

# Visible Transmittance Test Procedures for Tubular Daylighting Devices

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## **ABSTRACT**

The visible transmittance (VT) is an optical rating that determines how much light in the visible spectrum is transmitted through a window glazing or other fenestration. The Windows and Daylighting Group at Lawrence Berkeley National Laboratory (LBNL) performed a series of VT measurements on various tubular daylighting devices (TDD). There are industry standard VT ratings for typical windows and skylights, implemented by the National Fenestration Rating Council (NFRC). However, there is no established VT rating system for TDDs. This work aims to enable and support the development of such a standard. The VT measurement of a TDD must accommodate the geometrical complexity of light entering and exiting the device at angles that are more variable than those for a flat window pane. Therefore, a two meter integrating sphere, also known as Large Integrating Sphere (LIS) is used to average the spatial diversity of light exiting the TDD samples. A single VT result represents the total transmission at a given solar incidence angle. The LIS can rotate to allow collecting data for a range of solar altitude and azimuth incidence angles at any given time of day. Previous VT measurements using this instrument relied on the ratio of the response of an interior sphere sensor with and without the sample in place. This method required frequent mounting and un-mounting of large specimens to get data at various angles. To speed data collection, this process was replaced with an externally referenced technique that allows continuous measurement of VT vs. incidence angle during a slow sweep of the motorized IS. Data from the externally referenced sweep method agrees well with the previous internally referenced technique. For both methods, the sample is tilted relative to the sun to achieve varied incidence angle, such that it does not always have an equal view of the sky. At some extreme angles there can be influence from nearby buildings, and the air mass through which the direct component travels, is not always constant. The VT measurements presented in this paper represent a significant improvement of measurement throughput and versatility using this instrument without unacceptable sacrifice in measurement accuracy. This work provides an example of practical VT measurement technique for TDDs on a commercial production scale.

## **INTRODUCTION**

The visible transmittance (VT) is an optical rating that determines how much light in the visible spectrum is transmitted through an object such as a window glazing or other fenestration. While all other fenestration products (most of them flat) are rated at normal incidence of solar radiation, and even though it is debatable if normal incidence is appropriate even for flat products, it is especially true for tubular daylighting products that single normal incidence is not appropriate at all.

The Windows and Daylighting Group at Lawrence Berkeley National Laboratory (LBNL) in cooperation with the National Fenestration Rating Council (NFRC) have investigated the experimental methodology for VT measurement of various tubular daylighting devices (TDD). The TDD can be thought of as a larger scale version fiber optic or light guide. It directs light collected at the upper lens through a relatively long path (compared to width/diameter) by means of multiple bounces off the reflective wall of a tubular guide (usually circular in cross-section, but also square), ultimately delivering light to the interior of a room through a diffusing element or output lens. A TDD has many applications from large commercial installations to smaller residential installations. There are NFRC implemented VT ratings for typical windows and skylights but there is not currently a similar rating for TDDs. This work aims to enable and support the development of such a standard. The VT measurement of a TDD must accommodate the geometrical complexity of light entering and exiting the device at angles that are more variable than those associated with flat window products. Therefore, a two meter integrating sphere, also known as Large Integrating Sphere (LIS) is used to average the non-uniform light intensity distribution that leaves a TDD sample. A single VT result represents the total transmission at a given solar incidence angle.

## **MATERIALS AND METHODS**

### ***Large Integrating Sphere (LIS)***

The two meter diameter integrating sphere (LIS) is painted white inside to reflect light uniformly [1]. Four redundant Licor photometric sensors look into the sphere measuring the light intensity reflected off the wall of the sphere after multiple reflections inside the sphere average the spatially non-uniform light intensity entering the sphere. In previous work with this

instrument, the small current signal from the sensors passed through shunt resistors allowing measurement of millivolt level signals with a sensitive Agilent 34970A data acquisition system. Lux was then calculated based on manufacturer provided calibration values for the sensors. The VT was calculated as the ratio of two measurements taken by a single sensor looking inside the



sphere, comparing light intensity with the sample in place to a reference measurement with no specimen in place (unobstructed sphere aperture). Because the diameters of the TDD entrance aperture and the sphere aperture are different, an area weighted correction equation was applied to this ratio. To enable faster and more convenient measurements, a second data acquisition technique was implemented and compared to the previous technique. Instead of shunt resistors the new data acquisition amplifies the small currents signals with custom designed photometric op amp circuits. The 0-10V output from these amplifiers can be easily read at higher data rates with a typical USB data acquisition such as the 8 channel, 16 bit, Measurement Computing USB-1608FS.

The LIS aperture and sample can rotate to collect data for a range of solar altitude (SALT) and azimuth incidence angles (Relative azimuth angle or RAZ is measured from the plane of the TDD to the sun) at any given time of day. A new tilt angle sensor based on an accelerometer chip was implemented to read the angle of the sphere aperture plate relative to gravity. This allows an automated collection of data at different SALT angles. A sweep through SALT angles is accomplished through the use of motorized setup, which allows for slow, but continuous motion during which data is collected at a high spatial resolution, enabled by the rapid measurements of both light levels and sphere tilt angle. Previously, each fixed incidence angle required both mounting and un-mounting the specimen as well as a solar alignment procedure for the desired angle of incidence. With the sweep method, the sphere aperture plate is

first oriented relative to the sun to achieve an effective  $90^\circ$  solar altitude (normal incidence to TDD aperture) and effective zero relative azimuth (0 RAZ). The initial altitude angle measured with the accelerometer at normal incidence is defined as  $90^\circ$  and the incremental angles measured as the sphere tilts are subtracted from  $90^\circ$  to calculate the relative solar altitude angle (SALT), as reported.

Before collecting data, the sensors were carefully calibrated and modifications to the LIS were validated to ensure accurate results. Using the previous VT calculation method (a ratio of a single internal sphere sensor) the absolute calibration of each sensor was not critical. However, this method required taking the specimen on and off for each measurement which slowed the process and opened the measurement to uncertainty introduced by changing ambient light condition between the two measurements (the process usually took 1.5 to 2 minutes). To gain confidence in the swept data acquisition method, it was also important to confirm that taking optical data as the motor slowly rotates the sphere does not introduce error. Data taken at discrete angles with the sphere stationary were compared to the automated data collection method during a slow sweep. The optimum range of angles that can be measured changes with time of day and position of the sun. Therefore, several series of measurements were taken for the same specimens at different times of day, and different days, to investigate the influence of nearby objects, air mass, or other subtle variations in atmospheric conditions.

### ***Tubular Daylighting Devices***

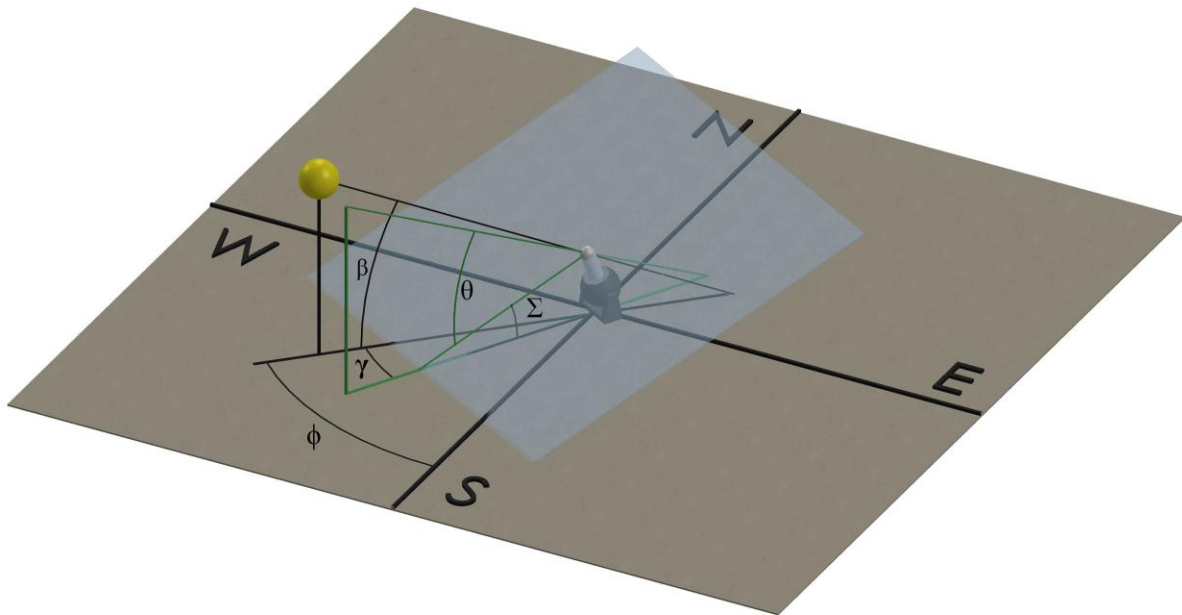
Four TDDs were provided from different manufacturers that are participating in development of a standard VT rating for their products. Fifth manufacturer was also scheduled to participate, but their sample sizes are 48 in. x 48 in. square, which is too big for this integrating sphere and so were not included in the study. The TDDs have a tube diameter of about 13 inches, but the dimensions are not identical. It was agreed to maintain all test specimens with the same ratio of 3.4 to 1 (length to diameter). Each tube was assembled in a straight line despite the option of rotating



elbows sections that allow for angular adjustments to a particular building. A plywood platform with angled wooden struts and/or tensions strings support the TDD during measurements at various angles. The TDD is placed on the 15" LIS aperture plate and clamps are used to hold the base platform of the TDD in position.

### *Solar Altitude and Azimuth Angles*

The LIS has one “solar altitude” rotational degree of freedom powered by a motor which can rotate 180 degrees from horizon to zenith, and back to opposite horizon. The second, “solar azimuth” degree of freedom is a manual rotation on a large horizontal turn table supporting the whole sphere. This turn table was used to obtain the relative azimuth angles (RAZ) defined as  $0^\circ$  (in the plane of Sun), as well as  $30^\circ$  and  $60^\circ$  off of the plane of the Sun. A discrete set of relative solar altitude angles (SALT) is reported for each relative azimuth angle (RAZ).



In the solar geometry figure above,  $\phi$  and  $\beta$  represent the absolute solar azimuth and altitude angles with regards to the local ground plane and cardinal directions. The relative solar azimuth  $\gamma$  and the relative solar altitude  $\theta$  are the angles used in these integrating sphere experiments. The effective horizon plane of the specimen is inclined by angle  $\Sigma$  relative to the ground, such that the specimen may have an atypical “sky” view including reflections off of the ground and surrounding objects.

Collecting data at many angles informs the potential VT rating system with data for typical rate of change and detail characteristics of VT vs. incidence angle. Once these trends are understood, a determination can be made as to how many angles should be measured to assure a fair, representative VT characteristic to compare products in a rating system. The inclusion of various azimuth angles further details the VT response for solar incidence angles expected throughout the day. The LIS includes a visual solar alignment scope that allows the aperture plate and TDD specimen to be aligned relative to the sun despite the position of the sun in the sky at that time. The scope projects a beam of light from a small aperture onto a translucent lens with concentric rings. Each of the five concentric rings engraved on the lens represents 1 degree of deviation from alignment. Typically this visual alignment is well within the first 1 degree circle.

### ***Test Conditions***

Two exterior looking photometric sensors, one shaded and the other un-shaded, are placed on a pole mounted off to the side of the face of the aperture plate. The exterior sensors are positioned in the same plane as the entrance lens of the TDD to avoid unwanted shading or reflections from the tube. These sensors are used for both external referencing and for measurement of the sky ratio. A two inch diameter black metal disk on a flexible wire 24 inches long is used to cast a shadow on one of the outside sensors. The outside shielded signal (diffuse light component) versus the unshielded sensor (direct plus diffuse component) provides a sky ratio characteristic that has been determined as means to evaluate whether appropriate sky conditions have been met for reliable measurements to take place. It is advised to maintain this ratio under a 0.3 for clear sky conditions, as discussed in the IESNA handbook and previous experiments [3]. Theoretically, the varied placement of the four redundant sensors looking inside the sphere should produce identical results [3]; however, it is useful to have multiple measurements with different views inside the sphere, to confirm a consistent response. The sensors are all baffled from viewing the aperture port directly, but it is not possible to baffle the view of the first bounce “hot spot” as this position varies with measurement incidence angle [2]. Three sensors are placed around the circumference of the aperture looking into the sphere. One sensor is a quarter rotation away from the aperture at the “bottom” of the sphere when it sits with the aperture plate on one side (looking toward the horizon).

### ***External Referencing and Slow Sweep Altitude Angle***

Past experiments used an internal referencing technique (IRT). This method first measured an internal looking sensor with light incident on an open sphere aperture port (no TDD specimen mounted), at a desired RAZ and SALT angles. The measurement was repeated with a TDD mounted on the LIS at the same incidence angles. A repeat open port measurement was taken after the specimen measurement, helping to observe, and average out, any drift in the sky conditions over the period of this multi-step measurement (usually about 3-4 minutes to complete all three measurements). Because the TDDs have varying entrance aperture diameters compared to the LIS aperture plate, an area correction formula is applied in order to calculate the VT. Equation (1), the ratio between the TDD and LIS open port aperture area multiplied by the open port illuminance, is applied to the open port measurements to normalize them to the tube dimension.

$$E_{Open, AreaCorr} = E_{Open, Raw} \frac{A_{Spec.Aper.}}{A_{SphereAper.}} \quad (1)$$

Following the area correction, equation (2) divides the TDD's illuminance by the average of the area corrected open port measurements to calculate the VT.

$$VT = \frac{2E_{Specimen}}{E_{OpenBefore, AreaCorr.} + E_{OpenAfter, AreaCorr.}} \quad (2)$$

Furthermore, the VT calculation executed independently for each of the four interior looking sensors is averaged to diminish any bias [2].

With the TDD mounted, more light within the sphere is reflected back into the LIS compared to the case for an open port [2]. To remedy the small increase in VT associated with this error, a sphere correction factor equation (3) can be used.

$$C = \left[ 1 - \frac{r_1 r_2 f_c}{1 - r_2 (1 - f_c)} \right] \quad (3)$$

However, the sphere correction factor can typically be neglected (as in past work), because samples with less than 50% reflectance have an error of less than 2% of VT [2]. This

approximation is convenient because the surface reflectance of a complex device such as a TDD is not well known or easy to measure, but it is much lower than 50%, since it is designed as a daylighting device to have high transmission.

Although the IRT method works reliably in steady sky conditions, to support a commercial rating system there is a strong need to perform the VT measurement with efficient throughput for many different products at several incidence angles without requiring extremely stable ambient conditions. The external referencing technique (ERT) improves on the tedious mounting and un-mounting of the specimen for each angle by using an external sensor as the reference signal. A measurement relating interior sensor response to exterior with an open port is still necessary (as seen in the denominator of equation 4), but this value has been found to remain relatively constant, referred to as the sphere response factor (SRF). The ERT VT equation (4) is the ratio of two separate interior and exterior sensor ratios, with appropriate area scaling to account for differences between the port and specimen aperture.

$$VT = \frac{\left( \frac{E_{int, spec} \cdot A_{sphere}}{E_{ext, spec} \cdot A_{spec}} \right)}{\left( \frac{E_{int, open} \cdot A_{sphere}}{E_{ext, open} \cdot A_{port}} \right)} \quad (4)$$

While the ERT speeds measurement considerably compared to the IRT, there remained further potential to automate measurements at various altitude angles. The slow sweep method uses the same ERT calculation for VT, with the addition of an accelerometer tilt sensor connected to the data acquisition system to allow recording angle of incidence data at the same time as photometric measurements, providing high spatial resolution of VT vs SALT automatically during a slow rotational scan of the motorized sphere axis.

## DATA: Internal vs. External Referencing and Angle Sweep Technique

Prior to testing TDD specimens, data was first taken from previously well characterized flat window samples to validate the various methods of calculating the VT before measuring the more complicated TDDs. The VT measured for flat window samples agreed with previous data, well within the 10% standard for NFRC interlaboratory comparisons, most better than 2%. Because the ERT was an unproven method with this integrating sphere, VT data for TDDs were collected and compared to the IRT to confirm that the method provided results that were repeatable, (see figure 1).

The fastest method to collect VT at many solar altitude angles involves a slow scan of the motorized sphere axis combined with an angle sensor connected to the data acquisition to automatically record the relative solar altitude in coordination with photometric measurements. Figure 1 also compares the slow scan VT technique using a fixed average SRF over the various angles, as well as an angularly dependent SRF. The general trend for SRF during an open port sweep was typically between 9.02-9.64 for the 11" aperture plate used to measure flat windows and 8.89-9.33 for the 15" aperture plate used to measure TDDs. Further analysis is required to determine if the SRF should be implemented as a constant or an angularly dependent value. For data on all tubes measured, see appendix.

Figure 1: Internal/ External Referencing Technique and Sweep

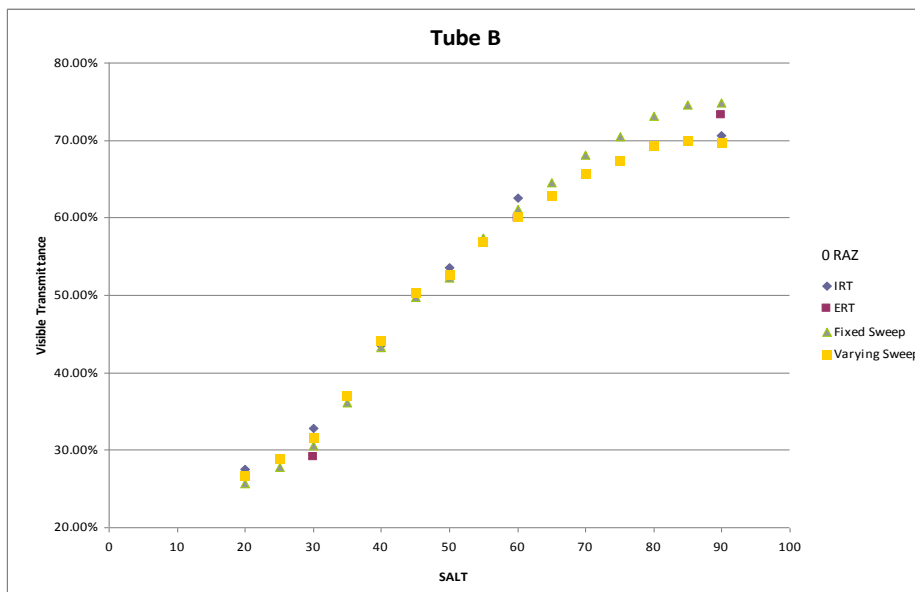
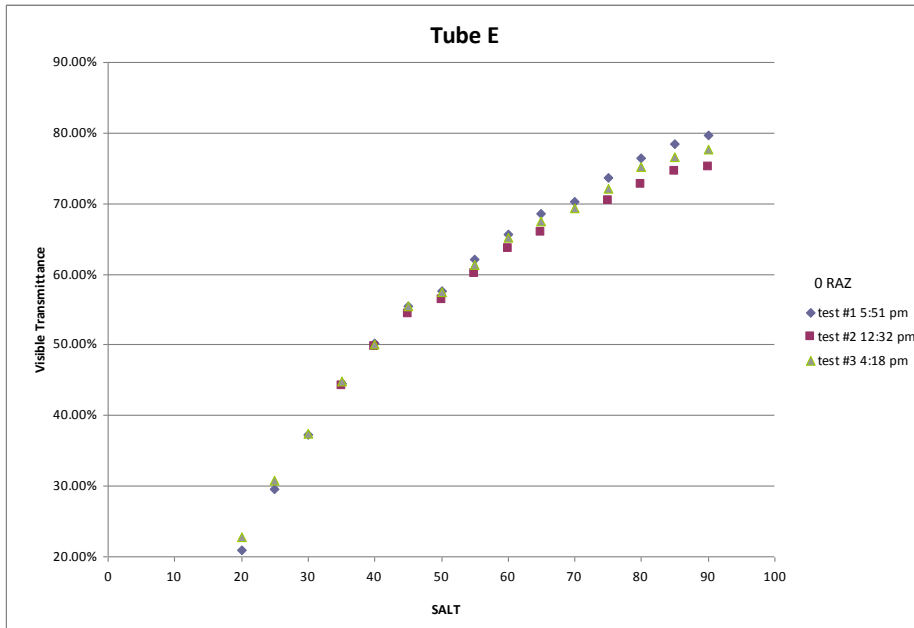


Figure 2: VT/SALT trends at different times of day



## DISCUSSION OF RESULTS

Although data was taken through three different methods, the results were quite repeatable. As a result of elapsed time between reference and specimen measurements, the IRT is susceptible to subtle changes in light intensity. External referencing removes this problem, but introduces a higher standard for sensor to sensor calibration, and maintenance of calibration over time. The automated solar altitude sweep method generated VT data at many more angles than previously measured at fixed angles. In order to collect a broad range of SALT, the full sweep should be a combination of sweeps performed at different times of day (noon for high SALT, and morning or afternoon for low SALT). Figure 3 illustrates different VT/SALT trends associated with sweep measurements taken at different times during the day. At the extremes the effective sky hemisphere is compromised by looking toward the horizon capturing the effects shading or reflections associated with the ground, trees, buildings or other objects. It is best to measure high SALT values near to solar noon and low SALT values nearer to morning or evening as long as the sky conditions are clear in all cases. By piecing together two scans taken at different solar positions, the specimen tube remains closer to vertical at all angles and does not view significant portions of surrounding objects.

Most observed deviations in measurements occurred at high SALT angles, suggesting that the first reflection hot spot bias inside the sphere associated with high SALT angles may introduce more error than the tube orientation and effective sky hemisphere view issue. Although the issue of air mass wasn't fully explored, it was apparent that data taken for the same angle at noon and evening could be quite reproducible at many angles, suggesting that these measurements were not highly sensitive to increased atmosphere path length and density of aerosols, etc. The ability to collect VT over a large range of solar altitude angles is very promising for speeding commercial production measurements to support an industry rating system, although the VT trends are smooth enough that numerous measurements are not necessary for a meaningful rating system, as long as they sufficiently cover the range of angles of interest. Occasionally, the outside un-shaded sensor would become shaded by the disc intended to cover the shaded sensor during a sweep which causes an erroneous VT of over 100% for a small range of angles. Also, for 60° RAZ reference sweeps, the open sphere aperture can be shaded by the post supporting the sensors which are at the plane of the typical tube entrance aperture. The exterior sensors for these reference scans without a tube in place should be repositioned to eliminate any error associated with shading the sphere aperture. A fairly consistent discontinuity between 30° and 40° SALT is observed in the 60° RAZ sweeps. This has not been fully investigated or explained at this point.

While the sweep technique measured SALT angles essentially down to zero, angles below 20° are not reported, because they are thought to be subject to more error, and they are outside the typical range of angles of interest for practical TDD daylighting (for this reason most of the zonal time weighted annual rating calculations presented in Appendix A consider times when the sun is above 15° altitude).

An important factor to consider when using an accelerometer to measure angle is that it is sensitive to vibrations and jerks in motion, so it is only reliable if the motion is very smooth. An angular encoder is likely a better choice of instrument to avoid this influence. The weight from the cantilevered TDD can cause an abrupt non-uniform motion when the center of mass passes over the pivot and the weight settles on the opposite side of the gear backlash. An abrupt motion like this will be recorded as an erroneous change in angle and this motion should be damped to avoid measuring unwanted accelerations.

Example zonal time (ZT) weighting formula for an annual rating:

Yearly efficiency =

$$(VT_{20} * ZT_{20}) + (VT_{30} * ZT_{30}) + (VT_{40} * ZT_{40}) + (VT_{50} * ZT_{50}) + (VT_{60} * ZT_{60}) + (VT_{70} * ZT_{70})$$

OPTION #1 7 angles (sunrise to sunset)			OPTION #2 6 angles (10° to 10°)			OPTION #3 6 angles (15° to 15°)			OPTION #4 3 angles (15° to 15°)			
SALT range	angle used	ZT	SALT range	angle used	ZT	SALT range	angle used	ZT	SALT range	angle used	ZT	
< 15°	20°	0.247										
15° - 25°	20°	0.176	10° - 25°	20°	0.307	15° - 25°	20°	0.234	15° - 35°	25°	0.486	
25° - 35°	30°	0.1895	25° - 35°	30°	0.2275	25° - 35°	30°	0.252				
35° - 45°	40°	0.1365	35° - 45°	40°	0.164	35° - 45°	40°	0.182	35° - 55°	45°	0.329	
45° - 55°	50°	0.111	45° - 55°	50°	0.133	45° - 55°	50°	0.147				
55° - 65°	60°	0.086	55° - 65°	60°	0.103	55° - 65°	60°	0.114	> 55°	65°	0.186	
> 65°	70°	0.054	>65°	70°	0.065	> 65°	70°	0.072				
		1				0.9995				1.001		

	Tube A	Tube B	Tube C	Tube D - ref	Tube E
#1, Yearly efficiency (sunrise) - 7 angles - 0 RAZ	0.27	0.31	0.35	0.26	0.37
#2, Yearly efficiency (10 deg) - 6 angles - 0 RAZ	0.35	0.40	0.48	0.33	0.47
#3, Yearly efficiency (15 deg) - 6 angles - 0 RAZ	0.36	0.41	0.46	0.34	0.49
#4, Yearly efficiency (15 deg) - 3 angles - 0 RAZ	0.36	0.41	0.46	0.34	0.50
#3, Yearly efficiency (15 deg) - 6 angles - 30 RAZ	0.32	0.40	0.47	0.34	0.49
#4, Yearly efficiency (15 deg) - 3 angles - 30 RAZ	0.32	0.40	0.47	0.34	0.49
#3, Yearly efficiency (15 deg) - 6 angles - 60 RAZ	0.29	0.39	0.46	0.34	0.49
#4, Yearly efficiency (15 deg) - 3 angles - 60 RAZ	0.29	0.38	0.47	0.34	0.48
<b>1/5*(50° @ 0 RAZ) + 2/5*(40° @ 30 RAZ) + 2/5*(30° @ 60 RAZ)</b>	<b>0.31</b>	<b>0.41</b>	<b>0.45</b>	<b>0.36</b>	<b>0.52</b>
<b>Simple Average between 0, 30 and 60 RAZ</b>	<b>0.32</b>	<b>0.40</b>	<b>0.47</b>	<b>0.34</b>	<b>0.49</b>

*Complete VT data sets in chart form follow:*

SRF – Sphere Response Factor

IRT – Internally Referenced Technique

ERT – Externally Referenced Technique

All measurements made with a sky ratio of under 0.3

Fixed sweep refers to fixed SRF reference, variable sweep refers to an angularly dependent SRF reference

## CONCLUSION

Using the IRT to measure TDDs is a tedious process that can be replaced by the more efficient, and likely more accurate, ERT and sweep methods, for numerous rapid measurements at varied angles of incidence. Time of measurement is an important factor for the practical implementation of a VT rating system based on physical experiments, and this work has demonstrated that it is viable to make these measurements on TDDs with acceptable efficiency for a production environment, without sacrificing measurement accuracy. In fact, new methods are showing improved repeatability, as some errors associated with ambient condition changes between IRT measurements are avoided. Sensors require more extensive calibration attention for the ERT compared to the IRT method, but this is a manageable burden to improve process speed for production measurements. Careful attention to sensor calibration has also demonstrated that there is significant directional bias in the sensitivity of some photometric sensors. When possible, a sensor with minimal observed directional bias should be used for the exterior measurement, as interior sphere sensors are exposed to less non-uniformity in light intensity. Repeated VT measurements of TDD specimens at different times and using different techniques are acceptably consistent under the standards of typical NFRC laboratory test comparisons.

There remains a question how to choose an appropriate reference value from the range of SRF measured as a function of angle. The open sphere aperture measurements likely introduce bias from first reflection hot spot that are not present when a specimen is in place. Data is presented for both a fixed average open port reference as well as an angularly dependent reference. The angularly dependent reference is thought to be more appropriate, but the fact that this difference exists, suggests that further work to baffle the sensors from viewing non-uniformities would be beneficial. Controlling the surroundings of the experiment is important. While limited options were available for this work, wide open spaces are preferred over areas with large buildings, trees, parked cars, etc. Installation of a fish eye camera that pivots with the specimen to observe and document the region making up the effective sky hemisphere would be helpful.

While it has been shown that collecting high spatial resolution data can be quick and convenient, the relatively smooth trends of the typical tube VT/SALT curves do not motivate specification of a large number of data points to be submitted to a rating system. Five to eight

measurements well distributed over the range of interest appears to be adequate to characterize optically complex products. Also, fewer required data points will allow more flexibility in the development of measurement techniques other than the motorized sweep. The table of various annual rating results in Appendix A provides further evidence that basing a rating system on more than three angles has little effect on the result (at least for the products measured in this work and the angles chosen in these examples). This work has shown there are fast, effective means to measure VT of complex fenestration products, such that a practical commercial testing and rating system could be established based on physical measurement since the computational simulation of complex products is not as feasible, at this time.

## REFERENCES

[1] J. Kessel, S. Selkowitz. Integrating Sphere Measurements of Directional- Hemispherical Transmittance of Window Systems, August 5-7, 1984. Lawrence Berkeley National Laboratory Report, LBL-17284. pp. 3.

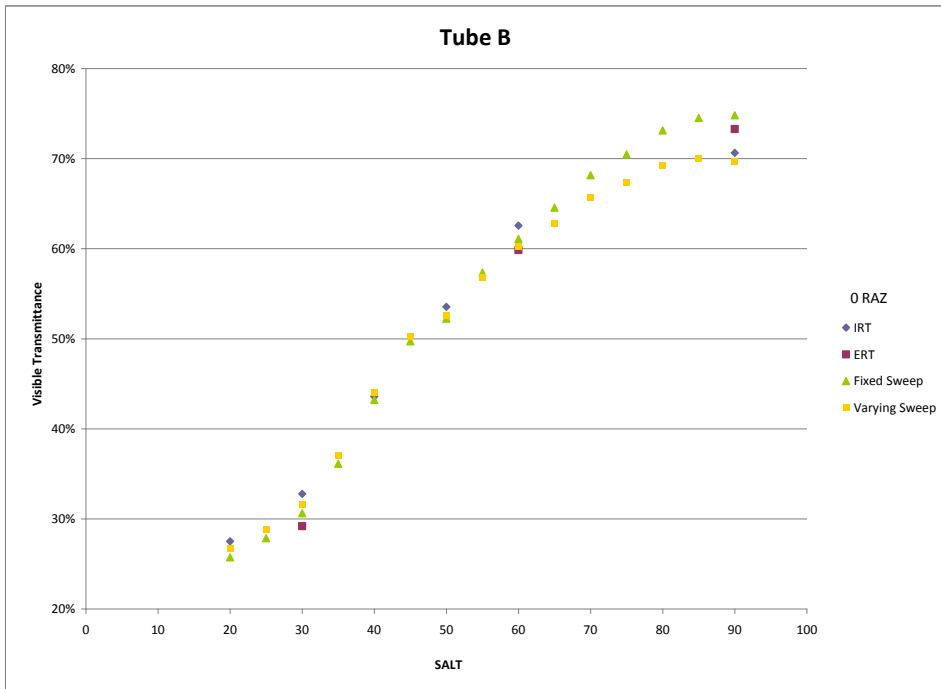
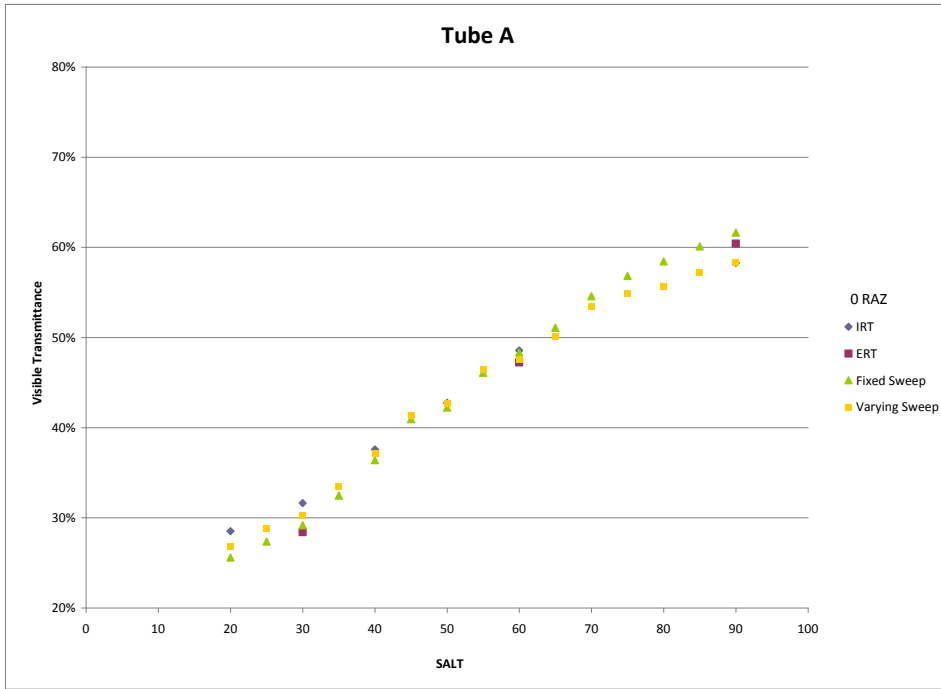
[2] H. Goudey, C. Kohler, M. Rubin. Complex Product Visible Transmittance Research Tubular Daylighting Devices, Nov.4<sup>th</sup> 2010. Lawrence Berkeley National Laboratory Report, NFRC project number 05-105-DR4, pp. 1-5, 14-18.

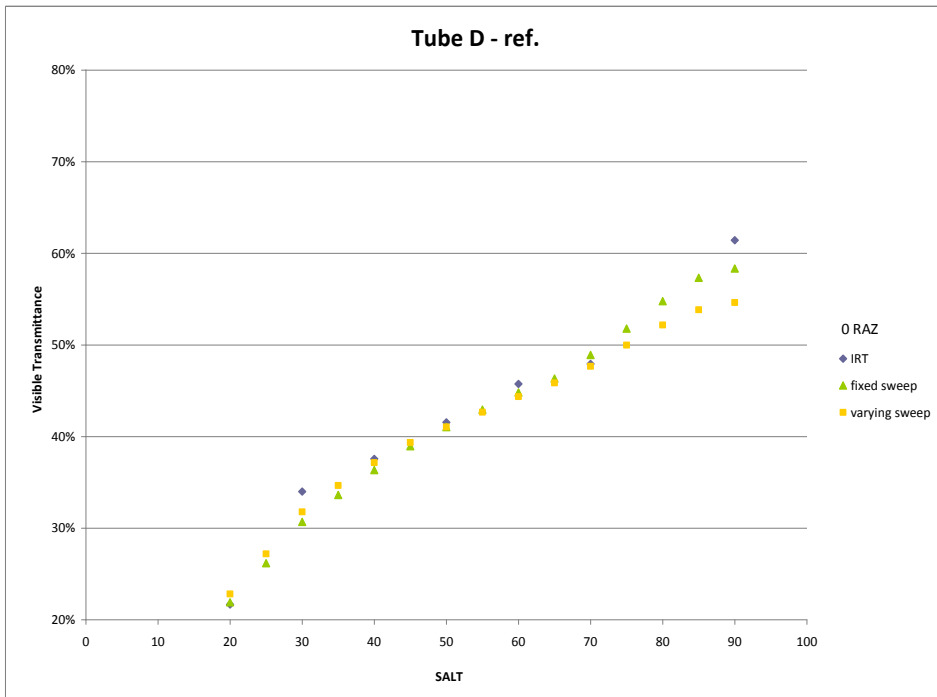
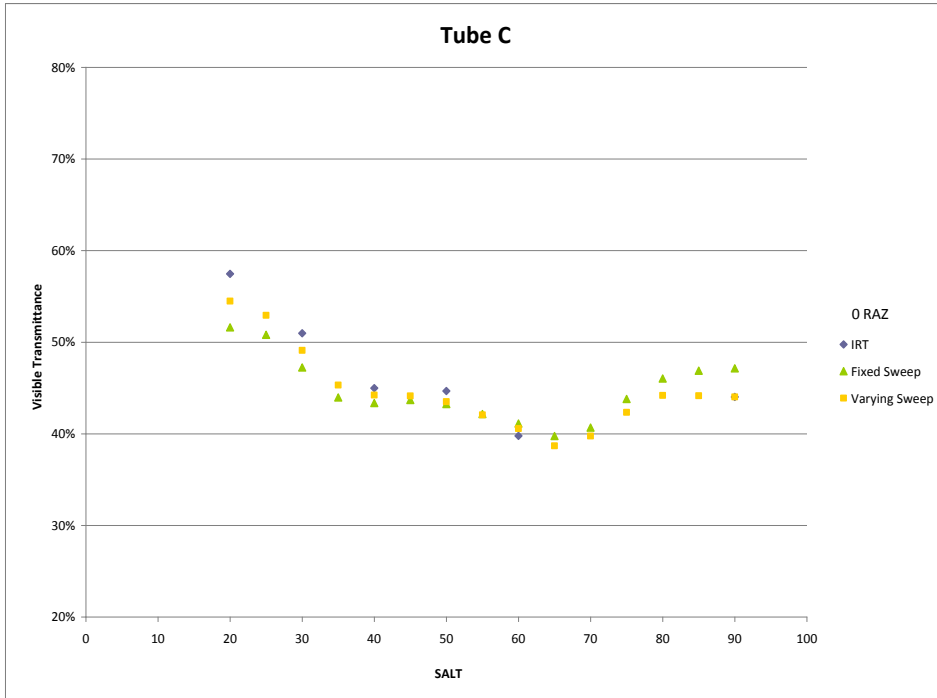
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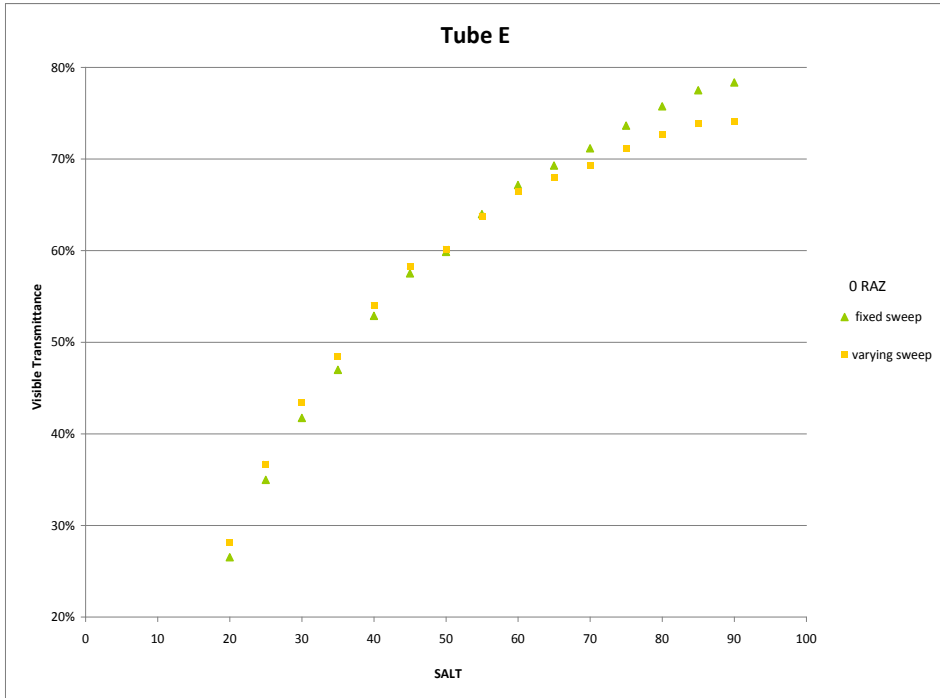


# Appendix A:

0 RAZ, 20-90 SALT

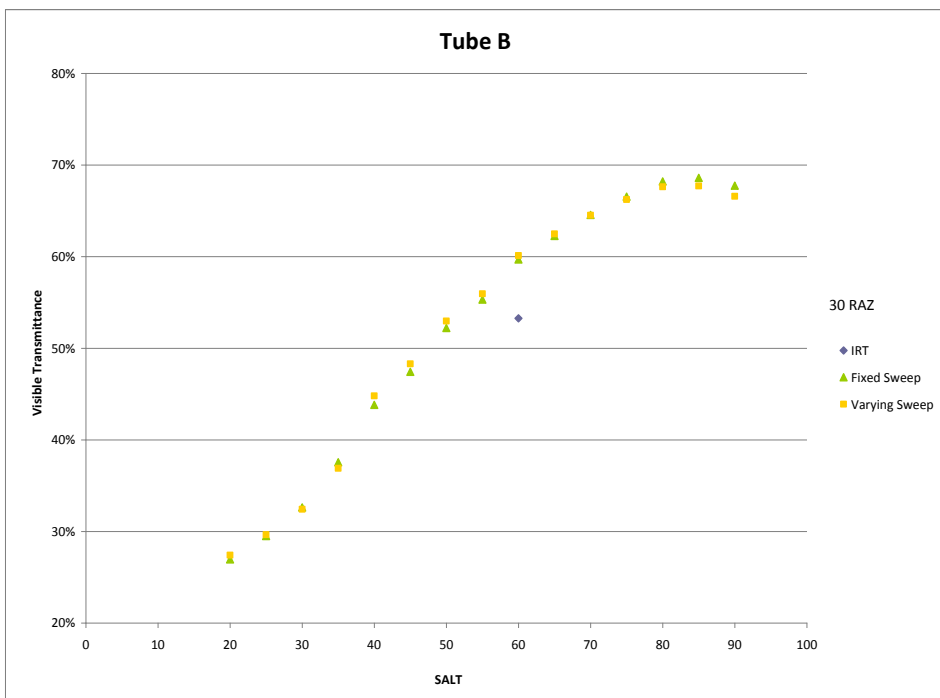
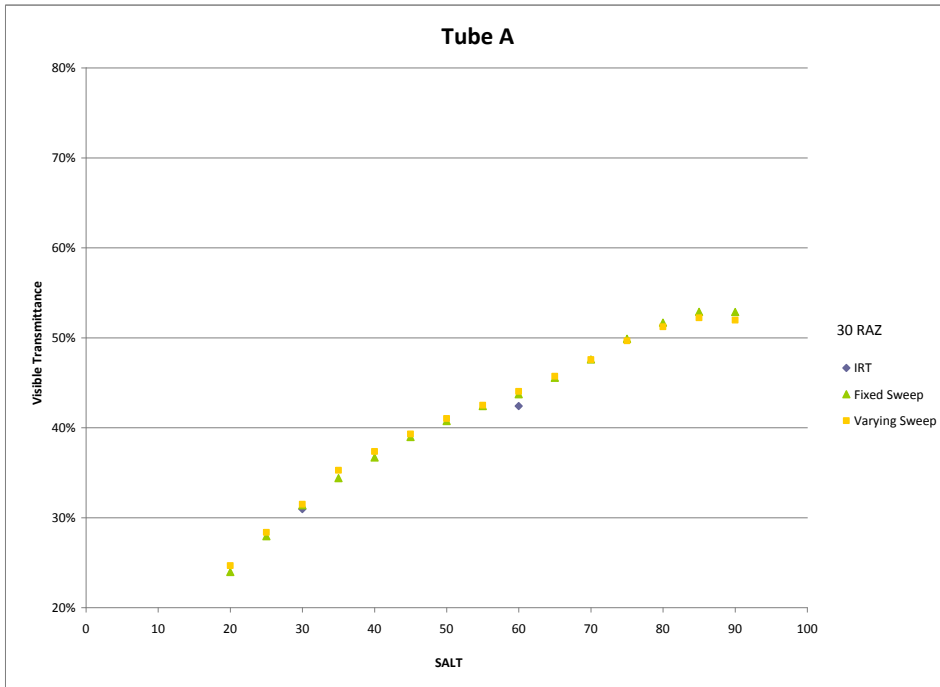


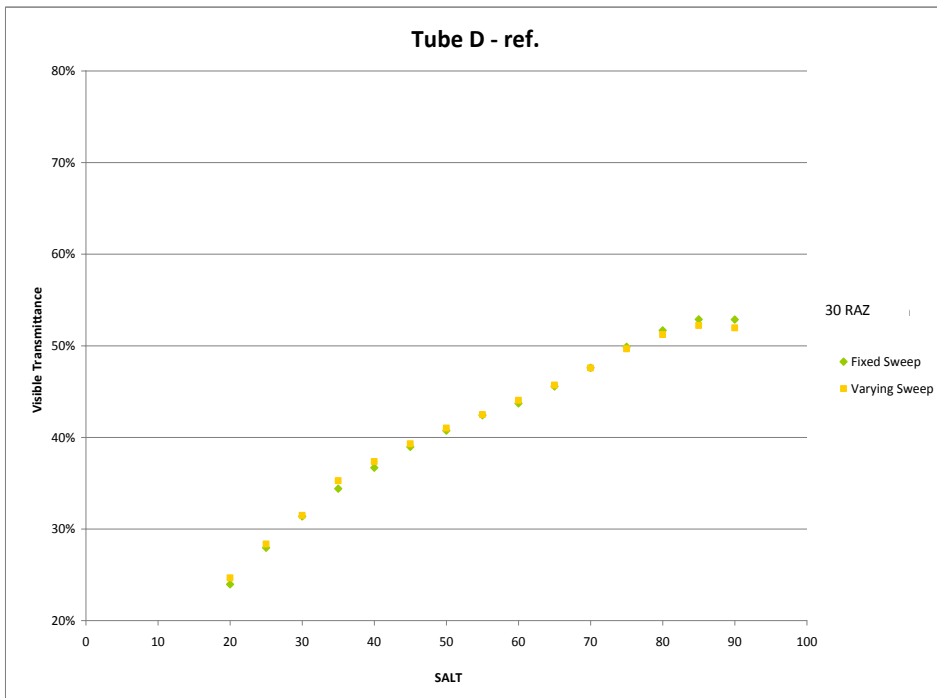
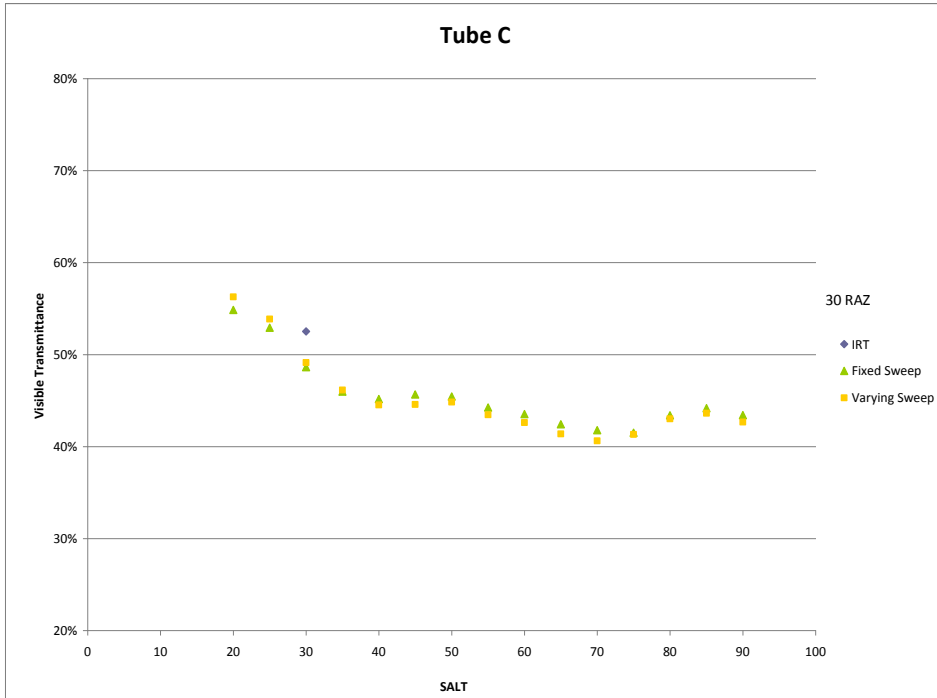


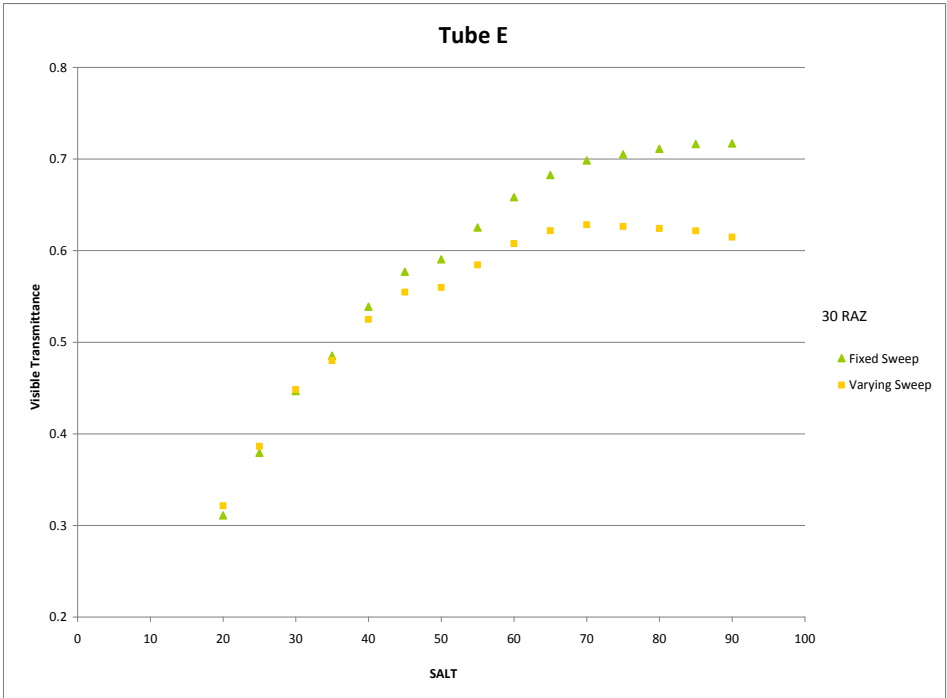


### 30 RAZ, 20-90 SALT

(note: previous IRT work with 30 RAZ was limited and with poor confidence)

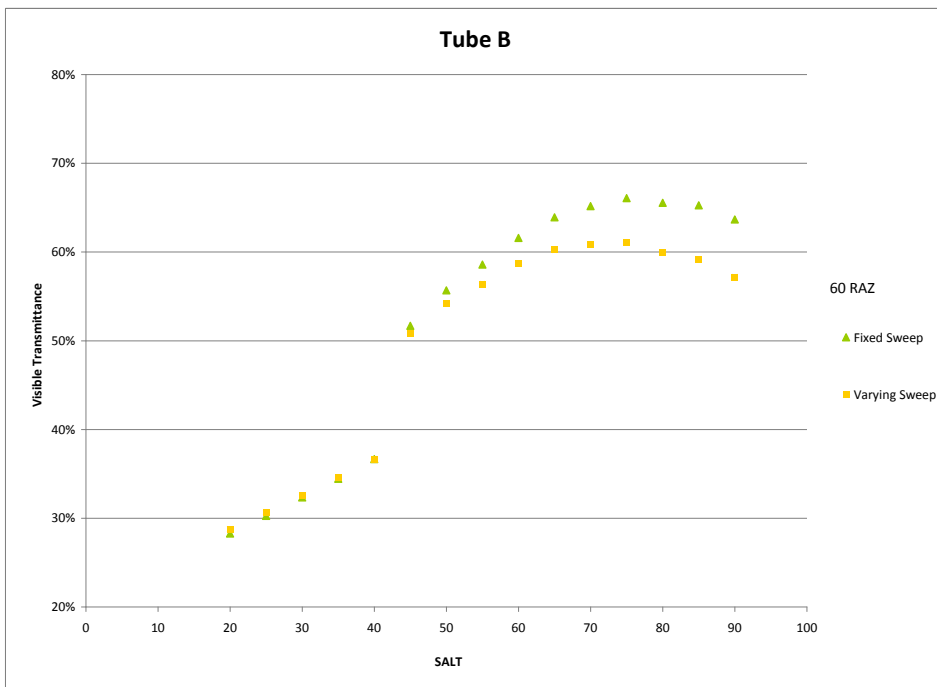
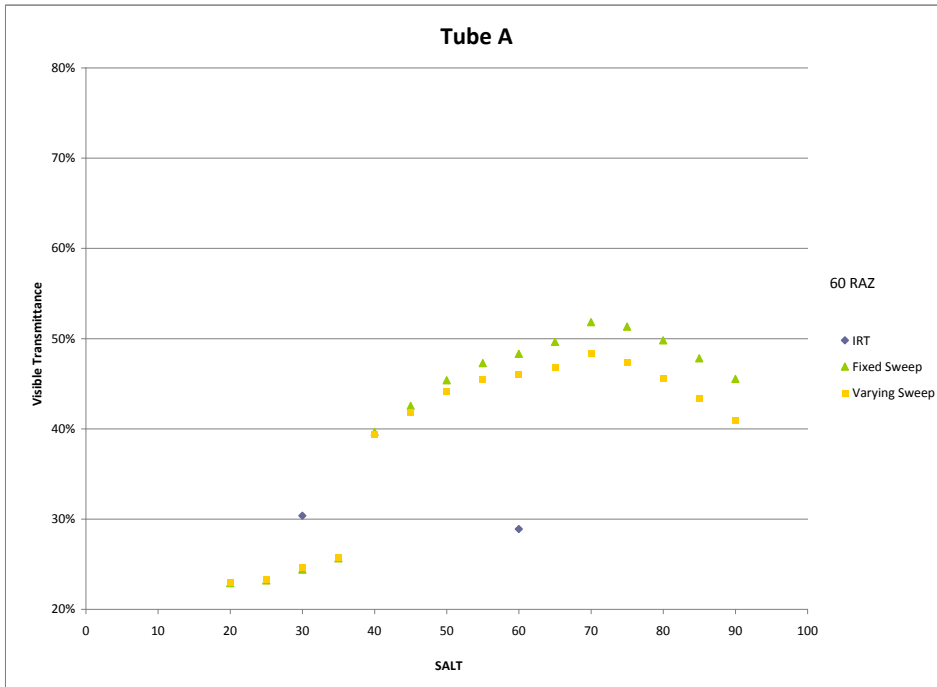


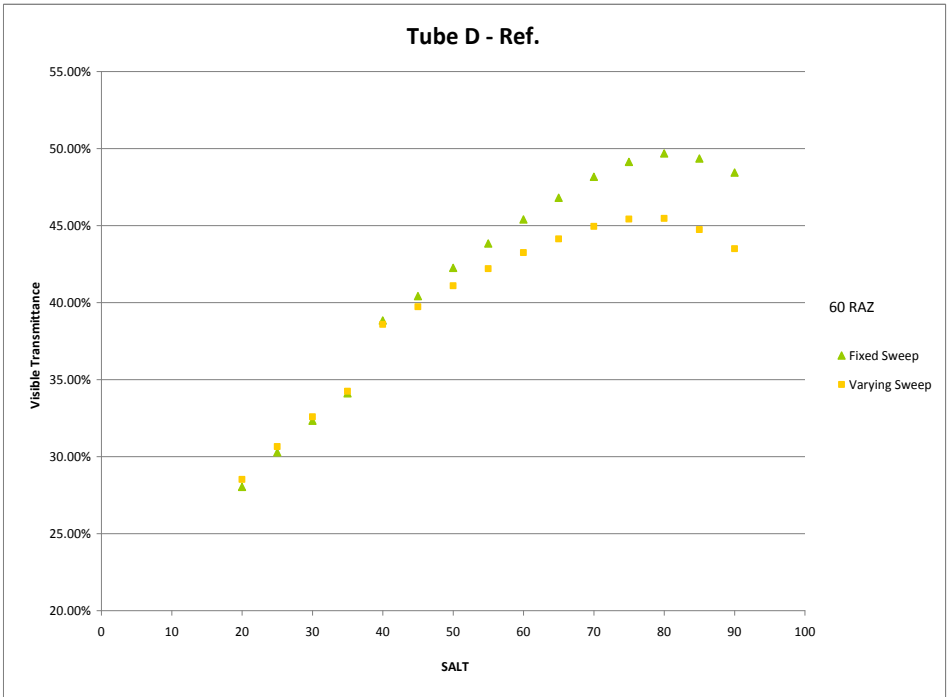
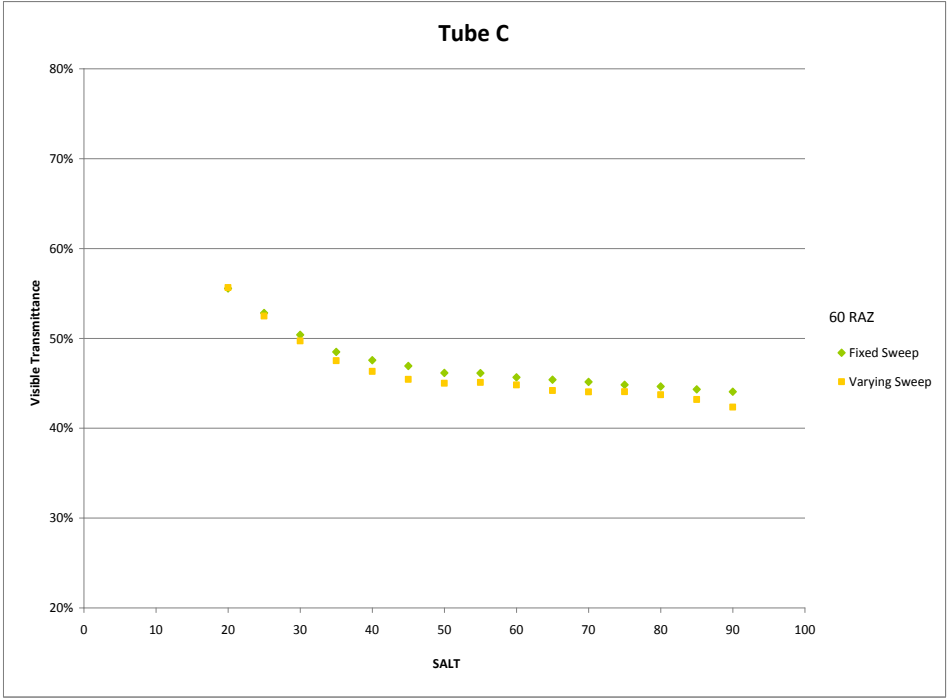


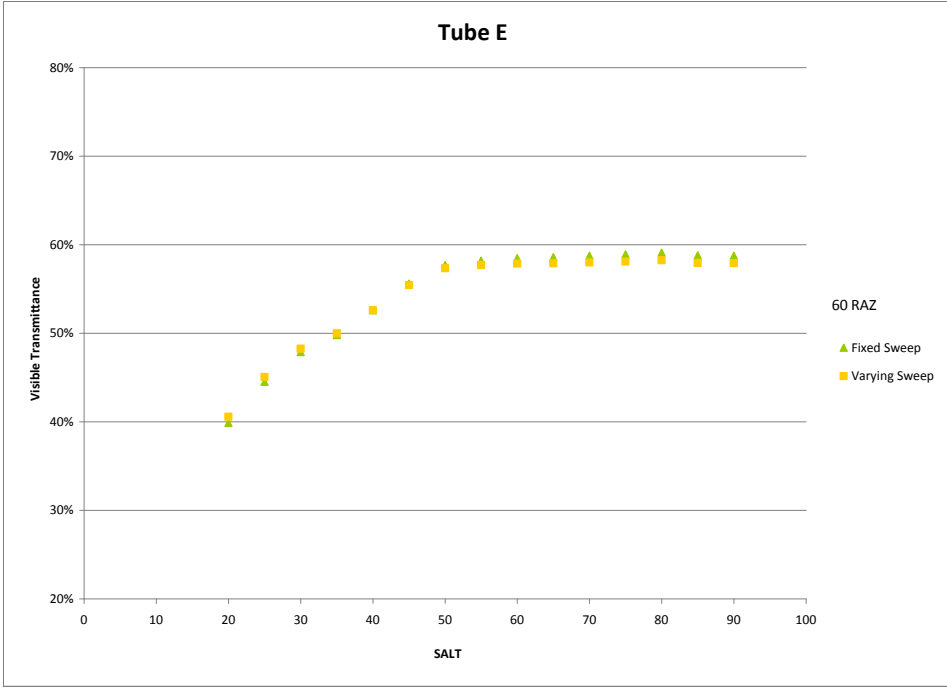


# 60 RAZ, 20-90 SALT

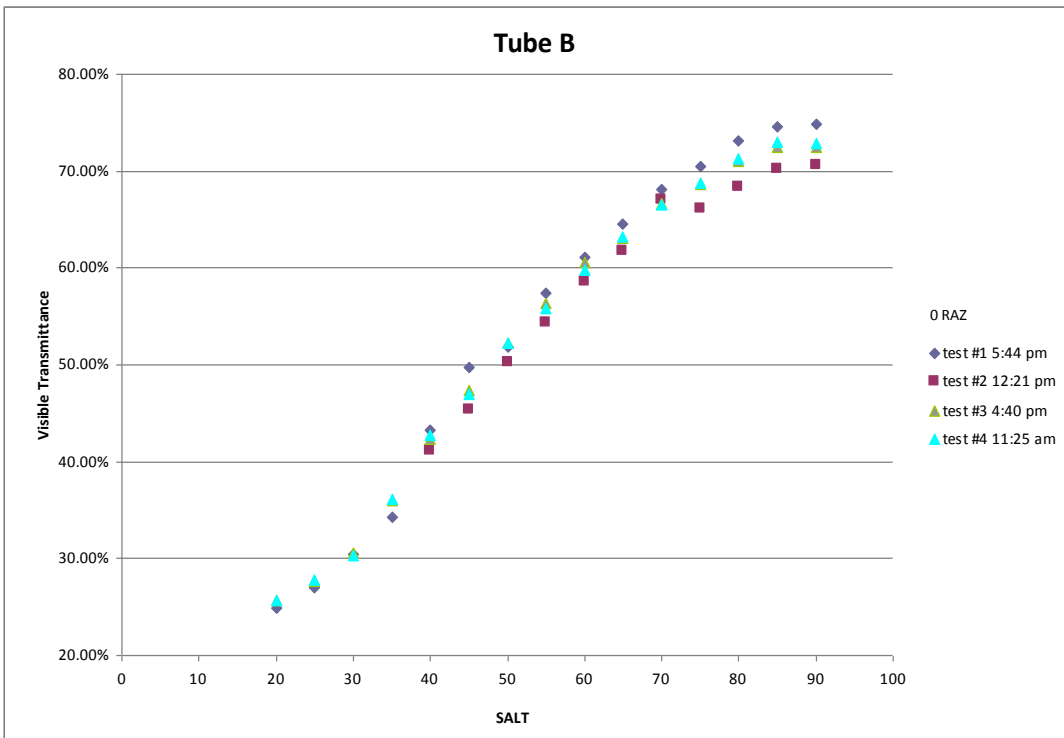
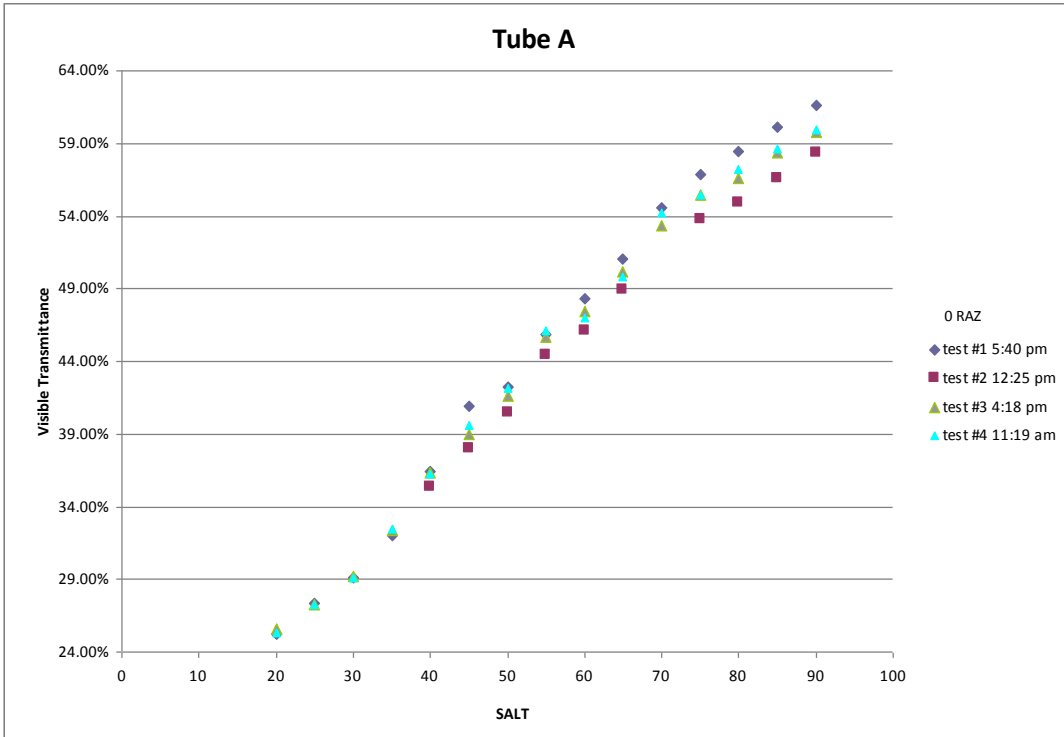
(note: previous IRT work with 60 RAZ was limited and with poor confidence)

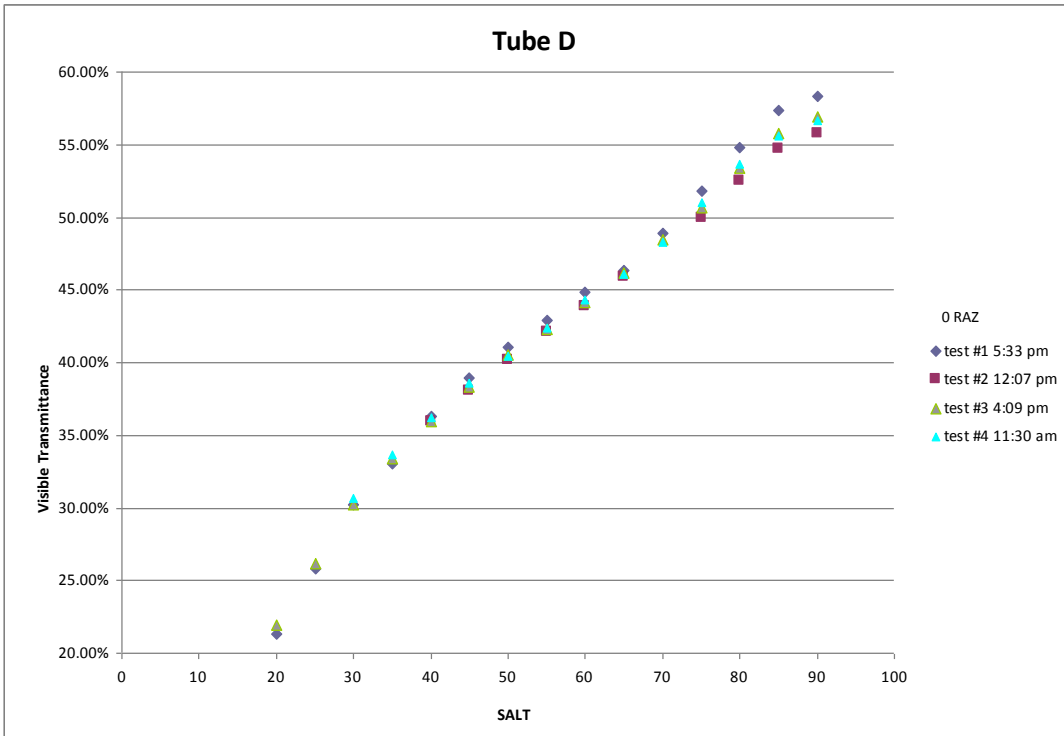
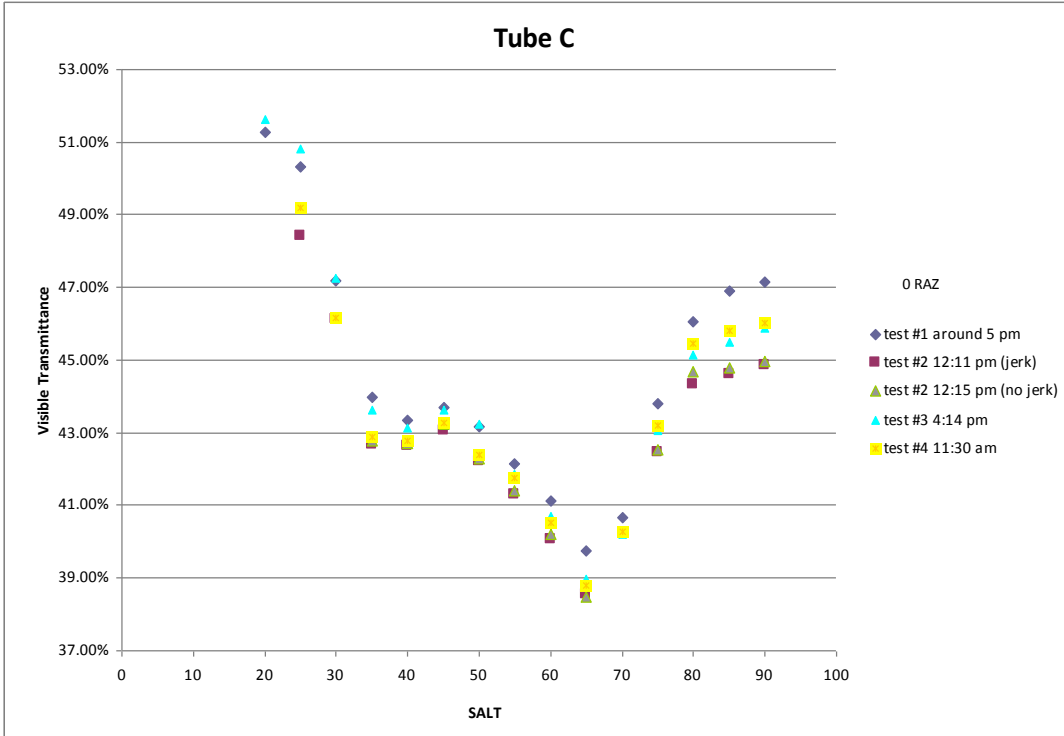






Appendix B: Fixed SRF with sweeps at different times of day





### Tube E

