Theoretical Operation of High-Efficiency
Ultraviolet Water Treatment Chamber

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1. Introduction

The NeoTech Aqua ReFleX™ water purification chambers are the most efficient and compact units available today. They require an order of magnitude less energy and less than 25% of the system volume to achieve the same or better purification result as competing chambers. This is the first in a series of three white papers explaining the benefits of these systems. This paper explains in detail the theory behind the operation of these chambers, including some computational examples of performance. The second paper presents both in-house and third party data demonstrating that performance in full scale systems as well as describing the protocols under which those data were taken. The final white paper presents an analysis of those results which show that the unique optical nature of the ReFleX™ chamber leads to the capability to measure the dose delivered to a target contained within the chamber simply by measuring the intensity of the ultraviolet light at a single point on the chamber wall and the water flow through the chamber.

2. Theoretical basis for chamber performance

The ReFleX™ chamber's striking size and performance is rooted in a fundamental law of physics: conservation of energy. The design of the ReFleX™ chamber allows it to deliver a much higher dose on the target for a given amount of light introduced into the chamber. It does so by eliminating, to the greatest extent possible, the loss of the light energy introduced into the chamber due to the chamber's structural elements. It is best to begin the description of how this chamber works by describing the optical situation in a UV treatment chamber.

2.1 Microorganisms and water quality

First, consider the water containing the microorganisms. A typical bacteria has a diameter of 2 micrometers (μm) [1]. Light illuminating the bacteria will see the bacteria as an absorber with a cross section of

$$\pi*(2\ \mu m)^2/4 = 3.14 \text{ X } 10^{-12}\ m^2 = 3.14 \text{ X } 10^{-8}\ cm^2$$

The concentration of microorganisms in most water is low. A typical Maximum Contaminant Level (MCL) for coliform bacteria in municipal water is less than one viable bacterium per 2000 cm^3 [2]. Even grossly contaminated water will usually have less than 100,000 bacteria per cm^3 [3]. Using that worst case number, the total cross sectional area of bacteria per one square centimeter of highly contaminated water illuminated by the light is

$$100{,}000 * 3.14 \text{ X } 10^{-8}\ cm^2 = 3.14 \text{ X } 10^{-3}\ cm^2$$

So, even in the most contaminated water, only about 0.3% of the light illuminating a volume of water one centimeter thick is actually intercepted by the bacteria on the first pass. Even if the light path through the water is 3 cm (1.2 inches) long, which is a typical distance to the wall or between lamps in a UV chamber, only 1% of that light impinges on the bacteria in the first pass for this highly contaminated water.

2.2 Deposition of light energy in a chamber

2.2.1 Conventional UV treatment chambers

Figure 1 shows the cross section of a conventional stainless steel-walled chamber.

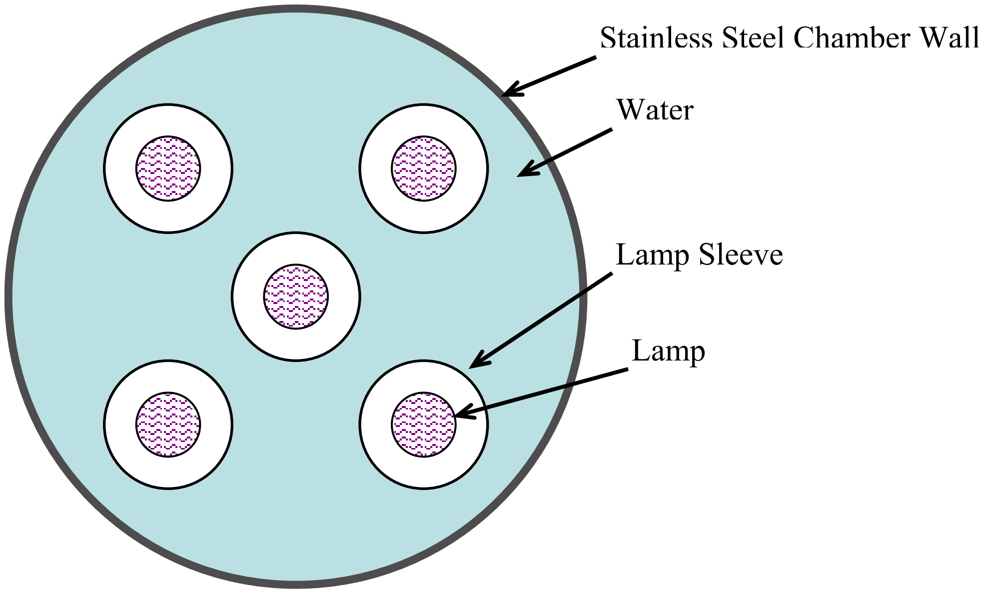

Figure 1. Conventional Stainless Steel UV Water Treatment Chamber.

In the example above, the light which is not absorbed by the bacteria or the other impurities in the water reaches the wall of the chamber. For effective UV treatment of all of the water, it is usually necessary that the light absorption due to other impurities in the water is relatively low. Normally, this means only a few percent of the light is absorbed in these impurities as well. The remaining light emanating from the light source impinges on the wall. For ultrapure water, the fraction of the initial light which reaches the wall is well over 90%. Even for drinking water, with its lower UV transmittance, the fraction of light impinging on the wall is well over 50% for a typical reactor.

The wavelength of light that inactivates bacteria is in the range of 240 nm to 280 nm. This wavelength range is in the "UV-C" range as described in some literature [4]. Most conventional high quality UV treatment chambers have 304 or 316L stainless steel walls. At these wavelengths, stainless steel has a reflectivity of at best 30% [5]. This is true regardless of the surface finish of the stainless steel – a rough finish can make the reflectivity even lower. This means that at least 70% of the light impinging on the wall of the chamber is absorbed and at most 30% is reflected back into the chamber.

The 30% of the light that is reflected back into the chamber sees the same optical conditions in the water as the incident light did, meaning only a small fraction of it encounters the bacteria in the water. Using our 3 cm path length example length above, and initially assuming that the bacteria and the wall are the only absorbers in the water, we can calculate a best case estimate of the percentage of light energy that is absorbed by the bacteria for this simplified example, with each term representing one pass:

Reflectance of Stainless Steel = Rss = 0.3
Absorbance of the bacteria in this case = AbsBac = 0.01

$SS = \sum[AbsBac*[Rss*(1-AbsBac)]^i]$ for $i = 0...6000$

$SS = \{0.01*1\} + \{0.01*[0.3*(1-0.01)]\} + \{0.01*[0.3*(1-0.01)]^2\} + \{0.01*[0.3*(1-0.01)]^3\} +...$

Numerically, this becomes:

$SS = 0.01 + 0.00297 + 0.000882 + 0.000262+ 0.0000778 + \ldots= 0.0142 \approx$ **1.4%**

Each term represents one pass through the water and reflecting off the wall. Note that almost all the deposition occurs in the first 3 passes (1.38 % out of the 1.42% total). There is very little light remaining in the chamber after those 3 passes, and most has been absorbed by the walls, not the bacteria. This is true despite the high bacterial count used.

2.2.2 ReFleX™ treatment chambers

The ReFleX™ treatment chamber is designed to overcome this limitation. The fundamental improvement in these units over conventional treatment chambers is the addition of a very highly reflective material to the chamber wall. This material is over 99% reflective at the germicidal wavelengths mentioned above. Figure 2. shows the cross section of such a chamber.

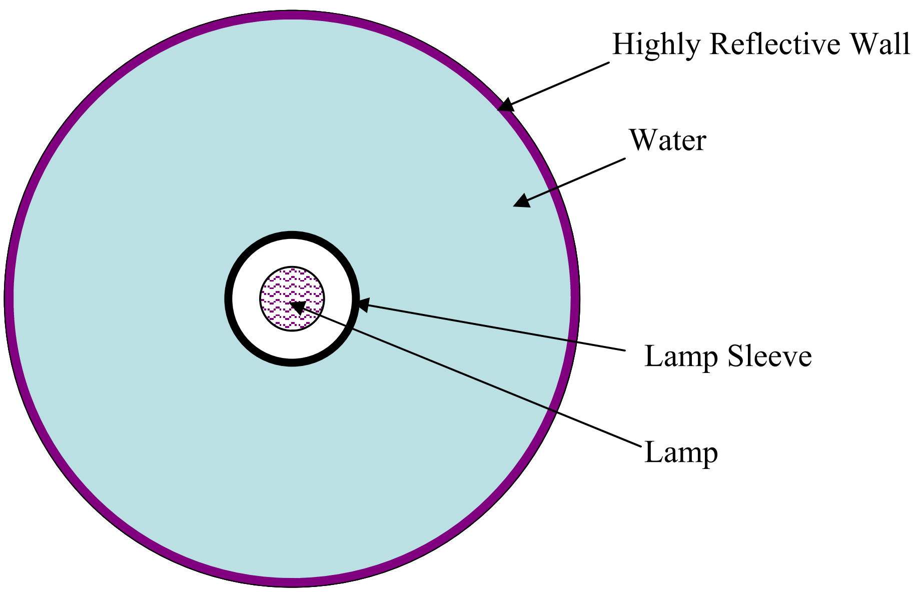

Figure 2. ReFleX™ Water Treatment Chamber

Under the same conditions, the amount of energy absorbed in the bacteria in this case is:

Reflectance of ReFleX™ reflector = Ruvs = 0.997
Absorbance of the bacteria in this case = AbsBac = 0.01

$ReFleX^{TM} = \sum[AbsBac*[Ruvs*(1-AbsBac)]^i]$ for $i = 0...6000$

$= \{0.01*1\}+\{0.01*[0.997*(1-0.01)]\}+\{0.01*[0.997*(1-0.01)]^2\}+\{0.01*[0.997*(1-0.01)]^3\}+...$

Numerically, this becomes:

$ReFleX^{TM} = 0.01 + 0.0099 + 0.0097 + 0.0096 + 0.0095 + \ldots= 0.826 \approx$ **83%**

After a large number of reflections (6000 for this example) the light has mostly been absorbed. However, in this case it has mostly been absorbed by the bacteria, **not** the wall. The relative amount of light absorbed by the bacteria in the ReFleX™ chamber compared to a conventional stainless chamber is:

83% / 1.4% = **59.3** times improvement

This ratio is equivalent to the increase in dose delivered from a fixed amount of input light by a highly reflective chamber as compared to a stainless steel chamber. This shows very clearly the tremendous performance increase when the walls absorb a very small fraction of the light impinging on them versus when they absorb most of the light.

This example is an idealized case. In the next section, factors which are expected in a real water treatment chamber are included to show the effect of a highly reflective chamber in "real world" situations.

2.2.3 Practical considerations:

In a practical system, the need for ports in the chamber (water inlet and outlet, lamp entry), the presence of other elements in the chamber (lamps, sleeves, baffles), and the presence of other light-absorbing material in the water (solids, dissolved chemicals, etc.) all work to reduce the potential benefit gained by using a highly reflective chamber wall. However, incorporating these factors in the calculations above shows that a highly reflective chamber still provides a significant performance improvement, even for a practical chamber treating water which contains light-absorbing material.

NOTE: The following analysis does not include the improved flow and uniformity of light intensity inherent in the ReFleX™ chamber. As a result, this analysis of the deposition of light under the stated conditions will produce a calculated performance advantage for the ReFleX™ chamber that is artificially low when compared to the actual measured performance of the unit. The improvement due to incorporating the improved flow and uniformity of light intensity is difficult to calculate due to the wide variety of standard stainless steel chamber designs. These effects are addressed qualitatively in Section 2.3, and experimental results demonstrating the measured performance advantage of the ReFleX™ chamber are presented in the next white paper in this series.

In general, the water inlet and outlet and the lamp ports for a conventional stainless steel chamber are a very small fraction of the chamber's inner surface area, and can be neglected. NeoTech Aqua's chamber designs maximize the percentage of the chamber wall that is covered with the reflector. ReFleX™ commercial chambers employing highly reflective walls have reflector coverages ranging from 95 to 98%, with 97% being a typical value.

The structures in a stainless steel chamber include lamps, lamp sleeves, baffles, and in some cases wipers. The lamps and lamp sleeves are by necessity very transmissive to UV, and are not a large source of losses in these chambers. The baffles and wiper hardware are usually made of the same stainless steel as the chamber itself. While these elements do affect the performance of a chamber due to shadowing, from the standpoint of light absorption, they are no different than the chamber walls, so they can be considered as part of the chamber wall for the purposes of loss calculation.

The ReFleX™ treatment chamber uses high quality synthetic quartz for all quartz components inside the chamber. This grade of synthetic quartz not only has essentially zero UV absorption, but also is not aged over time by the UV, so it in general does not contribute a significant loss at 254 nm. The

ReFleX™ chambers have no baffles or wipers in the treatment volume within the chamber, so there is no loss due to those elements.

Suspended solids, and dissolved solids and other dissolved chemicals such as chlorine in the water can increase the UV absorption by the water itself. High purity water such as pharmaceutical process water, semiconductor process water, and reverse osmosis permeate water usually transmits more than 98% of the UV light through one centimeter of water, which is defined as 98% UV transmittance (UVT). Tap water is typically between 92% and 95% UVT. Its lower UV transmittance is primarily due to the chlorine or monochloramines introduced into the water for disinfection purposes. In a multiple-barrier disinfection approach employing UV disinfection, the chemical disinfectants would be added after the UV disinfection step, and the water transmittance would be higher than that for tap water. Even so, we will use 95% UVT for this example.

Taking the same approach as the example in the previous section for a realistic stainless steel chamber, and incorporating these practical losses, the amount of light introduced into the chamber which is absorbed by the bacteria becomes:

Reflectance of Stainless Steel = Rss = 0.3
Absorbance of the bacteria in this case = AbsBac = 0.01
Chamber wall coverage = CovSS = 99% = 0.99
UVT_1 through 1 cm of water = UVT = 95% => UVT_3 through 3 cm = 0.95^3 = 86%

$SSp = \sum[AbsBac*[Rss*CovSS*UVT_3*(1-AbsBac)]^i]$ for i = 0...6000

SSp = 0.013 = **1.3%**

Note that this is essentially the same as the idealized case above. This is another clear indication that the stainless steel walls are the limiting factor in the performance of conventional UV treatment chambers.

For the ReFleX™ treatment chamber, incorporating the same losses yields the following result:

Reflectance of ReFleX™ reflector = Ruvs = 0.997
Absorbance of the bacteria in this case = AbsBac = 0.01
Chamber wall coverage = CovUVS = 97% = 0.97
UVT_1 through 1 cm of water = UVT = 95% => UVT_3 through 3 cm = 0.95^3 = 86%

ReFleX™p = $\sum[AbsBac*[Ruvs*CovUVS*UVT_3*(1-AbsBac)]^i]$ for i = 0...6000

ReFleX™p = 0.053 = **5.3%**

5.3% / 1.3% = **4.2** times improvement over stainless steel (worst case)

The ReFleX™ chamber's theoretical performance for a given input power is still significantly better when realistic chamber parameters and less than ideal water UV transmission are incorporated into the calculations. <u>However, this calculated improvement is actually **less** than the experimentally measured value of more than 10 times performance improvement for the ReFleX™ treatment chamber vs. conventional UV chambers produced in industry-standard biological challenge tests</u>. The reason for this, as mentioned at the beginning of this section, is that there are further design features inherent in the ReFleX™ treatment chambers which are improvements over conventional UV chambers and which result in this measured 10 times improvement. These features are described below.

2.3 Flow and dose uniformity considerations

The calculations in Section 2.2 assume perfectly uniform water flow and perfectly uniform UV intensity within the volume being treated. In practice, the ReFleX™ treatment chamber offers two distinct advantages which bring it much closer to the ideal flow and intensity profile than conventional UV chambers can achieve. As was mentioned above, a conventional UV chamber contains baffles to force its flow to be as uniform as possible. However, even with extensive baffling, it is difficult to create uniform flow over a large area and a long transit distance if the flow is too slow to be intrinsically turbulent, as is the case with most conventional UV chambers with their large diameters. It is also difficult to create highly uniform UV intensity over such a large volume replete with baffles and other obstructions. There will be shadowing from the baffles and lowered intensity at the chamber walls due to the farther distance from the lamps. This situation becomes even worse when the UV transmission of the water is low. The ReFleX™ treatment chamber is designed to overcome both of these performance-robbing difficulties.

<u>2.3.1 Flow Dynamics:</u>

The annular flow cross section in the active region of the ReFleX™ treatment chamber is sized such that the water flow is highly turbulent and approaches plugged flow at the rated water flows for the various treatment chamber sizes. This ensures that the net water velocity at all points in the active region is very close to the average velocity of the water flowing through the chamber. All of the water spends the same amount of time in the active volume, with no jets or sections with significantly higher than average velocity. This is shown graphically in Figure 3 below.

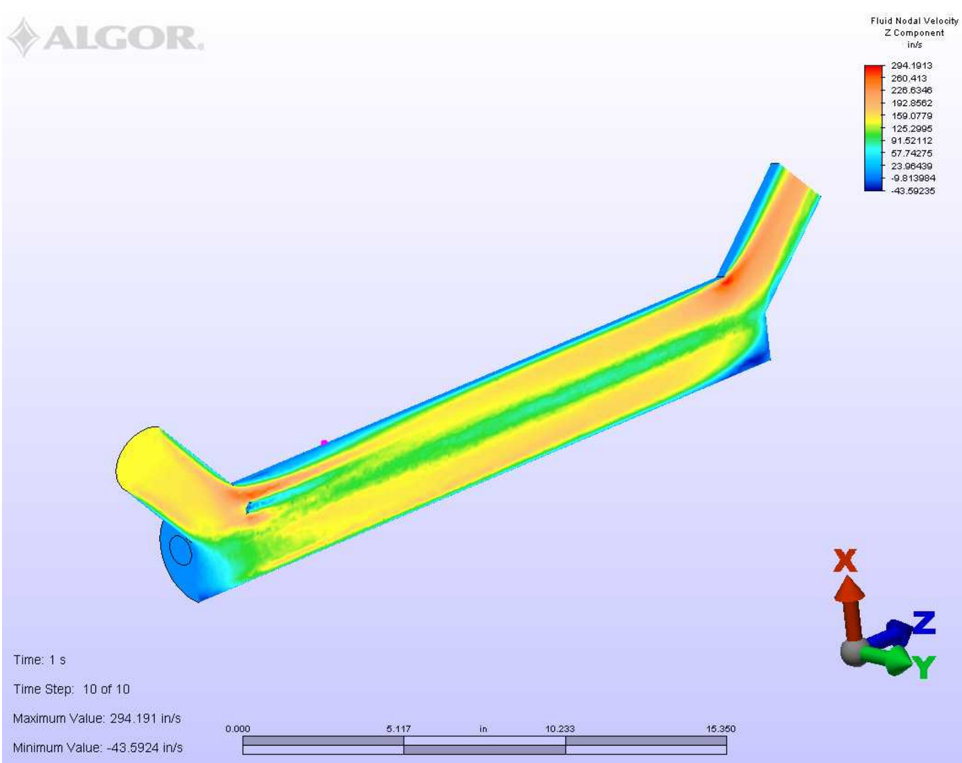

Figure 3. Flow velocity profile in the ReFleX™ 438 treatment chamber at 300 GPM (60% of full rating).

Note the high degree of uniformity in the large majority of the (baffle-free) active region – other than the small natural stagnation zones at the chamber wall and the small volume between the two lamps located in the center of the chamber, the flow is uniform throughout the active region to within a few percent. The uniformity improves at the full rated flow, ensuring that the residence time for any given volume of water is the same as that for all the others. This is one of the two things necessary for delivering a uniform UV dose to the water flowing through the chamber

2.3.2 Uniform UV Intensity:

The ReFleX™ treatment chamber's high reflectivity walls also serve to even out differences in UV intensity within the active volume. This effect is well known in optics and is exploited in devices such as integrating spheres [6]. The ReFleX™ treatment chamber encloses as much of the volume as possible with a highly reflective material, as does an integrating sphere. The large number of reflections individual photons experience before being absorbed leads to a very uniform intensity distribution of light within the volume. Figure 4 shows an optical "ray-tracing" simulation of the ReFleX™ chamber, in which 10 "rays" (or photons) were emitted by the light source in the center of the chamber.

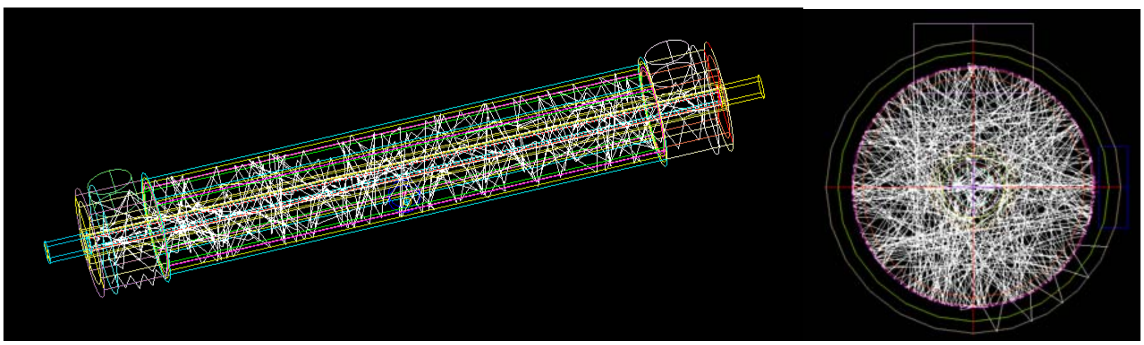

Figure 4. Ray –tracing simulation showing 10 rays inside a ReFleX™ chamber with a specular reflector. The left picture is a side view of the active region of the chamber and the right picture is an axial cross section showing the uniformity of the distribution of the rays within the volume.

The white ray traces show that even a small number of rays produce a uniform intensity distribution within the chamber. When a very large number of photons are injected, the uniformity of intensity is even higher.

A highly reflective chamber provides a more uniform dose even when the water has relatively low UV transmittance as well. This effect is particularly important for disinfection applications, where even a small region of undertreatment can spoil system performance.

To illustrate this effect, consider the one dimensional model used in Section 2.2 to quantify performance of a reflective chamber vs. a conventional chamber. In Figure 5, the assumption is that the water UVT is 80%. The effect is still present at both lower and higher UVT's than this, but this one was chosen to best illustrate the effect. Figure 5a) shows the intensity of the initial light output being attenuated as it through the water. The wall is at 3 cm from the light source, as shown in that graph. The curve in Figure 5a) then shows the intensity profile in the volume.

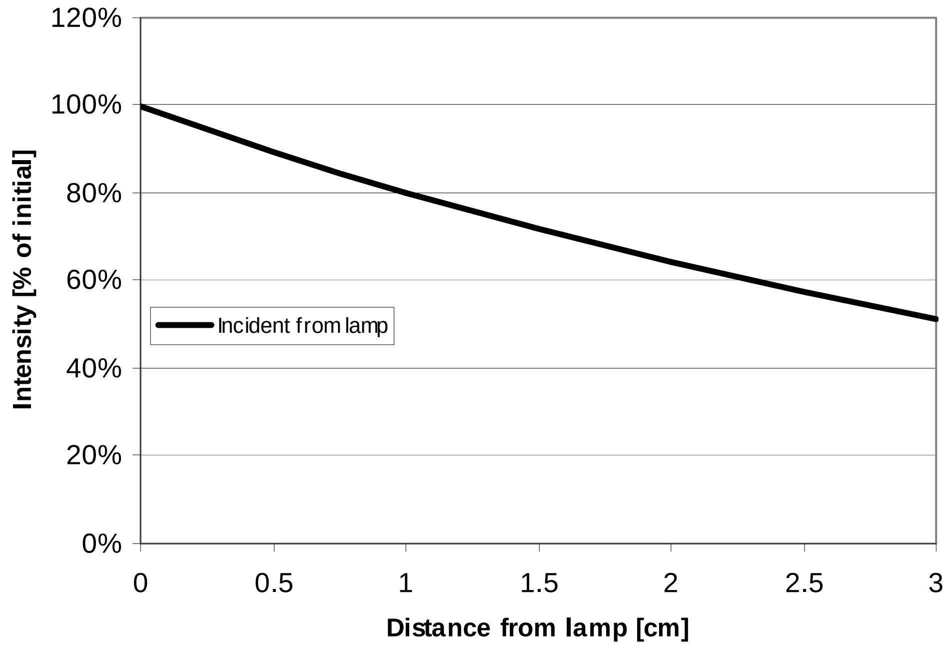

Figure 5a). The intensity of incident light attenuated while passing through 80% UVT water for 3 cm as a percentage of initial value.

The light that reaches the wall is reflected back into the water, and is attenuated as it travels back through the water as shown in Figure 5b). The initial value of the reflected light depends on the reflectance of the wall, so the initial value of the light reflected off the stainless steel wall is only 30% of the incident light on that wall, as shown here. The light intensity decays at the same rate as before as the light travels back toward the other wall. Subsequent reflections will occur, but the first two passes have the strongest effect, so only those two are shown here.

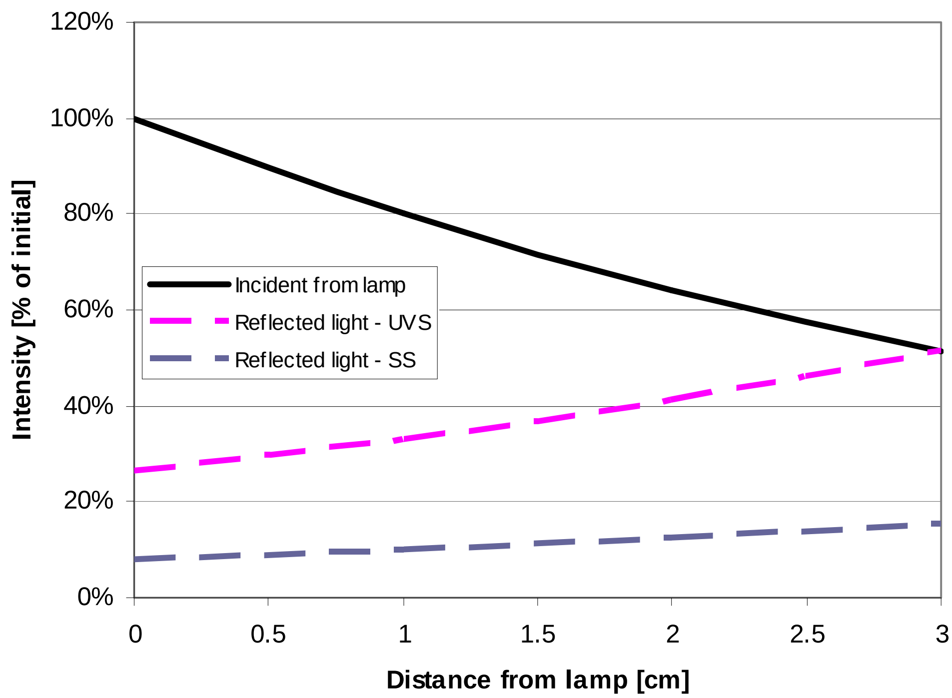

Figure 5b). The intensity of the incident light and the reflected light with a highly reflective wall and a 30% reflective stainless steel wall.

The intensities of the incident and the reflected light add together to form the total intensity, as shown by the curves in Figure 5c). The two things to note on Figure 5c) are that 1) the overall intensity is higher in the highly reflective chamber, and 2) the difference in intensity at the source and at the wall is much less when the wall is highly reflective. The reflector significantly improves the uniformity of the light intensity in the volume, in this example reducing the intensity variation from maximum to minimum from 47% down to 21%. As mentioned above, this holds true for all UV transmittances up to the point at which all the light is absorbed in the water before it reaches the walls, so the reflector provides an advantage under all practical conditions.

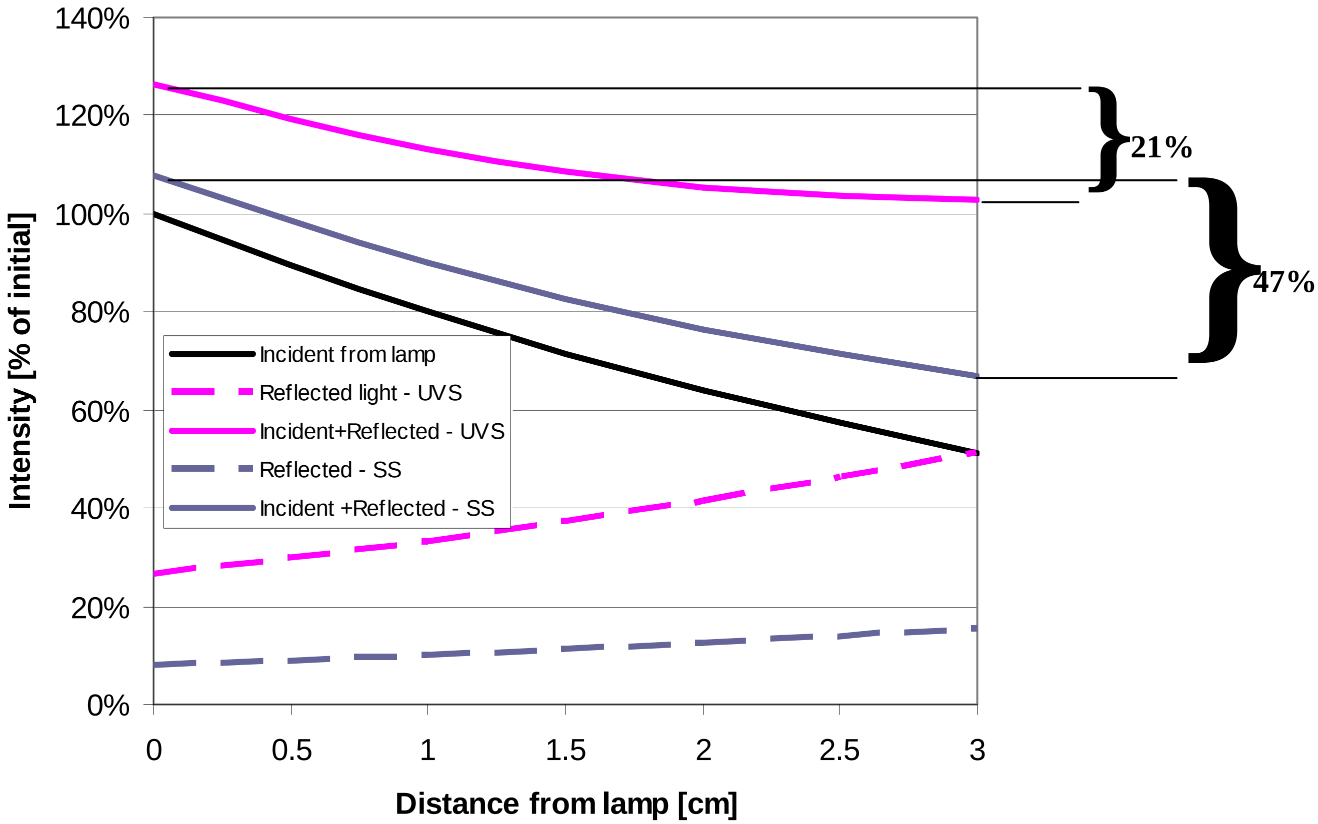

Figure 5c). The total intensity of the incident light plus the reflected light as seen in a chamber with a highly reflective wall, versus the total intensity with a stainless steel wall. Note the higher intensity and smaller variation of the light with the high reflectivity wall.

The information in this section shows that the highly uniform flow dynamics and the uniformity of the UV intensity within the chamber described in the paragraphs above provide an added performance advantage for the ReFleX™ chamber over conventional UV chambers beyond that of highly reflective walls alone. This increased uniformity translates directly to a more efficient usage of the energy introduced into the chamber and a correspondingly higher level of treatment for a given amount of energy than is found when only the total energy is considered.

3. Conclusions

This white paper describes the theoretical basis for the demonstrated superior performance of the ReFleX™ treatment chamber over conventional UV water treatment chambers. The combination of a highly reflective chamber wall, coupled with a hydraulic design that optimizes the flow dynamics and an optical and mechanical design that maximizes the uniformity of the UV dose delivered to the water, results in UV treatment performance that is as much as 10 times more efficient than that of conventional UV treatment chambers. Subsequent papers will describe the in-house and third party testing done to measure the performance improvement gained with the ReFleX™ chamber, and will illustrate some key operational benefits derived from the chamber design and verified by those test results.

References

[1] Gerardi, Michael H., Wastewater Bacteria, John Wiley & Sons, Inc., 2006, p. 19
[2] City of San Diego, Public Utilities Department, Water Operations Branch, “Annual Drinking Water Quality Report” 2009
[3] ANSI/IICRC S500-2006 “Standard and Reference Guide for Professional Water Damage Restoration”, 2006, (Category 3 wastewater)
[4] Bolton, James R. “Ultraviolet Applications Handbook, 2nd Ed.”, Bolton Photosciences, Inc., 2001, p. 6
[5] Kowalski, Wladyslaw, Ultraviolet Germicidal Irradiation Handbook, Springer Verlag Berlin Heidelberg, 2009, p. 184
[6] Labsphere Inc., “A Guide to Integrating Sphere Theory and Applications”, pp. 15-16