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Water Reclamation for Remote Environments: an Ecologically Sound Approach

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[Abstract] The objective of this paper is to explore the provision of clean, safe and healthy water to people living and/or working in extreme or remote environments by efficiently recycling waste water in a cost-effective and ecologically sound manner. Efficient, cost-effective, and environmentally friendly methods for reclaiming or regenerating used waste water to high standards of purity must employ low cost, low energy processes, and locally available resources, just as the earth itself does. The methodologies so developed will advance the goals of exploring the near-earth solar system, but just as importantly, they will also minimize adverse impacts on the local environment by reducing the use of scarce resources, minimizing waste products, and recycling water along with other so-called waste products. As well as protecting and preserving the extraterrestrial environments of the Moon and Mars, these methodologies might be employed around the earth within small remote communities (such as arctic bases, underwater research facilities, earth-orbiting stations, humanitarian aid outposts or developing indigenous societies) lacking adequate water purification technologies. These applications would certainly help in advancing existing and new technologies associated with human exploration, while at the same time improving upon the quality of life through the provision of safe and clean drinking and bathing water to both space- and earth-based peoples.

Nomenclature

ISS = International Space Station
kg = kilogram
MDRS = Mars Desert Research Station
NASA = National Aeronautics and Space Administration
PVC = Polyvinyl Chloride

I. Introduction

"WASTE not, want not!" How many times have we all heard that old adage? When it comes to water, we would do well to heed this advice. We often take our water supplies and earth's regenerative water cycle for granted, but only three percent of earth's total water supply is fresh, and more than two-thirds of that fresh water is frozen! More than thirty percent of earth's fresh water (0.9 percent of earth's total water) is in the ground, leaving only about 0.3 percent of the fresh water (0.009 percent of earth's total water) available at the surface, which is the water that most people use.[1] When too much water is diverted from natural storage locations (whether snow packs, rivers, or underground aquifers) to places other than where it naturally flows (such as to manmade reservoirs, aqueducts, farmlands, golf courses, swimming pools, and so on), ecosystems are altered and the well-being of the entire planet is impacted. Wherever we turn to explore, water is seen as a sign of life. Where there is water, life tends to thrive. Where there is no water, the land is dry and barren. And no new water is being produced! Here on present-day earth, the water that flows from our streams and rivers to the lakes and oceans is the same water that flowed during Biblical times, and the same water that hydrated the dinosaurs before that.

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In January of 2004 when President George W. Bush announced his vision for the country's space exploration program, America's dream of a human mission to Mars became a federal priority. NASA has been directed to plan and execute a series of return missions to the Moon and eventually a manned mission to Mars. In order to accomplish these objectives, we must gain a thorough understanding of what is needed to support the life and health of humans living in remote, low-gravity, synthetic environments over extended periods of time. The international space community's research in long duration spaceflight in low earth orbit is helping us prepare for these next steps, and a base on our nearby Moon will enable us to rehearse nearly every aspect required for the much less forgiving trip to the far more distant Red Planet.

This paper will explore the issues involved in providing clean, safe and healthy water to people living and/or working in extreme or remote environments by efficiently recycling waste water in a cost-effective and ecologically sound manner. The extreme/remote environments may be space missions to earth orbit, the Moon or Mars, underwater, high altitude or desert expeditions, or developing communities lacking modern infrastructure. For our primary example, this paper will focus on water reclamation for a lunar base. Modifications can be made to adapt our concept for the lunar base to other settings.

A. Background

As illustrated in Figure 1, our research to date strongly indicates that by far the largest mass category of consumables for space exploration missions is water (and more specifically, wash water).[2] If we fail to recycle water (especially wash water) for space missions, large amounts of it will have to be launched on a regular basis (or potentially harvested from polar or ground ice) to support the objectives of developing extraterrestrial human bases. Either re-supply from earth or mining local ice would be achieved at great expense. A more cost-effective and environmentally friendly solution would be to reclaim and recycle both wash and drinking water to the greatest extent possible in a closed loop life support system cycle. This regenerative approach would help to preserve resources on both the extraterrestrial body as well as the earth: consumables launch masses and frequencies would be reduced, with a concomitant reduction in the exploitation of natural extraterrestrial resources (e.g., ground and polar ice).

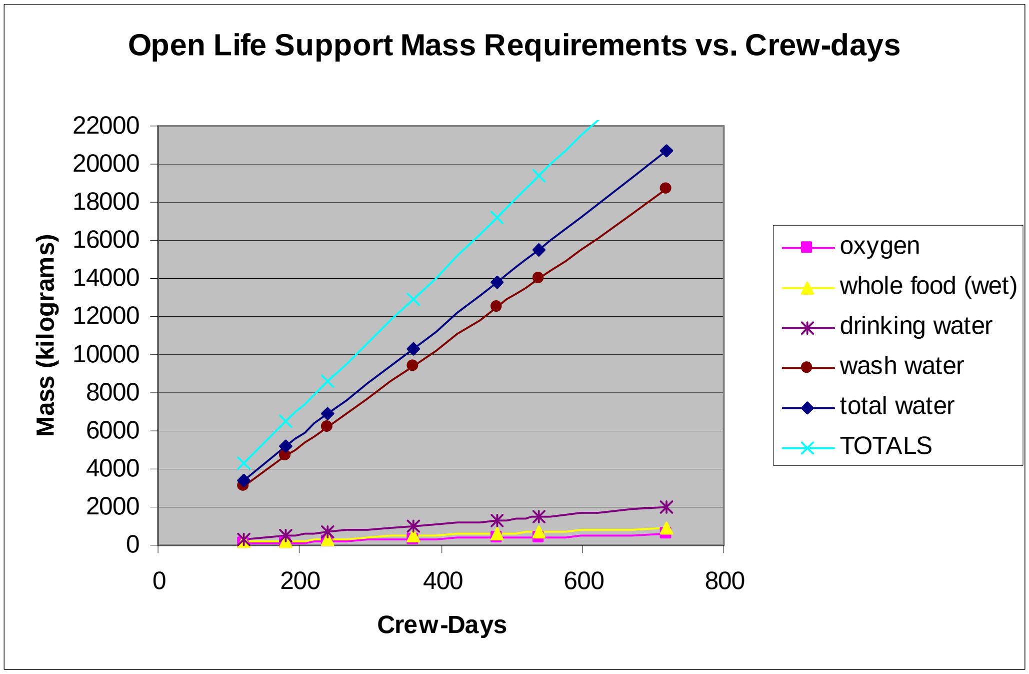

Figure 1. Open life support system consumables masses per crewmember per day.

This research program expects to develop efficient, cost-effective and self-sustaining methods and technologies for reclaiming or regenerating used waste water to high standards of purity using low cost, low energy processes and locally available resources. The methods and technologies developed for this purpose are intended to advance the goals of exploring the near-earth solar system (e.g., the Moon and Mars, as well as earth's extremes) by reducing the total amount of fresh water requiring transportation to the site. Just as importantly, they are also intended to minimize adverse impacts on the local environment (whether earth, Moon, or Mars) by reducing the use of scarce resources, minimizing waste products, and recycling water along with other so-called waste products.

In addition to preserving the extraterrestrial environments of the Moon and Mars and enabling exploration efforts, these methodologies could be employed around the earth within small remote communities (such as arctic bases, underwater research facilities, earth-orbiting stations, humanitarian aid outposts or developing indigenous societies) lacking adequate water purification technologies. These applications would promote existing and new technologies associated with human exploration, while at the same time improving upon the quality of life through the provision of safe and clean drinking and bathing water to both space- and earth-based peoples.

B. Problem Statement

The absence of abundant, easily accessible clean water sources in remote locations imposes financial and logistical constraints on the ability of humans to safely travel, live, explore, and work in such locations for extended durations. Possibly the most fundamental element of a human settlement on the Moon, Mars, or any other extreme location is the life support system. Of all the consumables provided for human life support, aside from perhaps oxygen, none is more essential to human survival than water. Without it, humans would not survive. The components of such a life support system would perform the same functions as life support systems used in other contexts, such as aircraft, spacecraft, submarines, and earth-based biospheres. However, the remote location, limited resources, unique surface environment, extended duration of use, and potentially altered gravity all contribute unique challenges to the design of robust and reliable life support systems for extreme environments.

C. Objectives

The explicit objectives of this study are to consider possible solutions for supplying clean water to crewmembers in remote locations, and to identify sustainable methods and technologies using local regenerable resources for reclaiming water in those locations. This will involve emulating the methods used by earth's natural ecosystem in regenerating water: naturally occurring microorganisms, plants, trees, and geophysical processes break down, degrade, and filter out hazardous substances from water, cleansing and treating contaminated water without the use of unnatural means (such as added chemicals or manmade technologies). A human base on the Moon will be used as our primary case study. It should be noted that this study is still in its infancy, thus the proposed processes are still conceptual at this point.

II. Discussion

A. Logistics Questions

As we contemplate a return to the Moon, a number of logistical questions come to mind. Will food, water, and oxygen be supplied from earth? Or will some or all of these inputs be completely recycled, regenerated, and reused? In all likelihood, for the initial relatively short duration recurring stays on the Moon, some of the oxygen, most of the food, and at least some of the drinking water will need to be transported from the earth. But the lack of ample and accessible clean water reserves in remote locations like the Moon imposes significant constraints on the ability of humans to stay in such places for long periods. Rather than assuming from the outset that reclamation is the preferred solution, let us first consider a range of possible solutions to this dilemma.

B. Possible Solutions

Perhaps the most obvious option would be to transport all the required water supplies (for drinking, cooking, personal hygiene, dish and clothes washing, plant watering, plumbing, etc.) from the home base to the remote location. Certainly from a quality control standpoint this might well be the safest solution. But transportation of all required water supplies from the home base would be cost prohibitive for long space missions. Astronauts on the International Space Station (ISS) in low earth orbit are currently restricting their water use to an average of just under two liters per day, which is provided through a combination of water produced by on-board hydrogen fuel cells, and partial water reclamation measures.[2] A less spartan (though far from luxurious) daily allowance of about 29 kilograms of water per person per day is proposed to maintain both physiological and psychological health over longer durations.[3] Whether the quantity is 2 or 29 kilograms per day, with a transportation cost to low earth orbit (the closest off-earth destination) of approximately $10,000 per kilogram[4], a cost range from $20,000 to $290,000 per person per day for water transportation costs make this approach prohibitive for low earth orbit, let alone for the Moon or further yet, Mars.

Another solution would be to harvest water from in-situ resources, such as (depending on location) mining and purifying ground or polar ice, desalinating salt water, tapping underground aquifers, and so on. Harvesting of water from in-situ resources is also very expensive, time consuming, and technology intensive. By the time harvesting equipment is purchased, transported, and installed, water might almost as well be transported from home base. Also, the in-situ resources may not be in the exact proximity where they are required, and may require extensive installation of transportation infrastructure to be accessed on a regular basis. For example, the greatest amount of water ice on Mars, and even potentially on the Moon, is expected to be in the polar regions. However, for various other technical and scientific reasons, it may be more advantageous to locate human bases closer to the equator on either celestial body.[5,6] Thus, getting water from frozen polar ice to the bases could involve long distance surface transportation by vehicles, pipelines, or other means on a regular basis.

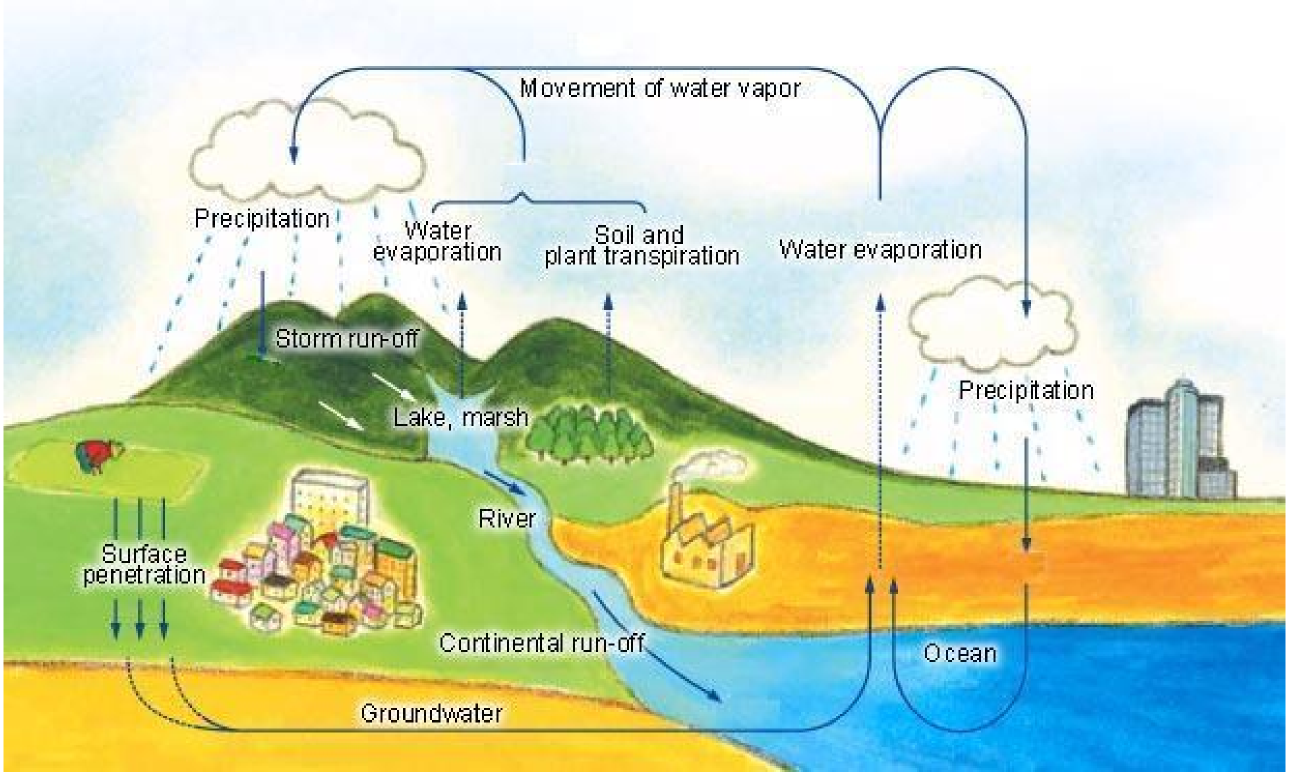

Figure 2. Diagram of earth's water cycle (adapted from Japan-based environmental planning company OM Solar website: http://www.omsolar.net; accessed on 22 December 2006).

A third, more cost-effective solution would be to reclaim and recycle a limited supply of water in a self-sustaining manner on a continual basis, with the initial supply being transported from the home base and possibly supplemented by local reserves. Reclaiming and re-using a limited supply of water would incur some relatively low initial set-up costs for establishing a self-sustaining, low energy, low-tech type of reclamation system, but would avoid the high infrastructure and operational costs associated with on-going transportation logistics and water harvesting technologies.

The Excel spreadsheet model illustrated in Figure 1 was constructed to estimate human life support consumable mass provisions for a lunar mission, calculated in terms of kilograms of oxygen, food, drinking water, and wash water required for each crewmember every day. Initial literature search and informal questionnaire surveys indicate that regeneration of black water into potable water may not be palatable to many individuals.[7] As quickly becomes obvious from Figure 1, the mass cost for provisioning of fresh drinking water and other consumables (e.g., oxygen and food) is small compared to that for wash water. Therefore, effective techniques for recycling gray/wash water offer the greatest potential launch mass savings of any of the basic groups of life support consumables. For example, the wash water mass requirement for 360 crew days is about 9360 kg (26 kg/crew/day), whereas the drinking water mass is only about 990 kg (2.75 kg/crew/day), the whole/wet food mass is only about 468 kg (1.3 kg/crew/day), and the oxygen mass is only about 288 kg (0.8 kg/crew/day).[2] The significance of this issue is recognized on the ISS, where the number of crewmembers is currently constrained to three, due in part to limited provisioning of water.

Multiple technologies currently exist which are able to regenerate both gray and black water to standards exceeding those of most municipal water providers.[8] If used water is purified and recycled in situ, less mass will have to be transported to the space habitat, and larger numbers of astronauts can be more efficiently supported. This will result in cost savings and increased productivity in space.

As illustrated in Figure 2, our earth reclaims and recycles water very effectively and sustainably through the processes involved in the hydrologic cycle without human intervention (in fact, human interference only decreases the effectiveness of earth's reclamation processes). Our approach will be to emulate as efficiently as possible the processes used by the earth in purifying its water resources.

C. Emulating the Earth

In order to efficiently emulate earth's natural water reclamation processes, our methods for regenerating used waste water to high standards of purity must use low cost, low energy processes, and locally available resources. Development of such sustainable methods and technologies will benefit ecosystems on the earth by conserving water resources that might otherwise be contaminated, wasted, or shipped off-planet, in addition to benefiting the local ecosystems wherever these technologies are used by re-using the water in the closed system rather than further exploiting and contaminating local water resources. Humanity will profit by conserving government and private funds that would otherwise be used to launch water and other life support consumables to the Moon and other destinations in the solar system. Some fringe benefits from the development of these sustainable regeneration technologies are expected to be atmospheric regeneration (as the plants used in the system will regenerate carbon dioxide into breathable oxygen), biomass fertilizer for food crop growing (from reclaimed solid waste and residual sludge), development of building materials from reclaimed solids, and an enhanced understanding of the earth's characteristics as a large-scale regenerative life support system.

D. Requirements

As outlined in Figure 3, the five primary categories of wastewater contaminants or impurities requiring removal are particulate (including particles of rust, dirt, sediment, rocks), dissolved inorganics (including non-carbonaceous chemicals such as asbestos and heavy metals like mercury, lead, chromium, silver, and so on), organics (including carbonaceous compounds like calcium, magnesium carbonates and nitrates, chemical solvents, pesticide residues and industrial pollutants), radiological contaminants (including naturally occurring and industrial radioactive substances such as radon and radium), and biological pathogens (including hazardous organisms such as bacteria, viruses and protozoa).

Contaminant Category	***Possible Constituent Impurities***
Particulate	particles of rust, dirt, sediment, rocks
Dissolved inorganics	non-carbonaceous chemicals; heavy metals
	(mercury, lead, chromium, silver, etc.) and asbestos
Organics	carbonaceous chemical compounds, calcium, magnesium
	carbonates, nitrates, solvents, pesticides, industrial pollutants
Radiological contaminants	natural and industrial radioactive contaminants: radon, radium
Biological pathogens	hazardous organisms: bacteria, viruses, protozoa

Figure 3. Primary categories of water contaminants.

E. Methods

The typical steps taken to remove the above contaminants in any water reclamation process are filtration and disinfection, typically executed via the following four phases:

1. Primary Phase: Removal of solids, via screens, filters, septic systems, etc.
2. Secondary Phase: Sterilization/disinfection of biological pathogens, via removal, radiation, oxidation, pasteurization, halogenic action, etc.
3. Tertiary Phase: Fine filtration via reverse osmosis, activated carbon, plant and/or animal processing, etc.
4. Polishing Phase: Removal of color, odor, and taste via reverse osmosis, activated carbon, ozone, etc.

Some of the methods listed above are energy-, time-, and/or resource-intensive, in that they require large amounts of energy (e.g., reverse osmosis), personnel time (e.g., filter cleaning), and/or consumable resources or parts (e.g., filters, halogenic agents, ozone) to operate and/or maintain. Since we have settled on emulating the earth's natural processes in order to enhance sustainability and environmental stewardship and reduce logistics requirements, let's take a closer look at how the earth accomplishes each of these four phases. First, the earth accomplishes primary filtration very effectively through percolation of water from the surface through sand/dirt, gravel and rock to underground aquifers, as well as through gravitational settling of denser solids in standing and running water (illustrated as "surface penetration", "groundwater" and "runoff" in Figure 2). Second, disinfection is accomplished through natural environmental exposure to ultraviolet radiation, salt-formers, oxidizing agents, and heat (taking place in marshes, lakes, rivers, ocean and runoff in Figure 2). Third, fine filtration is accomplished through the use of the water and its impurities in plant and animal metabolic processes (organisms break down and remove ammonia, nitrates, nitrogen, phosphorus, and carbon from the wastewater, and are themselves removed by further natural filtration processes). Final polishing, or the removal of color, odor, and taste as well as further sterilization, is accomplished through the earth's natural distillation process: evaporation from oceans, lakes, rivers and such as well as transpiration from soil and plants, followed by condensation of water vapor into clouds, and finally rainfall. It should be noted that these phases are not necessarily completed in an orderly, linear or chronological pattern within earth's water cycle. In other words, the processes are iterative. For example, some fine filtration may take place prior to thorough disinfection, and primary filtration may occur several times prior to final polishing. However, the water is almost unequivocally at its purest state following final polishing in the distillation process, prior to contact with the earth or any of its inhabitants, unless atmospheric pollutants are present.

F. Generic Application

In order to emulate earth's water reclamation process in a space appropriate to a small (perhaps four- to eight-person) exploration base, we need a scaled-down earth-like system with compact and efficient filtration and disinfection phases that can be adapted to suit a variety of environments depending on locally available resources.

Treatment Phases	***Methods***
Primary Filtration	rocks, gravel, sand; miniature marshlands
Primary Disinfection	exposure to intense radiation and heat; oxygen; halogens
Tertiary Fine Filtration	plant and animal metabolic processes; biofilms
Final Polishing	solar still; evaporation, condensation, and collection

Figure 4. Treatment phases and methods for a scaled-down earth-like water reclamation system for generic applications.

Our approach is outlined in Figure 4 and described below.

Primary filtration would be accomplished through percolation of the wastewater through sand or local regolith, gravel, and/or fractured rock as a sort of marshland draining to a lower elevation collection basin. Primary disinfection would be accomplished through exposing the filtered water directly to natural local sources of high frequency radiation (e.g., solar and/or cosmic radiation, radioactive isotopes), heat (e.g., sunlight, geothermal sources), oxidizing agents (e.g., ozone, atomic oxygen, free radicals), and halogens (e.g., chlorine, bromine). This phase may be supplemented with the use of natural biocides, if necessary. Fine filtration would be accomplished through the use of the water and its impurities in plant and animal metabolic processes (e.g., aerobic and anaerobic bacteria, algae, water plants, fish, snails, etc.). If low atmospheric pressure is readily available, (as on the Moon or Mars) this third phase may be combined with the fourth and final phase. Polishing, or the removal of color, odor, and taste as well as further sterilization, would be accomplished by natural distillation through heat- or low pressure-induced evaporation followed by condensation and collection.

Other researchers have developed small scale environmentally friendly water processing systems for various applications, such as University of Maryland's Greenhab System and Pennsylvania State University's Living Machine.[9, 10] Our proposed concept would use comparable treatment phases, with methods adaptable to a variety of applications and available local resources.

G. Purification Levels

Figure 1 above illustrates our finding that the predominant use of water is for various types of washing. Wash water is supplied, used and collected through the plumbing network of sinks, showers and laundry facilities. This means that the bulk of the water used by humans does not require extensive regeneration in order to be ready for safe re-use. This realization led to an innovative concept (illustrated in Figure 5 below) for water reclamation: portions of the water passing through our water reclamation system could be bled off in several stages for various uses, with only water requiring the greatest purity (drinking, cooking and dish washing water) passing through the entire system. For example, crop irrigation water and toilet water would require minimal purification and could be bled off early, whereas laundry water would require further purification and personal hygiene water even more purification, with drinking water and dish washing water receiving the full treatment. As with the other concepts proposed in this study, further development, testing, and analysis are required to determine the efficacy and practicality of this concept.

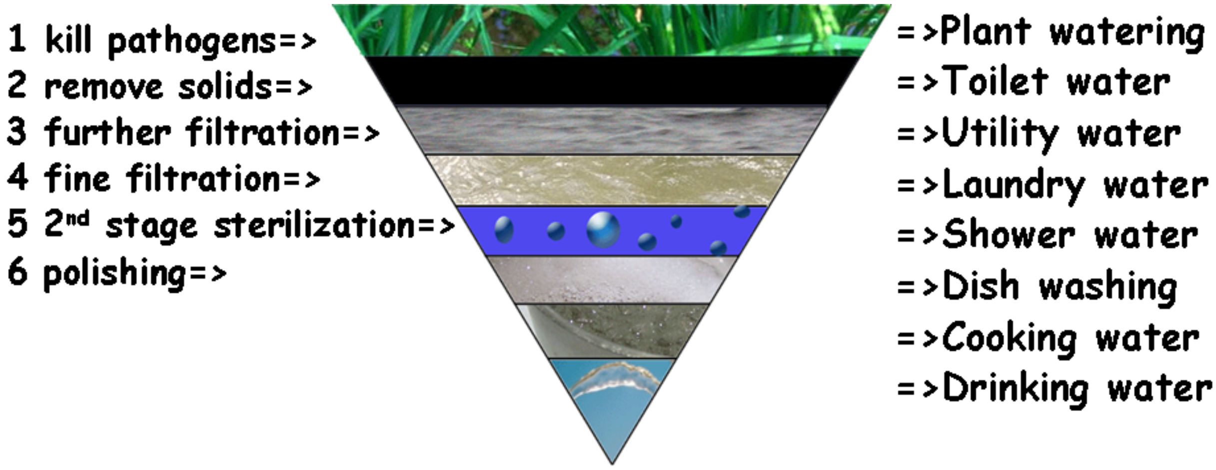

Figure 5. Stages of water reclamation and suitability for various applications.

H. Lunar Application

Our water reclamation implementation plan for a lunar base (which would work equally well on Mars) is described as follows. Used water and associated wastes (including sloughed skin, urine, feces, food particles, and biodegradable soaps) draining from lunar habitat showers, sinks and toilets flows via gravity to a pressurized lower elevation septic field and greenhouse area with a transparent enclosure and drain field of lunar regolith and explosively fractured lunar rock. Natural biocides may be applied to supplement the other methods (radiation, heat, and evaporation) of sterilizing the solid wastes as well as the water. Surface level solids captured in the regolith are “harvested” to fertilize the sterile lunar regolith for growing plants in the greenhouse. Water seeping through the regolith and fractured rock is captured in perforated PVC pipes several feet below the septic field. Water collected in the PVC pipes drains via gravity to lower elevation transparent pipes on the lunar surface, which are exposed to ambient sunlight and cosmic radiation for sterilization via radiation and heating. Water for plant irrigation and toilets could be bled off at this point, if the total water volume and overall reclamation timeline deem that to be practical and cost-effective. Next, the water drains via vacuum to a low-pressure enclosure, where the water immediately evaporates and subsequently condenses on the enclosure’s passively cooled slanted ceiling and walls. There the condensate collects and drains via wicking capillaries and gravity to a pressurized potable water collection reservoir.

It may be discovered that some of these treatment processes independently produce equivalent results and are therefore redundant. Hence, it may be possible to combine or eliminate some of the processes altogether, resulting in a more economical, compact and efficient system. However, those judgments will have to be made at a later stage when more data are available.

Further research and investigation are needed to accomplish the following objectives:

- Determine the optimal pressure level and/or pressure cycling strategy for a low-pressure distillation enclosure
- Design, build and test a functional distillation enclosure with passively cooled water vapor collection surfaces and condensation collection system
- Determine whether the radiation environment on the Moon is adequate during both lunar day and night to sterilize both solids and liquids
- Investigate naturally occurring or organically produced halogens, oxidants, or biocides that might be available at a manned lunar base to supplement the sterilization/disinfection process

- Investigate naturally occurring or organically produced substances that might be available to adjust water pH levels
- Determine safe and practical uses for solid wastes
- Determine the minimum water volume necessary to make water bleed-off stages for graduated purity levels practical
- Define purity standards for each water use application
- Investigate the pros and cons of separate black and gray water processing
- Determine the efficacy of each process, and which processes might best be combined or eliminated
- Build and test scaled-down prototypes of systems
- Test water quality at various stages

III. Conclusion

In conclusion, long duration cost-effective methods for regenerating used waste water to high standards of purity must employ low cost, low energy processes and locally available resources, regardless of the location. Taking advantage of unique local environmental attributes, such as high-energy radiation, low atmospheric pressure, and various types and sizes of sand and rock on the Moon or Mars will make local water processing more sustainable. Using the least amount of processing required for each type of water use should prove to conserve time, energy, and resources. Besides their obvious applications in extraterrestrial environments, some of these methods might be employed around the earth in communities lacking adequate water purification technologies.

Development of sustainable water reclamation methods and technologies for exploration missions will benefit humans, wildlife and ecosystems on earth by conserving water that might otherwise be contaminated, wasted, shipped off-planet or otherwise over-exploited. These methods and technologies will simultaneously advance the goals of human exploration; minimize adverse impacts on local and remote environments by reducing the use of scarce resources and minimizing waste products; and improve the quality of life through safe drinking and bathing water for space- and earth-based peoples alike.

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