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# Radiative Cooling to the Night Sky

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# Radiative Cooling to the Night Sky

An Undergraduate Honors College Thesis

in the

Department of Chemical Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

by

Alexander Raymond Enderlin

March 17, 2015

This thesis is approved.

Thesis Advisor:

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Thesis Committee:

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# Project Personal Involvement

As the team coordinator of the 2015 University of Arkansas WERC Task 4 project "Radiative Cooling to the Night Sky", I personally was responsible for many aspects of the project completion. My primary contributions to the project were the development of a mathematical model to predict the performance of a radiative night sky cooling system, a detailed economic analysis on two distinctly different full-scale cooling systems, and development of a research program. Secondary contributions included an environmental savings analysis, the literature review, and scale up designs for both systems.

The literature review was the first phase of this project. I spent about two full weeks researching night sky radiative cooling phenomenon and attempts to utilize this phenomenon to obtain useful cooling. While performing the research, I discovered several correlations for predicting the amount of radiation from the night sky. I selected several of these for further testing in the experimental program. The primary parameters that effect night sky radiation were discovered in the research. I also found many examples of systems that are implemented on a residential basis, and to a lesser extent, a commercial basis. These were the foundation of our design considerations and greatly guided us to only implement technology that was practically feasible.

Planning and implementing the research program was the next step of the project. I first guided the group to work on validating/selecting the proper correlation to predict radiation from the night sky. A series of plate experiments were designed to this end and allowed the selection of one correlation as ideal. The next phase of the research program involved testing an experimental prototype that could be scaled up easily. I helped construct the prototype and determine how it would be tested to ensure compatibility with the mathematical model.

I was heavily involved in the design of both a full-scale open and closed system that would be compatible with the Intel facility in Rio Rancho, New Mexico.

My largest contribution, and in my opinion, the most significant achievement of this entire project was the mathematical model that I developed. The model was developed in excel and included a rigorous heat balance on the prototype system. The heat balance included radiation from the top and bottom, radiation to the top, convection from the top and bottom, convection from the piping, and heat input from a submersible pump. This heat balance predicted the experimental performance very well.

I developed a full-scale simulation to model the performance of the full scale system using TMY-3 weather data. The performance predicted by the model dictated the economics of the project.

I performed an economic analysis including the capital investment of each component for the system, operating costs, and operating savings for each system for two full-scale designs. Payback period and rate of return on investment for each of the two systems were also calculated.

Lastly I determined the environmental savings that could be claimed by implementation of the project.

# Appendix:
# Group Report

# Task 4: Radiative Cooling to Night Sky

**Ralph E. Martin Department of Chemical Engineering**

**University of Arkansas**

**Fayetteville, AR**

# RADIATIVE COOLING TO THE NIGHT SKY

## Task 4

Night Hogs

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James Cummings
Will Dale
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**Ralph E. Martin Department of Chemical Engineering**
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**Fayetteville, Arkansas**

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## EXECUTIVE SUMMARY

Silicon wafer fabrication facilities require a significant amount of temperate cooling water to meet high internal cooling loads. The tertiary chilled water systems operate year round to fulfil the constant cooling load needed for production. Conventional chillers require a large amount of electricity to cool the water by the vapor compression cycle. As energy costs increase and environmental stewardship becomes the norm in industry, sustainable technologies are needed to chill process cooling water without the significant energy consumption of today's chillers.

Night sky radiation cools a medium by radiating heat from a warm medium to the colder night sky. The Intel silicon wafer manufacturing facility in Rio Rancho, New Mexico was selected to be an ideal location for the implementation of two full-scale designs. Numerous system designs were examined during a thorough literature survey, and an open water system was chosen as the best alternative because of its superior heat transfer ability and lower construction cost. At the suggestion of an external auditor, a closed system was studied further, designed, and economically analyzed. Recommendations for system choice are based on economic analyses, system operability, and environmental considerations.

To aid in model construction and full-scale design, an extensive research program was developed to confirm literature correlations and determine the effectiveness of radiation to the night sky as a method used to cool water. Experiments that cooled an aluminum plate through the ambient temperature were used to confirm and verify the accuracy of Berdahl and Martin's correlation for calculating the effective temperature of the night sky. A prototype for the open water system was built to demonstrate the cooling ability of the design. Operation of the prototype successfully demonstrated radiative night sky cooling, showed the benefit of convective heat transfer when the ambient air temperature is below the water temperature, and validated Berdahl and Martin's model.

With the experimental stage complete, the prototype system was scaled-up to a system for the Intel facility in Rio Rancho. The system diverts cooling water from Intel's cooling water system into surge tanks. From the surge tanks, water is pumped up to the roof and is distributed among corrugated metal roofing units placed on top of the Intel central utilities building. The corrugated panels are supported by a pressure treated lumber frame. The chilled water is

distributed and collected by a PVC piping network. Model simulations of the full-scale system determined the cooling capability of the system.

The full-scale simulation predicted that the system would eliminate over 90% of the night-time chiller cooling loads during the winter. Throughout the year, the chillers use $280,000 worth of electricity[1]. The radiative cooling system will save the company $75,000 in annual electricity costs, a decrease in electricity consumption of 27%. The electricity generation portfolio of PNM, Intel's electricity provider, was used to determine that the system will prevent approximately 930 tons of carbon dioxide from being released into the atmosphere. The reduction of produced electricity will also conserve 4,220,000 gallons of water, a scarce resource in the southwestern Unites States. For the open system, the total capital cost is $353,500 and the operating cost, including electricity to operate the unit, is $31,600/year. For the closed system, the total capital cost is $636,500 and the operating cost, including electricity to operate the unit, is $12,000/year. The average net reduction in annual electrical usage is 1,282 MW-hr and the average yearly electrical cost savings is $75,265 for both systems. The payback period for the open and closed systems are estimated to be 4.77 years and 6.8 years, respectively. The radiative cooling system will economically benefit the Intel facility; however, the reduction in carbon emissions and water usage is of immense importance to the public and a company as dedicated to environmental initiatives as is Intel.

## INTRODUCTION

As companies focus on decreased energy consumption and environmental sustainability initiatives, they increasingly utilize "green" energy sources. The chilling of process cooling water uses a considerable amount of energy. Elimination or reduction of the need for such chillers will have a significant impact on a facility's electric costs and carbon footprint. Finding alternatives to these energy intensive chillers is a huge step toward sustainable manufacturing. Task 4 investigates radiative cooling to the night sky as a means to chill the process cooling water of a silicon wafer manufacturing facility.

During night sky radiative cooling, a medium emits heat in the form of infrared radiation to the sky, which acts as a low-temperature heat sink[2]. In antiquity, the ancient people of Iran utilized night sky radiative cooling to form ice in desert at night while ambient temperatures were well about the freezing point of water[3]. For implementation at a silicon wafer manufacturing facility, a properly designed system can be designed to handle all the chiller loads during in winter during nighttime, using both radiative and convective cooling.

The Intel semiconductor manufacturing facility in Rio Rancho, New Mexico was chosen as an ideal location to implement the design of the full-scale night sky water cooling system. The low relative humidity and cool night temperatures of the Albuquerque area provide excellent opportunities for radiative heat transfer to the night sky. The following full-scale systems were designed for operation at the Rio Rancho facility in accordance with their process cooling needs.

## TASK PARAMETERS

The design considerations for task 4 are:

1. Design a scalable system for rejecting heat by radiative cooling to the night sky, using appropriate sponsor input.
2. Address the effect of thermal efficiency of the radiative panels, power efficiency of the pumps, and pumping energy penalty on the overall system performance.
3. Design the system to generate anywhere from 0-100% of the cooling load, based on an average load of 150 refrigeration tons for 6 Tertiary Chilled Water (TCHW) Systems. The chiller plant is highly efficient, requiring only 0.6 kW of electricity to produce ton of useful refrigeration.
4. Design the system to interconnect with the existing TCHW system which has a supply temperature of 65°F and a return temperature of 69°F.
5. Need for freeze protection incorporated into design.
6. Include an economic analysis for the project that provides proof of economic feasibility.
    a. The task sponsors specify a payback period of 5 years.
7. Discuss any safety and legal risks associated with the implementation of the design.

## SELECTION OF OPTIMAL DESIGN

Although commercial development of radiative cooling systems has been limited, many small scale, residential designs have been implemented and tested. The most prevalent designs are active and passive radiative cooling systems. Active cooling systems circulate a working fluid, usually water or air, with a pump or fan, respectively[4]. Passive cooling systems do not require circulation. Passive cooling systems often consist of tanks filled with water which act as a thermal mass to moderate diurnal temperature swings[5]. Both types of cooling systems may be closed or open to the atmosphere.

A passive cooling system was rejected because it could not be integrated into the existing TCHW system. A water based system was chosen because water has a high heat capacity, is more economically transported through the system as opposed to air, and easily integrates into the existing TCHW system[6].

Three water based system designs were investigated, a sprayer system, a closed water system, and an open water system. A sprayer system sprays microdroplets of water onto a radiator panel where it collects and drains down the panel[7]. The cooling occurs primarily through evaporation, convection, and to a lesser extent, radiation to the night sky. This design was quickly rejected due to the large water loss from evaporation and windage. A closed water system features water flowing underneath a radiator surface. The cooling occurs through convective heat transfer between the flowing water and panel, which cools via radiation to the night sky and convection to the air[4]. An open water system features water flowing over a radiator surface. The cooling occurs via radiation to the night sky from the water, radiation from unwetted radiator surfaces through the fin effect, and a small amount of water evaporation. The open water system provides the highest cooling rate due to the water directly radiating to the night sky[6]. The open water system was investigated further because of its lower capital cost, fewer maintenance requirements, and better cooling rates. This system design was scaled from the experimental prototype to the full-scale design. At the suggestion of an external auditor, a closed system was designed and simulated because it also has inherent advantages such as lower operating costs and no exposure to the atmosphere.

## EXPERIMENTAL APPARATUS DESIGN

### Plate Apparatus

To verify literature correlations calculating the effective night sky temperature, an apparatus was constructed to display the top of two aluminum plates to the night sky. A 4’ box frame was constructed using lumber to support a 4’ by 8’ sheet of plywood. Elevating the 4’ x 8’ sheet with the frame was necessary to raise the plates above the fence line around the roof on the building where the experiments were conducted. The elevation allowed the plates to have a complete view factor of the night sky. Two sheets of 1 ½” foam board insulation were adhered to the top of the plywood with construction cement. Figure 1 displays the side view of the frame and insulation sheet. Two 12” x 18” rectangles were cut from the center of the top sheet of the foam board insulation. Two 12” x 18” x 1 ½” aluminum plates were painted on top with flat black paint and were placed in the two cavities of the insulation. Figure 2 displays the top of the apparatus with the aluminum plates in place. Holes were drilled into the side of the plates for insertion of type K thermocouples into its center. For each plate, one of these thermocouples was attached to a thermocouple reader while the other was attached to a data logger. The ambient air temperature and the relative humidity were measured and recorded with a data logger, which was hung in the space below the 4’ by 8’ plywood sheet. The ambient temperature probe’s view to the night sky had to be totally obstructed to prevent any radiative cooling to the night sky, which would give an ambient temperature reading lower than the actual value. A SS sheathed thermocouple was hung next to the data logger underneath the sheet and connected to a thermocouple reader for live ambient temperature readings. Two 1500 W hair dryers were used to heat the plates above ambient temperature for the experimental trials.

Figure 1: Side view of plate apparatus and frame.

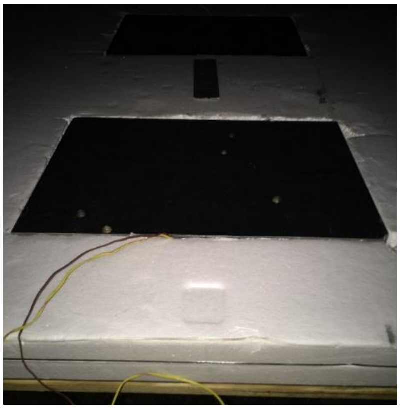

Figure 2: Top view of flat plate apparatus to insulate two plates.

**Prototype Apparatus**

The experimental prototype apparatus was designed as an open water system. The radiator panel consisted of a 4’ by 8’ sheet of corrugated metal roofing painted white. The corrugation style was 2 ½” wide channels with a depth of ½”. The sheet was supported by a 4’ high wooden frame. A perforated 1 ½” PVC sparger distributed the water flow evenly to each channel. The water flow from the sparger into the channels is shown in photogragh of Figure 3. A hole was drilled into the pipe above each flow channel on the corrugations. A 4” PVC half pipe collected the water as

Figure 3: Water flow through the sparger.

it exited the radiator, and a 4” PVC pipe carried the cool water into the reservoir, a 32-gallon trash can insulated with R-13 fiberglass insulation and a 1 ½” insulated lid and bottom displayed in Figure 4. The submersible pond pump (26.3 gpm at 10’ head) shown in Figure 5 was used to pump water from the reservoir through a 1 ½” PVC ball valve, which controlled the flow. The other end of the PVC tubing was attached to a 10 gpm rotameter which measured the flow from the reservoir to the sparger. The temperature of the water reservoir was monitored by two K-type thermocouples with one attached to a thermocouple reader and the other attached to a data logger. The ambient air temperature and the relative humidity were measured and recorded with a data logger hung under the radiator plate in a similar manner as described for the plate cooling experiments. Figure 6 displays the experimental prototype with the corrugation painted white. Figure 7 shows a process flow schematic (PFS) of the experimental prototype.

Figure 4: Insulated water reservoir.

Figure 5: Pond Pump

Figure 6: Experimental prototype.

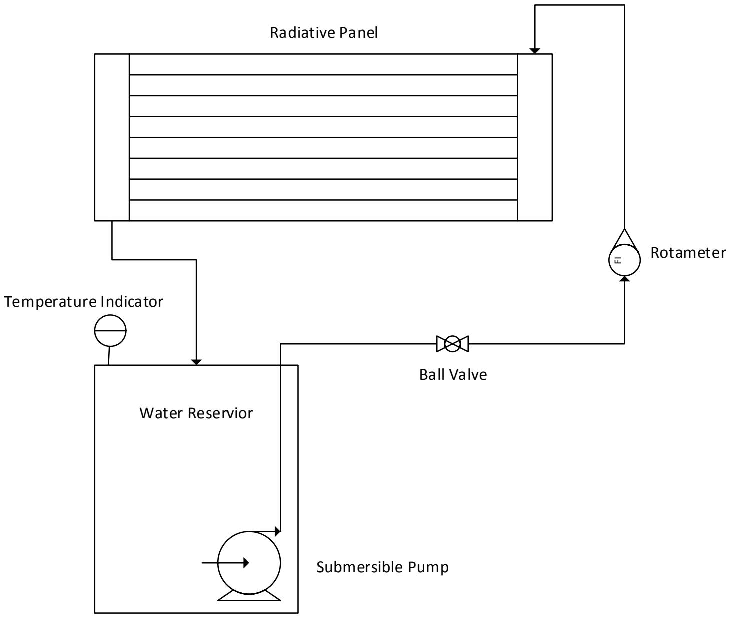

Figure 7: Experimental Prototype PFS.

## LABORATORY EXPERIMENTATION

### Plate Experimentation

To determine the effective night sky temperature, each plate was heated to 5 $^{o}$F above the ambient temperature and subsequently allowed to cool through the ambient temperature. Cooling through ambient temperature eliminated convective heat transfer from ambient air. This was repeated as time permitted. The temperature data was recorded over time with the data loggers.

### Submersible Pump Experimentation

A submersible pump was selected for use with the prototype apparatus. In order to perform a rigorous the heat balance on the prototype, it was necessary to experimentally determine the heat input from the pump. Several experiments were conducted in which the pump was fully submerged in a 5-gallon bucket with a ball valve on the discharge side of the pump. The 5-gallon bucket was highly insulated to prevent any heat loss. To monitor the temperature of the bucket over the experimental period, a data logger with a K-type thermocouple was placed within the water. Six, one hour experimental trials were performed at varying valve positions.

### Prototype Experimentation

In order to test the optimal cooling performance of the prototype, it was necessary to select a clear night for testing, so that clouds would not affect the radiative performance. The apparatus was installed in an open field to obtain the most favorable view factor with the sky. The system was tested with 24 gallons of water circulating through the system at 5 gpm. Warm water slightly above 100°F was used to start the transient cooling experiments and the water was allowed to cool to approximately 50°F. The reservoir temperature was recorded over time with a data logger.

## EXPERIMENTAL DATA REDUCTION

### Plate Data Reduction

The experimental data for the plate cooling through the ambient atmospheric air temperature was used in a heat balance to calculate an actual night sky temperature. Appendix “Plate Mathematical Model” explains the data reduction in more detail. Table 1 displays the reduced data for five nights of plate experimentation. For each night, the calculated night sky temperature from Berdahl and Martin’s Model was within 1℃ of the predicted night sky temperature.

Table 1. Experimental Plate Reduced Results

| | Night 1 | Night 2 | Night 3 | Night 4 | Night 5 |
|---|---|---|---|---|---|
| **Actual Night Sky Temperature ($^oC$)** | -29.02 | -6.57 | -24.92 | -35.94 | -34.92 |
| **Predicted Night Sky Temperature ($^oC$)** | -29.28 | -6.83 | -24.66 | -35.13 | -35.13 |

### Pump Data Reduction

A simple model calculated the heat input of the pump from the temperature change of the water in the insulated bucket. Appendix “Pump Mathematical Model” provides further explanation on the data reduction. The results indicated a constant heat input of 90 watts for all discharge valve positions.

### Prototype Data Reduction

A rigorous mathematical model was developed to model the prototype system. This model included radiative and convective heat transfer from the top and bottom of the corrugated sheet of the prototype. Heat transfer from the pump and piping were included in the analysis. For the un-wetted corrugated surface, a nodal analysis calculated the fin efficiency. The fin efficiency predicted by this analysis exceeded 90% for the chosen flow rate. A finite difference analysis with 16 elements was used to determine the water temperature variation along the corrugated channels. Appendix “Prototype Mathematical Model” elaborates on the model in greater detail. Figures 8 and 9 show the cooling curve predicted by the model as compared to the results actually achieved. The model was consistent with the experimental data for both nights of testing.

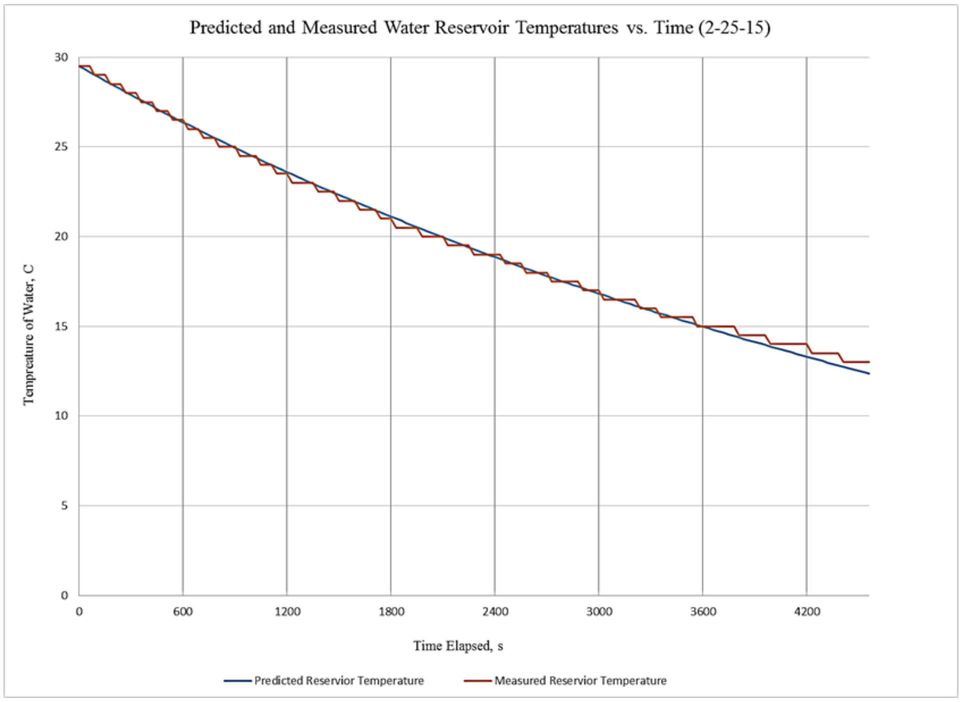

Figure 8: Predicted and measured cooling rate for prototype reservoir on 2-25-15.

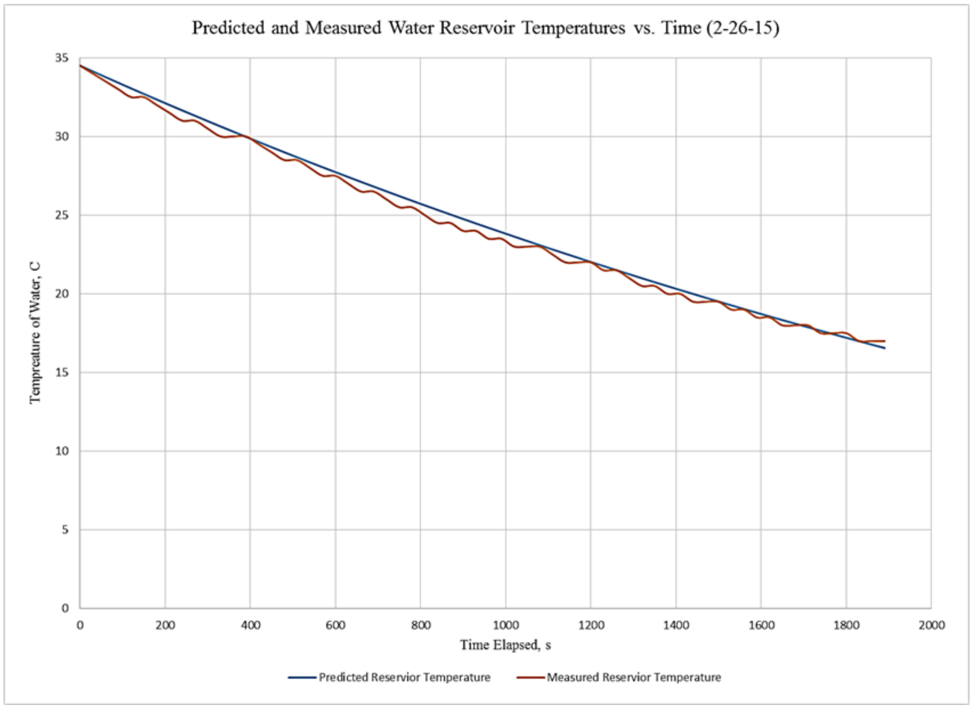

Figure 9: Predicted and measured cooling rate for prototype reservoir on 2-26-15.

## FULL-SCALE DESIGN

The Intel wafer manufacturing facility in Rio Rancho, New Mexico was selected as an ideal location for the scale-up design. Two full-scale systems, an open and a closed, were designed according to the facility's cooling needs.

### Open System

Figure 10: Intel utilities building.

The open system is designed to be located in the free space on top of the Intel utilities building shown in Figure 10. This location will allow the panels to have an unobstructed view of the night sky and offers the most convenient available space.

As displayed in Figure 11, the open design takes water directly from Intel's chilled water system and distributes the water over the radiator panels. The water removed from the cooling loop flows into the warm tank.  The water is pumped from the warm tank to the roof of the building where it is distributed along the radiator panels. After cooling on the panels, the water flows by gravity to the cool tank. A surge tank is included to handle an excess volume of water. A pump connected to the cool tank, moves water back into Intel's system where it will go through chillers if more cooling is needed. The warm tank/cold tank scheme ensures that the warmest water is sent to the panels to reject the most heat and the cool water is pumped back to the process with minimal thermal pollution. With proper ambient conditions, the open water system can handle the entire nightly cooling load.

Figure 10: Utilities Building Location

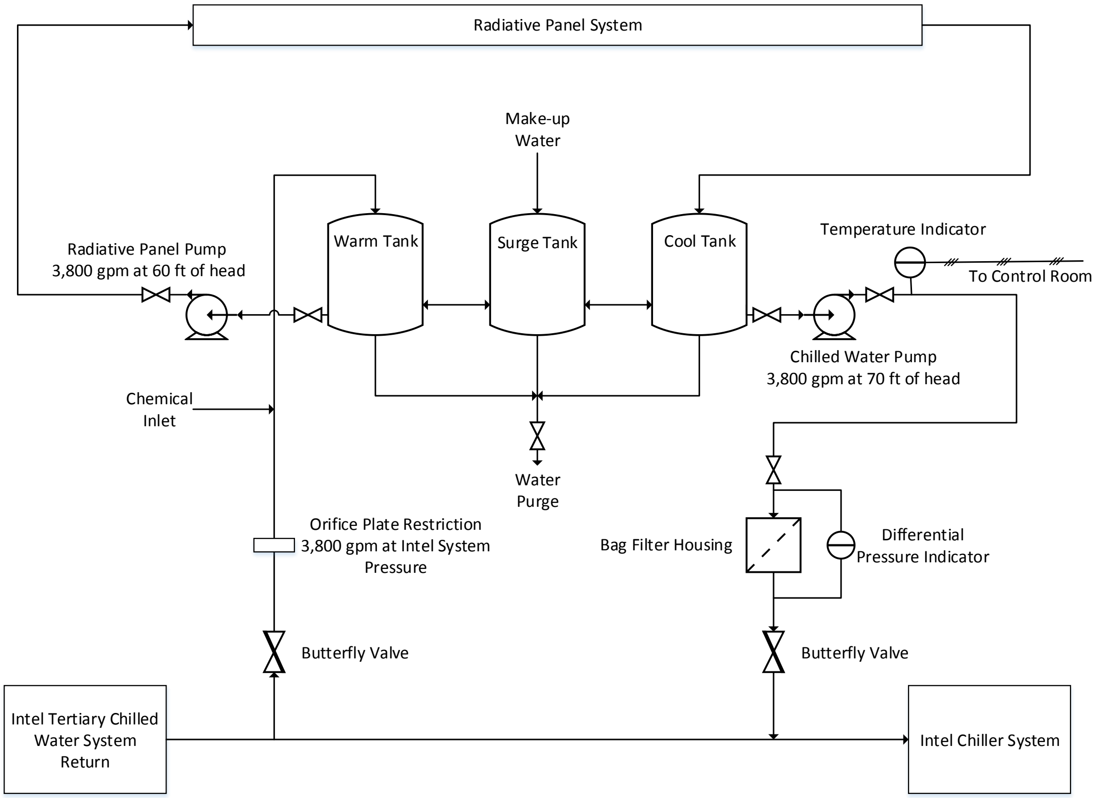

Figure 11: Visio process flow schematic of open system full-scale design.

There will be 216 panels placed on the roof each with the dimensions of 20’ x 20’. The panels will be supported by a wooden structure, which will lift the panels 4’ above the roof to allow the water to free drain and facilitate convective heat transfer on the underside of the radiator panels. Panels will be paired together with a 6” PVC half-pipe collector between them to collect the cool water. Each panel will have its own distributor. Corrugated galvanized steel roofing will be painted white, and overlaps between adjacent pieces will be silicone caulked. The panels will be secured to the wood structure with screws. The panels are divided into four different modules on the roof because of preexisting pipe racks on the roof. The panel pairs will be spaced out on the roof where each module will have nine columns and three rows of panel pairs as shown in Figure 12.

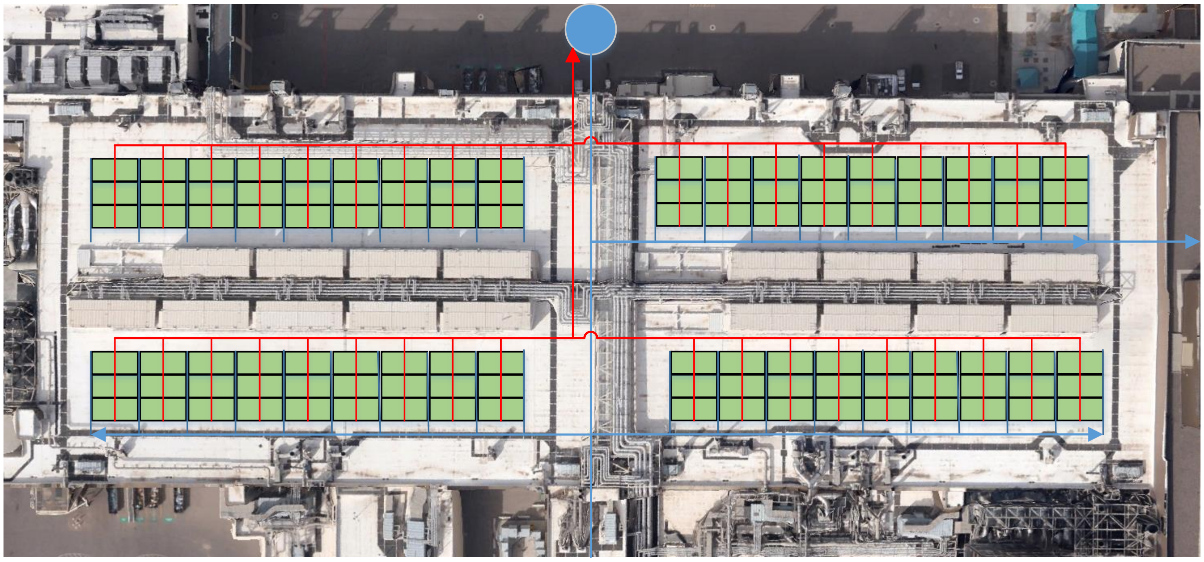

Figure 12: Intel open system scale-up design panel and piping configuration

The piping is vital to the success of this design. The flow into the panels will flow through a PVC piping distribution system. The piping network will allow the pressure of water to be approximately the same as it enters each of the distributors. There will also be PVC valves to control the flow at each of the distributors. The piping has to overcome the elevation head between ground level and the roof of the building, which is accomplished with a pump. The downstream flow of the supply pump uses 12” PVC piping and splits into four 6” pipes, which flow to each of the quadrants. Once the piping reaches the center of the quadrant, it flows into a distributor that disperses water into each column of panels. Once inside the columns, the water flows into a distributor shared by three panels and is fed onto each of the panels.

Once cooled, the water drains into 6” PVC half-pipe collectors shared by two panels. The collectors are supported by pipe straps spanning the distance between the two panels. The water flows out of the collectors and into 6” piping that drops 4’ to a 12” header. Each module has a 12” header that flows into the 12” main header along the center of the roof. The main header flows off the roof and into the cool tank. Calculations have been performed, which prove the effectiveness of the design to remove water from the system on the roof. The design prevents freezing by removing all the water from the roof when the system is not in use.

Chemicals and a filter are employed to keep the water clean and to protect the Intel cooling system. Biocides (glutaraldehyde and sodium bromide are possible choices) are required to control mold and other organisms in the water. Sodium nitrite can be added to prevent corrosion.

A bag filter housing requiring 13-100 micron bags will remove particles and other objects that collect in the water. The filters will be placed on the discharge side of the pump that sends chilled water from the insulated cool tank into Intel's cooling system. The filters are expected to need replacement once a month.

Open System Full-Scale Equipment List

Table 2 lists the equipment and materials needed to construct the full-scale open radiative night sky cooling system described above at the Intel Rio Rancho facility.

Table 2: Equipment and materials of construction for open system.

| Component | Quantity Needed |
|---|---|
| | |
| **Radiative Panels** | |
| 8' 4"x4" Pressure Treated Pine Lumber | 920.00 |
| 20' 2"x4" Pine Lumber | 3695.00 |
| 20' 2"x4" Pressure Treated Pine Lumber | 920.00 |
| 20'x26" Galvanized Corrugated Roofing | 2300.00 |
| Waterproof Silicon Sealant | 1127.00 |
| Exterior White 5-gallon Paint | 115.00 |
| | |
| **Piping and Fittings** | |
| 12" Schedule 40 PVC Pipe | 2285 |
| 6" Schedule 40 PVC Pipe | 11080 |
| 4" Schedule 40 PVC Pipe | 1980 |
| 2" Schedule 40 PVC Pipe | 9720 |
| Fittings (Additional 15% of total PVC Cost) | - |
| Filter Housing | 1 |
| | |
| **Pumps** | |
| Cast Iron 54 kW Centrifugal Pump | 1 |
| Cast Iron 62 kW Centrifugal Pump | 1 |
| | |
| **Tanks** | |
| 15,000 gallon Polyethylene Storage Tank | 3 |
| Insulation for Tanks | 1 |
| | |
| **Control Valves** | |
| 12" Water Butterfly Valve - 250 psig | 2 |

## Closed System

In addition to an open system, a closed system was also considered because water exposed to the atmosphere may not be compatible with the existing chiller system. Furthermore, companies may not want to add additional chemicals to their chilled water. The proposed closed system consists of aluminum finned pipe radiators. The closed system process flow schematic is shown in Figure 13. A pump is used to provide the differential head required to send the water through the fin system and back into Intel's chilled water system.

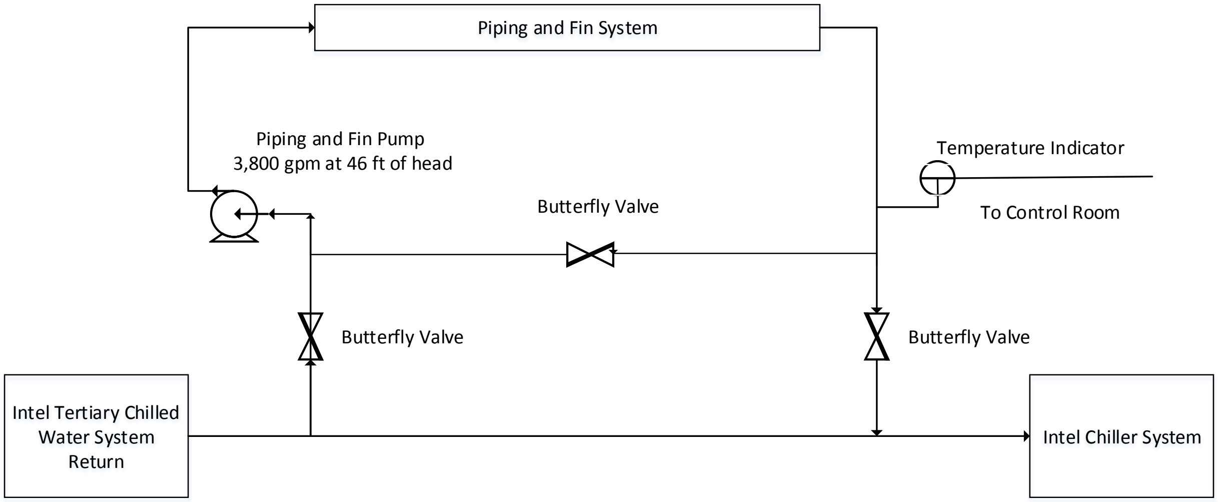

Figure 13: Visio process flow schematic of closed system full-scale design.

The finned piping system is divided into 4 quadrants. To achieve similar performance to the open system, each quadrant has 219 aluminum finned pipes that are 1.5" diameter and the fins are 4" long on each side of the pipe. The fins are 0.15" thick and have a fin efficiency of 90%. The finned pipes are 60' long and supported every 15' along the span of the roof. The supports are 4' high to allow convective heat rejection on the underside of the finned tubes. The finned pipes are painted white on top to achieve high radiative emittance and low solar absorbance. The water is pumped up on the roof via a 12" PVC pipe and is divided into the 4 quadrants with 6" pipes. The pipe extends to the middle of the quadrant and flows into a pipe distributor which transports water into eight 2" pipes. These 2" pipes distribute water into the 1.5" aluminum pipes. The exact same network is used on the collection side to direct the water into Intel's chilled water system. A connection line with a butterfly valve enables circulation of the water in the system upon startup until it is cool enough to be sent into the Intel chiller system. See Figure 14 for the view of the piping on the Intel central utilities building roof.

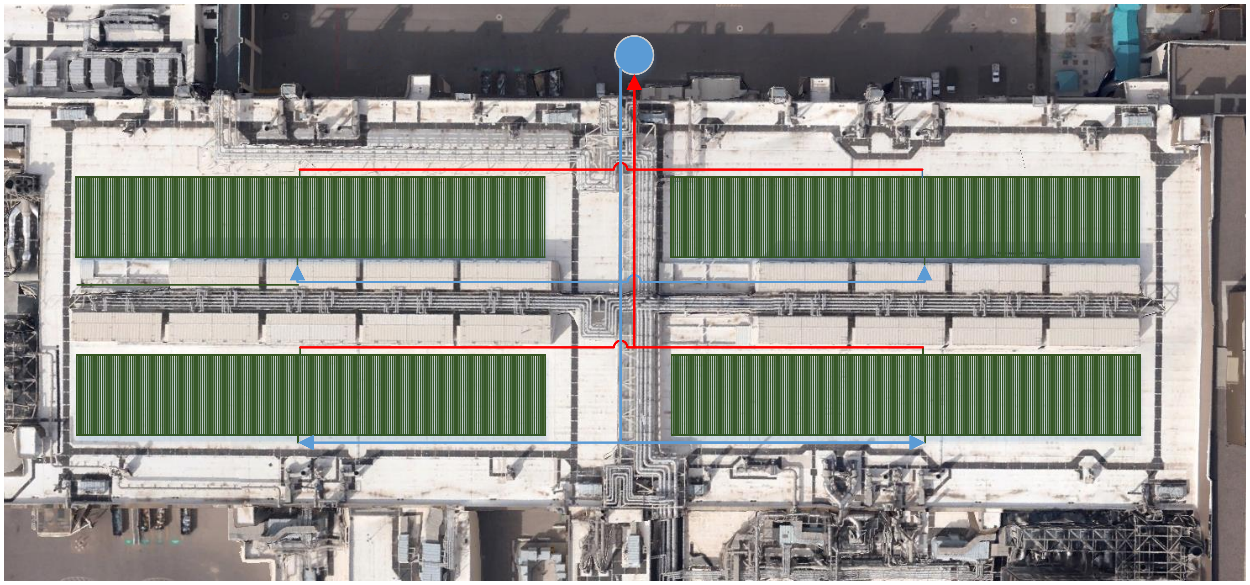

Figure 14: Intel closed system scale-up design panel and piping configuration

Closed System Full-Scale Equipment List

Table 3 lists the equipment and materials needed to construct the full-scale closed radiative night sky cooling system described above at the Intel Rio Rancho facility.

Table 3: Equipment and materials of construction for closed system.

| Component | Quantity Needed |
|---|---|
| | |
| **Radiative Panels** | |
| Extruded Aluminum Finned Tubes | 111259 |
| 8' 4"x4" Pressure Treated Pine Lumber | 864 |
| 20' 2"x4" Pressure Treated Pine Lumber | 1440 |
| Exterior 5-gallon Paint | 115.00 |
| | |
| **Piping and Fittings** | |
| 12" Schedule 40 PVC Pipe | 495 |
| 6" Schedule 40 PVC Pipe | 4920 |
| 2" Schedule 40 PVC Pipe | 2880 |
| Fittings (15% of PVC pipe cost) | |
| | |
| **Pumps** | |
| Cast Iron 42 kW Centrifugal Pump | 1 |
| | |
| **Control Valves** | |
| 12" Water Butterfly Valve - 250 psig | 3 |

### Simulation of Full-Scale Designs

After verification of the correlation developed by Berdahl and Martin[8] with the prototype, the performance of the prototype system design was scaled up. The simulation used TMY-3 meteorological data for Albuquerque, NM provided by the National Solar Radiation Database[9]. TMY-3 data is intended for use in simulations and Albuquerque was the closest site for reliable meteorological data. The mathematical model for the full-scale design includes convection and radiative effects on the panels. It was determined from the simulation that the full scale system should operate all year except July and August, when the cooling performance does not justify the energy required by the pumps. The system was designed to provide maximum nightly cooling during February. The simulation of the system indicates that it would provide about 27% of Intel’s total cooling load over the year, which means that, on average, 243 tons of the 900 ton average cooling load is provided by the radiative cooling system at night.

## ECONOMIC ANALYSIS

### Open System Economics

Table 4 lists the economic analysis for the open system radiative night sky cooling project.  The analysis includes the equipment and material, installation, and labor costs of building the system, system operating cost, and the savings incurred from reducing the use of the existing chiller system.

Table 4: Summary of costs and savings for open system at Intel facility.

| **EQUIPMENT COSTS** | **Basis** | **Cost** |
|---|---|---|
| Pumps | CapCost 2012 Program | $ 27,596.98 |
| Insulated Tank | Manufacturer | $ 53,423.00 |
| Radiative Panels | Sum of Component Costs | $ 73,883.98 |
| Piping | Manufacturer | $ 41,901.86 |
| Butterfly Valves | Manufacturer | $ 2,614.00 |
| Filter Housing | Manufacturer | $ 10,000.00 |
| **Total Purchased Equipment Cost** | | **$ 209,419.82** |
| | | |
| **DIRECT COSTS** | | |
| Purchased Equipment Cost | | $ 209,419.82 |
| Purchased Equipment Delivery | 10% of Purchased Equipment Cost | $ 20,941.98 |
| Purchased Equipment Installation Labor | Estimated Per Component | $ 104,082.92 |
| **Total Direct Plant Costs** | | **$ 334,444.72** |
| | | |
| **INDIRECT COSTS** | | |
| Engineering/Supervision | $100,000 per year assuming 1 months time | $ 8,333.33 |
| Contingency | 5% of purchased equipment cost | $ 10,470.99 |
| **Total Indirect Plants Costs** | | **$ 18,804.32** |
| | | |
| **Total Capital Investment** | Sum of Direct and Indirect Costs | **$ 353,249.05** |
| | | |
| **ANNUAL OPERATING EXPENSES** | | |
| Utilities | Electricity, Water | $ 30,500.00 |
| Water Treatment Chemicals | Manufacturer | $ 1,000.00 |
| Replacement Filters | Manufacturer | $ 100.00 |
| **Total Annual Operating Expenses** | | **$ 31,600.00** |
| | | |
| **ANNUAL OPERATING SAVINGS** | | |
| Utilities | Electricity | $ 105,645.00 |
| **Total Annual Operating Savings** | | **$ 105,645.00** |
| | | |
| **Net Annual Savings** | Difference of savings and expenses | **$ 74,045.00** |

The task specified a non-discounted payback period of 5 years. The non-discounted payback period calculated for the open system full-scale design was 4.77 years. The rate of return on investment was calculated to be 21%.

### Closed System Economics

Table 5 lists the economic analysis for the closed system radiative night sky cooling project. The analysis includes the equipment and material, installation, and labor costs of building the system, system operating cost, and the savings incurred from reducing the use of the existing chiller system.

Table 5: Summary of costs and savings for closed system at Intel facility.

| **EQUIPMENT COSTS** | **Basis** | **Cost** |
|---|---|---|
| Pump | CapCost 2012 Program | $ 10,900.00 |
| Radiative Piping | Sum of Component Costs | $ 442,856.74 |
| PVC Piping and Fittings | Manufacturer | $ 14,796.36 |
| Butterfly Valves | Manufacturer | $ 3,921.00 |
| **Total Purchased Equipment Cost** | | **$ 472,474.10** |
| | | |
| **DIRECT COSTS** | | |
| Purchased Equipment Cost | | $ 472,474.10 |
| Purchased Equipment Delivery | 10% of Purchased Equipment Cost | $ 47,247.41 |
| Purchased Equipment Installation Labor | Estimated Per Component | $ 76,400.00 |
| **Total Direct Plant Costs** | | **$ 596,121.51** |
| | | |
| **INDIRECT COSTS** | | |
| Engineering/Supervision | $100,000 per year assuming 2 months time | $ 16,666.67 |
| Contingency | 5% of purchased equipment cost | $ 23,623.71 |
| **Total Indirect Plants Costs** | | **$ 40,290.37** |
| | | |
| **Total Capital Investment** | Sum of Direct and Indirect Costs | **$ 636,411.88** |
| | | |
| **ANNUAL OPERATING EXPENSES** | | |
| Utilities | Electricity, Water | $ 11,500.00 |
| Water Treatment Chemicals | Manufacturer | $ 500.00 |
| **Total Annual Operating Expenses** | | **$ 12,000.00** |
| | | |
| **ANNUAL OPERATING SAVINGS** | | |
| Utilities | Electricity | $ 105,645.00 |
| **Total Annual Operating Savings** | | **$ 105,645.00** |
| | | |
| **Net Annual Savings** | Difference of savings and expenses | **$ 93,645.00** |

The task specified a non-discounted payback period of 5 years. The non-discounted payback period calculated for the closed system full-scale design was 6.8 years. The rate of return on investment was calculated to be 14.7%. Although the closed system does not fulfill the desired payback period of 5 years, the system offers a viable alternative if a closed system must be implemented.

## ENVIRONMENTAL, HEALTH, & SAFETY

A major concern with an open water system is the buildup of algae and biological contaminants on the corrugated roofing and in the reservoir. Glutaraldehyde and sodium bromide are biocides that eliminate the growth of biological organisms. Sodium nitrite is a corrosion inhibitor. They are all commonly used in agriculture and industry. The use of biocides and other water additives is regulated under the Safety Drinking Water Act (SDWA)[10]. The New Mexico Environmental Department enforces Section 402 of the Clean Water Act, which requires all facilities within the state to obtain a National Pollutant Discharge Elimination System permit every five years. These facilities must periodically monitor, collect, and analyze their wastewater samples and submit a Discharge Monitoring Report to demonstrate compliance. These requirements must be fulfilled by Intel or any other site, where the open water radiative cooling system is implemented. The maximum contaminant level of the biocides listed above must be under the following concentrations: 0.2 ppm for glutaraldehyde, 10 ppm for sodium bromide, and 1 ppm for sodium nitrite.

Due to the hazardous nature of these chemicals, precautions must be taken to eliminate exposure, contamination, or spill. Glutaraldehyde is an irritant that targets the eyes, skin, and respiratory system[11]. Sodium bromide can react with oxygen to form a bromate ion, which is a known human carcinogen[12]. Sodium nitrite overdose causes serious illness[11].At the manufacturing site, the proper precautions must be taken to ensure the safety of workers in regards to these hazards. In regards to the community, the site must properly treat or dispose of the water to prevent public exposure to these hazardous chemicals.

The full-scale design places a significant load on the roof of a building at the Intel site in Rio Rancho, New Mexico. The construction of the system must take into account all building codes for the area in order for the system to be built in a safe and legal fashion.

With such a large amount of water on the roof, a significant loss of containment could have adverse effects. Damage is possible the building and surrounding structures. If the water encountered any electrical equipment on the roof, the equipment could be damaged, and anyone in contact with the water would be at a risk for electrocution. To prevent these accidents, adequate drains must be in place to contain the spilled water.

## CONCLUSIONS AND RECOMMENDATIONS

1. An extensive literature survey regarding the implementation of radiative night sky cooling systems was conducted to explore existing technology.
2. As a result of the literature survey and preliminary economics, the open water radiative night sky cooling system was chosen for experimentation and modeling.
3. Five plate cooling experiments calculated an experimental night sky temperature within $1^{o}$ C of the temperature predicted by the Berdahl and Martin correlation[8].
4. The experimental prototype successfully demonstrated the cooling ability of the open water radiative night sky cooling system.
5. Full-scale open and closed water-based systems were designed for implementation at Intel's silicon wafer manufacturing facility in Rio Rancho, New Mexico.
6. Simulations of the full-scale systems verified the applicability of radiative night sky cooling to provide adequate cooling of Intel's process cooling water.
7. The economic analyses yielded a capital cost of \$353,500 for the open system and a capital cost of \$636,500 for the closed system.
8. The annual net operational savings of the open system was calculated to be \$74,050. The annual net operational savings of the closed system was calculated to be \$93,650.
9. The discounted payback period for the open system was calculated to be approximately 4.77 years. The discounted payback period for the closed system was calculated to be approximately 6.8 years.
10. The radiative cooling systems are predicted to save approximately 1.7 million kW-hr of electricity per year. Saving this much electricity prevents approximately 4.2 million gallons of water consumption and 930 tons of carbon dioxide emissions at the utility.
11. Implementing a radiative night sky cooling system would put the facility and company at the forefront of sustainable manufacturing and encourage others to do the same.

## APPENDIX

### Plate Mathematical Model

The experimental data for the plate cooling through the ambient atmospheric air temperature was used to calculate an actual night sky temperature. First an energy balance on the plate was utilized:

$$Energy\ Accumulated = Energy\ In - Energy\ Out \tag{1}$$

$$Energy\ Accumulated = \ mC_p\left(\frac{dT}{dt}\right) \tag{2}$$

$$Energy\ In = \ A_{plate}\sigma\varepsilon_{sky}T_{sky}^4 \tag{3}$$

$$Energy\ Out = A_{plate}\sigma\varepsilon_{plate}T_{plate}^4 \tag{4}$$

Substituting equations 2, 3, and 4 into equation 1 and solving for $T_{sky}$ yields:

$$T_{sky} = \left(\frac{\left(mC_p\left(\frac{dT}{dt}\right)+A_{plate}\sigma\varepsilon_{plate}T_{plate}^4\right)}{A_{plate}\sigma\varepsilon_{sky}}\right)^{\frac{1}{4}} \tag{5}$$

The correlation used to predict the night sky temperature was developed by Berdahl and Martin[8]. A correlation for sky emissivity as a function of dewpoint temperature on clear nights was provided:

$$\varepsilon = 0.711 + 0.56\left(\frac{T_{dp}}{100}\right) + 0.73\left(\frac{T_{dp}}{100}\right)^2 + 0.013\cos\left(\frac{2\pi t}{24}\right) + 0.00012(P-1000)$$

(6)

Sky temperature depression, $\Delta T_{sky}$, is the temperature of the sky with respect to the ambient air and was defined as:

$$\Delta T_{sky} = T_{air} - T_{sky} = \left(1-\varepsilon^{\frac{1}{4}}\right)T_{air} \tag{7}$$

Thus the predicted sky temperature can be calculated as:

$$T_{sky} = \varepsilon^{\frac{1}{4}}T_{air} \tag{8}$$

### Pump Mathematical Model

The following model was used to determine the heat input of the pump from the temperature change of the water in the insulated bucket:

$$Energy\ Accumulated = Energy\ In \tag{9}$$

$$Energy\ Accumulated = \ \rho VC_p\frac{dT}{dt} \tag{10}$$

## Prototype Mathematical Model

### Fin Efficiency Development

For an exposed fin length, $L_{fin}$, and a total node number, $N_{node}$, the length of each nodal element is:

$$\Delta X = \frac{L}{N_{node}-1} \tag{11}$$

The first nodal element is at the temperature of the water and is identified as $T_1$. For the interior nodes, $T_2$ to $T_{N-1}$, the following equation applies:

$$T_i = \frac{\left(\frac{h_{conv}A_p\Delta X}{kA_{cs}}(T_a-T_i)+\frac{\varepsilon_{rad}\sigma A_p\Delta X}{kA_{cs}}(T_{ns}^4-T_i^4)+T_{i-1}+T_{i+1}\right)}{2} \tag{12}$$

For the last half node, $T_N$, the following equation applies:

$$T_{N_{node}} = \frac{h_{conv}A_p\Delta X}{2kA_{cs}}\left(T_a - T_{N_{node}}\right) + \frac{\varepsilon_{rad}\sigma A_p\Delta X}{2kA_{cs}}\left(T_{ns}^4 - T_{N_{node}}^4\right) + T_{N-1} \tag{13}$$

The heat loss of each node along the fin is described for node 1 by:

$$Q_1 = \frac{h_{conv}A_p}{2}(T_1 - T_a) + \frac{\varepsilon_{rad}\sigma A_p}{2}(T_1^4 - T_{ns}^4) \tag{14}$$

For interior nodes (i = 2 to N-1):

$$Q_i = h_{conv}A_p(T_i - T_a) + \varepsilon_{rad}\sigma A_p(T_i^4 - T_{ns}^4) \tag{15}$$

For last node, N:

$$Q_N = \frac{h_{conv}A_p}{2}(T_N - T_a) + \frac{\varepsilon_{rad}\sigma A_p}{2}(T_N^4 - T_{ns}^4) \tag{16}$$

Fin efficiency can be calculated by:

$$\eta_{fin} = \frac{\left(\sum_{i=1}^{N} Q_i\right)}{Q_{fin,max}} \tag{17}$$

## Prototype Model Development

For a plate length, $L_{plate}$, and a total element number, $N_{fe}$, the length of each element is:

$$L_{fe} = \frac{L_{plate}}{N_{fe}} \tag{18}$$

An effective area is defined for the surface which incorporates fin efficiency for the non-wetted portion of the surface:

$$A_{fe_{eff}} = \frac{(A_{sw}+\eta_{fin}A_{snw})}{N_{fe}} \tag{19}$$

The first element is initially at the start temperature of the experiment, $T_{1,0}$. An energy balance can represent each element:

$$Energy\ Accumulated = Energy\ In - Energy\ Out \tag{20}$$

$$Energy\ Accumulated = 0 \tag{21}$$

$$Energy\ In = \left(\frac{Q_{pump}}{16}\right) + wC_pT_{i-1} \tag{22}$$

$$Energy\ Out = \left(\frac{T_{i-1}-T_a}{R_{pipe}}\right) + 2h_{comb}A_{fe_{eff}}(T_{i-1} - T_a) + \varepsilon_{bot}\sigma A_{fe_{eff}}(T_{i-1}^4 - T_a^4) + wC_pT_i + 4\varepsilon_{top}\sigma T_a^3\big(\Delta T_s - (T_a - T_{i-1})\big) \tag{23}$$

Thus each element can be solved for given the temperature of the element before it.

The reservoir temperature change can be modeled by calculating the heat loss across the plate and applying it to the reservoir, assuming it is fully mixed with no temperature gradients. An energy balance for the reservoir yields (pump heat was accounted for in radiator balance, but could have been included here):

$$Energy\ Accumulated = Energy\ In - \ Energy\ Out \tag{24}$$

$$Energy\ Accumulated = \ \rho VC_p\left(\frac{dT_1}{dt}\right) \tag{25}$$

$$Energy\ In = wC_pT_{N_{fe}} \tag{26}$$

$$Energy\ Out = wC_pT_1 \tag{27}$$

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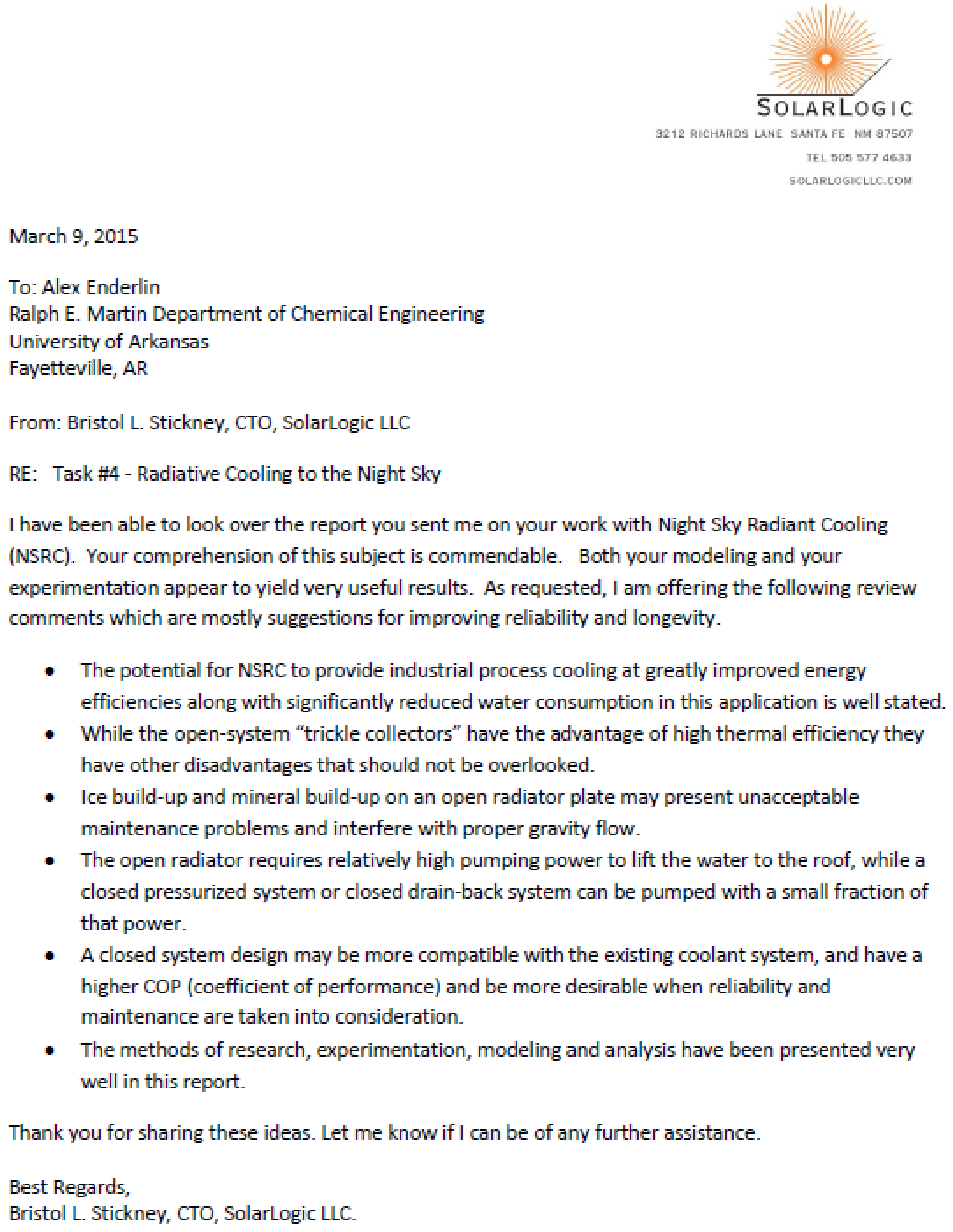

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March 9, 2015

To: Alex Enderlin
Ralph E. Martin Department of Chemical Engineering
University of Arkansas
Fayetteville, AR

From: Bristol L. Stickney, CTO, SolarLogic LLC

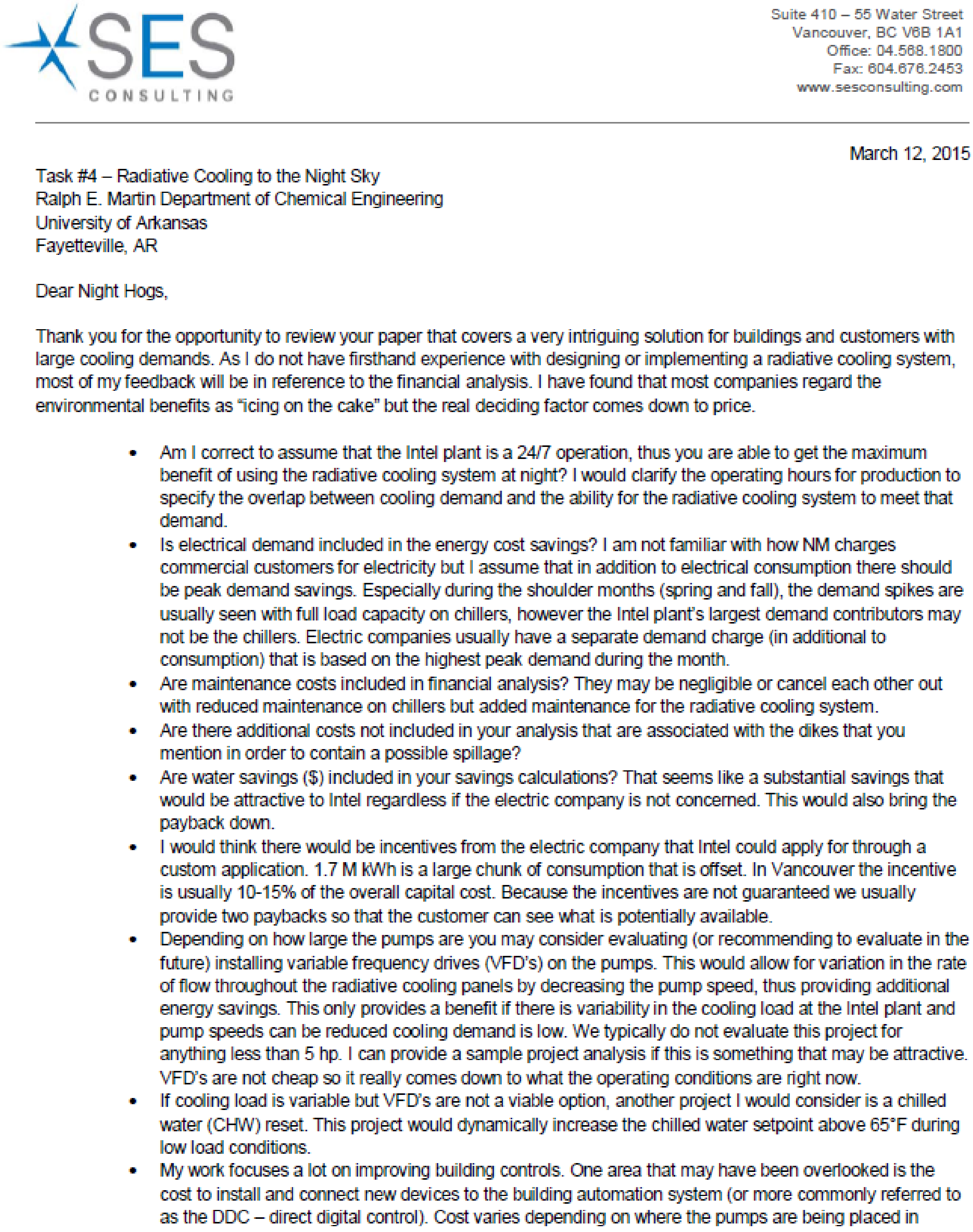
RE: Task #4 - Radiative Cooling to the Night Sky

I have been able to look over the report you sent me on your work with Night Sky Radiant Cooling (NSRC). Your comprehension of this subject is commendable. Both your modeling and your experimentation appear to yield very useful results. As requested, I am offering the following review comments which are mostly suggestions for improving reliability and longevity.

- The potential for NSRC to provide industrial process cooling at greatly improved energy efficiencies along with significantly reduced water consumption in this application is well stated.
- While the open-system "trickle collectors" have the advantage of high thermal efficiency they have other disadvantages that should not be overlooked.
- Ice build-up and mineral build-up on an open radiator plate may present unacceptable maintenance problems and interfere with proper gravity flow.
- The open radiator requires relatively high pumping power to lift the water to the roof, while a closed pressurized system or closed drain-back system can be pumped with a small fraction of that power.
- A closed system design may be more compatible with the existing coolant system, and have a higher COP (coefficient of performance) and be more desirable when reliability and maintenance are taken into consideration.
- The methods of research, experimentation, modeling and analysis have been presented very well in this report.

Thank you for sharing these ideas. Let me know if I can be of any further assistance.

Best Regards,
Bristol L. Stickney, CTO, SolarLogic LLC.



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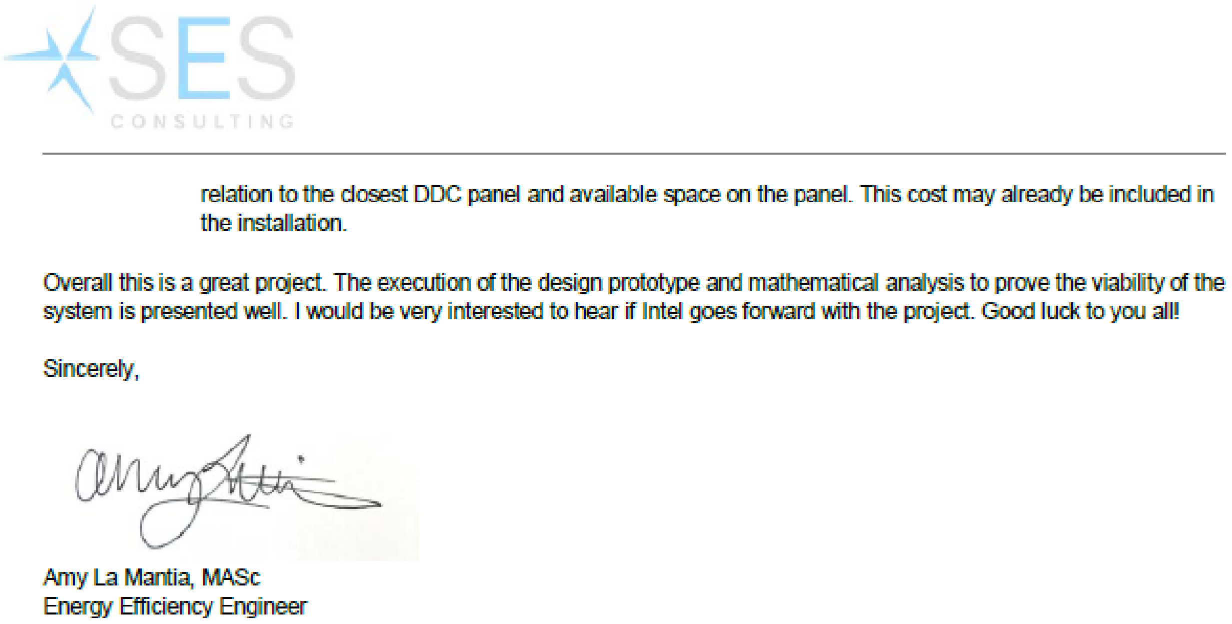
March 12, 2015

Task #4 – Radiative Cooling to the Night Sky
Ralph E. Martin Department of Chemical Engineering
University of Arkansas
Fayetteville, AR

Dear Night Hogs,

Thank you for the opportunity to review your paper that covers a very intriguing solution for buildings and customers with large cooling demands. As I do not have firsthand experience with designing or implementing a radiative cooling system, most of my feedback will be in reference to the financial analysis. I have found that most companies regard the environmental benefits as "icing on the cake" but the real deciding factor comes down to price.

- Am I correct to assume that the Intel plant is a 24/7 operation, thus you are able to get the maximum benefit of using the radiative cooling system at night? I would clarify the operating hours for production to specify the overlap between cooling demand and the ability for the radiative cooling system to meet that demand.
- Is electrical demand included in the energy cost savings? I am not familiar with how NM charges commercial customers for electricity but I assume that in addition to electrical consumption there should be peak demand savings. Especially during the shoulder months (spring and fall), the demand spikes are usually seen with full load capacity on chillers, however the Intel plant's largest demand contributors may not be the chillers. Electric companies usually have a separate demand charge (in additional to consumption) that is based on the highest peak demand during the month.
- Are maintenance costs included in financial analysis? They may be negligible or cancel each other out with reduced maintenance on chillers but added maintenance for the radiative cooling system.
- Are there additional costs not included in your analysis that are associated with the dikes that you mention in order to contain a possible spillage?
- Are water savings ($) included in your savings calculations? That seems like a substantial savings that would be attractive to Intel regardless if the electric company is not concerned. This would also bring the payback down.
- I would think there would be incentives from the electric company that Intel could apply for through a custom application. 1.7 M kWh is a large chunk of consumption that is offset. In Vancouver the incentive is usually 10-15% of the overall capital cost. Because the incentives are not guaranteed we usually provide two paybacks so that the customer can see what is potentially available.
- Depending on how large the pumps are you may consider evaluating (or recommending to evaluate in the future) installing variable frequency drives (VFD's) on the pumps. This would allow for variation in the rate of flow throughout the radiative cooling panels by decreasing the pump speed, thus providing additional energy savings. This only provides a benefit if there is variability in the cooling load at the Intel plant and pump speeds can be reduced cooling demand is low. We typically do not evaluate this project for anything less than 5 hp. I can provide a sample project analysis if this is something that may be attractive. VFD's are not cheap so it really comes down to what the operating conditions are right now.
- If cooling load is variable but VFD's are not a viable option, another project I would consider is a chilled water (CHW) reset. This project would dynamically increase the chilled water setpoint above 65°F during low load conditions.
- My work focuses a lot on improving building controls. One area that may have been overlooked is the cost to install and connect new devices to the building automation system (or more commonly referred to as the DDC – direct digital control). Cost varies depending on where the pumps are being placed in

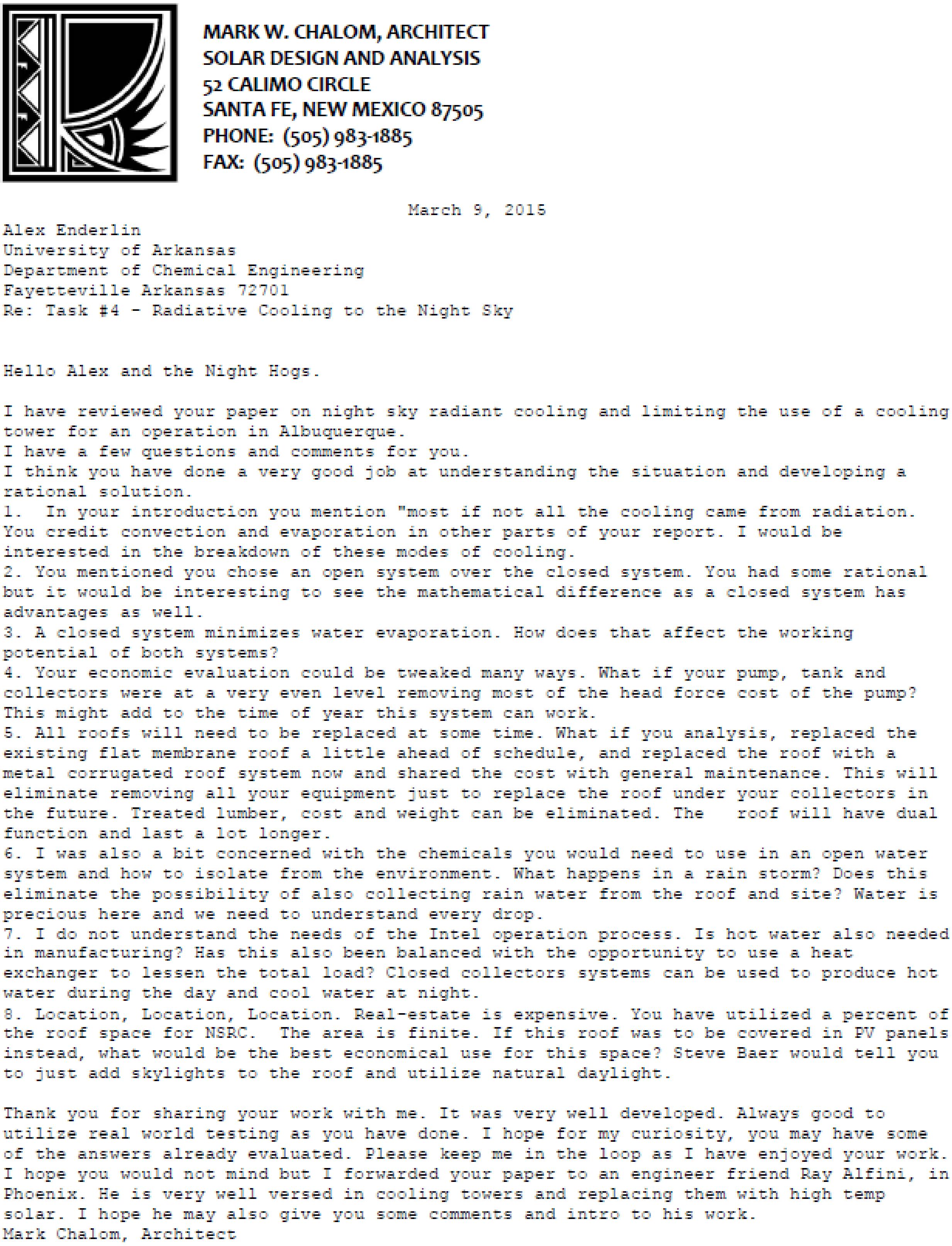


relation to the closest DDC panel and available space on the panel. This cost may already be included in the installation.

Overall this is a great project. The execution of the design prototype and mathematical analysis to prove the viability of the system is presented well. I would be very interested to hear if Intel goes forward with the project. Good luck to you all!

Sincerely,

Amy La Mantia, MASc
Energy Efficiency Engineer



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March 9, 2015

Alex Enderlin
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Fayetteville Arkansas 72701
Re: Task #4 - Radiative Cooling to the Night Sky

Hello Alex and the Night Hogs.

I have reviewed your paper on night sky radiant cooling and limiting the use of a cooling tower for an operation in Albuquerque.
I have a few questions and comments for you.
I think you have done a very good job at understanding the situation and developing a rational solution.

1. In your introduction you mention "most if not all the cooling came from radiation. You credit convection and evaporation in other parts of your report. I would be interested in the breakdown of these modes of cooling.
2. You mentioned you chose an open system over the closed system. You had some rational but it would be interesting to see the mathematical difference as a closed system has advantages as well.
3. A closed system minimizes water evaporation. How does that affect the working potential of both systems?
4. Your economic evaluation could be tweaked many ways. What if your pump, tank and collectors were at a very even level removing most of the head force cost of the pump? This might add to the time of year this system can work.
5. All roofs will need to be replaced at some time. What if you analysis, replaced the existing flat membrane roof a little ahead of schedule, and replaced the roof with a metal corrugated roof system now and shared the cost with general maintenance. This will eliminate removing all your equipment just to replace the roof under your collectors in the future. Treated lumber, cost and weight can be eliminated. The roof will have dual function and last a lot longer.
6. I was also a bit concerned with the chemicals you would need to use in an open water system and how to isolate from the environment. What happens in a rain storm? Does this eliminate the possibility of also collecting rain water from the roof and site? Water is precious here and we need to understand every drop.
7. I do not understand the needs of the Intel operation process. Is hot water also needed in manufacturing? Has this also been balanced with the opportunity to use a heat exchanger to lessen the total load? Closed collectors systems can be used to produce hot water during the day and cool water at night.
8. Location, Location, Location. Real-estate is expensive. You have utilized a percent of the roof space for NSRC. The area is finite. If this roof was to be covered in PV panels instead, what would be the best economical use for this space? Steve Baer would tell you to just add skylights to the roof and utilize natural daylight.

Thank you for sharing your work with me. It was very well developed. Always good to utilize real world testing as you have done. I hope for my curiosity, you may have some of the answers already evaluated. Please keep me in the loop as I have enjoyed your work. I hope you would not mind but I forwarded your paper to an engineer friend Ray Alfini, in Phoenix. He is very well versed in cooling towers and replacing them with high temp solar. I hope he may also give you some comments and intro to his work.
Mark Chalom, Architect