PHOTO 1 (Left) Advanced Photon Source (APS) aerial view; (Right) Interior view of storage ring tunnel.

Optimized Energy Recovery

BY MARVIN KIRSHENBAUM, MEMBER ASHRAE

Heat recovery is a common approach to improving the energy efficiency for a wide spectrum of building types. For commercial and research facilities, this is often restricted to preheating and some limited precooling of outdoor air. Most buildings rely on some form of heat for temperature control throughout the year, and some tap into available waste heat sources to fulfill some or all of this need. Expanding the reach of available waste heat would provide significant enhancement to a building's energy efficiency. Beyond this, tapping into waste heat streams to provide primary building heating in cold climates can open up new avenues for additional energy conservation.

This article addresses extending the application of waste heat recovery to both reheat and primary heating, allowing for a heat reclaim system no longer restricted to seasonal operation. It will begin with a review of work completed to date to illustrate our progression in waste heat utilization and finish with a description of a novel design that approaches the practical limits of utilization.

The overwhelming majority of electricity consumed by commercial buildings eventually turns into low-grade (temperature) waste heat at or below 90°F (32°C). While this waste heat can be recovered during cold weather for preheating outdoor air, its low temperature makes effective recovery and reuse for other purposes extremely difficult. The majority of this waste heat is rejected to the outdoors.

The Department of Energy reports, "Commercial buildings represent just under one-fifth of U.S. energy consumption.... In aggregate, commercial buildings consumed 17.9 quads of primary energy in 2009, representing 46% of building energy consumption and 18.9% of U.S. energy consumption." Over the past 15 years, we have designed and constructed mechanical systems

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that have expanded the use of heat recovery, focusing on applications that go beyond outdoor air preheat, with applications for reheat and perimeter heating.

While building heating operation is seasonal, reheat systems typically operate continuously to provide space temperature control. This is especially true in the case of laboratories, hospitals, and related facilities. Many large office buildings also employ reheat for space temperature control. In mild climates, the energy used by space reheat can dominate the building heating energy use, making it a prime candidate for recovered sources of energy.

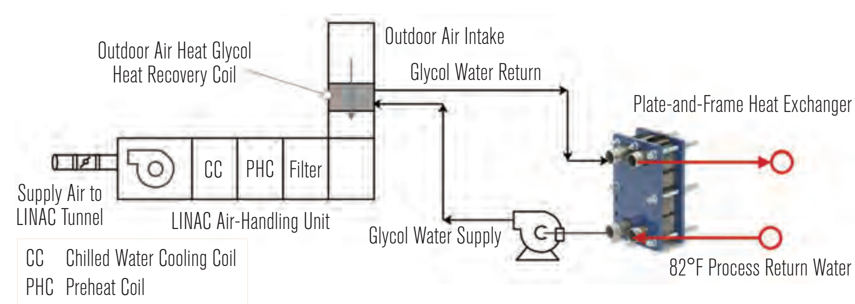
This discussion divides waste heat applications into two categories: high airflow demand (i.e., laboratory) and low airflow demand (commercial offices). High flow facilities have greater preheat and reheat demands, and shifting this load to waste heat sources magnifies the effectiveness of the energy savings. Low flow facilities, while less stressed by outdoor air preheat and reheat, can still benefit. Efforts to expand the waste heat source into the primary heating system can tip the balance of the economics.

Rapid improvement in lighting and office equipment energy efficiency has reduced internal loads, while the need to maintain indoor air quality has pushed increases in ventilation rates in many cases. This results in greater dependency on reheat to avoid space subcooling. Before presenting the final version of the proposed waste heat recovery system design, I'll summarize the evolution of increased use of waste heat.

Design Evolution

As part of our program for sustainability, a portion of the work at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL) has focused on the recycling of low-grade waste heat generated by the scientific tool set of that facility. The first efforts at APS focused on winter outdoor air preheat. A 4,000 cfm (1,888 L/s) dedicated outdoor air (DOA) unit supplying ventilation air to the APS electron linear accelerator tunnel (LINAC) was retrofitted with a conventional multi-row heating coil to establish the efficacy of using conventional, cost effective heating coils with very low-grade waste heat.

FIGURE 1 Linear accelerator tunnel (LINAC) heat recovery system.



This system (*Figure 1*) uses a plate heat exchanger to transfer 82.4°F (28°C) waste heat from the APS process cooling system with an approach temperature of less than 2°F (1.1°C), providing over 90% of the LINAC's preheat and, on average, saving approximately 400 million Btu (117 MWh) of energy.

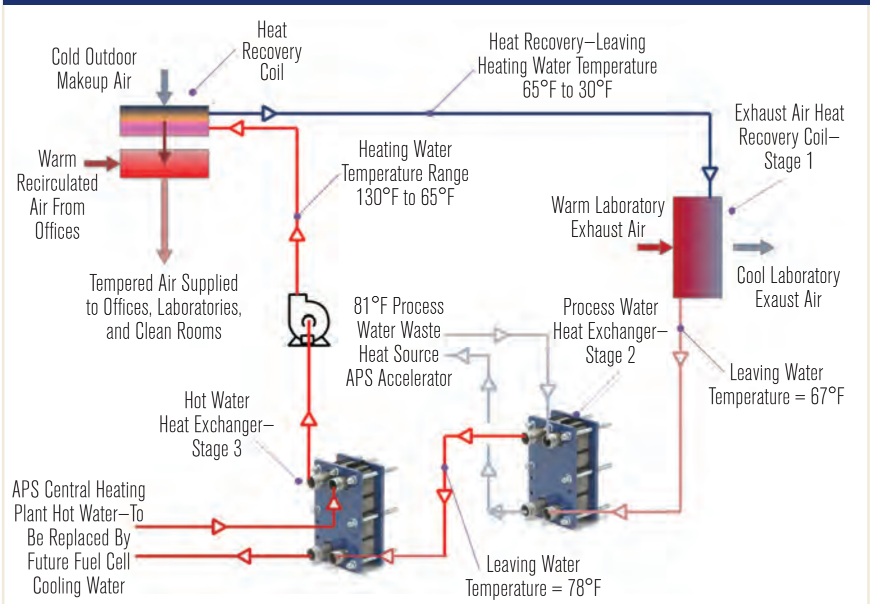
The next heat recovery application was for a new 85,000 ft^2 (7897 m^2) nanotechnology research building, completed in 2006, consisting of offices, laboratories, and cleanrooms. The most important consideration in the design of this system was maximizing the heat transfer potential, given the relatively low temperature (between 74°F and 81°F [23°C and 27°C]) of waste heat sources. Analysis of the energy flow and temperatures at each heat exchange juncture was critical. For optimization, the design uses a three-stage glycol runaround loop that draws waste heat from laboratory and cleanroom exhaust, APS process water, and a natural gas fuel cell (*Figure 2*).

The fuel cell is pending installation, and the heat is being temporarily supplied by the APS central heating plant. To make the best use of the available waste heat sources, the flow path of the glycol loop was staged with heat transferred from the lowest to the highest grade sources.

To maximize the glycol water to outdoor air heat transfer effectiveness, a single consolidated preheat/heat recovery coil was placed upstream of the return air point in the air-handling unit. This maximized air-to-glycol water temperature differentials, applying the waste heat as a first stage to the coldest possible airstream and mixing the building return air heat as a second stage. The coil control valve is controlled by a temperature sensor placed downstream of the mixed air point.

Using a single coil had the added benefit of eliminating the fan energy penalty associated with the more typical practice of using a heat recovery heat coil supplemented with a preheat coil. Data collected on this system's operation indicates that it averages approximately 3 billion Btus (880 MWh) of waste heat recovery per year, with 35% of the total extracted from the building exhaust. Due to space limitations, no bypass was provided around the exhaust air coil, but the calculated energy penalty was less than 3% of the total heat recovered and was deemed an acceptable compromise.

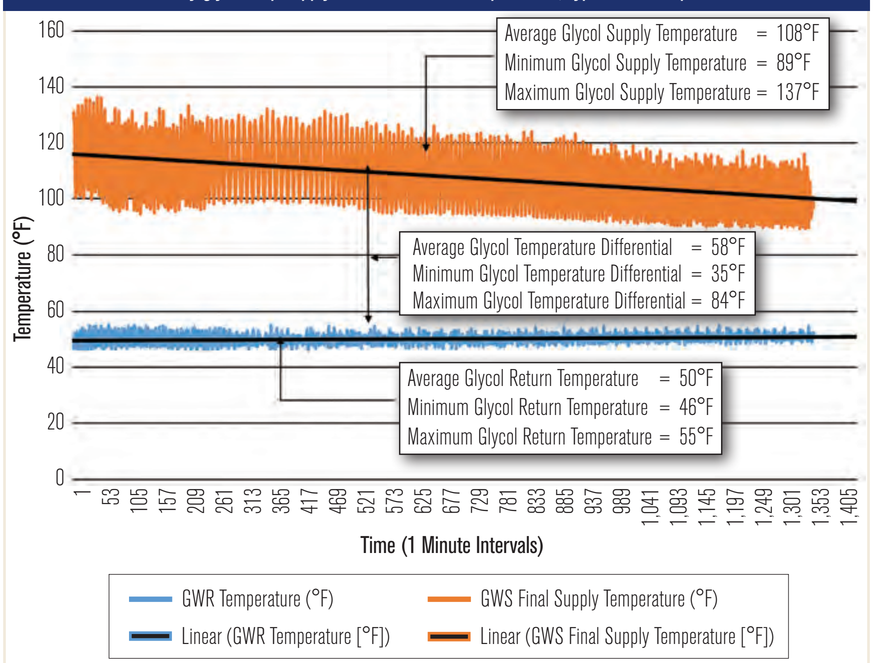
FIGURE 2 Nanotechnology building three-stage heat recovery system flow. Note: supply water temperature varies with outdoor air temperature.



Due to the low temperatures of the waste heat sources, delivering the lowest possible glycol supply temperature to the outdoor air heating coil is critical to minimizing heating from the third stage of the glycol loop (the APS central heating plant). Supply water temperature setpoint is varied based on outdoor air temperature.

Through careful heat recovery coil selection and trial and error experimentation with various glycol/water temperatures, the system operates with a large supply to return water temperature differential. This keeps flow to a minimum and maximizes the heat transferred per unit mass, enhancing the effective capture and reuse of the low-grade waste heat source (*Figure 3*).

FIGURE 3 Heat recovery glycol loop supply and return water temperatures, typical winter operation.



The heat recovery system performance was monitored through a number of winter cycles and provides approximately 55% to 60% of the total outdoor air preheat at near design day conditions (*Figure 4*). As weather moderates, the percent of preheat derived from waste heat approaches 100%.

The next step in design evolution moved beyond the outdoor air preheat application and expanded into the other two legs of the triad of the heating system: reheat and building perimeter heating. Reheat applications with air-to-water temperature approaches less than 10°F (6°C) are atypical and not normally attempted. As reheat is a common means of controlling temperature and humidity, satisfying this demand extends the time range of the application to the full calendar year. For this reason, it became the

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central focus in the further development of low-grade waste heat applications.

The first reheat application was for the upgrade of the APS electron storage ring tunnel HVAC system to improve temperature control. This space consists of a circular, at grade concrete tunnel of approximately 36,000 ft^2 (3344 m^2) in the APS Experiment Hall building (*Photo 1,* Page 30). Each air-handling unit was modified with a reheat coil supplied with 80°F (27°C) process water waste heat to reheat air from 60°F (15.6°C) to 76°F (24.4°C). Conventional six-row copper coils with aluminum fins were used, and they achieved approach temperatures of 3°F (1.7°C).

As an added benefit, using this low-energy content source increased the temperature stability of the system by reducing fluctuations in valve modulation that would drive the system into instability. Coupled with tuning of the controls, the space temperature fluctuations have been reduced by an order of magnitude to less than 0.1°F (0.05°C) peak to peak.

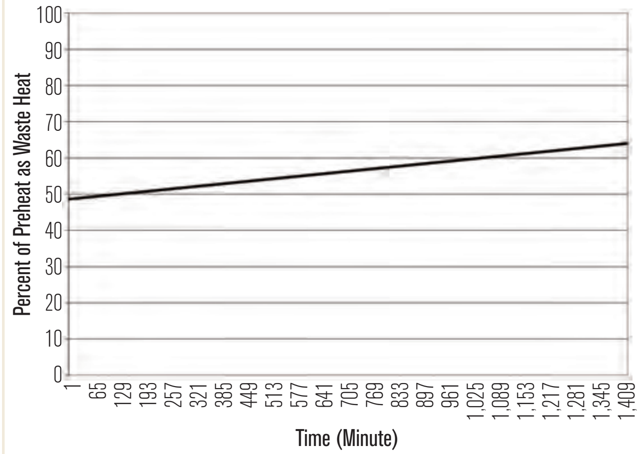
Culmination of Design Evolution

In 2012, the APS embarked upon the design of a new 5,500 ft^2 (511 m^2) addition to one of its laboratory office buildings. This building consists of a single-story office and laboratory suite with an independent air-handling and heating system. The building HVAC system is a variable air volume reheat system with perimeter ceiling hot water radiant heat. The reheat system taps into the APS process waste heat, extracting 82°F (28°C) heat in a two-stage heating loop with the second stage connected to the main APS heating system). The second stage operates only when the APS is in a maintenance shutdown to supplement a reduction in the temperature of the process waste heat.

The original intent of the reheat system was only to provide minimum supply air tempering, with winter perimeter heat provided by the APS hot water 180°F (82°C) heating system. In developing the design, the use of high-efficiency heat transfer coils was explored with the goal of achieving an extremely close air-to-water approach temperature of 2°F (1°C). It was also assumed that at minimum terminal unit airflow, the close approach temperature would allow a small portion of the building's winter heating load to be accommodated with waste heat.

For the fabrication of the reheat coils, a leading manufacturer of high-efficiency coils typically used in

FIGURE 4 Typical heat recovery performance at near design day winter operation.



runaround heat recovery loops scaled down its product to a size consistent with terminal unit applications. In the startup of the building, experimentation showed these coils could achieve approaches within 1°F (0.5°C). Further experimentation revealed that at substantially higher flow rates, approaches well within 2°F (1°C) could be obtained.

At that time, it was decided to push the limits of the system and shift the burden of the building's perimeter heating to the reheat system. This relegated the perimeter system operation to only the most extreme weather conditions. During the historic polar vortex occurrences of 2014 and 2015, the reheat system provided full building heating approximately 90% of the time. In terms of log mean temperature difference (LMTD), a conventional coil would operate with an LMTD of around 100°F (55°C). Our coils were providing nearly full building heating with an LMTD of around 9°F (4°C).

To provide sufficient building heat, the VAV perimeter zones were operated at the maximum design cooling flow rate; while this resulted in excessive reheat to compensate for the 58°F (14.5°C) discharge air temperature from the air-handling unit, the source (the APS) itself is a plentiful reservoir of waste heat, on the order of 7 MW, and added no cost impact to operations. With this much waste heat available, it was decided to continue operating the building in this manner as a pilot project to experiment with maximizing low-grade waste heat extraction.

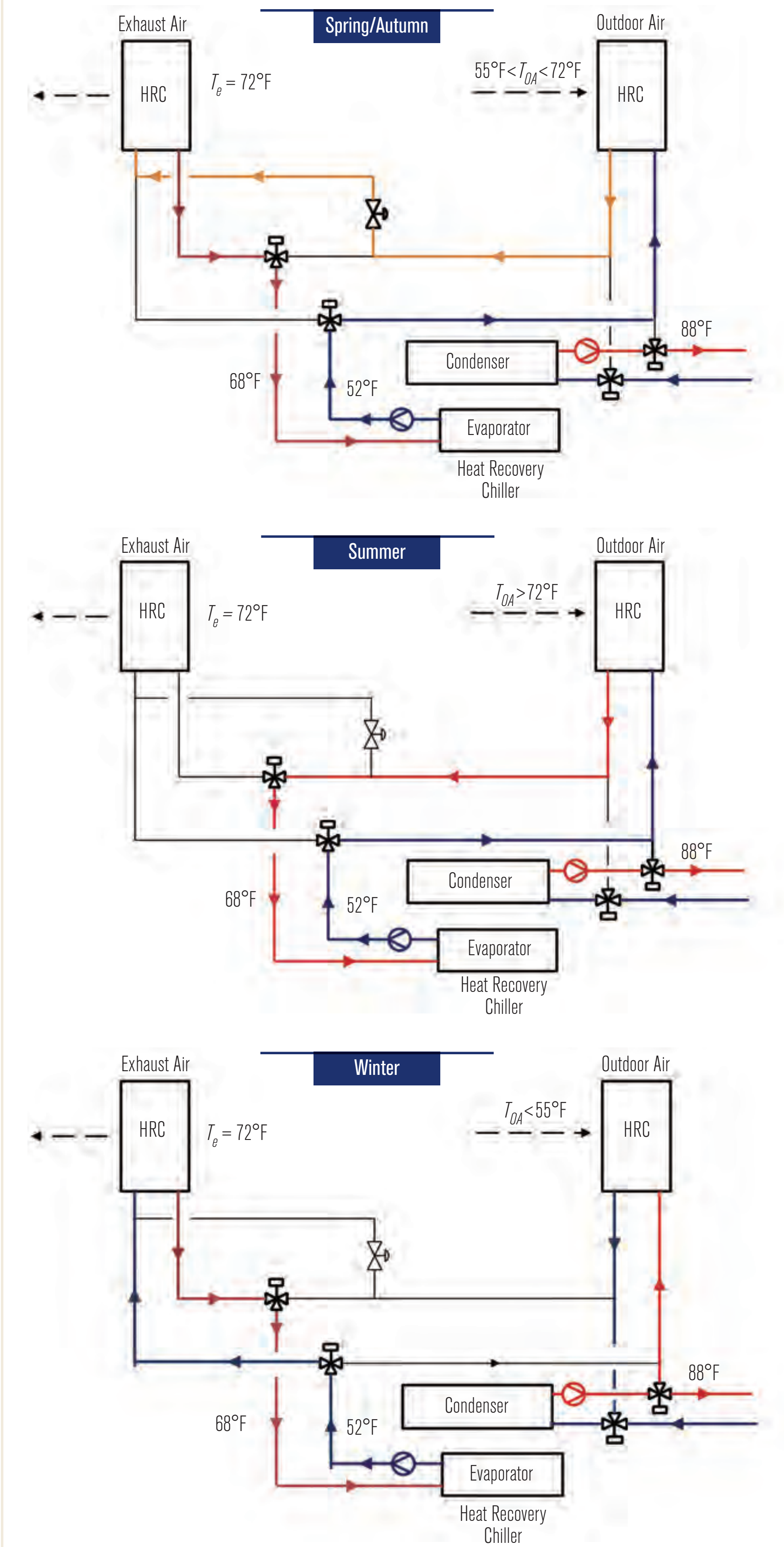
Data collected to date show that we average a recycling rate of over 51,180 Btu/h (15 kW) in winter weather conditions (–4°F [–20°C]) and 20,470 Btu/h (6 kW) in

the non-heating season. It is projected that the building will recycle an average 34,120 Btu/h (10 kW) of waste heat continuously, equal to 300 million Btu (88 MWh) of energy per year. When this number is corrected to remove the excess reheat due to high minimum airflow settings, the building yearly average waste heat energy recovery would be 188 million Btu (55 MWh) or 34,120 Btu/ft^2·yr (387.5 MJ/m^2·yr) [10 kWh/ft^2·yr (107.6 kWh/m^2·yr)]. To gain a perspective on the potential energy savings, if this technology were applied to one of our larger lab/office buildings (150,000 ft^2 [13935 m^2]), we would realize a yearly savings of $40,000 and over 270 metric tons of carbon.

The ability to provide space reheat with systems operating at these lower temperatures opens up a new avenue for low-grade waste heat recycling through both direct heat transfer and hybrid heat pump systems. With direct heat transfer, systems can provide heating without supplementation of heat pumps or other external energy-consuming devices. Alternatively, when heat pumps are required, this dramatic lowering of the operating temperature can significantly decrease their energy consumption, increasing system coefficient of performance by a factor of two or greater.

One concern typically raised when using low-temperature heating sources is the added pump and fan transport energy required due to increased water and airflows. While there is definitely an increase in energy consumption, this must be kept in perspective. The ratio of energy conveyed by the air or water to the energy of fluid transport can

FIGURE 5 Hybrid low grade waste heat recovery system in various modes of operation.



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be on the order of five to 10 or greater. Even an increase in transport energy by a factor of two when compared to the energy saved through heat recovery is small, and the overall energy savings large.

To illustrate this point, the laboratory/office building previously discussed has an air and water system designed using conventional criteria for sizing ductwork and piping. Under peak flow conditions, the total measured supply fan, return fan, and associated pump power consumption is on the order of 6.8 hp (5.1 kW) or 0.8 W/cfm (1.7 W/L·s), while under minimum flow conditions (typical for cooling-only air systems in winter operation) it drops to 1.9 hp (1.4 kW) or 0.3 W/cfm (0.6 W/L·s). Operating this system at peak cooling flow during the winter to leverage the waste heat source incurs a transport energy penalty of 0.5 W/cfm (1.1 W/L·s), but the waste heat delivered to the building is 2.5 W/cfm (5.3 W/L·s). This yields a net energy savings of 2 W/cfm (4.2 W/L·s).

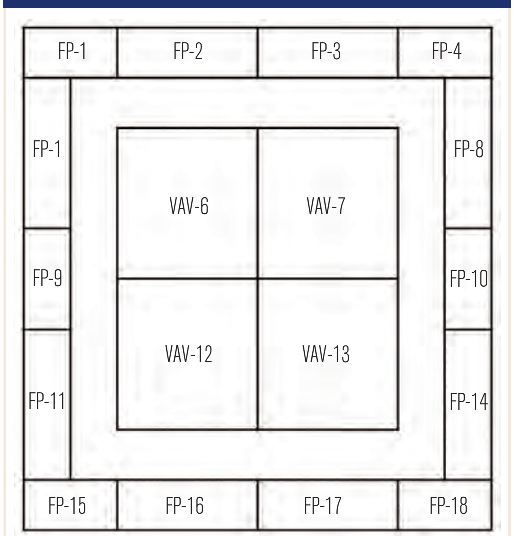
To be clear, this system was not intended to operate at these high airflow rates during the heating season; our intent was to allow this operation primarily to characterize low-grade heat source performance. A method of eliminating the majority of this excess fan energy penalty is described in the following discussion and employed in the system described below.

The experiments with the application of low-grade waste heat sources relied on a plentiful supply of heat from the APS accelerator; yet most facilities, such as laboratories or offices, do not have access to such a source. While the potential to apply very low-temperature sources to building primary heating is viable, identifying these sources and developing schemes to mine them for heat energy requires new techniques.

One proposal uses a hybrid runaround loop design that is capable of providing a continuous low-grade heat source throughout the year. In this design, a heat pump or heat recovery chiller is inserted into the runaround piping loop. It is used to extract and elevate heat to 88°F (30°C) from either the exhaust or outdoor airstream, depending upon demand and the seasonal variation in the outdoor air temperature; this system is illustrated in *Figure 5* (Page 36). The system allows for control of the fluid flow path to provide three basic heat recovery modes of operation: spring/autumn, summer, and winter, and is capable of providing simultaneous heating and cooling when required.

To estimate system performance, a simplified bin analysis was made of both a high flow laboratory facility and a low flow office building. The buildings' location was placed in Climate Zone 5 and used bin data from Chicago O'Hare International Airport. Each building was based on a 10-story structure of approximately 100,000 ft^2 (9,300 m^2) with a simplified temperature control zone plan consisting of 14 perimeter zones and four interior zones per floor (see *Figure 6*).

FIGURE 6 Typical floor HVAC zoning plan.



To optimize the effectiveness of airside heating with the 88°F (30°C) source and to minimize reheat demand, the perimeter zones use fan-powered variable air volume terminal units. This will maintain a low minimum cold primary airflow, while delivering a high total warm airflow into the space. The scheme also addresses the fan energy concerns previously discussed. In the laboratory building model, the laboratories are located in interior spaces and use variable-air-volume controls.

To accommodate the heat transfer demands of the laboratory, high-efficiency heat transfer coils were compared to conventional multi-row coils. The latter were found to be effective in achieving the minimum discharge air temperature. For systems that run with water temperatures of less than 88°F (30°C) or have higher minimum airflow requirements, the high-efficiency heat transfer coils would be used. In this regard the economic trade-off of the more expensive coils has to be weighed against the increased energy efficiency of operating at lower water temperatures.

The bin model analysis for the laboratory/office building was based on a 12-hour per day occupancy and yielded the following results: Estimated total

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heating demand of 68,240 Btu/ft^2·yr (775 MJ/m^2·yr) [20 kWh/ft^2·yr (215.3 kWh/m^2·yr)] with 58,000 Btu/ft^2·yr (658.7 MJ/m^2·yr) [17 kWh/ft^2·yr (183 kWh/m^2·yr)] provided from the waste heat source, reducing the building total heating demand by 85%. Using our facility (ANL) utility costs and an estimated capital cost of $120,000 for the complete heat recovery portion of the system, the simple payback is estimated to be three years.

The savings determined for the office building model, while not as impressive as that of the laboratory, still provided a reasonably good energy and cost savings. The total building heating demand was estimated to be 20,100 Btu/ft^2·yr (228.3 MJ/m2·yr) [6.4 kWh/ft^2·yr (68.9 kWh/m^2·yr)] with 17,060 Btu/ft^2·yr (193.7 MJ/m^2·yr) [5 kWh/ft^2·yr (53.8 kWh/m^2·yr]) from recovered waste heat. In this model the capital cost of the system was estimated to be $70,000 and a simple payback of five years.

Conclusion

Low-temperature waste heat is an abundant source of energy rarely tapped to its full potential. With careful analysis of the energy gradients of facilities and strategically controlling flow path, an economical means of reducing overall building energy consumption can be leveraged for a number of applications. The increasing efficiency of modern heat pumps can further be leveraged to elevate low-temperature heat sources to meet the threshold of usable energy. This will extend the availability of this energy source and open up avenues for more facility types to access and economically recycle waste heat.

Acknowledgments

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