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With more than twenty years of innovative teaching and high-tech industry experience, Dr. Raviv developed a fundamentally different approach to teaching "out-of-the-box" problem solving. For his unique contributions he received the prestigious President's Leadership Award, a national Award for Innovative Excellence in Teaching, Learning and Technology, The Faculty Talon Award by the Alumni Association in "Recognition of Exceptional Leadership, Commitment, and Service to FAU Students", the 2005-06 AeA University Researcher of the Year, and the 2005 FAU's Distinguished Teacher of the Year Award.

Dr. Raviv has been working with the National Inventors Hall of Fame on several national educational programs, and was the Keynote Speaker prior to the Induction Ceremony, where he shared his philosophy on the processes of invention and innovation with more than 60 inductees. He conducts innovation workshops nationally and internationally to various audiences at different universities, institutions, and businesses. Dr. Raviv is a co-holder of a Guinness World Record, and his major research interests are in vision-based autonomous navigation (driverless cars), "green" innovation, and innovative thinking.

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From Idea to Market:
A Case Study for Sustainable Innovation*

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Abstract

This paper describes an experience of working on a research project at Florida Atlantic University. It is unique in the sense that the working settings are different from an ordinary research project, and the intellectual property agreement is different from a standard university one. We have been working with a private investor and entrepreneur who came with the original idea. He has been very involved in the project with some business, humanitarian and environmental goals in mind in addition to academic interest.

We discuss different aspects of the project as it progressed from inception to commercial promise, intellectual property, the risks involved, technical ups and downs, teaming and communication issues, problem solving, overlapping between academic and non-academic interests, attracting water and electric utilities, and lessons learned. Since the focus of this ASEE section is entrepreneurship, we left the technical description towards the end of the paper.

The project is about a new method for making fresh water using distillation. Low-Cost Vacuum-Based Water Distillation uses naturally available vacuum to operate at low temperature to save energy. Simple and scalable, it can produce pure water for large cities and remote rural villages, for the First World or the Third. The process is estimated to be meaningfully more efficient than existing technologies. It is environmentally friendly, and can be configured to use waste heat from power plants, and can be suited for use in 3rd world countries using alternative energy sources. It is simple to operate and maintain and can be constructed using low-cost "off-the-shelf" components.

- This work has been supported in part by a grant to FAU by Michael R. Levine, Inventor and Entrepreneur.

Introduction

This paper describes an experience of working on a project that is different in settings from a normal research project. We have been working with an investor and entrepreneur who came up with the original idea, and who has been involved in the project with multiple goals in mind, only some of which are academic. We discuss different aspects of the project as it progressed from its inception to commercial opportunities, including intellectual property agreement, the risks involved, technical ups and downs, teaming and communication aspects, overcoming problems, overlapping between academic and non-academic interests, attracting water/electric utilities and other industries, and lesson learned.

The project is about a low-cost vacuum-based water distillation method that uses naturally available vacuum to operate at low temperature to save energy. Simple and scalable, it can produce pure water for large cities and remote rural villages, for the First World or the Third. The process is estimated to be more efficient than existing technologies. The system may be configured to use waste heat from power plants. It is simple to operate and maintain and can be constructed from low-cost "off-the-shelf" components.

The invention applies a discovery of Torricelli: atmospheric pressure supports a column of water 10 meters high inside a sealed tube. Torricelli proved that a vacuum could exist, specifically in the space above the water in the tube. The invention uses as evaporator and condenser identical "Torricelli Columns"; the salt water in the evaporator is kept hotter than the fresh water in the condenser. Since the pressure is low, water in the evaporator vaporizes, raising pressure slightly. The resulting pressure difference between evaporator and condenser causes vapor to flow through a pipe to the condenser where it contacts cold water and becomes liquid. We solve the problem of maintaining a temperature difference by pumping large amounts of hot salt water into the evaporator and cold fresh water into the condenser.

The story

There are three co-authors on this paper. As you read it you'll sometimes notice the use of "I", and other times "we". "I" refers to the project PI and the first co-author.

<u>The start and the risk</u>

As a college professor who teaches inventive thinking and innovation it has become "natural" for colleagues and friends to refer inventors to my office to discuss their ideas and receive some unofficial advice. Over time, I became less excited meeting these inventors since they approached me with a very non-mature idea, no prior literature search, little knowledge of what it takes to make it happen or what they really wanted, and usually no funding. So when in November 2004 a friend of mine introduced me to a sketchy idea by Michael Levine, an inventor and entrepreneur, I was skeptical. This changed when I realized that he had 76 patents, many of which had been very successful, and that he had followed them from inception to market. In addition, he had been thinking about this specific idea for more that four years and had protected the concept before we met. Funding was not an issue: his past success as an entrepreneur has given him the financial resources to support this project. The idea is a new economically-sound way to make fresh water, and he wanted FAU to make a feasibility study. There were several dilemmas associated with this project: (a) my ongoing research was in the Robotics area, not in water distillation, (b) the original idea was his, and this is very different from the way we have been doing research since we normally work on our ideas, and based on his past experience (c) he wanted complete ownership of the intellectual property and future royalties. Since the subject and its potential impact on our society and the environment was enormous, I decided to shift my research and “sacrifice” two years to focus on something which was exciting and new to me. I also had a solid “gut” feeling that once we start the project we would come up with many new and better ideas (which actually happened). The problem of ownership was resolved by a written agreement that stated that 10% of all gross royalties that result from this project will be granted to the University. This turned out to be a sound idea since we started the project with an entity that was willing not only to sponsor the project and pay for the patents, but also “buy it up front”; after all, most university patents sit on the shelves with no interested buyers in sight.

I hired three full time graduate students: one Ph.D. and two Masters. In addition, I hired an undergraduate to help in more basic daily operation. The graduate assistants were informed upfront of the risk involved, that even though I personally believed in this project, there were no guarantees that it would be successful. However, regardless of the outcome they knew that there would be enough “meat” for their theses.

In parallel to the work at FAU, some theoretical thermodynamic-related sponsored-research work was initiated at the University of Michigan. We all agreed that open communication is crucial and that we would establish an ongoing line of e-mail communication. I felt that occasional meetings with the sponsor were important and invited him to attend.

At this point we all felt that we could help the world and so we were willing to take the risks involved in this project.

Sharing royalties

In many universities, graduate students that are sponsored by research projects do not share royalties obtained from intellectual property. The research work is considered to be “part of what they are paid for”. In this project, I took a different approach: I decided to share a portion of my potential royalties with the students, since I felt that this teaming and appreciation approach was a better one. Indeed, it has made the students very thankful and more ambitious to make things happen.

About the design

While learning more about desalination and distillation and other prior art, we had several meetings to discuss the design and to find a space for the more than 10 meter high apparatus. It took several months to come up with a sound detailed design, to build it, and to find a temporary location for the project. It was finally located between the 2nd and 4th floor of the Science and Engineering building. This temporary location meant that we had to dismantle the apparatus after each experiment.

The original apparatus consisted mainly of basic “Home-Depot” type material: PVC pipes, screws, hoses, etc., but as we moved on with the project, more structure, sensors, pumps, etc. were added as it transformed from a low-tech to a more high-tech apparatus. At some point it became completely controlled, simulated and monitored from a central personal computer.

The first experiments and mounting frustrations

The first experiments were disastrous. Vacuum was lost on a regular basis and finding the location of the leak became very time consuming and frustrating. Water spilled all over the floor near professors offices… The worst part was that even after the leaks were fixed, it still did not work and there were no signs that something meaningful was going to happen. Not only did frustration begin to build-up, but team skepticism was heard loud and clear. From “I knew this would not work” to “If it is so great how come no one thought about it before”, to “I knew that this design will not work” (…no alternative suggested). When I told the idea to peers at FAU and beyond the response was “Ha-ha, sounds like another cold fusion…”, “There is nothing new about it”, and (semi-happily) “We heard that it failed”.

The sponsor decided that it was going to work on a particular day, invited more than fifty people (too late for us to undo), and … nothing happened. This was the time when I felt that more motivation meetings were essential to keep the moral high. We came up with more alternative designs, but unfortunately none of them worked. By then the sponsor had invested more than half of the project budget and had applied for multiple patents. In addition, at that point in time the Ph.D. student left the project and took a promising job in a different state.

The turning point

Due to many technical-related frustrations, we decided that the apparatus would stay at the temporary location and that we would not dismantle and move it each time we ran an experiment (and risk more vacuum leaks and damaged sensors). We overcame one problem at a time, redesigned different elements, and made it more robust. Even though we did not have it working yet, on Feb 3rd, 2006 I invited people from academia, industry, power, and water management to join us on Feb 17, 2006 to see what we had (no promises made).

During these two weeks we put all the time and personal energy that we could find in this project. New designs, more sensors and actuators, better simulation, and enhanced monitoring and control system were put in place. The visitors were invited to be there at 2pm. Despite many attempts to make the apparatus function nothing worked. At 1:30pm when the first visitors came…as we were testing a new design... it all worked! Water was boiling violently in the evaporator unit at room temperature, and about one liter of fresh water was produced in less than two minutes. What a relief!

After the first working experiment

In the coming weeks we repeated the experiment and performed additional ones. We invited more people and industry representatives to watch the “miracle”. Data were collected from every single experiment and graphs and predictions were produced. Criticism almost disappeared and there was a growing interest in the project. We started ongoing meetings with Florida Power and Light, South Florida Water Management District, The City of Fort Lauderdale and Ch2M-Hill to try to take the project to the next step: A pilot program to produce 50,000 liters per day. We also met with other industries as well. The motivation for sharing with industry was clear: larger scale of the project would need collaboration and financing, and implementation has to somehow be incorporated, at least partially, with power and water companies. The earlier the industry knew about it, the more time it had to think it through. This also enhances the cooperation between academia (specifically the college of engineering at FAU) and the industry. On a visit to Israel we also met with people from Israel Electric Company, Mekorot (The Water Authority in Israel), and the Technion, Israel Institute of Technology.

Applying for a national competition

The students applied to the National Collegiate Competition. The following is from the National Inventors Hall of Fame Website:

"Introduced in 1990, The Collegiate Inventors Competition has rewarded and encouraged hundreds of students to share their inventive ideas with the world. It promotes exploration of invention, science, engineering, technology, and other creative endeavors and provides a window on the future technologies from which society will benefit in the future".

Out of about 100 applications, there were four undergraduate and seven graduate finalist teams, from which three awards were granted: one for an undergraduate team, one for a graduate team and one grand prize. Our team became one of the seven graduate finalists, but did not win any of the prizes. The students had fun in the process from the application, to phone interviews, to spending several days in the DC area and meeting other team members as well as great inductees and inventors from the National Inventors Hall of Fame. (For more details on this great competition, please visit www.invent.org)

Papers, theses, and extensions

The process of academic writing and reporting started. We wrote several papers aimed at different aspects of the project to different conferences. One paper detailed the distillation process, another detailed the design, experiments and analysis, and a third one on the effect on third world countries and the environment. The students have started to outlines their theses and prepare for journal papers. In the process of writing the papers, the problem of separating the project into two theses (who is writing what) has been resolved.

Another advantage of the project is that it can be used as a tool to teach science, engineering, technology, water and environmental issues. We are currently in contact with other universities that specialize in writing and testing hands-on curricula.

Relevant patent applications

There were several related patent applications, all fully paid by the sponsor. Here we share the abstract of one of them. We are still awaiting the final response from the patent office.

"LOW ENERGY VACUUM DISTILLATION METHOD AND APPARATUS."
November 2005.
Co Inventors: Michael Levine, Daniel Raviv, Tom Kelly, Eiki Martinson, Brandon Moore.
Abstract: A sub-atmospheric pressure desalinating still employs a closed top, open bottom pipe filled with source water to be distilled, such as seawater, having a height greater than the height of a column of seawater that can be supported by the pressure at the bottom of the tank so that a sub-atmospheric pressure volume is formed at the top. Water from the source is also pumped into the sub-atmospheric volume and passed through an evaporator which enlarges its surface volume. A small percentage of the water is vaporized and the balance is cooled to provide the heat of vaporization and falls into the top of the seawater column, creating a downward flow. The vapor is drawn from the vacuum and condensed, preferably in a second sub-atmospheric volume above a column of fresh water. A degasser for the water to be distilled prevents the accumulation of gases dissolved in the seawater or the like in the sub-atmospheric volume.

Current business status

A company has been formed by the Investor and a president has been hired. The company is currently looking to hire engineers to build a small scale pilot system that can generate 50,000 liters a day. In addition, the students have been offered to join the company and get stock options. They are currently thinking about the opportunity with the understanding that joining the company at this point may delay their graduation day.

Economic, Environmental, and Societal Benefits

The invention can help most those already suffering from a lack of drinking water: the inhabitants of developing nations. They use only a tenth of the water a developed nation uses per capita. Water scarcity forces many to rely on unsanitary sources, leading to waterborne illnesses that claim the lives of 20 million children a year (*3*).

Vacuum distillation is a low-tech solution ideal for solving Third World problems. The prototype is constructed from PVC pipes and has no moving parts except for two commonplace water pumps. It can be adapted to use renewable energy or marginal heat sources.

This invention is also well suited for the First World. If current trends remain, the United States alone will require 15 trillion more gallons of fresh water per year by 2020. Furthermore, one half of total U. S. population growth is projected for the coastal states of Florida, California, and Texas, all of which are already suffering shortages (*4*).

Power plants and industrial processes reject a great deal of excess heat into the atmosphere or bodies of water, heat that can be used in our evaporator instead. Moreover, in coastal areas, power plants are often cooled with seawater. This source of hot saltwater is ideal for our system: a portion will be distilled into fresh drinking water, and the remainder will be released at lower temperature, reducing environmental damage.

Lessons learned

We hope that this paper, and in particular this section, would help others to deal with similar situations that may come up in the academic world.

Working with an inventor and entrepreneur has been a very unique experience. He has been energetic, involved, pushing, and continuously looking ahead for business opportunity, i.e., how to move the project forward and make it a reality beyond research. The on-going communication with him worked very well and eliminated potential misunderstanding. (There was one exception: inviting his friends too early to watch the water making caught us by surprise and could have been avoided by one short e-mail.)

Attempts should be made to separate between friendship and working relationship. We feel that too much overlapping may cause unnecessary disagreements.

The uncertainty of success for this project success added an unexpected aspect of entrepreneurship twist to it. The whole team knew that there was a risk of "failure", but also a chance for a rewarding success. This risk taking experience and the happy ending helped prepare the students to understand, at least in part, why entrepreneurs are sometimes sleepless.

We all learned to overcome tough technical problems that at first seem to be unsolvable. We all understood that the most important part at tough times was to continue to work as a team, to be open to others' thoughts, to communicate and minimize misunderstanding, to avoid taking individual credit, and not to blame others for any wrongdoing. Somehow it was clear that technical ups and downs are natural.

Humor and fun was kept alive for the duration of this project. For example, losing vacuum and occasional spilling of water were frustrating but led to a set of sarcastic jokes.

Whenever possible, when several graduate students work as a team on a specific project it is important to make it clear upfront, whenever possible, what is the thesis focus of each of them. In this project it was not a problem, but it can easily become so.

In order to move the project forward high-level decision makers must be involved. In our meetings with outsiders, no important decision were made since most participants were not in positions to make crucial decisions. Also, sometimes the meetings with industry and utility people became too big and caused some delays in accomplishing meetings' goals.

Projects of this kind when the investor is personally involved may cause some friction between academic goals (theses, papers) and business goals. We have experienced some unavoidable research/business overlapping, discussed them, and tried to minimize their impact.

Project details: Technical discussion

Core idea, design, and preliminary results

Desalinating water by distillation is nothing new. However, raising water to 100 °C takes a surprising amount of energy. Alternatively, water in a vacuum boils at room temperature, but achieving a vacuum typically takes so much energy that the benefit is lost. We have found a way out of this quandary by exploiting a "free" source of vacuum in nature.

Our invention applies a discovery of Torricelli: atmospheric pressure will support a column of water 10 meters high inside a sealed tube. Torricelli proved that a vacuum could exist, specifically in the space above the water in the tube. Our invention uses as evaporator and condenser identical "Torricelli Columns"; the salt water in the evaporator is kept hotter than the fresh water in the condenser. Since the pressure is low, water in the evaporator vaporizes, raising pressure slightly. The resulting pressure difference between evaporator and condenser causes vapor to flow through a pipe to the condenser where it contacts cold water and becomes liquid. However, in changing phase the vapor transfers heat, so eventually the process will reach thermal equilibrium and distillation will cease.

We solve the problem of maintaining a temperature difference by pumping large amounts of hot salt water into the evaporator and cold fresh water into the condenser. Vaporizing a single gram of water takes 540 calories and each calorie can change the temperature of 1 gram of water by 1 °C. So if we pump in 100 grams for each gram vaporized, the output evaporator temperature will be 5.4 degrees cooler than the input. The reverse is true for the condenser: water will exit 5.4 degrees hotter.

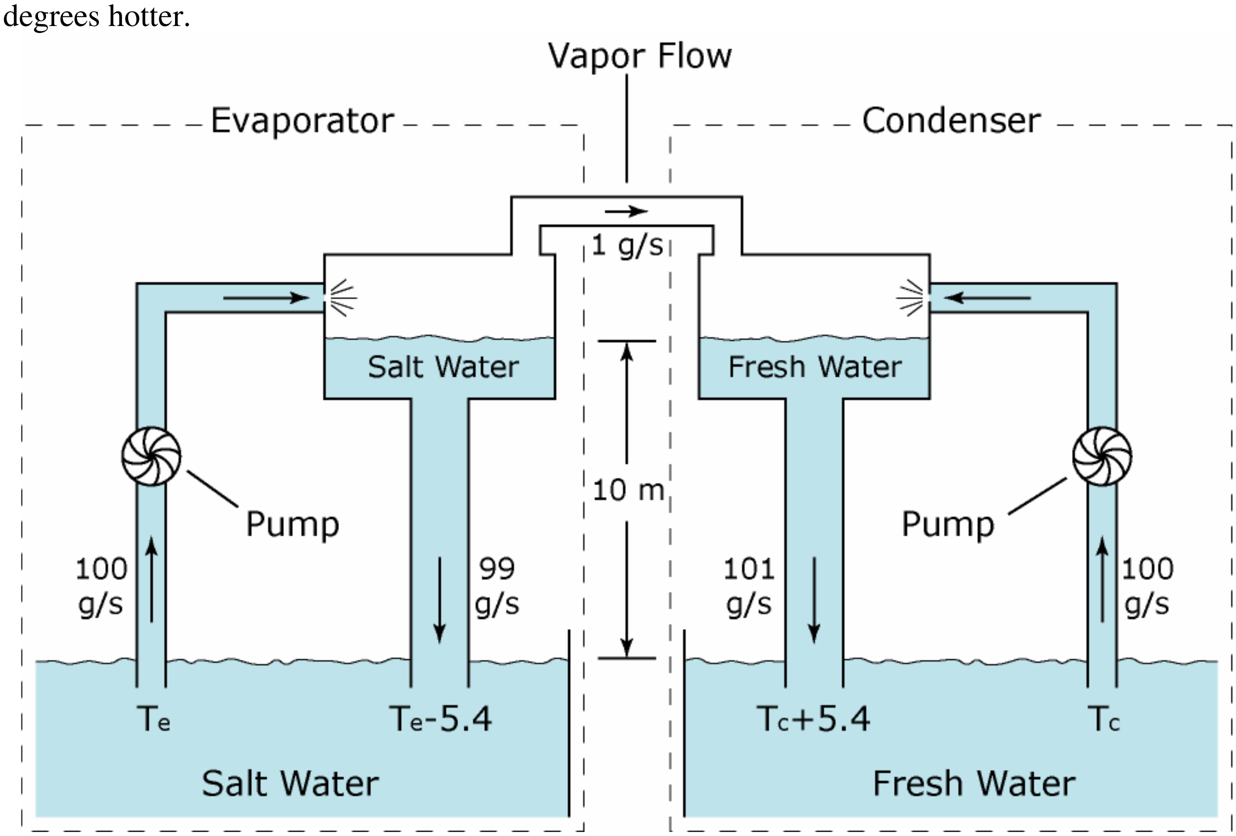
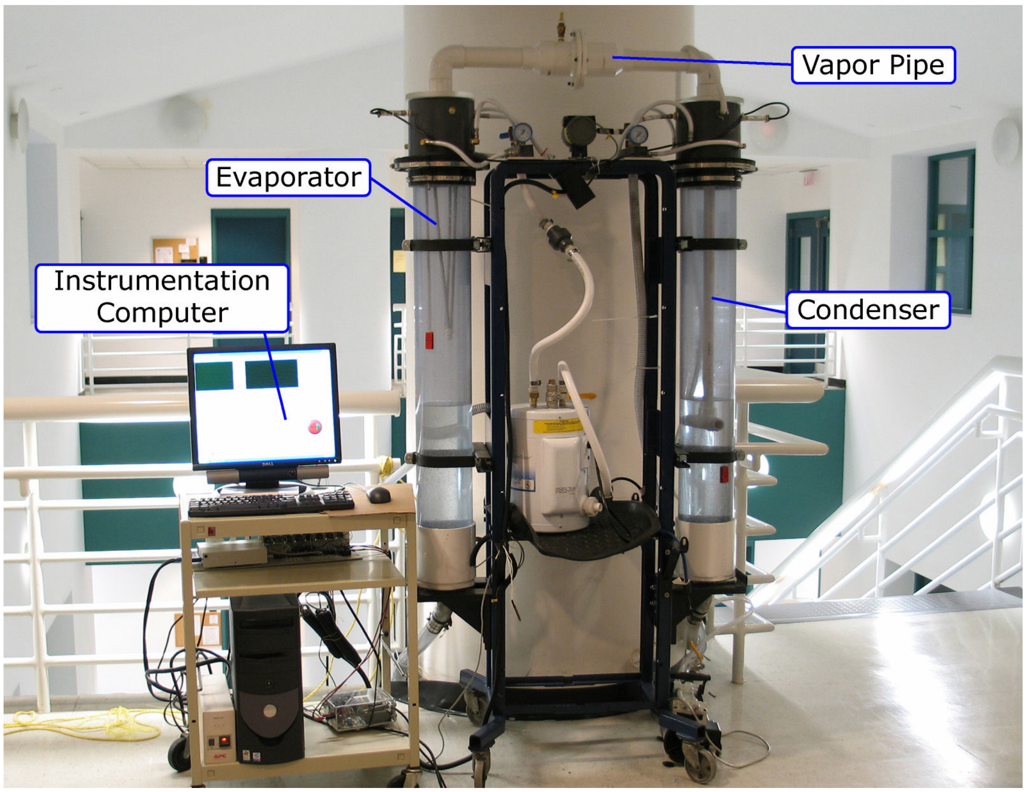


Figure 1: Distillation Process. T_e: incoming evaporator water temperature; T_c: incoming condenser water temperature.

Figure 1 illustrates the system producing 1 gram of water per second, but the unit could be anything – 1 gram, 1 liter, 1000 gallons, provided that 100 times the desired production rate is pumped into the chambers. Note the 5.4 degree change in temperature as water passes through the chambers. In practice the sources of hot salt water and cold fresh water will have to be large enough to keep our system from changing their temperatures (T_e and T_c) significantly; for example, the ocean and a freshwater aquifer are obvious choices. For our experiments we have made do with 55 gallon drums, which are too small to keep the process operating continuously. We also use small water heaters to add 3 kW of heat to the evaporator. The experimental apparatus is seen in figure 2.



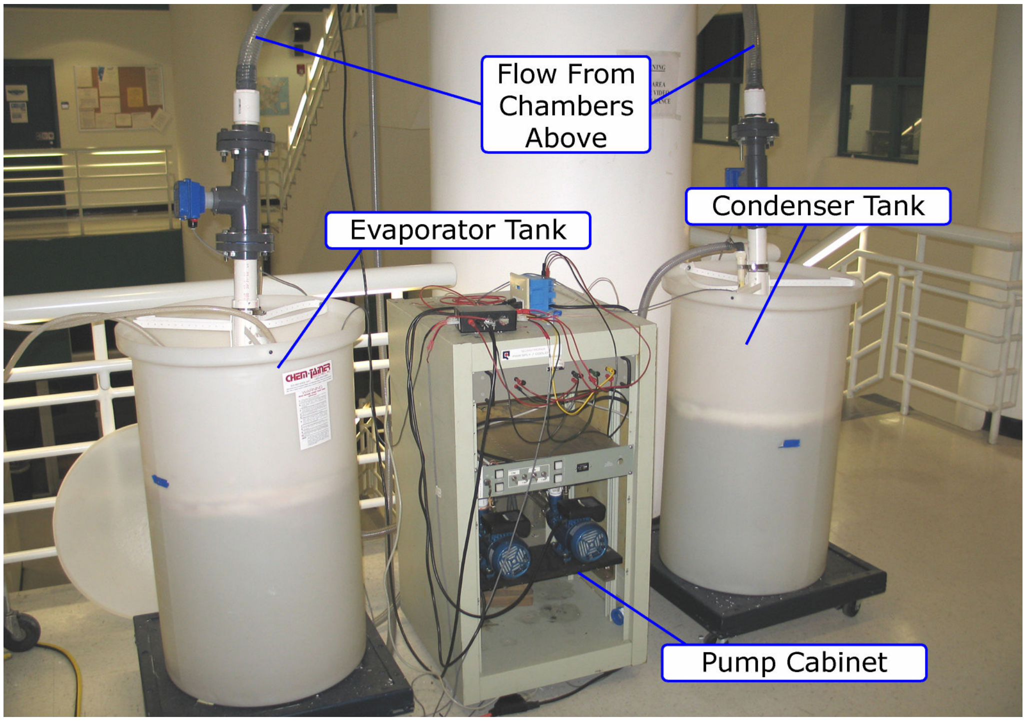


Figure 2: Experimental Apparatus. Evaporator and condenser are on the fourth floor, 10 meters above the tanks on the second floor.

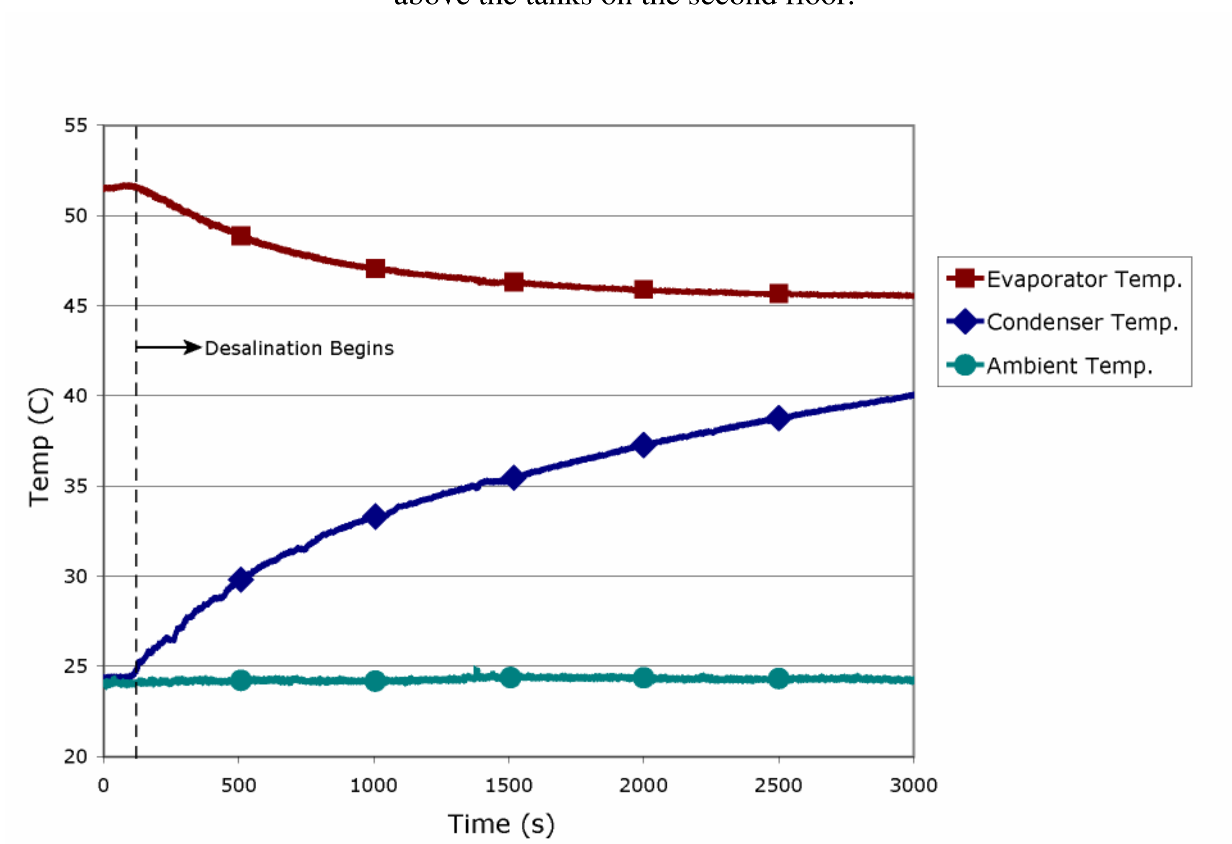


Figure 3: Desalinator Performance.

Figure 3 shows the results of a typical experiment. Observe the convergence of temperatures; the evaporator slope is less extreme due to the influence of the heaters. The temperatures change almost entirely due to phase change, as tested by a control experiment. Remembering that each gram of vapor releases 540 calories in condensing, we can predict the distillation rate according to:

$$\Delta V \approx \frac{\Delta T_C V_0}{540\,°\mathrm{C}}$$

where ΔT_C is the final change in temperature of the condenser, V_0 is the initial volume (in liters) of water in the condenser reservoir, and ΔV is the change in that volume (in liters), or the amount of water produced by the system.

In the case of the data shown above:

$$\Delta V = \frac{(15.69\,°\mathrm{C})(150\,\mathrm{Liters})}{540\,°\mathrm{C}} = 4.4\,\mathrm{Liters}$$

We have produced 4.4 liters of fresh water during the experiment. This result has been experimentally confirmed by measuring the water level.

Improving on Prior Technology

Reverse Osmosis (RO) is presently the fastest-growing method of desalination (*5*). RO plants apply high pressure saltwater to a membrane; the salt is rejected and fresh water permeates to the other side. RO plants operating on seawater require pressures of 1000 PSI, with all the powerful pumps and robust plumbing that necessitates (*5*). The membranes themselves are expensive and delicate, frequently requiring maintenance or replacement. In contrast, our invention is simpler and operates at safe and easily attainable pressure. RO is powered by electricity produced at less than 50% thermal efficiency, and then generates more heat in raising pressure to such a high level.

In contrast, our invention uses already wasted heat - the only energy paid for is electricity to power the pumps, which lift water by one meter or so (the Torricelli vacuum lifts the supply water to the 10 meter level). A very simple calculation yields, for a typical electricity price of 5 cents per kilowatt-hour and other costs being equal, a price for our desalinated water of 12 to 15 cents to distill 1000 gallons! Reverse Osmosis uses 10 times more energy (*5*).

References

1. United Nations Environment Programme, "Key Facts about Water", (2003, http://www.unep.org/wed/2003/keyfacts.htm).
2. Hinrichsen, Don, "The Coastal Population Explosion", *Trends and Future Challenges for U.S. National Ocean and Coastal Policy* (NOAA, 1999).
3. WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, *Water for Life: Making it Happen* (WHO Press, Geneva, 2005).
4. Sandia National Laboratories, *Desalination and Water Purification Technology Roadmap* (National Technical Information Service, Virginia, 2003).
5. Semiat, Raphael, "Desalination: Present and Future", *Water International* **25**, 54 (2000).

Appendix A: Prior Art

The following is a summary of the main prior art for our invention. It should be noted that none of the previous inventors have addressed the problems of low pressure desalination in the same way, or as successfully, as we have. For this reason, patents on our invention have been applied for and we expect they will be issued soon.

1. *Solar Heated Vacuum Still (Snyder, US Patent 2490659, 1949)*
   This is a distillation method using solar water-heating panels and a height difference to produce vacuum conditions in the evaporator. Several different configurations for the desalination plant are suggested. The presence of non-condensable gases is not considered.

2. *Water Desalination System using Low-Grade Solar Heat (Al-Kharabsheh and Goswami, 2003)*
   Dr. Al-Kharabsheh and Dr. Goswami (from the University of Florida at Gainesville) have published several papers and a PhD-thesis describing a system using a height difference to reduce pressure and an atmospherically cooled condenser. They have performed experiments and simulations on such a system. Their invention is designed to use solar energy to heat the evaporator, limiting its practical applications.

3. *Desalination Plant operating in Kavaratti, India (2005)*
   A new desalination plant operating in India makes use of the temperature difference that exists between warm surface waters and deeper sea water under low pressure conditions.

4. *Desalination System (Atwell, US Patent 4536257, 1989)*
   This patent presents a desalination plant that evaporates water at a lower pressure maintained using a vacuum pump. A fan is used to transfer vapor from evaporator to condenser at some cost in efficiency. Vapor condenses by contact with a conventional finned heat exchanger, unlike the water-on-water condensation used in our system.

5. *Desalination Apparatus with Power Generation (Humiston, US Patent 4302297, 1981)*
   Humiston describes a desalination apparatus using the temperature gradient from surface to deep ocean water. His invention is intended to produce electrical power by means of a turbine and generator powered by the passage of water vapor through the system.