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A COST BENEFIT ANALYSIS OF EMERGING LED WATER PURIFICATION SYSTEMS IN EXPEDITIONARY ENVIRONMENTS

THESIS

Alicia D. Binggeli, Master Sergeant, USAF

AFIT-ENV-MS-17-M-174

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Cost Analysis

Alicia D. Binggeli, BS

Master Sergeant, USAF

March 2017

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A COST BENEFIT ANALYSIS OF EMERGING LED WATER PURIFICATION SYSTEMS IN EXPEDITIONARY ENVIRONMENTS

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Abstract

The Air Force is a rapid mobile force responsible for national defense and reaction to calls for humanitarian aid across the globe. Rapid Global Mobility is a major tenant of the Air Force strategy. It provides the nation its global reach, underpins its role as a global power, and ensures that tomorrow, just as today, the United States can respond quickly and decisively to unexpected challenges to its interests. The ability to produce or acquire potable water is an essential piece of this tenant. Reverse Osmosis Water Purifications Units (ROWPUs), the workhorse for all military units, provide the necessary capability but do so at extraordinary capital and ownership costs. A 1500-gallon per hour rated ROWPU requires a dedicated 60kW generator, frequent element and filter replacement, and regular overhauls at a cost of nearly $40K per unit per occurrence. Developing LED UV technology is expected to make purification systems more robust, efficient, and cheaper than ever before. This research investigates UV LED emerging technology to determine if it can be configured to perform as a near term, cost effective alternative.

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Dedication

This thesis is dedicated those who kept my dream of an Air Force career alive, not through their direct effort or intervention, but their show of faith in me as a person. A special thank you to Stacy Cooke, for your continued support and motivation that helped me realize greater professional and academic accomplishments than I'd ever thought possible. And finally, to our very loved, yet oversized dogs who drove the decision to purchase a home with "potential", without which I would have finished this thesis months ago.

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Alicia D. Binggeli

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A COST BENEFIT ANALYSIS OF EMERGING LED WATER PURIFICATION SYSTEMS IN EXPEDITIONARY ENVIRONMENTS

I. Introduction

General Issue

The availability and usability of water are vital components to United States Air Force (USAF) strategy. Water availability is influenced not only by the USAF but also by the behaviors and needs of many other water users. The local population may not regulate the waste stream entering their water system, or the introduction of personnel may stress the native environment's capability to support all users. Additionally, water resource needs are not limited to hydration and hygiene but also include use in food preparation, hospitals, and for Nuclear, Biological, and Chemical (NBC) decontamination. The price of water involves direct costs, transportation, personnel hazards, heavy fuel consumption, use of scarce cargo space, and--for consumables--solid waste (Marstel-Day LLC, 2011).

When purification of locally available water is needed, Reverse Osmosis Water Purification Units (ROWPUs) have provided most of the necessary water supply in contingency and response environments but do so at an extraordinary cost. ROWPUs, the workhorse for all military units, are relatively large and expensive to purchase, operate, and maintain. A single ROWPU costs the USAF just over $750K to own and operate during its lifecycle. With an inventory of over 270 units, that's nearly $203M.

Ultraviolet (UV) radiation is an alternative method of water purification not previously found suitable for contingency environments. UV purification is typically

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accomplished through the use of mercury vapor filled fluorescent bulbs which lack the robustness required for contingency environments. As opposed to removing bacteria and viruses like the ROWPU or other purification products, UV inactivates bacteria and viruses by disrupting their DNA and inhibiting their ability to reproduce (EPA, 2006). Recent and rapid evolution of Light Emitting Diodes (LED) in the UV range, combined with research regarding their application to water purification, provides an alternative option for the USAF. LED devices use a fraction of the energy required by the ROWPUs and can be produced at a much lower cost. Storage space and maintenance requirements are also reduced with the use of LED devices. Depending on the configuration in which it is installed, LED devices can also negate the need for chlorine additives.

Problem Statement

The USAF faces the inherent challenge of predicting contingency environments, the nature of critical response events (national security, humanitarian, or disaster response), and the availability or status of a water supply. Having continuous access to adequate potable water is essential for every Air Force mission. Personnel may encounter situations where the ROWPU or potable water purchases are unavailable or impractical. Additionally, UV LED technology is in its infancy and currently lacks the efficiency and modality for complete application to all water purification needs of the USAF. As such, LEDs producing light in the UV range are still quite expensive but are expected to rapidly become cheaper and more functionally effective due to technology improvements (Peters, 2012). Unlike the ROWPU, UV LED purification units do not have the capability to desalinate water and a relatively clear water source--less than 60

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Nephelometric Turbidity Unit (NTU)--would need to be available in contingency and response locations. When relatively clear water is not available, additional pre-filtration is required and could include coagulation, sedimentation, or multimedia type methods.

Additionally, the Air Force last purchased ROWPUs in 2009. This was immediately following the 2008 surge in Iraq and near the most recent height of government defense spending. Since then, spending has decreased by 13.9% and is projected to continue decreasing over the coming years (Walker, 2017). Therefore, a cost benefit analysis of emerging UV LED water purification technology--which has not previously been conducted--would assist in quantifying potential cost savings. Without this information, decision makers may not consider this emerging technology when making future equipment replacement decisions.

Research Objectives

This thesis strives to provide quantitative and qualitative information to answer the following questions:

1. Do the costs justify UV LED water purification technology adoption and at what price point will this occur?
2. When will UV LED purification options be more cost effective than the incumbent technology?
3. How do other factors (i.e. fuel cost, alternative costs, maintenance and operation, etc.) impact the decision?

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Methodology

The literature review conducted during this research assisted in identifying methods to predict the cost reduction and technology improvement rates of emerging technologies --specifically the cost progression of LEDs. Methods used to make equipment replacement decisions were evaluated for application to the water purification issue addressed by this study. Cost data was then collected from current purchase contracts for ROWPUs, producers of UV LED bulbs, manufacturers' UV LED water purification products, and other commercially available water filtration products.

There are very few manufacturers of UV LEDs which severely limit data options. Only available data from participating manufacturers was used for comparison and evaluation. Available data were evaluated to determine the applicability of Haitz's Law (an LED improvement theory). UV LEDs are fundamentally similar to other LED technology and the efficacy and cost progression of these LEDs has been successfully estimated by Haitz's Law. However, an exact correlation between the progression of UV LED technology and Haitz's law could not be determined. Therefore, regression analysis was used to project the future performance and cost of UV LED bulbs and consequently, purification units. Haitz's Law was used to compute the same costs but only as a supplementary comparison to evaluate the optimal decision point based on changes in the improvement curves.

Next, a cost benefit analysis (CBA) was conducted to determine the feasibility of replacing ROWPUs with LED purification systems. The CBA follows the guidance outlined in AFMAN 65-506 for Economic Analysis due to their similar nature. Specifically, the life cycle cost (LCC) and net present value (NPV) were used in

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conjunction with the Time Valued Technology method to select the optimum replacement period and corresponding cost. Sensitivity analysis was then applied to the replacement problem to determine how factors--such as fuel prices and product useful life--affect the optimal strategy.

Summary

This chapter described the rational for evaluating current methods of water purification and considered UV LED technology as an alternative. It established the problem based on fiscal constraints as well as Air Force requirements. Chapter 2 will present a literature review that focuses on methods of water purification, LED technological advancements, similar equipment replacement problems, and the cost of water purification in contingency environments.

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II. Literature Review

Chapter Overview

This chapter discusses literature, research, and specific topics relating to water purification and its importance to the U.S. Air Force (USAF) in relation to contingency and humanitarian response environments. First, this research examines the current regulatory environment for water purification and the USAF's contingency water requirements. Second, alternatives capable of providing clean and usable water in contingency environments, including detailed exploration into the use of Light Emitting Diode (LED) purification technology, are surveyed. Finally, equipment replacement and economic analysis methods are reviewed.

Definition of Terms

The terms filtration and purification are often used interchangeably but for the purposes of this research a distinction is made. Filtration is the removal of large impurities or particulates from water accomplished by straining. In this basic sense, filtration does not necessarily make water potable (i.e. safe to use for consumption, food preparation, etc.). Purification involves the removal of much smaller microorganisms, total dissolved solids, toxic heavy metals, chemicals, and other contaminates making water potable and safe for almost all uses (Advanced Purification Engineering Corporation, 2016).

Military Contingency Water Needs

A military contingency "results in the call or order to, or retention on, active duty of members of the uniformed services… during a war or during a national emergency

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declared by the President or Congress" (U.S. Code 10 § 101). The USAF utilizes its Basic Expeditionary Airfield Resource (BEAR) response packages to provide vital equipment necessary for "bare" expeditionary sites with limited infrastructure and support facilities. These packages allow for flexible response of deployment forces in increments of 550 personnel. During bare base contingency responses, the USAF expects a population flow of 150 personnel in the first 24 hours, 500 in the first 48 hours, up to 2000 in the first 14 days, and up to 3000 in the first 30 days (AFP 10-2019, Vol 5, 2013). This study focuses on small, non-permanent contingency bases with up to 550 personnel and might be applicable for similar size forces from other branches within the Department of Defense.

Water consumption needs for all U.S. military forces are drawn from Joint Publication 4-03, *Joint Petroleum and Water Doctrine.* Each service uses this guidance to translate the essential water requirements into support package planning. Essential water requirements are identified as: drinking, personal hygiene, field feeding, medical treatment, heat casualty treatment, personal contamination control, patient decontamination in CBRN environments, and in arid regions, vehicle and aircraft maintenance. Based on these requirements, the USAF engineer panels determined a water use planning factor of 30 gallons per person per day (gpppd) in a bare base environment. The factor increases to 60 gpppd when in the beddown phase of a deployment or contingency or with the installation of permanent water treatment plants (AFH 10-222, Vol 1, 2012). These planning factors were further broken down into the categories shown in Table 1.

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	Water Usage Factor (gpppd)	
Functions	Using BEAR	Using Fixed Water Treatment Plant
Drinking	4.0	4.0
Personal Hygiene	3.0	3.0
Shower	3.0	15.0
Food Preparation	4.0	5.0
Hospital	1.0	2.0
Heat Treatment	1.0	1.0
Non-Potable Water **	12.0	25.0
10% Loss Factor	2.0	5.0
Total	30.0	60.0

**Note: Non-Potable water includes water usage for laundry, construction, graves registration, vehicle operations, aircraft operations, and firefighting (AFP 10-2019, Vol 5, 2013).

Table 1: Water Use Planning Factor Breakdown

Cost of Water

Determining the cost of water as a commodity is not as simple as it may seem. The mechanics of getting fresh water to USAF personnel may seem as straightforward as taping into the local water supply or purchasing cases of bottled water but other considerations need to be addressed. Water availability is dependent on the needs of many water users other than USAF personnel. The introduction of personnel may stress the native environment’s capability to support all users and purposes. The local populace is likely, and has the right, to demand compensation for water rights. The direct costs involved in purchasing water are extremely difficult to quantify given the uncertainties involved in predicting response environments--i.e. the location and availability of water (Marstel-Day LLC, 2011). Thus, converting the cost of an alternative into a true cost per gallon of water and comparing it to the cost of bottled water is beyond the scope of this study.

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Water Purification

Water purification is the process by which potable water is provided from a water source containing undesirable impurities. Water sources significantly impact the selection of the purification system. Factors that drive the amount of effort and equipment needed to purify water include: water condition (fresh, brackish, or salt water), source (well, river, lake ocean, or municipal supply), clarity or turbidity, distance from the established location, and water temperature (AFH 10-222, Vol 1, 2012).

Reverse Osmosis Water Purification Unit (ROWPU)

Reverse osmosis is a water purification technique that utilizes pressure differences to push water through a semipermeable membrane barrier in order to purify it. When two solutions with different concentrations of solute (impurity) are separated by a semipermeable membrane, a natural movement of solvent (water) occurs. This movement, referred to as osmosis, is the tendency of water to move in a direction that will result in an equal concentration of water to impurity on either side of the membrane. In reverse osmosis, the direction of flow is altered. A large amount of pressure is introduced to the high concentration side and results in a flow that is opposite to that of natural osmosis. The membrane barrier contains micropores that allow the flow of water but prevent the flow of suspended matter to include bacteria, chemical contaminates, salt, and other mineral solutes. The use of this purification method is most appropriate for desalination of sea water (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2012).

In response to contingencies, the USAF primarily employs a portable, self-contained purification system employing this process called the Reverse Osmosis Water

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Purification Unit (ROWPU). These systems are assembled into the water production system as part of a capability based BEAR asset kit. ROWPUs can be assembled in parallel to each other when more than one is required. The number of ROWPUs required to support a given contingency is based on the size of force the water production system is expected to support. Currently the USAF fields two models: the 600 ROWPU (Figure 1) and the 1500 ROWPU (Figure 2); they are capable of producing 600 and 1500 gallons per hour of potable water, respectively (AFP 10-2019, Vol 5, 2013).

Figure 1. 600 ROWPU

Figure 2: 1500 ROWPU

ROWPUs do not provide potable water as a stand-alone system; they require an external power source and are part of an overall Water Production System (WPS).

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During the initial contingency response phase, ROWPUs are powered by large generators which require relatively large amounts of fossil fuels. The amount of fuel required by the generator is dependent on the condition of the water. More turbid water requires more power and results in a slower purification rate; the opposite is true for less turbid water (AFP 10-2019, Vol 5, 2013). Turbidity is the cloudiness or murkiness of water and is further discussed in the "Ultraviolet Radiation Purification Basics" section of this chapter. The WPS is an all-encompassing water system comprised of the five subsystems described in Table 2 and Figure 3 (AFH 10-222, Vol 1, 2012). A "600 WPS" package, capable of producing a maximum of 36,000 gallons per day, contains three 600 ROWPUs. A "1500 WPS" package contains two 1500 ROWPUs and is capable of producing a maximum of 60,000 gallons per day. Table 3 shows the typical quantity of packages required to support 550 personnel. (AFH 10-222, Vol 1, 2012).

	Subsystem	Responsibility
1	Source Run Subsystem (SRS)	Provides raw water input (source water).
2	Water Production Subsystem (WPS)	Generate potable water for distribution to user facilities.
3	550-Initial Water Distribution System (550-I)	Distributes water from potable source to via pressurized pumping system to distribution line (can stand alone).
4	550-Follow-on Water Distribution Subsystem (550-F)	Expansion of the 550-I subsystem (not stand alone).
5	Industrial Operations and Flightline Subsystem	Expansion of 550-I, 550-F, or WPS designed to distribute water to isolated facilities (latrine, kitchen, etc.) with line safeguards (hose bridges) providing road crossing capabilities.

Table 2: Water Production System Components

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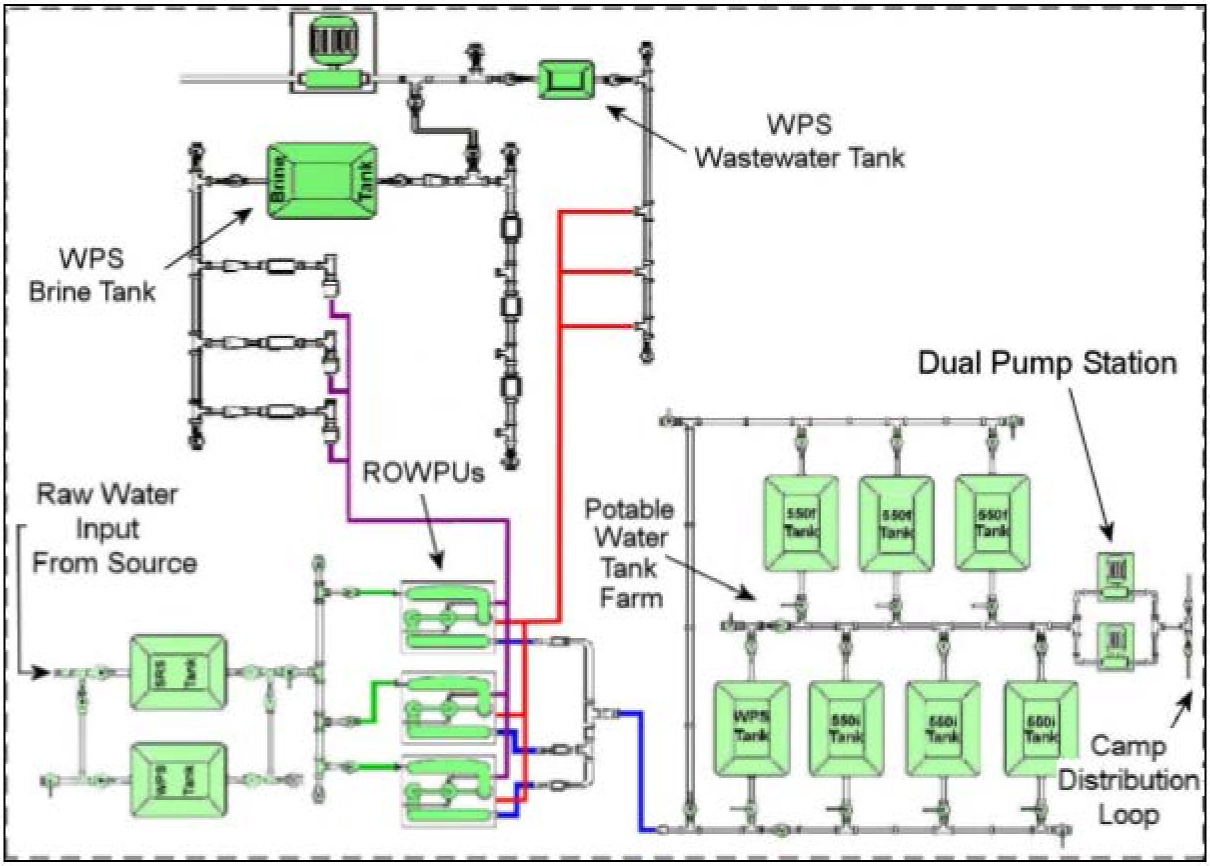

Figure 3: Typical Water Production System Layout

Total Gallons Required Per Day (30 gpppd)	600 WPS Packages Required	1500 WPS Packages Required
16,500	1	1

Table 3: Water Production Requirements

The ROWPU system has some weaknesses that prevent it from being entirely efficient. Not all water that is sent through the system is made potable. An average of 33% of fresh water and 50% of salt water sent through the system is rejected waste water or “brine”. Brine is not necessarily unusable and may have other purposes such as dust abatement (AFH 10-222, Vol 1, 2012). The ROWPU cannot be cycled on and off when demand is placed on the system--a warm-up and priming period is required. The actual

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time this takes is dependent on the ambient temperature, the temperature of the water, the downtime between system operation, and the experience of the operator. Additionally, ROWPUs are designed to produce a mass amount of water over a long cycle time (up to 20 hours) and require 4 hours of downtime for maintenance and cleaning. Because of these design characteristics, it is necessary to build-up a usable supply of water in large holding tanks (or bags) so it is available when needed (AFH 10-222, Vol 1, 2012). Due to the risk of recontamination while water is held in storage, chlorine becomes a necessary additive to this process (AFP 10-2019, Vol 5, 2013).

Ultraviolet Radiation Purification Basics

Ultraviolet (UV) radiation is energy in the invisible range of the electromagnetic spectrum between visible light and x-rays. The short-wave UV-C range, depicted in Figure 4, is referred to as the germicidal spectrum (or frequency) of disinfection (Germacidal Ultraviolet, 2016).

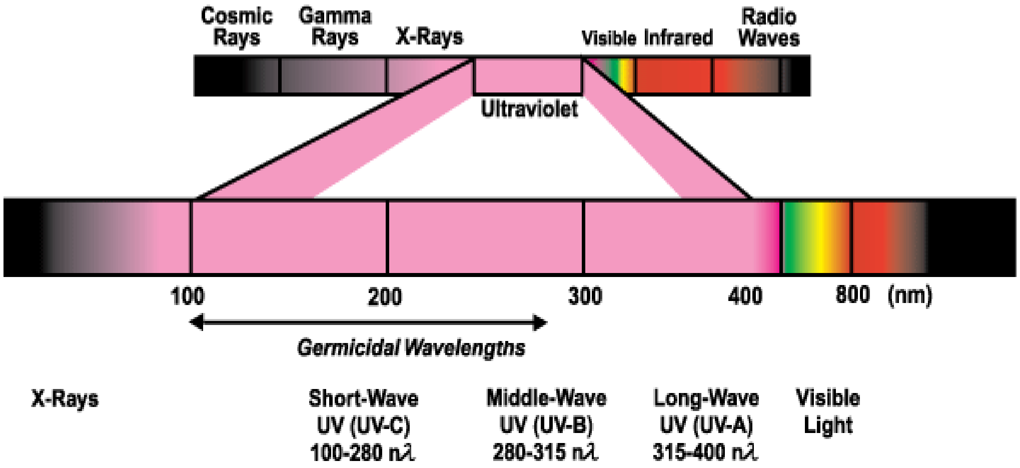

Figure 4: Electromagnetic Spectrum, UV-C Germicidal Wavelengths

In water purification, the energy created by UV-C "light"--at wavelengths between 100 nm and 280 nm--is used to deactivate microorganisms in water as opposed

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to using chlorine to kill them or filters to remove them. Exposure to UV energy causes damage to the DNA and/or RNA code which completely disables the ability of the microorganism to reproduce. Without the ability to replicate, the microorganism can no longer infect a host and are thus no longer a threat to the health of a host (Schmelling, et al., 2006).

The amount of exposure at the correct UV wavelength is important, but it is not the only factor to consider for a UV purification system. Microorganism sensitivity to UV light varies across species thus different doses of UV energy are required to render them incapable of microbial repair. UV dose, represented in joules per meter squared or millijoule per centimeter squared (J/m^2 or mJ/cm^2), is the product of the UV intensity and exposure time. UV intensity is energy measured at a particular point and represented by watts per meter squared (W/m^2). Exposure time is accounted for by the flow rate of water through the UV chamber--also referred to as the reactor (Schmelling, et al., 2006). The minimum acceptable dose of UV light in the water purification process is 40 mJ/cm^2 (Germacidal Ultraviolet, 2016). Two measurements, total suspended solids and turbidity, effect the dose microorganisms are exposed to.

Total suspended solids (TSS) are made up of mostly inorganic materials; TSS also include some bacteria and algae larger than 2 microns that contribute to the concentration of solids in water (Fondriest Environmental, Inc., 2014). Turbidity, also referred to as particle content or clarity, affects the ability of UV lamps to expose the water to the proper dose. A visual depiction of NTU measurements can be seen in Figure 5 (Water Shedds, 2017). As shown by Figure 6, these factors often overlap. Although not exact, turbidity can be used to estimate TSS (Fondriest Environmental, Inc., 2014). TSS is

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difficult to measure and predict and most locations do not have a set standard. Instead, many countries and organizations have established recommended turbidity levels from a baseline of prior measurements (Fondriest Environmental, Inc., 2014). In order for the dose to reach 40 mJ/cm^2, it is recommended that water have a Nephelometric Turbidity Unit (NTU) measurement less than 5 NTU (Water Shedds, 2017).

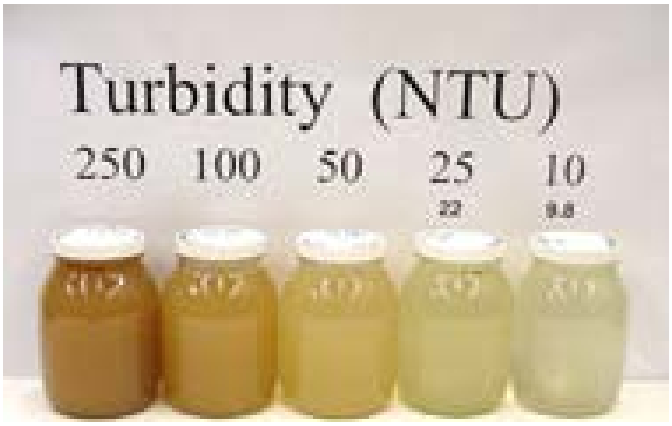

Figure 5: Nephelometric Turbidity Unit (NTU)

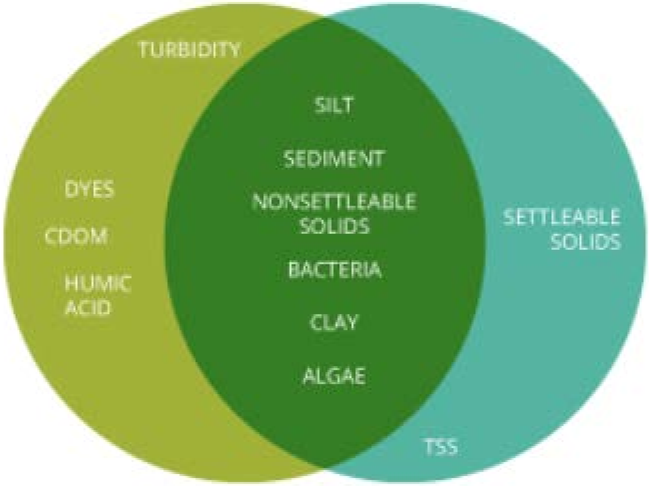

Figure 6: Turbidity and Total Dissolved Solids

UV light used in water purification is typically produced by mercury vapor lamps. Mercury lamps are fragile, sensitive to power fluctuations, manifest high energy use, and

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have the potential for drastic environmental consequences if they fail. Over the past several years, the technological advancement of light emitting diodes (LEDs) has created the opportunity for less expensive system costs, more efficient energy consumption, longer operational lifespans, decreased system special footprint, and the creation of portable, rugged devices. The basics of pre-filtration, UV light sources, and filters are discussed in the following pages.

Pre-Filtration Basics

Typically, lakes and streams in low flow cycles have a turbidity level around 10 NTU; however, this varies due to weather, geology, season, and water flow. Turbidity levels can reach above 100 NTU during high flow seasons or weather events (Fondriest Environmental, Inc., 2014). To reduce the turbidity of water to the recommended 5 NTU for UV purification, pre-filtration is required. Pre-filtration options include coagulants and flocculants, multimedia sediment filters, centrifugal screen filters, and micron cartridge filters. Each of these filters are rated by the size of particles—as measured in microns--they remove. Ratings can vary widely by filter type and manufacturer.

Coagulation and flocculation are often used together. Coagulants (typically a metal salt) work by destabilizing the suspended particles at the atomic level. The coagulant is positively charged while particles in water are negatively charged; thus, they attract and cling together forming a larger particle (Chem Treat, 2016). Flocculation is the addition of a polymer to water that clumps smaller particles together to form larger particles. The idea for both methods is that larger particles will either settle out of or be removed from the water more easily (Chem Treat, 2016).

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Multimedia sediment filters are layered with different sizes of media (i.e. coal, sand, gravel, etc.). Water passes through larger media and then works its way through progressively smaller media types. Solids are captured in these stages and removed from the water. To prevent clogging, periodic cleaning of the filter is accomplished through a backwash sequence whereby clean water is forced back through the filter to dislodge particles and push them out of the filter. Over time, the jagged edges of the media become smooth and need to be replaced in order for the filtration process to continue working (Puretec, 2016).

Centrifugal screen filters use centrifugal force to push heavy particles toward the walls of the device as water passes through it. Water is allowed to pass through a screen while the particles build up on the walls into what is known as “filter cake”. A backwash is required to clear it out and prevent the filter from clogging. The amount of water required for centrifugal backwash is much less than that required for the multimedia sediment filters (Federal Energy Management Program, 2012).

With micron cartridge filters, the removal of particles is high pressure driven which forces water through a semipermeable medium. The size of the pores in the media--driven by the size of the media fibers--dictate the size of particles that are filtered out of the water (Pentek, 2006). These types of filters are often seen in home filtration systems and are contained in small cylinder casings--see Figure 7. Inside the casing are the easily replaceable fiber filters. The life and efficiency of the micron cartridge filter varies as operating conditions change (Pentek, 2006).

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Figure 7: Micron Cartridge Filters

Mercury Vapor Lamp Basics

UV lamps are typically low pressure vapor, low-pressure high-output vapor, or vapor lamps with tube shaped envelopes made of quartz which are filled with mercury gas (Schmelling, et al., 2006). Electrodes are situated at both ends of the tube. Incoming electricity is regulated by ballast and introduced to the electrodes which, when energized, emit electrons. The electrons create an arc and ionize mercury gas which then emits UV energy (Lenk & Lenk, 2011). Fluorescent mercury lamps used for lighting operate on the same concept, but the envelopes are made of glass and have a phosphor coating along the inside that absorbs the UV energy and emits visible light. The phosphor coating is what gives the white appearance (Lenk & Lenk, 2011). Mercury lamps employed in the water

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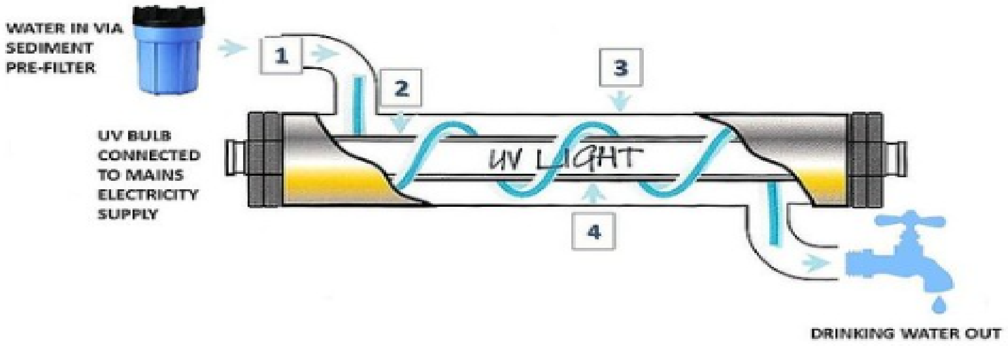
purification process emit UV-C energy in the 254 nm range. The typical set-up and process for most commercial water purification products is depicted by the Caerfagu Products UV Mercury Lamp in Figure 8 (Caerfagu Products, 2016). Pre-filters are necessary for all UV purification methods.



(1) Water enters the UV chamber and flows into an annular space between the quartz sleeve and the outside chamber wall (2). (3) The water is exposed to the UV light from the mercury germicidal lamp (4) disinfecting the micro-organisms and rendering it dead.

Figure 8: UV Mercury Lamp Process

Mercury lamps exhibit sensitivity to fluctuations in power and can have significant start-up or restart times after power has been interrupted. The lamps only begin to operate properly after they have warmed up and have had time to build to their full power. A cold start occurs after a significant time of no operation. A warm start is required after a loss of arc in the lamp. Cold start times can range from 4-7 minutes for low pressure variations of the lamps and 1-5 minutes for mercury vapor lamps; warm starts range from 2-7 minutes and 4-10 minutes, respectively (Schmelling, et al., 2006).

Degradation of mercury lamps occurs due to exposure to heat, deposits, or impurities collecting on the surfaces of the lamp envelope; additionally, disruption of power or “on/off” operation can degrade the lamps (Schmelling, et al., 2006). These

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degradation factors, along with usage habits, have a significant effect on the life of the lamps. When the lamps degrade, the output of the lamp decreases; this reduces the UV dose pathogens are exposed to thereby making the lamp less effective. The lamp life is considered complete when the UV output decreases by 25%. Average bulb life ranges from 10,000 to 12,000 hours (Platt & Stutz, 2008). Lamp sleeves, which are made of quartz, are also relatively fragile and extremely vulnerable to damage from the force of water passing around it, internal or external vibrations of the equipment or system, and improper handling during removal or insertion (Schmelling, et al., 2006).

Mercury is a highly toxic substance. The EPA cautions that mercury exposure can affect the brain, spinal cord, kidneys, and liver which can cause a host of health problems including memory loss and difficulty moving (EPA, 2016). Although bulbs are surrounded in quartz containers for protection, the fragility of the bulbs contributes to the risk of contamination. Clean-up when a contamination occurs also increases risk of exposure and cost of the system.

Light Emitting Diode Basics

A Light Emitting Diode (LED) is formed from semiconductors. As current is introduced to the semiconductor, it generates a photon which is emitted as light. LEDs are capable of emitting light across the electromagnetic spectrum with the exact wavelength being determined by the semiconductor material (Lenk & Lenk, 2011). UV LEDs do not take the shape of the LED bulbs seen in flashlights or holiday lights; they more so resemble microchips. LEDs are punched out of wafers then covered by flat or dome shaped lenses which allow transmittance of the UV rays (Peters, 2012). Figure 9,

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obtained from International Light Technologies, shows the relative size and shape of the LEDs used in water purification systems (International Light Technologies, 2016).

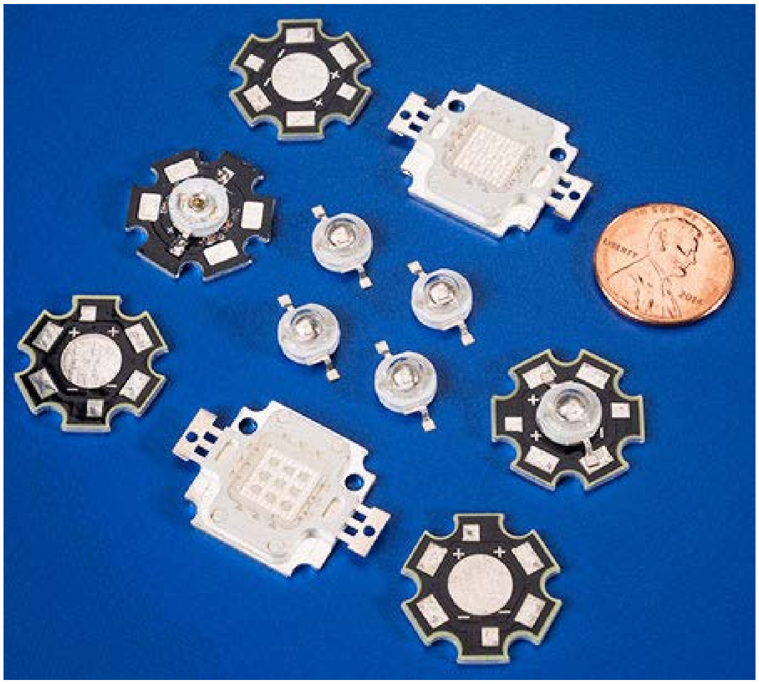

Figure 9: Ultraviolet Light Emitting Diode

UV mercury lamps are limited to production of one specific wavelength. Depending on their manufacturing design, LEDs are capable of emitting light at a single wavelength but can also be tuned during manufacture to emit one of several wavelengths within a specific band. This capability allows the device to be adjusted to the most effective wavelength for germicidal disinfection, no matter the application (Schujman, Smart, Liu, Schowalter, & Bettles, 2007).

UV LEDs will degrade over time due to exposure to heat. Unlike mercury bulbs, the source of heat is away from the lens which equates to less buildup--and therefore, less blockage of UV dose. Additionally, cycling the LEDs on and off is not a contributing factor to degradation. An LED bulb's lifespan is limited by its ability to dissipate heat

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which is largely attributed to the packaging. However, lifespans of some UV LEDs can be up to 30,000 hours; this is triple the lifespan of most mercury bulbs (Peters, 2012).

Power consumption by UV LEDs is currently comparable to that used by mercury bulbs, but it is far less than what is used by ROWPUs. Additionally, LEDs do not contain any mercury, are robust and light weight, require no warm-up period, have the ability to pulse, and can cycle on and off with user requirements (Aquisense Technologies, 2016).

UV LED purification units are comprised of pre-filters and the LED module. Water passes through pre-filters (to reduce the turbidity of water) and then into the UV LED module where it flows past the UV LED bulbs in the "reactor". Simplified depictions of the UV LED purification units and UV LED modules are shown in Figure 10 and Figure 11. The number and type of pre-filters depends upon manufacturer recommendations and the turbidity of the water source.

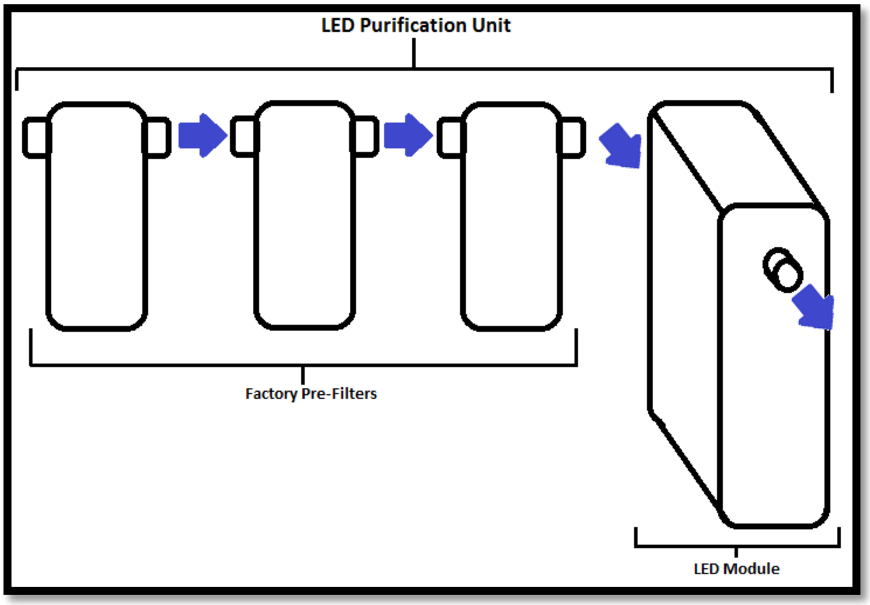

Figure 10: LED Purification Unit

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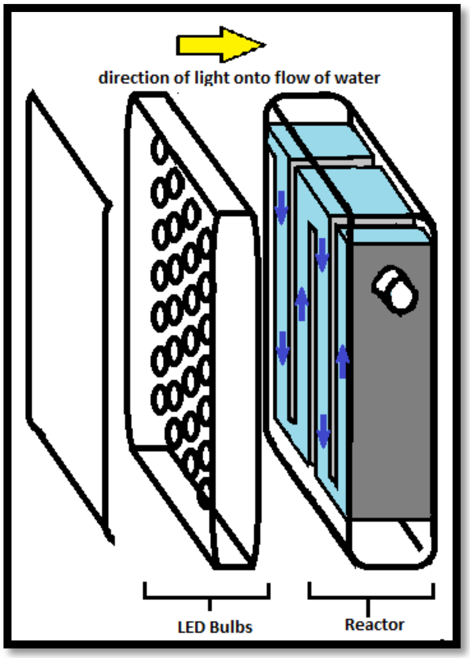

Figure 11: Broken-out UV LED Module

The water production system differs from that of the ROWPU when the UV LED purification units are used. Current UV LED purification units range in size from a common toilet paper roll to a desktop computer tower. This allows the purification units to be placed at the point of use (i.e. the faucet at each distribution facility or point) which makes it part of the camp distribution loop as opposed to the water plant with the ROWPUs. In BEAR base configurations, at least one UV LED purification unit would be necessary at six facilities or distribution points (i.e. potable water distribution point, dining facility, latrines, etc.). Therefore, a minimum of six UV LED units would be required. The water production system would be set-up according to Figure 12. If the turbidity of source water is above 60 NTU, additional pre-filters would be added upstream in the water production system of the UV LED purification unit. Although the additional pre-filters do not share a direct connection to the UV LED purification unit--

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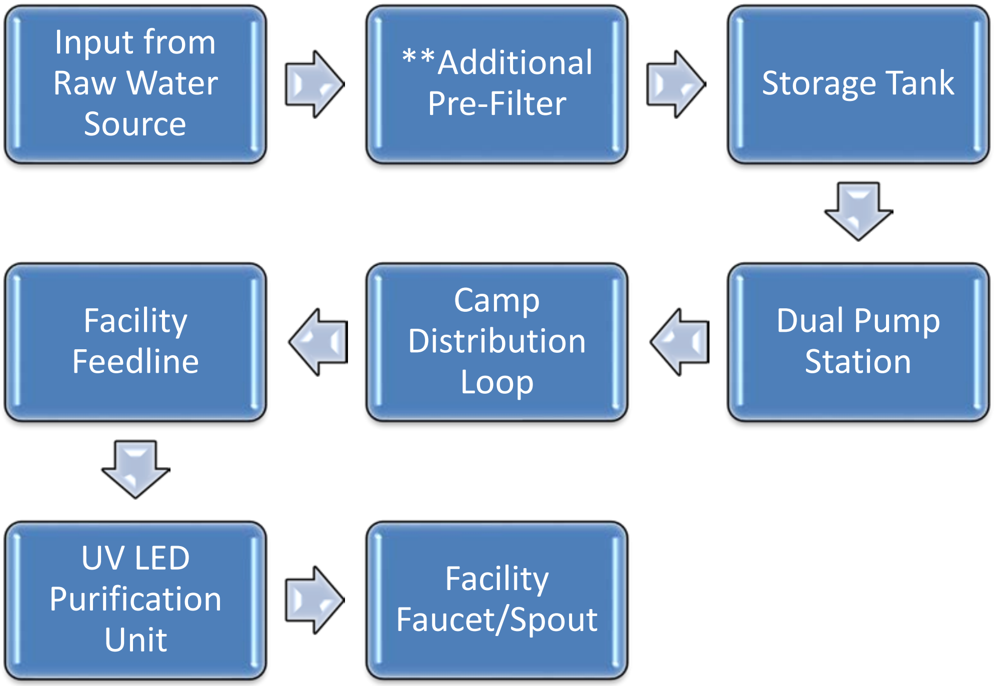
see figure 12--the cost of the pre-filters is still considered to be part of the UV LED purification unit cost.



**additional pre-filters that are not the same as those depicted in Figure 10

Figure 12: UV LED Water Production System

UV LED Cost and Performance Predictions

Similar to Moore's Law (a performance predictor for the microprocessor industry), Haitz's Law predicts the decrease in price and increase of performance for the LED industry. Introduced by Roland Haitz in 1999, it forecasts that for every decade, the cost per lumen of an LED will decrease by a factor of 10 and the amount of light generated will increase by a factor of 20. This trend will continue until the LED reaches its theoretical limit, although price will continue to decrease beyond that point (Lenk & Lenk, 2011). Due to production infancy, it has yet to be conclusively proven that the UV LEDs follow this pattern; however, researchers predict that UV LEDs will likely follow

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Haitz’s Law (Autin, et al., 2013; Bettles, Schujman, Smart, Liu, & Schowalter, 2007; Wurtele, et al., 2011).

Life Cycle Cost Analysis

Life-cycle cost (LCC) is used to formulate estimates, make equipment decisions, conduct replacement analysis, and create replacement models. It captures costs across the entire life of the equipment and is comprised of research and development (R&D), acquisition, operating and maintenance, salvage value, and disposal costs. In addition, LCC incorporates the concepts of depreciation, inflation, and investment which are integral to replacement analysis (Gransberg & O'Connor, 2015). R&D and acquisition costs are known as the initial investment costs (Peurifoy, Ledbetter, & Schexnayeder, 2002). Operating and maintenance costs include unscheduled maintenance (repair), scheduled maintenance (upkeep and overhaul), fuel, labor, and any other consumable equipment costs (AFMAN 65-506, 2011). Salvage value is the residual value associated to the equipment at the end of the usable life while disposal cost is the cost directly attributed to the disposal of the equipment (AFMAN 65-506, 2011).

Equipment Replacement Decision Analysis

Replacement decision analysis assists in comparing the costs of presently owned equipment and alternatives that could replace it. There are several methods, both theoretical and practical, that help decision makers and managers accomplish this task. The four seminal methods introduced by Dr. James Douglas are: 1) the intuitive method, 2) the minimum cost method, 3) the maximum profit method, and 4) the mathematical modeling method. Dr. Douglas explains that each of these methods are useful because no

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two decisions are the same; they can be catered to different types of owners and equipment replacement decisions (Douglas, 1978). The intuitive method resembles a common-sense approach and involves developing a baseline model for decision-making. The minimum cost method focuses on pinpointing the time where operating and maintenance costs are at their lowest. This most often applies to public sector equipment and is intended to help minimize the tax burden on the public citizen in relation to the equipment replacement decision. A replacement decision is made when the cost of maintaining the incumbent technology exceeds the cost of adopting the emerging technology (Douglas, 1978). The maximum profit method is used when equipment is owned by businesses looking to maximize their profit streams. The decision point is the point in time when profit streams are exceeded by maintenance and operating costs. The mathematical modeling method is used for large, very complex situations. It involves discounting costs to their present value, accounts for time value of money, and involves the association of cost to the technological advancements through the use of computer-based simulations (Gransberg & O'Connor, 2015).

In a recent thesis addressing a U.S. Air Force streetlight replacement decision, the author uses a method called Time Valued Technology (Ochs, 2012). It is similar to the widely used “cost minimization method” (Taylor, 1923) which “yields an optimum replacement timing cycle and a corresponding equivalent annual cost” (Peurifoy, Ledbetter, & Schexnayeder, 2002). Furthermore, the Time Valued Technology (TVT) method combines the minimum cost method with the mathematical modeling method. It “employs one or more predictive technology relationships to calculate the net present value (NPV) of several alternatives to replace the incumbent technology with rapidly

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emerging technology at different time periods over a selected time horizon" (Ochs, 2012). Ochs uses the minimum NPV of alternatives to determine the target replacement year of 250W halogen lights with LED streetlights. Ochs also makes key assumptions regarding the predictability of LED technological advancements through the use of Haitz's Law (Ochs, 2012).

Summary

This chapter provided an overview of the USAF contingency response water needs, relevant regulation, and policy considerations. An introduction of water purification alternatives and necessary considerations for each were presented. Additionally, the status of LED technology and mathematical techniques for predicting future improvement were explored. Finally, life cycle cost analysis and equipment replacement decision analysis were reviewed. The next chapter discusses the data collection, methodology, and analysis.

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III. Methodology

Chapter Overview

This chapter describes our methodology to analyze the financial tradeoffs of water purification utilizing Reverse Osmosis Water Purification Units (ROWPU) and Ultraviolet (UV) Light Emitting Diode (LED) purification units. We use several financial concepts to measure the effectiveness of the capital investment. First, economic analysis provides a systematic transformation of raw data into decision-making metrics, like life cycle cost (LCC) and net present value (NPV), while applying appropriate discount factors (AFMAN 65-506). Next, technology improvement projections are evaluated and applied to the NPV of the emerging LED technology alternatives. The point in time when the LED technology becomes a financially optimal decision (i.e., the technology adoption decision point) is then determined through the use of the Time Valued Technology method. Finally, sensitivity analysis is conducted to investigate the effect of several factors: fuel prices, performance improvement projections, discount factors, the number and length of occasions for which a water purification unit is utilized per year (also referred to as response events), the number of LED units required, and salvage value. Specifically, we use sensitivity analysis to examine the effect of these factors on each alternative's NPV and the technology adoption decision points.

Life Cycle Cost

Life cycle cost is "the total cost to the government for a system over its full life, including the cost of development, procurement, operation, support, and disposal" (AFMAN 65-506, 2011). Development and procurement costs (other than purchase

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costs) are generally applied to the life cycle cost of complex, undeveloped, government specific product acquisitions. The ROWPU and a limited number of UV LED purification units are currently commercially available. Neither alternative is intended exclusively for government use. Therefore, development and procurement costs are not included in the life cycle cost of either alternative. The purchase cost portion of procurement costs will be included. Operating and support costs include fuel, labor, repair and maintenance, chemical additive (chlorine), and replacement parts and filters. Disposal costs include salvage value and other costs associated with the disposal of the unit.

We determine the life cycle cost for the existing water purification product (the ROWPUs) as well as the emerging technology product (the UV LED purification units) on a functional basis. This means that the emerging technology must provide equivalent functions to that of the existing technology in order to be compared as an alternative. To establish equivalency, we first made the distinction that each response event would support a small contingency of approximately 550 personnel; each person would require 30 gallons per day which equates to 16,500 gallons per event per day (AFP 10-2019, Vol 5, 2013). A second consideration in establishing equivalency is the condition of the available water source. This is largely dependent upon the turbidity of water at the response location and cannot be predicted prior to making the equipment replacement decision. Although industry and Air Force subject matter experts expect the available water source to be below the required 60 NTU for UV LED purification, this might not be the case. Turbidity can increase above 100 NTU immediately following a heavy rainstorm or high volumes of runoff which are likely following some natural disasters

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(Fondriest Environmental, Inc., 2014). Therefore, we will make the comparison of purification alternatives under two cases of equivalency: at or below 60 NTU ("relatively clear" water) and above 60 NTU ("murky" water). Third, UV LED units are employed at six locations in a BEAR base setup; therefore, a minimum of six UV LED units are required for equivalency to one ROWPU. Note, UV LED units are not capable of desalination or chemical decontamination; consequently, this study is limited to only fresh water environments where the threat of chemical contamination is low.

Variables Impacting Life Cycle Cost

Unit Cost

The unit cost, also known as end item cost or purchase cost, is the cumulative cost of all components that make up a system. The baseline unit cost for the ROWPU is $248,500 which was determined by using GSA government contract pricing. This price is for the ROWPU only and does not include any other piece of equipment or item in the water production system.

A commercially available LED purification unit is used as the alternative to the ROWPU for this study. Details for this unit are contained in Appendix A. Unit costs are the sum of all parts making up the unit that provides equivalent capability. More specifically, the individual unit cost for the LED purification unit is the aggregate cost of the LED module and all pre-filters. The baseline cost of the LED purification unit is a multiple of the individual unit cost and number of systems required to produce potable water under equivalent terms to that of the ROWPU (see appendix A).

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The ROWPU is capable of producing potable water in relatively clear and murky water conditions. Conversely, the UV LED unit requires significantly different pre-filters for each water condition. When water is relatively clear, the manufacturer's recommended pre-filters are used. As turbidity increases above this threshold, additional pre-filters are required. Manufacturer recommendations were not available for these additional pre-filters; therefore, the researchers considered multiple options that would satisfy system requirements. Comparative evaluations of pre-filters used by the Red Cross as well other industries utilizing UV mercury bulbs for water purification were considered. Ultimately, a self-cleaning, multi-screen filter was selected based on its compatibility with the existing water production system, its ability to filter water at the required rate, and its ability to reduce the turbidity of the water prior to UV treatment. This selection provides an equivalent cost comparison of systems; however, further technical research is required to determine complete viability of this selection. Details for this filter are contained in Appendix A.

LED Bulb Cost

LED bulb costs are the main driver of the LED purification unit cost; therefore, we determine the overall portion of unit costs attributable to LED bulbs. Reduction in cost due to technological advancement of the LED lights was applied to this percentage of LED purification unit costs only. All other associated costs are assumed to be constant over the period of observation.

Number of Systems

A single ROWPU can produce clean water at an expected average flow rate of 1,500 gallons per hour. Individual LED purification units do not have flow rates

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equivalent to the ROWPU. By operating multiple LED units in parallel, an equivalent flow rate can be achieved. As the performance output of UV LED lights increases over time, so will the flow rate. However, flow rates are not only a function of UV LED performance output but also the efficiency of the reactor--the section of the unit where water is exposed to UV light. Efficiency of the reactor is a result of uncertain changes in materials and advances in proprietary engineering design. New materials and configurations are constantly being tested. Additionally, the reflective properties of materials used to line the reactor and the configuration of UV LEDs within the reactor differ by manufacturer and design. Therefore, due to the unpredictability of reactor efficiency improvements, the flow rate cannot be accurately forecast by this study. The flow rates for a single LED unit and the number of LED units required to match the output of a single ROWPU are listed in Appendix A.

Expected Life

The expected life of the ROWPU is 20 years. The expected life of the LED purification unit is driven by the expected life of the LED bulbs it contains. We anticipate that LED technology will continue to advance at a rapid rate with the expected life of the LED bulbs improving as well. However, the rate of improvement in life expectancy cannot be accurately predicted by this study. Therefore, the expected life of the current and future LED purification units is assumed to be equal to the current life of the LED bulbs contained in the system. The current bulb life is provided in Appendix A.

Number and Length of Response Events

Response events are the number of occurrences in a year for which the USAF deploys a water purification unit to sustain personnel in a location without the availability

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of clean, safe-to-use culinary water. Based on historical data and the expert opinion of USAF Item Managers and Career Field Managers, the number of responses and length of response events for this research are 2 per year and 30 days, respectively.

Labor Rate

The labor rate is the cost per hour of labor used to setup, monitor, train, maintain, or otherwise enable the use of either the ROWPU or UV LED units. The labor mixture used for set-up, training, and usage of the ROWPUs was provided by the United States Air Force (USAF) Career Field Manager. The applicable labor rates for the mixture were extracted from Table A20-1 of Air Force Instruction 65-503, U.S. Air Force Cost and Planning Factors. It is assumed that the same labor mixture and rates will be used for UV LED units.

Energy Costs

The ROWPU is powered by a diesel fueled generator. Diesel fuel costs are a mixture of how a piece of equipment is operated (in this case the number of operational hours used) and the cost of fuel (Peurifoy, Ledbetter, & Schexnayeder, 2002). To calculate the energy costs, a consumption rate for the most commonly used generator--the MEP 806B-Generator (5.06 gal/hour)--was multiplied by the fuel price and hours of usage for each year of operation. The 2016 average fuel cost ($2.49/gal) was obtained from the U.S. Energy Information Administration.

While UV LED units use much less energy and do not require a dedicated generator, they will require power from a diesel-powered generator in a response environment. Equation 1 was used to calculate the daily energy cost of the UV LED purification unit.

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$$\$\ \boldsymbol{per\ hour} = \frac{\boldsymbol{(W)}}{\mathbf{1000}} * \frac{\boldsymbol{P*C}}{\boldsymbol{L}} \qquad \textbf{(1)}$$

In Equation 1, *W* represents the electricity consumption (watts per hour) of the commercially available UV LED module (as obtained from the manufacturer's specification). Dividing by 1000 converts the usage rate to the standard electricity consumption rate of kilowatt per hour (kWh). Additionally, *P* represents the price of fuel ($ per gallon), *C* represents the generator fuel consumption rate (gallons per hour), and *L* represents the generator load capacity (kWh). The power consumption of the UV LED modules will decrease as they become more efficient, but this improvement projection is unknown and outside the scope of this research. The energy consumption of UV LED modules will be held constant at the rate provided by the manufacturer for the existing alternative. When additional pre-filters are required, energy consumption of the entire LED purification unit increases by the energy consumption of the additional pre-filters; these energy costs are included in the study.

Hours of Usage

Hours of usage is the total time the unit is operating during a single day of an event. Hours of use relates directly to the demand of the system which is driven by the number of individuals it supports. The hours of usage for each alternative also differs based on their efficiencies and innate operating capabilities. Production may be limited by available daylight, weather, access to the source, immediate needs of the force, or volatility of the situation (i.e. enemy activity). The ROWPU can produce the required

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16,500 gallons of water in 11 hours; therefore, this is used as the baseline requirement for all alternatives.

Setup and Teardown

We determined setup and teardown times based on input from both the users and the manufacturers of each product. The average setup time for the ROWPU is 4 hours and the average teardown time is 2 hours. These times are separate from the time it takes to setup or teardown the entire water production system.

Set-up for the UV LED units is assumed to require minimal or immaterial alteration of the existing water production system. Installation will be either in-line or at the point of use (at the faucet)--essentially a “plug and play” scenario. Therefore, expected setup and teardown times for the LED units are 20 and 10 minutes, respectively.

Maintenance Costs

Recurring maintenance costs include the costs to operate the system while non-recurring costs are realized due to scheduled overhauls. Maintenance costs include the repair, replacement parts, and filters. Labor hours, crew size, labor rate, and frequency were multiplied and added to material costs to calculate the total maintenance cost for a given task. Maintenance hours, crew size, and frequency were provided by the user community and the USAF Career Field Manager--see Table 4.

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1500GPH ROWPU Maintenance Time and Labor

Task	Labor Hours	Crew Size	Frequency
Water Quality Sample/Test	0.17	1	Hourly
Multimedia filter backwash	0.2	1	Daily
Bag Filter Maintenance	0.25	1	Daily
RO Element Cleaning	2.5	1	Weekly
Water Testing Equipment Calibration	0.17	1	Monthly or Teardown
Gauge Calibration	0.5	1	Monthly or Teardown
Chemical Feed Pump Maintenance	0.5	1	Monthly or Teardown
Raw Water Pump Motor Lubrication	0.08	1	Monthly or Teardown
RO Replacement	2	2	Annually
Visual Inspection	1	1	Annually
Operation	6	2	Semiannually

Table 4: 1500 ROWPU Maintenance

According to the USAF Item Manager, system overhauls occur twice over the useful life of the ROWPU--in approximately year 8 and 14. Highland Engineering, the ROWPU manufacturer, provided a cost of $39,900 per unit per overhaul. The cost of the reverse osmosis (RO) element replacement ($1681.25 per unit) was obtained from General Services Administration (GSA) contract pricing.

The LED purification units require no maintenance but do require regular replacement of some pre-filters. Pre-filters include the manufacturer recommended package for lower levels of water turbidity and additional filters for higher levels of water turbidity. The change out rate of the manufacturer recommended filters depends upon the turbidity and the measurement of suspended solids contained in the water. It is impossible to predict these values for future events and, thus, the exact change interval for the pre-filters. Pre-filters will be replaced at manufacturer recommended intervals (see Appendix A). Additional pre-filters will be replaced at the end of their usable life. Failure of the LED unit is easy to detect due to user friendly indicator lights monitored by

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any user. Therefore, no cost is attributed to monitoring the system. Additionally, there is no overhaul or scheduled maintenance for the LED units.

Salvage Value and Disposal Costs

ROWPUs are considered repairable, salvageable items. The salvage value and disposal costs for the ROWPU were provided by the USAF Item Manager and the OMB Circular. Disposal costs at the end of useful life is $4,000. The salvage value is calculated as 4.55% of the acquisition costs per remaining year of expected life (Office of Management and Budget, 2013).

UV LED units are not considered repairable. Once the useful life of the LED purification unit is reached, it is disposed and replaced. We assume the salvage value to be zero. The average cost of disposing 1 ton of garbage ranges from $67-$280 (Kinnaman, 2015). The UV LED purification units and accompanying pre-filters do not require special consideration when disposed. They are also not large enough to lead to a significant increase in the weight of garbage disposed or the cost of the waste stream. Therefore, we consider the disposal cost of these items to be zero.

Present Value

Life cycle cost was calculated as a present value. Present value is the value of a future sum of money in today's dollars after applying a return or interest rate. Larger interest rates equate to smaller present values. This method illustrates that a dollar today is worth more than a dollar tomorrow. The present value, PV, is calculated by discounting a future value, FV, by applying a constant yearly interest rate, i, over a period n years--see Equation 2.

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$$\boldsymbol{PV} = \frac{\boldsymbol{FV}}{(\mathbf{1}+\boldsymbol{i})^{\boldsymbol{n}}} \qquad \textbf{(2)}$$

The net present value, *NPV*, is the present value of a stream of discounted future payments received in years *1* through T. Equation 3 below provides the NPV formula.

$$\boldsymbol{NPV} = \sum_{\boldsymbol{t}=\mathbf{0}}^{\boldsymbol{T}} \frac{\boldsymbol{FV}_{\boldsymbol{t}}}{(\mathbf{1}+\boldsymbol{i})^{\boldsymbol{t}}} \qquad \textbf{(3)}$$

Discount Rates

The Air Force uses discount rates as opposed to interest rates. Discount rates assist the government in determining the value of a dollar tomorrow in today's dollars; this essentially represents the government's cost of borrowing. A discount rate is very similar to the minimum acceptable rate of return (MARR) utilized by industry. Discount rates are used to derive discount factors which are multiplied by the FV to calculate the PV. Discount rates are provided in Appendix C of the Office of Management and Budget (OMB) Circular A-94; these discounts rates are based on the interest rates on treasury notes and bonds with maturities of 3, 5, 7, 10, 20 and 30. Consistent with constant dollar analysis, real rates that coincide with the period of analysis are used for this thesis (AFMAN 65-506, 2011). The time domain for this project is 20 years and a 1.2% discount rate was used for this study.

Discount factors can be applied as an end-of year or mid-year factor. The costs in this study are assumed to occur in a steady stream rather than a lump sum at year-end. Additionally, funds are assumed to be distributed throughout the year rather than at the beginning or end. Therefore, mid-year factors will be utilized in this research (AFMAN 65-506, 2011).

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Constant Dollars

In addition to discounting, we normalize the cost data to account for inflation. Adjustments from the year in which costs are incurred are normalized to the base year of the analysis. Energy rates are escalated according to the Department of Energy indices. Energy escalation rates are published annually by the National Institute of Standards and Technology (NIST) in Handbook 135 and were used to inflate fuel prices through the expected life of each alternative (AFMAN 65-506, 2011). Adjustments to all other costs are accomplished through the use of the Joint Inflation Calculator which was published in January 2016 by the Naval Center of Cost Analysis.

Emerging Technology Forecasts

UV LEDs are a developing technology that has been improving and will continue to improve at rapid rates (Cortelyou, 2014). Technology specific forecasts are a required element in the use of the Time Valued Technology comparison technique. It must be incorporated when determining the NPV of the LED alternative to accurately reflect this improvement in both cost and performance. Haitz's Law is an advancement forecast developed for LEDs in all visible ranges of the light spectrum that predicts an exponential improvement of LED technology. It states that for every decade the cost per lumen (unit of useful light emitted) falls by a factor of 10 and the number of lumens generated per LED package increases by a factor of 20 for a given wavelength of light. While the UV spectrum is also measured in lumens, the industry recommended comparison measurement differs slightly from the visible spectrum. The output of the UV LED is the amount of energy emitted; it is measured in milliwatts (mW) and is directly related to the

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effectiveness of the LED in the purification process. Cost is linked to the output and measured in dollars per milliwatt of output. Both have been proven by industry to be better indicators of UV LED performance than the typical lumen and dollar per lumen metrics. While the variables differ slightly from Haitz's Law, the modified units were assumed to be applicable to these measurements, and thus, UV LED projections as well.

Evaluation of the historical data provided by industry revealed that improvements in the UV spectrum loosely follow the Haitz's Law predictions. This particular spectrum of LEDs is so new, that a conclusive determination for the applicability of Haitz's Law as a cost and improvement predictor could not be made. To determine if a more accurate prediction curves exist, the researchers conducted regression analysis--a technique widely used for prediction and forecasting. Specifically, two independent regression analysis were run--one on the industry cost data and one on the industry performance output data. Industry data is shown in Appendix A.

Historical performance and cost data passed the tests for assumptions of normality, homoscedasticity, and serial correlation. Two-tailed t-tests were then used to verify statistical significance at an alpha of .05. An ordinary least squares, bivariate regression of the performance output data revealed a quadratic equation that predicts improvement at a rate 15% faster than predicted by Haitz's Law. This means that instead of an increase in performance by a factor of 20 for every decade, the increase is by a factor of 23. The model was statistically significant with a p-value of .0214 and had an R^2 of 0.6139. An ordinary least squares, bivariate regression of the cost data revealed an exponential equation that predicts a larger decrease in cost than Haitz's Law. Instead of decreasing by a factor of 10 per decade as predicted by Haitz's Law, the cost decreases

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by a factor of 20. The initial decline predicted by the regression equation is much more rapid than Haitz's Law, but in the long run, both converge to a similar value—this value equates to fractions of a cent per mW. The model was statistically significant with a p-value of .0000 and had an R^2 value of 0.9147. Both Haitz's Law and the regression equations were applied to the emerging technology independently to form a comparison of the different improvement curves.

Time Valued Technology

Time Valued Technology is an analysis technique based on engineering economics that compares the net present values (NPV) of alternatives while accounting for rapidly changing technology. The Time Valued Technology technique identifies a point in the ROWPU and LED purification unit life cycles where the cumulative cost of ownership is at its minimum. As part of our comparison, we consider the range of possible adoption years of the new alternative. In this technique, the NPV equation is modified as shown in Equation 3. By minimizing the NPV with respect to *j*, it is possible to determine the most cost effective time to replace the incumbent technology. This equation assumes that the incumbent technology will remain in place until year *j-1* after which the emerging technology will be used for the remainder of the time horizon.

$$\boldsymbol{NPV(j) = \left(\sum_{t=0}^{j-1}(I_t * D_t) - S_t * D_t\right) + \sum_{t=j}^{T}(E_t * D_t)} \qquad \textbf{(4)}$$

$$\boldsymbol{Where\ 0 \leq j \leq J}$$

In Equation 4, *j* represents the year the new technology is adopted, I_t represents the cost in year *t* to operate the incumbent technology (ROWPU), E_t represents the cost in year *t* to operate the emerging technology (UV-LED), S_t represents the salvage value at the end

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of period *t*, and D_t represents the discount factor for period *t*. As discussed earlier in this chapter, the discount factor is the conversion factor used by the USAF to translate the value of future dollars into a present value. For this study, the base year (t=0) is equivalent to the beginning of 2016, and we consider a decision time frame of 20 years (i.e., T=20). Equation 3 is evaluated assuming the incumbent technology is replaced by an alternative in period *j* where *j* ranges from 0 to J and J is the last year of usable life for the incumbent technology.

Sensitivity Analysis

The appropriate time to acquire new technology is a complex decision. Reliance on fixed values or factors used in making the determination would be a flaw in the evaluation process. By conducting sensitivity analysis on key input factors, we can determine how robust our replacement decision is with respect to different inputs. Several sensitivity analyses were conducted in this study to better understand each factor's relationship to the optimal technology adoption decision point. Specifically, sensitivity analysis was conducted on operational costs (fuel), the LED cost and performance improvement rates (regression analysis vs. Haitz's Law), the number and length of response events, the discount rates, the number of LED purification units required, and the salvage value of the ROWPU.

Electricity in a response environment is produced by diesel powered generators. Fluctuations in fuel costs directly affect annual operating costs and the NPV of the alternatives. They have the potential to significantly impact the technology adoption decision point. The average monthly diesel fuel prices for 2009-2016 were obtained from

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the U.S. Energy Information Administration--see Figure 13. The fuel prices fluctuate from approximately $2.00/gal to $4.70/gal and do not follow a discernable pattern. Sensitivity analysis was conducted over this range.

Figure 13: Historical Diesel Fuel Prices

Predicted improvement curves may not accurately forecast what will actually be experienced by the UV LED industry. Haitz's Law, the LED industry predictor, is used as a comparative tool in this sensitivity analysis. LED improvement could potentially slow beyond or occur more rapidly than expected; therefore, an additional +/- 25% change to the improvement curve was analyzed.

Response events, which are often the result of natural disasters or wartime contingency operations, are unpredictable. In order to determine if the replacement decision is affected by the number of events, we analyze 2, 4, and 6 responses per year. Additionally, the length of response is difficult to predict and could impact the technology adoption point, so we consider response event lengths of 30, 60, 75, and 90 days.

Discount rates set by the OMB are not intended to be absolute. They are a prediction of real interest rates from which inflation has been removed and are based on

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economic assumptions (Office of Management and Budget, 2013). The chosen discount rate can have a big impact on the discounted cash flows and dramatically change the present value of alternatives. The Air Force recommended +/- 25% sensitivity on the discount rate is used (AFMAN 65-506, 2011).

Summary

UV LED water purification is a rapidly emerging technology which could prove advantageous as a replacement for our current capability--the ROWPU. Although not equivalent to the ROWPU on a one for one basis, LED purification units are expected to provide the same functionality in fresh water environments but at higher efficiency rates and a much lower cost in the near future. This chapter describes the methodology used by the researchers to investigate the specific point in time when this will occur. Financial methods used to accomplish this include economic analysis techniques, life cycle cost, net present value, and the Time Valued Technology method. Furthermore, sensitivity analysis was used to determine how specific variables effect the net present value of alternatives and technology adoption decision point. The next chapter will discuss the results of this research.

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IV. Analysis and Results

Chapter Overview

In this cost benefit analysis, our goal is to determine a strategy to satisfy our water purification needs over the next 20 years for contingency and humanitarian responses. To do so, we must consider an impending equipment replacement decision between three equipment alternatives: 1) continue operating the existing Reverse Osmosis Water Purification Unit (ROWPU) equipment, 2) replace the currently owned ROWPU with a new ROWPU, and 3) replace the currently owned ROWPU with an Ultraviolet (UV) Light Emitting Diode (LED) purification unit. For easy reference, they are labeled "incumbent", "renewal", and "emerging" alternatives, respectively. Additionally, the set of alternatives are considered under two independent conditions. Conditions were defined by the state of water expected in the response environment--relatively "clear" (less than 60 NTU) and "murky" (greater than 60 NTU). This chapter discusses the results of our analysis. First, we examine the values of renewal and emerging alternatives based on the net present value (NPV) for the 20-year time span to determine if one alternative is dominant over the other. Next, the technology adoption decision point is determined through the use of the Time Valued Technology (TVT) technique. Finally, we conduct sensitivity analysis on fuel prices, performance improvement projections, discount factors, the length and number of response events per year, and the number of LED units to illustrate how these factors affect the technology adoption decision point.

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Economic Analysis Results

Economic analysis (EA) is a method used to make rational decisions among competing alternatives and assists in setting the stage for the equipment replacement decision. Our initial analysis is conducted to determine whether any replacement decisions are dominated by others thus eliminating them from our TVT analysis. First, the procurement, operation, support, and disposal costs are used to formulate the base-line costs of each alternative. The base-line costs for the renewal alternative are listed in Table 5. Note, the overhaul cost in Table 5 is per occurrence and two overhauls are required during the 20-year usable life of a ROWPU. ROWPUs are capable of operating in relatively clear and murky water conditions without modification. The LED units, however, require additional pre-filters to operate in murky water. To denote the difference based on these conditions, a distinction was made between the alternatives. "Emerging (C)" represents the LED unit for relatively clear water conditions (i.e. when turbidity less than 60 NTU). "Emerging (M)" represents the alternative for murky water conditions (i.e. when turbidity is greater than 60 NTU). The base-line costs for the LED alternative in both cases are in Appendix A.

	RENEWAL
CAPITAL COSTS	
EQUIPMENT	$248,500.00
OVERHAUL*	$39,900.00
TOTAL	$288,400.00
O&M COSTS PER YEAR	
OPERATING LABOR	$6,133.58
FUEL	$7,797.32
PARTS AND MAINTENANCE	$3,362.50
TOTAL	$17,293.41

Table 5: ROWPU Cost Summary

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Next, the baseline costs are used to formulate the NPV of alternatives over the 20-year time period. The salvage values of alternatives at the end of the period are included as inflows (negative dollar amounts) in the final period of cash flows. The emerging (C) and emerging (M) costs are the total cost of all LED purification units necessary to provide a flow rate equivalent to one ROWPU (see Appendix A). Table 6 shows the results of this analysis for clear water purification alternatives. Table 7 shows the results for murky water purification alternatives. All values are presented in FY16 dollars.

	RENEWAL	EMERGING(C)
NET PRESENT VALUE (W/O SALVAGE COSTS)	$759,845.16	$323,918.00
DISCOUNTED SALVAGE VALUE	($4,654.99)	$0.00
NET PRESENT VALUE (W/ SALVAGE VALUE)	$755,190.16	$323,918.00

Table 6: NPV of Alternatives for Clear Water Purification

	RENEWAL	EMERGING(M)
NET PRESENT VALUE (W/O SALVAGE COSTS)	$759,845.16	$592,002.43
DISCOUNTED SALVAGE VALUE	($4,654.99)	$0.00
NET PRESENT VALUE (W/ SALVAGE VALUE)	$755,190.16	$592,002.43

Table 7: NPV of Alternatives for Murky Water Purification

The NPVs of the emerging alternatives are lower than the renewal alternative; however, further evaluation is required to show dominance of one alternative over the other. First, we evaluated alternatives in the clear water case. Figure 14 shows the operating costs and Table 8 shows the capital costs of alternatives for clear water conditions.

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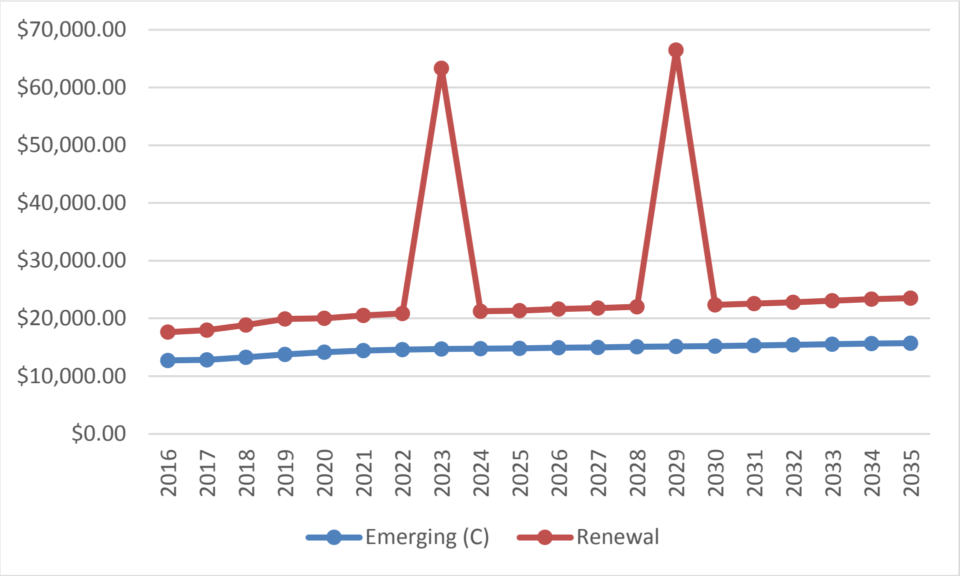

Figure 14: Operating Costs of Clear Water Alternatives

Emerging (C)	Renewal
$30,557.84	$248,500.00

Table 8: Capital Costs of Clear Water Alternatives

In every year, operating costs for the emerging (C) alternative are lower than the renewal operating costs. The capital costs of the renewal alternative are constant over the 20-year period and will never decrease no matter what time period it is realized in. Capital costs of the emerging alternatives include all purchases of LED units over the 20-year period. Additionally, based on the prediction of UV LED cost improvement, we can conclude that overall capital costs of the emerging (C) alternative will continue to decrease over time. From these observations, we conclude that there will never be an instance when the NPV of the renewal alternative is lower than the NPV of the emerging (C) alternative. Thus, if the replacement decision is based on the assumption of relatively clear water, we will always replace the incumbent with the emerging (C). The emerging (C) alternative

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is dominant, and therefore, we do not need to include the renewal alternative in our TVT analysis.

Figure 15 shows the operating costs and Table 9 shows the capital costs of alternatives for murky water conditions.

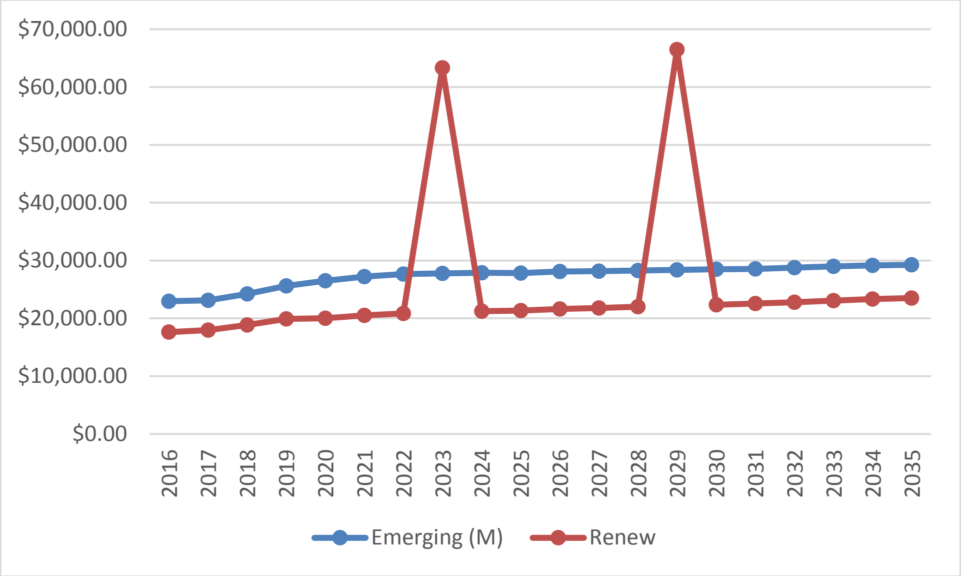

Figure 15: Operating Costs of Murky Water Alternatives

Emerging (M)	Renewal
$44,146.34	$248,500.00

Table 9: Capital Costs of Murky Water Alternatives

Capital costs for the emerging (M) alternative are, and will always be, lower than the capital costs of the renewal alternative. Neither alternative dominates the operating costs as the cost of pre-filtering for the emerging technology increases the annual operating cost to a level that is greater than the cost of the renewal option for all years except when overhauls of the ROWPU system occur. Therefore, both alternatives will be included in the TVT analysis for murky water conditions.

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Time Valued Technology

The Time Valued Technology (TVT) method uses the periodic costs of the alternatives to compute the NPV for a given decision period (i.e., NPV(*j*)). To calculate this, the NPV of the incumbent alternative is combined with the NPV of replacing it with the emerging alternative. As a reminder, in the TVT equation, the variable *j* represents the decision period. It assumes that the incumbent technology operates through the end of period *j-1*, the replacement alternative is procured in the beginning of period *j*, and operational capability begins immediately. Since the Air Force acquired most of its ROWPU inventory in 2009, the incumbent alternative is considered to be 8 years old with 12 years of usable life remaining at *t=0*. When selecting from the available alternatives, it is only possible to choose the incumbent alternative until the end of its usable life. After this point, the decision maker is left with only one alternative in the clear water case--emerging (C)--and two in the murky water case--the renewal or emerging (M). If the replacement decision is delayed beyond 2028, the user would experience an unacceptable gap in water purification capabilities. Once the renewal or emerging alternative is selected, it is assumed to be used until the end of year 20. In the case of the emerging alternative, the LED units will be repurchased only at the end of each serviceable life. Therefore, NPV(*j*) values only need to be determined through 2028 (i.e., *t=12*). The results of this analysis are shown in Figure 16 for the clear water conditions and Figure 17 for the murky water conditions.

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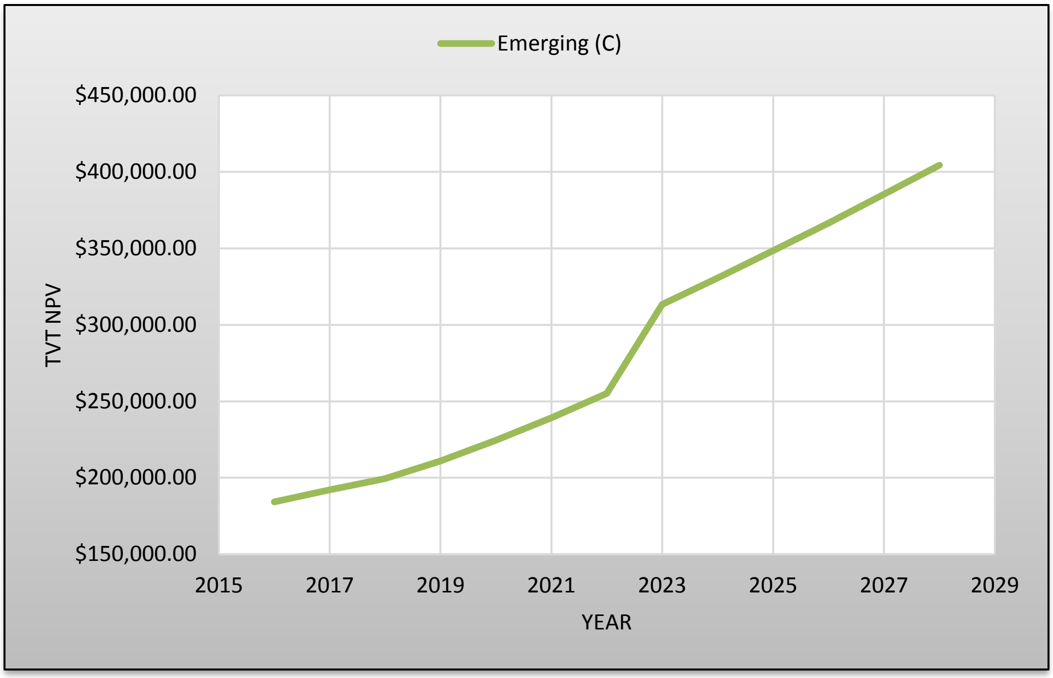

Figure 16: TVT Results for Clear Water Conditions

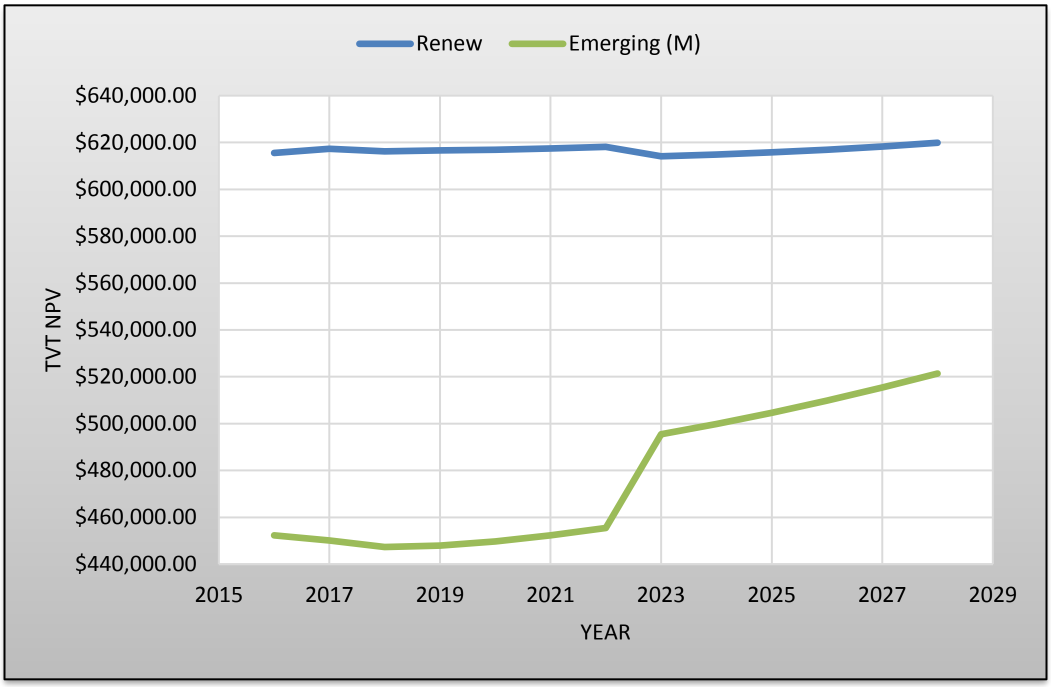

Figure 17: TVT Results for Murky Water Conditions

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In TVT analysis, the optimal decision point is identified by the minimum NPV. For the clear water case, this occurs in the first year at an NPV(*j*) of $184,237. The values rise at an average rate of about $11,819 per year until 2022 when the value increases significantly. This is due to the last overhaul of the incumbent technology in that year. Between 2016 (the optimal year of replacement) and 2019, increases in TVT range from 5% to 14.5%. This means that the cost risk for delaying the replacement of a single ROWPU is small; however, when large portions of the Air Force ROWPU inventory are considered for replacement, the risk would amplify the overall cost difference significantly.

When considering murky water conditions, the NPV(*j*) of the emerging (M) alternative is always lower than the renewal alternative--renewal is never the better alternative. The minimum NPV(*j*) for emerging (M) occurs in 2018 at an NPV of $447,322. The increase in NPV from 2018 to 2022 is only $1243. The cost risk of delaying the decision from one to three years is very low in this case. It may be advantageous to delay the decision and allow more time for the emerging (M) technology to improve and mature.

Sensitivity Analysis

All sensitivity analysis results are summarized in Table 10 and Table 11. The base case for exclusion of the renewal alternative in the clear water case no longer holds when running sensitivity analysis. It is included to determine if the input changes cause a shift in the decision; notably, this never occurs. Further details of the results will be discussed in this section.

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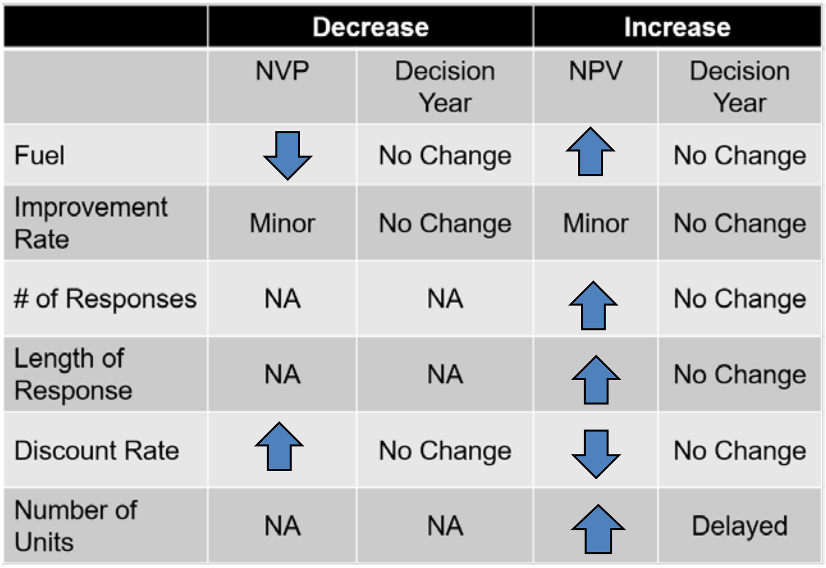
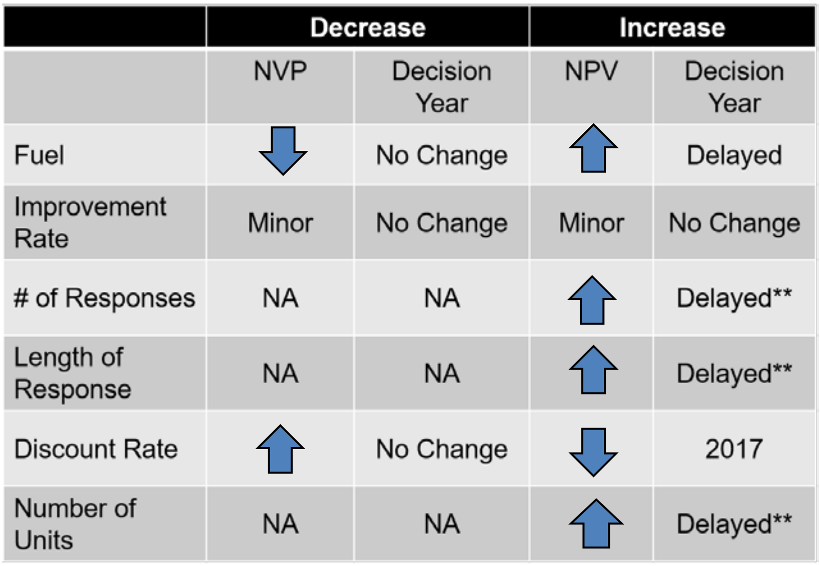


	Decrease		Increase	
	NVP	Decision Year	NPV	Decision Year
Fuel	⇩	No Change	⇧	No Change
Improvement Rate	Minor	No Change	Minor	No Change
# of Responses	NA	NA	⇧	No Change
Length of Response	NA	NA	⇧	No Change
Discount Rate	⇧	No Change	⇩	No Change
Number of Units	NA	NA	⇧	Delayed

Table 10: Sensitivity Results for Relatively Clear Water



	Decrease		Increase	
	NVP	Decision Year	NPV	Decision Year
Fuel	⇩	No Change	⇧	Delayed
Improvement Rate	Minor	No Change	Minor	No Change
# of Responses	NA	NA	⇧	Delayed**
Length of Response	NA	NA	⇧	Delayed**
Discount Rate	⇧	No Change	⇩	2017
Number of Units	NA	NA	⇧	Delayed**

**indicates a change in the optimal decision at some point in the sensitivity

Table 11: Sensitivity Results for Murky Water

Fuel Prices

Fuel costs are a significant portion of the overall cost of both systems; they account for 36-49% of the ROWPU life cycle costs and 38-45% of the LED unit life cycle costs. Fuel prices were varied from low to high values within the historical price

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range. The overall NPV in the clear water case increased as fuel prices increase, but the optimal decision year does not change. The change in NPV for a given change in fuel price are shown in Figure 18.

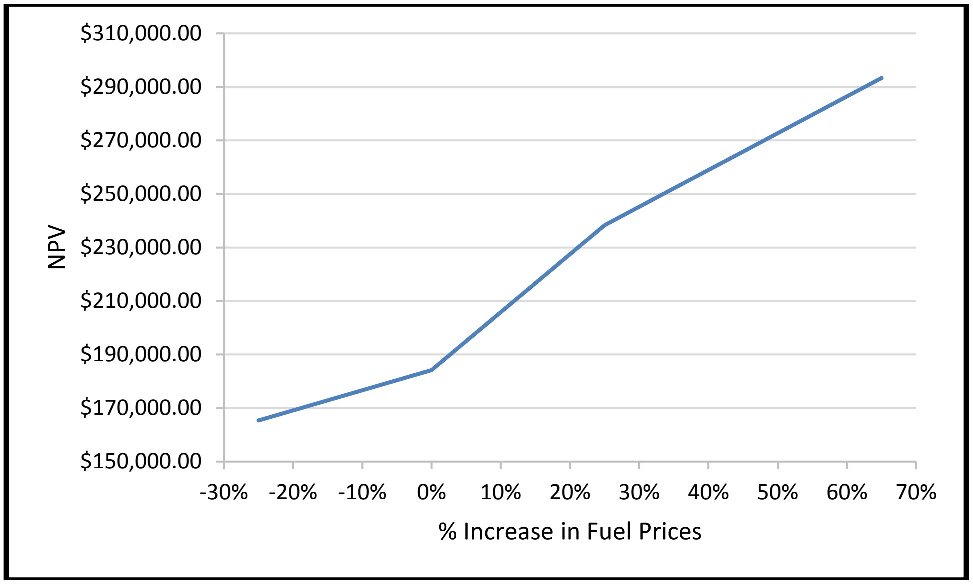

Figure 18: Fuel Sensitivity for Clear Water Case

In the murky water case, the effect of fuel sensitivity on the overall NPV and optimal replacement decision year are shown in Figure 19. The optimal decision never shifts from emerging (M) to renewal. However, as fuel prices increase, the optimal decision year to select emerging (M) changes. For example, when fuel prices increase by 45%, the optimal decision year moves from 2018 to 2022 and the overall NPV increases from $447K to $649K. Because of the large refurbishment costs realized in 2022 for the incumbent alternative, the replacement year hovers at 2022 until fuel costs increase by 220% (~$5.50 per gallon). This large increase is not unrealistic for war time or humanitarian responses as fuel prices could easily rise above this amount in extremely isolated areas.

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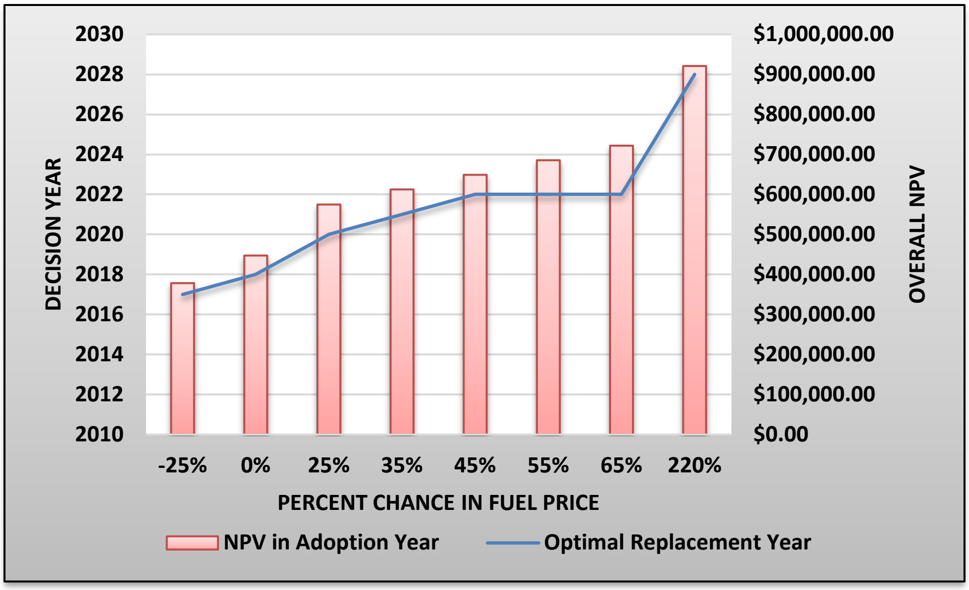

Figure 19: Fuel Cost Sensitivity for Murky Water

Improvement Rate

The rate of technological advancement was formulated through a regression analysis of historical cost and performance data. It is possible that this rate will not hold true to the actual improvement rates. Improvement rates were slowed by 0-25% and hastened by 0-35% from the predicted rate. This caused no change to the optimal decision point and only minimal change in the overall NPV for both the clear and murky water conditions. Improvement was also compared to Haitz's Law predictions--see Figure 20 and Figure 21. The NPV curves--based on either Haitz's Law or the regression improvement prediction--have very similar shapes under both water conditions. When using Haitz's Law as the improvement predictor, the optimal decision point is shifted to 2017 and, in the murky water condition, the NPV curve is shifted down.

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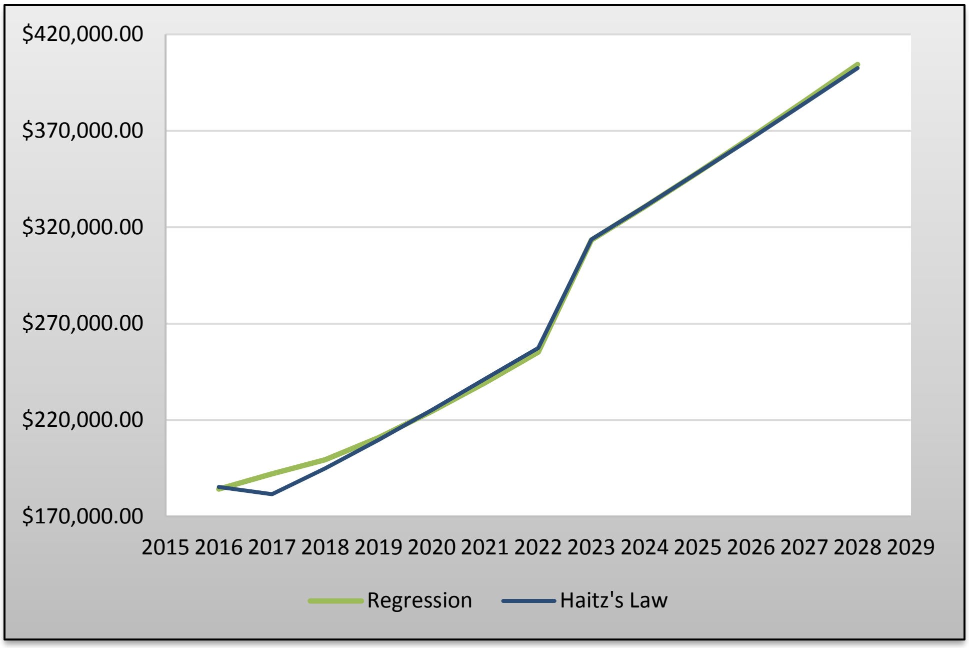

Figure 20: Regression vs. Haitz's Law Clear Water

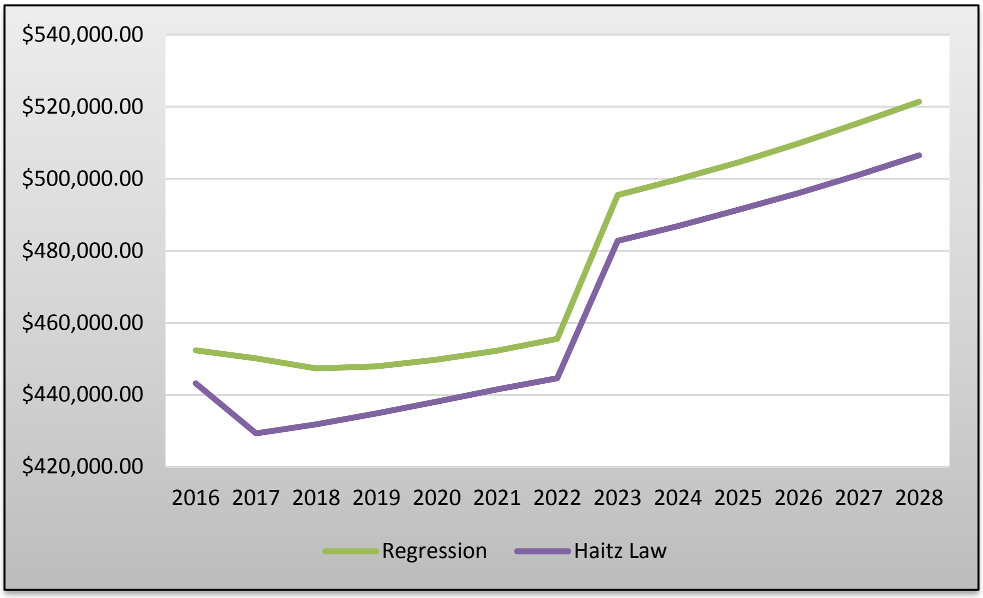

Figure 21: Regression vs. Haitz's Law Murky Water

Number and Length of Responses

The number and length of response events is unpredictable and could vary drastically depending on the status of war or number of humanitarian aid responses each

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year. When running this sensitivity analysis, it is important to note that the LED unit's usable life is provided by the manufacturer in usage hours. Utilizing the assumed number of operating hours, number of responses, and length of responses this value was translated into years. Because usable life is based on the number and length of responses, a change in either of these factors also affects the years of usable life. Consequently, the number of LED unit repurchases made within the time domain also changes. This was accounted for in the NPV calculations. For both water conditions, increases in the number of responses or length of the responses increased the total NPV. In the clear water conditions, there were no changes to the optimal decision point or alternative. In the murky water condition, the optimal technology adoption decision year was delayed as the number of responses or length of response increased. Additionally, when there were more than 4 responses or the length of response reached 67 days or more, the alternative selection shifted to renewal (see Figure 22 and Figure 23).

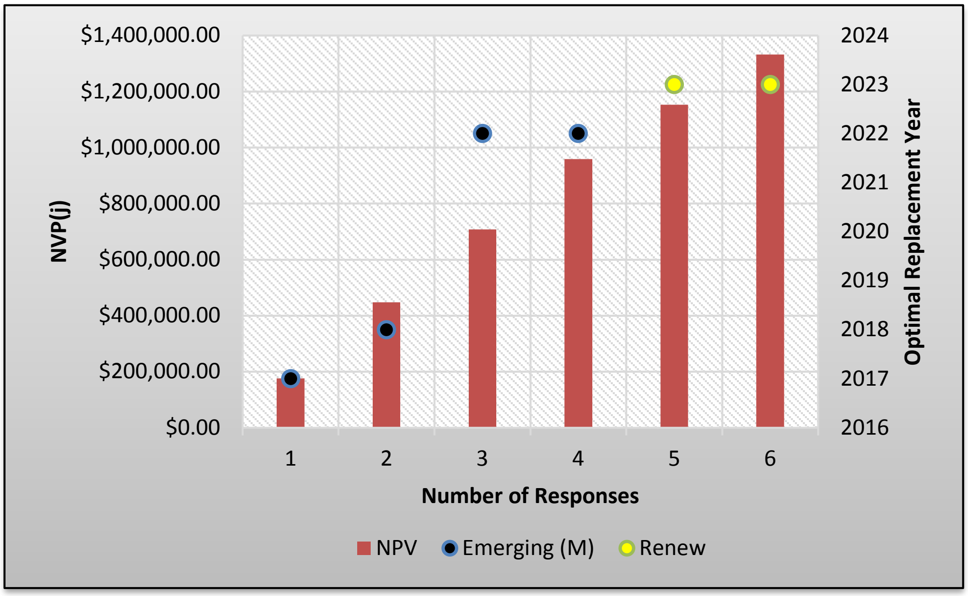

Figure 22: Number of Response Events Sensitivity for Murky Water

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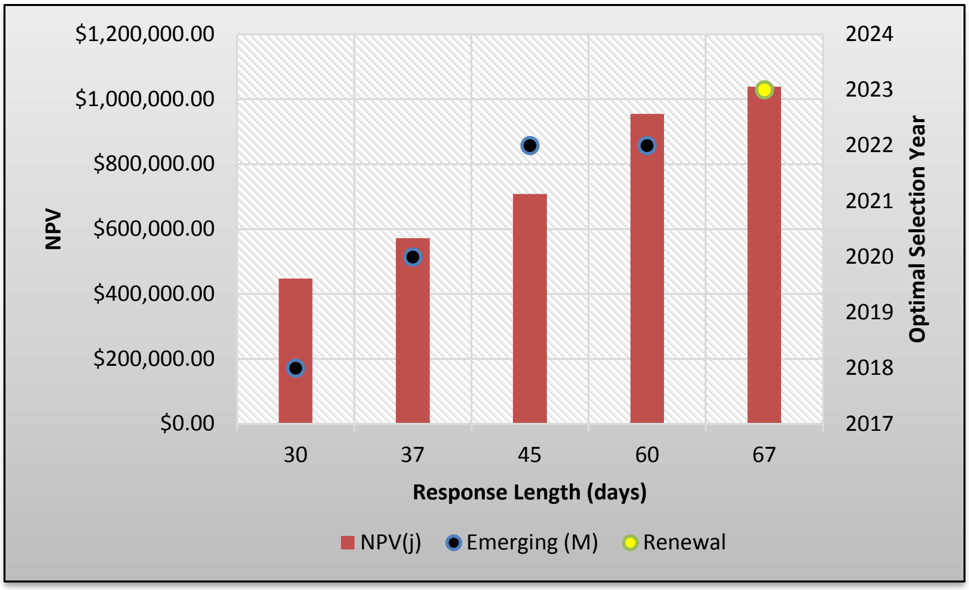

Figure 23: Length of Response Events Sensitivity for Murky Water

Discount Rates

Discount rates were evaluated at an increase and decrease of 25%. An increase in the discount rate (higher interest rate) represents a smaller discount factor, while a decreased discount rate (lower interest rate) represents a larger discount factor. In the clear water case, neither an increase nor decrease had any effect on the optimal adoption decision point for the emerging (C) alternative. In the murky water condition, the only change occurred when the discount rate was increased; the result shifted the optimal decision year from 2018 to 2017.

Number of LED Units

Although the number of units required for an equivalent flow rate was calculated based on manufacturer specifications, the operational application of UV LED technology may require more units than originally anticipated. For example, users may need more clean water access points (faucets) for potable water than assumed in the base case. The

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optimal technology decision point is delayed for every increase in quantity under both water conditions--see Figure 24 (clear water) and Figure 25 (murky water). In the murky water case, as the quantity increases over 125% (and every increase after that), the optimal alternative shifts from emerging (M) to renewal. This increase may be feasible depending on the usage needs, environment, or mission of the response. An operational implementation analysis should be conducted to definitively outline the required number of units to meet the needs of the force.

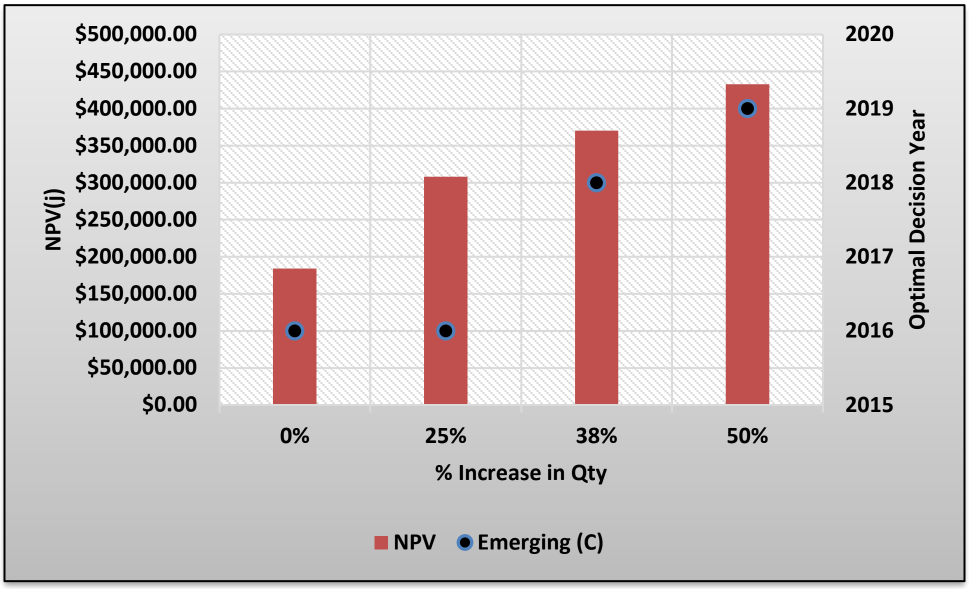

Figure 24: LED Quantity Sensitivity for Clear Water Case

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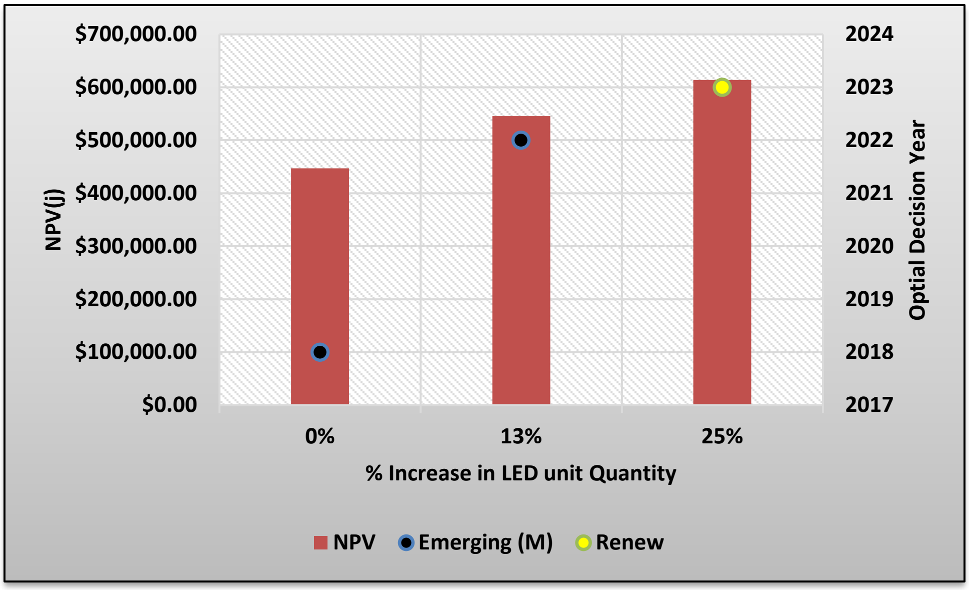

Figure 25: Increase LED Unit Quantities

Salvage Value of the ROWPU

The final sensitivity analysis was conducted on the salvage value of the ROWPU. The salvage value is estimated as a percentage of acquisition costs. Depending on market fluctuations and customer preference (i.e., in the price of scrap, the practicality of the incumbent technology, etc.), this value is subject to change. It was varied from 0 to the recommended 4.55%. An increase over 4.55% would be greater than a straight-line depreciation of the ROWPU and is not expected. Under clear water conditions, as the salvage value dips below 2%, the optimal decision point is delayed to 2018. For murky water conditions, salvage values below 3.5% delay the optimal decision point to 2022. The reason for the delay is because the salvage values are counted as negative cash flows for the ROWPU and act favorably to an early replacement decision by decreasing the overall NPV.

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Summary

This chapter detailed the results of the economic and Time Valued Technology analyses considered in this study. Economic analysis results clearly show that purchasing a new ROWPU is never the preferred alternative in relatively clear water environments. Time Valued Technology was used to evaluate the optimal decision point for both clear and murky water environments. The optimal replacement years are 2016 and 2018 for clear and murky water environments, respectively. In both water environments, the overall NPV is sensitive to the price of fuel, the number and length of responses, the number of LED units required, and the salvage value of the ROWPU. In clear water environments, the optimal decision point is only sensitive to the LED unit quantities and the salvage value of the ROWPU.   In murky water environments, the optimal decision point is sensitive to fuel prices, the number and length of responses, the discount rate, the LED unit quantities, and the salvage value of the ROWPU. In murky water conditions, the optimal alternative is sensitive to the number and length of responses and LED unit quantity. Overall, even though LED units cannot replace a ROWPU on a one for one basis, adoption of this technology within the next decade displays a promising cost benefit for the USAF.

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V. Conclusions and Recommendations

Chapter Overview

This study sought to analyze the cost benefits of emerging Ultraviolet (UV) Light Emitting Diode (LED) water purification techniques to the United States Air Force. To do so, the cost benefit analysis applied economic analysis and Time Valued Technology techniques to discover the optimal technology adoption point and the associated cost. Two separate water conditions were considered--relatively clear (turbidity less than 60 NTU) and "murky" (turbidity greater than 60 NTU). This chapter concludes the findings of this research and recommends actions and future research for the Air Force.

Addressing the Research Questions

The specific results of the cost benefit analysis provide answers for our three research questions.

1. **Do the costs justify UV LED water purification technology adoption and at what price point will this occur?**

   Yes, the Air Force could realize a cost savings by adopting the UV LED technology in either water condition. Price points are shown in Appendix A.

2. **When will the UV LED purification options be more cost effective than the incumbent technology?**

   In relatively clear water cases, UV LED technology is unequivocally the better option at the current price point and should be adopted immediately. In more turbid water, time should be allowed for the improvement of LED technology before adopting it in 2018. This delay allows the LED technology and capabilities to mature and costs to decline.

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3. **How do various input factors (such as energy costs, maintenance and operation costs, etc.) impact the decision?**

   In the clear water condition, the optimal decision point is only delayed by an increase in the quantity of LED units required or a decrease in the ROWPU salvage value. In the murky water condition, the decision year is delayed by increases in the price of fuel, the number and length of responses, the quantity of LED units required, and decreases in the salvage value. Additionally, when there are more than 4 responses, response length is longer than 67 days, or the quantity of LED units is more than 125% of the baseline, the optimal alternative is to purchase a new ROWPU and not LED purification units.

Conclusions

Methods applied in this study allowed the researchers to evaluate the rapidly changing technology and cost improvements of UV LED purification units for fresh water sources when the risk of chemical contamination is low. The analysis revealed that, in clear water conditions, the adoption of UV LED purification units is the best alternative and purchasing a new ROWPU is never the optimal decision. When relatively clear water is expected, the optimal decision point is 2016. When more turbid water is anticipated, the optimal decision point is 2018. However, there is a very small loss in benefits by allowing the LED technology more time to develop and mature before making the replacement decision. The difference between the NPV of the LED alternative in 2018 and 2022 is less than 2%.

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Sensitivity analysis indicated that decreases or increases in the price of diesel fuel, the number of responses, or length of responses have similar effects on the overall NPV. As fuel reaches the upper end of observed prices--around $4/gal--the technology adoption decision point stalls at 2022. This is due to the high overhaul cost for the incumbent technology that is not offset by the increase in energy costs. Adjustments to the rate of improvement, including adjusting the rate to reflect Haitz's Law, have little effect on the replacement strategy. Using Haitz's Law to predict improvement is the only adjustment that effects the replacement decision; this change causes a delay in the optimal adoption decision point to 2017 for clear and murky water. Adjustments to the discount rate also produce little change in the replacement strategy. The only change in the replacement decision occurs in the murky water condition; when the discount rate is increased by 25%, the optimal decision year is delayed to 2019. The factors that had the greatest effect on the overall technology adoption decision point were the number of responses, length of responses, and the quantity of UV LED units required. When the number or length of responses increase by more than a factor of 2, the optimal alternative becomes the ROWPU with an optimal decision year of 2023. A minor change to the LED quantity requirement could delay adoption of emerging technology to 2022 for both water conditions. In murky water conditions, increases in quantity above 125% also shifted the preferred alternative from the LED units to the ROWPU. This shows that it is very important to establish a definitive requirement for the number of units prior to the adoption of the emerging technology. Finally, decreases in the salvage value of the ROWPU will delay the adoption decision point because of the positive effect that salvage values have on the overall NPV for both water condition.

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Significance of Research

Research on emerging UV LED water purification alternatives for use by the U.S. Air Force has not previously been conducted. This thesis established the potential financial benefits of considering emerging technology alternatives through the evaluation of improvement predictions in combination with existing financial analysis techniques. Specifically, this thesis provides an analysis of the equipment replacement decision to satisfy water purification requirements in terms of total present value and the optimal replacement year. Additionally, it evaluates sensitivities that may affect both the overall alternative selection and technology adoption decision point.

There were some limitations to this study. First, techniques used in this thesis are intended to help decision-makers consider the best time and price point to purchase equipment, as opposed to just the earliest possible replacement time. However, cost is only one of many factors that need to be considered by decision-makers. Other key factors--that can play a role in determining the best equipment replacement alternative and should be evaluated--are security risks, regulatory constraints, the size of response location footprints, and availability of fuel resources. For example, in situations where the footprint is restricted or fuel is scarce, the UV LED purification unit is clearly the better choice and enables greater flexibility in response package decisions. However, other situations lend themselves to selection of the ROWPU. Second, adopting UV LED technology requires alterations to the existing water production system. These alterations, while based on sound assumptions, are currently theoretical and have not been tested. The true usability of the UV LED technology would require operational testing. Finally, using UV LED based systems may require a shift in the mindset of the

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technical expert and user community. The infancy of the UV LED technology could cause some doubt in its ability to adequately purify a water source.

Recommendations for Future Research

Future research should further investigate the functional application and required modifications for the inclusion of the UV LED purification units into contingency event response water production systems. If possible, necessary alterations and changes to operations should be quantified and applied to the cost analysis conducted in this study. Future research could also consider the cost of water as a commodity. Lastly, UV LED purification alternatives could be evaluated on larger scales for existing U.S. Air Force owned or operated culinary water systems. This could result in additional cost savings and the possible elimination of chlorine additives in drinking water.

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Appendix A

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14. ABSTRACT
The Air Force is a rapid mobile force responsible for national defense and reaction to calls for humanitarian aid across the globe. Rapid Global Mobility is a major tenant of the Air Force strategy. It provides the nation its global reach, underpins its role as a global power, and ensures that tomorrow, just as today, the United States can respond quickly and decisively to unexpected challenges to its interests. The ability to produce or acquire potable water is an essential piece of this tenant. Reverse Osmosis Water Purifications Units (ROWPUs), the workhorse for all military units, provide all the necessary capability but do so at an extraordinary capital and ownership costs. A 1500-gal per hour rated ROWPUs requires a dedicated 60kW generator, frequent element and disposable filter replacement, as well as regular overhauls at cost of nearly $40K per unit per occurrence. Developing LED UV technology are expected to make purification systems more robust, efficient, and cheaper than ever before. This research investigates UV LED emerging technology to see if it exists as a near term more cost effective alternative.

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