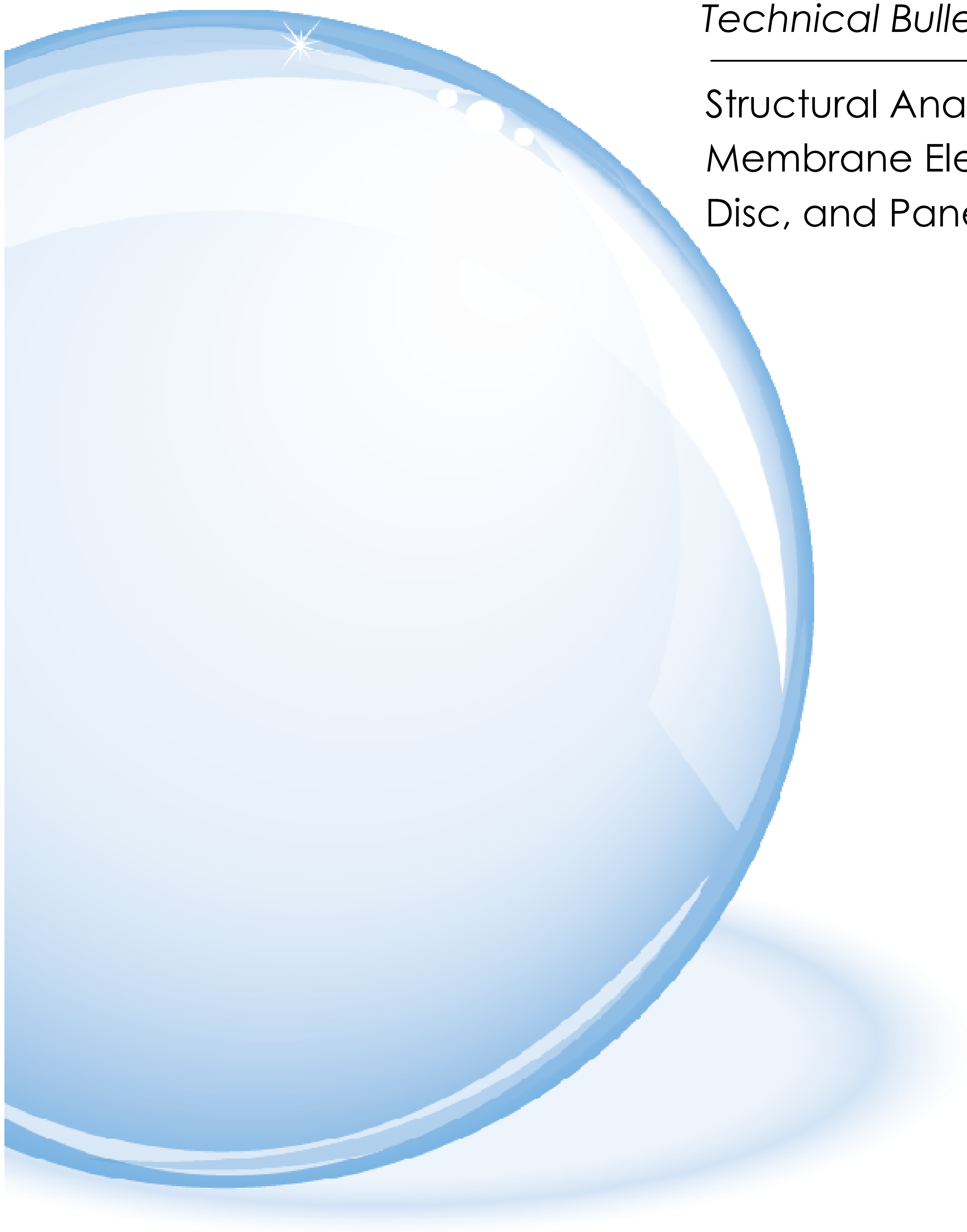
Technical Bulletin 138

Structural Analysis of Membrane Element for Tube, Disc, and Panel Diffusers



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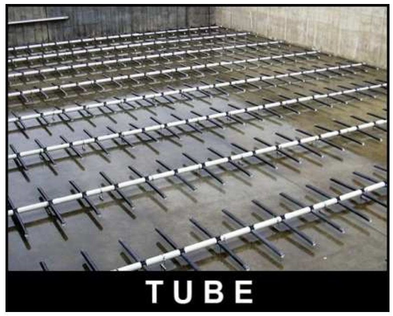
BULLETIN BRIEF

Flexible membrane diffusers have undergone several design iterations since the introduction of the technology in the mid-1970's. Most flexible membrane diffusers may be generically categorized as one of the following:



While the primary manufacturers of these products have refined their designs over the years, the inherent mechanical design characteristics for each configuration remains largely unchanged.

In general, the stress in the membrane element influences the mechanical performance of the diffuser product in terms of membrane service life and operational flexibility (turn-up capacity). Design engineers and end users should be aware of this condition and carefully evaluate the performance objectives and requirements for their applications when selecting a flexible membrane aeration device.

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Membrane diffusers may be modeled as a thin-walled pressure vessel where the membrane element or vessel wall offers little resistance to bending. Reference information on the mechanical design of membrane elements is provided by "Stresses in Thin-Walled Pressure Vessels", Mechanics of Materials, Ferdinand P. Beer and E. Russell Johnston, Jr., McGraw-Hill Book Company.[1]

Using this evaluation technique, the attached mechanical stress for each of these three (3) generic diffuser configurations may be estimated as follows.

Tubular Diffusers:

The mechanical stress in the membrane element of a tubular diffuser or cylindrical pressure vessel is illustrated in Figure No. 1a & 1b.

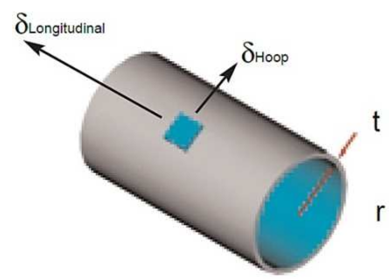

Figure No. 1a

Primary Stress:

As shown, the primary stress in the membrane is hoop stress (δHoop).

This stress is equal to:

$\delta_{Hoop} = p\ r\ /\ t$

where:

p = internal pressure

(For diffuser applications, internal pressure is equivalent to the operating dynamic wet pressure (DWP) of the device)

r = radius (inside)

t = wall thickness

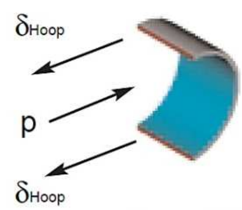

Figure No. 1b

The hoop stress in a tubular membrane diffuser is typically very low and is self-contained within the membrane resulting in a very efficient mechanical design.

For the EDI FlexAir® Magnum and MiniPanel™ diffuser, the estimated δ_{Hoop} in these diffusers is as follows:

EDI FlexAir® Magnum™ Diffuser:

where: $p = 15$ in DWP @ 3.5 scfm/sf
$r = 1.85$ in
$t = 0.0787$ in for EPDM membrane
$= 0.0280$ in for Urethane membrane

δ_{Hoop} (EPDM Membrane)

$= 0.54$ psi * 1.85 in / 0.0787 in
$= 12.7$ psi (8.7 N/cm^2)

δ_{Hoop} (Urethane Membrane)

$= 0.54$ psi * 1.85 in / 0.028 in
$= 35.7$ psi (24.6 N/cm^2)

EDI FlexAir® MiniPanel™ Diffuser:

where: $p = 12.5$ in DWP @ 3.5 scfm/sf
$r = 2.24$ in
$t = 0.0787$ in for EPDM membrane
$= 0.0280$ in for Urethane membrane

δ_{Hoop} (EPDM Membrane)

$= 0.45$ psi * 2.24 in / 0.0787 in
$= 12.8$ psi (8.8 N/cm^2)

δ_{Hoop} (Urethane Membrane)

$= 0.45$ psi * 2.24 in / 0.028 in
$= 36.0$ psi (24.8 N/cm^2)

The operating stress in these tubular membrane diffusers is very low and confirms the conservative mechanical design typical of tubular diffusers. Field application of EDI's products supports this condition as rarely do EDI's tubular membrane diffusers mechanically fail.

The conservative mechanical design common to tubular diffusers allows significant operational flexibility in terms of diffuser gassing rate. The diffuser gassing rate for tubular products may be increased significantly without inducing material fatigue. In terms of operating capacity, tubular diffusers are capable of operating at gassing rates in excess of 10 scfm / ft^2 (183 nm^3 / hr - m^2) of perforated diffusion media without material fatigue.

Secondary Stress:

The secondary stress in a tubular membrane is longitudinal stress (δ_{Long}). This stress is equal to:

$$\delta_{Long} = p\,r / 2\,t$$
$$= 1/2 \text{ of } \delta_{Hoop}$$

where:

p = internal pressure
r = radius (inside)
t = wall thickness

The membrane clamping requirement for a tubular product is directly related to longitudinal stress. The clamps on a tubular diffuser serve to create a seal between the membrane and the support tube. In this case, the structural requirement for the clamp is very low and is approximately equal to the operating pressure (DWP) of the diffuser. In addition to sealing, the clamp may be designed to longitudinally restrain the end of the membrane. As the longitudinal stress in the membrane is very low, 1/2 of the hoop stress, minimal clamping pressure is required to satisfy this criteria. On some tubular diffuser designs, longitudinal movement of the membrane is allowed reducing the functional requirement for the clamp to sealing pressure.

Simple band clamps are commonly employed on tubular diffusers. These clamps provide uniform clamping pressure and are available with a shielding feature to prevent damage to the membrane sleeve. Additionally, the materials of construction for the clamp may be selected to maximize field performance. Standard materials of construction include 304 and 316 stainless steel, and non-metallic materials. A finite element analysis (FEA) confirms the stress levels calculated by the analytical approach. For the FlexAir Magnum diffuser, the hoop stress in the EPDM membrane is approximately 13.5 psi (9.3 N/cm^2).

Panel Diffusers:

There are several types of panel diffusers currently available in the market. As illustrated in Figure No. 3, the geometry of an individual operating membrane section on a panel is equivalent to a longitudinal section of a cylindrical pressure vessel. Thus, the mechanical design and corresponding stress in the membrane may be estimated as follows:

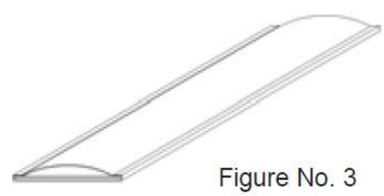

Figure No. 3

Primary Stress

US Manufacturer (Figure No. 4):

where

p = 28 in DWP (advertised operating pressure)
r = 5.94 in, $(4b^2 + c^2) / 8b$ (reference Manual of Steel Construction, AISC)[2]
b = height (field measurement = 0.8125 in)
c = length of cord (field measurement = 6 in)
t = 0.028 in (assumed value)

δ_{Hoop} (Primary Stress)

$= p\,r / t = 1.0 \text{ psi} * 5.94 \text{ in} / 0.028 \text{ in}$
$= 212 \text{ psi } (146\ N/cm^2)$

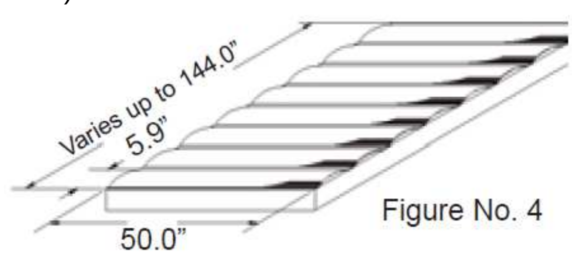

Figure No. 4

German Manufacturer – Type N and T (Figure No. 5a & b):

where:

p = 40 in DWP (advertised operating pressure)
r = 6 in (advertised value)
t = 0.028 in (advertised value)

δ_{Hoop} (Primary Stress) = p r / t = 1.45 psi * 5.9 in / 0.028 in
= 305 psi (210 N/cm^2)

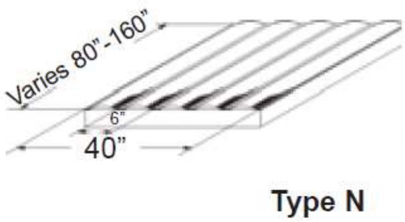

Figure No. 5a

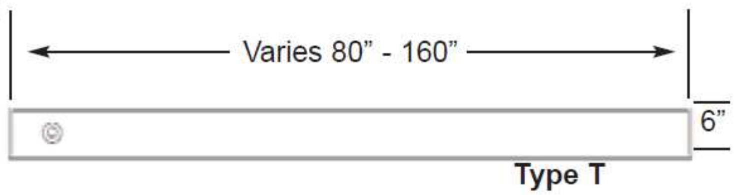

Figure No. 5b

The operating stress in membrane panel diffusers ranges from 200 to 300 psi (140 to 200 N/cm^2). Panel diffusers inherently operate at higher membrane stresses than tubular diffusers due to the geometry of the device. This reinforces the requirement for prudent mechanical design and proper membrane material selection for these products. Furthermore, as the membrane stress on these units is inherently higher than for tubular or disc units, reduced operational flexibility is provided and should be considered in terms of overall plant operational capacity.

<u>Secondary Stress:</u>

Unlike the design requirements for tubular diffusers, the clamping system on panel diffusers must be designed to both seal and transfer the operating stresses in the membrane to the support structure. The structural requirements for the clamping components may be estimated as follows:

US Manufacturer (Figure No. 4):

The overall dimensions of this product are 50” x 144” (127 cm x 366 cm). A structural perimeter frame is used to hold the membrane in place. The frame uses integral cross bracing to reduce the stress and minimize the upward deflection of the membrane. This frame is attached to the diffuser support structure by means of fasteners around the perimeter of the device.

The mechanical forces on the structural frame may be estimated as follows:

Uplift Force = operating pressure x area
= 1.0 psi * 50 in * 144 in
= 7,200 lbs (3,266 kgs)

Clamping Force *(Required to Transfer Primary (hoop) Stress)*

Membrane Pull-out Force = force per unit area x cross sectional area
= δ_{Hoop} * t
= 212 psi * 0.028 in
= 5.94 lbs per lineal inch
(1.1 kgs per lineal cm)

Clamping Force = 5.94 lbs per lineal inch / 0.5
where: Coefficient of friction = 0.5 (assumed)
= 11.9 lbs per lineal inch
= 11.9 lbs per lineal inch * Perimeter
= 11.9 lbs per lineal inch * (50 + 144) * 2
= 4,600 lbs (2,090 kgs)

Total Clamping Force (est) = 7,200 + 4,600 lbs
= 11,800 lbs (5,350 kgs)

German Manufacturer – Type T:

The overall dimensions of this product (Model T4) are - 5.9" x 158" (15 cm x 400 cm). A structural perimeter frame is used to retain the membrane as shown in Figure No. 7. The mechanical forces on the structural frame may be estimated as follows:

Uplift Force
= 1.45 psi * 5.9 in * 158 in
= 1,352 lbs (613 kgs)


Figure No. 7

Clamping Force (Required to Transfer Primary (hoop) Stress)

Membrane Pull-out Force = δ_{Hoop} * t
= 310 psi * 0.028 in
= 8.7 lbs per lineal inch
(1.55 kgs per lineal cm)

Clamping Force = 8.7 lbs per lineal inch / 0.5
Where: Coefficient of friction = 0.5 (assumed)
= 17.4 lbs per lineal inch
= 17.4 lbs per lineal inch * Perimeter
= 17.4 lbs per lineal inch * (5.9 + 158) *2
= 5,690 lbs (2,580 kgs)

Total Clamping Force (est) = 1,352 + 5,690 lbs
= 7,043 lbs (3,195 kgs)

German Manufacturer – Type N:

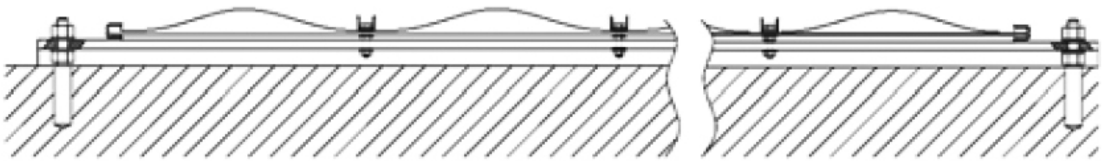

Figure No. 8

The overall dimensions of this product (Model N 4) are 41” x 158” (104 cm x 400 cm). The clamping system uses a structural perimeter frame with intermediate cross supports as shown in Figure No. 8. The mechanical forces on the structural frame may be estimated as follows:

Uplift Force = 1.45 psi * 41 in * 158 in
= 9,393 lbs (4,260 kgs)

Clamping Force (Required to Transfer Primary (hoop) Stress)
Membrane Pull-out Force = δ_{Hoop} * t
= 305 psi * 0.028 in
= 8.7 lbs per lineal inch
(1.55 kgs per lineal cm)

Clamping Force = 8.7 lbs per lineal inch / 0.5
where: Coefficient of friction = 0.5 (assumed)
= 17.4 lbs per lineal inch
= 17.4 lbs per lineal inch * Perimeter
= 17.4 lbs per lineal inch * (41 + 158) *2
= 6,925 lbs (4,775 kgs)

Total Clamping Force (est) = 9,393 + 6,925 lbs
= 16,318 lbs (7,400 kgs)

These calculations approximate the theoretical mechanical design requirements for the clamping system for panel diffusers. As no clamping systems are 100% efficient, stress concentrations exist and should be considered for proper functional performance. Numerous mechanical failures of the membrane have been experienced with these types of products. As anticipated, stress fatigue around the perimeter of the device and at bolt locations has occurred leading to a mechanical failure of the membrane element.

<u>Disc Diffusers:</u>

The membrane element on a disc diffuser is structurally equivalent to a thin-walled sphere, reference Figure No. 9. As illustrated, the primary stress in the element is equal to:

$\delta = p\, r / 2t$

where:
p = pressure
r = radius
t = thickness

Figure No. 9

Nine (9) inch (23 cm) Disc Diffuser:

where: p = 10 in DWP @ 3.5 scfm/sf
r = 8.7 in
t = 0.0787 in (minimum)

δ = 0.36 psi * 8.7 in/(2 * 0.0787 in)
= 20 psi (13.8 N/cm2)

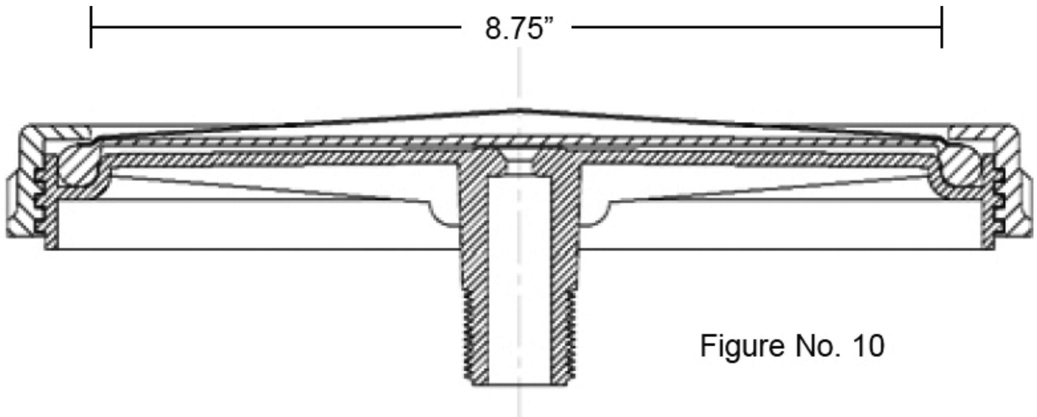

Figure No. 10

The operating stress in the membrane is approximately 150 to 200% of the stress in a tubular diffuser. The stress in a membrane disc increases with diffuser diameter and several mechanical failures of large diameter discs have been experienced in the industry.

A perimeter retainer ring is commonly used to restrain the membrane. The overall diameter of a nine (9) inch disc is 8.75” (22.2 cm). This dimension excludes the perimeter O-ring that is used to secure the membrane to the disc base plate, see Figure No. 10. The estimated mechanical forces on the retainer ring are as follows:

Uplift Force = p r^2 π / 4 = 0.36 psi * 8.75 in2 * π / 4
= 22 lbs (10 kgs)

Clamping Force (Required to Translate Primary Hoop Stress)
Membrane Pull-out Force = Stress * t
= 20 psi * 0.0787 in
= 1.6 lbs per lineal inch
= 1.6 lbs * π * 8.75
= 43 lbs (19.5 kgs)

There are several attachment mechanisms used in the industry to attach the membrane element to the support structure. These include threaded retainer ring, perimeter ring with fasteners, slip-over membrane design, and center fastener. As the mechanical forces on the membrane retainer system are significant, the specific method of attachment should be carefully evaluated to maximize the service life for the system.

Membrane Materials:

Generally, there are three polymeric materials used by manufacturers of flexible membrane diffusers. These include:

- EPDM (ethylene propylene)
- Urethane (polyether)
- Silicone

Properly designed, EPDM rubber formulations have proven to be an excellent material for most municipal and many industrial applications where the presence of solvents and oils is low. Today, advanced compound formulations are available from the leading suppliers in the industry. Additionally, some specialty compounds are engineered for high tear strength to better accommodate the die cut perforations in the membrane. In terms of mechanical strength, quality EPDM rubber compounds commonly have an ultimate tensile strength of about 1,300 to 2,000 psi (900 to 1,400 N/cm^2) and tear strengths (Die T) of 50 to 70 pli (9 to 12 kgs per lineal cm).

Urethane polymers have been effectively applied in municipal and several industrial applications. Urethane provides improved resistance to oils and solvents as compared to EPDM rubber. However, urethane is more susceptible to creep under conditions of high stress and elevated temperatures. Recent advances include high temperature urethanes that extend the application range for this material. In terms of mechanical strength, urethane compounds commonly have an ultimate tensile strength of about 5,500 to 6,000 psi (3,800 to 4,000 N/cm^2). While the strength of urethane compounds is greater than EPDM rubber, urethane membrane elements are generally thinner than their EPDM rubber counterparts to reduce the operating pressure for the diffuser.

Several diffuser manufacturers promote silicone membrane compounds. Generally, silicone offers excellent heat resistance though the mechanical properties of the material are modest with low mechanical strength, 200 to 1,500 psi (130 to 1,000 N/cm^2), and poor tear resistance. The heat resistance provided with silicone is of minor benefit as the common materials of construction used in diffused aeration systems (PVC) offer modest heat resistance, less than 140℉ (60℃).

Summary

The operating and environmental conditions under which a diffuser will operate are important to consider when selecting a diffuser product. As there are many diffuser products available in the market, consideration of the following items will maximize the performance and service life of the product.

- In terms of mechanical design, a low stress design will afford greater operational flexibility and service life.

- Tubular diffusers are mechanically superior to both disc and panel diffusers. Typical membrane stress is <15 psig for a tubular device, approximately 20 psig for a 9-inch disc, and 200-300 psig for a panel diffuser.

- Select a membrane material that is compatible with the chemical constituents in the wastewater. As material compatibility is often difficult to estimate, select a vendor that offers multiple material options. Field trials are beneficial both prior to initial installation and concurrent with normal operations to maximize the long-term performance and service life of the diffuser.

- All membrane diffusers utilize some form of a mechanically perforated membrane. Vendors offering multiple perforation patterns can custom engineer the product to match the oxygen transfer, gassing rate, and operating pressure criteria for the application.

Flexible membrane diffusers are the diffuser technology of the future. Properly designed, flexible membrane diffusers are the most economical aeration technology available when considering capital cost, installation cost, operating efficiency, service life and maintenance requirements. Prudent selection of the diffuser component for your system will result in excellent long term, cost effective performance of your aeration systems.

For additional information on flexible membrane diffuser technologies contact your local EDI representative or by contacting Environmental Dynamics International directly at edi@wastewater.com or by calling +1 877.EDI.AIR8 (334-2478)

References:

1. F. P. Beer and E. R. Johnston, Jr., "Mechanics of Materials" (McGraw-Hill Book Company)
2. Manual of Steel Construction, American Institute of Steel Construction, Inc., Properties of the Circle.