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**NCER Assistance Agreement Project Report Executive Summary**

**Date of Project Report: 3/15/16**

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**Project Title:** TrashWalls: Ultra Low-Cost Energy Retrofits (ULCER)

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**Project Period:** October 1, 2015 through August 30 2016, Pullman, WA

**Description and Objective of Research:**

**Description:**

There is no current, effective approach to retrofit rental units in low-quality housing to conserve energy and save money for the poor. While green building research has indicated very effective paths to create new low energy and zero energy structures, these paths are meaningful only for those with capital. Little research has gone into finding ways the poor can “go green.” We propose a pathway specifically focused on those with little money, who live in some of the least energy efficient buildings in the country, to take charge of their own living spaces and implement their own energy conservation methods, that will not only save energy, and reduce pollution but will save them needed money from utility bills. The proposed research entails designing temporary interior building envelopes by interdisciplinary student teams draw from Architecture, Civil Engineering and Mechanical Engineering. These interior envelopes, built from no-cost, locally-harvested, materials recycled from the waste stream will dramatically reduce heat losses from rented apartments, improve the comfort of those spaces during cold weather, and save the renter significant money on their utility bills. By significantly reducing the space heating load, these TrashWalls, will also reduce utility load and thus prevent air pollution from burning fossil fuels. Since the TrashWalls will be built primarily for locally-harvested waste materials, they will also reduce solid waste going into incinerators and landfills.

**Objective:**

This project focuses on developing and testing a new approach to retrofitting energy conservation measures in rented residential buildings. Due to perverse incentives where landlords pay for capital improvements and renters pay utility bills, many rental properties remain woefully energy inefficient. The burden of high utility bills then falls on those least able to pay them. The purpose of this project is to develop and test a new approach, “TrashWall” in which a temporary interior insulating envelope is built within the existing exterior wall of a rented residential building. In order to keep initial costs as low as possible, this interior wall is fabricated primarily of materials harvested from the local solid waste stream such as scrap cloth, paper, corrugated cardboard, and polystyrene. By keeping the cost of each TrashWall below ten cents per square foot, the payback period from energy savings in utility bills due to each TrashWall should be 200 days or less, or less than one heating season.

**Summary of Results (Outputs/Outcomes):**

Our interdisciplinary team has been successful in completing two design and build iterations of TrashWall concepts. In the first iteration, the team designed and built four TrashWall prototypes, including one 4 foot wide x 8 foot high TrashWall prototype assembled from four shopping bag quilts. These quilts were manufactured by rescuing polyethylene shopping bags from the waste stream, cutting the bags into square sheets, and heat welding them into square pockets, which were stuffed with shredded paper. Individual pockets were then heat welded together into large quilts which were layered together to form a thickness of approximately eight inches. Material costs for this shopping bag quilt was thus zero ($0.0 per ft2). Heat transfer measurements indicated an R-Value of RSI =1.3 m2 C/W (RUS = 7.3 hr ft2 F/Btu) for a four-layer, eight-inch thick quilt.

Interviews with the WSU Fire Marshal indicated serious fire safety concerns for a TrashWall manufactured from polyethylene sheet and shredded paper without any fire break. In addition, difficulties with manufacturing prototypes caused discussion about how fabrication might be streamlined. As a result the student designers revisited their prototype design goals, and refocused their efforts to redesign TrashWall prototypes with an emphasis first on fire safety and second on design for manufacture and assembly (DFMA). This resulted in a new iteration of TrashWall system design based into three complementary subsystems or functional components: a structural component or skeleton, an insulating component or filler, and an aesthetic facing component or skin. Two new structural/skeleton concepts were developed, several insulation/filler options were investigated, and a large number of aesthetic/skin possibilities were designed.

To address the requirement for fire safety, a number of aesthetic skins were designed specifically with this constraint as one of the primary considerations. One skin option, taking the form of hexagonal tiles, fabricated out of paper and concrete in a paper mache like process, called “papercrete,” appears particularly promising. The resulting tiles are very fire resistant, with tiles not igniting after 15 minutes exposure to the flame of a propane torch held to the tile.

To assess insulation/filler options, steady-state heat flow measurements were made on individual modules (individual units that are assembled together to build a structural skeleton) holding the three potential insulating fillers: shredded paper, commercial cellulose insulation, commercial fiberglass insulation., R-values for four inch thick modules were found to be 1.7 m2K/W (R10 US) for shredded paper, 2.2 m2K/W (R12 US) for commercial cellulose and 2.8 m2K/W (R16 US) for commercial fiberglass fillings.

A complete 4 foot wide x 8 foot high TrashWall prototype was assembled from many individual shredded-paper-filled modules, with a material cost of $0.50/ft2. Hot Box measurements on this prototype indicated a disappointingly low R-Value of RSI =0.9 m2 C/W (RUS = 5.1 hr ft2 F/Btu). This R-value, just over half of the R-value for an individual shredded-paper-filled module indicated a significant heat leak in the prototype. Rebuilding the prototype wall with attention focused on reducing air infiltration routes through the wall while maintaining uniformity in filling, and retesting the heat transfer rate through the rebuilt prototype wall indicated a new increased R-value of RSI =1.2 m2 C/W (RUS = 7.0 hr ft2 F/Btu). This R-value for the rebuilt large-section prototype while higher than the previous iteration, is still 20% lower than the R-value found for an individual module.

**Conclusions:**

Based on the results gathered to date, the TrashWall team has demonstrated that its internal envelope insulating walls fabricated from materials recycled from the waste stream could be built with measured R values of RSI =1.2 m2 C/W (RUS = 7 hr ft2 F/Btu) for material costs below $0.10 per ft2.

Creative use of materials by the student design team has led to very interesting and attractive wall treatments. With a focus on design for manufacture and assembly (DFMA) a second iteration of prototypes was designed based on a component subsystem approach. Each TrashWall system was broken down into a structural skeleton, insulating filler and aesthetic skin. This new approach has led to TrashWalls that are much more flexible and can support a wider variety of insulating options and aesthetic finishes. In addition, using a component approach with a focus on design for manufacture and assembly (DFMA) has led to prototypes that can be quickly and easily assembled from modular components. Those modular components are in turn simpler and faster to manufacture.

Fire safety concerns emerged as a significant issue midway through the project. Fire safe options for all three components of the TrashWall system have been identified. However, greater fire safety appears to come at a trade-off of greater cost. First, both the structural skeleton and the aesthetic skin can be made significantly more fire resistance by the incorporation of “papercrete,” a combination of both cellulose fibers and concrete. Second, the fire safety of insulating filler can be increased through the use of either commercially available cellulose insulation or fiberglass insulation. The incorporation of any or any combination of these three options will necessarily trade greater installed cost for greater fire safety.

Based on work that has been completed, and TrashWall prototypes built and tested, it appears safe to say that it is possible to fabricate an interior insulating wall with a measured R-value of at least 1.2 m2K/W or R7 US, built almost entirely from recycled materials harvested from the waste stream at an installed cost of less than $0.10/ft2 of wall. Such an installation would consist of the four-inch thick cardboard structure filled with shredded paper insulation filler and faced with 1/8” thick papercrete tiles for fire resistance tested in Phase I of this project. Installed in a rental unit with walls with effective R-value of R = 1.5 m2K/W or R9 US and situated in a climate like Pullman, WA, typical for the Intermountain West, such a TrashWall would save the renter 9 Whr per day per ft2 of wall leading to a utility bill savings of 0.12 cents per day per ft2 of wall. These savings would lead to a payback period for the installed TrashWall of 80 days or just under 3 months.

For comparison, it would be possible to increase the fire resistance of the TrashWall by shifting from shredded paper to fiberglass insulation which would significantly increase the cost of the TrashWall from $0.10/ft2 to 0.30 $/ft2. This higher cost would lead to the much longer payback period of 175 days. The payback period would then stretch out to almost 6 months or about one heating season.

This project has contributed to the goal of pollution prevention in two major and complementary ways. First, the project addressed the prevention of solid pollution by reducing the amount of solid waste being disposed of. We reduce the disposal of solid waste, by reusing locally-harvested, waste materials as building materials for our energy saving TrashWalls. This supports the EPA’s mission under SWDA: Solid Waste Disposal Act--Section 8001: by contributing to resource recovery and conservation, production of usable forms of recovered resources; and waste reduction. Second, the project addressed the prevention of air pollution, by reducing combustion gases, including greenhouse gases that result from the burning of fossil fuels. We worked to reduce the production of combustion gases, by designing insulating TrashWalls that will reduce the energy needed to space condition the residential buildings they are installed in. This supports the EPA’s mission under CAA: Clean Air Act--Section 103, by preventing air pollution, particularly from utility electrical production and from the burning of fuels (such as natural gas) for space heating. Finally, our work has focused on developing an approach that lends itself to “Do-It-Yourself” (DIY) solutions that empower and encourage community members to save energy and prevent pollution, by designing and building TrashWalls in their own dwellings, wherever they live.

In summary, the prototype TrashWalls under development in this project utilize recycled materials that would have entered landfills, and have the capability to reduce greenhouse gases associated with the combustion of fossil fuels: either through reduced utility-generated electrical power use or reduced natural gas or heating oil use. Beyond these cost and energy savings, TrashWalls could enhance the lives of low-income renters by enhancing their living spaces. Those renters employing TrashWall solutions would experience much reduced drafts and a higher mean radiant temperature leading to greater comfort in their residence. The renter would also have claimed greater control over their own lives and the ability to enhance their own living space.

**Proposed Phase II Objectives and Strategies:**

The goal of the proposed work is to design, build and test a TrashWall prototype that would cost less than $0.30/ft2, and has an R-value of R10 US with a payback from energy savings within one heating season (or less than 180 days) for installation in a home with R-9 walls (wall R values representative of many older residents in the US).

 Based on the results found in Phase I of this project, the most promising route to meet these goals is through the development of a modular TrashWall system that builds on the most successful aspects of the prototypes previously developed. That system would be based on the three component subsystem model with a modular structural skeleton stuffed with insulating filler and faced with an aesthetic skin. The structural skeleton would be built from interlocking modules, an approach that significantly simplified the manufacture and assembly of our second iteration prototypes. However, instead of constructing individual modules out of cardboard we proposed to fabricate them from papercrete material. This approach yields two significant advantages: much improved fire resistance, and much greater freedom in the geometry of the individual modules. The greater freedom in geometry in turn enables more control in how individual modules stack together, with the potential for simpler assembly, as well as much tighter assemblies with less potential for air infiltration. Providing for uniform insulation fill, while minimizing thermal bridging, and air infiltration are key goals for the next phase of this work.

TrashWall structural modules will be characterized for both mechanical properties and geometric tolerances to ensure they will perform acceptably first during assembly and then during service. Optimization of module manufacture will focus on producing TrashWall structural modules having 3D geometries with the greatest flexibility in installation and the simplest assembly into tight insulating structures at the lowest possible cost.

 Once basic structural modules have been fabricated and tested for mechanical properties, the fire resistance of the TrashWall system will be assessed by tests conducted by an independent testing laboratory. The thermal performance both at the component level and for complete TrashWall systems will be documented. The thermal measurements on the component level will focus on the relative advantages of the three insulating fill materials: shredded paper, commercial cellulose and commercial fiberglass. The tradeoff between thermal resistance, cost and fire resistance will be of particular importance. The thermal performance for complete TrashWall systems will be focus on air permeability and overall wall R-value.

 Finally, a prototype TrashWall system will be installed in a student apartment to serve as a means to market the concept to potential clients, to document both its performance as an energy conservation measure and to assess its success as an element of architectural and interior design. The TrashWall installation will be documented with photographs, sketches and short written descriptions illustrating the design intentions and the finished, installed product. A Wi-Fi-enabled data acquisition system will be installed into the TrashWall. This data acquisition system, based on the Arduino microprocessor, will include a heat flux meter at the surface of the TrashWall, as well as temperature sensors at the interior surface of the TrashWall, in the space between the TrashWall and the building exterior wall, and just outside the exterior wall. All measurements will be relayed via internet to an on-campus computer for monitoring and recording. These measurements (as well as utility bills) should enable us to identify the rate at which heat is lost through the TrashWall, and to compare that heat loss rate to the rate that the original exterior wall would have lost heat. This information will, in turn, enable us to identify the energy and money savings associated with the installation of the TrashWall, under real living conditions.

 Outreach to potential TrashWall end users will also take place through our partnership with the Community Action Center of Whitman County (CAC).

**Publications/Presentations:** *None to date*

**Supplemental Keywords:**

*Building energy conservation, green building, sustainable infrastructure design, design for the environment, energy conservation for the poor*

**Relevant Websites:**

 <https://labs.wsu.edu/trashtalk/>

**A. Summary of Phase I Results**

1. **Background and Problem Definition**

Energy use in buildings, residential and commercial accounts for almost half of all energy used in the United States. The same is true for most industrialized nations around the world [1]. The largest use for energy in homes and businesses is heating and cooling. Significantly reducing the demand for energy for heating and cooling in buildings would have a large impact on total energy use, and on emissions of greenhouse gases from fuels burned to supply that energy in the US, and around the world. While much work has been done on how to build new buildings with very low or zero energy use, much less work has been done on how to retrofit older buildings to reduce their energy use. The challenge becomes greater, the older and the less energy efficient an existing building is to start with. Retrofitting older, run-down, or decrepit buildings to reduce energy use is extremely difficult and seldom attempted. This is particularly true of older residential housing stock. The problem is compounded, because many of those living in older apartments and houses are renters, and many are poor. Unfortunately, for most renters there are perverse incentives in the economics of energy conservation. The landlord usually bears the cost of capital improvements, such as energy conservation measures, while the renter usually bears the cost of utilities. As a result, landlords have no economic incentive to invest in energy conservation, since they pay no penalty for energy waste and inefficiency. To the contrary, the landlord has an economic incentive to avoid making energy conservation improvements, since improvements just cost money and result in no cost benefit to the landlord. The common result is that older rental properties are often energy inefficient and cost renters high utility bills for energy that is largely wasted [2, 3, 4]. The fact that many renters are poor only exacerbates the pain. The poorest of renters can find themselves paying utility bills that are a sizable fraction of their monthly income during the most extreme months of the year. Accounts of poor residents suffering and even dying because of their inability to pay for energy to heat or cool their home are not difficult to find [5, 6, 7].

Finding an appropriate design solution to the challenge of retrofitting energy inefficient rental homes and apartments for the poor is a daunting technical challenge. [4, 8, 9,10] Since the renters paying for the energy improvements will have few resources, those retrofits must be extremely inexpensive up front. Likewise, since renters often do not stay in the same residence for an extended time, the payback time for the initial investment, from reduced energy costs, must be very short, ideally less than a single heating or cooling season. Again, since renters may leave a given apartment or house, the retrofits must not permanently damage or alter the rental unit. Ideally then, retrofits should be temporary, and if possible removable and reusable in another location. Since these energy conservation methods must be accepted into the personal living space of a resident, the retrofits must be aesthetically acceptable to the people who use them, must fit into the preferred lifestyle of the residents employing them, must be convenient and add to the comfort to the users. If a design solution is unattractive or inconvenient, then it will surely not be widely employed. Finally, to keep costs low and flexibility high, it would be best if retrofits could be installed and removed by unskilled labor, preferably the renters themselves, perhaps working with friends or volunteers. Empowering renters to “do it yourself” (DIY) will increase the available market of retrofits, allow residents to choose their own solutions and so give a large population more control over their own lives and environment.

 In sum, to meet the challenge of designing solutions to retrofit energy inefficient rental homes and apartments, the designer must develop a retrofit strategy that is extremely cheap, that pays back its costs in energy savings within months, that does not damage or permanently alter the rental unit, is aesthetically pleasing, convenient and comfortable for the occupant, and that preferably can be installed and removed by the occupants themselves, using only unskilled labor.

If such a retrofit option were available it would enable many people with little money to improve their living conditions, to waste less energy and so be responsible for less pollution by utilities, and to accrue significant savings by reducing heating and cooling bills. Such a solution would clearly advance sustainability through helping people live in healthier, more comfortable homes, reducing pollution and saving money (People, Planet, Prosperity).

To meet these formidable challenges, we propose a strategy we have dubbed “TrashWall.” In the TrashWall approach, we propose to develop an insulating wall, built from recycled materials that can be installed inside the existing envelope of a rental house or apartment. The TrashWall will act to significantly reduce heat losses through exterior walls and windows, leading to significant energy savings in meeting heating and cooling loads and significant monetary savings on utility bills for the rental unit occupants. The need for very low initial cost is to be met by assembling each TrashWall from locally-harvested, recycled materials using simple assembly methods employing only commonly used tools. The use of simple assembly procedures using common tools should enable us to drive labor costs down by enabling residents and volunteers to “do-it-yourself” and so contribute “sweat equity.” Using this approach, it appears possible to install TrashWall insulating walls in rental units for costs below much lower than any existing retrofit strategy.

Keeping installation costs very low, enables the possibility that TrashWall systems can have extraordinarily short pay back periods, even paying back their initial investment within a matter of months. Energy retrofit payback periods depend on the initial energy efficiency of the building, as well as the cost of the retrofit, the expected energy savings, and the cost of energy. Retrofitting apartments that lose more energy (are less energy efficient or experience more extreme temperatures), or homes in locales with higher energy costs will result in faster payback periods. Taking representative values for US building stock can provide idea of expected payback periods.

Consider a residential building in the mountain west of the US with a typical exterior wall R value of R11 (Fft2hr/Btu) or RSI 2 (m2C/W) experiencing 2000 heating degree days during the heating season, with heat supplied by electric power at the average US cost of $0.13) [11,12]. Assuming we can install a TrashWall inner wall with an R value of RSI = 2 m2C/W (R11 US) for an initial capital cost of ten cents per square foot, then we could expect a payback period of about 90 days or just three months. If the residence retrofitted were, like many rental properties, inadequately insulated with exterior walls with R values of RSI = 1.6 or R = 9, then the payback period shrinks to just over 60 days or two months. Recent work by Ucar and Balo on payback periods for retrofitting insulation in existing housing stock in Turkey finds similar numbers [13]. Attaining moderate R-values, while keeping low installation costs very low opens up many opportunities.

The TrashWall project impacts all three aspects of sustainability: Planet, Prosperity, People. First, TrashWall is kind to the planet with a positive environmental impact, reducing air pollution, particularly greenhouse gases, while also reducing solid waste. Addressing the problem of the low energy efficiency of much rental housing using recycled materials locally-harvested from the waste stream is a win-win strategy: use solid waste to reduce energy waste to save money and reduce air pollution.

Second, TrashWall increases the prosperity of those who need it most, the poor. TrashWall will reduce energy bills for lower-income residents of rental housing, while using low-cost or no-cost recycled materials. Residents will be able to invest their own, sweat equity to modify their living spaces to conserve energy. Money saved on utility bills, will be money in the pocket of those who need it most.

Finally, TrashWall helps people, especially the people who need it most, by giving them more control over their environmental and their pocket book. The poorest of our citizens will benefit the most from these savings. The TrashWall system is intended to empower individuals to redesign the space they live in to be more comfortable, and use significantly less energy by employing materials they can harvest themselves. Thus, people living in rented spaces can transform those spaces to save resources and money, and to better represent their own values.

 Thus, TrashWall can help promote Sustainable Communities, by giving communities the tools to help them save money, save energy and reduce air pollution and solid waste.

The success of the TrashWall concept, and its penetration into the wider community will depend on several factors: First, it will depend on the student groups’ success in designing and fabricating interesting, attractive and money saving TrashWall designs. The barrier of disbelief in a process that claims to turn trash into an energy saving approach that is both attractive and simple to apply is very high. Second it will depend on our ability to communicate the value of this approach, as well as the “how-to” of designing and building this kind of energy and money saving approach. It is incumbent on us to be able to convey the value of TrashWall through our TrashTalk web page. Only if this approach can “go viral” through the internet and can be understood and taken up by many others based on what they can pick up from our online presence can this project achieve long-term viability and be considered truly successful.

**2. Purpose, Objectives, Scope**

To meet these challenges, we planned that our interdisciplinary groups of Architecture and Engineering students would develop their own TrashWall designs ultimately to be installed in selected rented apartments and houses. Our original goal of a TrashWall prototype was a design that would cost less than $0.10 per square foot, and have an R-value of R20 US with a payback from energy savings in 100 days or less for installation in a home with R-18 walls (recommended wall R values for the Intermountain region of the US). The research plan called for prototype designs first to be tested under laboratory conditions to determine their thermal resistance (R value), air permeability and uniformity. Then, TrashWall prototypes installed in student’s residences would be monitored to document their performance in reducing energy use under actual use by instrumenting them with web-enabled data acquisition systems. Data from the monitoring of in situ TrashWalls would be streamed to a website dashboard where students and others could see in real time the impact of their designs on their own energy use.

**3. Data, Findings, Outputs/Outcomes**

The original research plan outlined in the proposal called for the student design teams to go through two complete design iterations resulting in the construction of five TrashWall prototypes. Both design iterations were scheduled to be completed by the end of month three of the project with the second iteration prototype TrashWalls built by the middle of month four. Documentation of the prototypes was to include concept sketches, photographs detailing the construction, installation, disposition of the wall over its lifetime, and disassembly at the end of its useful life, as well as prototype performance data including laboratory measurements of the wall’s thermal resistance, air permeability, as well as IR thermographs to document each wall’s spatial uniformity. The first assessment of each prototype TrashWall was to involve testing of the prototype’s thermal resistance (R value), air permeability and uniformity under laboratory conditions. A Hot Box test was to be used to measure prototype R value and air permeability. Next, the uniformity of the prototype was to be assessed using an Infrared (IR) Camera. The IR camera was to be used to assess and to identify heat leaks, by scanning for local hot and cold spots across the wall’s front. Finally, a standard Blower Door test apparatus fitted to the Hot Box was to be used to measure the air infiltration rate through the prototype wall, quantifying its air permeability. These laboratory measurements were scheduled to be completed by month five of the project.

The goal of these measurements was to characterize our TrashWall prototypes sufficiently to predict their performance in particular installations. Given data about heat losses and/or heating load for a given living space, we hoped to be able to make reasonable predictions about how much energy and money a resident could save by installing the particular TrashWall design in the given living space. The next phase of the project was then to test these predictions by measuring the performance of the prototype design in situ, installed in the living space of members of the student groups, and documenting actual energy and money savings of a real TrashWall installation. In addition, installing TrashWall prototypes in student apartments was to enable its success as an element of architectural and interior design. Prototype installation was scheduled to completed half way through month six of the project

Our interdisciplinary team was successful in completing two design and build iterations of TrashWall concepts. In the first iteration, the team designed and built four TrashWall prototypes. Those initial prototypes were constructed almost entirely of recycled waste materials, and all had material costs of less than $0.10 per square feet, ranging from $0.10/ft2 to $0.0 in material costs. The most successful of these initial concepts, judged on the basis of aesthetics and structural integrity, prototype four, was assembled from a skin of cardboard forming a triangular prismatic surface, backed by a quilt fabricated of plastic shopping bags filled with shredded paper. The prototype thus had an aesthetic “skin” backed by a quilt like “core” filled with insulating material. This TrashWall was not rigid, the design team intending it to be hung on an interior wall.

Based on this effort, initial tests were undertaken to determine the R-value of the most promising TrashWall concept. To do this a second insulating quilt fabricated of plastic shopping bags filled with shredded paper was installed in the Hot Box. The quilts were assembled by rescuing polyethylene shopping bags from the waste stream. The bags were cut into square sheets, doubled up, and heat welded into square pockets, which were stuffed with shredded paper. The individual pockets were then heat welded together into large quilts. A complete 4 foot wide x 8 foot high TrashWall prototype was assembled from four shopping bag quilts layered together to form a thickness of approximately eight inches. The Hot Box tests indicated that the shopping bag quilt had an R-Value of RSI =1.3 m2 C/W (RUS = 7.3 hr ft2 F/Btu). Infrared photos of the quilt showed some nonuniformity in temperature, with visible hot and cold spots.

Next, it was decided to consult the WSU fire marshal on the team’s initial designs. Fire Marshal Rod Holmes was invited to meet with the team joining a design review session covering the work accomplished up to that time. The Fire Marshal’s assessment to the student design team with overwhelmingly negative. The Marshal emphatically rejected the notion of placing any potentially flammable material within the building envelope of a residential structure. He discouraged the use of any cellulosic material such as paper, cardboard, or wood, or the use of any fabric within a living space because of their potential as combustion fuels. Moreover, he strongly discouraged the use of any plastic because of the potential for producing smoke and toxic fumes upon combustion. The strongly negative message on the fire safety from the Fire Marshal caused the students to step back and reconsider their designs.

It was decided to revisit both the prototype design goals as well as the project goals based on the lessons learned from the first design iteration. As a result of the first design iteration the design team reached several conclusions. Internal envelope insulating walls having R values of RSI =1.3 m2 C/W (RUS = 7.3 hr ft2 F/Btu) for prototype thickness of 8 inches, could be built entirely from readily available recycled materials rescued from the waste stream. Thus there were no material costs or costs = $0.0. It appeared that higher R-values could be attained through better design. In addition, the walls could be made attractive with creative use of materials students reclaimed at no cost directly from the waste stream. However, these first TrashWall prototypes were both difficult and slow to manufacture and assemble. A focus on design for manufacture and assembly (DFMA) of the next iteration of prototypes was crucial to ensure that proposed TrashWalls would be easy and convenient to use. In addition, addressing fire safety concerns was the paramount unresolved issue standing in the way for any realistic TrashWall application.

Based on lessons learned from this first iteration the team decided to reboot and reconsider their design approach, to develop a more coherent design approach. The approach the team arrived at involved breaking entire TrashWall system down into three complementary subsystems or functional components: a structural component or skeleton, an insulating component or filler, and an aesthetic facing component or skin. The team then divided into two interdisciplinary teams working on the design of two new prototype components that could be flexibly combined to create new TrashWall designs. Thus the effort turned from entire system design to component designs, with components that were mutually compatible for assembly into complete TrashWall prototypes. Design for manufacture and assembly of each component was to be a prime area of focus for each component. In addition, both teams committed to addressing TrashWall fire safety issues in two ways: (1) developing fire safe components and (2) researching fire safety and building codes to understand the regulatory environment into which any TrashWall prototype must fit.

The second design iteration resulted in a number of structural/skeleton, insulating/filler, and aesthetic/skin components that could be mixed and matched to assemble new TrashWall prototypes.

First, two structural/skeleton concepts were developed. One structural/skeleton was fabricated of a cardboard box module assembled using beams fabricated from PET soda bottles. The screw tops of the PET soda bottles were used as nut and bolt connectors to enable quick assembly and disassembly of the cardboard box modules. A second structural/skeleton was fabricated of cardboard box modules assembled with cardboard tube connectors.

Second, several insulating/filler options were investigated. For these fillings, the design teams considered three potential insulating fillings: shredded paper, commercially obtained cellulose insulation, and commercially obtained fiberglass insulation. These three choices illustrate the tradeoffs in design the student groups faced. The shredded paper filling is easily obtained from the waste stream, and costs nothing to harvest, but without treatment is not fire safe. Commercial cellulose insulation is a product that is recycled from newsprint taken the waste stream, but has a significant cost associated with it. However, as it is treated with fire retardants, it is considered relatively fire safe. Commercial fiberglass insulation is also at least partially recycled from glass taken from the waste stream, and also has a significant cost. However, fiberglass, being inorganic, is fire safe. For all three of these fillings, the cardboard box modules in each of the two structural/skeleton solutions provided a means to hold and contain the insulating fillings. As a result, any filling could be used in any structure.

Third, a large number of aesthetic/skin possibilities were developed. All of the skins created can be seen at the Trashtalk website: <https://labs.wsu.edu/trashtalk/>. Maximum flexibility for the use of these skin options was ensured by designing all skins to be glued to the front of the cardboard modules making up the structural skeleton in the same way. In this way any TrashWall could make use of any skin option or combination of skins.

To explore the impact of fire safety on TrashWall design, a number of aesthetic skins were designed specifically with this constraint as one of the primary considerations. One skin option, taking the form of hexagonal tiles, fabricated out of paper and concrete in a paper mache like process, called “papercrete,” appears particularly promising. The resulting tiles are very fire resistant, with tiles not igniting after 15 minutes exposure to the flame of a propane torch held to the tile. These tiles are lightweight, and easy to fabricate from recycled paper sources. The amount of concrete used in each tiles is small, leading to a $ 0.06 per square foot cost. Finally, the fabrication process is quite flexible, making the tiles easily customizable with a wide variety of surface finishes possible.

Based on the second design iteration, further characterization tests were undertaken to determine the thermal performance of the new TrashWall prototypes. First, a set of heat flow measurements following ASTM C 518 standard test method assuming a steady-state heat flow were made using a LaserComp Fox 304 heat flow meter. Measurements were made on the three potential insulating fillers: shredded paper, commercial cellulose insulation, commercial fiberglass insulation. Measurements were made under service conditions expected for actual TrashWall installations: temperatures in the range of 25 C to -10 C or 77F to 14 F. Since the cardboard modules in the two structural skeleton systems to be stuffed with insulating filler were slightly different (one module with PET bottle connectors, and a second with cardboard tube connectors) comparison measurements were made in both modules filled with cellulose. Four-inch thick modules were used for the measurements. For modules with tube connectors, R-values were found to be 1.7 m2K/W (R10 US) for shredded paper, 2.2 m2K/W (R12 US) for commercial cellulose and 2.8 m2K/W (R16 US) for commercial fiberglass fillings. Measurements for the modules with PET bottle connectors were found to be 15% lower than the tube connectors, (e.g. 1.9 m2K/W (R11 US) for the PET connected module filled with commercial cellulose).

Hot Box measurements were then made on a complete 4 foot wide x 8 foot high TrashWall prototype with a structural skeleton fabricated of cardboard box modules assembled with PET bottle connectors. The cardboard modules were stuffed with shredded paper. The Hot Box tests indicated that the 4’ x 8’prototype had an R-Value of RSI =0.9 m2 C/W (RUS = 5.1 hr ft2 F/Btu). Since the individual module heat transfer measurements indicated an expected R-value of 1.5 m2K/W (R9 US) for shredded paper, the Hot Box tests appeared to be surprisingly low, just over half of what the team expected.

The very low measured R-value for the prototype TrashWall was a matter of great concern. Two possibilities have been explored explain the anomalously low measurements: Heat leaks through the wall due to nonuniformity in the filling of the structure, or heat leaks due to air infiltration through the prototype. The possibility of air infiltration through the prototype appeared to be the most likely possibility. Failure to properly seal all joints between cardboard modules could have led to air infiltration paths through the wall. A close visual inspection of the TrashWall prototype revealed a number of possible infiltration routes.

As a result of these observations, the prototype wall was rebuilt with attention focused on reducing air infiltration routes through the wall while maintaining uniformity in filling. Retesting the heat transfer rate through the rebuilt prototype wall indicated a new increased R-value of RSI =1.2 m2 C/W (RUS = 7.0 hr ft2 F/Btu). This R-value for the rebuilt large-section prototype while higher than the previous iteration, is still 20% lower than the R-value found for an individual module.

The rebuilt prototype was then examined with the IR camera to investigate for nonuniformity in the wall. Infrared images of the TrashWall revealed significant temperature variation, with easily visible hot and cold spots. As a result, nonuniformity in the wall appears to lead to thermal bridging that contributes to the reduced R-value measured.

The team is presently engaged in reviewing the design of the latest prototypes to address the cause of the reduced R-value. In addition, air permeability measurements are clearly needed. In order to move forward with these measurements, the team is modifying the Hot Box to accommodate our model 1000 Retrotec Blower Door system to directly measure infiltration rates through the TrashWall.

Our original project schedule indicated completion of all TrashWall laboratory measurements by the end of month five. As of the writing of this project report (March 15, 2016), we are now in the second week of month five of the project, which began October 1, 2015. Thus, air permeability measurements are two weeks behind schedule as of 3/15/16. Likewise, the installation of prototype TrashWalls (scheduled for 3/15/16), has been delayed because of the need to complete the laboratory measurements, and the desire to diagnose the cause of the 20% deficit in prototype R-value. However, all other milestones for the design, building, testing and documentation of the prototype TrashWalls have been met on schedule. Much of that documentation in the form of photographs, sketches and short written descriptions illustrating the design intentions and the finished products can be accessed on the project web page: <https://labs.wsu.edu/trashtalk/> .

Based on the results gathered to date, the present investigation into the technical effectiveness and economic feasibility of the TrashWall approach is as follows. The TrashWall team has demonstrated that its internal envelope insulating walls fabricated from materials recycled from the waste stream could be built with measured R values of RSI =1.2 m2 C/W (RUS = 7.0 hr ft2 F/Btu) for material costs below $0.10 per ft2. Creative use of materials by the student design team has led to very interesting and attractive wall treatments. With a focus on design for manufacture and assembly (DFMA) a second iteration of prototypes was designed based on a component subsystem approach. Each TrashWall system was broken down into a structural skeleton, insulating filler and aesthetic skin. This new approach led to TrashWalls that are much more flexible and can support a wider variety of insulating options and aesthetic finishes. In addition, using a component approach with a focus on design for manufacture and assembly (DFMA) has led to prototypes that can be quickly and easily assembled from modular components. Those modular components are in turn simpler and faster to manufacture. Next, fire safety concerns emerged as a significant issue midway through the project. Fire safe options for all three components of the TrashWall system have been identified. However, greater fire safety appears to come at a trade-off of greater cost. First, both the structural skeleton and the aesthetic skin can be made significantly more fire resistance by the incorporation of “papercrete.” a combination of both cellulose fibers and concrete. Second, the fire safety of insulating filler can be increased through the use of either commercially available cellulose insulation or fiberglass insulation. The incorporation of any or any combination of these three options will necessarily trade greater installed cost for greater fire safety. Finally, the testing of an improved prototype TrashWall, based on a modular design for simpler and quicker manufacture and assembly, expected to have improved thermal performance, while also incorporating fire resistance materials has not been completed.

**4. Discussion, Conclusions, Recommendations**

Based on TrashWall prototypes built and tested it appears safe to say that it is possible to fabricate an interior insulating wall with a measured R-value of at least 1.2 m2K/W or R7 US, built almost entirely from recycled materials harvested from the waste stream at an installed cost of less than $0.10/ft2 of wall. Such an installation would consist of the four-inch thick cardboard structure filled with shredded paper insulation filler and faced with 1/8” thick papercrete tiles for fire resistance tested in Phase I of this project. Installed in a rental unit with walls with effective R-value of R = 1.5 m2K/W or R9 US and situated in a climate like Pullman, WA, typical for the Intermountain West, such a TrashWall would save the renter 9 Whr per day per ft2 of wall leading to a utility bill savings of 0.12 cents per day per ft2 of wall. These savings would lead to a payback period for the installed TrashWall of 80 days or just under 3 months.

For comparison, it would be possible to increase the fire resistance of the TrashWall by shifting from shredded paper to fiberglass insulation which would significantly increase the cost of the TrashWall from $0.10/ft2 to 0.30 $/ft2. This higher cost would lead to the much longer payback period of 175 days. The payback period would then stretch out to almost 6 months or about one heating season.

Installing these TrashWall systems would utilize recycled materials that would have entered landfills, and would reduce greenhouse gases associated with the heating fuel: either reduced utility-generated electrical power use or reduced natural gas or heating oil use. Beyond these cost savings, the renter would experience much reduced drafts and a higher mean radiant temperature leading to greater comfort in their apartment. The renter would also have claimed greater control over their own lives and the ability to enhance their own living space.

**5. Assurance that research misconduct has not occurred during the reporting period**

No research misconduct, including fabrication, falsification, or plagiarism in proposing, performing, or reviewing research, or in reporting research results [65 FR 76262. I], or ordering, advising or suggesting that subordinates engage in research misconduct has occurred during the any of the work related to this project or the writing of this report.

**Proposal for Phase II**

**1. P3 Phase II Project Description**

Proposal Quality

Based on the results from Phase I of this project, it appears possible to design and build insulating interior walls, TrashWalls, from recycled materials that are both attractive and fire safe and that can reduce heat losses through exterior walls sufficiently to pay back their up-front costs in one year or less. These results of course depend on an engaged resident, who will invest time and energy in upgrading their own living space. While not as good as our original goal (payback in three months or less) this result is better than any energy retrofit strategy that we are aware of. Indeed, recent results have indicated that more traditional home weatherization strategies may pay back less in energy savings than the upfront costs invested. [14]

The present approach is different from more traditional weatherization or energy retrofit strategies in several ways. The TrashWall project seeks to drive the cost of the retrofit down to the lowest possible value, first by making use of the cheapest possible materials, waste materials destined for the landfill, and then by using the simplest possible processing path. Wherever possible, that processing should be something that a resident could do themselves with common tools and supplies. This approach lends itself to simple, inexpensive, temporary modifications of a resident’s living space. Those modifications then can be easily uninstalled either if the resident moves, or if living space modifications fail to live up to expectations, for whatever reason. With invested capital very small, the risk of a bad investment becomes more manageable. As a result, with much less investment required by the resident, this very low-cost approach is expected to face a lower barrier to acceptance.

However, as emphasized at the beginning of this report/proposal, success for this approach requires a retrofit strategy that is extremely cheap, that pays back its costs in energy savings within months, that does not damage or permanently alter the rental unit, is aesthetically pleasing, convenient and comfortable for the occupant, and that preferably can be installed and removed by the occupants themselves, using only unskilled labor. Our original goal of a TrashWall prototype was a design that would cost less than $0.10 per square foot, and have an R-value of R20 US with a payback from energy savings in 100 days or less for installation in a home with R-18 walls (recommended wall R values for the Intermountain region of the US).

Based on work to date, we have modified this aspirational goal. In particular, challenges in attaining R-values without making TrashWall prototypes too thick, and acknowledging the necessity to ensure occupant fire safety constrains the designs possible and requires trade-offs among design goals. In particular, ensuring fire resistance in TrashWall designs significantly restricts possible choices among recyclable materials and in many cases adds cost. However, the overarching goal of this project remains unchanged: to provide an energy saving solution, built from materials recycled from the waste stream, that is cheap enough for the poorest Americans to use, and that has a payback period short enough to be attractive. Adding in these constraints, it still should be possible to design, build and test a TrashWall prototype that would cost less than $0.30/ft2, and has an R-value of R10 US with a payback from energy savings within one heating season (or less than 180 days) for installation in a home with R-9 walls (wall R values representative of many older residents in the US).

 Based on the results found in Phase I of this project, the most promising route to meet these goals is through the development of a modular TrashWall system that builds on the most successful aspects of the prototypes previously developed. That system would be based on the three component subsystem model with a modular structural skeleton stuffed with insulating filler and faced with an aesthetic skin. The structural skeleton would be built from interlocking modules, an approach that significantly simplified the manufacture and assembly of our second iteration prototypes. However, instead of constructing individual modules out of cardboard we proposed to fabricate them from papercrete material. This approach yields two significant advantages: much improved fire resistance, and much greater freedom in the geometry of the individual modules. The greater freedom in geometry in turn enables more control in how individual modules stack together, with the potential for simpler assembly, as well as much tighter assemblies with less potential for air infiltration. Providing for uniform insulation fill, while minimizing thermal bridging, and air infiltration are key goals for the next phase of this work.

 The proposed project will build on significant work already accomplished by our partners in WSU’s Composite Materials and Engineering Center (CMEC). Recent research at CMEC indicates a clear path toward fabricating TrashWall modules with highly controllable and customizable geometries: hot pressed three dimensional recycled newsprint modules or 3-D RNPM’s. The goal of the project will be to produce TrashWall systems using recycled newsprint (RNP) material as substrate for the modular structural skeleton. These 3-D RNP modules will then form a robust, lightweight TrashWall structure with aesthetic, and fire-resistant papercrete skins layers and cavities filled with insulation such as shredded paper, cellulose or fiberglass.

The present work builds on a long history of research with similar three dimensional (3-D) wood-based panels for more conventional floor, wall, and roof applications at CMEC. Researchers at CMEC (and member of our team) have helped to develop these kind of 3-D panels manufactured using hot-pressed oriented-wood strands with mechanical and thermal properties far superior to traditional building materials. [15]

A similar approach employing recycled newsprint has shown promise to produce modular structures with superior properties and very low cost. Previously published research on RNP as a structural building material dates back to the early 1970’s. A U.S. patent was filed in 1976 for producing recycled composition paper flake board [16]. This patent describes a dry process to press composite panels using recycled newspaper strips known as “paper flakes.” These paper flakes were combined with wood flour or finely fragmented cellulosic matter and bonded with a thermosetting resin like urea-formaldehyde (UF) or phenol-formaldehyde (PF). Pressed panels varied in thickness from ¼ inch to 1½ inches with densities ranging from 30 pcf to 60 pcf. Likewise, Canadian researchers have successfully developed a dry manufacturing process for pressing shredded paper strips from recycled phone books [17]. This study investigated the use of plastic grocery bags in addition to the more traditional PF Resin as the source for the adhesive, and were able to produce panels with mechanical properties comparable to commercially available wood-based panels.

More recent work at WSU CMEC, has also indicated the feasibility of producing TrashWall structural modules starting from RNP strands or flakes using a hot-press process [18]. This study demonstrated a process that could result in flat panels with mechanical properties that compare favorably to the cardboard stock used to fabricate our Phase I TrashWall prototypes. The work identified important processing variables and their effect on the final product’s properties. In particular, this research identified paper fiber orientation, adhesive type, quantity, and distribution, as well as material surface quality, and processing parameters such as hot-pressing pressure, temperature, and schedule as having significant impacts on the resultant panel mechanical properties.

One concern that has been raised for the use of recycled newsprint is the chemical modification of newsprint fibers used to expedite the printing process that can reduce the bonding potential of those RNP fibers [19]. The potential exists that these additives could set an inherent limit on the mechanical properties achievable with 3DRNPM’s. However, one study in which Medium Density Fiberboard (MDF) was manufactured using recycled newsprint fiber, in a process very similar to the one proposed here, was able to overcome this problem to achieve very favorable mechanical properties [20].

Based on this previous work, the production of TrashWall structural modules for an effective interior insulating wall, by hot-press processing of recycled newsprint into the requisite geometries, appears feasible. To achieve this result, the project will focus on manufacturing the 3d geometry modules required, determining their mechanical properties, and then integrating those structural modules with insulating fill materials and with fire resistant, aesthetic facings.

Module manufacturing will begin with the harvesting of newsprint rescued from campus recycling bins. Recycled newsprint will be cut into strips with widths between 0.75 and 1.5 inches and then combined with adhesives. Low-cost, starch-based adhesives, commonly employed in cardboard manufacturing will be used here. A shake table will then be used to ensure RNP strips are oriented parallel to one another as they are formed into mats. Mats will then be pre-pressed to create a uniform density profile within the RNP plies and hot-pressed into either flat panels or the desired 3D structural panel geometry using an aluminum mold.

TrashWall structural modules will be built up from 3D geometry panels by gluing multiple layers together using modified polyisocyanurate adhesive, phenol-resorcinol adhesive, or a good gap-filling adhesive, and then facing them with fire resistant papercrete outer skins. These TrashWall modules will be designed to slide together and then mechanically couple in order to assemble infiltration resistant envelopes.

Once fabricated, the resulting TrashWall structural modules will be characterized for both mechanical properties and geometric tolerances to ensure they will perform acceptably first during assembly and then during service. Optimization of module manufacture will focus on producing TrashWall structural modules having 3D geometries with the greatest flexibility in installation and the simplest assembly into tight insulating structures at the lowest possible cost.

 Once basic structural modules have been fabricated and tested for mechanical properties, the decision on insulating fill material will be addressed. The relative advantages of the three insulating fill materials: shredded paper, commercial cellulose and commercial fiberglass, will be weighed with particular attention on the tradeoff between cost and fire resistance. Since the cost of the TrashWall system will depend on the balance between up-front installation costs versus energy savings, we will need accurate information about relative system R-values for the three insulating fill materials. To make this comparison, first a set of component level heat flow measurements will be made using the LaserComp Fox 304 heat flow meter (following ASTM C 518 standard test method, steady-state heat flow) on individual modules filled with each insulating material. Then, system level heat flow tests using 4’ x 8’ test walls consisting of multiple structural modules assembled together and then filled with each insulating material Three walls will be tested first for wall heat transfer rates in the Hot Box and then for air infiltration rates using the Retrotec Blower Door system. Comparisons of R-value, Air Permeability and installed cost will be documented for walls filled each of the three insulating materials.

 Fire resistance of the TrashWall system will be assessed by tests conducted by an independent testing laboratory in accordance with ASTM E 1354-16 standard test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter. This benchmarking test will evaluate the ignitability, heat release rates, mass loss rates, effective heat of combustion, and visible smoke development of materials and products. Three specimens (10 cm by 10 cm by 5 cm thick) will be tested. Evaluation will first focus on the TrashWall ‘s exterior papercrete skin, and then on the structural modules’ RPN material. Evaluation report will include time to sustained flaming, heat-release rate per unit area with respect to time, total heat released by the specimen, average effective heat of combustion, average specimen mass loss and mass loss rate, and smoke obscuration. Fire performance results will establish the benchmark values of TrashWall’s ignitability, heat release rates, mass loss rates, effective heat of combustion, and visible smoke development.

 Once mechanical, thermal and fire-resistance measurements have been made, we will begin addressing the integration of TrashWall systems into existing residential interiors. At this point, architectural issues become paramount. In particular, the team will focus on issues such as how the TrashWall modules will be fitted against existing interior walls, how they will be detailed around windows and doors, or other fixtures such as radiators or duct openings and how electrical connections will be made through the modules. In addition, the team will finalize the treatment of the aesthetic skin that will cover the structural modules. The team will explore a number of skin surface treatments as well as detailing options to provide a range of architectural options for prospective TrashWall adopters.

 Finally, a prototype TrashWall system will be installed in a student apartment to serve as a means to market the concept to potential clients, to document both its performance as an energy conservation measure and to assess its success as an element of architectural and interior design. The TrashWall installation will be documented with photographs, sketches and short written descriptions illustrating the design intentions and the finished, installed product. A wifi-enabled data acquisition system will be installed into the TrashWall. This data acquisition system, based on the Arduino microprocessor, will include a heat flux meter at the surface of the TrashWall, as well as temperature sensors at the interior surface of the TrashWall, in the space between the TrashWall and the building exterior wall, and just outside the exterior wall. All measurements will be relayed via internet to an on-campus computer for monitoring and recording. These measurements (as well as utility bills) should enable us to identify the rate at which heat is lost through the TrashWall, and to compare that heat loss rate to the rate that the original exterior wall would have lost heat. This information will, in turn, enable us to identify the energy and money savings associated with the installation of the TrashWall, under real living conditions.

All data documenting each prototype TrashWall will be posted online in the “TrashTalk” webpage. The Webpage will provide ongoing information about the design, construction, installation and performance of each prototype TrashWall. The website will act as an educational tool both to update students in the University on the progress of the project. It will also be a means to reach out to potential TrashWall end users both in the University and beyond in the wider community.

Outreach to potential TrashWall end users will also take place through our partnership with the Community Action Center of Whitman County (CAC). Personnel at the CAC have already generously shared their perspectives and experience on energy retrofit and home weatherization projects as well as their insights into the needs and preferences of low-income renters and home owners with the TrashWall student design team. The CAC has also agreed to support the TrashWall project by displaying prototype TrashWall designs in the lobby of the CAC main office in Pullman, and by enabling conversations between the design team and prospective TrashWall end users.

The expected outputs of this project will be a prototype TrashWall system based on a 3DRNP structural module, filled with an insulating material and faced with a fire resistant and aesthetic skin, along with full documentation of the prototype’s design and mechanical, thermal and fire safety characteristics. In addition, the documentation of the TrashWall design will include sketches, and photographs detailing the manufacture, assembly, installation, and performance of the TrashWall installed in a living space. The “TrashTalk” website will provide a public forum for all documentation of the design and performance of the prototype TrashWall designs. This will allow all team members, and members of the wider university community, as well as interested parties around the country to learn about the TrashWall concept. The online documentation is expected to a primary means to reach out to the wider community to identify possible TrashWall end users.

Research outputs and outcomes will be tracked and measured against the following milestones:

1. Design of 3D RNP structural modules and fire-resistant/aesthetic skins by student design group.
2. Manufacture of 3DRNP structural modules.
3. Mechanical characterization of 3DRNP structural modules and optimization of processing variables.
4. Fire resistance measurements of fire-resistant/aesthetic skins and module materials.
5. Thermal characterization of individual insulation filled modules and measurement of 4’x8’ test walls.
6. TrashWall detailing and installation
7. TrashWall data acquisition to TrashTalk website.

The project will be managed by the faculty advisors, with Prof. Yadam overseeing the manufacture and mechanical testing of the structural modules, Prof. Richards overseeing the thermal design and testing, Prof. Swensen overseeing the web-based data acquisition and Prof. Miyasaka overseeing the Architecture design and installation. All faculty will jointly be responsible for milestone 1. Prof. Yadama will focus on the teams progress toward Milestones 2 and 3, while Prof Richards will focus on Milestone 5, Professor Miyasak on Milestone 6, and Prof. Swensen on Milestone 7. Professors Yadama, and Richards will take joint responsibility for Milestone 4.

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| Milestones | Sept | Oct | Nov | Dec | Jan | Feb | Mar | April | May | June | July | Aug | Sept | Oct | Nov | Dec | Jan | Feb | Mar | April |
| Prototype Design |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Manufacture 3DRNP Modules |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Mechanical Characterization |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Component Fire Resistance |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Thermal Characterization |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Arch Detailing & Installation |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Data Acquisition |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

Overall Sustainability

The TrashWall project impacts all three aspects of sustainability. First, consider the environmental impact. TrashWall will reduce air pollution, particularly the production of greenhouse gases, while also reducing solid waste. TrashWall is expected to address the problem of the low energy efficiency of much rental housing. Reduced energy use by residents of rental units, will pay off immediately in reduced greenhouse gases and other air pollution associated with that energy use. Likewise, since TrashWalls will be built primarily of materials locally-harvested from the waste stream, this approach will take solid materials destined for landfills and reuse and recycle them to save energy. This is a win-win strategy: use solid waste to reduce energy waste to save money and reduce air pollution.

Next, consider the economic impact. TrashWall will reduce energy bills for lower-income residents of rental housing, while using low-cost or no-cost recycled materials. Residents will be able to invest their own, and their friend’s sweat equity to modify their living spaces to conserve energy. Money saved on utility bills, will be money in the pocket of those who need it most. The poorest of our citizens will benefit the most from these savings. The first such citizens we expect to impact will be students, who face real economic challenges, with high tuition and access to mostly low-paying jobs. While this project begins with students it is not expected to end with them. The TrashWall project, if successful, is expected to be a model whereby any renter can find a means to cut their energy use, and their energy bills using an approach that they can implement themselves using materials that they can harvest themselves.

The social impact of the TrashWall project grows out of its environmental and economic effects. The process we are developing is intended to empower individuals to redesign the space they live in to be more comfortable, and use significantly less energy by employing materials they can harvest themselves. Thus, people living in rented spaces can transform those spaces to save resources and money, and to better represent their own values. In some sense, renters can use this approach to take possession of their living space and make it their own. In addition, TrashWall offers people a way to take on the sometimes overwhelming issues of air pollution, solid waste, greenhouse gases and global climate change and do something on a personal and local level that can have a global impact. TrashWall empowers individuals to reduce their own energy needs in order to make a difference in their own lives, by saving money, and in the lives of all people by reducing the environmental impacts of generating that energy.

The overall goal of the project is to save money and reduce pollution by decreasing the amount of energy that is wasted in low-quality housing. The savings go to those who need it most, those with the fewest resources. However, the success of this concept, and its penetration into the university community and beyond will depend on several factors: First, it will depend on the student groups’ success in designing and fabricating interesting, attractive and money saving TrashWall designs that can be built by a wide swath of the public with little special skill, for very little upfront cash. Second it will depend on our ability to communicate the value of this approach, as well as the “how-to” of designing and implementing this kind of energy and money saving approach. Only if this approach can “go viral” and taken up by many others based on what they can pick up from our online presence can this project achieve long-term viability and be considered truly successful.

Education and Teamwork

 The student team will be built from a cross disciplinary group of mechanical engineering, civil engineering and architecture students. Architecture students will be recruited from Prof. Miyasaka’s design course in the graduate curriculum. Civil engineering students will be recruited from the students involved in CMEC by Prof. Yadama. Mechanical engineering students will be recruited from Prof. Richards’ capstone thermal design class. The TrashWall project will have significant educational benefits for the students involved in the design and build teams, especially in teaching principles of sustainability to architecture and engineering students. Architecture students will be recruited from Prof. Miyasaka’s design class ARCH 531 Advanced Techtonics. Design and fabrication of the TrashWall prototypes, including joint and assembly systems will be part of their class design work, and will evolve within the structure of that course. Mechanical engineering students, drawn from Prof. Richards’ capstone design class ME402 Thermal Fluid Design will focus on the thermal calculations, optimization and testing of the TrashWall designs. Civil engineering students drawn from CMEC will be central to the design, manufacture and testing of the 3DRNP structural modules. All students will thus see an interdisciplinary view of design that is driven by the three aspects of sustainability and triple bottom line accounting: responsiveness to the needs of people (social responsibility), meeting the needs of the planet (environmental responsibility) while meeting the need for profitability (making economic sense) for those involved. Since the project ultimately entails that students (literally) live with the results of their design work, and that they see a strict environment and economic accounting for the outcomes of their design work, the TrashWall project is expected to help this interdisciplinary group of students come to a much deeper understanding of what sustainability is and what it means as a living reality.

In addition, the TrashWall team has begun outreach to K12 students using TrashWall as a vehicle to discus, solid waste, recycling, energy use and air pollution. K12 students can assemble their own insulating walls using the modular TrashWall components the team has built from recycled material. In this way, TrashWall can serve as a fun, hands-on teaching tool to help students begin to understand how to save energy in their own homes. TrashWall team members have already scheduled presentations to elementary students in Moscow, Idaho, and to high school students from the Nez Perce tribe in Lapwai, Idaho.

1. **Quality Assurance Statement**

 All TrashWall prototype components developed during this project will be tested for structural strength, thermal properties (R-value), and fire resistance. In addition, complete TrashWall prototypes will be tested for energy savings in realistic installations. Comprehensive uncertainty analyses will be presented for all measurements characterizing the research products, to ensure comparisons with project objectives are clearly documented and statistically significant. All data will be published on the TrashTalk project website, reported in our final report to the EPA, and documented in papers submitted to professional conferences.

1. **Partnerships**

We will be partnering with the Community Action Center of Whitman County to help our student design team to better understand the challenges underlying home energy retrofits and to gain greater knowledge about the needs and desires of the low-income home owners and renters we hope to reach with our TrashWall strategy. The CAC will provide advice and insight on the appropriateness and value of the products coming out of this project as well as critiques of prototype designs. In addition, the CAC will help the student team reach out to potential customers who might consider installing a TrashWall system in their own living spaces.

**References**

1. Krarti, Moncef, (2012) Weatherization and Energy Efficiency Improvement for Existing Homes: An Engineering Approach, CRC Press, Boca Raton, FL, USA, 04/2012.
2. McNary, Bill and Berry, Chip, (2012) “How Americans are Using Energy in Homes Today,” *2012* American Council for an Energy- Efficient Economy Summer Study on Energy Efficiency in Buildings*,* U.S Energy Information Administration, pp. 1-204 – 1-215.
3. Pivo, Gary, (2012) “Energy Efficiency and its Relationship to Household Income in Multifamily Rental Housing,” Fannie Mae, pp. 1-20,September 12.
4. Katrakis JT, Knight PA and Cavallo JD, (1994) Energy‐Efficient Rehabilitation of Multifamily Buildings in the Midwest, ANL/DIS/TM‐16 , Argonne National Laboratory, Argonne, Illinois.
5. Nicholson, Blake, (2014) Propane shortage fuels reservation crisis, AP wire service, Feb. 7.
6. Hsu, Andrea, (2014) For the poor, warmth in the winter comes at a steep price, NPR, March 14.
7. Barry, Dan,(2012) In fuel oil country, cold that cuts to the heart, NY Times, Feb. 3.
8. Levine, A., *et al.*, (1982) Energy Conservation in Rental Housing: Landlords' Perceptions of Problems and Solutions, SERI/RR‐744‐1308, Solar Energy Research Institute, Golden, Colo., March.
9. Laquatra J, (1987) Energy Efficiency in Rental Housing, Energy Policy15(6), pp.549‐558.
10. DeCicco J, Smith LA, Diamond R, Morgan R, Debarros J, and Nolden S, (1994) Energy Conservation in Multifamily Housing: Review and Recommendations for Retrofit Programs, American Council for an Energy Efficiency Economy, Research Report A945.
11. Levy, J.I., Nishioka, Y., Spengler, J.D., (2003) The public health benefits of insulation retrofits in existing housing in the United States,” Environmental Health, 11 April, <http://www.ehjournal.net/content/2/1/4>
12. US Energy Information Administration, (2014) Table 5.6.A. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, <http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a>
13. Ucar,A., Balo, F. (2010) Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls, Renewable Energy, 35(1), pp.88-94, 2010.
14. Fowlie, M., Greenstone, M., Catherine Wolfram, Do energy investments deliver? Evidence from the Weatherization Assistance Program, WP-021,The E2e Project, June, 2015.
15. New reference on Vik Yadama’s CMEC work on Waffle Panels
16. Balatinecz, J. J. (1976). *Patent No. 4111730.* United States of America.
17. Ellis, S. C., Ruddick, J. N., & Steiner, P. R. (1993). A Feasibility Study of Composites Produced from Telephone Directory Paper, Plastics, and Other Adhesives. *Forest Products Journal* , 23-26.
18. Voth CR. Lightweight sandwich panels using small-diameter timber wood-strands and recycled newsprint cores. MS Thesis, Dept. of Civil and Env. Eng., Washington State University, Pullman, WA 2009:92p.
19. Suchsland, O. (1998). Laboratory Experiments on the Use of Recycled Newspaper in Wood Composites. *Forest Products Journal Vol. 48, No. 9* .
20. Nourbakhsh, A. e. (2008). Evaluation of the Physical and Mechanical Properties of Medium Density Fiberboard Made from Old Newsprint Fibers. *Journal of Reinforced Plastics and Composites, Vol. 00, No. 00* .
21. Stat-Ease. 2007. Design-Expert® 7.1 for Windows – Software for Design of Experiments (DOE). Minneapolis. http://www.statease.com/dx71descr.html
22. ASTM. Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. C518-10, West Conshohocken, PA, 2015.

1. Davies JM. Lightweight sandwich construction. John Wiley & Sons, 2008.

**RELEVANCE**

**A. Relevance to EPA**

1. The TrashWall project contributes to the EPA’s progress towards fulfilling its mission of protecting human health and the environment by directly addresses two of EPA’s Strategic Goals: Goal 1: Addressing Climate Change and Improving Air Quality and Goal 3: Cleaning Up Communities and Advancing Sustainable Development.

 Energy use in buildings, residential and commercial accounts for almost half of all energy used in the United States, and the largest use for energy in homes and businesses is heating and cooling. Significantly reducing the demand for energy for heating and cooling in buildings would have a large impact on total energy use, and on emissions of greenhouse gases from fuels burned to supply that energy in the US, and around the world. The EPA’s own goal for reducing greenhouse gas emissions from buildings is 215.50 MMTCO2Eq.

 While much work has been done on how to build new buildings with very low or zero energy use, much less work has been done on how to retrofit older buildings to reduce their energy use. The challenge becomes greater, the older and the less energy efficient an existing building is to start with. The TrashWall project addresses this problem focusing on the poorest Americans, living in the most energy inefficient buildings in the US. The TrashWall project proposes to address climate change by reducing greenhouse gas emissions associated with the fuels used to provide energy to heat and cool the homes of low-income Americans.

TrashWall works to address climate change by making it economically feasible and economically advantageous for low-income Americans to use less energy. The environmental impact of the TrashWall project goes hand in hand with its economic effects. The process we are developing is intended to help individuals gain the economic power to redesign the space they live in to be more comfortable, and use significantly less energy by employing materials they can harvest themselves. Thus, people living in rented spaces can transform those spaces to save resources and money, and to better represent their own values. In this way, TrashWall offers people a way to take on the sometimes overwhelming issues of air pollution, solid waste, greenhouse gases and global climate change and do something on a personal and local level. TrashWall empowers individuals to reduce their own energy needs in order to make a difference in their own lives, by saving money, and in the lives of all people by reducing the environmental impacts of generating that energy. In this way TrashWall works toward EPA’s goal of addressing climate change and improving air quality, by reducing greenhouse gas emissions and developing adaptation strategies to address climate change and protect and improve air quality.

1. The TrashWall project also addresses and EPA’s Goal 3: Cleaning Up Communities and Advancing Sustainable Development. TrashWall advances sustainable development by giving low-income Americans a way to reduce the energy they need to heat and cool their homes. TrashWall can help promote Sustainable Communities, by giving communities the tools to help them save money, save energy and reduce air pollution and solid waste.
2. It is important to point out that the benefits of this project will go primarily to the poorest Americans, helping to protect disproportionately impacted low-income and minority communities. Since the rental properties and homes where low-income Americans live are often the most energy inefficient buildings, those renters suffer high utility bills for energy that is largely wasted. The combination of high energy bills and low income poor only exacerbates the pain. The poorest of renters can find themselves paying utility bills that are a sizable fraction of their monthly income during the most extreme months of the year. Accounts of poor residents suffering and even dying because of their inability to pay for energy to heat or cool their home are not difficult to find.
3. The TrashWall process is also a vehicle to help people in the community to increase their understanding of and participation in energy issues. We believe that documenting the TrashWall designs and performance on the TrashTalk website will make energy conservation more transparent by allowing people to see real solutions implemented in actual residences. Both individuals and society benefit when the tools of self-determination are widely spread.

For this approach to really be successful, it is incumbent on us to design and fabricate interesting, attractive and money saving TrashWall designs. It is also necessary to communicate the value of this approach, as well as the “how-to” of designing and implementing this kind of energy and money saving approach. Only if this approach can “go viral” and taken up by many others based on our online presence can this project achieve long-term viability and be considered truly successful.

Finally, the proposed project will contribute to the goal of pollution prevention in three major and complementary ways. First, the project will directly prevent solid pollution; reducing the amount of solid waste being disposed of, by reusing locally-harvested, waste materials as building materials for our energy saving TrashWalls. This supports the EPA’s mission under SWDA: Solid Waste Disposal Act--Section 8001: by contributing to resource recovery and conservation, production of usable forms of recovered resources; and waste reduction. Second, the project will directly prevent air pollution; reducing combustion gases, including greenhouse gases that result from the burning of fossil fuels, by markedly reducing the energy needed to space condition the residential buildings we install our TrashWalls in. This supports the EPA’s mission under CAA: Clean Air Act--Section 103, by preventing air pollution, particularly from utility electrical production and from the burning of fuels (such as natural gas) for space heating. The final goal of this work is to result in a “Do-It-Yourself” (DIY) approach that will empower and encourage community members to save energy and prevent pollution, by building TrashWalls in their own dwellings, wherever they live