Package Content</th>
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<tr>
<td>1551197</td>
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<td>2.8 ± 0.2 0.11 ± 0.01</td>
<td>245 ± 2.0 9.65 ± 0.08</td>
<td>200 7.87</td>
<td>&gt; 45 1.77 &gt; 145 5.71</td>
<td>1.5 0.4</td>
<td>carton</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pallet</td>
<td>189</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 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
- Food grade

Note
A special tutorial you get on request. Please follow the link or QR code to watch our tutorial video.

http://www.us.schott.com/pbr-tutorial
<table>
<thead>
<tr>
<th>Item No.</th>
<th>Outside Diameter Tube on Side 1</th>
<th>Outside Diameter Tube on Side 2</th>
<th>Package Description Package</th>
<th>Description</th>
<th>Package</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>Number of Couplings</td>
<td></td>
<td>Weight approx. kg approx. lb</td>
</tr>
<tr>
<td></td>
<td>in</td>
<td>in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1530116</td>
<td>54</td>
<td>54</td>
<td>24 bag</td>
<td>Standard (1)</td>
<td>6.9 15.3</td>
</tr>
<tr>
<td></td>
<td>2.13</td>
<td>2.13</td>
<td>960 pallet</td>
<td></td>
<td>277.7 612.2</td>
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<tr>
<td>1581056*</td>
<td>65</td>
<td>65</td>
<td>24 bag</td>
<td>Standard Slim (2)</td>
<td>5.6 15.3</td>
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<tr>
<td></td>
<td>2.56</td>
<td>2.56</td>
<td>1824 pallet</td>
<td></td>
<td>224.6 612.2</td>
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<tr>
<td>1463260</td>
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<td>65</td>
<td>24 bag</td>
<td>Standard (1)</td>
<td>6.1 13.4</td>
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<td></td>
<td>2.56</td>
<td>2.56</td>
<td>960 pallet</td>
<td></td>
<td>219.4 483.7</td>
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<tr>
<td>1581035</td>
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<td>65</td>
<td>24 bag</td>
<td>Standard Slim (2)</td>
<td>5.9 13.4</td>
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<tr>
<td></td>
<td>2.56</td>
<td>2.56</td>
<td>1824 pallet</td>
<td></td>
<td>236.2 483.7</td>
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</tbody>
</table>

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

* available in 2018

Additional Equipment

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Outside Diameter Tube on Side 1</th>
<th>Outside Diameter Tube on Side 2</th>
<th>Package Description Package</th>
<th>Description</th>
<th>Package</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>Number of Couplings</td>
<td></td>
<td>Weight approx. kg approx. lb</td>
</tr>
<tr>
<td></td>
<td>in</td>
<td>in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1530120</td>
<td>54</td>
<td>54</td>
<td>4 carton</td>
<td>Maintenance kit (no partition wall) (3)</td>
<td>0.9 2.0</td>
</tr>
<tr>
<td></td>
<td>2.13</td>
<td>2.13</td>
<td>576 pallet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1530105</td>
<td>65</td>
<td>65</td>
<td>4 carton</td>
<td>Maintenance kit (no partition wall) (3)</td>
<td>1.0 2.2</td>
</tr>
<tr>
<td></td>
<td>2.56</td>
<td>2.56</td>
<td>576 pallet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1534828</td>
<td>65</td>
<td>63.5</td>
<td>4 carton</td>
<td>Adapter (4)</td>
<td>1.0 2.2</td>
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<tr>
<td></td>
<td>2.56</td>
<td>2.50</td>
<td>576 pallet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Standard, length 80 mm
With partition wall to assure glass separation and smooth transition

(2) Standard Slim, length 45 mm

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

(4) Adapter, length 80 mm
Allows connection to pheriphery tubes with 2.5 inch outer diameter
Product Range
Borosilicate Glass Manifolds DURAN®

Fence System

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

- Bio secure 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

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Description</th>
<th>Package</th>
<th>Package Content</th>
<th>Minimum Order Quantity (MOQ)</th>
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<tr>
<td>1532688</td>
<td>Manifolds 10 arms closed 54 mm</td>
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<tr>
<td>1532689</td>
<td>Manifolds 5 arms flange 54 mm</td>
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<td></td>
<td>25</td>
</tr>
<tr>
<td>1573546</td>
<td>Manifolds 8 arms closed 65 mm</td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>1573547</td>
<td>Manifolds 4 arms flange 65 mm</td>
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<td></td>
<td>25</td>
</tr>
<tr>
<td>1589377</td>
<td>Manifolds 6 arms open 65 mm</td>
<td>carton</td>
<td>2</td>
<td>1 pallet</td>
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<tr>
<td></td>
<td></td>
<td>pallet</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>
Packaging

**Cartons**
- Tubes, up to 2.5 m length
- U-Bends
- Couplings
- Manifolds

**Wooden boxes**
- Tubes, 5.5 m length, smaller quantities

**Special Pallets**
- Tubes, 4 m and 5.5 m length
# Borosilicate Glass Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Metric</th>
<th>US</th>
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<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>$63 \cdot 10^3 , N \cdot mm^{-2}$</td>
<td>$91 \cdot 10^3 , lb \cdot in^{-2}$ (psi)</td>
</tr>
<tr>
<td>Poisson’s ratio $\mu$</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Thermal conductivity $\lambda_w$ 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) $n_d$</td>
<td>1.473</td>
<td>1.473</td>
</tr>
<tr>
<td>Stress-optical coefficient (DIN 52 314) K</td>
<td>$4.0 \cdot 10^{-6} , mm^2 \cdot N^{-1}$</td>
<td>$4.0 \cdot 10^{-6} , mm^2 \cdot N^{-1}$</td>
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</tbody>
</table>

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

main components in approx. weight %

<table>
<thead>
<tr>
<th>Chemical Resistance</th>
<th>Hydrolytic Class (DIN ISO 719)</th>
<th>HGB 1</th>
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<tbody>
<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>
Transmission

Transmission of DURAN® glass (d=2.2mm) in configuration air/glass/air.

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 maximum pressure resistance (p)

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

Estimation of the minimum wall thickness (WT)

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

K = 70 bar

permissible load referring to standard DIN EN 1595: Pressure Equipment made from Borosilicate Glass 3.3 General Rules for Design, Manufacture and Testing

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.

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

Other points to be considered:
- 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.
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 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 closed 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

Use of GMO* for improved production process
- GMO production is possible with closed reactor design

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

**Light transmission**
- Excellent light transmission (see page 17 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 polymer pellets
- 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

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Sagging of water-filled tubes
(outside 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.
Pressure Drop in Tubular Photobioreactors

For the optimum construction of a photobioreactor the expected pressure loss in the system must be known. This information is relevant for the lay-out of the ideal pump design. For the calculation of the pressure drop of the entire photobioreactor system the pressure drops of the individual components can be added together. The individual pressure drops must be calculated for the desired velocity, \( u \).

In the following table (p. 21) the individual pressure drops of representative glass components are shown for a typical flow velocity of 0.7 m/s. The pressure drops depend on the dimensionless zeta-values, which slightly decrease at larger velocities. Please contact SCHOTT technical service for assistance and additional simulations.
Pressure loss

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

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

\(\Delta p\): pressure loss  
\(\zeta\): pressure loss number (zeta)  
\(\rho\): algae culture density  
\(u\): linear velocity of algae culture

<table>
<thead>
<tr>
<th>(u = 0.7 \text{ m/s})</th>
<th>(\zeta)</th>
<th>(\Delta p \text{ [Pa]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round Tube</td>
<td>1.96</td>
<td>480</td>
</tr>
<tr>
<td>((D = 65 \text{ mm}, \text{ WT} = 2.2 \text{ mm, L} = 5.5 \text{ m}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-Bend</td>
<td>0.252</td>
<td>62</td>
</tr>
<tr>
<td>((D = 65 \text{ mm}, \text{ WT} = 2.8 \text{ mm}))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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  
\(\Delta p\): Sum of pressure loss in Pa  
\(Q\): Volume flow rate in m\(^3\)/s  
\(\eta_p\): Pump efficiency at operating point (0 < \(\eta_p\) < 1)
References of Glass Tubular 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.

www.us.schott.com/wastewater-treatment
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