Design considerations and solutions in rapid-prototyping an ultraviolet reactor for ice borehole disinfection

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Abstract

Antarctic subglacial lakes are of great interest to the science community. These systems are considered to be in pristine condition potentially harbouring an environment containing undisturbed sedimentary sequences and ecosystems adapted to cold oligotrophic environments in the absence of sunlight.
Gaining access to subglacial lakes presents major technological challenges. To comply with conventions covering the exploration of pristine Antarctic environments access should be conducted so the lake is not contaminated in any way. Consequently, all equipment to enter the lake must be sterile and the entrance should isolate the lake from the external environment.
Currently clean access to these environments is achieved using a hot water drilling system (HWD). Differences between the hydraulic pressure head of the lake and the glacial surface results in a section of the borehole being air filled. It is imperative that this section is disinfected prior to isolating the entrance and introducing any sampling equipment. This paper describes the design process involved in rapid prototyping an Ultraviolet disinfection reactor for achieving this goal. Considerations such as UV output, physical constraints, temperature management, and deployment procedures are assessed. We present a design that addresses these considerations.

Introduction

Antarctic subglacial lakes were discovered rather by accident during a flight to determine landmarks to aid flight navigation in Antarctica(Robinson 1960). Several airborne surveys followed and to date 387 subglacial lakes have been catalogued. These lakes were formed thousands of years ago at the same time as the Antarctic Ice sheet (Priscu, Achberger et al. 2013). Since their discovery there has been interest to access these lakes and explore them with two primary goals: to find and understand life that may inhabit these pristine environments and to recover stratigraphic records that may be held in the sediments. Lake Ellsworth is a subglacial lake in West Antarctica located at 78° 58' 34" S, 090° 31' 04" W within the uppermost catchment of the Pine Island Glacier. It is formed at the bottom of a deep trough approximately 3000-3250 below the ice surface(Siegert, Hindmarsh et al. 2004, Vaughan, Rivera et al. 2007). The Lake Ellsworth Project is a consortium of mainly British researchers and is an initiative undertaken by the United Kingdom’s Natural Environment Research

Council (NERC) to sample water and sediment in Lake Ellsworth (Siegert, Clarke et al. 2012).

There is still some uncertainty whether subglacial lakes exist in an open or closed system(Brito, Griffiths et al. 2013). Given the pristine state of these lakes both the Scientific Committee for Antarctic Research (SCAR) (Alekhina, Doran et al. 2011) and the US National Research Council (NRC) Committee on Principles of Environmental Stewardship for the Exploration and Study of Subglacial Environments (2007) recommend that access to subglacial lake should not contaminate the existing ecosystem, see also (Siegert, Clarke et al. 2012).

At present, clean access to subglacial lakes has been achieved by using a hot water drilling system (HWD)(Makinson 1994). This drilling technique uses re-circulated melt water to form a borehole by pumping it through a nozzle as this is progressively lowered through the ice. The technique involves the formation of a reservoir chamber close to the glacier surface but below the predicted hydrostatic pressure head of the lake. Two shafts connect with the chamber from the surface, one extending to the lake for sampling; the other terminating in the chamber for drawing up melt-water to supply the drilling nozzle. The hydrological water level of sub-glacial lakes can vary but it is expected that the upper section of the lake access shaft will be air-filled and in the case of Lake Ellsworth this is estimated to be approximately 300m (Vaughan, Rivera et al. 2007, Siegert, Clarke et al. 2012). This shaft is susceptible to contamination from air-borne bacteria that can drop in from machinery, personnel, and the environment during the drilling process prior to being sealed off from the environment with an airlock. Before introducing pre-sterilised equipment through this portal it is imperative to de-contaminate the air-filled spaces in the borehole.

This paper presents work undertaken to design a UV reactor that can be lowered down the shaft to decontaminate the air filled section prior to the introduction of any sampling equipment.

General Concept

The design of the reactor was based around cylindrical UV reactors used to disinfect wastewater (Qualls and Johnson 1983, Bekdash, Kurth et al. 1996, Gardner and Shama 1999, Bolton 2000) since the constraining aperture for introducing equipment into the borehole was a circular hole in the base of a sterile airlock. This aperture was 20.0cm in diameter. The reactor unit was to be lowered down the borehole on a conducting tether terminated by a connector common to all powered equipment deployed down the shaft.

The design paradigm was to create a high output UV source using a quartz glass cylinder that had been reserved for the consortium with an appropriate length and diameter to comply with the constraints of the airlock (Nicholas Rundle, comm). The output needed to be high enough to deliver a sufficient UV dose within the time allocated to it among the total period available to achieving all of the sampling objectives before the borehole refroze. The apparatus also required a means of determining when the unit contacted the water surface at the bottom of the air-fill section of the shaft and needed protection from water ingress should it be immersed at this point.

Design considerations

Quartz glass supply

The quartz glass cylinder, the sleeve, was an "end of line" off-the-shelve product 95.3cm long and of varying outer diameter (OD) between 16.82 – 16.88cm. The cylinder had a nominal 5 mm wall thickness along the majority of its length.

Because drawing quartz glass of this size is a less than precise art dimensions can vary considerably with this product therefore fitting tolerances between the flanges and glass, to accommodate 0-ring seals, were kept relaxed so that if at some point in the future a replacement was required there was a good chance it would fit.

The timeframe set for delivery made this a high-risk to the project since no spare was available within the deadlines for shipping to the Antarctic consequently the quartz sleeve was treated with extraordinary care to protect it from physical damage.

Fortunately quartz is, thermally, more robust and has an extremely low thermal coefficient of expansion 5.5×10^{-7}/°C (20–320 °C) resulting in an ability to undergo large, rapid temperature changes without cracking(De Jong, Beerkens et al. 2000). This gave us assurance that even though it may be relatively hot, through absorption of heat produced by the UV lamps, it would not shatter and should remain intact when it reached the water level, even if entering near freezing water.

Power

Based on high UV output, price, physical dimensions and immediate availability 12 low pressure mercury tubes and their associated dual electronic ballasts could be accommodated within the quartz sleeve. This determined the power requirement for the reactor. Power was supplied to the unit by a Glassman LP6000 power supply through 4000m of multicore tooling cable (Cortland Fibron BX) in the form of a DC voltage at a nominal 8.0 amps. Because of the voltage line loss over that distance, DC power was fed at 240V to achieve a starting voltage of 180Vdc at the reactor to power the electronic ballasts and the lamps. The advantage of using electronic ballasts is that they can operate on a DC voltage obviating the need to convert the supply to AC. This simplified the circuit design considerably.

When a fluorescent lamp 'strikes' the ionising mercury vapour forms a low impedance pathway to the high voltages supplied from the ballasts (Gluskin 1999). This effect momentarily draws high current that settles to a lower usage, regulated by the ballast, once the lamp has struck. Had all 6 ballasts struck their lamps simultaneously the current required will exceed what the power supply was capable of supplying. However the simple power distribution system was, in a sense, self-regulating because the time constants for components within the starting circuits of individual ballasts will be slightly different as a result of resistance and other manufacturing differences. Consequently the ballasts are not drawing the available current evenly at start up. Those not receiving sufficient will be unable to strike until other ballasts regulate their lamp current to a lower demand once struck and free resources. This produces, de facto, a sequential start up.

Temperature management

Ultra-violet output from the lamps is temperature dependent and peak output of the lamps occurs at a working temperature corresponding to the lamp wall temperature being around 35°C. Lamp output efficiency drops at temperatures over 48-50°C, and operating lamps outside the designed temperature range can reduce their lifespan as well as their output. This drop in efficiency also causes the ballasts to run hot. (Clancy 1993, Graovac, Dawson et al. 1998).

Under normal operating conditions fluorescent lamps rely on airflow over the surface to prevent heat building up. Consequently, because the lamps were in a sealed enclosure, one factor driving the design was to provide a means of losing waste heat to the environment. Additionally the ballasts have a thermal cut out at 70°C and required protection from temperatures in excess of this.

A large temperature gradient between the operating environment (circa -18°C) and the reactor should work in the designs favour.

To aid the dissipation of heat, ducts and a set of internal concentric tubes allow cooling air to flow through the inside of the reactor (see Fig 1). The inlet ducts on the lower flange were angled so there would be forcing of influent air as the reactor descended the shaft. The centremost tube conducted cables for power and signal while the surrounding tube provided the space through which air could flow. The ballasts were then positioned in the lower, coolest, part of the assembly. The central (cable) duct was sealed at either end by a gland (IP68) to prevent water ingress to the electrical spaces should the lamp be immersed in water at the bottom of the air-filled section of the borehole.

Fig 1: 3-D CAD cut-away drawing showing major structural and electrical elements of the reactor assembly as well as indicating the cooling airflow through the unit during operation.

Water contact switch

Since the reactor was required to transit to the air water interface it was anticipated with would come in contact with water and so there was a requirement to make some provision for dealing with this eventuality. The standard method for doing this is to use a conductivity sensor, formed of two exposed electrodes energised with a voltage between them and connected to a meter or alarm of some sort in the operator area.

It was anticipated that the conductivity of the borehole water would be low. Previous studies indicate that the glacial melt water is likely to be between the conductivity of distilled water (10 $\mu S/cm^2$) and tap water ($100 \mu S/cm^2$), or 0.1MΩ to 0.01MΩ (Gurnell and Fenn 1985, De Mora, Whitehead et al. 1994, S.J.de Mora 1994, Vandal, Mason et al. 1998, Lyons, Leslie et al. 2012) Combined with a tether resistance of 200Ω (Edward Waugh, comm) this would give a total resistance of 0.1002MΩ between two contacts 1cm apart if the lower value is chosen. A supply voltage of 200Vdc would induce a current of 1.9mA to flow between the two terminals on meeting the water surface, an easily detectable current with most modern metering equipment. While these currents are low compared with shorting in more conductive environments it is the experience of one of the authors on other tethered sampling systems over longer cable lengths and with similar DC input voltages, that currents in excess of 500mA can be drawn in the event of a seawater short.

While not used in the final assembly due to a last minute breakage, provision for a water contact switch was made by installing appropriate electrical connections and a suitably tapped penetration of the lower flange to mount a 2-pin male connector (Teledyne Impulse XSG-PBCLM) on the base plate of the lamp unit to act as a simple water contact switch with the option to interface with more sophisticated detection systems in less conductive environments. The penetration was subsequently blanked off and the risk of water contact managed though other means (see deployment risk assessment section).

Light output calculations

It is established that exposure to Ultra-violet light inactivates bacteria(Andrew 2005, Labas, Brandi et al. 2006). DNA strongly absorbs radiation at wavelengths in the vicinity of 200 to 250nM, changing the mode of operation of nucleic acids in the organism and disrupting their ability to propagate. They become biologically inactive (Andrew 2005, Gayán, Monfort et al. 2011). At shorter wavelengths secondary effects can also occur when ozone and hydroxyl groups can form that have an additional germicidal effect (Bekdash, Kurth et al. 1996)

UV radiation at these wavelengths can be produced by various methods, striking an arc through mercury vapour at low pressure(Bekdash, Kurth et al. 1996, Heering 2004), pulsed UV sources (Bohrerova, Shemer et al. 2008), cold plasma jets (Abramzon, Joaquin et al. 2006), and Deep UV Light Emitting Diodes (Yagi, Mori et al. 2007, Shur and Gaska 2010, Bowker, Sain et al. 2011)

In the present case low-pressure mercury vapour lamps (GE T8 G13 base 55W Germicidal lamps - Primark G55T8-GE), in association with electronic dual lamp ballasts (2x55W Tridonic Electronic ballasts - Primark PC2/55TC-LBE), were chosen for their size, availability and relatively high UV output of 18W at 254nm in comparison to other available lamps.

The reactor was formed from a set of individual lamps arranged in a circle around a central column. Consequently any point above the reactor surface will be exposed to the output of 6 to 7 lamps of the full compliment of 12, and will be shadowed from the full output of all but the adjacent lamp.

Radiant energy passing through a three-dimensional point, or volume element, from all directions is defined as the fluence rate for that point and is expressed in terms of Watts per square meter (Wm^{-2})(Bolton 2000). UV Dose, or Fluence, through this volume element is the fluence rate multiplied by the irradiation time and is given in terms of Joules per square meter (Jm^{-2})(Bolton 2000).

Qualls and Johnson, and Bolton give equations for calculating UV fluence and dose from cylindrical reactors with linear light sources based on the multiple point source summation method (MPSS)(Jacobm and Dranoff 1970, Qualls and Johnson 1983, Bolton 2000). Under MPSS a linear lamp is divided into smaller sub-units and the radiant power of the source divided evenly between them. Their individual contribution to the fluence rate through a volume element is calculated taking account of their distance from, and angle of incidence to, the volume element. These individual results are then summed to determine the total fluence rate at the volume element.

Both these papers assume a single linear lamp, however in the present case multiple linear lamps are contributing variously to the UV fluence at the volume element. Accordingly, for the purpose of calculation, it was assumed that the lamp closest to the chosen volume element contributed 100% of its output, each lamp of the pair bracketing this lamp contributed 75% of their output (so 2(0.75)=1.5 lamps for the pair), and the next pair contribute 45% each (so 2(0.45)=0.9 of a lamp for the pair). The third pair is taken to be completely shadowed by intervening lamps from the measurement point and was not accounted for in this simplified estimation but will contribute to the reflected irradiative background.

Under these working assumptions the output from each lamp was calculated separately under the MPSS method using 5cm long lamp sub-units, for a volume element 9cm from the reactor surface and midway, longitudinally, along the lamp. These individual lamp outputs were then combined to estimate the total fluence rate through the volume element. This point was chosen because it was the distance where the wall of the borehole would be expected to be during deployment. The calculation was run twice, once using the Bolton and once using the Qualls and Johnson equation as a means of sense-checking the magnitude of the result.

Equation 1 was used first (simplified after Bolton 2000) to calculate the contribution of each subsection of lamp to the fluence at the volume element.

$$E'(x,H)=\frac{\Phi}{4\pi Lx}\left[\arctan\left(\frac{L/2+H}{x}\right)+\arctan\left(\frac{L/2-H}{x}\right)\right] \qquad \text{Equation 1}$$

Where E' is the fluence rate at a radial distance x and a longitudinal distance H above the centre of the lamp. L is the length of the lamp (95.3cm) and Φ is the source's radiant power in watts (18W @ 254nm).

So for each lamp the output is given as the sum of these point sources thus:

$$E_{lamp}=\sum_{H_n}^{H_0} E'(x,H)$$

To calculate total reactor output these individual lamp results were combined in the following fashion.

$$E_{total}=\left(E_{lamp}+2(0.75\times E_{lamp})+2(0.45\times E_{lamp})\right)\times 0.9$$

$$\therefore$$

$$E_{total}=(5.18+6.17+3.35)\times 0.9$$

$$E_{total}=13.23\ mW/cm^2$$

This model neglects reflection and refraction by the quartz tube, and transmission loss through the quartz is accounted for after the fluence rate calculation as recommended in Bolton (Bolton 2000) by degrading by 10%.

Equation 2 (Qualls and Johnson 1983) was next used.

$$I_{(Z_L)(R,Z_c)} = \frac{(S)}{4\pi\left[R^2+Z_{LC}^2\right]} exp\left(-a[R-R_1]\frac{P}{R}\right) \qquad \text{Equation 2}$$

Equation 2 gives the intensity (I) at a point (R, Z_C) near the lamp (the volume element) from a point source, Z_L, from the base of the linear lamp. The term "*a*" is the absorbance of the medium between the lamp surface and the volume element, which was treated as zero since the transmission loss through dry air over the short distances involved is zero. After the calculation, as in Equation 1, account was taken of the 10% transmission loss through quartz by multiplying the result by 0.9.

The total intensity at point $I_{(R,\ ZC)}$ is the sum of the contributions of each point source (at each Z_L) over the source length.

$$I_{(R,\ Z_C)} = \sum_{Z_{Ln}}^{Z_{L0}} I_{(Z_L)(R,Z_C)}$$

And the total fluence through a volume element is calculated for the pairs of lamps capable of directly radiating the area, so:

$$I_{total} = \left(I_{(R,Z_C)} + 2\left(0.75 \times I_{(R,Z_C)}\right) + 2(0.45 \times I_{(R,Z_C)}\right) \times 0.9$$

$\therefore$

$$I_{total} = (5.51 + 6.56 + 3.55) \times\ 0.9$$

$$I_{total} = 14.06\ mW/cm^2$$

Both the Bolton and the Qualls & Johnson equations agreed within a small margin with each other at $13.23 mWcm^{-2}$ and $14.06 mWcm^{-2}$ respectively.

Dose

As the lamp is lowered down the shaft the UV dose delivered to the borehole walls depends on the rate at which it is lowered. The period of exposure begins with the lower part of the lamp passing the measurement point and ends as the upper end passes it by. The time allocated to the borehole disinfection stage was around 30 minutes and the borehole was calculated to be air filled for the first 270-300m (Siegert, Clarke et al. 2012). In order to cover this distance in the allocated time the lamp needs to descend 1 metre every 6 seconds,

Dose (mJ/cm^2) = Fluence (mW/cm^2) X Exposure time (s^{-1}) Equation 3

And Exposure time is given by the length of the incandescent part of the reactor multiplied by the descent rate, thus:

76.44 mJ/cm^2 = 13.23 mW/cm^2 x (0.963m x 6) s^{-1}

Gives the dose for a volume element on the borehole wall during the downward transit of the reactor through the air space at the target descent rate. This rate was chosen so an effective dose would be delivered only on the downward transit to guard against the small risk of the lamp being extinguished on contact with the water.

The dose required for disinfection will vary depending on the organism under consideration (Qualls and Johnson 1983, Bekdash, Kurth et al. 1996, Andrew 2005, Guivan, Kamikozawa et al. 2010). Furthermore disinfection is not an absolute term but a statistical concept representing a particular level of microbial inactivation, most commonly interpreted as a reduction in their ability to form colonies.

"Complete destruction" as defined by the US Environmental Protection Agency (EPA) is a log 3 reduction (99.9% inactivation) and requires doses of between 3.4 mJ cm^{-2} and 26.4 mJ cm^{-2} for most common bacteria (*Bacillus subtilis* is commonly used as the definitive test subject because it is one of the most persistent types). Mould spores are the hardest to inactivate, some requiring over 300 mJ cm^{-2} to achieve log 3 inactivation (Bekdash, Kurth et al. 1996).

A number of studies have sought to characterise the microbial communities in different environments on the Antarctic continent, and glacial ice in general (Karl, Bird et al. 1999, Priscu, Adams et al. 1999, Christner, Mosley-Thompson et al. 2000, Christner, Mosley-Thompson et al. 2001, Jungblut, Hawes et al. 2005, Yergeau, Newsham et al. 2007, Lanoil, Skidmore et al. 2009).

One wide survey of microbial communities across a range of habitat in Antarctica has shown the Ellsworth mountain area to be a separate biogeographic region characterised by extremely low nutrient input and exposure to high UV levels during the summer (Yergeau, Newsham et al. 2007). Bacterial counts and biomass were low and the community structure is narrow, skewed toward dominance by *Bacteroidetes* of the Order *Sphingobacteriales,* the vast majority of these being related to the genus *Chitinophaga*(Yergeau, Newsham et al. 2007). The order *Sphingobacteriales* are the dominant bacterial group in Antarctic microbial soil communities and are common globally (Roesch, Fulthorpe et al. 2012)

This study (Yergeau, Newsham et al. 2007) surmised that these species may dominate because they possess a combination of environmental hardiness and a specialised metabolism more adapted to the low nutrient availability. Potentially these resistant characteristics include a higher than normal resistance to UV radiation given the high UV regime in this environment, a factor that has a tendency to skew community structure to resistant strains (Manrique, Calvo et al. 2012).

From these preliminary calculations the design would appear to exceed the criteria of log 3 reductions for most common bacteria types when coupled with a descent rate of 10m/min.

Deployment risk assessments

The lamp is the first component of the scientific payload to enter the borehole after it has been formed. Consequently it is a test case for the subsequent deployment of other equipment. It is uncertain where the actual level of the water will be in the shaft since that will depend on a number of difficult to calculate factors that will determine the actual head of the lake once the ice barrier had been broached. The head pressure will be a combination of the density of overlying ice, influent/supply water pressure and pressure dissipating mechanisms within the hydraulic system. Working calculations by team engineers estimate the water level will stabilise between 270-300m below the surface of the ice(Siegert, Clarke et al. 2012).

The UV lamp assembly is assigned a nominal IP68 rating based on the specification of components used at its most vulnerable points. These are the gland seals around the central cooling shaft and it's concentric cable duct. Under normal circumstances these should be able to withstand a brief immersion to 1(one) metre but they are not rated for greater depths, nor can they be relied on for any length of time. No seal is entirely reliable and they become less so as temperatures drop, O-ring seals harden and metals contract. Consequently it was considered prudent to avoid immersion of the lamp at the bottom of the shaft if at all possible.

As reported earlier in this paper the original design allowed for a water contact switch to alert personnel when the base of the lamp made contact with water. In the event of this becoming inoperable, reserve measures and contingencies needed to be available to avoid more than partial immersion of the unit.

The first feature in favour of mitigating the risk is that the lamp assembly displaces more than its own weight in water and would float provided the seals don't leak. However the unit is attached to heavy tooling cable, which will force the unit further down if it continues to be paid out resulting in an unplanned immersion.

Another available safeguard is the presence of a load cell on the out board sheave of the deployment winch which has sufficient sensitivity to detect the load coming off the cable as the UV lamp assembly became buoyant. The use of the load cell however relies on the winch operator being aware of the change in the numerical readout on the display at the time the unit enters the water and becomes buoyant. This is aided by a line out measurement taken from a counter that records the number of rotations of the outboard sheave allowing the winch operator to know exactly how much cable has been paid out so they can be extra vigilant when approaching the depth of the calculated pressure head.

Based on all sources of information procedures were derived and formal risk assessment carried out. Probability values were then assigned to the relative likelihood of certain scenarios playing out. These are represented in the fault tree presented in Fig 2.

A fault tree is a well known method for modelling and estimating the reliability of a system where the likelihood of system failure depends on the likelihood of several potential modes of failure(O'Connor 2005). In addition to providing a visual, easy to understand, interpretation of how a failure mode may propagate in the system, a fault tree also uses sound probability theory to compute the likelihood of the top failure event ever taking place.

In such diagrams, the logic probability functions are captured in 'and' or 'or' gates. An 'and' gate represents the scenario where all base failure modes need to occur in order for the top failure event to realise; an 'or' gate represents the scenario where only one failure event needs to occur in order for the top failure event to realize. Fig. 2 shows that the top-level failure event, failure to maintain the pressure head over the lowest seal at less than 1m below water level, can be caused by instrument failure or human error. Based on the assessments

provided for each failure mode we were able to estimate the likelihood of failure to keep the pressure head 1m below water level as 0.029. This equates to a chance of approximately 1 in every 34 deployments. Human error is the most likely failure mode at level 1. The most likely causes for human error are: 1. Operator forgets to zero the wire counter and 2. Operator fails to notice the drop on the load cell by being distracted, or because there is too much noise in the load cell output to distinguish a signal originating from the change in load from the background fluctuation in the display.
The fault tree contains only 'or' gates. Failure to keep the pressure head less than 1m below water level can be caused by any of the eight base failure modes. As a result the reactor deployment sequence was defined by taking into account mitigation actions for these base failure modes at different phases of the deployment (Kevin Saw, comm).

Fig. 2: UV Lamp fault tree and final relative probabilities

Detailed description of the design

The lamp's design can be summarise as being a single quartz glass tubing section with a chamber either end and two, internal, concentric aluminium tubes providing a water resistant air duct up the middle of the structure and ducting for electrical cables down the centre of the assembly (refer Fig. 3). Arranged radially around the air duct and within the wall of the quartz tube are 12 T8 fluorescent tubes emitting 18 watts of Ultra-Violet radiation (254nm) each. The top flange accommodates a multi-way bulkhead connector supplying power and signal connections from the surface. These are internally routed via a four-conductor cable to the bottom chamber that houses six dual-lamp electronic ballasts. These are supplied with a DC voltage of at least 180Vdc. Incoming power is connected via multi-pole bulkhead connectors in the lower section of the bottom chamber to distribute power between the six ballasts that control two low-pressure mercury lamps each. Multiple solid core switchgear wires (conductor cross-sectional area $1mm^2$) returned power up the central conduit to complete the lamp circuit. Each conductor in this loom has a cross-sectional area of $1mm^2$ and is capable of conducting 15 amps at 600V.
Electrical connections are isolated from chassis components by 30% glass filled PEEK insulating inserts to prevent any bare wires from contacting the metal casing of the assembly. The entire circuit was protected at the power supply by residual current detection devices and connection to a common ground.

Fig. 3: Final UV Lamp assembly

The wiring was modularised to allow disassembly of separate ends should any maintenance be required with in-line and bulkhead connectors at strategic points.

Discussion

This UV reactor was designed and built so that the Lake Ellsworth Consortium had a means of borehole disinfection to meet the aims, and the spirit, of the SCAR and the NRC principles of environmental stewardship for the exploration and study of subglacial environments. These principles call for contamination reduction technology at every step of the lake access process(Anonymous 1991, Siegert, Clarke et al. 2012). Contamination, whether chemical or biological, has the potential to alter these environments, confound interpretation of samples and limit the degree to which we might understand the nature and functioning of these environments (Siegert, Clarke et al. 2012, Anonymous 2013, Priscu, Achberger et al. 2013, Wadham 2013). The implementation of the consortium's decision to provide this technology was undertaken late in the preparation stages of a 2012 attempt to access and sample the lake. As a result this reactor is a form of rapid prototyping and no time was available following assembly to comprehensively test the apparatus other than to confirm it operated. The reactor was run for a short period (60min) in a refrigerated container (-20°C) after equilibrating to this temperature overnight. This test was conducted using the same power supply and a similar test cable proving that the unit would start up and run in temperatures equivalent to Antarctic ambient temperatures though no attempt to measure the fluence rate could be made due to a lack of calibrated test apparatus or time to exhaustively conduct a series of measurements.

While lake access was not successful on this occasion the scientific objectives remain relevant and it is expected that a subsequent attempt will be made in the future so there may be the opportunity to conduct more comprehensive tests at some later date under simulated environmental conditions.

Refreezing of an ice hole can take just a few tens of hours depending on the diameter and depth of the hole (Makinson 1994). This leaves limited time to prepare for clean access to the borehole once drilling has been completed; UV disinfection of the air filled headspace is a component of that process. Therefore it was an important feature of any disinfection system that an effective dose is delivered in the shortest amount of time possible. The calculations conducted in this paper indicate a transit time of 30 minutes, in addition to a recovery period, would be sufficient to deliver a dose far in excess of that required to achieve the requisite log 3 disinfection for most common bacteria. This was achieved at relatively low cost with commercially available UV sources. This availability fitted well with the short production timeframe.

Research conducted in preparation for this project into other technologies indicate pulsed UV sources to be extremely effective (Bohrerova, Shemer et al. 2008) and medium pressure xenon and iodine vapour lamps, which concentrate output at around 253.7nm (the most potent wavelength for bacterial inactivation), are also proving more effective than LPM lamps without the hazards inherent with using mercury (Guivan, Kamikozawa et al. 2010). The Pulse UV methods are of particular interest. The dose from a Pulsed UV source is of high intensity on a very short duty cycle that can be repeated until the required dose is achieved. As a result these types of lamp are not prone to the same accumulation of heat as are the LPM tubes and through control of the pulse sequence there is the potential to excite vulnerable molecules and proteins at frequencies, and in sequences, that maximise the potential for disruption. However both these systems had much greater lead times, and would have required significant re-engineering of the light source and power supply to fit within the geometric constraint of the sterile air-lock delivery system. On balance then, not only was the system presented in this paper far less expensive that other options, it required less re-engineering of primary components and could be delivered in a much shorter timeframe.

There are several unknowns currently on the performance of the lamp and a comprehensive test programme would be a logical next step in proving of the efficacy of this technology in this deployment scenario. As mentioned previously UV output is dependent in part on temperature and we did not have the opportunity to characterise the output under a representative range of temperatures. The balance between the endogenous heat output of the lamp and the heat dissipation measures would determine the effect this has on the UV dose capable of being delivered. Consequently we must, for the time being, rely on the generosity of safely factors built into our assumptions and calculations for surety that we can achieve effective disinfection doses.

It would also be useful to confirm the accuracy of our calculations in the context of work done recently by Li, Qiang and Bolton (Li, Qiang et al. 2012, Li, Qiang et al. 2013), that support the assumption made in this paper that adjacent fluorescent tubes in a circular reactor shadow volume elements from the full output of all lamps. Li et al modelled and experimented with a three-lamp scenario and it would be interesting to extend and compare their findings to the lamp described in this paper through a series of measurements under controlled conditions.

We believe there is the potential to repurpose this low cost technology to be a component of systems for clean access to other pristine environments, particularly though not exclusively to scenarios involving a frozen fluid. When an internal volume requires disinfection, and access to the volume is confined, this apparatus could easily be applied especially when an annular design provides the most effective way of accessing a space and delivering a UV dose.

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