Final Design Report

BIOdiesel COGENeration Project (BioCoGen)

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ENGR 492: Senior Project II
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ABSTRACT

The Biodiesel Cogeneration Project (BioCoGen) is a renewable, residential-scale cogeneration system. The design focuses on the waste heat recovery system; it gathers heat normally lost in the exhaust gases and stores it in a water tank. In production, the system should connect to an electric-grid intertie system: the generator is sized to produce enough electricity to offset the monthly consumption of an average college student residence housing five people. The grid supplies the actual demand of the house.

The Integrated Renewable Energy Design Group's (INREN Design) working prototype of BioCoGen is renewable because it uses a diesel generator that will be powered by biodiesel, a renewable, clean-burning, vegetable oil-based fuel. It is designed according to the electrical power, space heating and domestic hot water needs of the SALT house, a student home at Messiah College. The system will run about fours hours each day; during operation the generator will produce 20 kWh of electricity and 52 500 Btu of heat. This will meet the average monthly electric need of the house and exceed the average domestic hot water need. This recovered heat also represents an increase in the overall genset efficiency of more than 15%.

INREN Design is composed of leader Aaron Dahlstrom and team members Luke Brostek and David Wagner. The BioCoGen project is deeply indebted to Kurt Hertzler of Cleveland Brothers Equipment Company in Manada Hill, Pennsylvania for providing a generator and to Dr. Harold Underwood of the Messiah College Engineering Department for serving as project advisor.

1 INTRODUCTION

1.1 Description

Context

Common to most U.S. homes is the need for electric power and heat. The traditional means of supplying heat and electricity relies heavily on non-renewable resources such as petroleum and fossil fuels. There are large losses associated with centralized power generation and distribution when using these fuels as well as byproducts that are harmful to the environment. So we decided to find a way to

- avoid detrimental emissions (typical of petroleum based fuels),
- use a renewable rather than non-renewable power source,
- avoid the energy losses inherent in electric generation without waste heat reclamation,
- avoid the energy losses associated with electric power distribution.

This meant that we would be designing a clean energy system that focused on a local need.

Research

The INREN Design team examined the literature concerning the various alternative energy sources in use today. Among the alternative solutions to the problem we are trying to address are wind and hydropower generation. Some companies, Green Mountain Power for example, produce their power exclusively through these means and thus are providing renewable energy to their customers. In our research we also found out about an alternative fuel to fossil fuels called biodiesel. It is an organic substance made from vegetable oil and therefore is renewable.

We read most extensively, however, about solar power, wood stoves and cogeneration; this research is more fully detailed in Section 1.2 which illustrates our intention to link all three of these systems together. As we thought about how to combine the power generation capabilities of photovoltaic and cogeneration systems, we read about battery storage units and about connecting up to the power grid. We also began to think more specifically about joining a solar collector, a wood stove and a generator to provide heat for our system.

Analysis

Since our desire was to meet a local need, we examined the electrical power and heating needs of one half of the SALT house duplex, a student home at Messiah College. First, we calculated the electric need by averaging the daily kWh consumption across two years of data from the SALT house electric bills. We then assessed the daily, monthly, and seasonal heating profiles of the SALT house using the oil bills[1] and standard domestic heating loads from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE).[2] (See the Engineering Design Report for these analyses.) This enabled us to describe three needs:

1) *Average Daily Electrical Need*: 20 kWh / day
2) *Average Daily Domestic Hot Water Need*: 65.5 gal of 120 F water = 37 500 Btu / day
3) *Average Yearly Space Heat Need*: 81 000 000 Btu / year.

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[1] See Krieder, Hoogendoorn, and Kreith 1989, chapter on Load Calculation, for a description of "degree days."
[2] Based on standard data from the *ASHRAE Active Solar Heating Systems Manual* (pp 1-3 to 1-4) and "Chapter 45: Service Water Heating" in *1995 ASHRAE Handbook: HVAC Applications*.

1.2 Literature Review

Initial Brainstorming

People have found numerous ways to provide heat and power for their homes. Some of the more traditional heating systems include fireplaces, wood stoves, coal furnaces, or natural gas furnaces. These are fairly simple technologies that have been around for years. Homes can also be heated using electric furnaces or space heaters powered by kerosene, propane, or electricity. Moving towards more renewable methods, solar collectors and photovoltaic cells have been a popular method but currently only implemented by the environmentally conscious and those privileged enough to afford them. One of the most proven methods for heating is still the wood stove. As we just mentioned, some alternative means of producing power are with wind generators and water turbines.

Initial Research

Since we desired a renewable approach our defined problem, we began by researching solar collectors and wood stoves, thinking that a diesel engine or generator might be a good secondary or back up system. For the solar and wood methods we found that these are both highly developed and are currently implemented all over the world as viable alternatives to the typical heating systems already mentioned. Solar collectors continue to become more and more advanced and innovative to maximize their heat gain and resistance to the elements. One such manufacturer boasts their collector "cannot boil, freeze or corrode," that "it performs well in all weather," and that its "efficiency remains high in diffused light (cloudy conditions). On an annual basis over 70% of the available energy from the sky is converted into heat regardless of the intensity of the light."[3] Even so, solar energy has its limitations and cannot supply all the heating needs of an average house without a large thermal mass (extra thick floor and/or walls that store heat during the day and reradiate it at night) or other auxiliary system. Also, this is not an extremely viable solution for the northern half of the United States because the intensity of the sun's light is bordering on insufficient.

Wood stoves are also an extremely mature technology. Some companies such as Jotul and Morso have been around since the mid-1800s! One of the present-day innovations is that the stoves have a specialized burning chamber that redirects the escaping fumes and smoke back over the flames resulting in a burning process that is ultra-efficient and clean. The reason is because this raises the temperature of the flames which causes more of the wood to be burnt (and thus gives less ashes) and, more importantly, it breaks down most of the toxic hydrocarbons that remain in less hot fires into harmless substances. There are wood stoves that run on wood pellets that only have to be filled once per week as a large tank automatically feeds the flames as they need more pellets. There are even stoves that operate on corn pellets!

When we began to think about combining all three of our ideas into one system, we realized that not only could we produce our electrical power with photovoltaics and with the generator's output, but that all three of the systems could each produce heat. Each of the three subsystems would heat water that would be fed into a radiant floorboard system in a house. Because wood-burning stoves are so advanced and already used in many different ways to completely supply a house with all of its heating needs, we thought we could use it as a fail-proof back-up system. We then began to find out more about cogeneration, realizing that on the large industrial scale

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[3] From "An 'All Weather' Solar Energy System Able to Deliver Hot Water Even in the Cold…." From http://www.solarthermal.com/overview.html. Thermomax Industries LTD. Accessed September 2002.

much is already being done. Trying to link a solar collector with a small-scale cogeneration system seemed to fit with our project goals well. We dropped the wood stove option and after further research on cogeneration, we decided to drop the solar as well. This limited our scope considerably, but still left us with a viable alternative.

Cogeneration

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines cogeneration as "the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream, such as oil, coal, natural or liquefied gas, biomass, or solar." [4] Most often cogeneration systems use an engine to produce both mechanical and thermal power. The mechanical power is often utilized to produce electric power using a generator; it can also be used to drive compressors or pumps. The thermal power can be used directly for heating or indirectly for cooling (with absorption chilling).[5] A related term, "Combined Heat and Power" (CHP), refers to the production and use of heat and power from the same source.

Cogeneration technology originated in the 1880s in Europe and the United States. Industrial plants produced their own heat and electricity from coal-fired burners and steam-turbine generators for much of the early parts of the 20th century. However, as fuel prices tumbled and reliable electric grids began distributing relatively inexpensive electric power, industrial cogeneration installations sank. More recently, especially after dramatic rises in fuel prices beginning in 1973, cogeneration systems have reemerged in industrial applications; due to their increased efficiency and reduced emissions, governments in Europe, Japan and the US have encouraged cogeneration development through research programs, regulatory revisions, and monetary incentives.[6]

Presently, then, cogeneration systems for commercial and industrial use have been in existence for quite some time. However, residential-scale cogeneration has not yet received the same focus or development. Through its ATLAS project, the European Union assessed their future energy demand and supply: regarding combined heat and power (CHP) they report, "highly efficient CHP technology for the commercial sector is now mature and well established. For the domestic sector, where CHP units might serve individual houses, further technology development is needed." [7]

Packaged Cogeneration Systems for residential-scale applications are just beginning to emerge. European, American, and Japanese researchers each have contributed to the field. A Carson City, NV company called Vector CoGen introduced the first US production-model cogeneration systems on 10 December 2002; the 3, 5, and 15 kW systems use Kawasaki natural-gas reciprocating engines as their prime mover.[8] In Japan, Yanmar Diesel Engine Company and Osaka Gas Company cooperatively developed the "E Combi," a gas engine cogeneration system

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[4] *1996 ASHRAE Handbook: HVAC Systems and Equipment.* 7.1. Chapter 7 of the Systems and Equipment handbook is "Cogeneration systems and Engine and Turbine Drives"; it probably provides the most comprehensive summary of cogeneration design of any resource.
[5] *Educogen* 7.
[6] The information in this paragraph draws heavily from *Educogen* 7-8, which briefly outlines the history of cogeneration.
[7] *Energy Technology, the Next Steps: Summary Findings from the ATLAS Project, December 1997*
[8] See www.vectorcogen.com for detailed product information, specifications, etc. (Accessed 10 December 2002).

touted as the smallest system in Japan, with a rated output of 9.8 / 8.2 kW (60/50 Hz).[9] And in Europe, a trade association called COGEN Europe is coordinating with the European Committee on Standardization to formulate standards for cogeneration systems under 10 kW to ease their application in the domestic market.[10]

Even with the development of these systems, the field of renewable energy cogeneration needs more research. The EU's ATLAS project reports, that the most common engine "is the spark-ignition gas engine. … Other technologies under development include: small (<1MW) gas turbines, external combustion reciprocating engines (Stirling engines) and fuel cells."[11] They did not explore the possibility of biodiesel-fired combined heat and power. Other sources have proposed using various biomass products to fire cogeneration processes, but our research encountered no production or development of biodiesel-fired small-scale cogeneration systems.

Biodiesel Engines

General Information

Biodiesel is a fairly well studied and developed renewable resource. In the US there is a National Biodiesel Board and a standardized ASTM Spec requirement for the production and sale of biodiesel in the US. Biodiesel is an alternative fuel that passes the Clean Air Act and is fully compatible in existing diesel engines with no major modifications needed. It is the cheapest of the alternative fuels on the market and is easily compliant with state regulations Biodiesel is an alternative fuel that contains no petroleum products but can be blended at any level with petrodiesel to create a petroleum blend. Biodiesel is created from natural oils (such as vegetable oil, soy bean oil, fish oil, etc.) that undergo a fairly simple process in which the glycerin is removed. This fuel is now compatible with practically any diesel engine on the market. Aside from any household concoctions, the most commonly used biodiesel blends are B20 (20% biodiesel, 80% petrol), B50 (50% biodiesel, 50% petrol), and B100 (100% biodiesel, 0% petrol).[12]

Performance

Biodiesel fuel is compatible with existing diesel engines. In a 15 million-mile infield test biodiesel B20 performed the same as petrodiesel with respect to engine fuel consumption, horsepower and torque. Biodiesel was found to greatly improve the lubricity—at a 1% biodiesel level of concentration in petrodiesel, there was a 65% increase in lubricity and distillation of fuels.

Here are the results from a Life Cycle Summary[13] comparison between B20 and Petrodiesel:

- Biodiesel was four times as efficient as diesel in utilizing useable fuel from fossil fuels
- Biodiesel contains 35% less CO than diesel
- The ratio of fuel energy to energy used was 83.28% for diesel and 80.55% for biodiesel.

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[9] "Smallest Gas Engine Cogeneration System in Japan with High Power-generation Load factor." Available at http://www.caddet-ee.org/infostore/details.php?id=2836.

[10] A "Workshop Agreement," which will form the basis for standards, is due to be published in December 2002. See http://www.cogen.org/projects/cen_workshop_agreement.htm.

[11] *Energy Technology, the Next Steps: Summary Findings from the ATLAS Project, December 1997*

[12] From "Commonly Asked Questions." From www.biodiesel.org/resources/fuelfactsheets/. National Biodiesel Board. Accessed on 25 September 2002.

[13] From "Lifecycle Summary." From www.biodiesel.org/resources/fuelfactsheets/. National Biodiesel Board. Accessed on 25 September 2002.

- Using biodiesel results in an 83% reduction in particle matter and exhaust
- Biodiesel is completely sulfur-free
- Hazardous solid wastes emitted when using biodiesel were 96% lower
- Biodiesel is virtually nontoxic

Biodiesel is not compatible with certain elastomers—it causes the fuel hose and pump to wear down over time, and the higher the biodiesel concentration the faster it will corrode. The hoses may have to be changed more often or a more compatible hose installed. Pure biodiesel is more likely to cause clogging in the fuel filter as well. In colder weather biodiesel experiences cold flow, in which the fuel starts to gel. This is a more serious problem for B100. Temperature at which B20 begins to experience cold flow is at 3-5° F. A solution can be mixed with the biodiesel fuel in order to prevent gelling. [14]

Benefits

For the past few years, the price for petroleum fuel has been at a record high, whereas the price of products gained by agricultural commodity has been at a record low. Since Biodiesel fuel relies heavily on farm crops such as soybeans, biodiesel could be produced domestically, thus improving local economies, increasing domestic security, and decreasing dependence on foreign oil. Biodiesel requires no major engine modifications so it can be applied to fleets already in use, engines and parts currently being produced, with no need for new, specialized mechanics. The performance and fuel economy are the same for both bio- and petrodiesel, but there are no harmful side effects to the environment. It contains no sulfur (cause of acid rain) and shows a dramatic improvement in harmful exhaust emissions (nontoxic, organic residue, green gas). The high lubricity of biodiesel fuel adds life to the engine, and its high flash point makes it safer to use and store.[15]

Cost

The typical diesel engine gets 40-50 miles/gal. One case stated that biodiesel costs about 6.1 cents/ mile and $2.45/gal, making it cheaper than gasoline but more expensive than petrodiesel. In another study, B20 was estimated at being 15-30 cents more than petrodiesel. Another basis for pricing is the market price for vegetable oil. Those using biodiesel, such as a bus fleet in a US city running off B20, report that their total annual cost was lower when they used biodiesel.[16]

Case of Implementation

In one case a man installed a biodiesel generator to power in his home using an old Toyota diesel pick up with a 2.2 L diesel engine. He tested the engine, found it to be in good working condition, and used it to charge a battery pack to provide power for his home. He reported that he produces enough power to go 2-3 days without firing the generator, and it takes 3-5 hours using 2.5 gallons of biodiesel to completely charge his battery. He says he has enough power to run "several rooms and a computer."[17]

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[14] From "Performance." From www.biodiesel.org/resources/fuelfactsheets/. National Biodiesel Board. Accessed on 25 September 2002.

[15] From "Benefits." From www.biodiesel.org/resources/fuelfactsheets/. National Biodiesel Board. Accessed on 25 September 2002.

[16] From "Fleets." From www.biodiesel.org/resources/markets/fle/default.asp. National Biodiesel Board. Accessed on 25 September 2002.

[17] From "Home Brew Biodiesel Genset." From www.eline2000.com/eline/articles/biogen/biogenset.htm. Terry McGlesh.

1.3 Solution

Alternatives

In our brainstorming, we came up with several alternative energy options to solve our problem: solar, wind, hydro, wood, alternative fuels and cogeneration. We decided against buying power from a company like Green Mountain Power because even though the electricity is produced through renewable means, there are still distribution losses. We ruled out both wind and hydropower because they produce only electricity and they are not as suitable for residential application, especially in urban areas. When we researched biodiesel, we learned that it is almost identical to the oil used in oil burners. The radiant floorboard system of the SALT house is equipped with an oil-fired burner and we thought we could just fuel it with biodiesel. We were not sure what this would do to the burner and this option would only provide for the heating needs. The solar and wood options seemed more attractive to us, but since we were designing to meet a local need, we soon realized that central Pennsylvania is far enough north for the solar efficiencies to be significantly reduced and that wood is not readily available to most people in this area.

Final Solution

In light of these reasons, the literature we reviewed and the problem we are trying to address, we chose to use a cogeneration system. We feel this is the best solution to the problem when we take into consideration our goals and our location. A small-scale cogeneration system could meet both the electricity and heating needs of one house. This meets the local need and eliminates the distribution losses. If we use diesel generator, we will be able to use biodiesel and make the system renewable. We would also be almost completely eliminating harmful emissions and increasing the efficiency of the generator.

Objectives

After our research and analysis, we were better able to define our project with these objectives:

- BioCoGen will supply at least 20 kWh per day, which is the average electrical energy needed each day by the SALT House.
- BioCoGen will harvest at least 9 000[18] Btu / day of waste heat from the exhaust of the diesel engine.
- BioCoGen will harvest at least 22 000[18] Btu / day of waste heat from the engine block cooling system.
- BioCoGen will consume 1.2 - 1.5 gallons of biodiesel fuel per day.
- The BioCoGen system will add at least 15% to the efficiency of the genset by utilizing the waste heat. ($\eta_{new} = \eta_{old} + 15\%$)
- The BioCoGen prototype system will have a total cost less $500.

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[18] Note: In our Engineering Design Report we somehow managed to switch these numbers so it incorrectly read that we could harvest 9 000 Btu / day from the coolant and 22 000 Btu / day from the exhaust. We found this error as we searched our analysis calculations for a reason why our heat recovery objectives do not add up to 37 500 Btu / day (see Section 1.1). The reason why our exhaust heat recovery objective is so low when compared with our results is because we only had data from large-scale industrial cogeneration systems and we were not sure how accurate their figures would be when scaled down to our residential-scale system. So to be safe, we cut the percentage of the expected amount of energy in the exhaust gases in half. We found out in our testing that the data provided in our research was extremely accurate even for our small system and that we would have been fine to assume 18 000 Btu / day from the exhaust, which would give us a combined total objective of 40 000 Btu / day.

2 DESIGN

2.1 Cogeneration Design

According to *Educogen*, a report on the management and design of cogeneration systems, choosing the best cogeneration design for a particular application poses a difficult problem. *Educogen* separates the major design decisions into six categories; our design addresses each of these categories.[19]

Type of Cogeneration Technology	Bio-diesel fired diesel cycle reciprocating engine
Prime Movers (Number and Nominal Power)	1 prime mover, 3 - 7 kW required
Heat Recovery Equipment	Standard finned tube air-liquid exchanger
Need for Thermal or Electric Storage	No Electrical Storage; Thermal Storage Needed (50 gal water tank)
Interconnection with the Utility Grid	Two-way (produce for grid and draw from grid)
Operational Mode of the System	Continual generation of electric power; generation of thermal power to maintain tank at 160 - 180 ºF.

In the following sections we review the details of these design outcomes.

2.2 Electrical System

The two main options for supplying power to the house are with batteries that are charged up or by connecting to the power grid. Battery storage may prove less favorable due to its low efficiency and need for yearly maintenance and possibly disposal and replacement. Using batteries produces hazardous waste and is a source of recurring cost; therefore we have concluded that the employment of batteries does not support our pursuit of applying renewable technology on the residential scale. It also poses complication for our genset's run profile, because the battery pack has a limited storing capacity and therefore, either an extremely large battery or a shorter runtime is required. Finally, losses in the battery pack mean that not all generated power can be used.

Grid Connection, however, poses many benefits. As the generator runs, the power it produces is sent to the grid, where it is then distributed throughout the community. Meanwhile, the house itself remains supplied by the electric utility; if the amount the grid sends to the house and the amount the house sends to the grid equal each other, the electric bill for the house will cancel out. After the initial process of actually connecting to the grid, the system requires only minimal maintenance. This option is also beneficial because, in the event that the system does experience problems, the house can still receive a power supply from the grid. Furthermore, connecting to the grid means that the homeowner can use all the power that they generate; this contrasts with the losses associated with using batteries. The user should check with his local power utility to ensure his system is up to code. For example, Pennsylvania Power and & Light (PPL) requires all designs to be signed by a professional engineer and safety mechanisms must be installed. PPL also charges a $300 non-photovoltaic processing fee.

Our design calculations called for a 3 – 7 kW diesel generator. The size is somewhat flexible because the amount of time it runs can vary as well. The run profile stipulations are that it not

[19] *Educogen* 127. Educogen provides a useful outline of the whole cogeneration design process "Optimal Design and Operation of Cogeneration Systems."

run for short periods of time (less than an hour) and that it not run upwards of 20 hours each day. As we already mentioned, we wanted to make sure the generator was diesel so we could power it with biodiesel. We also considered fuel efficiency. In order to achieve optimum fuel efficiency, the generator must run continuously within the range of ½-¾ of its maximum output. The last criterion was that the genset be water-cooled.

The interesting part of the "story" is that it proved to be rather difficult to find all of these requirements in one generator. Several people we talked to told us that small, diesel generators were a dime a dozen. We found, however, that most small generators are gas and that any diesel generators we did find were air-cooled. We began calling everything from generator dealers to lawn mower dealers, from mechanics to junkyards. We even contacted one sailboat dealer as far away as Boston, Massachusetts! Finally we had contacted Cleveland Brothers Equipment Company northeast of Harrisburg. After meeting with Kurt Hertzler, we found a generator they had in their shop that they were able to loan to us for the entire semester!

2.3 Heat Exchanger

The purpose of the heat exchanger (HX) is to gather heat from the generator exhaust and store it in the water. Through a process of analysis, research, and design we arrived at the final specifications for the exhaust heat exchanger.

Analysis

To size our heat exchanger, we needed to determine the maximum rate at which the engine could dissipate heat through its exhaust. Using the maximum electric power rate, the standard efficiencies of diesel gensets, and the total running time of the genset, we calculated that the exhaust heat exchanger could remove 3121 Btu / hour.

We then estimated our minimum exhaust entrance temperatures, minimum coolant entrance temperatures, and our maximum tank water entrance temperature. This enabled us to calculate the (heat rate / initial temperature difference), which allowed us to characterize the heat exchanger we desired. We estimated that the exhaust air-to-liquid exchanger would need to dissipate 15.60 [Btu / (hr deg F)]. See the Engineering Design Report for the detailed calculations.

Research

We performed market research to determine whether we should purchase an Heat Recovery Muffler from a manufacturer or adapt a finned tube heat exchanger already on hand.

Maxim WHS Heat Recovery Unit.

We contacted several heat recovery muffler manufacturers. Beaird Industries provided us with the most helpful information. Their Maxim Heat Recovery Unit line includes several models designed to transfer heat from diesel exhaust into water; however, the smallest unit in this line is designed for engines six times larger than our design. Other manufacturers provided even less information when contacted; therefore, we determined that we could not purchase a Heat Recovery Muffler of the size we needed.

Messiah College owns several Lytron-brand finned tube heat exchangers; we contacted Lytron to determine if they could capture enough heat for this application. Greg Ducharme of Lytron reported that the heat exchangers we owned are not normally used for the high temperatures of diesel exhaust; he

Lytron 6599 Finned Tube HX.

cautioned that differences in the thermal expansion of the fins and the tubes could cause them to lose contact and greatly decrease heat transfer. Additionally, his thermal models are not normally used for air near room temperature, not diesel exhaust at 700 F. However, based on estimations of the exhaust temperature, the exhaust flow rate, the water temperature, and the water flow rate, Greg Ducharme estimated that would easily exceed our heat exchange specifications.

Therefore, we chose to adapt a finned tube heat exchanger.

Design

The Lytron 6599 finned tube heat exchanger is often used to transfer heat from a hot liquid to ambient air; we needed to design a sealed box to enclose the unit in order to force the exhaust across the fins and pipes.

We looked for an enclosure that:

- was manufacturable in Messiah's machine shop,
- easily connected to the exhaust pipes,
- allowed the water pipes from the Lytron exchanger to pass through the walls,
- sealed to ensure that no exhaust escaped,
- could be opened and closed (for inspections and cleaning), and
- did not cause excessive pressure drop.

With these criteria, we produced a design for a sheet metal box made of two interlocking "C"-shaped sheet metal pieces. The two pieces are attached by screws along their seams; between the two pieces of sheet metal lies slotted furnace packing to ensure that no exhaust can escape. The exhaust pipes connect to exhaust hose adapters welded to the sheet metal. The water pipes pass through the box wall through holes drilled in one of the sheet metal pieces. This design satisfies our criteria:

- manufacturability: detailed manufacturing plan
- exhaust pipe connection: using exhaust hose adapters
- water pipe connection: through holes in HX Box wall
- sealed against exhaust leaks: by furnace packing
- opens / closes: by using screws that can be removed
- minimal pressure drop: single-pass HX directs exhaust across HX only once.

Final Specifications

The sealed sheet metal box required the following materials:

- Sheet Metal, 18 gauge (8 ft^2)
- Sealants
    - Slotted Fiberglass Furnace Packing (1 in. wide, 8 ft. long, 1/16 in. thick)
    - Fiberglass Packing Cement (1 oz.)
    - Furnace Cement (1 oz.)
- Insulation (Interior and Exterior)
- Hardware
    - Screws (1 in. 10 × 32 machine screws)
    - 2 in. OD Exhaust Hose Adapters

- Compression Fittings (2 elbows for 3/8 in. tube, 2 elbows converting from 3/8 in. to ½ in. tube)
- Engine Back pressure Monitor
    - Pressure Gauge (0-20 psi)
    - Fitting (1/8 tubing to male NPT elbow)
    - 1/8 in. Copper Tubing (3 ft.)

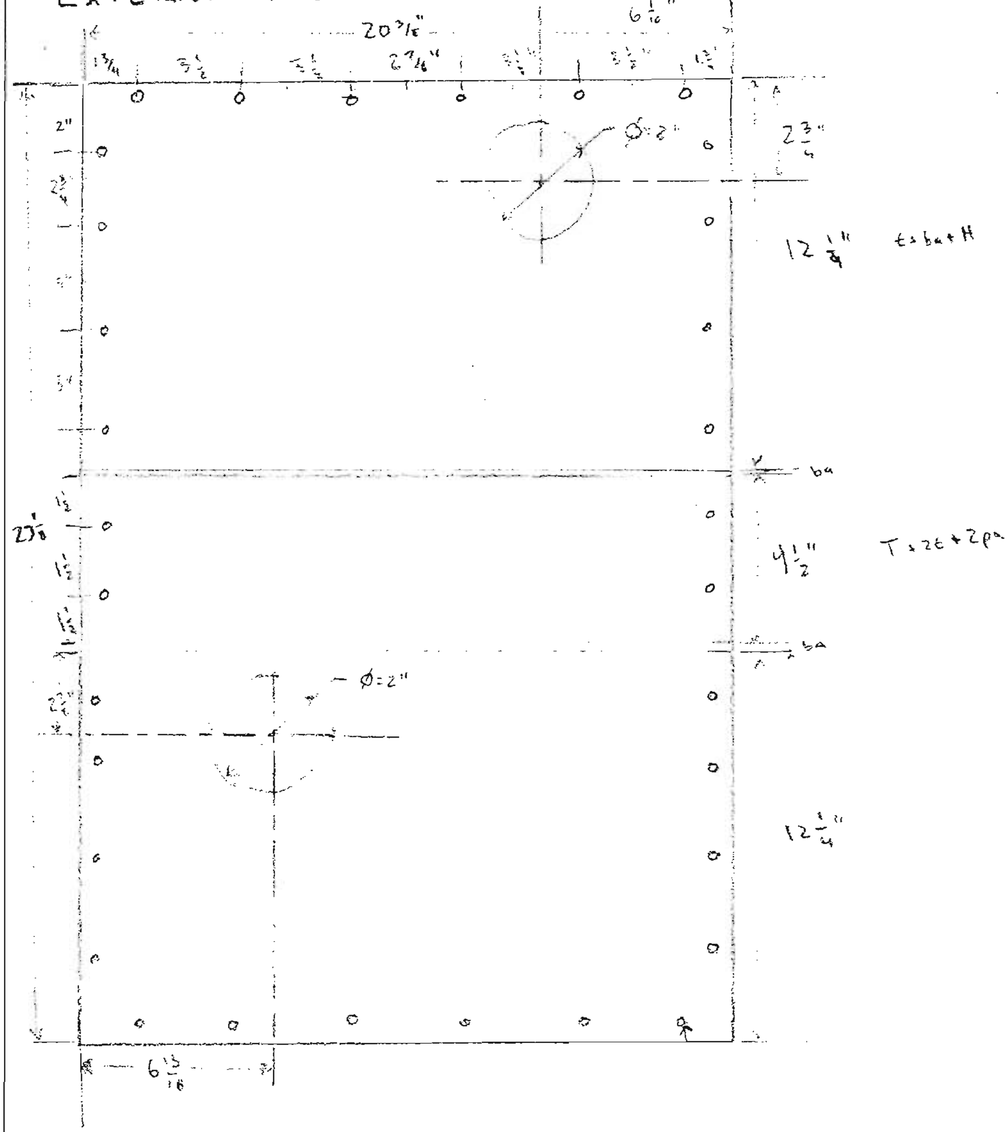
See the schematics on the following two pages for the details of the sheet metal design (size, shape, flanges, holes, bends).

INREN DESIGN
AARON DAHLSTROM

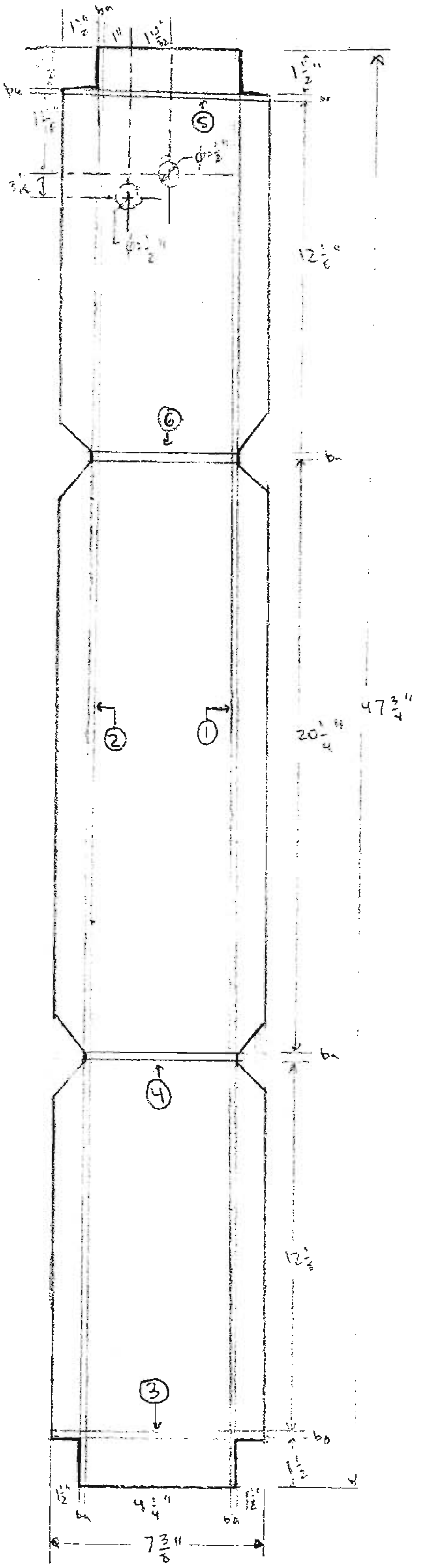
FINAL DESIGN LAYOUT
HX BOX

not to scale

EXTERIOR PIECE



INTERIOR PIECE -33



VERTICAL MARKS

- 1 1/2
- 1 7/16
- 13 11/16
- 13 3/4

HOLE MARKS

(2 9/16", 3 5/8")

(4 5/32", 3 1/4")

BEND ORDER

SIX BENDS

ORDER INDICATED BY ① → ⑥

2.4 Water System

The main function of the water system is to provide a way for storing and transporting hot water throughout the house for domestic use.

Analysis

Water Storage

In order to determine the appropriate size for our water tank (our thermal storage), we developed a model of the heat addition and heat removal from the tank. We assumed that we only wanted to store heat over the course of a 24-hour period and not from one day to the next. We determined that the maximum thermal storage is required when the system produces its maximum daily heat and needs that heat at other times besides the generating period. The maximum amount of heat is generated when the maximum daily amount of electric power is generated. Using the maximum daily electric load from SALT House data (30 kWh), we used standard efficiency ratings for diesel engines[20] and for generators to determine the amount of exhaust heat and block coolant heat that our engine would produce.

We fully modeled our generator's heat supply profile. Using a 3kW generator within its acceptable load fractions to supply 30kWh resulted in running it for 15 hours at 2 kW; using our standard efficiency ratings we calculated how much heat would be generated with that electric generation rate.

Then, we determined when we would need to store significant amounts of this heat. First, we refined our heat removal model; using our house's thermal resistance from section 2.3.1 of the EDR[21] and a standard estimate of domestic hot water loads,[22] we modeled water-heating loads for every day of the year.

Combining the heat load model with the genset's supply model, we found that:

- in the summer time, much of the heat was rejected, and the maximum loads did not require large amounts of storage,
- in the winter time, all of the heat generated was used nearly instantaneously, with no need for storage,
- in the fall and spring, the heat produced by the genset could all be used, and needed to be stored for use at other times.

Using the thermal load for 1 October, we determined how long the heat produced by the generator needed to be stored before the load would begin to remove some heat. This determined how much heat we needed to store; we set a limited daily temperature gain for the tank (so that the temperature wouldn't rise above boiling or descend below a certain usable temperature). Given a temperature gain, a heat amount, and water's specific heat, we determined the volume of water required. This yielded a tank size of 50 gal. Refer to EDR for the detailed calculations of this analysis.

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[20] From Horlock, J.H. *Cogeneration – Combined Heat and Power (CHP)*. and Orlando, Joseph A. *Cogeneration Design Guide*.

[21] Multiplying the thermal resistance by (65 deg F – Ambient Temp) gives the instantaneous space heat load; we assumed an average heating year and a sinusoidal variation of temperature ranging from the maximum daily temperature to the minimum daily temperature over 24 hours.

[22] We assumed that a water draw rate of ¼ the daily load was applied evenly for two hours in the morning and two hours in the evening. See our Analysis sheets.

The Tank Insulation was determined through a quick analysis; the calculations can be viewed in the EDR. Basically, we chose an average possible heat output based on a generator supplying 20 kWh per day in electric power. Using this data, and estimations in average tank size dimensions and convection coefficient, we calculated how much heat we could allow to escape on a given day. We chose to allow 1 % of the average Btu / day heat output to be lost because it only allows a minimal amount of heat to escape and gives a reasonable R-value of 15. It is important to note that this analysis assumes radiation losses to be negligible.

Water Transportation

First, we considered how to fill the tank. Because the scope of this prototype was not to permanently connect to a house, we decided to use an average green garden hose leading from a cold water outlet in the basement to the water storage tank.. This made filling the tank simple and allowed for easy disconnection from the house, giving us more time to focus on the heat exchange loop.

We decided that copper tubing should connect the heat exchange loop and its different components. This is in accordance with conventional systems, so it is readily available and affordable. We chose flexible copper tubing because it would be easier for us to work with and would allow for more innovative possibilities, should any unexpected twists crop up in our final construction and testing of our system. In addition, it limited the number of joints that would need to be soldered and thus limited the number of potential leaks.

If the copper piping would provide the path for the water to move through, a water circulator would provide the necessary force to take water from the storage tank and move it through the heat exchange and back to the tank as stored water. We wanted to be sure that our pump could provide enough head to push the water back into the tank. Since we were relying on donations for most of the components in our water system, it was uncertain what the specific height and size of our tank would be. However, since our system was designed for the basement of a residential home, we estimated the height that the pump would have to push the water would be no higher than the ceiling of the basement of the house. We therefore decided that a pump capable of pushing water 6 – 10 vertical feet would more than meet our requirements.

Water Pressure

Because we were dealing with a closed system containing water experiencing temperature changes from 50 °F to potentially 180 °F, we knew we would have to consider pressure changes. Water expands as it heats up, threatening our system with the possibility of cracking or even exploding. Therefore, because they deal with temperature changes similar to our system, we looked at conventional boiler systems and found an existing subsystem that met our need.

The expansion tank is basically a large bladder that can expand or contract depending on the pressure in the system, giving the heated water some more room to move around. An air vent is placed atop the expansion tank, at the highest point in the system, to release all air trapped in the system. The expansion tank solved our problem well.

In addition to this, should the pressure be too much for the expansion tank, we found out that most boilers and water heaters are equipped with a temperature pressure relief valve. This functions mainly as an emergency relief. If the pressure should become too great due to abnormally high temperatures, the valve will open, and a pipe leading from the valve at the top of the tank to the basement floor will allow some water to escape, thus relieving the system.

Finally we needed to consider the pressure of the water entering the tank from the house. Standard cold water pressure from a house is usually between 60 – 80 psi. In compliance with standard heating systems and for safety, we wanted to reduce the entering water pressure to 12 –

15 psi**.** So we decided we also needed a pressure-reducing valve at the cold water supply entrance to the tank.

Acquisition

With initial design in place, we needed to actually acquire the components for our system. Because of our limited budget of $500, we relied on donations from local businesses for larger components. Having decided what we wanted, we contacted local plumbing and heating companies, talked to them about our project, and inquired what was available at what price. Finally, Blizzard's Plumbing and Heating, located in Dillsburg, PA, informed us they had several items that might be of interest to us and that they were willing to donate. From them we acquired a water storage tank, pump, expansion tank with air purger and vent, and pressure reducing valve.

The rest of the items needed to complete the water loop, such as 10 – 30 feet of copper pipe, a ball valve at the cold water supply, and compression fittings and joints to connect the components to the piping, we bought at R.F. Fagers, a local plumbing and heating store located in Camp Hill, and Lowe's in Mechanicsburg.

Final Design

The donated components were well within our original design requirements. The water tank we acquired was a brand new domestic water heater by A.O. Smith, 50 gallons, with existing insulation and one cold water inlet and one hot water inlet existing at the top of the tank. Within the tank the cold water inlet followed a tube down to the bottom of the tank to ensure that the coldest water would always be at the bottom and the hottest water always at the top. An existing drainage valve at the bottom of the tank provided an excellent way for the cold water to exit the tank and head to the heat exchanger, before reentering the tank through the hot water inlet. The cold water supply line fed the water through the pressure reducing valve and into the cold water inlet at the top of the tank.

We initially wanted to run the pipeline out through the tank's drain valve by connecting the valve and pipe with a compression fitting. The connection was not tight enough, mainly due to the fact that the drain valve was plastic thread of poor quality, unfit for what we intended. Therefore we moved the cold water exit to the top of the tank, branching it off the entrance pipe by means of a copper T joint, which then piped back down to the pump. It is important to note that this change still allowed water to be pulled from the bottom of the tank, due to the long internal pipe stemming from the cold water inlet on the tank.

Although we received a workable taco – 007 water circulator, the pump needed extra work in order to attach it to our system. Because the taco – 007 is a conventional item, parts are readily available at any plumbing store. We needed flanges and copper fittings for each end of the pump before it could be soldered to the copper piping system. The pump had no plug so that also needed to be bought and attached to the wires before we could plug it in and run it. The taco – 007 is actually designed to push water through a three – story house. Obviously, this is much more pump power than we need, and with this pump the water from our system would move potentially too fast to exchange any heat. This was a problem because we wanted to pass the water through slowly to ensure maximum heat exchange. Therefore we decided to solder in a small flow regulator after the pump to limit the flow rate of the water through the heat exchanger.

We chose to run copper pipe of ½ in. inner diameter. The heat exchanger had preexisting pipe connections of ¼ in. inner diameter. To connect the heat exchanger entrance and exit to the rest of the pipeline, we used compression fittings that were sized appropriately on each end. Other added parts included two male copper fittings to connect the air purger to the pipeline, and another one for the threaded connection at the hot water entrance.

Finally, we realized that we needed a way to monitor the pressure and temperature change of the water as our system ran. So we designed for a temperature sensor to be soldered into the pipeline before the heat exchanger and another temperature –pressure sensor at the hot water entrance of the tank. This way we could measure the water pressure in the tank and calculate how much temperature difference there was in the cold water (before) and hot water (after).

Final Specifications

- Water Storage
  - Tank Capacity: 50 gal
  - R – value: 15
  - Cold Inlet: ¾ in threaded female*
  - Hot Inlet: ¾ in threaded female*
  - Temperature – Pressure Relief Valve (Standard)
  - ½ male copper fitting
- Pump
  - Taco – 007
  - Flanges (2)
  - Wire and Plug
  - ¾ in. male copper fitting* (2)
- Expansion Tank
  - Expansion Tank
  - Air Purger
  - Air Vent
  - 1 in male copper fitting* (2)
- Miscellaneous
  - ¾ in x ¼ in compression fitting (2)
  - ¾ in male copper fitting (2)
  - Garden Hose
  - Pressure Reducing Valve
  - ½ in x ¾ in 90 deg elbow
  - copper tee (½ in)
  - hose to thread connection
  - copper tees*, copper 90 deg elbows*, threaded copper tee* (½ in)

*meaning the fitting is threaded, with the opposite end reducing fit over to ½ in ID copper pipe (soldering required).

3 Implementation

3.1 Construction

3.1.1 Electrical System

Genset

Upon receiving the generator, there were just a few maintenance issues to take care of before it was operational. It had been sitting for three years and needed a new battery, a new oil filter and a new fuel filter. We had to buy some fuel line and some flexible exhaust tubing that piped the exhaust from the generator to the heat exchanger and then out of the garage. The major issue was properly wiring the generator to give us the traditional 120 V power we needed. We had to buy some heavy-duty 30 amp wire, a circuit breaker box with fuses, some more wire and outlets and then the generator was ready to run. One major problem we had was after it had been running for a short while, the voltage rapidly changed from 120 V to 220 V and then to 40 V. We found that it was just a loose connection inside that took only a few minutes to fix.

Electrical Storage

Only in the production model would we have to go through the rigors of meeting power grid regulations. For our prototype we will simply power an appliance that draws the amount of power we are producing.

3.1.2 Heat Exchanger

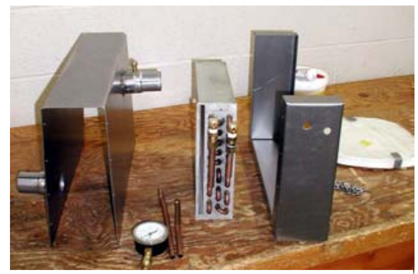
The box was manufactured in the Messiah College Machine Shop using the vertical band saw, the drill press, the sheet metal punch, the tapping tool, the MIG welder, and various hand tools.

When finally assembled, the box was attached to the exhaust tube coming from the generator and to the water pipes coming from the water system.

Detailed Manufacturing Instructions

1. Shearing Sheet Metal
   a. Shear sheet metal to create two pieces (Interior Piece, Exterior Piece) of given dimensions.
2. Lay out Bend Lines, Notch Lines, and hole centers with scriber on the sheet metal pieces. (see schematic in Sec. 2.3, Heat Exchanger Design)
3. Drilling / Punching Holes
   a. Drill Two 2 in. diameter holes for exhaust inlet and outlet, with hole saw on the exterior piece.
   b. Drill Two 1/2 in. diameter holes for water inlet and outlet on the interior piece.
   c. Punch holes for bolts (32) on exterior piece. (see schematic drawing for location.)
   d. Some bolt holes are inaccessible to the punch due to clearances. Drill these holes.
   e. Countersink / Ream all holes.
4. Cutting Notches
   a. Cut square notches on the corners of the interior piece according to schematic.
   b. Cut 45 degree notches on interior piece at flange mating locations.
5. Drilling and Tapping.
   a. Drill and tap the access hole for the pressure sensor on the exhaust inlet tube.
   b. Cut 3 ft. of 1/4 in. copper tube for the pressure sensor.

6. Bending.
    a. Bend Interior Piece on large break according to bend order on schematic.
    b. Bend Exterior Piece on small break.
7. Drilling and Tapping Bolt Holes
    a. Lay the Packing in its appropriate location on the Interior Sheet Metal Piece.
    b. Place the Exterior Piece over the Interior Piece.
    c. Place a centering punch in the bolt holes on the Exterior Piece to mark their location on the Interior Piece.
    d. Drill the bolt holes on the interior piece.
    e. Tap the bolt holes in the interior piece.
8. Welding and Sealing
    a. Tack the exhaust inlet and exit tubes onto the exterior sheet metal piece.
    b. Place the water tubes in their appropriate locations.
    c. Seal around the water tubes and the exhaust tubes with furnace cement; seal seams of the sheet metal as necessary.



Parts for HX Box after Step 8a.

9. Affix the Packing
    a. Affix packing to the exterior piece using Packing Cement.
    b. Cut and place packing on exhaust flanges to seal with the exhaust hose.
10. Assemble.
    a. Place Insulation Batting on the inside of the interior piece.
    b. Place the heat exchanger into the interior piece; slide it over the water tubes.
    c. Tighten the compression fittings that connect the heat exchanger to the water tubes.
    d. Place the insulation batting on top of the heat exchanger.
    e. Place the exterior piece over the interior piece.
    f. Tighten the screws that connect the interior piece to the exterior piece.
    g. Insert thermocouple wire in the exhaust hose, then place flexible exhaust hose over the packing and the exhaust flanges of the HX box.
    h. Wrap the hose with the tin foil and exterior insulation.

Heat Exchanger Installed

3.1.3 Water System

The water system was stored in the basement of a Messiah Satellite Housing Facility through the approval of proper Messiah personnel. The Messiah Engineering Shop provided the hand tools and soldering equipment needed for construction. The main tasks for construction included cutting pipe and soldering the joints to the pipe. We then had to assemble the whole system in our basement and tighten all the fittings before filling with water.

Detailed Manufacturing and Assembly

1. Cutting Pipe
    a. Cut copper pipe into four 5 ft lengths and two 10 ft lengths.
    b. Cut one of the 5 ft lengths into three roughly equal sections
2. Soldering Joints

a. Pump to Heat exchanger
    i. Solder pump connection to one end of 5 ft length of pipe
    ii. Solder the exiting pump connection to a section of the divided 5 ft length of pipe
    iii. Solder Flow Regulator Valve to pipe connecting to pump fitting and other section of divided 5 ft length of pipe
    iv. This pipe then leads to temperature sensor, which needs to be soldered in as well. The final fragment of the divided 5 ft length of pipe will be soldered to the opposite end of the sensor and meet the heat exchanger box entrance
b. Expansion Tank
    i. Solder one side fitting to 10 ft length of pipe, whose other end leads down to meet heat exchanger box exit
    ii. Other fitting is soldered to a 5 ft length piece of pipe leading to hot water inlet
c. Hot Water Inlet
    i. Cut two small sections off 5 ft length of pipe coming off expansion tank connection
    ii. Solder copper tee to opposite end of remaining pipe from expansion tank fitting
    iii. Solder small section just removed to perpendicular tee connection (a female threading will need to be soldered on also fro the temperature pressure sensor)
    iv. Solder other small section to copper tee on one end, to ¾ in male copper fitting on the other
d. Cold Water Inlet / Outlet
    i. Solder 10 ft length of pipe to threaded tee and on other end solder an elbow connecting this and the other side of the other pipe connection
e. Temperature - pressure Relief Valve
    i. Solder ½ male copper fitting to remaining length of pipe

3. Assembly
    a. Attach necessary thread and elbow to pressure reducing valve and attach that to ball valve which then adapts to the hose. (thread the cold water exit T joint in as well, with the pipe leading down to the pump.)
    b. Fit pump fittings to pump flanges and tighten pump flanges to pump. Note: make sure that the pump is pointing the right way. The pump exit flow should be the connection with the flow regulator and temperature sensor soldered on.
    c. Tighten compression fittings around ½ in. pipe and ¼ in. pipe of heat exchanger box. (both entrance and exit, the exit connecting to the 10 ft length of pipe going to expansion tank fitting)
    d. Tighten air purger to pipe with the soldered fittings
    e. Connect remainder to hot inlet.
    f. Connect expansion tank and air vent to air purger (may want a frame to support expansion tank apparatus; remember, it is important to keep it at the highest point of the system)
    g. Put on temperature pressure sensor
    h. Thread in temperature – pressure relief valve to central hole on top of water tank. Thread in soldered ½ male copper fitting to remaining length of pipe and, once secure, bend downward 90 degree
4. Connect hose to house supply
5. Run water through hose to fill system – open air vent and make sure ball valve is open
6. Disconnect from house supply – close ball valve, shut off water, disconnect hose

Note: Pipe will have to be bent during assembly to ensure the proper fits. Avoid pinching the pipe and avoid putting too much exertion on the soldering joints.

3.2 Testing

Once the construction of the BioCoGen Prototype was complete, we selected two tests to perform: a Heat Recovery Test and a Corrosion and Fouling Study.

Heat Recovery Test

Procedure

We implemented the Heat Recovery Test to test to characterize the rate at which BioCoGen gathers heat when the generator produces electricity at around its prime rating (6 kW).

1. We attached electric appliances to the generator until the generator produced 5.3 kW.
2. Our system has two temperature sensors, one where cold water is drawn from the tank (before the heat exchanger) and one where hot water returns to the tank (after the heat exchanger). We recorded the initial temperature (48 F) and the temperature at both sensors for the duration of the test.
3. Due to fuel constraints, we decided to test for about two hours; we ran the generator for 1:54, producing 10.1 kWh.
4. After the set period, we turned off the generator and continued pumping the water through the tank. We assumed that after pumping for 15-20 minutes, the tank water would be well mixed and both temperature gauges would show the average temperature of the tank water after the test.
5. At the end of the test, the temperature gauges read different numbers; we assumed that the older gage with a more limited range was inaccurate, and took the average temperature of the tank to be 101 F.
6. See Section 8.1, Heat Recovery Test Results, for the complete data table.

Estimate the heat gathered in this test

1. The amount of heat gained in this two hour test can be calculated from the following formula: Heat = (mass) * (specific heat) * (Temp. Change)
2. *Mass*: 50 gal water in tank + 10 gal in pipes and expansion tank = 60 gal = 227 kg.
3. *Specific Heat*: 4.18 kJ / (kg*K)
4. *Temperature Change*: 53°F = 29.44 K
5. *Heat* = 227 * 4.18 * 29.44 = 27 934 J = 26 477 Btu
6. *Average Heat Transfer Rate* = 26 477 Btu / (1 + 54/60 hr) = 13 935 Btu / hr
7. This test generated (114/60 hour) * 5.3 kW = 10.1 kWh of electrical energy.

Estimate the heat that would be gathered in a 20 kWh test

1. Assume that the heat transfer rate stays the same throughout the test.
   (The exhaust was much hotter than the water; we measured an average exhaust temperature of around 650ºF. The projected temperature gain of the water (from 48-160ºF) is small compared to the temperature difference between the water and the exhaust. Therefore, the heat transfer rate should stay about the same.)
2. Thus, the heat transfer rate = 13 935 Btu / hr.
3. The time required for generating 20 kWh = 20 kWh / 5.3 kW = 3.77 hr.
4. *Heat* = 13 935 * 3.77 = 52 500 Btu.

Estimate the Efficiency Gain for the Generator
Inputs

140000	Btu / gal fuel
1.2	gal fuel used
168000	TOTAL BTU Input to system
1.90	Hours on
88421.05	Heat Input Rate [Btu / hr]

Outputs
Electrical

5.3	ELECTRICAL OUTPUT [kW]
18084	ELECTRICAL OUTPUT [BTU/hr]
20.45%	ELECTRIC ONLY EFFICIENCY

Heat

4.084	HEAT OUTPUT [kW]
13935	HEAT OUTPUT [Btu / hr]
15.76%	**HEAT ONLY EFFICIENCY (ADDTN'L Efficiency)**

Corrosion and Fouling Study

Diesel exhaust contains soot (particulate matter) and sulfur. Both of these could cause damage to the finned tube heat exchanger:

- particulate matter could accumulate on the fins, clogging the passageway and making heat exchange more difficult, and
- sulfur vapors could condense into sulfuric acid on water pipes colder than 300ºF, corroding the aluminum fins and copper pipes.

We designed for biodiesel fuel, which has nearly no sulfur and very little soot in its exhaust. However, we tested with petroleum-based diesel, so we wanted to examine the effect of the diesel exhaust on the heat exchanger.

Therefore, after our heat recovery testing, we took apart the heat exchanger unit and examined the interior surfaces. Soot did accumulate on the heat exchanger: note the black coating on the insulation, pipes, and fins. Also, small globs of transparent whitish liquid had condensed on the fins and fin supports. We did not test to see how acidic the condensate was; it could have been largely water vapor. However, water can corrode steel. The fittings that connected our copper water pipe to our heat exchanger were not fully tight; the water dripping into the heat exchanger box caused spots of rust in the steel sheet metal.

4 SCHEDULE

Our actual schedule for the Fall and Spring Semesters changed from our original plans. Initially our scope was to integrate a generator, a wood stove, and a solar water heater, for space heating and domestic water use in the SALT House, and we researched and conducted analyses in these areas. However, we realized our scope was too large, and we spent the greater portion of the semester narrowing our scope and doing research to finally achieve a feasible and effective design. This cut away time for final design and analyses for our decided system, and forced us to make our design decisions towards the end of the semester. We again realized we needed to limit our scope to only focusing on collecting heat from the exhaust gases, instead of both the coolant and exhaust waste heat (see EDR for details). Finally, figuring in a much longer acquisition phase than originally anticipated, we came up with our final Gantt Chart (see Appendix 8.4).

5 BUDGET

Item	**Budget**	**Cost**	**Value**
Electrical System			
6 kW diesel generator set	$0	$0*	$5200
Fuse Box, Fuses, Wiring and Outlets		$50	$50
Exhaust Tubing and Aluminum Foil		$25	$25
Fuel Line		$6	$6
Diesel Fuel (2.5 gal)		$4	$4
SUBTOTAL ELECTRICAL SYSTEM		**$85**	**$5285**
Heat Exchanger			
Finned Tube Air-to-Liquid Heat Exchanger	$0	$0*	$550
Sheet Metal, 18 gauge (8 ft^2)		$10	$10
Slotted Fiberglass Packing (10 ft.)		$2	$2
Fiberglass Gasket Cement, (1 oz.)		$1	$1
Bolts and Nuts, 10 × 32, (32)		$2	$2
High Temp. Insulation Batting, 4 sections, (3 ½ in. by 18 in.)		$0*	$5
Exhaust Hose Adapter, 2 in OD (2)		$4	$4
Compression Fittings (4 elbows, 2 Tube-Pipe Adapters)		$5	$5
Copper Pipe, 3/8" L, 2 6-in. sections		$0*	$1
Furnace Cement		$0*	$0
Pressure Gage		$0*	$10
Copper Tubing		$1	$1
Exterior Furnace Insulation		$0*	$10
Plate Liquid-to-Liquid Heat Exchanger	$0	--	--
supplemental exhaust fan	$30	--	--
20 feet ducting	$30	--	--
SUBTOTAL HEAT EXCHANGER		**$25**	**$601**
Water System			
Hydronic heating circulators (Budget:2, Project:1)	$80	$0*	$60
Pump Flanges		$12	$12
Water tank (50 gallons)	$0	$0	$400
30 ft piping	$40	$30	$30
Expansion Tank and air purger		$0*	$30
Air Vent		$0*	$12
Flow Regulator		$20	$20
Temperature sensor		$15	$15

Temperature – pressure sensor		$0*	$20
Temperature – pressure relief valve		$0*	$40
Ball valve		$15	$15
Garden hose		$20	$20
Fittings, adaptors, and joints		$16	$16
4 bulkhead fittings	$40	--	--
solenoid valve	$150	--	--
SUBTOTAL WATER SYSTEM		**$128**	**$690**
Miscellaneous Parts			
Type T Thermocouple	$0	$0*	$20
Hardware (screws, bolts, washers, etc.)	$100	--	--
B-20 biodiesel fuel (5-10 gal.)	$10	--	--
PC with Labview, Data Acquisition Card	$0	--	--
30 feet control wire	$5	--	--
SUBTOTAL MISCELLANEOUS PARTS		$0	$20
TOTAL	**$485**	**$238**	**$6596**

* Received as Gifts-In-Kind from Messiah College Dept. of Engineering, Messiah College Building and Property Services, Cleveland Bros. Equipment Supplies, and Blizzard's Heating and Plumbing

-- parts in Original Budget but not in final design

6 CONCLUSIONS

6.1 Successes and Limitations

INREN Design designed, constructed, and tested a prototype residential scale cogeneration system. Our tests and our calculations showed that we substantially met key performance objectives: we projected that BioGen could generate enough heat and electricity to meet the average electric load and average domestic hot water load for a Messiah College residence.

Objective	*Target*	*Result*
Electrical Energy	20 kWh / day	20 kWh / day
Heat from Engine Exhaust	9000 Btu / day	52000 Btu / day
Heat from Engine Coolant	>22000 Btu / day	0 Btu / day
Fuel Consumption	1.2 - 1.5 gal / day	2.2 – 2.5 gal / day
Efficiency Increase	add at least 15%	added 15%
Prototype Cost	< $500	

If Socrates and Voltaire could claim that "All I know is I know nothing," it seems fitting that senior engineering majors might not know everything about the problem they attempt to attack. In our Engineering Design Report, we set several objectives without knowing what was involved in meeting them. Our research and design taught us that harvesting heat from the engine coolant system involved working with tight tolerances on the return temperature of the coolant, purchasing expensive high-temperature control parts, and designing a sensitive control system; therefore, we decided to focus only on gathering heat from the exhaust. We made a general estimate for fuel consumption; the generator we acquired simply used more fuel per hour than we expected. Therefore, we missed these two objectives.

However, the crucial purpose of the BiCoGen project was to harvest and store waste heat to increase the efficiency of the generator. We can harvest more than *five* times our objective for exhaust heat; we easily meet our electrical energy objective. In our two hour test, we demonstrated that we increased the efficiency of the generator by more than 15%. All of these demonstrate that we achieved the first step towards the full development of a renewable residential cogeneration system.

6.2 Lessons Learned

One central pleasure of engineering work is that doing design and manufacture lets you become an expert as you go. As we proceeded with our design and manufacture, we gained crucial experience in the design process, we became familiar with the state-of-the-art in cogeneration, and we became experts in our individual specialties.

Through the course of our senior project, we gained experience that will enable us to design with more efficiency and more focus in the future. We've always heard that engineers need to plan lead time in between ordering parts and receiving them; our experience in searching for parts to fill our specs helped us understand in our gut what had been told to us previously. We gained experience in making the practical adaptations to designs that are required when parts don't function as expected. Though book knowledge of engineering principle is necessary for any design, this practical experience will make it much us much better engineers as we confront our first projects.

We also learned the value of consulting both visionary and pragmatic experts. Some professors provided enthusiastic encouragement, others realistic analysis; some heating and plumbing experts easily dreamed along with us and some were quick to point out all the difficulties. By talking with a wide range of people, we were able to create a clear design, accomplish efficient manufacture, and understand the issues and difficulties that still face our project. Thus, we became convinced of the need to talk to a range of people to know how to create good designs.

We also learned about cogeneration in general and about electrical generators, household plumbing, and air-to-liquid heat exchangers in particular. Our general research helped us learn the present state of cogeneration; our particular design and construction process taught us the necessity of pressure release valves and expansion tanks, the purpose of wire clamps and grounding wires, and the dangers of condensation from exhaust.

7 Future Work

The achievements of our project notwithstanding, we have several important areas for future work and development.

- **Conversion to Biodiesel:** Our generator uses diesel fuel presently; it needs several small rubber seals changed so that it can run on biodiesel fuel without long-term corrosion problems. A future project could make these adaptations.
- **More Efficient Heat Exchange:** better insulation is needed along the exhaust pipe so that no heat is lost as the hot exhaust gases travel to the heat exchanger box. In addition, we noticed that the heat exchanger box became quite hot during testing, and insulation around the heat exchanger box would surely increase water temperature change.
- **Coolant System:** Our present system harvests waste heat only from the coolant system. Our cogeneration research showed that a similar amount of heat leaves the generator through the generator coolant loop. A future project could attempt to harvest this heat.

- **Corrosion and Fouling Study:** Because our tests were short-term, we could not assess the effect of potential corrosion and fouling on the heat exchanger system. Running the system for a long time on diesel fuel could seriously damage the heat exchanger, as the sulfur in diesel exhaust may condense into sulfuric acid on the heat exchanger and eat away at the heat exchanger's pipes. However, biodiesel exhaust has nearly no sulfur emissions; a future project could study the amount of condensation and the likelihood of corrosion when biodiesel exhaust is used. Also, soot from diesel exhaust could clog the fins of the heat exchanger; because biodiesel emissions have less particulate matter than petrodiesel, switching to biodiesel should help with this difficulty as well.
- **Permanent House Connection:** Our project did not permanently connect our hot water tank to the house's water system or our generator to the house's electric system. Though this would require thoughtful design and careful adherence to code requirements, a future project could fully implement BioCoGen by making these connections. For permanent house connection, the team would have to optimize the sizing of the biodiesel fuel tank, create a solution to noise pollution caused by the generator, and design so that the tank actually provides hot water and heat to the house.

8 APPENDICES

8.1 Heat Recovery Test Results

Initial Water Temperature: 48 ºF (from the "Before" Temperature Gage).
Initial Water Pressure: 28 psig.

Time	Water Temperature Before HX	After HX	Electric Power	Exhaust Temp.
3:26pm	48 ºF	--	5.5 kW	520 ºF
3:30pm	50 ºF	--	5.5 kW	520 ºF
3:35pm	50	70	5.5 kW	600 ºF
3:40pm	50	71	5.5 kW	620 ºF
3:45pm	50	71	5.4 kW	605 ºF
3:50pm	50	72	5.4 kW	635 ºF
4:00pm	51	72	5.4 kW	615 ºF
4:05pm	51	72	5.3 kW	627 ºF
4:10pm	51	74	5.3 kW	604 ºF
4:20pm	60	80	5.3 kW	626 ºF
4:25pm	68	85	5.3 kW	630 ºF
4:30pm	72	88	5.3 kW	618 ºF
4:35pm	75	90	5.3 kW	621 ºF
4:40pm	76	92	5.3 kW	624 ºF
4:45pm	77	94	5.3 kW	640 ºF
4:50pm	78	96	5.3 kW	645 ºF
4:55pm	79	96	5.3 kW	637 ºF
5:00pm	80	98	5.3 kW	651 ºF
5:05pm	81	99	5.3 kW	644 ºF
5:10pm	84	100	5.3 kW	638 ºF
5:15pm	87	102	5.3 kW	638 ºF
5:20pm	92	105	5.3 kW	647 ºF
5:25pm	94	94	*	*
5:30pm	96	89	*	*
5:45pm	101	90	*	*

-- initial temperatures out of range; "After" temperature gage could not read them
* generator turned off at 5:20 pm; therefore, no electric draw or exhaust heat after this point.

Final Water Pressure: 31 psig.
Fuel Consumed: 1.2 gal.

8.2 References

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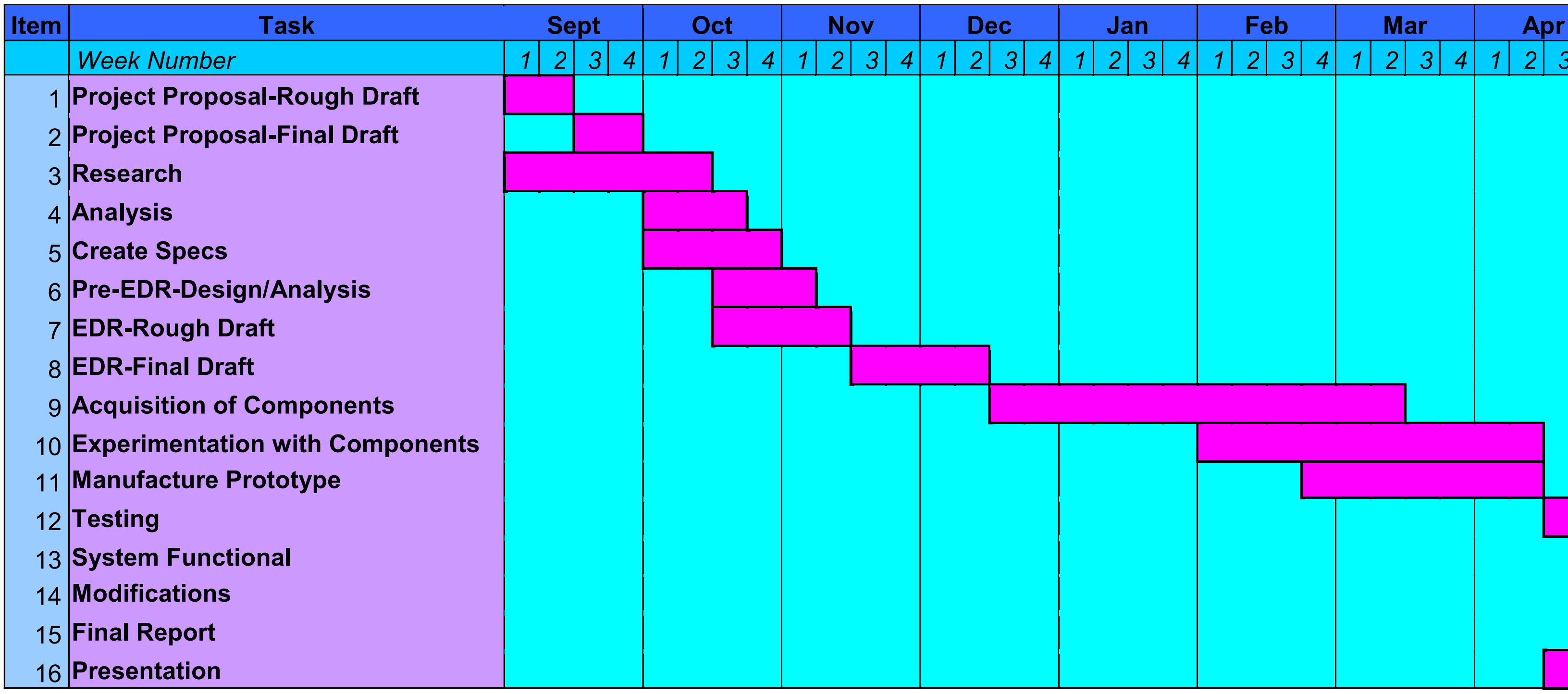
8.4 Gannt Chart

8.4 Gantt Chart

This chart indicates final completion dates.



8.5 Résumés

Please find attached the résumés of the project team participants.

Lukas John Brostek

College Address: Messiah College, Grantham, PA 17027 (717) 796-5006
Permanent Address: 17 Silver St. Fairfield, ME 04937 (207) 453-0008
Email Address: lb1174@messiah.edu

CAREER OBJECTIVE:
To utilize my mechanical engineering skills in various project applications

EDUCATION:
Bachelor of Science- Mechanical Engineering, May 2003
Messiah College, Grantham, PA

RELEVANT SKILLS:
Good listener, serious worker, self-motivated, ethical, passionate about projects, travel experience, excellent writing ability, experience in speech making, cooperative.

RELATED EXPERIENCE:
Food Scale
- Designed and built a measuring scale from gingerbread

Bike-powered table saw
- Appropriate technology for sawing wood
- saw blade attached to bicycle chain
- one team member powered the bike, the other ran the wood through the saw

Mousetrap racecar
- Designed and built small toy racecar whose only motive force was by utilizing the spring in mousetrap
- Received second place for whole physics class

Steam box
- an old pvc pipe as steam chamber sealed on each end
- Connection to a kettle of water on a stove by two rubber heater hoses
- After placing soaked wooden dowels in pipe, water was boiled
- Chamber filled with steam, overtime the wood became soft and bendable

WORK EXPERIENCE:
- Part-time Lifeguard at Waterville Boys and Girls Club
- Field Supervisor for E.D Bessey & Son's Products from the Northern Forests
- Food Server/Busboy/Dishwasher for AMFAC's Yavapai Lodge Cafeteria in the Grand Canyon National Park
- Construction Worker for H.E. Seargent's Construction
- Custodial Assistant through Messiah College's Work Study Program

CROSS-CULTURAL EXPERIENCE:
- One-week Missions trip to Dominican Republic (January 1999)
- Three-month Studies Abroad in Israel (Spring 2001)

Aaron Dahlstrom

School: Box 5263; Messiah College; One College Avenue; Grantham, PA 17027 ▪ 717.796.5075
Permanent: 245 Fox Run Road; King of Prussia, PA 19406 ▪ 610.962.0920 ▪ ad1170@messiah.edu

Objective

To utilize my technical ability, leadership experience and communication skills in service to my clients, coworkers and firm through environmentally sensitive building design.

Education

Messiah College
Bachelor of Science in Engineering expected May 2003 Grantham, PA
Mechanical Engineering Concentration ▪ Spanish Minor ▪ GPA: 3.98
Course Highlights: Heat Transfer, Control Systems, Fluid Mechanics, Appropriate Technology

Work Experience

Messiah College Biodiesel Cogeneration Senior Design Project
Project Team Leader 2002 – 2003 Grantham, PA
- Designed, fabricated, and tested residential cogeneration system
- Managed team of three engineers (documentation: http://webstu.messiah.edu/~ad1170/)

El Rancho Agropecológico en Especies Menores "Ebenezer" (RAEME)
Farm and Rural Development Volunteer Summer 2002 Niquinohomo, Nicaragua
- Participated in sustainable agriculture work, research ▪ facilitated training seminars

Messiah College Department of Engineering
Engineering Research Assistant Summer 2001 Grantham, PA
- Conducted literature survey about landmine problem, solutions
- Started Messiah College Landmine Action Project, a research and education group

Upper Merion Parks and Recreation Department
Swim Program Director Summer 2000, King of Prussia, PA
Swim Program Co-Director, Instructor Summer 1999, Fall/Spring 1994 -1999
- Led 15 instructors and 10 lifeguards, commended for interaction with clients
- Promoted from Instructor to Lifeguard to Co-Director to Director in succeeding years

Qualifications, Honors and Skills

- **James T. Scroggin Excellence in Engineering Award** – given to single graduating senior to recognize service, leadership, and scholarship in Messiah College Engineering
- **Other Honors** – Dean's List ▪ National Merit Scholar ▪ Who's Who Among Students
- **Eagle Scout** – Gold Palm ▪ 3 years Boy Scout summer camp work
- **Engineering Intern cert. expected** – ABET-accredited program ▪ took FE exam
- **Green Building Association of Central Pennsylvania** – member
- **Spanish Fluency** – 8 weeks in Nicaragua ▪ 5 months study abroad in Ecuador
- **Computer Fluency** – extensive MS Office experience ▪ SynerGEE, Interactive Heat Transfer, CyclePad ▪ HTML, JavaScript programming ▪ Matlab ▪ SilverScreen (CAD)
- **Speaking Ability** – Senior Design Presentations, Messiah Board of Trustees presentation

College Activities

Messiah College Landmine Action Project
Founder: planned weekly meetings ▪ managed 3 ENGR / education teams

Messiah College Engineering Department
Diplomat: regularly presented life at Messiah to 40-50 prospective students.

David M. Wagner

Until May '03: 1 College Ave., Box 6292, Grantham, PA 17027 (717) 796-5368
After May '03: 601 Hughes Place, Bolingbrook, IL 60440 (630) 972-1438
Email: dw1168@messiah.edu

OBJECTIVE

- obtain an entry-level mechanical or civil engineering position
- make a worthwhile contribution with my academic training, ability to learn new skills rapidly, Spanish proficiency and team leadership/participation experience.

SUMMARY OF SKILLS

- → Fluency in conversational Spanish
- → Computer/programming/internet proficiency
- → Enjoy designing/building/working with hands
- → Extensive cross-cultural involvement
- → Work well with others
- → Responsible, Good communication

EDUCATION Bachelor of Science in Mechanical Engineering, May 2003
Messiah College, Grantham, PA 17027
Study Abroad: Universidad San Francisco de Quito, Ecuador, Fall 2000
Jerusalem University College, Israel, Spring 2000
Cumulative GPA: 3.6

INTERNATIONAL EXPERIENCE

Bolivia *(1981-97)*	***Israel*** *(Spring 2000)*	***Ecuador*** *(Fall 2000)*
growing up (years 5, 12, 14 & 15 were spent in the United States)	one semester of study volunteered at an orphanage led backpacking trips	one semester of study (all classes in Spanish) led backpacking trips

ACTIVITIES & INVOLVEMENT

- **Rocky Mountain National Park, Colorado, Summer 2002**
  built log bridges, rock steps and drains, and cleared trees on a trail maintenance crew
- **Resident Assistant, Messiah College, 2001-2002**
  served students in a freshmen/sophomore dormitory by incorporating new students into college life, counseling, resolving conflicts, and enforcing school policy
- **Messiah College Landmine Action Project (MCLAP), 2001-2002**
  founding member of MCLAP, a group designed to increase campus awareness about the landmine problem and to facilitate student-lead projects related to landmine action
- **Dokomoi Ergatai, Spring 2001**
  an organization devoted to developing appropriate technologies for use in under-developed nations; currently working on a project in Burkina Faso, West Africa
- **Service Day, April 2001, April 2002**
  participated in a service project to the community, aiding in the design and construction of a straw bale shed (appropriate technology)

REFERENCES

References will be furnished upon request.