AC 2011-514: USING A LIVING-BUILDING LABORATORY (BUILDING AS A LABORATORY) AS A FLUID MECHANICS LABORATORY PROJECT IN THE ENGINEERING TECHNOLOGY CURRICULUM

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Abstract

This paper is written as a follow-up to two papers, one presented in 2007 and the other in 2010, at the ASEE Annual Conference and Exposition. In the paper presented at the 2007 conference the concept of using the actual Engineering & Design building at our institution as a Living-Laboratory was proposed. This building is a relatively new building and construction was completed in the fall of 2005. During the early design stages provisions were made to allow students access to various types of data used in the operation of the building. The desire was that the building would be used by students as a Living Laboratory for such classes as thermodynamics, fluid mechanics, strength of materials, and HVAC. Students would be able to see how the theory that was taught in their classes was put into practical use throughout the building. Courses taught in the department could use the actual data from the building in laboratory assignments. Although provisions for installing all of the desired equipment were part of the final design, as the construction of the building progressed fiscal concerns caused a reduction in the number of Living-Building Laboratory components that were actually funded. Over the past three years members of the School of Computing & Engineering Sciences have been using resources provided through a National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement program (CCLI) grant to obtain and install some of this equipment and to make the data available for student use. The paper presented at the 2010 conference describes the use of the Living-Building Laboratory data in a thermodynamics course to analyze the Variable Air Volume (VAV) mixing box in the thermodynamics laboratory room using the actual data from the building. This paper describes the use of the Living-Building Laboratory data in a Fluid Mechanics course. For the laboratory exercise discussed in this paper one of the potable water pipes in the building was instrumented and the data was made accessible to the students through the internet. An assessment of the effect of using the actual building's data in place of an educational laboratory apparatus on the students' ability to understand the course material is also discussed.

Introduction

In the fall of 2005 the School of Computing & Engineering Sciences at our institution moved into a newly constructed building. During the early design stages provisions were made to allow students access to various types of data used in the operation of the building. The desire was to have the building used by students as a Living Laboratory. Students would be able to see how the theory that was taught in their classes was put into practical use throughout the building. Courses taught in the department could use the actual data from the building in laboratory assignments. Core mechanical engineering courses such as thermodynamics, fluid mechanics and strength of materials would be able to use this data for student lab work. Electrical engineering students would be able to observe the digital control and feedback processes as well as the power equipment used to drive various building functions. Both disciplines would be able to collaborate in collecting data from the building and making predictions as to how they might be able to improve the efficiency of its operation. Modifications were made to the original design in order to provide for this new use of the building. Modifications made to the building included making the HVAC/control room extra wide to provide access for students to observe equipment and take readings as well as leaving structural elements exposed to provide locations to mount strain gages to record the loads on the building's structure. Additional instrumentation was proposed that included valve position sensors, fan and pump speed sensors, humidity sensors, additional temperature readings, and so forth. Although the provisions for installing all of the desired equipment were part of the final design, as the construction of the building progressed fiscal concerns caused a reduction in the number of Living-Building Laboratory components that were actually funded ultimately resulting in little of the original concept existing in the completed building. A grant through the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement program (CCLI) was obtained in order to restore some of the benefits of the Living-Building Laboratory concept and this paper describes the use of some of this newly available building data in a fluid mechanics laboratory exercise.

Introduction to the Living-Building Laboratory Concept

The idea of using the academic building as a laboratory is an easy concept to grasp. Students in the sciences (and really all disciplines) should be taught to examine the world around them; asking questions and seeking answers. Students majoring in technical disciplines should have a more personal connection with the technical details of building operations. Typical of many, our department saw ourselves purchasing educational laboratory demonstrators for such engineering processes as pipe flow, pump performance, heat exchanger operation, etc. All the while these same processes were taking place in real-time within the very building the students were in. Creating a method to access these actual processes that would allow the students to study them would take them from the realm of scaled-down, simplified educational models to the actual equipment they would be working with in industry. Exposing students to actual industrial equipment and processes they would see in industry is a worthy goal but ultimately the purpose of using the actual building should be to enhance the learning experience. To see where the Living-Building Laboratory concept fits into a student's educational experience it can be helpful to reference Bloom's Taxonomy.

One of the challenges in education today is trying to bridge the gap between students who often view education as an effort to try and push as many important facts into their brains as possible versus the understanding that we as educators have that students need to be able to synthesize that knowledge and be able to use it to make decisions (what we often call Design). Certainly, many courses that students take early in their program emphasize the learning of information and tools that are necessary foundations to making good engineering decisions. As they progress in their program of study they should be exposed to increasing levels of creative design. All of this is merely a discussion of an idea presented in 1956 by Benjamin Bloom in his Taxonomy.[1] Bloom identified three types of learning, one of which is the cognitive domain. Within his cognitive domain he identified six levels that most educators think of when referring to Bloom's Taxonomy. As a quick review, the original six levels of Bloom's cognitive domain are presented in Figure 1.0 below.

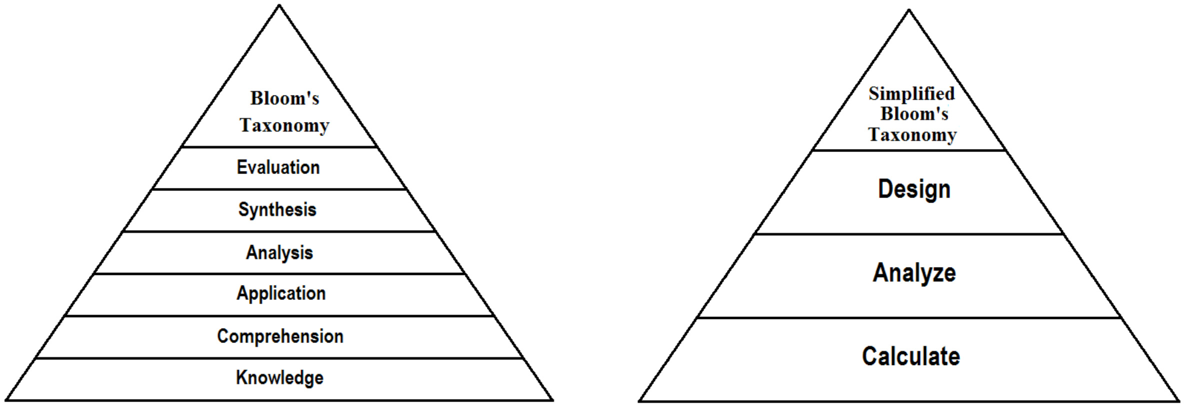

Figure 1.0, Bloom's Original Taxonomy and a Simplified Version of Bloom's Taxonomy

Educators are very familiar with the concept presented in Bloom's Taxonomy. The idea that students can learn at different levels is a driving force in how educators develop and construct their lessons. We know that students can learn at a lower level where all they are able to do is recognize the material; at a higher level they can repeat back what they have learned but at the highest levels they are able to synthesize their knowledge to analyze and draw conclusions. We all aspire to help students to reach the highest level which of course requires the greatest understanding of the topics and ideas.

As a simplification in teaching engineering technology the six levels can be collapsed into a three stage process that somewhat mimics the progression students go through in higher education: First we teach them how to Calculate; Second we teach them how to use their calculations to Analyze; and Third we teach them how to Design. Having only three levels is easier to remember and use in creating course curriculum.

Engineering Technology program classes in the freshman and sophomore years often emphasize the Calculate aspect as the students are still building their foundation of knowledge and tools. Senior level courses should be emphasizing the aspect of Design and decision making to prepare them for this final level before they graduate. In the middle is an often overlooked aspect that bridges the gap between Calculate and Design and that is Analysis. If students can become effective in analyzing an existing design they will improve their own design skills. Often times when students are given their first intensive Design problem they come up with unworkable solutions. Often the blame is noted as a failure to adequately teach design but in cases where the students did, in fact, design something and they were very creative in their approach it seems that the problem needed to be better defined. Where they likely had trouble was in attempting to bridge the gap between Calculate and Design. It is this skill that we set out to emphasize by using the building as a laboratory. This gives students the opportunity to analyze an existing design and then use their design skills to develop recommendations for improvements to the design. Other research confirms the idea that having students analyze the building components provides similar benefits to engaging in research.

Students that have not faced open-ended design problems will find that their education is insufficient when they enter the workforce. There has been a great response to this need including accreditation requirements requiring students to work in a collaborative, team-oriented, capstone design project. Another avenue to expose students to this type of work is undergraduate research. But using an existing building as a laboratory lends itself more to analysis than it does to research. In other words, the students will be seeking data to answer questions posed to them by their instructor. The students will be studying questions that, in many cases, already have answers. This might lead to the thought that it will be of lesser value to the student. Some studies, however, indicate that when students are working on a large, complex, hands-on project, to them it is research and they derive many of the same benefits from such a project. ". . . the only difference between research and inquiry based learning is the prior state of knowledge of the broader community. In research it is unknown by all; in inquiry it is only unknown by the learner" (Fortenberry[5], 1998, p.54). To the student, the task of being assigned to analyze the complex workings of a building has much in common with research and the student will derive many of the same learning objectives from this approach.

Along these lines the same benefits provided to students in research should apply to the use of the Living-Building Laboratory. Some of these benefits as outlined by Malachowski[8] (1997), Karukstis[7] (2006) along with Goodwin and Hoagland[6] (1999) are: First, it can lead students to graduate school or a particular industry as students experience a particular type of work. Second, much of the monotony of school is absent in a project such as this. Third, students can feel a sense of accomplishment and confidence in their abilities. They will become more curious and inquisitive. Fourth, students might have to apply their knowledge in a different manner in order to understand or solve a problem. Fifth, all projects require reporting on the work completed. That is accomplished through verbal communication with a faculty member or in a formal paper or presentation. This will strengthen and enhance student communication skills and better prepare them to function in their future careers. Finally, even though this is not research it will require critical thinking and problem solving skills by the students. It has also been shown that student projects carried out while being mentored by a faculty member results in increased student retention and achievement. This is important not only to our institution but to the local community as well since we are currently a net importer of employees to fill positions in the high-technology career fields (Regalado[9], Dec/Jan 2006, p.37).

It is also a concern that in the rush to satisfy this need for open-ended design work by students combined with the changing demographics of entering freshmen, engineering and technology students often end up skipping over the important skill of analysis and thus miss out on this important bridge between theory and design. In generations past engineering and technology students often came from work on farms and in industry that gave them a background in the operations of mechanical devices. They had some familiarity with the function and operation of technical equipment designed to perform a specific process. As the United States has become a more service-oriented economy more and more students enter technical majors without such a background (Egan[4], Feb 2007, p.36).

Problem solving has become a highly advocated skill that is being taught in courses ranging from English to mathematics and science and technology. This is occurring throughout the educational curriculum down into the elementary grades. The potential shortsightedness of this approach comes from the desire to teach students how to solve problems without first helping them obtain the tools necessary to complete the task. Teaching the students theory provides one important tool needed for effective design. The other important tool is analysis. Students need to spend some time analyzing the solutions of others in order to gain the necessary problem-solving skills they will need on the job.

We also negate some of a student's natural curiosity when we ignore the technical aspects of the world right around us. We want our students to be curious about their world. We want them to examine today's technology to see how others have achieved solutions to society's problems. It must be confusing to a student to come to a class encouraging them to explore their environment and then completely ignore the technology of the building in which that class is being held. A fluid mechanics student is rigorously tested on his ability to understand the flow of water through pipes and fixtures but he is never allowed to ponder that same process as it is taking place in real-time above the ceiling tiles right over his head. It's as if everyone is pretending that the process is not even there. Using the building as a laboratory illustrates to a student that technology can be anywhere and they should continue to be curious and look for it everywhere. It opens up their world of possibilities.

Gaining Access to the Data

As originally envisioned a large variety of data would be obtained from all over the building. It would be used in various courses in the Engineering & Technology curriculum. Students in thermodynamics would be able to study the mixing of hot and cold air streams, students in fluid mechanics courses could study the operation of pumps and the flow of water through pipes, strength of materials students could study the loads on the building's structure, and electrical engineering students could study the process of a feedback circuit to maintain the operating conditions of the building. The NSF grant allowed a revival of the Living-Building Laboratory concept but the cost of the equipment meant that the grant would not be able to fund all of the originally envisioned equipment but there would be a sufficient number to provide an enhanced laboratory experience for multiple courses. Three classes that will be using this building data are our thermodynamics class, our HVAC class and our fluid mechanics course. This paper deals with the equipment installed in a potable water line and used in the fluid mechanics course. The water line selected for the installation of the additional equipment is one that runs in the basement of our building. The basement of the Computer and Engineering Building is divided into three major sections: a metallics lab, a non-metallics lab, and a material testing lab. Because of the nature of the equipment installed in these basement areas there are no ceiling tiles and so all of the plumbing is visible. That made this an ideal region to add instrumentation to a length of piping for the students to use as a lab exercise. The question then came about of how to best present and make this data available to the students. Although data from the flow of water in the pipe wasn't part of the heating, ventilation and cooling system, based on our previous experience in adding instrumentation to the HVAC system we were able to utilize the same system to display the date for this water pipe. A picture of a portion of the instrumented pipe is shown below as Figure 2.0.

Figure 2.0, Portion of Instrumented Pipe.

Typical of modern construction, the building's operations are computer controlled and networked to a central physical plant facility. Process control software used for the new building is an ASHRAE/ANSI standard product known as BACnet®[2,3]. This makes much of the data desired for the Living-Building Laboratory concept already available. The latest version of this software was installed to run the building and it has a very user-friendly Webtalk graphic interface. A user ID and password are required to access the software and this involved some careful study in order to make certain that the security of the campus infrastructure would remain intact. Student and instructor accounts were set up that would not allow any control authority over the system. This was probably one of the biggest pieces of the puzzle to work through as it required the coordination of various departments on campus all with valid concerns about network security. Because of the ease of accessing information over this system, especially due to its graphical nature, it was decided to use this BACnet® system to also display the data from the water pipe. The home screen for this system shows a diagram of the building and allows you to navigate to HVAC data anywhere in the building as well as to the pipe flow data that is accessed by the icon shown on the left of the building outline. A screen shot of this is shown in Figure 3.0 below. Note the "CEB_LL Water Flow" tab on the left that links to the display of the pipe flow data.

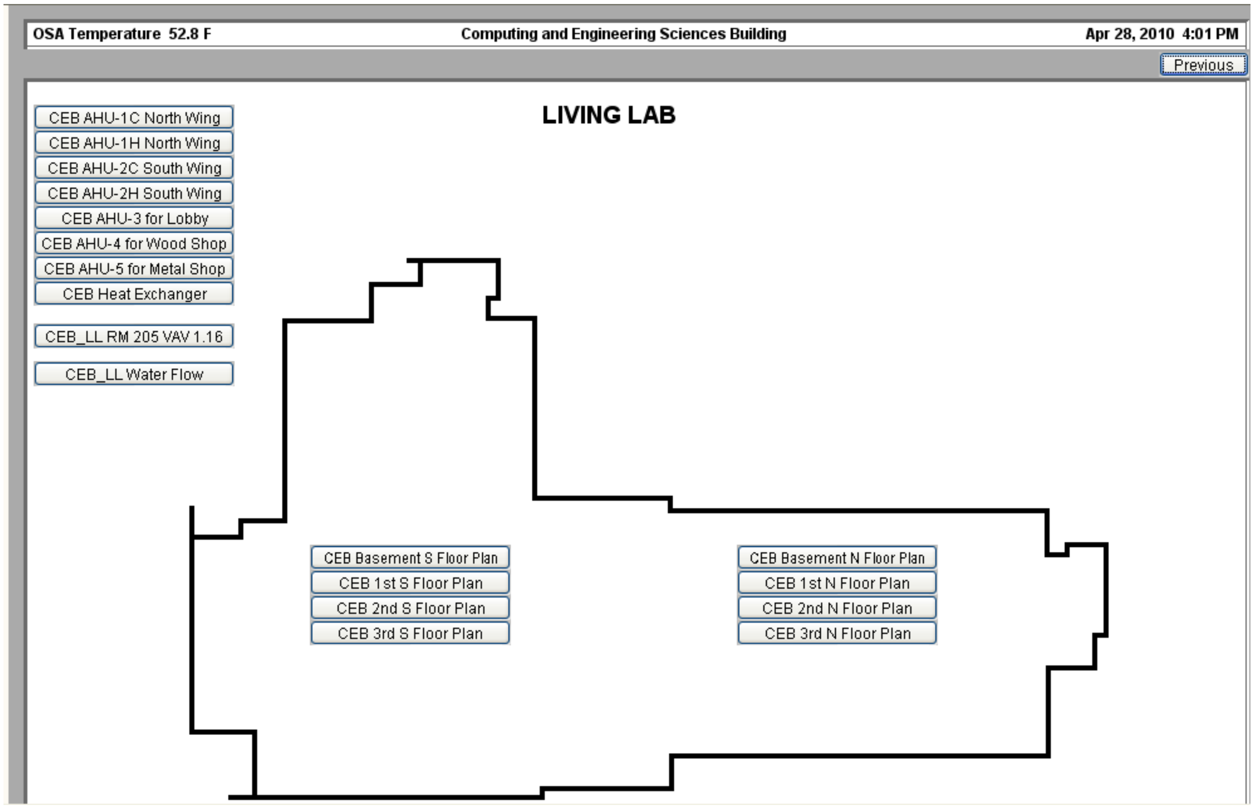

Figure 3.0, Webtalk display of building layout.

The Student Laboratory Exercise

The amount of instrumentation that could be installed was limited by the cost and so the decision was made to make the lab from a series flow and not a more complicated parallel flow portion of the piping system. This length of piping is completely visible to the students in the ceiling of our non-metallics lab, it passes through a wall and then terminates in a faucet in the materials testing laboratory. There are various branching tees along the instrumented pipe but the flow in these branches is turned off during the lab exercise so that there is only a single series flow. In addition to these tees, the length of instrumented pipe also includes some diameter changes, some elbows and elevation changes. The students were given access to the data for the pipe through the internet connection on a computer that resides in the vicinity of the actual pipe. They were able to see the numerical data presented on a graphical representation of the instruments on the pipe. The computer screen that displays the data is shown in Figure 4.0.

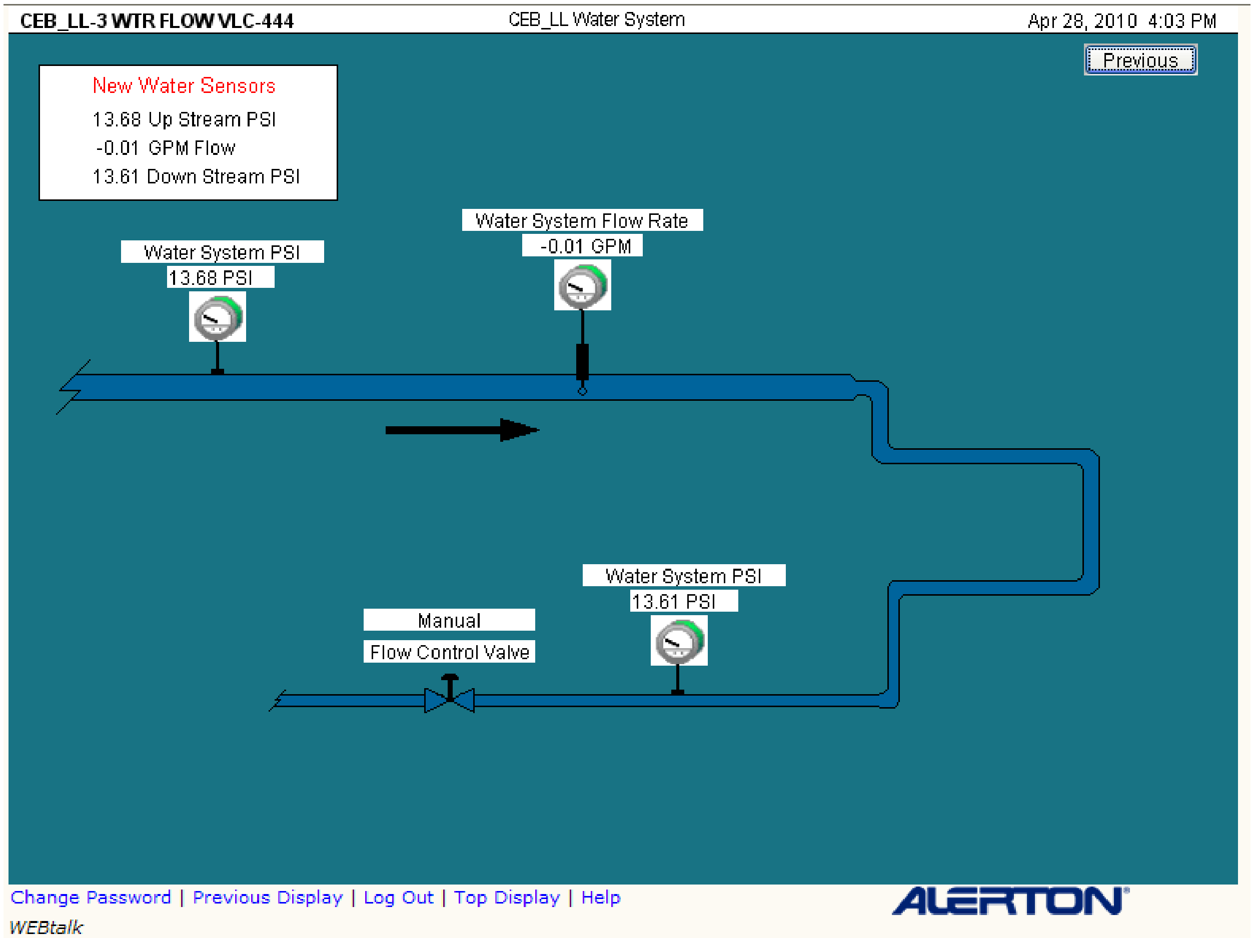

Figure 4.0, Graphical display of the instrumented pipe.

The exercise was given to the students in the latter half of a one quarter fluid mechanics course. The laboratory actually took place in two different steps. First the students were taken down to the room and shown the piping system where the location of the instruments as well as the various fixtures and fittings were pointed out. Ideally the students would be responsible for measuring all of the lengths of pipe, the drops in elevation and the diameters of the pipe. Unfortunately because these pipes are overhead this would require work on a ladder and so for safety reasons this information was given to the students in their lab handout. Students were then required to take that information and calculate a theoretical value for the pressure drop across the length of pipe using what they have learned in their class. The students then brought this value with them for the second part of the lab experience where they actually turned on the water flow and utilized the faucet to set a given flow rate and then compared the actual pressure drop with the theoretical value they had previously calculated. They then calculated the percent difference between their theoretical value and the actual value and then spent some time writing down what might account for the difference between these two values.

The students used the Darcy-Weisbach equation to calculate the losses in the pipe.

$$h_L = f \frac{Lv^2}{D2g} \qquad \text{Eqn. 1}$$

They used a modification of this to account for the minor losses from the fixtures and diameter changes:

$$h_M = K\left(\frac{v^2}{2g}\right) \qquad \text{Eqn. 2}$$

The values for the loss coefficient, K, came from their textbook and consequently they were very general values not specific to the exact equipment installed in the pipe. When the students were asked to discuss their results in their lab report they should have recognized this as one potential source of error. Finally, the students used these values in the general pipe flow equation to calculate the theoretical drop in pressure along the length of pipe. It should be noted that at the time in the course that the students performed this laboratory exercise they had already used some educational lab equipment to recreate a portion of the Moody diagram and were thus familiar with theoretical and empirical values for friction losses in pipes.

Effectiveness of the Living-Building Laboratory

The overall score for the students in the fluid mechanics course for the laboratory exercise that used the Living-Building Laboratory was 90%. The overall score of all 10 laboratory exercises for the entire fluid mechanics course was 82%. This leads me to believe that the students were better able to understand the fluid concept because they saw its use in an actual device and could easily relate to the device's purpose. Much of the laboratory equipment used in the fluid mechanics course can be somewhat convoluted in its approach to present the fluid problem. For example, we have a pipe flow lab setup that circulates water from a tank around a circuit and then pours the water right back into the original tank. Students often lack the necessary motivation to perform thorough calculations on this equipment that seems to have no useful function. This can feel artificial and confusing to the students. However, the flow of water through a pipe to a faucet in the actual building is easy to understand as is the purpose of this pipe flow system.

At the conclusion of the laboratory exercise the students were asked a series of questions in order to help assess whether the students felt that the use of the actual building improved their ability to understand the pipe flow concepts. Two simple, modified Likert scale questions were asked as well as one that required the students to think and provide a paragraph on their impression of the experience. The Likert scale questions were intentionally very simple as we have found that the more involved the assessment tool, the more likely the students rush through it and don't pay attention. These questions are given below in Table 1.0 along with the percentage of student responses.

Table 1.0, Student responses on their laboratory experience.

	Definitely Yes	Somewhat	Not Really	Definitely No
Did the pipe flow calculations make more sense to you because you used an actual piece of building equipment rather than using a simplified lab experiment?	55%	35%	7%	3%
In addition to the length of building pipe we used for the lab, the entire building heating and ventilation system is controlled by a network and accessed through the same website that we used to do this laboratory. Would you be interested in using more of the building data in future classes/labs?	87%	13%		

The selection of the four point Likert scale forced the students to make either a positive or negative assessment of their experience. It can be seen from the results that the majority of the students preferred to use the building to study pipe flow rather than the educational equipment in the fluids lab. The second question clearly indicates that the students would like to do more of these types of Living-Building Lab exercises in future classes.

In addition to these two questions, the students were also asked to write a short paragraph to answer the following question:

"Finally, what do you think was the most worthwhile aspect of using the building as a laboratory and how could the experience be improved?"

Here are some of the good and bad responses that students included from this section of their report write-up:

> "This is more complex than theoretical work."
>
> ". . . seems like actual field experience."
>
> "Just being able to use a real piping system."
>
> "It was very interesting to apply what we know to an actual system."
>
> "I think just seeing how the pipe systems are built in actual buildings gives an idea of effective use of designs."

> "When we use the Living Lab it seems that theoretical answers never match the actual values. I would like to see those answers match better."
>
> "The most worthwhile aspect was simply applying things we learned in class to real life problems."
>
> ". . . made it easier to understand."
>
> "Observing how the flow rates changed dramatically and thinking about how everything in the building would be affecting it."
>
> "Easier to understand the application of our knowledge."
>
> "Realistically better than doing the Questions in the textbook."
>
> "The system could be more extensive and elaborate."
>
> "The border between academics and real applications are extremely hard to cross. I often wonder how we will use a lot of what we learn in class."

The answers were overall extremely positive. Most students wished they could have done more with the data. It was obvious to see that there were students that were initially frustrated that their theoretical calculations didn't exactly match what they saw in the real building pipe flow. This created a really beneficial learning experience to discuss how the theory was derived and how simplifications were often required to develop a model of a real system. Helping students work through this frustration was one of the most rewarding educational experiences of the class. It was also interesting to note that since the students had used some other lab equipment prior to this lab to study friction loss in pipes they should not have been quite so surprised when they didn't get an exact match between their theoretical calculations and the actual pipe. It almost seemed as if they had more faith in the actual building's pipes as a representation of pipe flow than the educational lab equipment they used previously and therefore expected that the numbers from the building's pipes should be closer to the theoretical than they saw when using the educational equipment. Another indication of the success of this lab experience was that quite a few students wished that they would have had more time to spend with the lab equipment to better understand the values that they obtained.

Educational Outreach

The first data we accessed from the Living Building Laboratory was from the HVAC system and was used in our thermodynamic course. Students really enjoyed having access to the building data but were disappointed that they would not be allowed to change any parameters in the system. One of the benefits of the pipe flow system is that it can be a very hands-on experience where the students have direct control over the flow rate by manipulating the faucet. We have used the HVAC equipment during visits by middle and high school students to the university with great success. We anticipate that future visits by these types of students will be even more fun as we will be able to provide this more hands-on experience where the students control everything about the system.

Areas for Future Study

This paper examined the use of the Living-Building Laboratory data as it was applied in a single laboratory exercise for a fluid mechanics course. It was also envisioned from the beginning that the Living-Building Laboratory would serve as a link to the community. Information on the operation of the building would be available through the internet. Citizens who helped fund the building would have some access to observe its operation. With information available over the internet it would be readily available for use in elementary, middle and high school courses. Engineering & Design department faculty and students could have that information available and use it in outreach programs to community schools. Although department faculty are able to log into the website and display this data to students during visits to other educational institutions, an independent website granting any user access to this data is currently available only for the HVAC data.

Conclusions

Our institution is not the first to access building data in order to use the building as a laboratory. Initial assessment data from our institution seems to indicate that the students relate to the material taught in their fluid mechanics class much better by using the building as a laboratory. Comments were favorable and the teaching experience was more enjoyable as well. Assessments from other institutions that have done something similar seem to all be positive. In spite of these favorable assessments it still remains a little-used approach to technical education. It is our goal to include more of the building data in future laboratory exercises in the hopes that it will further enhance the student learning experience in multiple classes over multiple content areas. As mentioned earlier we are also using building data in our thermodynamic course and have future plans to use it in our HVAC course as well.

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Appendix:
Sample Living-Building Laboratory
Student handout

TECH 382
LABORATORY #9
Living Lab – Pipe Flow

June 1st & 2nd, 2010

Report submitted by:

____

TECH 382 Fluid Mechanics Lab #9, Living Lab – Pipe Flow

Introduction: Last week in class you were given a Take-Home Exam that involved performing some theoretical calculations on a length of pipe that carries water inside the Computer and Engineering Building. Now that you have used the theory to predict what the pressure drop across that length of pipe "should" be, we will turn on the water and use the newly-fitted instrumentation to see how close our predicted results come to reality.

Procedure: Have the instructor bring up the computer connection to the instruments in the pipe. Coordinate between members of your group to set a flowrate of 1.00 gpm and then 1.50 pgm. Use a percent difference calculation to compare your calculated result from the exam with the values observed in the actual pipe. Complete your work on this lab handout, answer the question sheet that will be given to you in the lab, put the two together and turn them in.

For 1.00 gpm:

From actual pipe flow: P1 = _________, P2 =_____________;

$\Delta P = P1 - P2 =$ ____________

ΔP from exam calculations: ____________

% Difference: ____________________

For 1.50 gpm:

From actual pipe flow: P1 = _________, P2 =_____________;

$\Delta P = P1 - P2 =$ ____________

ΔP from exam calculations: ____________

% Difference: ____________________

Question: What could be the reasons why there is a difference in your values?

Finally, I hope you can see that this laboratory is a little different from what we usually do. Most of the time we use a small piece of educational laboratory equipment to demonstrate a fluid property. We wanted to make the laboratory experience more realistic for you and so we made it possible for you to see the actual data being used in the building itself and then use the building as your laboratory. Consequently, we want you to answer a couple of questions relating to the use of this building as a laboratory:

	Definitely Yes	Somewhat	Not Really	Definitely No
Did the pipe flow calculations make more sense to you because you used an actual piece of building equipment rather than using a simplified lab experiment?				
In addition to the length of building pipe we used for the lab, the entire building heating and ventilation system is controlled by a network and accessed through the same website that we used to do this laboratory. Would you be interested in using more of the building data in future classes/future labs?				

Finally, what do you think was the most worthwhile aspect of using the building as a laboratory and how could the experience be improved?

Appendix B
Take – Home Exam used for theoretical calculations

TECH 382
Fluid Mechanics
Exam #3
Spring 2010

NAME: ______________________

Open Book, Open Notes, TAKE HOME Exam, Due Monday at the Start of Class
Show all Work
Work your problems on Engineering Green Grid paper.

This test requires you to complete a theoretical calculation on a portion of the actual piping system in the Computer and Engineering Building. The portion of piping you will be analyzing is a length of copper pipe that brings potable water to the vent hood in the Material Testing lab. Your instructor will take you down to the basement of the CEB and show you this length of piping. The length of piping has 2 points where pressure is measured. For the exam you are to calculate the difference in pressure (ΔP) between these two points for 2 different flow rates: 1.00 gpm & 1.50 gpm. The water temperature is $70^{o}F$. Be sure to include all pipe friction losses and all minor losses. In order to complete the calculation you will need the following information:

TAG Number	Component	Pipe Length (inches)	Elevation Change (in.)	Outer Diameter (inches)
T1	Pressure Sensor	181.0" to T3		1.625
T2	Flow Meter			
T3	"T"	55.0" to T5	8.0	1.125
T4	Elbow			
T5	Ball Valve	115.0" to T6		1.125
T6	"T"			0.625
T7	Elbow	11.0" to T8	2.50	
T8 (tag missing)	Pressure Sensor			

Note that the pipes are all Schedule L copper tube. A table of Schedule L copper tubing is attached. Ignore any losses that might come from the Flow Meter. Also, for the Ball Valve use a value of Le/D = 70. All elbows are standard radius.