A TECHNICAL ASSESSMENT OF THE
PREVENTION OF MICRO-FOULING ON OTEC
HEAT-TRANSFER SURFACES THROUGH THE
USE OF ULTRAVIOLET RADIATION

MASTER

FINAL REPORT

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ABSTRACT

An Ocean Thermal Energy Conversion (OTEC) system for a 10 MW power plant requires approximately 6.095×10^5 gallons of warm seawater per minute for the evaporator. Since heat exchanger surfaces lose efficiency with biofouling, it is desirable to explore methods which will reduce this condition. One such source of biofouling comes from microorganisms. To reduce or eliminate this problem it has been suggested that the seawater entering the heat exchanger be sterilized (or at least sanitized) by UV radiation at 253.7 nm. However, there are no UV units presently handling such volumes of water so the feasibility of applying this technology to OTEC has become the object of this paper. Trivial calculations based on the Lambert-Beer equation and reasonable (albeit very favorable) assumptions about seawater quality and the intensity of irradiation obtainable from a UV lamp suggest seawater may be transparent enough to a collimated beam of UV light to deliver effective germicidal doses to nearly 150 cm (5 feet) under some conditions. However, the practical limit on the depth of effective radiation from commercial lamps is severely restricted by many factors including the natural divergence of light, absorption and scattering in the media, intensity of radiation from the light source and so forth. Even under very favorable conditions a common design allowing UV light to penetrate 30 cm of water would have to permit the water at that distance to be in contact with the light for 20 seconds or so (depending on circumstances) to deliver the germicidal effect of high quality sanitization but not necessarily sterilization. Macro-fouling, which may be more severe than micro-fouling, will not be affected by UV radiation (presuming an absence of symbiotic relationships). Parasitic power required for UV sources may be prohibitive

under unfavorable conditions (i.e., unexpectedly high absorptivities of seawater, or excessive turbidity) or the absence of an industrial effort to scale up present UV equipment appropriate to OTEC needs. This latter event is unlikely for it appears that present UV lamps can be adapted to OTEC needs without major technological advancement. Power and cost estimates for UV installation and operation vary widely depending on the number of lamps needed for the OTEC configuration and the intensity of UV radiation actually required to prevent biofouling of heat transfer systems in OTEC designs. Further specific laboratory research is recommended before engineering studies are conducted to determine the economical and technical details for adopting UV irradiation technology to OTEC systems.

1.0 INTRODUCTION

The prospect of utilizing Ocean Thermal Energy Conversion (OTEC) units for large scale production of electricity is compromised by any event that reduces the efficiency of heat exchangers. OTEC units are expected to pump some 6.095×10^5 gallons per minute (gpm) of warm seawater per 10 megawatts through their heat exchangers.[58] There is concern that microorganisms will colonize heat exchange surfaces and lead to substantial decreases in efficiency and/or unacceptable head losses. It has been reported that an organic fouling deposit of 0.0025 mm (0.001 in) can reduce heat exchanger efficiencies by as much as 32 percent.[72,79,80,81,82] For these reasons it is desirable to explore the feasibility of exerting some control on seawater microorganisms that would be effective in preventing them from fouling heat exchangers.

In this respect the ideal solution would be the development of a surface inherently resistant to microbial colonization yet having acceptable thermal exchange properties, mechanical durability, and environmental compatibility. In the absence of such a technological breakthrough, it is desirable to inhibit metabolic processes of microorganisms to such an extent that significant colonization on heat exchange surfaces cannot occur. In the absence of data which might define some minimal degree of acceptable metabolic attenuation it may be necessary to assume that OTEC needs can be met only through total sterilization of seawaters.[71] Alternately it may be that less than 100 percent destruction of microorganisms (and their spores) will serve OTEC needs on a site-specific basis.

Methods for achieving desired levels of water sanitization include chemical and photometric oxidation methods. Chemical methods which have received considerable attention include ozonation (O_3) and chlorination (Cl_2) of the water. Photometric methods presently being considered include the irradiation of water with ultraviolet light (UV) at 253.7 nm.

This latter technique has never been attempted on quantities of water as large as the OTEC requirement and certainly could not be used to effect complete sterilization of those waters. However, UV electromagnetic radiation has been successful in the economic sanitization of water in many other systems including large fish hatcheries. [1,6,7,12] If seawater sanitization instead of absolute sterilization should prove to be adequate for OTEC needs the radiation intensity required for such "acceptable" treatment would be site-specific but possibly obtainable. As a practical upper limit that radiation intensity probably would not greatly exceed the radiation limit set by the Public Health Service for the sanitary control of the shellfish industry. [5,6] In fact the necessary radiation intensity would more likely be less than this limit since it has been shown that in many instances better than 99.9 percent of microorganism populations are destroyed by UV light of lessor intensity than the Public Health Service mandates. It is therefore reasonable to undertake a critical evaluation of the applicability of UV technology to OTEC requirements.

2.0 ULTRAVIOLET SOURCES

The ultraviolet spectrum generally is considered to range from 200 to 390 nm and is segmented into three convenient ranges: Long-wave, Middle-wave, and Short-wave. Long-wave ultraviolet ranges from 325 to 390 nm, occurs naturally in sunlight, and has little if any germicidal value. Middle-wave ultraviolet (295 to 325 nm) also occurs in sunlight and is responsible for certain photochemical reactions such as suntanning. It has some germicidal effect with long exposure times. Short-wave ultraviolet (200 to 295 nm) also appears abundant in sunlight, but is strongly absorbed by the ozone layer in the upper atmosphere and, therefore, does not occur naturally at the earth's surface. Short-wave ultraviolet is often referred to as the "abiotic region" because it has intense germicidal effectiveness particularly at 253.7 nm [3] (Figure 1).

Germicidal properties of UV were first documented in 1878 but practical use of this discovery could not be implemented until the advent of a practical, reliable source. The first mercury vapor lamps were invented in 1901 by Peter Cooper Hewitt and placed in service by 1910 (at Marseilles) in an attempt to disinfect municipal water supplies. [2]

2.1 SOURCES OF SHORT-WAVE ULTRAVIOLET

In practical operation there are two classifications of UV lamps: the "cold" and "hot" cathodes.

The "cold" cathode features mercury vapor in a long, cylindrical tube not unlike a common fluorescent lamp (albeit a very thin one). The mercury is at a greatly reduced pressure (10^{-3} cm of Hg or less) and the cylinder is from 1.0 (0.4 in) to 2.0 cm (0.8 in) in diameter. Since

Figure 1. Germicidal Effectiveness of UV.

The relative germicidal effectiveness of UV radiation is greatest at 253.7 nm.

TC81C04G000

ordinary leaded glass absorbs 253.7 nm UV strongly, the cylinder is made of "synthetic" or "fused" quartz where a maximum output of UV radiation is desired. If the lamp is to be submerged in water it usually comes as a unit placed within the larger, heavier cylinder of quartz which in turn provides the requisite thermal and the mechanical shielding.^{1} These bulbs tend to have acceptable operation parameters from bulb temperatures of 30 (86 degrees F) to 49 degrees C (120 degrees F) with an optimum temperature being around 40 degrees C (104 degrees F). Operating conditions imposing bulb temperatures beyond these limits greatly reduce bulb efficiencies. The "cold" cathode described above tends to be the "workhorse" of the industry.

In some designs of "cold" cathodes the inner and outer cylinders are made of optically acceptable glass. These bulbs tend to operate at higher temperatures and sometimes are called "hot" cathode bulbs even though they operate at low mercury pressures.^[2]

"Hot" cathode UV sources are more properly distinguished by their operating conditions featuring internal mercury vapor pressures up to 1 to 3 (or higher) atmospheres. Such tubes always are encased in fused quartz and operate at much higher temperatures.^[2] However, even

(1) Manufacturing techniques for suitable quartz require production in the absence of hydroxide ion (OH^-) and in silver plated furnaces (iron absorbs strongly at 240 nm).^[86] Clearly mass producing this fragile "fused" quality quartz provides an economic and technical liability.^[22] An alternate approach has been to replace at least the shielding quartz sleeve with a transparent TEFLON pipe and irradiate water flowing through the pipe by lamps arranged around the outside of this pipe.^[56]

if these lamps are immersed in the warm seawater OTEC is to use, it has been calculated that these lamps will not contribute significantly to the temperatures of that flowing water.^[18]

Other sources of UV include mercury-xenon or just xenon vapors in compact, short-arc lamphouses. These bulbs are designed more like ordinary flood light bulbs. They are rated from 500 to 12,000 W and their present design would not allow the light sources to be placed within a flowing stream of water. These lamps do not seem applicable to OTEC needs at this time.^[21]

2.2 OPERATING CONDITIONS

With appropriate design, cold and hot cathode UV lamps can operate at hydraulic pressures up to 8.5 atmospheres (125 psi)^[1] and flows up to 4.26 meters per second (14 fps).^[23] The intensity of radiation from a lamp is properly expressed in microwatts per square centimeter (uwcm^{-2}) of the lamp's surface area. Germicidal effectiveness, on the other hand is a function of both the radiant energy and exposure time and is expressed in microwatts seconds per cm^2 (uwsec.cm^{-2}). Lamp manufacturers, however, often presume that a given lamp will be used to produce 1 second exposure so they routinely rate lamp output in uwsec.cm^{-2} apparently to better correlate the lamp's output to its germicidal effectiveness in the user's mind. This admittedly incorrect (although pervasive) practice will be continued in this paper except for special discussions.

Most commercial firms surveyed provide cold UV bulbs emitting from 30,000 to 35,000 uwsec.cm^{-2} ^[1,8,22] which

seems to be a state-of-the-art optimum (if not maximum^[1]). Hot cathode lamps can emit intensities around 90,000 uwsec.cm⁻².^[7,32] The strategy used to increase the total flux of radiation from a given lamp has been to increase the length of the lamp. Available lamp lengths range from 19.0 cm (7.5 in) to 122.0 cm (48.0 in), but this too represents a state-of-the-art practical limit imposed by power requirements needed to "strike" the arc to initiate operation.^[1]

Cold cathode lamps reach full UV output almost immediately after being struck. They can be started and stopped at will, have effective lives of from 3,000 to 10,000 hours^[2] with 6,000 to 8,000 hour lives commonly reported.^[3,8,22] Hot cathode tubes (high pressure) require a glow switch starter to preheat electrodes before ignition and take more time to reach optimum intensity.^[32] They cannot be reactivated after turning off without a cooling-off period, they tend to have shorter lives (1,000 to 2,000 hours), and they require heavier ancillary equipment for operation.^[2] Furthermore, as the vapor pressure increases, a proportionately lesser percentage (down to only 7 percent) of the UV radiation emitted is at the 253.7 nm wavelength. By contrast, the cold cathode, operating at its very low pressure, emits around 85 to 90 percent of its UV energy at 253.7 nm.^[2]

Cold cathode UV sources are quite sensitive to both temperature and to a careful matching between the bulb and the (electrical) ballast. An incorrect ballast match will either reduce the UV output or shorten the life of the bulb--or both.^[1] Voltage fluctuations from 110 to 100 v can lower UV intensity as much as 22 percent. Vapor temperatures, on the other hand, of from 0 to 10 degrees C (32 to 50 degrees F) can reduce UV intensity to 26 percent

of output at 20 degrees C (68 degrees F) for lamps within quartz jackets.^[4] This latter factor will not impact on OTEC systems irradiating surface waters. Deep sea ocean waters range from an average of around 28 degrees C (surface near equator) to near zero at abyssal depths.^[73] Cold OTEC seawater is expected to run closer to 10 degrees C.

As a general rule the ratio of UV output to electrical input for cold cathode lamps runs between 1:2.2 to 1:15 (45.5 percent to 7 percent efficient respectively).^[2,3] Total input wattage rarely exceeds 200 w.^[2] The higher efficiencies tend to accrue to the larger bulbs.

When used for irradiating water, it is customary to either suspend the UV bulb above the flowing water (depth regulated by an appropriate baffle) or have the bulb immersed in the water stream. In the former case inefficiencies are necessarily introduced simply because not all light is directed toward the target. Since UV light is absorbed by air and even the surface of reflectors, it does not reflect efficiently. There is no way to deliver the entire output of a suspended lamp to the target.^[7]

Where large volumes of water are to be irradiated, the more common practice is to place the UV bulb within its quartz jacket and mount the pair axially in a steel (or other appropriate material) cylindrical chamber (Figure 2). The water flows through this radiation chamber at a rate appropriate for the radiation dose desired. Baffles may be used, especially on longer tubes, to cause water turbulence and assure complete exposure of all microorganisms to the light. Such a system is, of course, one of maximum efficiency since all UV radiation emitted by the source

Figure 2. Structure of Typical UV Radiation Chamber.

UV irradiation chambers are about as long as the UV lamp. Depth of irradiation is determined by the distance from the quartz sleeve to the chamber wall. Incidental "clouding" on the exterior of the quartz sleeve due to inorganic precipitation and so forth is removed by wiper. Lamp slips in and out without requiring dismantling of chamber. [22]

passes into the water. These flow-through modular units are commercially available in sizes up to flow rates of 1,968 liters per minute (lpm) (520 gpm).^[8,22] Large flow rates such as the 5.67×10^4 lpm (15,000 gpm) capacity at the Greenlake National Fish Hatchery in Ellsworth, Maine are obtained by placing large numbers of radiation chambers in parallel.^[8]

The design of flow-through units apparently suffers from some inherent difficulties associated with the quartz jacket.^[75] It is brittle, fragile, difficult to seal (requiring individually fitted "O" rings at either end), requires the frequent attention to anti-fouling protocol to keep the quartz jacket clean and it provides substantial resistance to flow with consequent head losses. In addition, experience has shown that flow within conventional chambers is uneven. It varies considerably from idealized plug-flow parameters used for design purposes of many systems including those of this paper. It has been estimated that at least in some cases, this latter difficulty leads to underdesigning by a factor as high as four.^[75]

An alternate approach is available in which water passing through a main is shunted through special TEFLON headers. UV lamps are mounted on either side of the headers. TEFLON is transparent to UV radiation hence the bulbs are mounted parallel to the headers but external to the water flow.^[56]

This design apparently has certain advantages (viz., less head loss, better flow, absence of quartz with its fouling-cleaning regimes, easier cleaning and some latitude in design due to simpler tooling characteristics of TEFLON).^[75] However, this technology is more recent so

its disadvantages, if any, particularly in terms of the efficiency of use of available UV light have not been documented in the general literature.

2.3 MAINTENANCE

The UV irradiation concept is readily amenable to modularization and could be designed for convenient, on-line maintenance.^[18]

Cold cathode UV lamps have less than 10 percent of their radiation in the visible spectrum. That portion of light appears as a pale, blue-violet glow. It is possible, therefore, to simply look in the vicinity of the bulb to tell if it is burned out. However, these cold cathode bulbs are able to emit visual radiation even when they have deteriorated to a point where 253.7 nm radiation has effectively vanished.^{(1)[1,2]} A maintenance schedule would require either a routine lamp replacement program or a procedure for examining bulbs with a special UV sensor which is readily available from manufacturers. This sensor can also be "built in" for continuous monitoring.^[8]

It must be noted that this wavelength of UV radiation, whether direct or reflected, is very harmful to living tissue and worker eye and skin protection would have to be rigidly enforced. Since lamp life is very long (6,000 to

(1) UV lamps do not really "burn out". After a year or so of operation the quartz of the lamp becomes "solarized" or "channelized" and more or less opaque to UV. When 35 to 40 percent of the original intensity of UV has been lost, the bulb should be changed.^[2,8] This effect is not reported in TEFLON.^[56]

8,000 hours on an average), scheduled replacement routines from 8 months to a year⁽¹⁾ should not interfere unduly with operations.^[22] Furthermore, since the lamps are separate from the quartz jacket, they can be replaced quickly by simply slipping the old one out and the new one in (time estimates for this vary from 5 to 15 minutes per lamp).^[8,18] Periodic cleaning of the quartz jacket (which is susceptible to fouling from suspended and dissolved matter) is estimated to vary from annually to "...almost continual".^[75] Simple cleansing with the built-in wiper is quick, but each wiper must be custom fit to close tolerances (an added expense)^[75] and, if misaligned, could lead to destruction of the fragile jacket. To remove, clean and reinstall a jacket takes about 15 minutes per unit.^[8,22,32,75] Units employing TEFLON headers, on the other hand, have the bulbs mounted for "convenient service" but no time estimates are given for service to either the lamp or the TEFLON headers.^[56]

Biofouling by macroorganisms, particularly in seawater, presents a more serious maintenance problem. Larval shellfish, barnacles, and so forth can enter these UV systems and affix themselves to the container walls by a polysaccharide slime.^[30] These organisms would not be affected by the UV light. In fact, they may attach themselves directly to the quartz jacket or the TEFLON

(1) There is some feeling that hot cathodes would be better than cold cathodes, especially in conditions of high turbidity.^[7,18] If so, the shorter life (around 3 months) of the hot cathodes would obviously alter maintenance schedules.

header. Since the only effective way to remove these strongly adhering organisms is through mechanical methods, a significant loss due to breakage, especially of quartz jackets, can be expected. Furthermore, even the successful removal of these organisms from the quartz jacket or TEFLON header would not assure a return to full efficiency. These organisms use a powerful organic adhesive to affix themselves to any surface. Residues of this glue are bound to be left behind after cleaning and should be expected to absorb at least some portion of the UV radiation. In passing, it would be noted that one "advantage" to using hot cathodes would be the more frequent maintenance requirement and, therefore, the more control exerted on the colonization attempts of the macroorganisms.

Experience with large volume flows in conventional, water-cooled facilities, has shown repeatedly that very large objects can bypass protective screening. Certainly, screening of OTEC waters will be necessary, but penetration is to be expected resulting in breakage of quartz jackets and bulb destruction.^[18] It has been estimated that over a 20-year period each set of quartz jacket with lamp will be broken at least once.^[18]

2.4 COSTS

Since there is no currently operating unit irradiating flows anywhere near 609,500 gpm, costing becomes extremely speculative. It is entirely possible that a viable OTEC program would trigger an industrial response to build units more in proportions to OTEC needs hopefully with corresponding cost reductions. The information gathered in Table 1 represents data available on the biggest units reported in the literature.

Table 1: UV Requirements to Treat Seawater for OTEC: 6.095×10^5 gpm warm seawater, absorptivity is 0.0044 cm^{-1} , no significant organics or turbidity, irradiation $16,000 \text{ } \mu\text{wsec.cm}^{-2}$.

Items	Hot Cathodes	Cold Cathodes			
	Hydranautics ⁽¹⁾	Aquafine ⁽⁶⁾	Sanitron ⁽⁶⁾	UV Purif. Systems, Inc.	Hypothetical Design ($a=0.001 \text{ cm}^{-1}$)
Lamp life, days	90	333	313	365	365
Type of lamp		CSL-24R/60	GX48VZ	G36T6L	
Length of lamp, cm (in)	196 (77)	163 (64) ⁽⁵⁾	122 (48)	152 (60)	122 (48)
Lamp output of UV, $\mu\text{wsec.cm}^{-2}$	23,000	>33,000	>30,000	>30,000	>30,000
Depth of water per lamp, cm (in) ⁽²⁾	83.8 (33)		15 (6)	3.8 (1.5)	63 (25)
Number of lamps needed ⁽³⁾	9 (Append. 8.4)	28,200	14,643	50,750	729 ^(a)
Power Consumption per lamp, w ⁽⁴⁾	15,000	83 ^(b)	140 ^(b)	65 ^(b)	75 ^(b)
Total power used, all lamps, MW	.336 or 0.149 (Append. 8.4)	2.34	2.05	3.3	0.055

Footnotes for Table 1:

1. This study did not consider illuminance decrease with distance from the source, only effect of absorptivity assuming seawater $a = 0.0044 \text{ cm}^{-1}$. Therefore the data in this column are not comparable to the rest of the data.
2. Either optimum depth from calculations is used or apparent depth as calculated from data given for in-service units.
3. Number calculated from estimated number of units OTEC would require from in-service units except where marked with (a).
4. May not account for ballast lost except where marked with (b).
5. This length is assumed based on overall length of unit.
6. Calculations based on in-service units not suitable to OTEC but presumed to be used off-the-shelf anyway.

It is extremely important that Table 1 be read with great caution. The numbers do not reflect real possibilities which may come from an operating system. The numbers only summarize and extrapolate from presently available information.

2.5 ENVIRONMENTAL AND TECHNICAL CHARACTERISTICS

Ultraviolet treatment produces no residual effects in unpolluted seawaters^[1,18] nor does it enhance normal corrosion rates (in fact with bacterial removal those rates may be reduced). There is no such thing as an "overdose" and the evidence suggests that UV effectiveness is immediate.^[2]

Ultraviolet radiation does cause deterioration of rubber, plastic, and other organic components often employed for seals. Screening of the water is necessary and good transmission characteristics of the water must be maintained (i.e., very low in organics and reasonably free of turbidity). Routine cleaning of the quartz jacket (or TEFLON header) is necessary. UV has no effect on inorganic components of the water; if conditions are right for their deposition, UV will not prevent their precipitation. Similarly, UV is not particularly effective in controlling slimes or organisms much larger than about 0.4 micron.^[2]

3.0 CHARACTERISTICS OF UV RADIATION

3.1 DISINFECTION

It has been known since the work of Downes and Blunt in 1878 that UV radiation has germicidal powers.^[1,2] Microbial organisms (<30 microns) have been found to be particularly susceptible to adverse effects under radiation at 253.7 nm (Figure 1).^[1,3,25] At shorter wavelengths

there seems to be a minimal effect between 230 to 240 nm, then a gradually increasing effect. At wavelengths greater than 253.7 nm germicidal properties drop precipitously.[4] More recent research has shown that viral organisms also are destroyed by radiation in the 250 nm range.[2] Under certain circumstances even larger organisms such as paramecia (200 microns) have been destroyed by 250 nm UV radiation.[1]

The destruction of microorganisms under UV radiation follows simple first order kinetics so long as the threshold dose has been administered.[24] The exponential equation expressing this event is:

$$N = N_0 e^{-Et/Q} \quad (\text{eqn. 1})$$

where N = average number of organisms surviving
 N_0 = original number before irradiation
 E = intensity (more correctly, scalar irradiance) of UV energy impinging on microorganism (uwsec.cm⁻²)
 t = time of exposure in minutes
 Q = threshold lethal exposure for given microorganism (generally Q is set equal to 2,400 uwsec.cm⁻²)[4,75]

Microorganisms vary considerably in their response to UV radiation. Even a partial list includes B. Megatherium sp. (spores) which suffer complete destruction at 5,200 uwsec.cm⁻² to Sarcina lutea which requires some 26,400 uwsec.cm⁻² for total destruction. Yeasts may require upwards to 17,600 uwsec.cm⁻², mold spores as high as 330,000 uwsec.cm⁻² (Tobacco mosaic) and protozoan up to 200,000 uwsec.cm⁻² (Paramecium) for complete destruction.[8,87] However, Escherichia coli (100 percent

destruction at $6,600 \text{ uwsec.cm}^{-2}$) has been reported to have a greater resistance to UV radiation than most waterborne enteric pathogens.^[4] As a general rule, most bacteria are destroyed by radiation from 6,000 to 13,000 uwsec.cm^{-2} .^[8] Out of these considerations the U.S. Public Health Service has required that a minimum UV dosage for water sanitization, offering appropriate safety factors, be $16,000 \text{ uwsec.cm}^{-2}$ at 253.7 nm.^[2]

It is significant to note that the exponential character of equation 1 prevents N from reaching zero. This emphasizes the fact that 100 percent sterilization is not an attainable goal for UV radiation in any realistic design for OTEC or any other application where time (t) can not approach infinity.

The exact mechanism(s) leading to the death of an organism through UV radiation is unknown. However, it is reasonable to assume that lethal de-couplings of nucleic acid chains in either (or both) DNA and RNA molecules occur.^[2,23,76,77]

Explicit information on the organisms likely to be "seen" by an OTEC system is not available. Extensive surveys of deep sea microorganism populations, however, have been conducted by the Soviets.^[60,61] They have systematically sampled to depths of 5,000 m routinely and 7,000 to 8,000 m on occasion in all oceans. Their data are correlated with both latitude and longitude and list eighteen nonsporing rods (with numerous varieties of each) including Bacterium, Pseudomonas, Vibrio and Pseudobacterium; twelve spore forming (with many varieties) Bacillus; twenty-one Cocci (with many varieties), species of Micrococcus; five Mycobacterium species (with varieties), Actinomycetes globisporus, Proactinomycetes

albus, and 12 species of yeasts (with varieties).^[60] The maximum densities of these microorganisms occurred at the surface (0 to 25 m) where photosynthesis takes place and populations reached more than 100,000 organisms per ml. As deep as 250 m populations of microorganisms averaged 10,000 microorganisms per ml. Below 300 m and down down to 4,000 m only a few hundreds to a few thousands/ml were reported. At "very deep" limits this population is reported to be less than 10 per ml.^[60,61] As expected, populations at any depth generally are greater in tropical waters.

However, it was not possible to identify from the literature those specific organisms which might be expected to interfere with OTEC operations. Furthermore, there were no references helpful in determining the susceptibility of these (or other) marine microorganisms to UV light. Where reports are given on microorganism destruction by UV light, the target organisms generally are either shoreline or estuary pathogens or organisms originating in non-marine environments. Therefore, for lack of more appropriate information, it will be assumed for the rest of this paper that every marine microorganism may impact unfavorably on an OTEC heat exchanger and that marine microorganisms are at least as susceptible to destruction by UV light as those organisms that are reported. To this end the subjective judgement will be made that a dose of $16,000 \text{ uwsec.cm}^{-2}$ UV radiation at 253.7 nm will adequately sanitize OTEC waters prior to their flow through the heat exchangers. Of course it is possible that this dose may not be adequate, particularly if troublesome organisms are spore forming, and certainly not if complete sterilization is mandated. However, once the appropriate data have been collected and analyzed, a more objective value for the dose can be substituted. That in turn can be evaluated in terms elaborated upon throughout the remainder of this paper.

3.2 TRANSMISSION IN WATER

The transmission of a collimated beam of electromagnetic radiation through a transparent media is described by the relation commonly known as the Lambert-Beer Equation:⁽¹⁾

$$P = P_0 e^{-bk} \quad (\text{eqn. 2})$$

where P = radiant power (or intensity) of
transmittal radiation (uwcm^{-2})
 P_0 = radiant power (or intensity) of radiation
at the source (uwcm^{-2})
 k = "index of absorption" or "absorption
coefficient" such that

$$k = (4\pi k' n) / \lambda$$

where k' = index of absorption (a constant for
any given media)
 n = index of refraction of media
 λ = wavelength in vacuum of incident
radiation [9,10]
 b = distance collimated beam of light travels
through a media (in cm)

It is informative to note that temperature is not a variable here and hence temperature fluctuations are not pertinent factors.

(1) Terms and symbols used here are consistent with those specified by the Joint Committee on Nomenclature in Applied Spectroscopy established by the Society for Applied Spectroscopy and the American Society for Testing Materials. Equivalent terms used in older publications are reviewed in Appendix A.

Rearranging equation (2) and substituting identities gives:

$$\ln(P/P_0) = 2.303 \log_{10} (P/P_0) = -kb \quad (\text{eqn. 3})$$

$$\text{hence } \log_{10} (P_0/P) = kb/2.303 = \text{Absorption} \quad (\text{eqn. 4})$$

$$\text{but } \frac{k}{2.303} = a = \text{absorptivity} \quad (\text{eqn. 5})$$

$$\text{hence Absorbance (A)} = \log_{10} (P_0/P) = abc \quad (\text{eqn. 6})$$

where c = molar concentration ($c = 1$ when working with a pure solvent) and (a) and (b) retain their previous definitions (equations 2 and 5).

Clearly the larger the value for absorptivity for a given media the greater the opacity of that media to the particular radiation.

The absorptivity for UV radiation of aqueous systems varies markedly throughout the literature, indicating that it is not the nature of water per se that affects the transmission of this light. In fact water is a useful solvent for UV analyses from 200 to 380 nm.^[16] A spectral scan of seawater from 175 to 300 nm (Figure 3)^[3,83,85] shows an absorption maxima extending from about 180 to 225 nm (peaking at approximately 212 nm where the absorptivity = 1.4 cm^{-1}). This peak is believed to be due to bromine, nitrate, and some organics.^[3,11,12] Iron (both Fe^{2+} and Fe^{3+}) absorbs UV strongly in concentrations from 1 PPM (in the 650-660 nm range)^[62] to greater than 4.8 PPM (at 253.7 nm).^[4,6] Such iron concentrations are not characteristic of seawaters although could perhaps occur around iron vessels or through the use of large iron conduits. At

Figure 3. UV Absorbance with Variations in Wave Length.

A spectral scan of the Absorbance (A) of UV radiation in seawater shows a maxima around 220 nm but barely more than that of double distilled water at 253.7 nm, the wavelength of germicidal effectiveness.

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253.7 nm the absorptivity of seawater is hardly distinguishable from that of double distilled water^[11] which has a maximum absorbance at 167 nm^[16] but absorbs only about 4 percent of the UV light at 3 cm at 257 nm^[62] (up to 51 percent at 45.72 cm (Figure 4)^[74]). This high transmissibility of 253.7 nm radiation in seawater is reported in many sources.^[12,14,15] In fact there is some evidence that in the blue-violet end of the spectrum, clearest oceanic waters appears to be more transparent than double distilled water.^[63] This is decidedly untrue of coastal waters where water soluble yellow pigments (mostly from rivers^[63]) absorb the shorter wavelengths more strongly,^[64,69] in waters where high turbidity of tropical or subtropical oceanic waters are encountered and in temperate oceanic waters.^[63] Color of water is a factor in UV light transmission albeit poorly documented.^[4,78] One author reported that inorganic color from 90 to 150 PPM posed no interference.^[6]

Of course UV spectroscopists have long used the 250 nm region (200 to 480 nm) for characterizing certain organic molecules precisely because those organics, particularly aromatics, absorb strongly in that region (Figure 5). UV absorption characteristics of organic molecules depend on the electronic transitions that can occur and the effect (particularly coupling events) on the electron environment caused by the transitions.^[16] In this respect it is consistent for microorganisms also to absorb strongly in this region, which indeed they do.^[3] It would appear that the single greatest factor influencing the absorptivity (at 253.7 nm) in natural seawaters is the presence of certain organics. There is a clear correlation between the availability of organics in water and the reported absorptivities (Table 2), and there is a corresponding significant difference in UV absorption

FIGURE 4. Transmission of UV Light Through Various Depths of Distilled Water. [74]

The transparency of distilled water to 257.3 nm light varies from approximately 98 percent to 63 percent for optical paths ranging from 2.54 cm to 45.72 cm respectively.

FIGURE 5. Absorbance of UV by Organic Compounds.

The UV absorption of organic molecules (particularly conjugated systems) is very strong on the 250 nm region.

Table 2. Absorptivities of Natural Waters at 250 nm:
Absorptivities (a) reported for various natural seawaters
at 250 nm range from 0.0 cm^{-1} to 0.143 cm^{-1} .

Source of Water Sample	Absorptivity (a) (cm^{-1})	Ref.
North Pacific Offshore Water	0	17
Tokyo Bay	0.08 (avg)	17
Sagami Bay	0	17
Minamata Bay	0.02 (avg)	17
Seawater	0.0044	23
England Rivers	0.143 to 0.0008	2
River Waters	0.2, 0.04, 0.02, 0.01	12
Fish Hatchery Waters	0.1	8
"Clear Seawater"	0.028	11
Atlantic Surface Water	0.016	26
2 Kilometer Depth (Seawater)	0.011	26
Irish Sea Water	0.025	26
Seawater Near Bridge Pier	0.019	12

between open seawater and off-shore waters (Figure 6) due to volatile organics in the water. [17,19,27] However, the organics in natural deep sea waters, while present in prolific varieties of molecules, are in concentrations of from only 10^{-6} to 10^{-9} g/l requiring concentrations of from 10^3 to 10^5 times just to study. [66] Some representative values are given in Table 3. Considering oceanic water absorptivities documented elsewhere in this paper, these natural organics alone apparently are not significant to the proposed use of UV light in OTEC systems.

Some theoretical penetrability studies for a collimated beam of 253.7 nm radiation through media of absorptivity ranging from 0.1 to 0.2 cm^{-1} are given in Figure 7 and for absorptivities of 0.0044 to 0.04 cm^{-1} in Figure 8. Since most commercial UV lamps are made to produce radiation at around $30,000 \text{ uwsec.cm}^{-2}$ it is clear from Figures 7 and 8 that a collimated beam from such lamps would deliver the requisite $16,000 \text{ uwsec.cm}^{-2}$ to a range of at least 140 cm (4.6 feet) through seawater under favorable conditions. This is approximately 53 percent transmission at 250 nm --an interesting number when compared to data indicating that light of 310 nm (the shortest wavelength reported) has a normal transmission value of 86 percent per meter for the first 10 meters in clear oceanic water. [70] Extrapolation of those data suggest that if the absorption curve is not unduly pertubated between 300 to 250 nm, the transmission value should be around 65 to 70 percent per meter at 250 nm. The presence of certain organics in the water (e.g., from spilled petroleum or its products, for example), may decrease this optimum range precipitously. However, since the radiation from long, cylindrical UV lamps is not collimated, the radiation diverges and the radiant intensity delivered at any point is markedly less than that predicted by the Lambert-Beer expression. This

FIGURE 6. Variation of Absorbance of UV with Source of Seawater.

The Absorbance (A) of various wavelengths of UV radiation by seawater differs both by source of seawater and wavelength.

Table 3. Representative organics and their concentrations in marine waters.

Source of Water	Organic Compound	Concentration
"clean" Oceanic Water [67]	Methane (CH_4)	49.5 nl/l
	Ethane (C_2H_6)	0.5 nl/l
	Propane (C_3H_8)	0.34 nl/l
	"Aromatics"	33 ng/l
	Trichlorofluoromethane (CCl_3F)	$7.6 \pm 7.2 \times 10^{-12}$ vol/vol
	Iodomethane (CH_3I)	$135 \pm 248 \times 10^{-12}$ vol/vol
	Carbotetrachloride (CCl_4)	$60 \pm 17 \times 10^{-12}$ vol/vol
Sargasso Sea [68]	Hydrocarbon (surface)	2.8 ± 0.6 ug/l
	Hydrocarbon (2,000-4,427 m)	0.0
	Aromatics	1 ± 1 ug/l
Gulf of Mexico [68]	Hydrocarbons (surface)	29.3 ± 11.9 ug/l
	Hydrocarbons (500 m)	7.3 ± 3.8 ug/l

FIGURE 7. Penetration of UV in Slightly Transparent Seawater as Predicted Solely by Lambert-Beer Law.

The calculated optical path through seawater needed to reduce 253.7 nm UV light to $16,000 \text{ uwcm}^{-2}$ depends on the intensity of the lamp and the absorptivity of the seawater.

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FIGURE 8. Penetration of UV in Highly Transparent Seawater as Predicted Solely by Lambert-Beer Law.

The calculated optical path through seawater needed to reduce 253.7 nm UV light to $16,000 \text{ uwcm}^{-2}$ does not exceed 270 cm (106 in.) even when lamp intensities reach $50,000 \text{ uwcm}^{-2}$ and seawater absorptivity is 0.0044 cm^{-2} .

phenomenon is reviewed in detail in section 3.4.

3.3 EFFECT OF TURBIDITY

Before microorganisms can be destroyed by UV radiation they must be exposed to a given intensity for a requisite period of time. Since matter causing turbidity is large (>40 microns) compared to microorganisms, it is reasonable to assume that a certain percentage of microorganisms will survive a radiation protocol simply by "hiding" in the shadow of particulates. Even severe turbulence within the stream cannot assure adequate exposure for all microorganisms under conditions of high turbidity.

Turbidity produces a certain light scattering which is independent of turbulence. Rayleigh's well-known formula for incoherent scattering is:

$$\text{scattering power} = (8 \pi N e^4) / (3 m^2 V_o^4 \lambda^4) \text{ (eqn. 7)}$$

N = number of dipoles per unit volume

e = the electronic charge

m = electronic mass

V_o = natural frequency of the oscillating dipole
(normally well into the ultraviolet region)

λ = wavelength of the incident light

While this expression is applicable only when $(V_o/V)^2 \gg 1$ (where V = frequency of incident radiation), Rayleigh's equation can be used to estimate the extent of scattering of short wavelength radiation. If $\lambda = 253.7$ nm, V will be relatively high and the scattering power will be significant although less than that for, say, blue light. When $(V_o/V)^2 \ll 1$ the scattering formula becomes Thompson's Scattering Formula:

$$\text{scattering power} = (8 \text{ Ne}^4)/(3\pi^2 c^4) \quad (\text{eqn. 8})$$

where c = speed of light.

Such conditions occur only when using irradiation in the X-ray region and represent an extreme which is irrelevant to OTEC.^[9]

The attenuation () of collimated light due to back scattering alone has been shown to pass through minima well into the visual region (500 to 600 nm) for distilled water, bay-coastal waters, and oceanic waters.^[84] From those data it is clear that forward and backward scattering, particularly in waters rich in plankton, will have some affect on the depth of penetration of 253 nm ultraviolet light. However, radiant losses due to scattering probably are minor (in terms of bacterial survival) compared to the effect of turbidity. That, in turn, is difficult to evaluate since work done in this area is reported with a wide range of variability in methodology and measurement standards. A rough summary of related results in this area is given in Table 3.

Experience has shown that turbidities below 10 JTU are not likely to be significant in the OTEC systems.^[4,20] If higher turbidities are encountered in OTEC seawaters it may be necessary to plan for more UV sources in the stream flow. The exact number of additional units needed would depend on a site-specific evaluation.

It should be noted that in-stream gas bubbles are usually too large for Rayleigh-Scattering applications. The geometry of most bubbles, along with the refractive indices of gases (which usually are very different from that of water) produce a system which is, at best, only

Table 4. Effects of Turbidity on the Survival of Microorganisms: Turbidities in excess of 40 JTU, reduce the effectiveness of UV radiation in destroying micro-organisms.

Turbidity		Light Intensity ($\mu\text{wsec.cm}^{-2}$)	Exposure Time	Reported Survival	Ref.
JTU	PPM				
	20			Max. 12% reduction in coliform survival (highest density = 0.2 MPN/100 ml)	6
411		25,000	120 sec.	Coliform kept to 70 MPN	20
130		"Hot cathode"	16 l/min.	Bacterially acceptable	7
		"Cold cathode"	18 l/min.	Bacterially acceptable	7
43 to 82				"Turbidity becomes critical"	7
45				No effect on survival	4

that of water) produce a system which is, at best, only translucent and of indeterminate value for sterilization of water by UV irradiation.

3.4 LUMINOUS INTENSITY

As light passes through a given media (other than a vacuum) its intensity (or flux per unit area) in the direction of light propagation is subject to attenuation through a variety of factors such as dispersion, reflection, interferences, diffraction, absorption, and scattering. Of these only absorption and scattering have potential significant to the immediate discussion on OTEC applications. Those are addressed in sections 3.2 and 3.3 of this paper.

Ordinary light (i.e., noncoherent and noncollimated light) also decreases its intensity with distance according to the well-known inverse square law [9]:

$$E = (P_0 \cos \theta) / (r^2) \quad (\text{eqn. 9})$$

where E = the illuminance (i.e. flux per unit area)
falling on a surface

P_0 = radiant power at the source (uwcm^{-2})

θ = angle at which the light ray strikes the
surface

r = distance between the source and the
surface (cm)

Strictly speaking the inverse square law applies only to a point-source of radiation, a condition not met in the long UV lamps OTEC would be likely to use.

A more useful approximation for OTEC would be to consider the UV lamp as made up of increments of an infinite number of minute, cylindrical lamps. For a given increment (Figure 9), assume there exists a light disk of radius (r_2) lying perpendicular to the lamp. This disk is of finite thickness, Δt . Light from the source (the center of the disk) of intensity P_0 will be lost in all directions (θ) off the plane of the disk, but for the purposes of this approximation it will be assumed that such losses will be effectively recouped from radiation lost by neighboring increments. The radiant flux (F) emitted from the surface area of the lamp of radius (r_1) in the plane of the disk will emit a radiation intensity per unit area in a vacuum given by:

$$P_0 = \frac{F}{2\pi r_1 (\Delta t)} \quad (\text{eqn. 10})$$

The radiation intensity per unit area at the edge of the disk of radius (r_2) will be caused by the same flux (F) and is expressed by:

$$P = \frac{F}{2\pi r_2 (\Delta t)} \quad (\text{eqn. 11})$$

Combining equations 10 and 11 and simplifying produces:

$$P = \frac{r_1 \times P_0}{r_2} \quad (\text{eqn. 12})$$

where P is the approximate intensity of radiation per unit area delivered onto the disk's edge ("A" in Figure 9).

However, in an OTEC system, that light will have traversed a media of absorptivity (a) and suffered an

FIGURE 9. A Model for the Variation in Light Intensity with Distance from a Nonpoint Source.

Light from a thin cylindrical UV bulb will spread over an area (A) at a given distance (r_2) and be diminished in intensity in proportion to that area.

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attenuation of intensity due to divergence of the non-collimated beam. Other factors, such as scattering and organic matter, also will act to decrease light intensity at any given point in the media. These latter factors are comparatively minor, however, and will not be considered in the following comments.

The function of the light intensity (P) at a distance of $(r_2 - r_1)$ cm from the surface of the lamp is given by equation 12. The incremental decrease in light intensity with (r_2) is given by:

$$dP/dr_2 = - P_0 r_1 / r_2^2 = - P^2 / (r_1 P_0) \quad (\text{eqn. 13})$$

The affect of absorption (eqn. 2) over the same incremental distance is given by:

$$dP/dr_2 = - P_0 K e^{-K(r_2 - r_1)} = - KP \quad (\text{eqn. 14})$$

Hence the total amount of light absorbed over the distance increment becomes:

$$dP/dr_2 = (-P^2/r_1 P_0) - KP = -P[(P/r_1 P_0) - K] \quad (\text{eqn. 15})$$

Integration of equation 15 gives:

$$\frac{1}{K} \ln \frac{P}{(P/r_1 P_0) + K} = -r_2 + C \quad (\text{eqn. 16})$$

Since each increment is in effect, the source of light for the succeeding increment, the value for the integration constant is given by setting $P = P_0$ which requires, in turn, that $r_2 = r_1$. Hence:

$$C = r_1 + \frac{1}{K} \ln \frac{P_0}{(1/r_1) + K} \quad (\text{eqn. 17})$$

Substitution and solving:[60]

$$\frac{P}{P_o} = \frac{Kr_1 e^{-K(r_2-r_1)}}{Kr_1 + 1 - e^{-K(r_2-r_1)}} \quad (\text{eqn. 18})$$

From equation 18 it can be shown that the ratio (P/P_o) decreases exponentially through a medium of $a = 0.001 \text{ cm}^{-1}$ as given by the curve of Figure 10. The most significant loss of light intensity (around 95 percent) occurs within 20 cm from the center of the lamp, being about 3 percent less loss at any given distance for 2 cm radius lamps than 1 cm radius lamps (Figure 11). A media absorptivity of 0.0044 cm^{-1} produces P/P_o ratios of only approximately 4 percent greater value at each point from the lamp.

If the presumption is that the chamber wall is to receive a $16,000 \text{ uwcm}^{-2}$ dose, then the effective radius of the chamber for lamps of different radii, media of various absorptivities and lamps of different intensities can be determined. Sample values are given in Table 5.

3.5 ESTIMATING NEEDS FOR OTEC

An OTEC unit irradiating water flowing past a UV lamp may be forced to use a number of lamps in series to obtain the requisite dose per unit of water. This may be necessary since the effective dose is a function of both illuminance and exposure time and, from the discussion of section 3.4, clearly illuminance will be less at the wall of larger diameter jackets than the (arbitrary) $16,000 \text{ uwsec.cm}^{-2}$ dose. Only by increasing the number of lamps the water flows past can the required dose be obtained.

FIGURE 10. Decrease of Light Intensity with Distance from Lamp.

The intensity of a non collimated beam of light decreases exponentially along the optical path as a function of media absorptivity, source intensity and lamp size.

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FIGURE 11. Ratio of Incident Light to Original Light Intensities at Different Distances from the UV Source.

The loss of light intensity along a 20 cm optical path amounts to approximately 94 percent and 97 percent for sources of 1 cm and 2 cm radius respectively.

Table 5. Distance light travels through different media to reach an intensity of $P=16,000 \text{ uwcm}^{-2}$ from various lamps.

Lamp Intensity (P_0) uwcm^{-2}	P/P_0	Distance (cm) from lamp perimeter to jacket wall			
		$a=0.02 \text{ cm}^{-1}$		$a=0.0044 \text{ cm}^{-1}$	
		lamp radius=2 cm	1 cm	2 cm	1 cm
20,000	0.80	0.45	0.23	0.48	0.24
40,000	0.40	2.55	1.36	2.83	1.44
60,000	0.27	4.39	2.40	5.06	2.58
80,000	0.20	6.22	3.46	7.39	3.80

Let the flow be through irradiation chambers (having one UV lamp per chamber) of radius (r_x cm) as determined necessary to deliver a radiation of (P uwsec.cm⁻²) to the container wall from a lamp of intensity (P_o uwsec.cm⁻²) through a media of absorptivity (a cm⁻¹). Let the length (L cm) of each chamber be equal to the bulb length. Assume the most conservative scenario in which water to be irradiated moves as an ideal plug flow parallel to the wall of the irradiation chamber and the required irradiation dose is to be delivered to the laminar flow on the chamber wall.

If the entire seawater flow (Q cm³/sec) to be handled is known, it would take

$$\frac{Q \text{ cm}^3/\text{sec}}{V \text{ cm}^3/\text{chamber}} = Q \text{ cm}^3/\text{sec} \times \text{chamber}/V \text{ cm}^3 = Q/V \text{ chambers/sec}$$

to contain that flow for 1 second. If the desired disinfectant radiation is (P_r uwsec.cm⁻²), the radiation received at the wall of any chamber would only be (P/P_r) the desired radiation, so the total number of chambers, in series, which a given unit of water would have to pass through would be (P_r/P). If the retention time for each irradiation chamber is (n sec) the total number of UV bulbs required becomes:

$$N \text{ lamps} = \frac{1 \text{ lamp}}{\text{chamber}} \times \frac{Q \text{ cm}^3}{\text{sec}} \times \frac{\text{chamber}}{V \text{ cm}^3} \times \frac{P_r \text{ uwsec.cm}^{-2}}{P \text{ uwsec.cm}^{-2}} \times \frac{n \text{ sec}}{1} \quad (\text{eqn. 19})$$

Example:

$$\begin{aligned}
 \text{Let } Q &= 6.095 \times 10^5 \text{ gal/min} = 3.85 \times 10^7 \text{ cm}^3/\text{sec} \\
 P_r &= 1.6 \times 10^4 \text{ uwsec.cm}^{-2} \\
 n_r &= 1 \text{ sec} \\
 P &= 1,771 \text{ uwsec.cm}^{-2} \quad (P_o = 30,000 \text{ uwsec.cm}^{-2}; \\
 &\quad \text{lamp radius} = 1.27 \text{ cm}; a = 0.001 \text{ cm}^{-1}; \\
 &\quad \text{ref. 9}) \\
 r &= 21 \text{ cm} \\
 L &= 122 \text{ cm} \\
 V &= \pi r^2 L - \pi (1.27^2) L = 1.6832 \times 10^5 \text{ cm}^3
 \end{aligned}$$

$N = 2,066$ lamps, where each lamp is in an irradiation chamber and there are (P_r/P) chambers linked together in series to form a unit for a total of (NP/P_r) units per OTEC system (e.g., in this example there would be 9 chambers per unit and 228 units per 10 MW OTEC system).

Although the above sample calculation assumed extremely favorable conditions (ideal plug flow characteristics, very low absorbtivity ($a = 0.001 \text{ cm}^{-1}$), no organics or scattering, 21 cm radius chamber, 1.27 cm radius lamp with its protective jacket⁽¹⁾) the value of

(1) This assumption about the lamp and jacket is not inconsequential. If, for example, the quartz jacket is 3.5 cm in diameter, the volume it occupies in a 21 cm radius irradiation chamber is only about 0.7 percent of the total chamber volume. However, the value for (r_1) in equation 10 (and following) becomes effectively equal to the radius of the jacket (e.g., the jacket acts as the radiant source for calculation purposes). This, in turn, alters the distance of effective light penetration and the optimum radius for the irradiation chamber. Furthermore, as the lamp ages the effective radiant flux decreases. This alters the distance of effective light penetration and the optimum radius of the irradiation chamber. Such factors would have to be evaluated carefully in a design phase.

2,066 lamps can be considered as some reasonable estimate of the number of UV lamps such a 6.059×10^5 gpm OTEC might need. The physical arrangement of this system would include a bank of 9 chambers, connected in series, each chamber having an effective volume of $168,320 \text{ cm}^3$ (44.5 gal) and a retention time of 1 second. There would be a total of 230 such banks of chambers servicing the unit. Assuming 75 watts per lamp (with ballast) this arrangement represents a parasitic loss of 1.55 percent from a 10 MW operation.

3.5.1 Minimum Requirements for OTEC

While the above solution illustrates a technically feasible arrangement for seawater irradiation in a 10 MW OTEC system, it is useful to explore the theoretical limits permitted by this approach. The obvious departure point here is to consider the consequences of expanding the girth of the irradiation chamber. Since the radiant flux on the chamber wall never reaches zero (Figure 12), chamber expansion should lead to some reduction in lamp requirements.

By solving equation 19 for systems of varying chamber radii it can be shown that the calculated number of UV lamps required does decrease to a point but then passes through a minimum and increases rapidly thereafter (Figure 13).

It must be understood that the calculated value for the required number of UV lamps is driven by both the volume of the container and the light intensity delivered onto the chamber wall (eqn. 19). This latter is, in turn, a function of the absorptivity of the media. If absorptivity is particularly low, there is a point along

FIGURE 12. Chamber Wall Irradiation Dose Relative to Chamber Volume.

After approximately 35 cm the radiant dose received by the chamber wall decreases much more slowly (on radius increase) than the chamber volume increases.

FIGURE 13. Lamp Requirements and Chamber Arrangements for a 10MW OTEC System ($a=0.001 \text{ cm}^{-1}$).

For media of very low absorptivity the calculated minimum number of lamps is dictated by the number of units in series required for adequate irradiation.

the continuum where the influence of increasing volume exerts an unrealistic influence on the calculation. Thus at the radius of 700 cm through a media of $a = .001 \text{ cm}^{-1}$ the calculated minimum number of lamps required is 150 (Figure 13). However, the light delivered to the chamber wall would be only 22 uwcm^{-2} requiring a minimum of 727 chambers (each with one lamp) in series to deliver the requisite $16,000 \text{ uwsec.cm}^{-2}$. Clearly, in this case, the minimum number of required chambers in series (196) dictates the true minimum number of lamps required (Figure 13). In media of greater absorptivity this particular problem does not appear (Figures 14, 15). In those cases the minimum number of lamps required occurs at chamber radii of 69 ($a = 0.01 \text{ cm}^{-1}$) and 8 cm ($a = 0.1 \text{ cm}^{-1}$) where only 71 and 10 chambers in series respectively are needed to deliver the $16,000 \text{ uwsec.cm}^{-2}$ to water moving along the chamber wall.

The power requirement for the example given above is calculated on the assumptions that the arc length for each lamp is 122 cm, the radius of the jacket/lamp assembly is 1.27 cm, light intensity at 253 nm at the jacket surface is $30,000 \text{ uwcm}^{-2}$ and the lamp assembly (including ballast) operates at 40 percent efficiency. Thus the 196 lamps would consume 73 watts/lamp or 0.14 percent of the output from a 10 MW OTEC power plant if water absorptivity = 0.001 cm^{-1} . For a less ideal situation ($a = 0.01 \text{ cm}^{-1}$) power requirements to operate the 1,500 lamps (Figure 14) would consume 1.07 percent of a 10 MW output. Parasitic losses would amount to 11.2 percent of a 10 MW output (Figure 15), where $a = 0.1 \text{ cm}^{-1}$.

It is distinctly possible that factors other than those considered here may interact to influence costs and/or design. It is informative to note that calculated

FIGURE 14. Lamp Requirements and Chamber Arrangements for a 10MW OTEC System ($a=0.01 \text{ cm}^{-1}$).

A calculated minimum of 1,500 lamps in 69 cm radius chambers with 71 chambers in series for each unit are required for irradiating OTEC waters ($a=0.01 \text{ cm}^{-1}$) at $16,000 \text{ uwsec.cm}^{-2}$.

FIGURE 15. Lamp Requirements and Chamber Arrangements for a 10MW OTEC System ($a=0.1 \text{ cm}^{-1}$).

A minimum of 14,946 lamps in 8 cm radius chambers with 10 chambers in series for each unit are required for irradiating OTEC waters ($a=0.1 \text{ cm}^{-1}$) at $16,000 \text{ uwsec.cm}^{-2}$.

parasitic power losses due to the operation of UV lamps ($30,000 \text{ uwcm}^{-2}$, $a = 0.001$, radius of lamp = 1.27 cm) decreases most rapidly for chamber radii from 9 cm (3.53 percent) to approximately 50 cm (0.66 percent) and much more gradually thereafter to 317 cm (0.14 percent) (Figure 16). Thus chamber radii of between 49 cm (912 lamps) to 317 cm (196 lamps) may be acceptable depending on other design considerations. One such point may be at chamber radii of about 63 cm where the number of chambers in series (27) equals the number of sets of chambers required (Figure 17). This configuration requires 729 lamps and draws 0.52 percent parasitic power.

For a somewhat broader perspective it is informative to examine simultaneously the influence of lamp intensity, seawater absorptivity, and required chamber wall dose on both the number of lamps required and the percent of power relative to a 10 MW OTEC station needed to service those lamps (Figure 18). It is immediately clear that once seawater absorptivity reaches 0.1 cm^{-1} , parasitic power losses from about 11 percent to 33 percent can be expected. For any given combination of chamber wall dose and absorptivity, however, there is no power advantage to using lamps of greater output (while the requisite number of lamps decreases, the power needed per lamp increases leading to no net savings in power). Irradiating chamber walls with greater intensities ($16,000 \text{ uwcm}^{-2}$ to $48,000 \text{ uwcm}^{-2}$) is a much greater power disadvantage as absorptivity increases (only 0.3 percent greater for $48,000 \text{ uwcm}^{-2}$ than for $16,000 \text{ uwcm}^{-2}$ at $a = 0.001 \text{ cm}^{-1}$, 2.2 percent greater over the same range at $a = 0.01 \text{ cm}^{-1}$, and 22 percent greater at $a = 0.1 \text{ cm}^{-1}$).

Usually quartz-jacket irradiation chambers employ a turbulent plug-flow technology which should introduce some

FIGURE 16. Decrease of Parasitic Power Losses with Increasing Chamber Radius.

Within the first 100 cm of chamber radius increasing chamber sizes decrease the number of lamps required and leads to significant savings in parasitic power losses.

FIGURE 17. Chamber Arrangements Needed to Deliver $16000 \text{ uw sec cm}^{-2}$.

A chamber radius of 63 cm will produce a configuration in which 27 units with 27 chambers in series for each unit will deliver $16,000 \text{ uw sec cm}^{-2}$ to seawater volumes required by a 10 MW OTEC system ($a=0.001 \text{ cm}^{-1}$).

FIGURE 18. Parasitic Power Requirements as Influenced by Lamp Intensities, Required Target Doses and Media Absorptivities.

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advantages. For example, no single volume unit would be expected to remain at the point of minimum irradiation throughout its entire transit. Since all units would move through regions of greater radiation intensities, the intensity at the wall would be a less restrictive factor. The chamber radius could, therefore, be larger and the number of lamps decrease proportionately.

Another factor that may decrease actual numbers of required chambers is the possibility that OTEC waters may not need irradiation dosages as high as $16,000 \text{ uwsec.cm}^{-2}$. If in fact an adequate dose for OTEC needs is less than $16,000 \text{ uwsec.cm}^{-2}$, there will, of course, be fewer lamps needed.

However, counterpoints can be made to dampen these optimistic views. For example, turbulent plug-flow irradiation chambers in service do not perform ideally and even exhibit "short circuiting". Actual retention times run around 40 to 55 percent of theoretical times with minor portions of tracer materials exhibiting virtually no retention time at all.^[75] It has been estimated that as many as four times more lamps are needed in practice as are calculated to be needed. In addition some expert opinions hold that OTEC purposes can not be met without total sterilization of the water^[71] --a criterion UV irradiation can not meet. Even if this latter pessimistic view is not found to be completely accurate, there remains the possibility that irradiation intensities in excess of $16,000 \text{ uwsec.cm}^{-2}$ will be needed, especially for spore destruction. Any of these factors in turn would require greater power losses due to parasitic requirements. Finally it needs to be repeated that the calculations of this section addressed theoretical limits which advanced design and industrial innovation may approach in the

future. Present technology was better represented in the illustrative calculation for equation 19 in which a minimum of 2066 lamps were postulated. If in fact this number should be off by a factor of four, a 10 MW OTEC may need as many as 8264 lamps which are equivalent to a 6.2 percent parasitic power loss.

4.0 DISCUSSION

The feasibility of using UV radiation to prevent microorganisms from fouling the inner surfaces of OTEC heat exchangers cannot be examined from the standpoint of merely translating proven technology into OTEC design. On the other hand there is nothing inherent in the concept that would mitigate against its potential use. However, there are a number of critical issues which apparently have not been addressed and a number of key options which may come on-line with comparatively modest advances in the state-of-the-art technology.

4.1 INTENSITY OF RADIATION REQUIRED

Present literature sources recommend that effective radiation intensity be $16,000 \text{ uwsec.cm}^{-2}$. This number is used apparently for no other reason than the U.S. Public Health Service has decided on that level of radiation as necessary to assure the destruction of E. coli with an appropriate level of safety factor. In fact, there is no evidence that this (or any other level of radiation) is appropriate for destroying microorganisms which are present in deep seawater and likely to foul heat exchangers. Since E. coli is considered to be particularly resistant (100 percent mortality is reported variously at $6,600^{[8]}$ or $7,040^{[22]}$ uwsec.cm^{-2}) there is reason to suppose that organisms offensive to OTEC units can be controlled with

less radiation than the $16,000 \text{ uwsec.cm}^{-2}$ required for water sanitization purposes. If so, the energy and equipment savings could be very significant.

4.2 RADIATION CHAMBER CONFIGURATIONS

Throughout this paper there has been an emphasis on presenting radiation chambers as single-lamp units. The main reason for this has been that such a configuration is representative of most of the commercially available units. However the needs of OTEC may call for a more innovative design.

For example, there is a design by Ultraviolet Technology, Inc.^[56] which runs water through transparent TEFLON pipes, irradiating the water by externally mounted UV lamps. If we assume that for a given OTEC system the maximum depth of effective UV penetration is 21 cm, then a TEFLON pipe of 42 cm diameter would have to be served by 2 UV lamps, one mounted on either side of the pipe. With induced turbulence in the water flow it may be possible to increase the diameter of the TEFLON headers to a point where the water volume served by two lamps is greater than the water volume served by two lamps in the more conventional systems. Then, with a carefully planned stacking employing alternate layers of TEFLON pipes and lamps, it may be that all regions of every pipe could be assured of receiving at least the minimum required dose. This configuration may not only reduce parasitic power costs but save on maintenance since neither the UV lamps nor fragile quartz glass cylinders are exposed to flowing water and subsequent fouling and/or breakage.

Alternately, it may be possible that only a certain percentage of all the OTEC water need be irradiated to

attenuate microfouling to acceptable limits. This would reduce requirements for UV lamps and irradiation chambers. Perhaps it would even permit pumping of OTEC water to a non-iron reservoir and the intermittent immersion of a bank (or banks) of UV lamps to achieve desired results.

Another configuration which may enter speculation would employ optic fibers to deliver UV light to the system. It is difficult at this time to construct a scenario in which optic fibers might play a significant role in reducing costs. Of the manufacturers contacted, only Welch Allyn offered fibers which could transmit 254 nm UV light and then the efficiency was only some 20 percent for a light pipe length of 500 mm.^[57] However, it would appear that the most likely use of fiber optics would be to deliver light to the inner surface of the heat exchanger tubes. Such a configuration would have the exchanger tubes receiving UV radiation continuously. This in turn would achieve effective levels of radiation through the use of only a very small amount of UV radiation over a very long exposure time. This would be likely to reduce parasitic power requirements, but its effect on the efficiency of the heat exchangers and the construction/maintenance costs have not been evaluated.

4.3 OBJECT TO BE IRRADIATED

There are two ways micro-fouling on heat exchangers might be abated. In one protocol the UV lamps would be positioned to irradiate the inner surface of the heat exchange unit directly. In the second protocol (discussed extensively in this paper) all water moving toward the heat exchangers would be irradiated prior to entering the exchangers. Only the latter appears to have realistic possibilities for OTEC.

Perhaps one of the biggest advantages for considering UV radiation is that UV units can be arranged in a modular design so that maintenance schedules need not interfere extensively with operations. In this respect considerable engineering would be necessary to utilize the advantages of modular design in a system where UV was used to irradiate the inner walls of a heat exchanger. However, since such a system would give the walls effectively an infinite exposure time frame, it would be sure to keep micro-fouling to a minimum. It has been shown that irradiation levels of 10 to 30 uwsec.cm⁻² are effective in keeping underwater windows free of bacterial slime films and settlement of metazoan larvae.[29]

4.4 MACROORGANISM

No matter how effective UV may be in reducing biofouling by microorganisms, it will have no effect on macroorganisms except possibly to affect some reduction of food supplies to them. Since shellfish species are particularly effective in producing "glues" which are extremely strong, their colonization of any and all surfaces, including the quartz jackets around the UV lamps or the inner surfaces of TEFLON pipes, must be expected and their removal may be far more significant to the maintenance of an operating system than all considerations of micro-fouling. In fact, it is possible that the rate of macro-fouling will be great enough that it would become significant to operations before micro-fouling.

4.5 INTERFERENCES TO UV TRANSMISSION

Turbidity of the seawater can interfere with the effectiveness of UV irradiation in a number of ways.

Microorganisms can "hide" in the shadow of particulate matter and thereby escape exposure. Introducing turbulence in the passing stream of water can reduce the chances of organisms escaping all exposure. However, adequate exposure is a function of time as well as intensity. Thus, if a pumping system is designed to move water past a given point at an optimum rate of (x) gallons per second (gps), as the turbidity increased the pump rate would have to decrease. The turbulence-creating devices may have to come into service also but this, in turn, will introduce engineering complications.

From the implications of Rayleigh's equation (eqn. 7) and the comparatively short wavelength OTEC will employ (253.7 nm), it follows that turbidity can be expected to cause UV scattering. This scattering would increase the optical path length traveled by each ray. This in turn would lead to an increased light absorbance at all ranges from the lamp. As a result, radiation intensities at ranges appropriate to nonturbid waters may be utterly ineffective under turbid conditions.

Experience has shown that turbidities below 10 JTU probably are not significant to OTEC.^[4,20] If higher turbidities are to be expected it may be necessary to plan for more UV sources in the stream flow.

An entirely different source of interference would appear with even small amounts of certain kinds of organic matter -- especially the aromatics of petroleum products -- in the water. This organic matter absorbs strongly in the 250 nm region due to electron transitions normally from the nonbonding (one of an unshared pair) electron to an antibonding π position or a π to an antibonding π .^[31] These events occur in the far ultraviolet region except in

energy-lowering conjugation systems (such as occurs in some organics, certain dienes and so forth) where the electron transitions occur at wavelengths from 200 to 740 nm. As a result, water passing through OTEC would have to be free (or very nearly so) of petroleum products such as oils, greases, refined fuels escaping the hull, oil slicks from damaged tankers, bilge washings, organic pesticides and/or their solvents, body and/or garbage wastes, and so forth. The organic matter naturally present in ocean water is used for microbial nutriment^[88] and can have a wide range of concentrations, especially in littoral and meritic waters.^[89] For the most part, these "natural" organics do not interfere with UV transmission at 253 nm.

To illustrate the magnitude of the "cleanliness" (with respect to organics) required of OTEC waters it is necessary to point out that organic chemists address this issue using molar absorptivity (formally called "molar extinction coefficient") symbolized, customarily, " ϵ ". When expressing molar absorptivity at the wavelength of maximum absorption the expression " $\epsilon_{\max}$ " is usually used.

Thus, Lambert-Beer's Law becomes:

$$A = \epsilon_{\max} bc \quad (\text{eqn. 20})$$

Since even double-beam instrumentation experiences increasing percent instrumental errors when (roughly) more than 90 percent of the incident radiation is absorbed (i.e. $P/P_0 = .1$), it often is convenient to use $A = 1$ as a reference point beyond which the absorbance is too great for reliable measurements. Thus, if the cell path length is 1 cm,

$$\epsilon_{\max} \text{ M}^{-1} \text{ cm}^{-1} = b c \quad (\text{eqn. 21})$$

where c = molar concentration in a suitable solvent needed to give absorbance = 1.[16]

From the above considerations it can be shown that where literature values for $\epsilon_{\max}$ range from roughly 60,000 to $10 \text{ M}^{-1}\text{cm}^{-1}$, these represent concentrations of from 1.66×10^{-5} to 0.1 M as are required to reduce radiation intensity by 90 percent or more. To illustrate the range of organic concentrations referred to here, some sample organic compounds are reviewed in Table 6. Again note that conjugated systems have significant $\epsilon_{\max}$ especially when compared to, say, a saturated ketone (acetone). Also note that the region of maximum absorption for water is at 167 nm, well below the 253.7 nm used for effective disinfection. To help place perspective on these numbers, the presence of approximately 2,500 gallons of benzene ($\epsilon_{\max} = 215 \text{ M}^{-1}\text{cm}^{-1}$) in 6.095×10^5 gallons of seawater would make the seawater opaque to UV radiation. Certainly benzene is not soluble enough in seawater to reach such concentrations, but wave action does lead to droplet inclusions which in turn will affect UV transmittance.

5.0 CONCLUSIONS

Based on the technology review that has been conducted, a number of conclusions can be stated:

- 5.1 UV radiation at 253.7 nm can penetrate clean seawater to depths sufficient to make this technology feasible for consideration for OTEC.
- 5.2 Seawater temperatures do not affect UV radiation depth of penetration.

Table 6. Absorptivity Values for Selected Organic Compounds: The concentration (moles per liter) of selected organic compounds needed to absorb 90 percent of incident UV (i.e. $a = 1.00$) in a 1 cm cell varies with wavelength and molar extinction coefficients.

Compound	Wavelength Max. Absorb (nm)	Molar Extinction Coefficient Max. $M^{-1}cm^{-1}$	Conc. of Compound Needed (moles per liter)	Ref.
2,5-Dimethyl-2, 4-Hexadiene	241.5	13,100	7.63×10^{-5}	3
1,3,5- Hexatriene	258	35,000	2.86×10^{-5}	16
Benzene	255	215	4.67×10^{-3}	16
Styrene	282	450	2.22×10^{-3}	16
Methyl iodine	259	400	2.50×10^{-3}	16
1,3,5- Hexatriene	263	52,500	1.91×10^{-5}	16
Acetone	279	13	7.70×10^{-2}	16
Water	167	7000	1.43×10^{-4}	16

- 5.3 Open seas warm water turbidity might be low enough to avoid interference with microbial disinfection using UV radiation.
- 5.4 At present no commercially available UV radiation system can be applied directly to OTEC needs. It is necessary to stimulate industry to design more appropriate units. However, the basic problems apparently can be solved through engineering scale-up using available UV lamps. No new major technological advances appear to be needed.
- 5.5 A much broader data base is needed with respect to microbial kill ratios, variety of pertinent species, colonization habits and so forth. These must be studied from the standpoint of specific needs for OTEC and using natural seawaters. The use of drinking water standards is not suitable for OTEC needs.
- 5.6 Maintenance requirements for modular UV units appear to be at an acceptable level. "Cold cathode" UV lamps and housing require service approximately once- or twice-a-year. Modular designs permit a continuous maintenance protocol and thereby obviate scheduling for prolonged system shut-down periods.
- 5.7 UV radiation at 253.7 nm is an effective microbial disinfectant for organisms smaller than about 40 microns.
- 5.8 There are no apparent adverse environmental effects caused by UV radiation of water.
- 5.9 Radiation intensity of noncollimated light decreases exponentially with distance from the source. The

specific amount of decrease is a function of media absorptivity, the radius of the lamp and the intensity of the lamp. For a media $a = 0.001 \text{ cm}^{-1}$ the radiation attenuation reaches approximately 98 percent at 57 cm (22.5 in.) from a lamp 1.27 cm (0.5 in.) in radius.

- 5.10 The number of UV lamps needed to deliver a predetermined dose of radiation to water moving along the chamber wall passes through a minimum with increasing chamber radius, but that minimum is strongly affected by media absorptivity.
- 5.11 The optimum design of radiation chambers (e.g., that which would require the minimum number of UV lamps to run OTEC) is not necessarily obtainable with present technology.
- 5.12 Calculated minimum number of lamps and chambers may be underestimated by as much as a factor of four depending on the effectiveness of chambers to approximate ideal conditions.
- 5.13 Parasitic power requirements for supplying UV disinfectant services to OTEC increases sharply (from 0.14 percent to 32.7 percent) with both the absorbancy of the seawater ($a = 0.001$ to $a = 0.1 \text{ cm}^{-1}$) and the intensity of the radiation dose desired (16,000 to 48,000 uwsec.cm^{-2}).
- 5.14 The parasitic power requirements mentioned in 5.12 are not sensitive to the intensity of radiation from the UV lamp.

- 5.15 If 100 percent sterilization of OTEC water is found to be a requirement, UV irradiation will not be a viable alternative.

6.0 RECOMMENDATIONS

It is recommended that:

- 6.1 That UV radiation be further studied for specific application to OTEC systems as a means to control biological micro-fouling.
- 6.2 That preliminary laboratory tests be conducted, using natural seawaters with microorganisms similar to OTEC conditions, to determine seawater absorbancies and minimum UV irradiation needed to maintain $R_f = 0.0001$ on typical OTEC heat transfer surfaces.
- 6.3 That based on favorable results from the above laboratory tests, engineering studies be conducted to determine the economic and technical feasibility of adapting UV radiation equipment to OTEC systems.

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8.0 APPENDIX A

8.1 MODERN TERMINOLOGY USED IN SPECTROPHOTOMETRY AND CORRESPONDING TERMS FORMALLY USED

Absorbance (A): $A = \log_{10}(1/T) = \log_{10}(P_0/P) = abc$

where T = transmittance

a = absorptivity (cm^{-1})

b = optical path length (cm)

c = molar concentration (M)

P_0 = radiant power at the source

P = radiant power at distance (b)

formally "Optical Density" (O.D.)

"extinction" (E)

"absorbancy"

Absorptivity (a): $a \text{ cm}^{-1} = A/bc$

(also = "specific absorbance")

formally "extinction coefficient"

"absorbancy index"

"specific extinction"

"absorption coefficient"

"coefficient of absorption"

molar absorptivity (ϵ)

$\epsilon \text{ M}^{-1} \text{ cm}^{-1} = A/bc$

formally "molar extinction coefficient"

"molar absorbancy index"

"molar absorption coefficient"

Radiant Power (P)

$$P = P_0 e^{-abc}$$

formally "intensity" (I)

Transmittance (T)

$$T = (P/P_0)$$

formally "transmittancy"

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8.3 COMPANIES CONTACTED

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Aquafine Corporation
1869 Victory Place
Burbank, CA 91504

La Jolla Scientific Company
P.O. Box 2055
La Jolla, CA 92038

Math Associates, Inc.
"The Fiber Optics People"
6 Manhasset Avenue
Port Washington, NY 11050

Optical Radiation Corporation
6352 N. Irwindale Avenue
Azusa, CA 91702

Optical Research Associates
550 North Rosemead Boulevard
Pasadena, CA 91107

Oriel Corporation
15 Market Street
Stanford, CT 06902

Refco Distribution Systems Inc.
P.O. Box 2356
2010 Farallon Drive
San Leandro, CA 94577

Sanitron Ultraviolet Water Purifiers
Atlantic Ultraviolet Corporation
250 N. Fehr Way
Bay Shore, NY 11706

Ultra-Violet Products, Inc.
5100 Walnut Grove Avenue
San Gabriel, CA 91778

Ultraviolet Purification Systems
111 Business Park Drive
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7835 Wilkerson Court
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8.4 LITERATURE SEARCH CONDUCTED

An extensive literature search was conducted relative to seeking out information on ultraviolet radiation for control of seawater micro-fouling of heat transfer surfaces. In the initial phase of the search, personal contacts were established and from them information was obtained concerning other prominent sources that could be useful to the project including several specific references and reference listings. Also in this phase, VJCA searched their own files to obtain a list of corporations dealing with pertinent UV technologies. Letters of inquiry were sent to those identified as potential sources of information. Most companies replied with reference materials and personal knowledge, along with a (company) brochure describing their specific product. This information proved useful to the search.

Perhaps the most useful method of obtaining information on this topic was the bibliography search. Dr. James M. Morgan, Jr., conducted a DIALOG literature search through the VMI Preston Library, and The Virginia Water Resources Center, Blacksburg, Virginia. The descriptors used in these searches were:

disinfection
ultraviolet radiation
seawater
saline water
sterilization
marine micro-fouling
ultraviolet-generators/lamps

From the above search methods a comprehensive list of possible references was compiled. This working list was then used as a guideline for obtaining relevant references from the library. The George Mason University Library in Fairfax, Virginia, and the Library of Congress, Washington, DC, were convenient for locating several journal references and textbooks. The majority of the material, however, was obtained from the Environmental Protection Agency Library in Washington, D. C. Additional resources consulted included listings from VJCA library and the personal holdings of Dr. G. A. Garrigan, Professor of Chemistry, NVCC-Woodbridge. Ms Amy Pratt of V. J. Ciccone & Associates, Inc., is commended for her invaluable efforts in obtaining reference material.

VJCA found the references compiled to be sufficient in the information needed to prepare a comprehensive report on the problem of micro-fouling. Compiled for review were 89 reference sources; contacted were numerous individuals who provided personal information and opinions; and 11 major companies responded to our inquiries and sent useful material relevant to the problem. All of this material has been reference listed and organized for review under the References portion of this report.

8.5 ASSUMPTIONS USED TO CALCULATE VALUES GIVEN IN TABLE 1

8.5.1 Hydronautics

a) Given 330 lamps irradiating warm water (420 lamps for cold water) this is 0.897 lamps per MW or about 9 lamps per 10 MW (warm water, 20 lamps total for 10 MW). Alternate approach: it is also given that lamps are 196 cm long and set 167.6 cm (5.5 ft) apart. Thus they radiate only to 83.8 cm (2.75 ft). A corresponding chamber, then, must be $7022.4 \text{ cm}^2 \times 196 \text{ cm} \times \pi \times (11/1000 \text{ cm}^3) \times 0.2642 \text{ gal/l}$ or 1142.4 gal per chamber. If retention time is 1 second per chamber, one chamber could handle 68,544 gpm or about 9 chambers would be needed to handle 6.095×10^5 gpm. Therefore, 9 lamps would be needed.

b) Lamp output was estimated assuming a radiation flux of $16,000 \text{ uwsec.cm}^{-2}$ at 83.8 cm and applying only the Lambert-Beer Law (as Hydronautics does) and absorptivity = 0.0044 cm^{-1} .

c) $16.5 \text{ KW/lamp} \times 9 \text{ lamps} = 0.149 \text{ MW}$. Alternately Hydronautics estimates that for all 750 lamps/368 MW plant require 12.4 MW parasitic power which comes to 0.336 MW per 10 MW plant.

8.5.2 Aquafine

a) 520 gpm per unit, hence 1,172 units needed for 10 MW OTEC. Each unit has 24 lamps (total of 2.82×10^4 lamps) and is rated at 2 KW (total of 2.344 MW for 10 MW OTEC).

b) 24 lamps/unit consume 2 KW, hence this amounts to 83 W/lamp, ballast included.

8.5.3 Sanitron

a) 7,500 hours life at 24 hrs/day = 313 days.

b) $(51.5 \text{ UV watts} \cdot \text{sec} \times (10^6 \text{ uw/w})) / (2\pi \times 1.27 \text{ cm} \times 122 \text{ cm}) = 52,901 \text{ uwsec} \cdot \text{cm}^{-2}$ where the lamp radius of 1.27 is assumed. However, telephone conversation with the company placed this value closer to 30,000 $\text{uwsec} \cdot \text{cm}^{-2}$.

c) Eight lamps per unit, each unit rated at 333 gpm, hence 1,830 units are needed (14,643 lamps). Total of 1,120 w/unit = 2.049 MW required (ballast included).

8.5.4 UPS, Inc. (Cold cathode)

a) $(13.8 \text{ UV watts} \cdot \text{sec} \times (10^6 \text{ uw/w})) / (2\pi \times .79 \text{ cm} \times 76.2 \text{ cm}) = 36,485 \text{ uwsec} \cdot \text{cm}^{-2}$.

b) Assumptions used here are the same as used for UPS, Inc., hot cathode since there is no distinction made in the literature between operation of model EP-120 with either lamp.