University of Kent

A report on the optical power and irradiation dose available from Purified Air UVC Germicidal Lamps used in airflow enclosures UVGI 1000 and UVGI 1500

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Summary

In the right circumstances airflow conduits that include an enclosure volume (box) containing sources of UVC irradiation can achieve the neutralisation of pathogens carried by the airflow in the immediate vicinity of the UVC source. For a sufficiently high level of irradiation pathogens carried on fine mist into the volume of the enclosure can be neutralised in this way.

The purpose of this technical report is to provide data on the irradiance levels available from 254 nm (UVC band) discharge lamps manufactured specifically for Purified Air Ltd by a Specialist UV lamp manufacturer. Lamp irradiance is evaluated both in free space and inside unit enclosures UVGI 1000 and UVGI 1500 commercialised by Purified Air Ltd.

The work at the University of Kent consisted of a series of optical power measurements in the UVC band, centred at 254 nm, over a range of separation intervals from lamps in different configurations, as follows:

a) one individual lamp (G36T5L/HO/4 SD UVC 780 mm High Output Quartz Germicidal Lamp) in free space, uncooled;

b) one twin lamp (LTCQ70L/2G11, 380 mm Compact Quartz Germicidal Lamp) in free space, uncooled;

c) different configurations of multiple 380 mm lamps or 780 mm lamps placed inside two types of enclosure geometry (UVGI 1000 and UVGI 1500) and forming part of an airflow circuit. The hypothesis that the addition of reflective elements along the internal walls of the enclosure has also been tested, and at different fan speeds for the airflow passing over the lamps.

The data collected suggests that the power available from either of the two lamp models comfortably exceeds 10 mW/cm^2 from a single lamp at close range (several cm from the lamp surface). Based on existing studies, it is known that irradiance levels of this magnitude are sufficient to neutralise pathogens including Covid-19 with at least a 1-log reduction.

The existence of an ideal operating temperature of about 40°C has also been suggested by the variation of optical power from switch-on. When lamps operate above this temperature a reduction of as much as 50% can be expected in the irradiance output. However, a significant mitigating factor is the circulation of air over the surface of the lamps, which helps maintain a cooler operating temperature.

The tests on the enclosures suggest that the combination of multiple lamps (at least 4 at the highest airflow levels) in either of the two enclosure models would be sufficient to achieve average levels of dose of 9.2 mJ/cm^2 over the shortest travel path inside the UV lamp enclosures and in excess of this level over the likeliest travel path.

Introduction

The purpose of Purified Air Limited's ultraviolet germicidal irradiation (UVGI) units is to reduce the pathogen population in the air by achieving an inactivation rate high enough to cause a 90 - 99.9% reduction, dependent on airflow. This level of reduction is classed as disinfection rather than sterilisation which requires 6 log (99.9999%) reductions and above (Kowalski and Bahnfleth, 2000). Reaching sterilisation levels of microbial reduction is neither necessary, nor achievable for most microorganisms with this particular application of UVC because of the large volume flow rates these units must handle.

The aim of this study is to make a determination on whether the required irradiance level can be met with a certain number of lamps in two types of enclosure geometries. The air passed through the relevant UV chamber containing the UVC lamp arrangements and then out again at speeds set by a step fan with five speed settings. A UV light meter measured the irradiance at different locations, which enabled the UV dose received by a particle travelling through the units to be calculated.

The impact of reflective surfaces, using polished aluminium grade 5251 lining the inside of the chamber, has also been investigated by taking measurements with and without the reflective surfaces. The use of reflective surfaces is having a significant impact on the irradiance readings, and helping achieve the same dose rate as a setup with more lamps but no reflective surfaces.

Although only testing two units, Purified Air Ltd manufacture a variety of different models that differ in size and airflow handling capabilities to that of the two units that have been tested. The selection of units consists mostly of those that fit into pre-existing airflow ductwork systems but also includes the VIU Mobile, a simple plug in and run system. The calculations carried out as part of this report can be used to assess the effectiveness of these units as well.

Background

Pathogen particles present in airflows that pass through enclosures containing sources of UV irradiation could be neutralised when they are subjected to UV light above a minimum irradiance level. This minimum irradiance level is dependent on the pathogen type in question. The current COVID-19 pandemic has prompted much interest in the ways in which UVC radiation can be utilised to inactivate the SARS-CoV-2 virus.

Although large variations are currently being reported in the studies carried out to date, they appear to be caused by the experimental conditions selected and the consensus in the scientific community is that coronaviruses are extremely sensitive to UVC light. Recently published figures, derived from a review of 30 peer-reviewed publications over the last few years, for the dose required to cause log-reduction (90% reduction) identify the true median value as 3.7 mJ/cm^2 *(M. Hessling et al. 2020).*

Purified Air have extensive knowledge of using UV radiation to enhance ozone levels for disinfecting air within airflow conduits; the germicidal units are a natural extension of using UV light for disinfection purposes. The lamps used in UVGI application, however, are low ozone lamps, designed to emit UV radiation at 254 nm – a high enough wavelength to prevent ozone synthesis. To inactivate the microorganism, a UV wavelength of 254 nm is both easy to generate with a low pressure mercury lamp and is close to the optimal UV absorption wavelength (265nm) by microorganisms. Specifically, the UV at this wavelength will destroy parts of the microorganism's genomic sequence and disrupt its vital metabolic processes, attenuating the pathogen and resulting in its inactivation (*Tseng CC and Li CS*). Optical radiation in the 254nm wavelength range is absorbed by microbes with genetic material in the form of DNA and/or RNA, which allows for targeted germicidal treatment for a multitude of microorganisms (see Table 1).

Calculating the Dose

The effect of UVC radiation is the 'dose' delivered. Dose is the product of light irradiance and the cumulative exposure time to that intensity. It is the product of irradiance and time (in seconds) and is expressed in units of Joules per square centimetre (J/cm^2 or mJ/cm^2).

$$Dose\ (mJ\ cm^{-2}) = Irradiance\ (mW\ cm^{-2}) \times Exposure\ Time\ (s)$$

Irradiance, expressed in units of Watts per square centimetre (W/cm^2), is the optical power of the light received at a surface per unit area of the surface exposed.

The measurements presented in sections 2 – 4 record the irradiance (also known as radiant flux) of the radiation emitted by the lamps and captured on a detector. This is used in the equation above with values of exposure time that is derived from the transit time through the two units tested, which depends on the volume of air being pulled through it at any given instant.

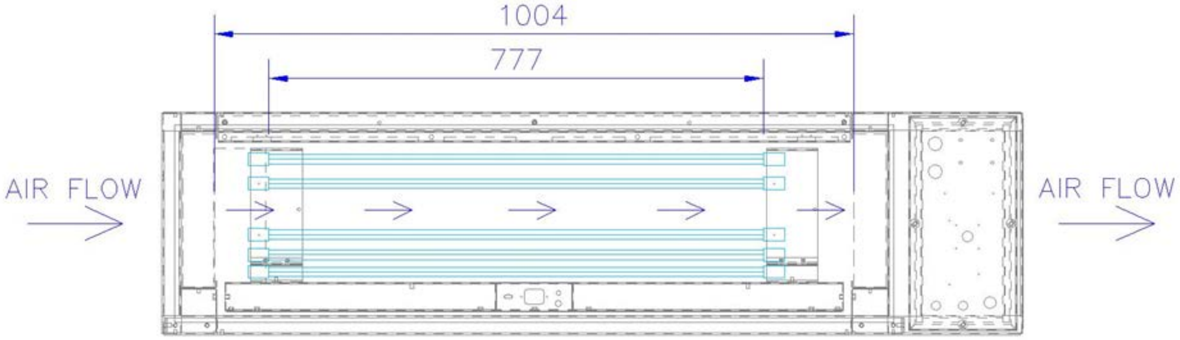
Table 1 *The dosage of UVC radiation at 254 nm required to generate lethal 1-log, 2-log and 3-log reductions in microbial populations of multiple coronaviruses and airborne disease agents.*

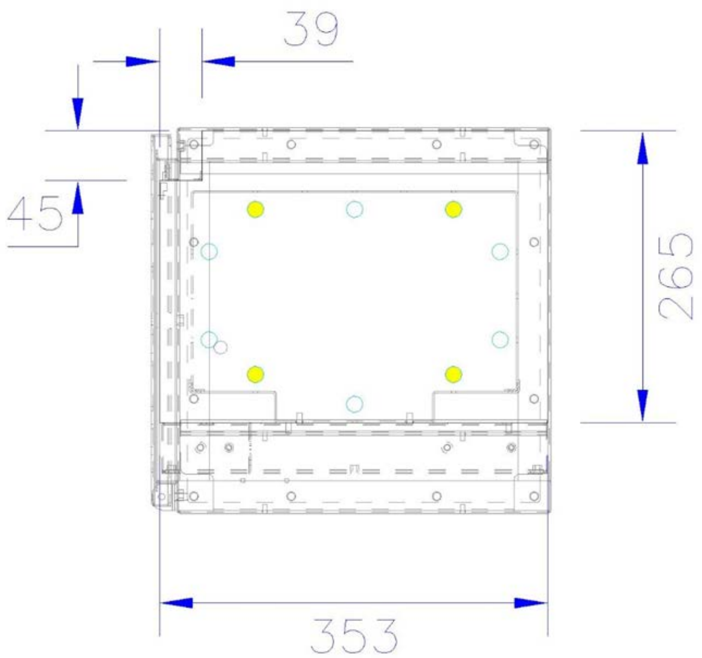
Organism	Dose (mJ/cm^2)			Reference
	1 log reduction (90%)	**2 log reduction (99%)**	**3 log reduction (99.9%)**	
Berne virus *(Coronaviridae)*	0.750	1.250	2.1	Weiss & Horzineck (1986)
Pseudomonas aeruginosa	1.300	2.700	4.3	McKinney, et al. (2012)
Murine Coronavirus (MHV-2)	1.500	3.000	4.7	Hirano, *et al.* (1978)
Corynebacterium diptheriae (Diptheria)	2.2	4.3	6.5	ProLampSales (2020) **
Salmonella typhimurium	1.8	4.8	6.4	Wilson, et al. (1992)
Staphylococcus aureus	3.9	5.4	6.5	Chang, et al. (1985)
Hantavirus	2.8	5.6	8.4	Meunier, *et al.* (2017)
Poliovirus (Type 1 Mahoney)	3.0	7.0	14.0	Sommer, *et al.* (1989)
Legionella pneumophila	3.1	5.0	6.9	Oguma, *et al.* (2004)
Mycobacterium tuberculosis (TB)	3.3	6.7	10.0	ProLampSales (2020) **
Hepatitis A	4.0	8.0	12.0	Battigelli, et al (1993)
SARS-CoV-P9	4.0	8.0	12.0	Duan, *et al.* (2003)
Influenza A	4.5	9.0	13.5	Meunier, *et al.* (2017)
Citrobacter freundii	5.0	9.0	13.0	Giese and Darby (2000)
SARS-CoV	5.7	11.4	17.1	Kariwa, *et al.* (2004)
	6.1	12.2	18.4	Walker & Ko (2007)
E.coli	6.0	6.5	7.0	Sommer, et al. (2000)
Streptococcus faecalis	6.6	8.6	9.8	Chang, et al. (1985)
Human Parainfluenza Virus (HPIV)	14.3	28.6	42.9	Meunier, *et al.* (2017)
Hand, foot and mouth disease virus (HFMD)	22.2	44.4	66.600	Meunier, *et al.* (2017)

Airflow Chambers – Diagrams and Technical Specifications

UVGI 1000

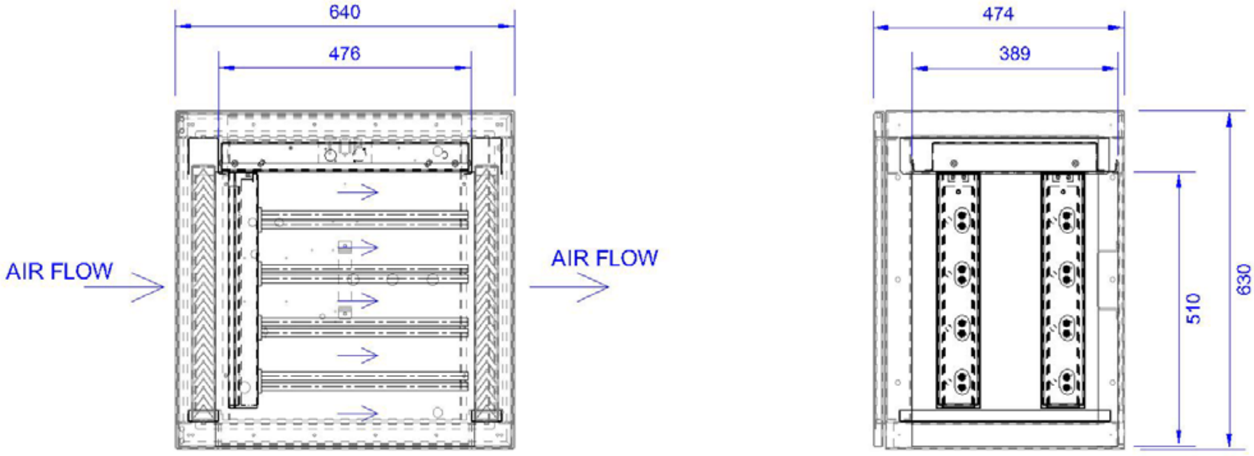
The UVGI 1000 unit is capable of housing a combination of 2, 4, 6, 8 or 10 G36T5L/HO/4 SD **780 mm High Output Quartz Germicidal Lamps** which are located parallel to the airflow direction through the unit to ensure maximum UV exposure time.





UVGI 1000	
Electrical Supply:	200/240V 50Hz
Maximum Power Consumption:	700 Watts
Maximum Air Volume:	0.47 m^3/sec
UV Chamber Dimensions W x H x L (mm):	353 x 265 x 1000

UVGI 1500



The UVGI 1500 unit is capable of housing a combination of 2, 4, 6 or 8 LTCQ70L/2G11 **UVC 380 mm Compact Quartz Germicidal Lamp** pairs which are fixed parallel to the airflow direction.

UVGI 1500	
Electrical Supply:	200/240V 50Hz
Maximum Power Consumption:	544 Watts
Maximum Air Volume:	0.7 m^3/s
UV Chamber Dimensions W x H x L (mm):	389 x 510 x 465

Study parameters defined

The work undertaken in the School of Physical Sciences laboratories at the University of Kent was carried out in order to gather irradiance data from two types of UV lamps emitting in a narrow spectral range centred around 254 nm.

The lamps are fixed parallel to the direction of airflow in their respective enclosures, in a variety of selections and combinations, as detailed in Sections 2 and 3. The detector was positioned at several different separations from the lamp axis, ranging from 5 cm to 100 cm.

The detection equipment used was a detection kit calibrated for monochromatic irradiance at 254nm and exhibiting a cosine response for the lamp length and distance, described in paragraph 1.1.

Only short term parameters were measured, on timescales of up to several minutes from switch-on; long term lamp behaviour does not constitute the object of this study, therefore any fading effects over many hours of operation are not taken into consideration.

Section 1: Irradiance Measurements from Individual Lamps in Free Space

1.1 Experimental Setup

Testing was carried out in accordance with the recommended procedure for UV lamps *(Lawal, et al. 2017)*.

Measurements carried out in Section 1 did not involve forced cooling of the lamps.

Irradiance values were measured using an ILT 770 light meter manufactured by International Light Technologies using light meter detector XCB 254NB calibrated with the ILT 770 unit. The calibration certificate is shown below.

InternationalLight TECHNOLOGIES

CALIBRATION CERTIFICATE

OPTICAL CALIBRATION CERTIFICATE

International Light Technologies certifies that the calibration results published in this certificate were obtained using equipment capable of producing results that are traceable to NIST and through NIST to the International System of Units (SI). ILT is Accredited to ISO/IEC 17025:2017. Calibration conforms to ANSI/NCSI Z540.1-1994 and ANSI/NCSI Z540.3-2006.subclause 5.3

Rendered-to: PURIFIED AIR LIMITED

Detector: XCB254NB #00083 — Input Optic: N/A #

Filter: N/A # — Misc.: N/A #

Calibrated With: ILT770 #00117 — +5V Bias Off

(PIR) PEAK IRRADIANCE RESPONSE SENSITIVITY FACTOR AS CALIBRATED ON: 13-Jul-2020

3.701E-4 (A)(cm2)(W-1) assuming monochromatic irradiance at 254nm
3.701E-07 (A)(cm2)(mW-1) assuming monochromatic irradiance at 254nm

Unit will read directly in watts per square centimeter or milliWatts per square centimeter when used with the sensitivity factor above.

REFERENCE PLANE: Front

PRIMARY STANDARD: U.S. National Institute of Standards and Technology Detector Response
I219 - December 3, 2015 - NIST Test No. 685/287304-15/2 Calibration Due: December 3, 2025
D204 - December 2, 2015 - NIST Test No. 685/287304-15/1 Calibration Due: December 2, 2025

INTERNATIONAL LIGHT TECHNOLOGIES PRIMARY TRANSFER STANDARDS:

SED240 #1029 N/A N/A

ILT Transfer Uncertainty to Customer = +/- 6.5% plus NIST Uncertainty of: +/- 2.4% Confidence Level of Uncertainty is 95% (k=2)

LIGHT SOURCE: Jelight Model 9290 Exposure Chamber — LAMP OUTPUT: 4.97E-2 W/cm2

INSTRUMENTATION: SL021/T2NS254 — PROCEDURE: OP-0087

TEMPERATURE: 21.1 degrees C — HUMIDITY: 33%

CALIBRATED BY: J - Hoyt
Calibration Technician: Jon Hoyt

THIS CERTIFICATE APPLIES ONLY TO THE ITEMS IDENTIFIED AND SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE SPECIFIC WRITTEN APPROVAL BY INTERNATIONAL LIGHT TECHNOLOGIES, INC.

Calibration Date: 7/13/2020 Certificate No: 007130902 Sales Order #: 168670

ilac-MRA PJLA Calibration Accreditation

International Light Technologies, Inc.
10 Technology Drive, Peabody, MA 01960 USA
978-818-6180 / 978-818-6181 fax
intl-lighttech.com

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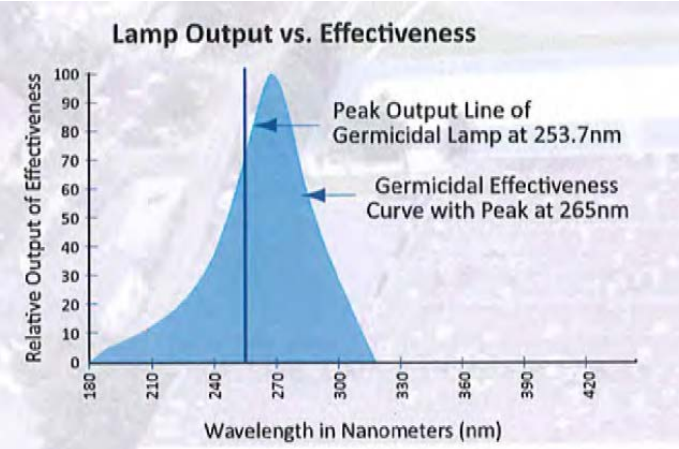
Importantly, the detector was positioned such that power level measurements from individual lamps included only a very small amount backscattered radiation from surfaces situated a few cm behind the lamps which could provide a level of uncertainty of the order of the background scatter (0.1 mW/cm^2) compared to when lamps are measured from the side.

Because measurements were performed with a flat surface detector (1cm^2 surface area), for lamps of a long aspect effective irradiance falling on point particles or small volumes may be underestimated and is very likely to be significantly higher than the measured values.

1.2 Methods of Sampling Irradiance Data

The lamp manufacturer quotes absolute outputs that are very close (190μW/cm^2 vs 195μW/cm^2 for the 780 mm and 380 mm lamps respectively) at 254nm wavelength. We measured a value of 460 μW/cm^2 = 0.46 mW/cm^2 (integrated over the entire UVC band) using the ILT light meter which is expected and consistent with the information in the spectrum shown below, representing a typical lamp spectral output over a wider wavelength range extending from 180 nm to 300 nm.



This value was achieved by covering the entire length of the lamp using a blocking material (opaque to UV radiation) and leaving only a small central slit active and visible. The detector was then placed 5 cm away from the surface of the lamp.

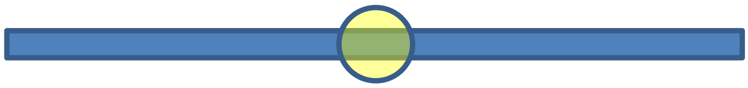
Incidentally this also showed a heating effect (reading peaked followed by a decrease), implying that the heating effect seen in past results is due primarily to the lamps (since a few hundred μW are not enough to heat up the detector).

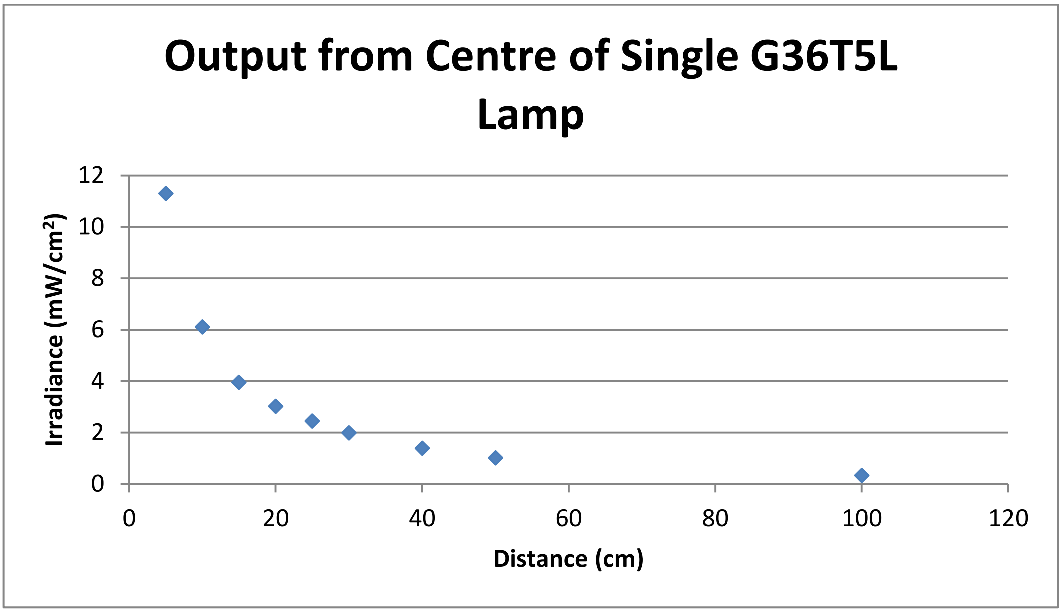
1.3 Measured Irradiance Values

1.3.1. G36T5L Lamps (Individual and Pair)

1.3.1.1 Individual Lamp

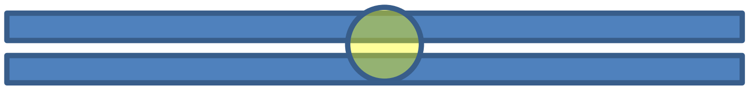
The output from the centre of one individual G36T5L lamp was measured by placing the detector in the configuration shown diagrammatically below. The irradiance at different distances from the lamp was recorded with the peak irradiance at 5 cm being **11.3 mW/cm^2**.



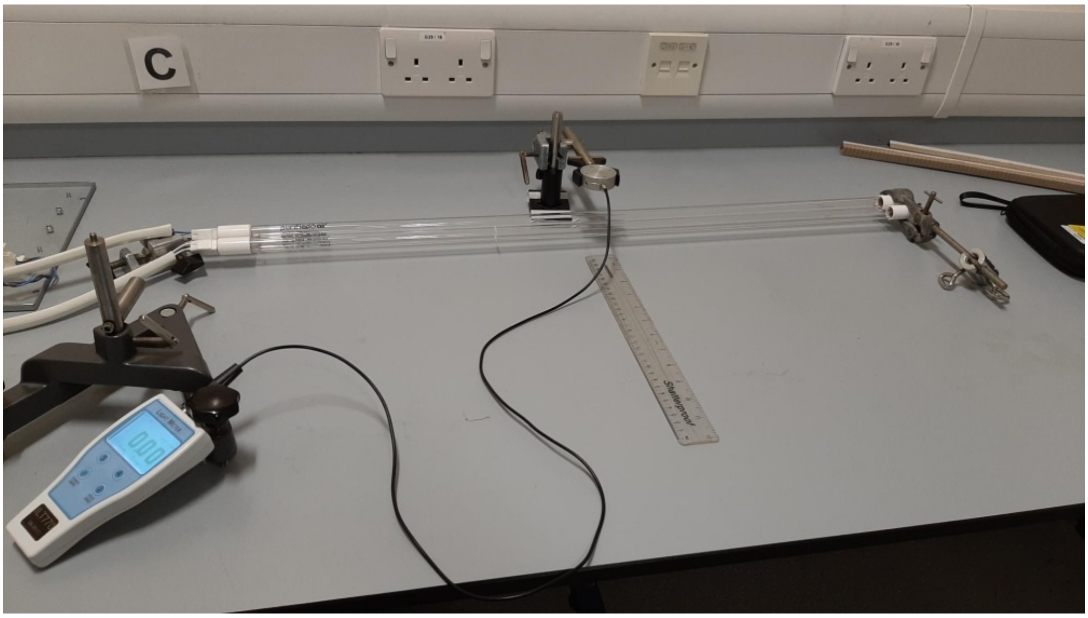


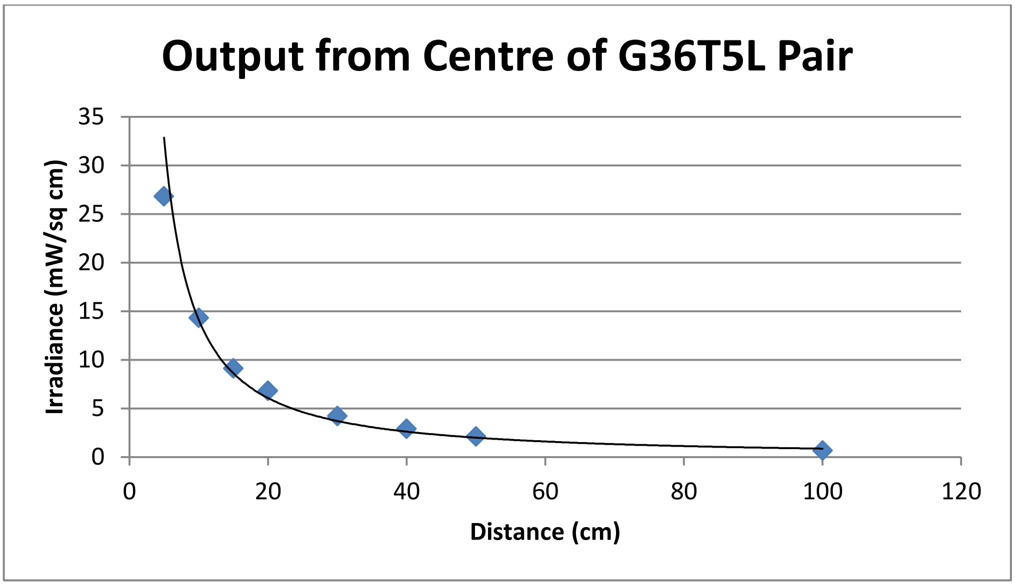
1.3.1.2 Lamp Pair

The output of a pair of individual G36T5L lamps was measured by placing the detector in the configuration shown diagrammatically below and in the image.

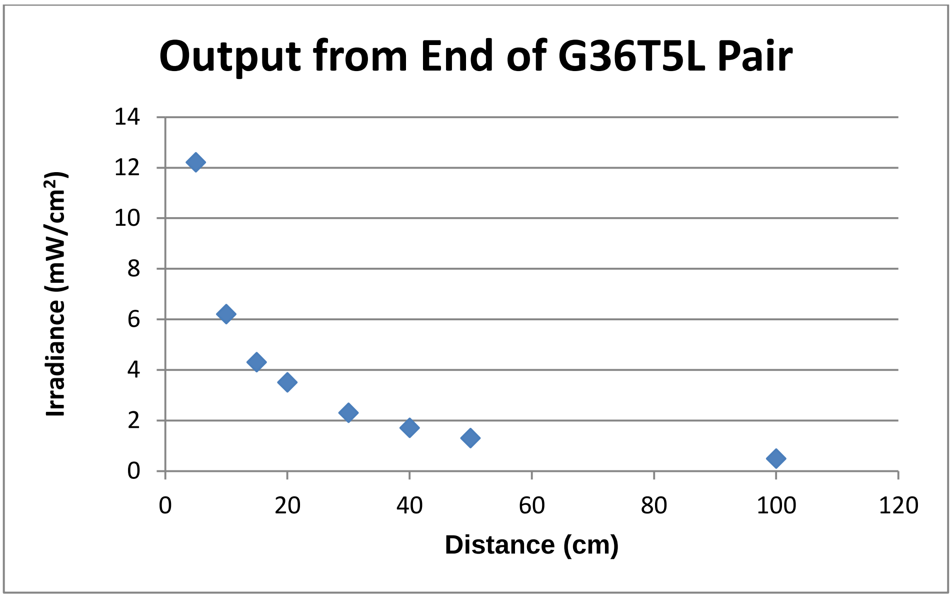


The interval separating the two lamps was 25 mm (axis to axis). The irradiance at different distance from the lamps were recorded and the peak irradiance at 5 cm from the centre of the lamps was 26.8 mW/cm^2. This is consistent with the previous measurement and furthermore confirms that it is justified to regard irradiance from two lamps as cumulative.





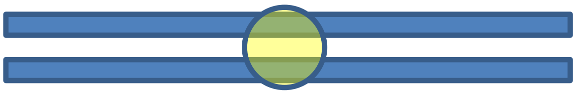
Placing the detector in the configuration shown diagrammatically below, peak irradiance at 5 cm from the end of the lamps was 12.2 mW/cm^2.

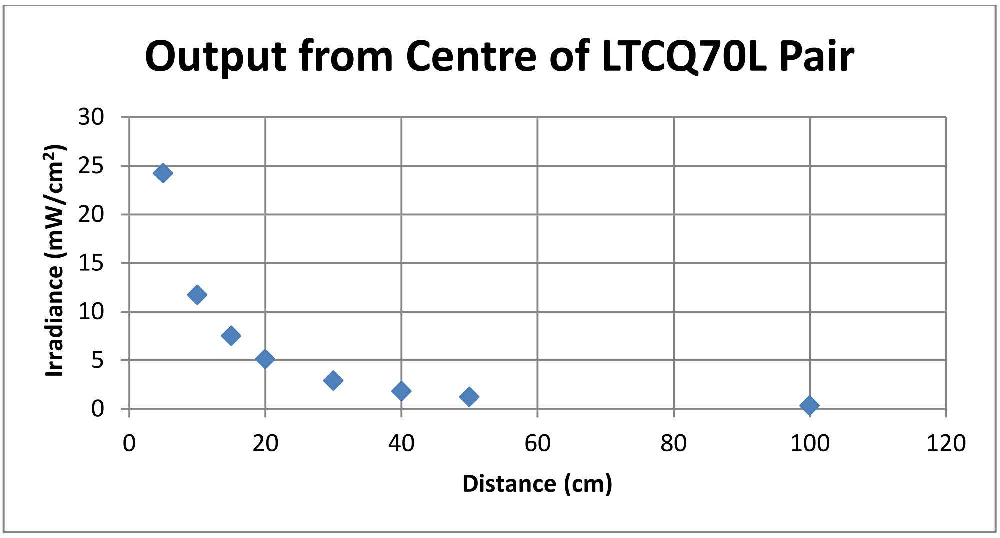


The variation between the end of the lamp arrangement and the centre is non-linear; the value of 26.8 mW/cm^2 is rapidly approached as the detector is placed sequentially at locations approaching the centre. The average value over the length of the lamp is **20.5 mW/cm^2.**

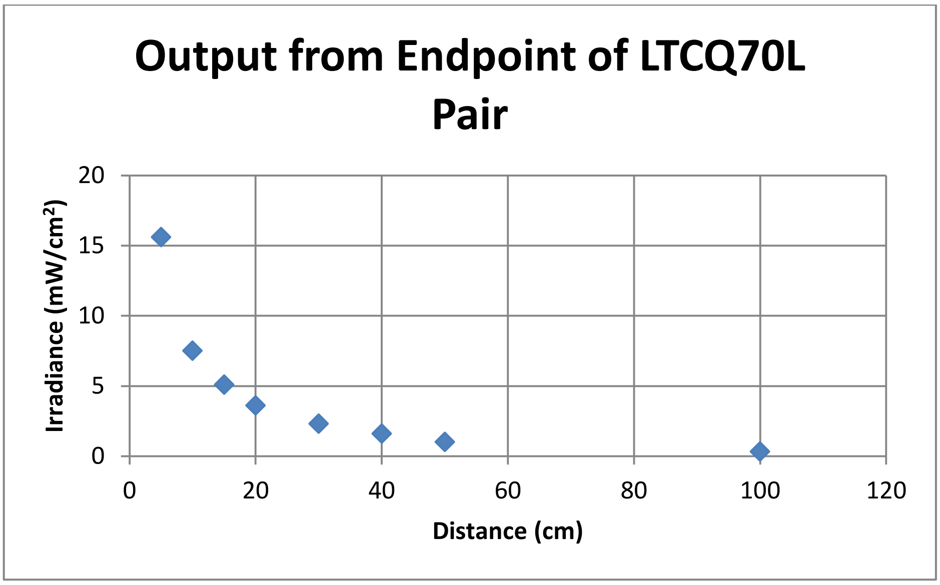
1.3.2. LTCQ70L Lamps

Placing the detector in the configuration shown diagrammatically below, peak irradiance at 5 cm from the end of the lamps was 24.2 mW/cm².





Placing the detector in the configuration shown diagrammatically below, peak irradiance at 5 cm from the end of the lamps was 15.6 mW/cm². The average peak irradiance at 5 cm was found to be 22.1 mW/cm² along the length of the tube.



Section 2: Irradiance Measurements from LTCQ70L (380 mm) Lamps in UVGI 1500

2.1 Airflow Rates calibration

Airflow was measured prior to both enclosure units for 5 different fan settings spanning a range from 0.2 m^3/s for the lowest fan setting (1) to 0.66 m^3/s for the highest fan setting (5).

There were only small variations in the irradiance values at the 5 different settings, within a narrow range of one another, indicating that the fan provided sufficient cooling to the lamps at all settings.

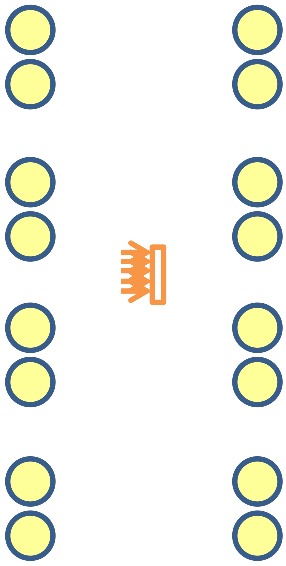
For the UVGI 1500, the maximum airflow that can pass through the unit is 0.7 m^3/s. This is the airflow at which pathogens travelling with the moving volume of air will be spending the least amount of time exposed to UV radiation and so this should be the value at which the dose will be calculated in section 4.

2.2 Experimental Setup and Methods of Sampling Irradiance Data

The UVGI 1500 was inserted into the test ductwork and fan system, which ensured the lamps do not overheat and are maintained at the optimal operating temperature by the cooling effect of the air pumped into the chamber. The detector was placed inside the enclosure, with the side covers closed; this was made possible by threading the detector cable linking it to the digital display unit through the end grille of the UVGI 1500 unit. The desired number of lamps were inserted into their sockets and the unit was switched on.

2.3 Measured Irradiance Values – LTCQ70L

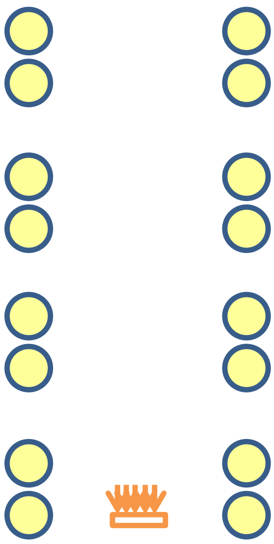
2.3.1. Eight Twin Lamp Setup, Sensor Positioned at the Centre of Unit, Facing Sideways (Facing Away from the Door)



As air was forced through the enclosure sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts showed an increase from **32.6 mW/cm^2** to **33.8 mW/cm^2** (average **33.6 mW/cm^2**).

2.3.2. Eight Twin Lamp Setup, Sensor Positioned at the Bottom of Unit, Facing Upwards

As air was forced through the enclosure sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts showed an increase from **27.4 to 28.1** mW/cm^2, average **28.0** mW/cm^2



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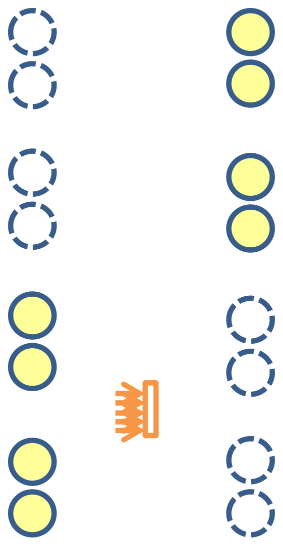
If the fan is switched off, without the cooling effect of airflow the output intensity of the lamps drops to below 50% of the unit's peak output due to higher lamp temperature.

2.2.3. Four Twin Lamp Setup, Sensor Positioned at the Level of the Midpoint of the Two Lower Lamps, Facing Sideways



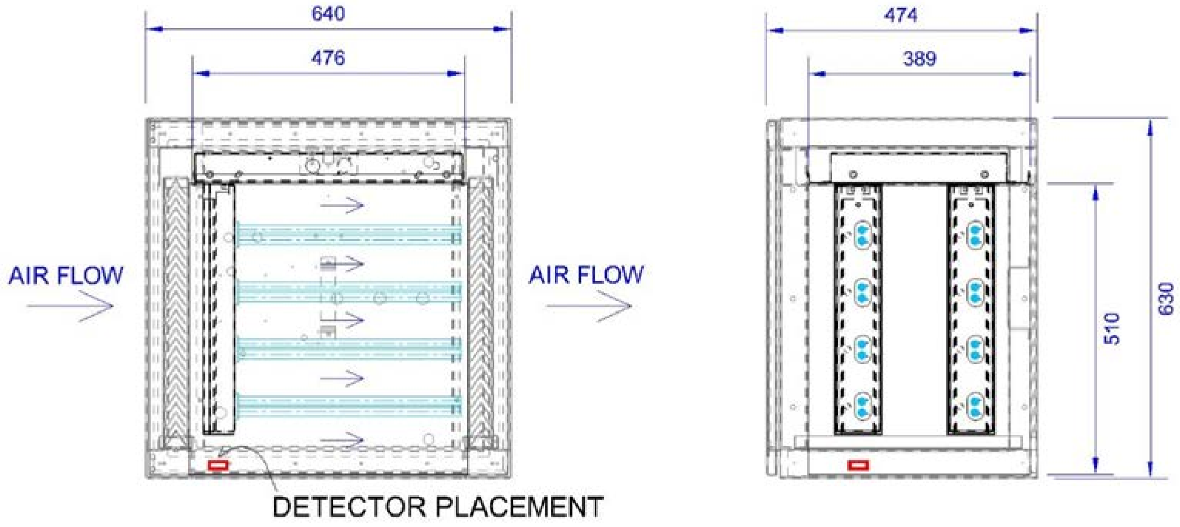
As air was forced through the enclosure sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts showed an increase from **28.0 to 28.4** mW/cm^2, followed by a decrease to **27.3** mW/cm^2, average **28.1** mW/cm^2.

As before, if the fan is switched off, without the cooling effect of airflow the output intensity of the lamps drops to below 50% of the unit's peak output due to higher lamp temperature.

Because of the way the detector faces only two lamps (the pair in the bottom left and the one immediately above it), this is an estimate of the output from just those two twin lamps, and **can be safely multiplied by a factor of 2** to obtain the likely illumination from both sides (i.e. the active detector side and the opposite, inactive, side), which results in a **value of just over 50 mW/ cm^2**. This is the level of irradiance likely to be experienced by a small particle.

2.2.4 Eight (LTCQ70L) Twin Lamp Setup, Sensor Positioned in Bottom Corner of Unit

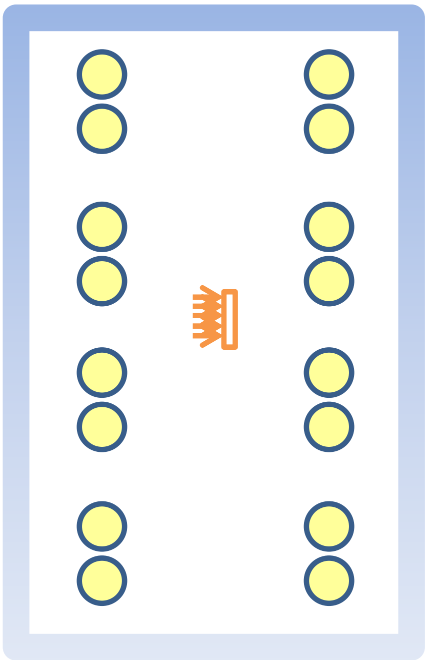
A final measurement in the UVGI 1500 enclosure was carried out by placing the detector in the corner of the unit at 45 degrees to the horizontal plane of the unit, where it was separated by the nearest lamp by a distance of 4 cm. Due to the corner position creating multiple shadowing effects and the separation from other lamps, this is the location receiving the smallest amount of irradiation. With 8 active lamps switched on, the irradiance level measured was **10.5 mW/cm^2**.


640
476
AIR FLOW
AIR FLOW
DETECTOR PLACEMENT
474
389
510
630

2.3 UVGI 1500 Irradiance measurements with Reflective Surfaces

The reflective surfaces of 2.0mm polished aluminium grade 5251 were fixed inside the unit covering the top, bottom, back wall and door surfaces so that the only part of the inside of the unit not covered by reflective surfaces, were the ends connected into the air duct.

2.3.1 Eight Lamp Setup with Sensor Facing Back Wall of Unit (Reflective Surfaces)



The irradiance measured was **42 mW/cm^2** which is a **24% increase** compared to the same setup without reflective surfaces. Because the two arms of the lamp module, which make up the twin lamp, are identical, and because irradiance is cumulative, this value should be doubled to produce the **84 mW/cm^2** which is the combined all-angle irradiance that would be experienced by a small particle. This is still a conservative estimate because it doesn't account for the radiation incident on the top and bottom of the sensor, so it can be regarded as an underestimate. Following the same trends as the test data from the previous Section 1, the value is likely to be in excess of **100 mW/cm^2**. The **84 mW/cm^2** level of irradiance would be almost an order of magnitude larger than that required **to inactivate SARS-CoV-2 based on the most recently published peer reviewed data in literature** and this will be discussed further in section 4.

Section 3: Irradiance Measurements from G36T5L (780 mm) Lamps in UVGI 1000

3.1 Airflow Rates Calibration

Airflow was measured prior to testing for 5 different fan settings spanning a range from 0.11 m^3/s for the lowest fan setting (1) to 0.4 m^3/s for the highest fan setting (5). As in the case of the UVGI 1500 unit, there were only small variations in the irradiance values at the 5 different settings, within a narrow 0.1 mW/cm^2 range of one another, indicating that the fan provided sufficient cooling to the lamps at all settings.

For the UVGI 1000, the maximum airflow that can pass through the unit is 0.47 m^3/s (obtained on the highest fan setting). This generates the highest propagation velocity through the chamber is the airflow rate at which pathogens in the air will be spending the least amount of time exposed to UV radiation and so this should be the value at which the dose will be calculated in section 4.

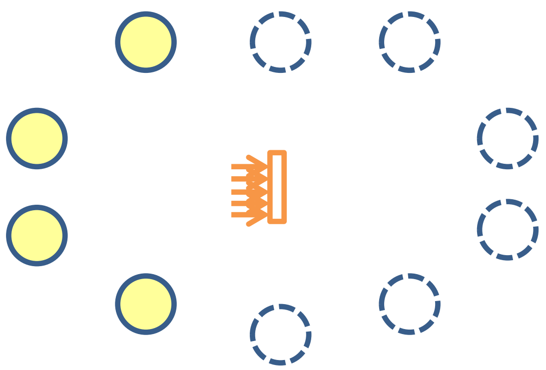
3.2 Experimental Setup and Methods of Sampling Irradiance Data

The UVGI 1000 is inserted into the test ductwork and fan system, and the airflow generated in this way has a beneficial effect on lamp temperature, ensuring that the lamps do not overheat. The detector was placed inside the enclosure, with the side covers closed, which was made possible by threading the detector cable linking it to the digital display unit through the end grille of the UVGI 100 unit. The desired number of lamps are inserted into their positions and the unit is switched on.

3.3 Measured Irradiance Values from UVGI 1000 Without Reflective Surfaces

3.3.1 Four Lamp Setup with Lamps Concentrated on One Side of the Unit

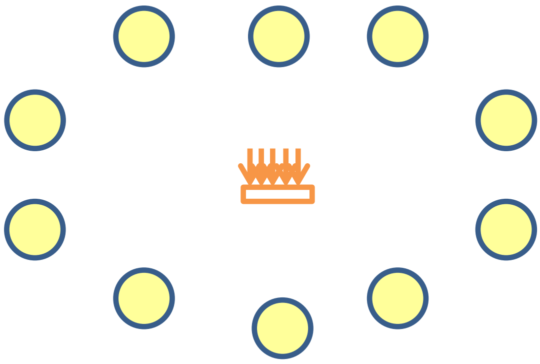
Measured irradiance values for UVGI 1000 configured with 4 active G36T5L lamps (See diagram) and sensor positioned in the centre of the lamp arrangement, facing **sideways**.



As air was forced through the enclosure sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts stayed in the narrow range **17.8 – 17.9 mW/cm²**. After the fan was switched off, the readout dropped to **12 mW/cm²** due to the heating effect of the lamps.

3.3.2 Ten Lamp Setup with Sensor in the Centre of the Unit Facing Upwards

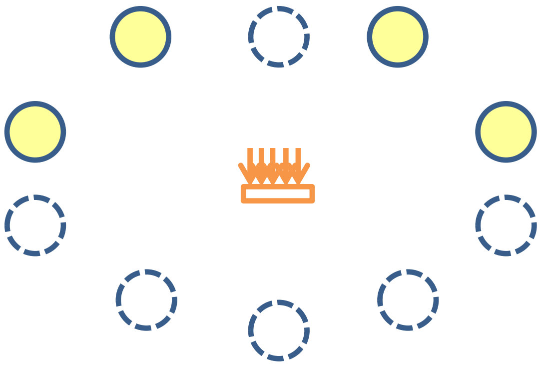
Measured irradiance values for UVGI 1000 configured with 10 active G36T5L lamps and sensor positioned in the centre of the lamp arrangement, facing **upwards**.



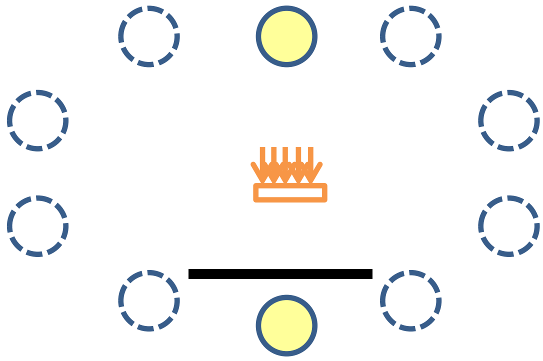
As air was forced through the enclosure sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts stayed in the narrow range **23.3 – 23.9 mW/cm²**. The temperature reached inside the enclosure was moderated by the forced fan cooling, and in the absence of cooling (when the fan was switched off) the readout dropped to **11 mW/cm²**.

3.3.3 Measured irradiance values for UVGI 1000 configured with 4 active G36T5L lamps and sensor positioned in the centre of the lamp arrangement, facing upwards.

As air was forced through the enclosure sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts stayed in the narrow range **8.3 – 8.4 mW/cm²**.



3.3.4 Measured irradiance values for UVGI 1000 configured with 2 active G36T5L lamps and sensor positioned in the centre of the UVGI volume and lamp arrangement, facing upwards.



The detector is placed at a distance of 81 mm from the top lamp.

In this arrangement, the bottom (active) lamp was covered in its entirety to prevent any light coming through, so the readout was only due to the emission of the top active lamp arrangement (and the reflective material behind it).

As air was forced through the enclosure sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts stayed in the narrow range **8.3 – 8.4 mW/cm^2.**

Keeping the sensor in the same position relative to the side walls but translating it longitudinally to a location near the lamp end, the maximum readout recorded was **6.3 mW/cm^2** (fan setting 3), which is only marginally higher than readouts at fan settings 2 and 4

3.4 UVGI 1000 Reflective Surfaces

The reflective surfaces of 2.0mm polished aluminium grade 5251 were fixed inside the unit covering the, top, bottom, back wall and door surfaces so that the only part of the inside of the unit not covered by reflective surfaces were the ends connected into the air duct.

3.4.1 Two Lamp Setup (Reflective Surfaces)

The first configuration to be tested was the two lamp setup, with the centre top and centre bottom lamp on (see paragraph 3.3.4). The irradiance ranged between **9.60 – 9.72 mW/cm^2** which is a **20% increase** compared with the same measurement taken without reflective surfaces.

3.4.2 Four Lamp Setup with Sensor Facing Back Wall of Unit (Reflective Surfaces)

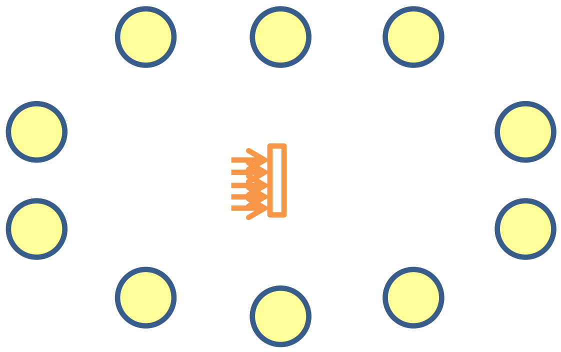
The four lamps are placed in the positions closest to the back wall as illustrated in the diagram in section 3.3.1 with the **sensor facing sideways**. The irradiance ranged between **31.7 – 31.9 mW/cm^2** which is a **77% increase** compared with the same measurement taken without reflective surfaces. Because the lamps on the opposite side of the unit simply mirror the four active for this measurement, it is safe to assume that a particle suspended in the centre of the unit would receive the exact same irradiance from the other four lamps if eight lamps were operating, and since irradiance is cumulative the expected level would be doubled to **63.4 mW/cm^2.**

3.4.3 Same Four Lamp Setup as 3.3.1 but with Sensor Facing Opposite Direction (Reflective Surfaces)

The sensor is faced away from the lamps (facing the unit's door) so that it is receiving UV radiation that is being reflected off the door reflective surface. This UV light travels three times the length of the UV light that travelled directly from the lamps in section 3.4.2. The irradiance ranged between **6.40 – 6.44 mW/cm^2** which should be added to the irradiance received by the sensor in section 3.4.2. This gives the irradiance received at the front and the back of the sensor.

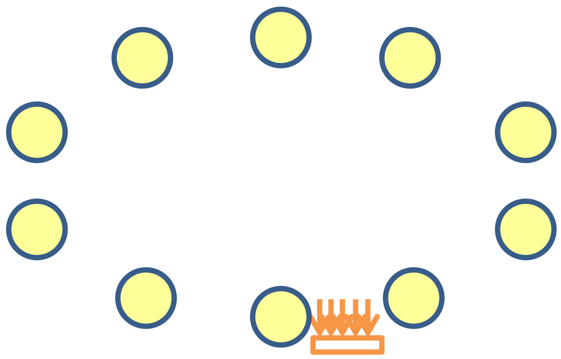
3.4.4 Ten Lamp Arrangement, Sensor Placed Centrally and Facing Sideways

As air was forced through the enclosure at different flow rates sequentially by selecting fan settings 2,3,4,5, the irradiance readouts stayed in the relatively narrow range **28.8 – 29.7 mW/cm^2**.



3.4.5 Ten Lamp Arrangement, Sensor Placed on the Bottom Surface and Facing Upwards

As air was forced through the enclosure at different flow rates sequentially by selecting fan settings 1,2,3,4,5, the irradiance readouts stayed in the relatively narrow range **38.0 – 40.9 mW/cm^2** but dropped to below **16 mW/cm^2** when there was no cooling (fan switched off).



To conclude this section on the benefits of using reflective surfaces to recirculate the radiation inside the chamber, it is clear that such recirculation has a significant impact on the irradiance received by the sensor. The percentage increase varies significantly from 20% in the two-lamp setup to 77% in the 4-lamp setup. The sensor in the two-lamp setup, however, was pointing directly at the top lamp which was taking up most of its field of view. The four lamp setup is more likely to give a better indication of the percentage increase because the sensor was not pointing directly at a single lamp and therefore single obstructions of the mirror images by the lamps themselves didn't play a significant part.

Section 4: Minimum Dose Values for Pathogen Neutralisation in Purified Air UVGI Units – Lamp and Airflow Requirements

The most important question that this study aims to address is "what is the minimum number of lamps in each UVGI enclosure that can provide the level of irradiance quoted in literature"?

4.1 UVGI 1000

4.1.1 Ten Lamp Setup

Because pathogens are likely to be carried on particles of fine mist, without obstructions or shadowing, irradiance (which is additive) is received from all angles.

Using the worst case scenario, a particle travelling along the central axis, following the shortest path straight across to the other end of the UV chamber, will experience an irradiance of at least **80 mW/cm^2** with reflective surfaces. This figure is obtained from the results in sections 3.4.2 and 3.4.3 which also discussed how the real level was likely to be in excess of **100 mW/cm^2**. Therefore, using a very conservative irradiance of **80 mW/cm^2**, the dose received by the particle at maximum airflow can be calculated by multiplying irradiance and travel (exposure) time through the unit, which for the highest airflow level is 0.2 s is **15 mJ/cm^2**.

Airflow (m^3/s)	0.2	0.3	0.4	0.5
Chamber volume (m^3)	0.094	0.094	0.094	0.094
Transit time (s) calculated as volume/airflow	0.468	0.312	0.234	0.187
Dose (mJ/cm^2)	37.4	24.9	18.7	15.0

These values are very high and would achieve an even more significant **3 log (99.9%) reductions** for most pathogens (see Table 1).

4.1.2 Four Lamp Setup

As demonstrated by our measurements, along its length a single G36T5L lamp can provide an average irradiation of **11.3 mW/cm^2 at a distance of 5 cm.**

Given the lateral dimensions of an internally reflective UVGI 1000 enclosure, 4 such lamps provide a cumulative level of **31.5 mW/cm^2** in the centre of the enclosure (see section 3.4.2).

Airflow (m^3/s)	0.2	0.3	0.4	0.5
Chamber volume (m^3)	0.094	0.094	0.094	0.094
Transit time (s) calculated as volume/airflow	0.468	0.312	0.234	0.187
Dose (mJ/cm^2)	14.7	9.82	7.37	5.89

A more judicious distribution of the lamps could be achieved to ensure a greater irradiance along the central axis, so again this is a conservative estimate of the dose that a pathogen propagating along the shortest path might receive.

It is therefore recommended that at **least 4 lamps** are used in the UVGI 1000 enclosure, which should be fitted with reflective surfaces, in order to obtain the dose of at least **5.89 mJ/cm^2**.

4.2 UVGI 1500

4.2.1 Dose Achieved with Eight Lamp Setup

Along its length a single LTCQ70L 380 mm long lamp can provide an average irradiation of **22.1 mW/cm^2 at a distance of 5 cm.**

Taking the dimensions of the UVGI 1500 from the technical specification in the introduction (389mm x 510mm x 465mm), and the maximum airflow of the unit (0.7 m^3/s), the shortest time spent inside the unit by a pathogen particle along the shortest path length is **0.132 seconds**.

This must be then multiplied by the irradiance value to obtain the dose received by the particle. With all 8 lamps operational inside the unit **fitted with reflective surfaces**, the average intensity inside the unit is calculated (by doubling the value measured in section 2.3.1) to be **84 mW/cm^2** meaning the average dose inside the unit is **11.1 mJ/cm2** which is a factor of 3 larger than the published **1 log reduction level for SARS-CoV-2** current literature *(M. Heßling et al. 2020 and Bianco et al. 2020*).

Airflow (m^3/s)	0.2	0.3	0.4	0.5	0.6	0.7
Chamber volume (m^3)	0.092	0.092	0.092	0.092	0.092	0.092
Transit time (s) calculated as volume/airflow	0.46	0.31	0.23	0.18	0.15	0.13
Dose (mJ/cm^2)	38.7	25.8	19.4	15.5	12.9	11.1

4.2.2 Dose Achievable with Four Lamp Setup

With only **4 lamps** operational inside the unit and the arms of the lamp module redesigned so that the 4 lamps are equally spaced out, the intensity alongside the central axis (situated at 160 mm from each lamp) is **30 mW/cm^2. By combining the data from the reflective measurements performed in sections 2.3.1 and 2.2.3** and assuming the extra reflections can be modelled as mirror sources situated a correspondingly longer distance away we obtain **50 mW/cm^2 from direct irradiance and another 20 mW/cm^2 from the cumulative reflected irradiance from the 8 "mirror" sources**). The overall expected value for the irradiance is therefore **70 mW/cm^2.**

Turbulence and eddy currents in this particular design of UV chamber make it very likely that the transit time experienced by particles diverted towards the sides of the enclosure upon entry is significantly longer than that of particles propagating straight along the horizontal axis of symmetry, which experience the shortest transit time and consequently the lowest levels of irradiation. Such straight propagating particles are a small proportion of the total but even they are receiving a dose higher than **9.2 mW/cm^2**, which is more than twice the 1-log deactivation level of **3.7 mW/cm^2**.

Airflow (m^3/s)	0.2	0.3	0.4	0.5	0.6	0.7
Chamber volume (m^3)	0.092	0.092	0.092	0.092	0.092	0.092
Transit time (s) calculated as volume/airflow	0.46	0.31	0.23	0.18	0.15	0.13
Dose (mJ/cm^2)	32.3	21.5	16.1	12.9	10.8	9.2

4.3 Other UVGI Units

Purified Air Ltd manufacture several different UVGI units. Not all have been tested by the University of Kent, but the calculations carried out as part of this report can be used to assess the effectiveness of these units in the same way. Ensuring these other units use either of the two lamps featured in this report, irradiance values inside these units can be calculated.

Just as has been calculated in 4.1 and 4.2, such irradiance values can further be used to obtain dose values received by a particle passing through the unit at a specific airflow speed.

4.4 Conclusions and recommendations

Although current literature contains many references to the use of UV with the purpose of deactivating viruses, there are no studies of virus concentration in a volume of air that passes through a UVGI unit.

This study gathered full data sets on experimental measurements of irradiance and used the data to calculate dose. **Both enclosure models, UVGI 1500 and UVGI 1000, would provide multiples of the minimum dose at the highest fan speed, and even higher levels of dose at lower fan speeds, if fitted with 4 lamps (models LTCQ70L and G36T5L respectively).**

Another way to arrive at irradiance data could be to model it in optical design software, which allows the calculation of irradiance from extended sources. The existence of the data would make such an exercise particularly useful as it can be referenced to actual measured values in order to help tweak the model. An alternative (or additional) way to model irradiation is to use an approximation called the Keitz equation, which is known to be an underestimate of the real irradiance values (Sasges, et al. 2012 and Jaworowicz, 2019). The Keitz equation can give an estimate of the irradiance at any distance away from the unit, provided that lamp parameters such as the total output power are known with a high degree of confidence. This irradiance is then used to calculate the dose so that it can then be determined if the unit is producing the required dose to inactivate specific pathogens.

Another important aspect is that for continuous UV operation, increases in lamp temperature can bring significant performance limitations. The lamp manufacturers confirmed that the optimum temperature for UVC intensity output is about 40°C and temperatures higher or lower than 40°C will negatively impact the UVC output. In the absence of a cooling mechanism, certain combinations of lamp current and ambient temperature could drive lamp temperatures to above 80°C. The UVGI units tested are designed to force air through the UV chamber which alleviates the need for additional cooling.

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