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TWO SENIOR CAPSTONE DESIGN PROJECTS ON THE POTENTIAL ENERGY SAVINGS AT THE PETTIT NATIONAL ICE CENTER

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Abstract

This paper presents the results of two real-world mechanical engineering senior capstone design projects at the University of Wisconsin-Milwaukee. These projects focused on methods for obtaining potential energy savings at the Pettit National Ice Center (PNIC) in Milwaukee, Wisconsin. The authors were originally requested by the State of Wisconsin's Division of Energy to perform a feasibility study on ways to reduce the large energy costs incurred at this facility. The authors chose to use this project as the basis for two senior design projects. A three-student team was assigned to each project. Each team worked closely with the authors throughout the semester. The first project centered on identifying and analyzing waste heat recovery options for the PNIC, while the second project focused on options for adding on-site power generation to the facility. To provide a real-world experience for the students, the faculty took on the role of project managers, defining the project goals, overseeing the progress to keep the teams focused, and critiquing the work to assure that the students considered quality and all reasonable options. The students identified the specific goals of their projects, formulated their design action plan, researched possible solutions, performed the engineering analysis, interacted with PNIC staff, government officials, and industrial personnel, prepared the final report, and formally presented their results.

The use of this open-ended feasibility study allowed the students to use a great deal of creativity in solving and analyzing a problem in a real-world setting with realistic constraints. Details of the students' final designs, cost analyses, and recommendations as well as the educational experiences of the mechanical engineering undergraduate students who worked on these projects are described.

Background[1]

The Pettit National Ice Center (PNIC) in Milwaukee, Wisconsin is an Olympic Training Facility for U.S. Speedskating (Fig. 1). Built in 1992, the PNIC has served such Olympic medallists as Eric and Beth Heiden, Dan Jansen, and Bonnie Blair, and currently serves as an official training facility for new members of the team. The PNIC has also hosted several prestigious speed skating events including the National Championships, World Cups, World Championships, and the Olympic Trials. The PNIC does not receive grants from the U.S. Olympic Committee and is operated by a non-profit organization.

Figure 1. The Pettit National Ice Center in Milwaukee, Wisconsin.

The facility spans 11,800 m^2 with an ice surface area of 9,000 m^2. It features a 400-meter speed skating oval that encircles two international size skating rinks, each 61 m by 30 m. A 450-meter running/walking track with two lanes surrounds the speed skating rink. The center can seat 3,000 spectators, has a full-service Pro Shop, a banquet facility, administrative offices, conference rooms, locker rooms, showers, and concession areas. An ammonia refrigeration system is used to maintain the ice surface, while a HVAC system conditions the air within the facility.

The operation of the PNIC has been plagued by high-energy costs since the facility opened. Electricity bills range from $22,000 to $25,000 per month, while fuel costs for heating operations are approximately $8,000 a month. Some of these costs are expected, as the facility is a large building, with a huge ice surface. To keep the ice frozen and the building at a comfortable temperature requires a large amount of electricity (typically 830 kW) and heat.

The equipment used at the PNIC for ice making and heating is not optimally sized for the system. First, there are many more compressors in the ice making system than required, as evidenced by the typical use of only 2 of the 8 compressors at any one time. This does not have a substantial impact on the electricity costs, though, as the compressors that are not in operation are not consuming power. It only suggests that the original system was oversized and had a larger capital cost than necessary. The greater factor on energy costs is the boiler system used for heating purposes. The two boilers are oversized and under normal operations only one boiler is needed. In addition, that boiler frequently cycles on and off. Such boiler operation is not efficient and increases operating expenses.

As part of any refrigeration system, such as the ice making equipment at the PNIC, a tremendous amount of heat is rejected to the environment. It is estimated that approximately 1.2 MW of heat are rejected to the environment from the refrigeration system. While it is unlikely that all of this energy can be recovered, it is very possible to design a system that will recover some of this energy for use in heating the PNIC. As a side benefit, this efficient removal of the rejected heat will reduce thermal pollution to the environment.

It is also estimated that the current heating load in the PNIC is approximately 500 kW. It is clear that there is plenty of energy available in the rejected heat from the compressor system to provide heating for the building. The temperatures of the fluids in the refrigeration system are such that it is possible to transfer a portion of the rejected heat to the air-handling units to cover the heating load.

Lowering the electricity costs with on-site generation is not a straightforward task. Unlike an energy recovery system where heat that is already generated is being transferred within the overall system, an on-site power generation system requires the installation of new equipment. In addition, some of the on-site systems, such as fuel cells and gas turbines, have on-going fuel costs. Other on-site systems, such as solar cells or wind turbines, utilize a free, renewable source of energy. Unfortunately, such systems tend to either produce less energy or are costly. When coupled with the unreliability of their energy source, the costs of some renewable systems are prohibitive.

The Mechanical Engineering Department at UWM requires our undergraduates to enroll in one of two senior design courses we offer each semester. *MECHENG 496: Senior Design Project* is the senior year "capstone course" the majority of our students participate in. The primary component of this course is the execution and presentation of a project that involves new product design, product improvement, failure analysis and resolution, product design changes necessitated by manufacturing process changes or other similar endeavors. Projects are generated from actual, current situations supplied by local industry, activities at student's co-op sponsors, or research of interest to the students. Projects are of sufficient scope to require the participation of three to four team members. The department also offers MECHENG *390: Design Project* that is viewed as the alternative senior year "capstone course" that meets ABET requirements. The student projects in this course must have design, including but not limited to design analysis, as their primary form. An applicable evaluation of the design must be included, and a working model that can be tested is desirable. At the completion of the course, a full final report must be filed with the instructor. In general, student projects are assigned on an individual basis, although suitable group projects are also allowed.

From the background information collected by the authors, two projects for the MECHENG 496 course were devised. One project involved a group of students investigating the feasibility of installing a waste heat recovery system at the PNIC. The students' tasks were to research different types of systems, determine the best system to use at the PNIC, and to determine an approximate cost for the system. The second project involved a group of students studying the feasibility of installing an on-site power generation system. These students would have to research available local on-site electricity production methods, determine the feasibility from a cost and size standpoint for installing the systems at the PNIC, and then design and price a system for the PNIC. We now describe the work performed by the MECHENG 496 students on these projects.

Waste Energy Recovery System Project[2]

Three students were assigned as a group to design a waste energy recovery system. The students started by understanding the current mechanical operations at the PNIC (Fig. 2). Several visits were made to the PNIC to visually inspect the various mechanical systems. On these trips the student group interacted with the Facilities Manager who explained the operations and showed the various components of these systems. The students discovered that the PNIC operates via four loops: an ammonia refrigeration loop, a chilled glycol loop, an air handling loop, and a heating glycol loop. The refrigeration system consists of two different loops: a primary refrigeration loop and a secondary chilled glycol loop. Figure 3 displays a schematic of the refrigeration system at the PNIC.

The equipment in the ammonia loop consists of eight compressors, a condenser, a high-pressure receiver, and the oval/rink chiller. Of the eight compressors in the loop, only two operate at a given time with use rotated throughout the year. Figure 4 displays a schematic of the chilled glycol loop that supplies cold glycol to the two hockey rinks and the speed skating oval. The equipment in the chilled glycol loop consists of eight pumps, a glycol holding tank, and an oval/rink chiller. The air-handling units (AHUs) are used to condition the air within the facility. The system consists of six AHUs, two natural gas boilers as a source of heated water, and an AHU chiller as a source of chilled water. A schematic of the AHU system is shown in Fig. 5. The final system is the heating glycol loop that is used to prevent permafrost below the hockey rinks and the skating oval. It also provides heat for the snow pit to melt the ice shavings from the Zamboni machines after ice resurfacing. The equipment in the heating glycol loop includes four pumps and a glycol heater. Figure 6 is a schematic diagram of the heating glycol loop.

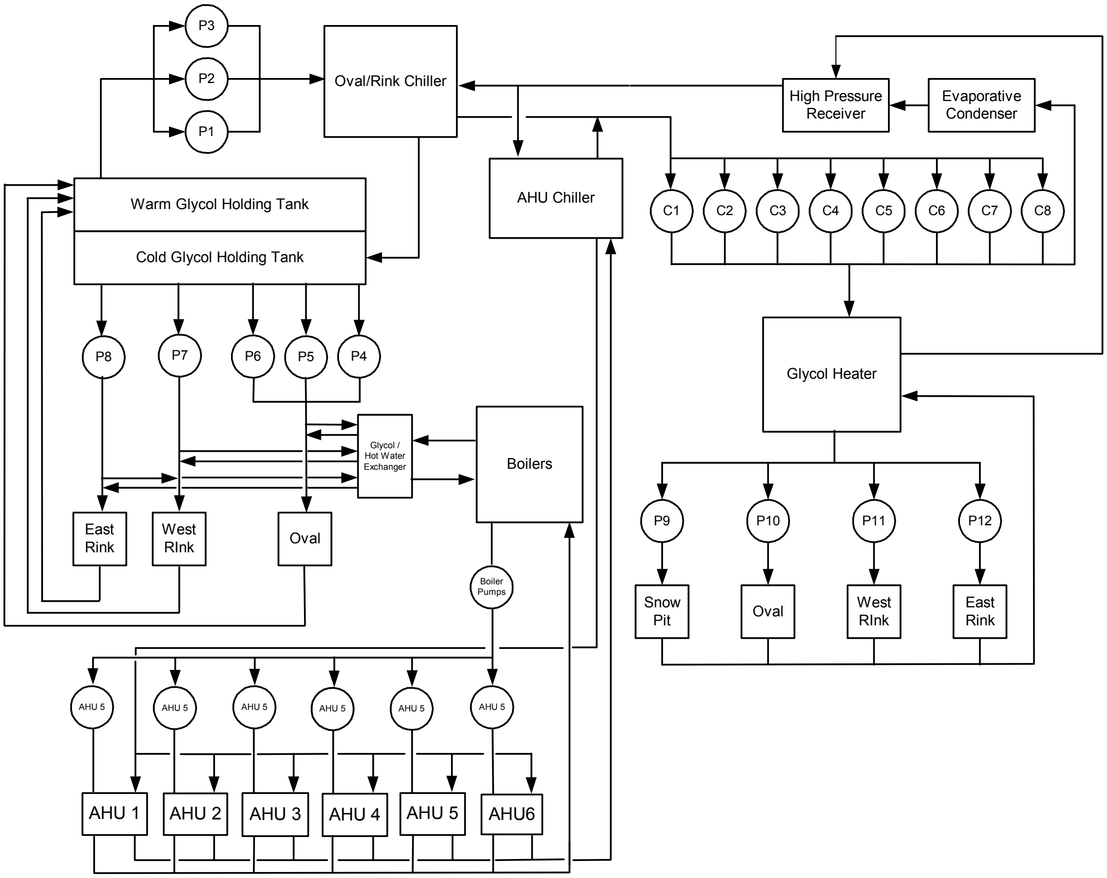

Figure 2. Schematic of existing mechanical systems at PNIC.

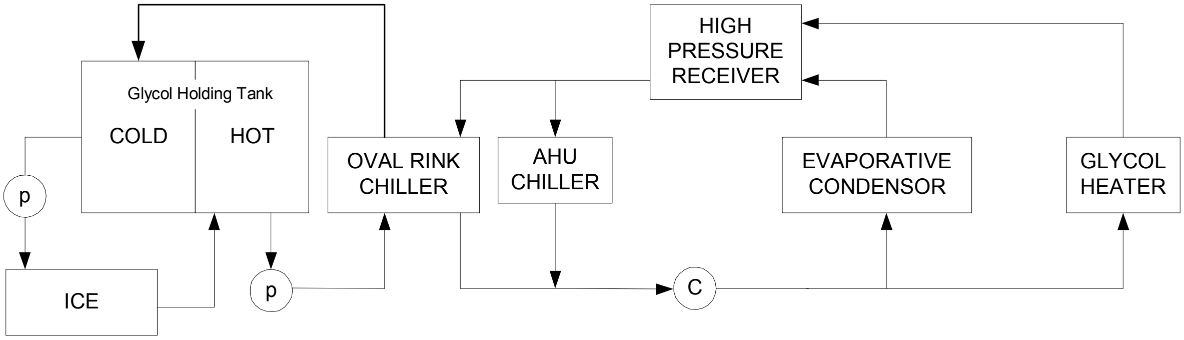

Figure 3. PNIC ammonia refrigeration loop.

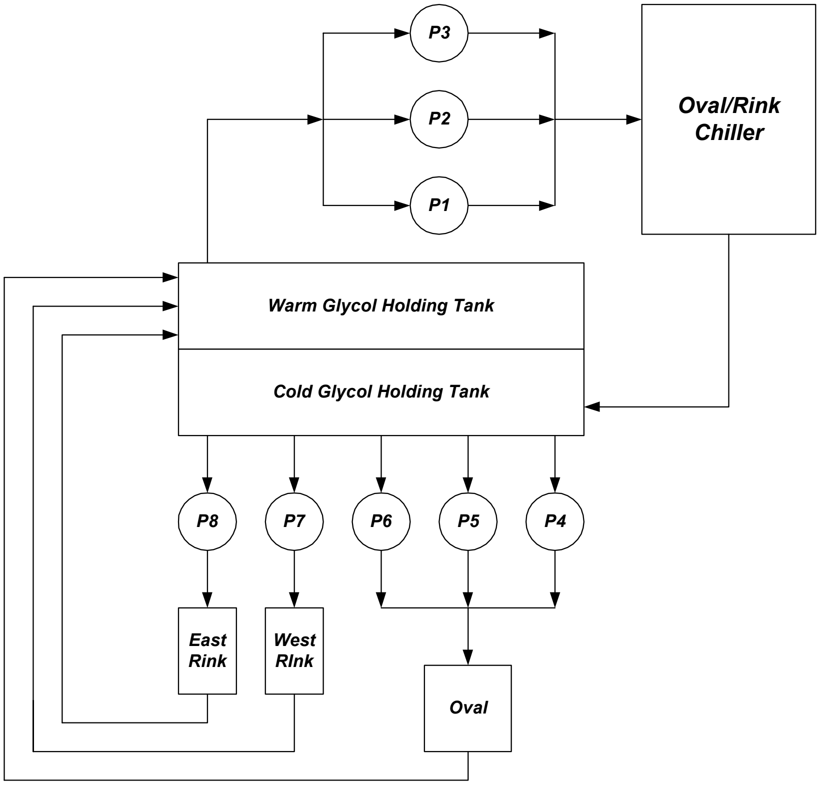

Figure 4. PNIC chilled glycol loop.

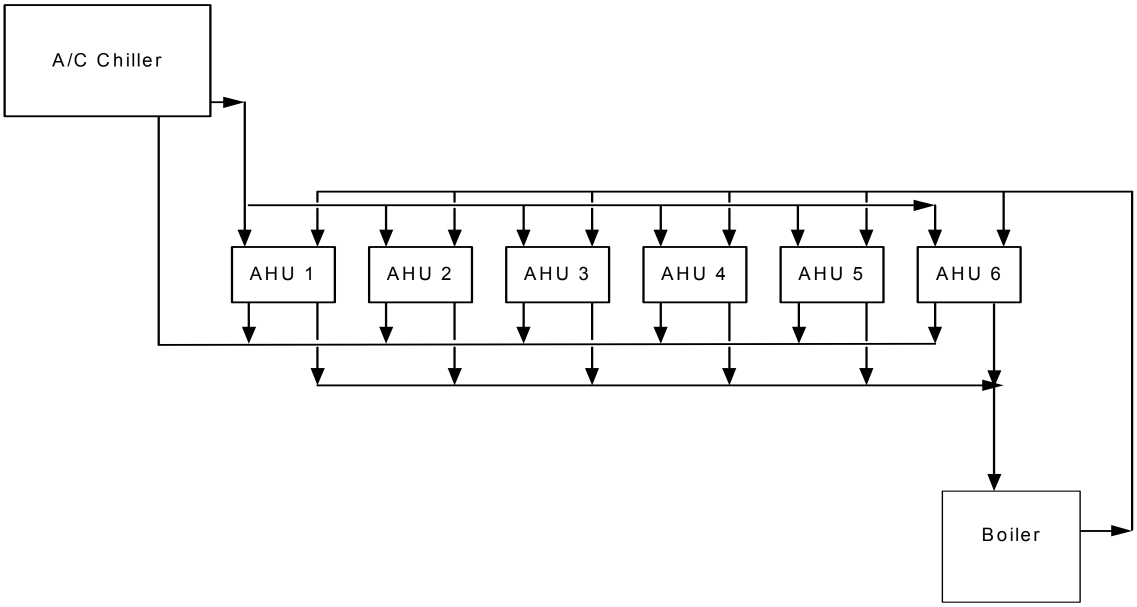

Figure 5. PNIC air-handling system.

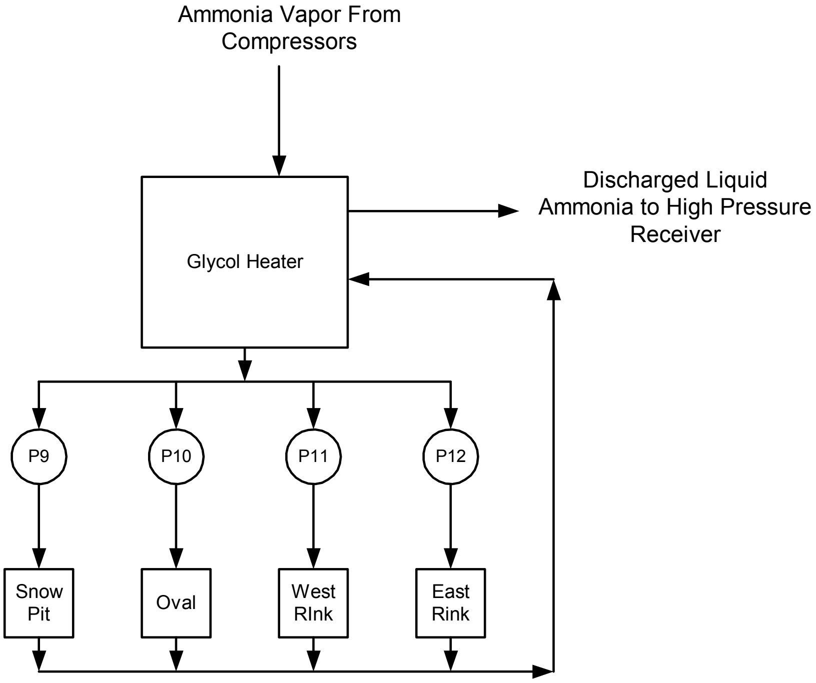

Figure 6. PNIC heating glycol loop.

For their project, the student group considered 10 options for heat recovery. These included run-around coil systems, regenerative heat wheels, heat pipes, fixed-plate exchangers, single condenser systems, dual condenser systems, heat recovery heat pumps, cascade multi-stage systems, desuperheaters, and shell-and-tube heat exchangers. After performing a feasibility study on each heat recovery option and after close consultation with the authors, the students decided to incorporate the shell-and-tube-heat exchanger option into their design.

The students' final design utilized the fact that approximately 1.2 MW of heat are rejected to the environment by the ammonia loop system, while two natural gas boilers supply 580 kW of heat to the AHUs. The students concluded that the existing oversized boilers should be replaced with a shell-and-tube heat exchanger to utilize this waste heat. Figure 7 displays the design of this new heat exchanger in the existing system. More specifically, the shell-and-tube heat exchanger is designed to use the high temperature vapor ammonia being discharged from the compressors as the hot side fluid to heat supply water. The heat exchanger transfers this heat to supply hot water at approximately 93°C to the AHUs. The hot water in turn will heat supply air that will be distributed to the entire facility. Thus, the heat exchanger will eliminate the need for the oversized two-boiler system.

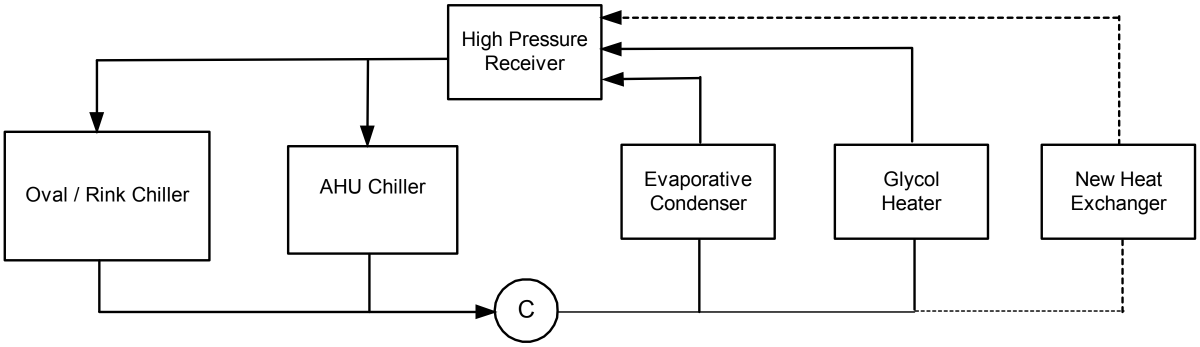

Figure 7. Design for new heat exchanger in existing PNIC system.

As a safeguard in case the new heat exchanger fails or if the ice-making equipment is shutdown for a time, the students proposed a second loop containing a smaller-sized 500 kW boiler. A three-way temperature valve before and after the secondary loop allows the system to bypass the boiler if the water leaving the heat exchanger is at the desired temperature. Figure 8 details the new boiler design.

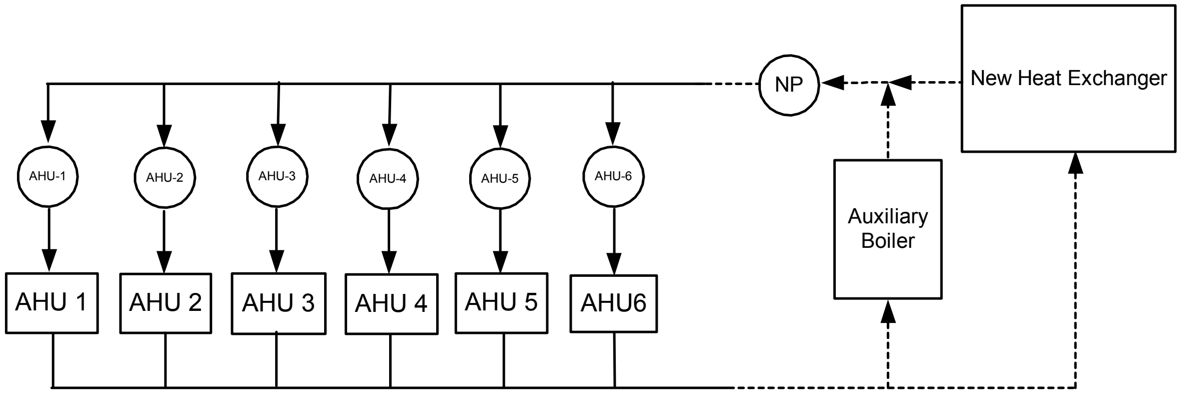

Figure 8. Proposed energy recovery system: AHUs, new heat exchanger, new boiler and new pump.

The students also performed a cost analysis on the proposed waste energy recovery system (Fig. 9). The analysis included a salvage cost of $30,000 for the existing two boilers (original purchase price was $40,000 per boiler), a $22,000 cost for the new 500 kW auxiliary boiler, a $5,000 price tag for the new phase-change shell-and-tube heat exchanger, and $1,200 for the three-way temperature valve. Pipe installation, boiler removal, boiler installation, heat exchanger and pump installation fees as well as engineering consulting costs were estimated by contacting local contractors. The analysis produced an estimated net cost of $97, 200 that could be paid-off in energy cost savings in approximately 13 months.

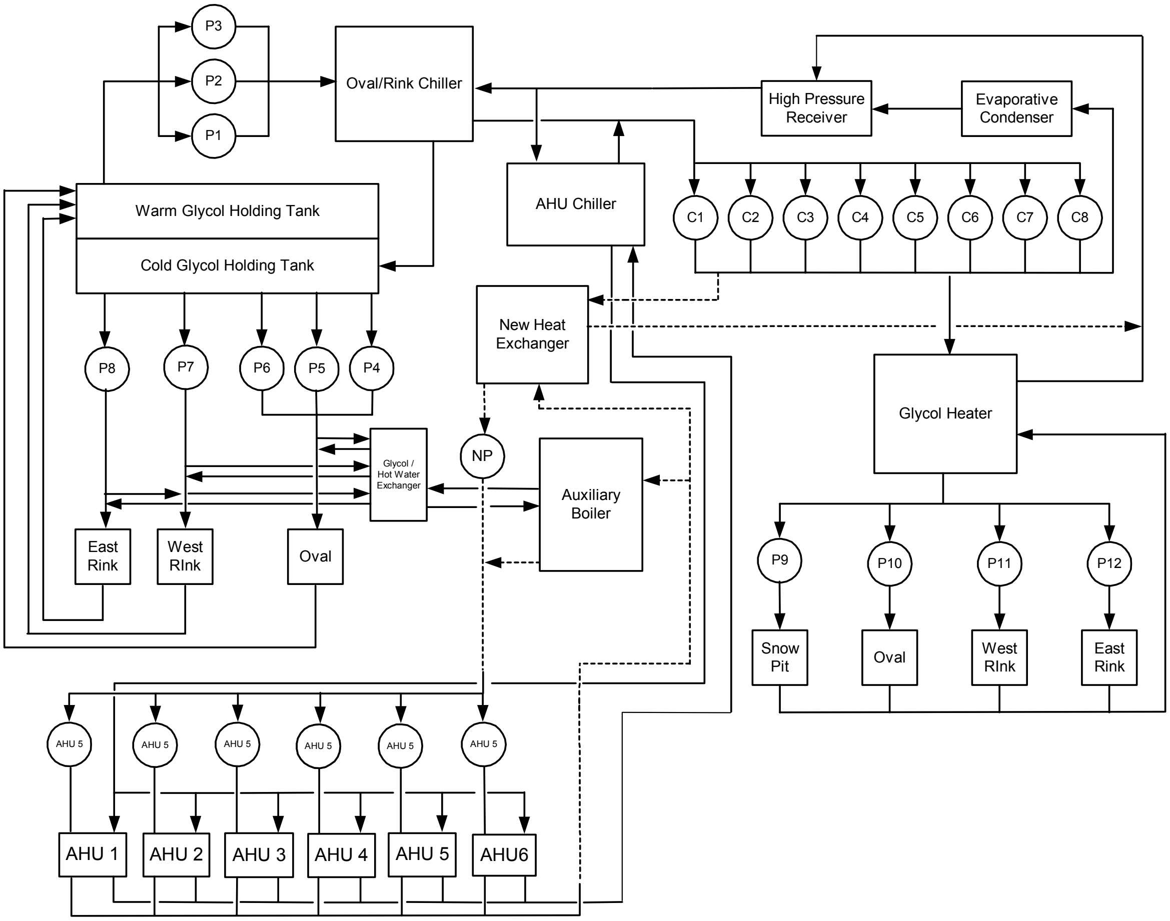

Figure 9. Proposed PNIC waste energy recovery system design.

On-Site Power Generation Project[3]

A group of three undergraduates chose to work on the on-site power generation project in the MECHENG 496 course. These students in consultation with the authors considered four alternative energy generation methods: solar power (solar thermal and photovoltaic), fuel cells, wind power, and gas turbines. The student group compared the four options using the following selection criteria compared the four options: aesthetics, noise, space, annual maintenance, initial cost, lifetime, and energy cost. The systems were independently rated in each category on a scale of 1 to 5 (1 representing least favorable option and 5 representing a most favorable option). The highest total for each of the four alternative energy systems was used to determine the two most feasible options.

The students learned that wind turbines and solar power are considered renewable sources with no fuel costs, but often-large capital costs. Gas turbines and fuel cells require a fuel source, which adds to the operational costs of the systems. After in-depth research on each option, the students determined that solar power was too expensive and required too large of a system to produce enough power to significantly reduce electricity usage from outside sources. The students also found that fuel cells are still in a developmental stage, and are too expensive at this time to be feasible for implementation at the PNIC. If a hydrocarbon fuel, such as methane, could be used directly in the fuel cell, this option would become more feasible. However, use of hydrocarbon fuels in fuel cells has been an area of research for many years, and systems using hydrocarbons have not been successfully developed.

The students concluded that from a technological viewpoint, both wind turbines and gas turbines were viable options for the PNIC. However, both systems have high costs associated with them. As a result, it was determined that further consideration as to what the goal of on-site electricity generation at the PNIC was needed. There would appear to be two possible options. One goal would be the on-site production of all electricity used at the PNIC. The second possible goal would be to produce only a fraction of the electricity used on-site, but use the site as a demonstration location for alternative energy production.

With the first goal, the students found that the clear choice for on-site electricity generation is the use of a small gas turbine. The gas turbine technology is well proven, and systems providing adequate power in a small space exist. The students selected a 1.2 MW gas turbine Model Saturn 20 produced by Solar Turbines of San Diego, California. This turbine provides 3,600 – 17,000 kg/hr of steam that could be used to replace the existing boiler system as an added benefit. In the student design, the output of the steam would be routed into a phase change heat exchanger that would eventually heat supply air for the AHU system. This co-generation system would be sufficient to handle the necessary loads in most conditions, but an auxiliary boiler would still be needed in case of system shutdown.

The students estimated the payback time for such a system to be approximately 16.5 years, although the fluctuating nature of fuel prices can cause this to vary significantly. The students suggested that if price reductions in the system could be achieved through the use of the system as a demonstration project for a gas turbine manufacturer, it would be a good option to pursue because the payback time would be reduced. The students also found that the payback period could also be reduced via negotiations of a more favorable excess electricity sale price to the utility company. However, if such enhancements cannot be negotiated, the students found it difficult to recommend the use of on-site electricity generation for production of all electricity needed at the PNIC. It should be noted that the students learned that the other systems would need to be too large and expensive to adequately supply all the electricity used at the PNIC.

Moreover, the students learned that much more promise exists for the use of the PNIC as a site for a demonstration project for an alternative energy technique. For example, the student group selected a Model V47-660 kW wind turbine produced by Vestas of Denmark and estimated the total power output for each month for one turbine exposed to an average wind speed of $\underline{+}$5 km/hr. The power output for each month was then compared to the actual energy consumption per month for the PNIC in order to determine how many wind turbines are required to sufficiently decrease the amount of energy purchased by the PNIC. Figure 10 illustrates the difference in installing one wind turbine versus two wind turbines. As shown, the students recommended that two wind turbines be installed to reduce PNIC energy costs. After surveying the PNIC and the adjacent Wisconsin State Fair Park, the student group proposed placing the two wind turbines inside the nearby Milwaukee Mile Racetrack to satisfy required safety concerns.

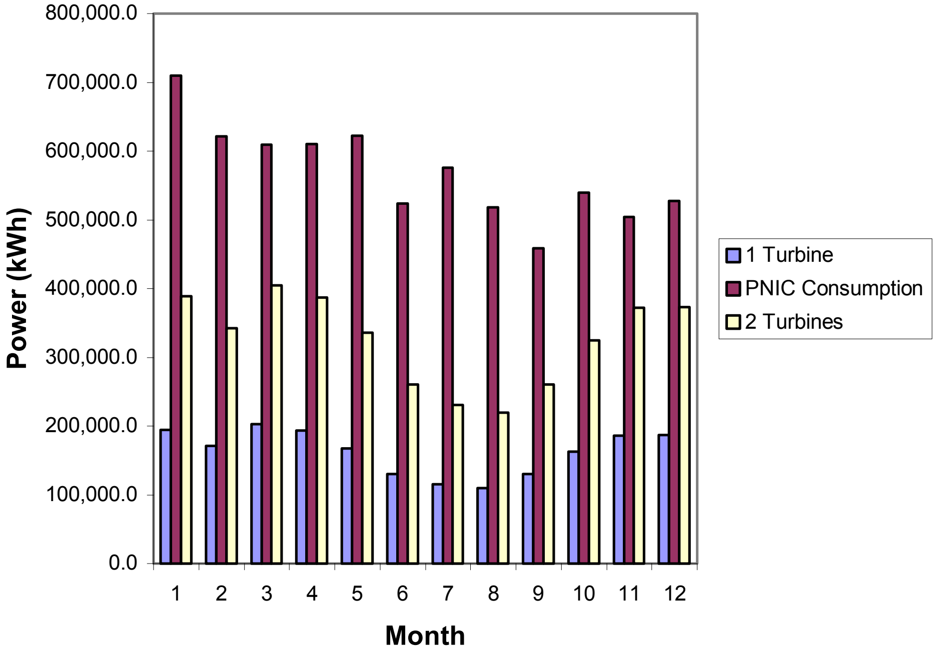

Figure 10. Power output via wind turbines versus PNIC demand.

The students estimated that the installation of two wind turbines at the PNIC will result in an estimated payback time of over 33 years. The students concluded that the two wind turbines would still not meet all the electricity needs of the PNIC, but that it was still a reasonable idea to use the site as a wind energy demonstration location. The students reasoned that if an agreement with a wind turbine manufacturer to install one wind turbine for free or at a greatly reduced cost can be reached, great benefits for all parties could be achieved. The PNIC would be able to generate some power on site, and reduce its electricity bills accordingly. The manufacturer would gain access to a high-visibility site to promote its product, which should increase sales. So while in such a plan the PNIC may not eliminate all electricity costs, the costs would be reduced. While a similar approach could be pursued with solar power or fuel cell interests, the visibility of wind turbines at the PNIC would seem to suggest that wind power would be the best on-site demonstration project for power generation.

Educational Experience

The two projects described above had important elements of a capstone design project. Both projects required the students to research alternative solutions to their problems, which already existed. They needed to familiarize themselves with current technology, and practice using and interpreting site and system diagrams for a complex facility. They needed to learn how to interact with other engineers and industry professionals in order to learn what their problems were, or how their product would help solve a problem. The students in each project needed to design a system that would meet the needs of the PNIC, and they needed to perform a cost analysis to determine if the solution was viable. The students working on the power generation project also had an opportunity to learn a great deal about the societal impact of their project, and they were also given insights into the workings of business and government entities. The students working on the energy recovery system gained the benefit of designing a system, much like consulting engineers, which may very well be implemented in a form at least close to what they designed. In summary, the primary benefit of these capstone design projects is that the students were able to apply their engineering education in a real-world environment in investigating solutions to problems at an existing facility. In other words, the capstone design projects achieved the goal of providing the students an engineering experience that would be very comparable to their entry-level job after graduation.

Conclusions

A summary of two senior design projects in which undergraduate mechanical engineering students were responsible for the feasibility, design, selection, and cost analysis of system designs that would provide potential energy savings at the Pettit National Ice Center in Milwaukee, Wisconsin were presented. The final reports of the student groups were forwarded along with a detailed summary by the authors to the Wisconsin Division of Energy for review. The proposed modifications to the PNIC are currently being considered. A web page (http://www.uwm.edu/Dept/Energy/pettit.html) was created by the authors to provide info to the public sector.

Acknowledgments

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