NAVAJO HOME HEATING PRACTICES, THEIR IMPACTS ON AIR QUALITY AND HUMAN HEALTH, AND A FRAMEWORK TO IDENTIFY SUSTAINABLE SOLUTIONS

WYATT MARK CHAMPION

B.S. Env.E., University of Central Florida, 2011
M.S. Env.E., University of Central Florida, 2013

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Doctor of Philosophy
Environmental Engineering
Department of Civil, Environmental, and Architectural Engineering
2017

Advisor: Lupita D. Montoya, Ph.D.

Signature Page

This dissertation entitled:

Navajo Home Heating Practices, Their Impacts on Air Quality and Human Health, and a Framework to Identify Sustainable Solutions

has been approved for the Department of Civil, Environmental, and Architectural Engineering

Dr. Lupita D. Montoya, Committee Chair

Dr. Angela R. Bielefeldt

Dr. Clint Carroll

4/18/2017

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Abstract

Navajo Home Heating Practices, Their Impacts on Air Quality and Human Health, and a Framework to Identify Sustainable Solutions

Wyatt Mark Champion

Ph.D. Dissertation Defense in Environmental Engineering

Department of Civil, Environmental, and Architectural Engineering

Dissertation directed by Assistant Professor Lupita D. Montoya, Ph.D.

Most homes on the Navajo Nation (NN) use wood, coal, or a combination of the two fuels for heating in residential stoves that are often old, damaged, or improperly designed for coal use. Health effects from this practice have been observed for residents in the NN cities of Shiprock, NM, Fort Defiance, AZ, and Tuba City, AZ. In response to a call for assessing heating options available in the NN, a mixed-methods framework was developed to identify the most viable options in terms of culture, perception, costs and benefits. A residential wood stove change-out program was supported by findings of all three independent assessments. Next, the combustion emissions of two wood and two coal types commonly used on the NN were characterized with an *in-use* residential wood stove. On a fuel energy basis, coal compared to wood emitted significantly more fine particulate matter ($PM_{2.5}$), organic carbon (OC), and carbon monoxide (CO).

The emission factors developed from the testing were then utilized in a chemical mass balance model to predict steady-state indoor concentrations in a "Typical" Navajo home. The model was validated against data from a 2014 indoor air quality study on the NN conducted by the Hannigan research team at CU Boulder. The model-predicted concentrations of $PM_{2.5}$, EC, and

CO were not significantly different than field-measured concentrations for coal burning homes. With further validation, this model may serve to estimate emission reductions from the wood stove change-out program on the NN scheduled for 2017.

Lastly, aqueous extracts of $PM_{2.5}$ sampled from the emissions tests were assessed using an oxidative stress model in murine macrophage cells. Both wood and coal induced the oxidative stress protein heme oxygenase-1 (HO-1) and the inflammatory cytokine tumor necrosis factor alpha (TNF-α). The magnitude of both responses correlated with mass particle content of low volatile OC, EC, and soluble copper. This research incorporated development of a mixed-methods framework, traditional emissions modeling, residential stove emissions testing, and the use of biological assays to assess the current issue of wood and coal use on the NN.

Table of Contents

Signature Page iii

Abstract iv

Table of Contents vi

List of Figures xii

List of Tables xiii

1. Introduction 1

1.1 The Issue of Home Heating on the Navajo Nation 1

1.2 Wood and Coal Combustion 2

1.2.1 Fuel Classification 3

1.2.2 Solid Fuel Combustion Processes 3

1.3 Dissertation Overview 5

2. Perception, Culture, and Science: A Framework to Identify In-home Heating Options to Improve Indoor Air Quality in the Navajo Nation 8

2.1 Abstract 9

2.2 Introduction 9

2.2.1 The Navajo Nation 9

2.2.2 Air Quality and Health in Shiprock, NM 11

2.2.3 The In-home Heating Alternatives Project (IHAP) 14

2.3 Study Design and Methods 15

2.3.1 Diné Analytical Framework 15

2.3.2 Study Design and Implementation 15

2.3.3 Selection of Heating Alternatives 16
2.3.4 Community Perception Assessment 18
2.3.5 Cultural Assessment 19
2.3.6 Technical Assessment 20
2.4 Results and Discussion 23
2.4.1 Community Perception Assessment of Heating Alternatives 23
2.4.2 Cultural Assessment of Heating Alternatives 24
2.4.3 Technical Assessment of Individual Heating Alternatives 26
2.5 Conclusions 30
2.6 Acknowledgments 33
3. Emission Factors of Fine Particulate Matter, Organic and Elemental Carbon, Carbon Monoxide, and Carbon Dioxide for Four Solid Fuels Commonly Used in Residential Heating by the Navajo Nation 35
3.1 Abstract 35
3.2 Introduction 36
3.3 Materials and Methods 39
3.3.1 Homestoves 39
3.3.2 Fuels 40
3.3.3 Experimental Setup 41
3.3.4 Sampling 42
3.3.5 Filter Analyses 44
3.3.6 Test Protocols 45

3.3.7 Emission Factors ... 48

3.3.8 Carbon Balance ... 49

3.4 Results and Discussion ... 49

3.4.1 Mass Emission Factors ... 49

3.4.2 Energy Emission Factors ... 53

3.4.3 Correlation of $PM_{2.5}$ and CO Emission Factors ... 54

3.4.4 Real-time conditions ... 55

3.5 Conclusions ... 58

3.6 Acknowledgements ... 59

4. Comparison of Field Determined $PM_{2.5}$, OC, EC, and CO Concentrations in Wood and Coal Burning Navajo Homes with Steady-state Concentrations Predicted by a Chemical Mass Balance Model ... 60

4.1 Abstract ... 60

4.2 Introduction ... 61

4.3 Materials and Methods ... 63

4.3.1 Field Sampling ... 63

4.3.2 Chemical Mass Balance Model ... 63

4.3.3 Fuel Grouping ... 67

4.3.4 Model Optimization ... 68

4.4 Results and Discussion ... 69

4.5 Conclusions ... 72

5. Fine Particulate Matter from the Combustion of Wood and Coal Types Commonly Used on the Navajo Nation Induce Oxidative Stress and Inflammatory Responses in Murine Macrophage Cells 74

5.1 Abstract 74

5.2 Introduction 75

5.3 Materials and Methods 77

5.3.1 Fuels 77

5.3.2 Testing 78

5.3.3 Sampling 79

5.3.4 Gravimetric and Carbon Analyses 80

5.3.5 Sample Extractions 80

5.3.6 Soluble Metal Analysis 81

5.3.7 Endotoxin Assay 82

5.3.8 Cell Culture and Stimulation 82

5.3.9 Western Blot of HO-1 82

5.3.10 Measurement of TNF-α in Cell Culture Media 83

5.3.11 Determination of Cell Viability 83

5.3.12 Data Analysis 84

5.4 Results and Discussion 84

5.4.1 Organic and Elemental Carbon Content 84

5.4.2 Soluble Metals 86

5.4.3 Endotoxin 87

5.4.4 Oxidative Stress Response 88

5.4.5 Oxidative Stress Response and Particle Composition 90

5.4.6 Inflammatory Response 92

5.4.7 Inflammatory Response and Particle Composition.. 94

5.4.8 Cytotoxicity.. 96

5.5 Conclusions... 96

6. Conclusions... 99

6.1 Summary of Findings... 99

6.2 Study Limitations... 100

6.3 Practical Implications... 101

6.4 Future Work 102

7. References... 103

8. Appendix... 122

8.1 Chapter 2: Perception, Culture, and Science: A Framework to Identify In-home Heating Options to Improve Indoor Air Quality in the Navajo Nation 122

8.1.1 Technical Assessment Equations... 129

8.1.2 Cost Details and Methodologies 145

8.1.3 Memo from Ken Davidson (USEPA) to Katie Stewart (USEPA). Residential Wood Combustion (RWC) Benefits-per-ton (BPT) Values for the Navajo Nation. 06/19/2014.. 182

8.2 Chapter 3: Emission Factors of Fine Particulate Matter, Organic and Elemental Carbon, Carbon Monoxide, and Carbon Dioxide for Four Solid Fuels Commonly Used in Residential Heating by the Navajo Nation.. 184

8.2.1 Washing and Calibration Protocols 184

8.2.2 Carbon Balances ... 185

8.2.3 Error propagation for $PM_{2.5}$ Mass Emission Factors ... 187

8.3 Fine Particulate Matter from the Combustion of Wood and Coal Types Commonly Used on the Navajo Nation Induce Oxidative Stress and Inflammatory Responses in Murine Macrophage Cells ... 189

8.3.1 Results and Discussion ... 189

List of Figures

Figure 1-1. Overview of Solid Fuel Combustion.. 4

Figure 2-1. Map of the Navajo Nation and Four Corners Area…………………………………...10

Figure 2-2. Summarized Methods and Results of Technical Assessment. 29

Figure 2-3. Integrated Results of Perception, Cultural, and Technical Assessments.. 31

Figure 3-1.Navajo *Homestove* with Firebox Dimensions……………………………………...40

Figure 3-2. Schematic of *CUEST* Experimental Facility. 43

Figure 3-3. Overview of Phases and Equations for *mEF* and *eEF* 46

Figure 3-4. $PM_{2.5}$ and CO EF for a) *Test* Phase and b) *Cycle*. 55

Figure 3-5. Real-time *Test* Phase (a,b) CO and (c,d) TSP Concentrations, and (e,f) MCE.. 57

Figure 4-1. Terminal Velocity of Particle Deposition………………………………...…………..65

Figure 4-2. Optimization of Flue Efficiency to Fit *Model* to *Field* Determined Concentrations . 69

Figure 4-3. Test Statistic (k) to Compare *Model* to *Field* Measured Concentrations.................. 71

Figure 5-1. Navajo Wood-burning Stove……………..……………………………………...78

Figure 5-2. Composition of $PM_{2.5}$ 85

Figure 5-3. Induction of Heme Oxygenase 1 (HO-1) 89

Figure 5-4. Correlations of Particle Components with HO-1 Induction...................................... 90

Figure 5-5. Concentration of TNF-α in the Cell Culture Media.. 93

Figure 5-6. Correlations of Particle Components with TNF-α Production.................................. 95

Figure 5-7. Three-tier Model for Oxidative Stress Response. 97

List of Tables

Table 3-1.Proximate Analysis and Higher Heating Value of Fuels Tested 41

Table 3-2. *Test* Phase Conditions.. 47

Table 3-3.Mass Emission Factors for *Test* Phase 50

Table 3-4. Energy Emission Factors for *Cycle* 53

Table 4-1. Mean *Homestove Cycle* Burn Rate and Mass Emission Rates…………………………...67

Table 4-2. Mean *Homestove* Mass Emission Rates 67

Table 4-3. *Model* Predicted Steady-state and *Field* Determined Indoor Concentrations. 70

.Table 5-1. Soluble Metal Content of $PM_{2.5}$ (% w/w) Ranked by Mean Concentration…………87

1. Introduction

1.1 The Issue of Home Heating on the Navajo Nation

The Navajo Nation (NN), *Dinétah*, is the largest Native American sovereign territory and home to majority of the 300,000 enrolled Navajo tribal members. The "Land of The People" resides in the Four Corners, a relatively cold region of the United States where home heating is widely necessary fall through late spring. Most Navajo homes burn wood, coal, or a combination of the two fuels indoors for heating.

Coal mining has been occurring on the NN as early as the 1920's (O'Sullivan, 1958). It is said that when the harmony of *Black Mesa*, the Mountain Mother of the Navajo spirit, is destroyed, the *Diné* will be endangered (Grinde and Johansen, 1995). *Black Mesa* is one of the largest coal fields in the United States, and is centrally located on the reservation. Navajo tribal policies of the 1970's and 1980's pushed resource development and coal mining, potentially contributing to the contemporary use of coal in many Navajo homes.

Use of a residential solid fuel stove has been associated with respiratory disease in the Navajo communities of Ft. Defiance and Tuba City, AZ (Robin et al., 1996; Morris et al., 1990). The *Diné* College and US Geological Survey identified that respiratory disease burden in the NN's largest city, Shiprock, NM, may be reduced by "changing indoor home heating behavior" (Bunnell et al., 2010). An assessment of the potential of these wood and coal emissions to induce cellular responses *in vitro* may elucidate the mechanisms by which they cause health effects. Particulate matter induces the generation of reactive oxygen species (ROS) and can result in inflammation and disease (Breysse et al., 2013). Combined with additional analyses, the specific particle components that promote oxidative stress or inflammation responses may be identified.

Specific to Native American communities, holistic problem-solving approaches that link "social, cultural, and spiritual values, beliefs, and practices" to the environment are needed (Arquette et al., 2002). Racial and ethnic subpopulations including Native Americans are often more at risk to air (Jones et al., 2014), water, and soil pollution (Pollock III and Vittas, 1995) compared to other Americans. Previously in Native American communities, traditional risk assessment models and problem-solving frameworks have not provided representative impact estimates, nor effective solutions (Quigley et al., 2000; Akwesasne Task Force on the Environment, 1997), and therefore may unfairly justify decision-making (O'Brien, 2000). Assessment of this current wood and coal use must account for economics (Leach, 1992), personal preference and education (Heltberg, 2005), and habit (Mekonnen and Köhlin, 2009). Traditional and scientific Native American knowledge is an essential asset to decision-makers in these communities (Arquette et al., 2002). Therefore, a comprehensive and holistic approach to the issue of wood and coal use in Navajo homes is explored in this dissertation.

1.2 Wood and Coal Combustion

Wood and coal combustion in a residential heating stove is a complex process that can emit variable levels of health-damaging pollutants indoors. The standardized testing of a representative Navajo stove with common practices may provide a direct comparison between the solid fuel types widely used in this community (i.e., wood vs. coal). Emissions test results may also inform public and tribal policy, provide educational materials, and offer refinement of emissions-based models utilized for this community.

Currently these models rely on emission factors for residential wood stoves published by the US EPA. These "reference" emission factors may not represent emissions and subsequent exposures observed in wood-burning Navajo homes. Additionally, the US EPA has never certified a coal stove, and there exist no standard emission factors for this stove type, nor for coal combustion in a residential wood stove.

1.2.1 Fuel Classification

Wood is classified into softwoods (i.e., gymnosperms) and hardwoods (i.e., angiosperms). Softwoods are generally higher in carbon and energy contents compared to hardwoods, but contain less fixed carbon (Lamlom and Savidge, 2003). Wood has three main components: cellulose, hemi-cellulose, and lignin, each comprising roughly 40, 35, and 25% by mass. Cellulose is a polymer of carbohydrates (i.e., polysaccharide) consisting of hundreds to thousands of linked glucose units and the primary component of vascular plant cell walls. Hemi-cellulose is a copolymer of sugars with a more random, weaker structure. Lignin is a cross-linked aromatic-rich polymer that is primarily responsible for the strength of the cell walls of vascular plants.

Coal is classified by rank, or the degree to which the organic matter has been transformed into graphitic carbon (i.e., coalification). Lower-rank coal contains more of the original structures (i.e., cellulose) and has lower carbon and energy contents. Higher-rank coal contains a more ordered structure of chains and sheets of carbon (i.e., graphite), and has higher carbon and energy contents. Coal is ranked by content of volatile matter, and major classifications are (from low to high rank): lignite, sub-bituminous, bituminous, and anthracite. Within each, there is further sub-classification.

1.2.2 Solid Fuel Combustion Processes

Solid fuel combustion can be considered to occur in four steps, as visualized in Figure 1-1. Heat transfer into the bulk fuel drives the 1) drying, 2) devolatilization, 3) ignition and flaming combustion, and 4) smoldering combustion processes. These processes occur at varying rates throughout the bulk of the fuel, moving radially inwards from the surface. Drying of fuel moisture begins immediately upon heat transfer into the fuel, and is an exponential function dependent upon the temperature gradient between the flame (or heat source) and fuel. Next, devolatilization of the fuel occurs through mixed-phase reduction and oxidation reactions occurring on the fuel surface. Some key reactants and products for the devolatilization of wood and coal are included in Figure 1-1 (Di Blasi, 2008; Cypres, 1987; Mohan et al., 2006).

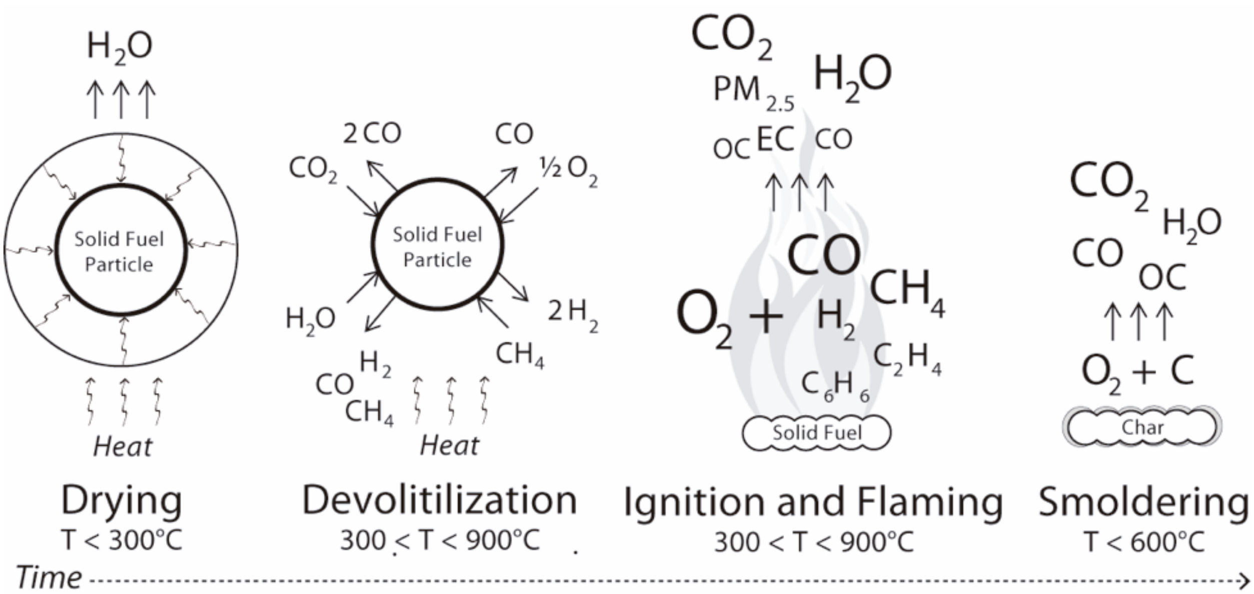


Figure 1-1. Overview of Solid Fuel Combustion.

Ignition and flaming combustion begins when the energy-rich gases (i.e., H_2, CH_4, CO, C_2H_6) from devolatilization ignite (initially at around 300°C) which begins flaming combustion. Flaming combustion produces high temperatures, rapidly drives the drying and devolatilization steps to produce more combustibles, and is self-propagating. Smoldering combustion begins when production of combustible gases drops below that needed to maintain flame propagation. The remaining charcoal or coke is oxidized at a much slower rate than by flaming combustion, and proceeds until the fuel is consumed.

1.3 Dissertation Overview

This dissertation is comprised of four main chapters, each addressing one hypothesis:

Hypothesis 1: *A methodology incorporating perception, culture, and engineering leads to a well-defined set of recommendations to support an appropriate and sustainable stove change-out intervention.* A parallel convergent mixed-methods approach was employed to assess the current issue of wood and coal use in Navajo homes. A mixed-methods framework was developed that included cultural significances, community perception, and health-based cost benefit modeling. Seven heating alternatives identified by community stakeholders were assessed. A *homestove* (i.e., residential wood stove) change-out program for the NN was supported by findings of the three parallel and independent assessments. This work was published in *Science of the Total Environment* and presented in Chapter 2.

Hypothesis 2: *Emission factors of $PM_{2.5}$ and its components (elemental carbon, organic carbon, Ca, Al, Na, K, Fe, Mg, Pb, Cu, Mn) are greater for wood types (Ponderosa Pine and Utah Juniper softwoods) than for coal types (Black Mesa and Fruitland bituminous) used by the Navajo under controlled laboratory conditions and fixed stove type.* The University of Colorado's Emissions Testing and Standardization (CUEST) facility was designed and constructed to test wood and coal types commonly used in the NN. Standard protocols were adapted and modified for both *cookstoves* (data not presented in this dissertation) and *homestoves*. Fine particulate matter ($PM_{2.5}$) was sampled for analyses of mass, organic and elemental carbon content (OCEC), and trace metals. Emission factors were developed by normalizing mass emissions by both fuel mass and fuel energy consumed. On an energy basis, coal compared to wood emitted more than two fold the $PM_{2.5}$, OC, and CO. Wood and coal emitted similar EC per unit fuel energy. Emissions peaked following fuel addition, suggesting that exposures are highest during the devolatilization and initial flaming combustion phases. *Ponderosa Pine* developed a hot charcoal bed with lower emissions compared to *Utah Juniper*. This work was submitted to the *Journal of the Air and Waste Management Association* and is presented in Chapter 3. Trace metal content of the fuels are discussed in Chapter 5.

Hypothesis 3: *Emissions of $PM_{2.5}$ and its components in the laboratory follow the same trends as those measured in Navajo homes.* A chemical mass balance model was utilized to estimate steady-state indoor concentrations in a representative Navajo home burning wood and coal. Model assumptions were based on home characteristics and emissions data developed and presented in Chapters 2 and 3. *Model* predicted indoor steady-state concentrations were compared against *field* measured three-day average indoor concentrations, as determined from a spring 2014 air quality study of Navajo homes conducted by the Hannigan research group (University of Colorado Boulder). *Model* predicted indoor concentrations of wood-burning homes were significantly lower than *field* measured indoor concentrations for $PM_{2.5}$ and CO, significantly higher for EC, but not significantly different for OC. For coal-burning homes, the *measured* compared to *field* concentrations were not significantly different for $PM_{2.5}$, EC, and CO. Therefore the model developed may be useful for understanding current exposures inside of a representative Navajo home burning coal in a wood stove. This work is presented in Chapter 4.

Hypothesis 4: *$PM_{2.5}$ sampled from laboratory experiments and Navajo homes heated with wood and coal can induce adverse cellular effects in murine macrophage cells.* A three-tier hierarchical oxidative stress model using murine (i.e., mouse) macrophage cells was employed.

Cells were exposed to two doses of $PM_{2.5}$ aqueous extracts (AEs) prepared from filter samples collected during wood and coal tests at CUEST (Chapter 3). The AEs of *Ponderosa Pine, Utah Juniper,* and *Black Mesa* caused significant induction of pro-oxidant mediator heme-oxygenase 1 (HO-1). AEs of *Ponderosa Pine* and *Black Mesa* also caused significant release of the pro-inflammatory cytokine tumor necrosis factor alpha (TNF-α). Co-emitted particle mass content of low-volatility OC and EC, as well as AE mass content of soluble copper were correlated to both HO-1 and TNF-α responses (i.e., oxidative stress and inflammation markers). This work is presented in Chapter 5.

A summary of findings, limitations of this work, and recommendations for future research is presented in Chapter 6.

2. Perception, Culture, and Science: A Framework to Identify In-home Heating Options to Improve Indoor Air Quality in the Navajo Nation

Champion, W.M.[1], Charley, P.H.[2], Klein, B.[2], Stewart K.[3], Solomon P.A.[4], and Montoya, L.D.[1]

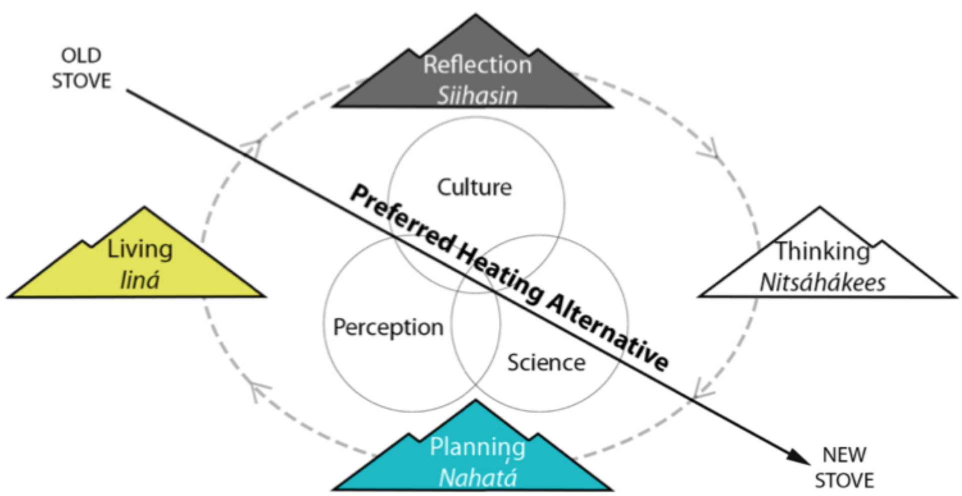
[1] University of Colorado Boulder, Civil, Environmental, and Architectural Engineering Department, Boulder, CO 80309

[2] Diné College–Shiprock Campus, Diné Environmental Institute, PO Box 580, Shiprock, New Mexico 87420, United States

[3] United States Environmental Protection Agency, Region 9 Air Division, Air Toxics, Radiation, and Indoor Air Office, 75 Hawthorne St, San Francisco, CA 94105, United States

[4] United States Environmental Protection Agency, Office of Research and Development, 944 E. Harmon Ave., Las Vegas, NV 89119, United States

Published in *Science of the Total Environment (DOI: 10.1016/j.scitotenv.2016.11.053)*



Graphical Abstract

2.1 Abstract

A 2010 study identified higher than average incidence of respiratory disease in Shiprock, NM, the largest city in the Navajo Nation. That study suggested that the potential cause was the combustion of solid fuels in in-home heating stoves and that respiratory disease could be greatly reduced by changing indoor heating behaviors and improving heating stove quality. Since the Navajo people are deeply embedded in culture and traditions that strongly influence their daily lives, a new framework was needed to identify feasible heating alternatives that could reduce the negative environmental and health impacts related to solid fuel use while respecting the culture of the Navajo people.

The resulting Navajo framework included perception, cultural, and technical assessments to evaluate seven heating alternatives *perceived* viable by Navajo stakeholders. Cultural experts at the Diné Policy Institute identified potential *cultural* limitations and motivating factors for each alternative. A limited *technical* assessment of the health benefits of these options was conducted and integrated into the process. The results and framework developed and presented here may be useful for decision makers in communities heavily reliant on solid fuels for heat, especially Native Nations, where culture plays an important role in the success of any intervention.

2.2 Introduction

2.2.1 The Navajo Nation

The Navajo Nation (NN) is the largest sovereign Native American nation within the United States (population 175,000) (US Census Bureau, 2014a) occupying about 69,930 km^2 within Arizona, New Mexico, and Utah (Figure 2-1). Its population is growing nearly twice as fast as the US average (Navajo Housing Authority 2011) and 32% of the population is under six years old

(US Census, 2014b). These populations are at a higher risk of health effects from indoor air emissions (Sly and Flack 2008). The poverty rate in the NN is 42% (US Census Bureau, 2014c) compared to the US average of 16% (US Census Bureau, 2014d), directly impacting their access to clean energy.

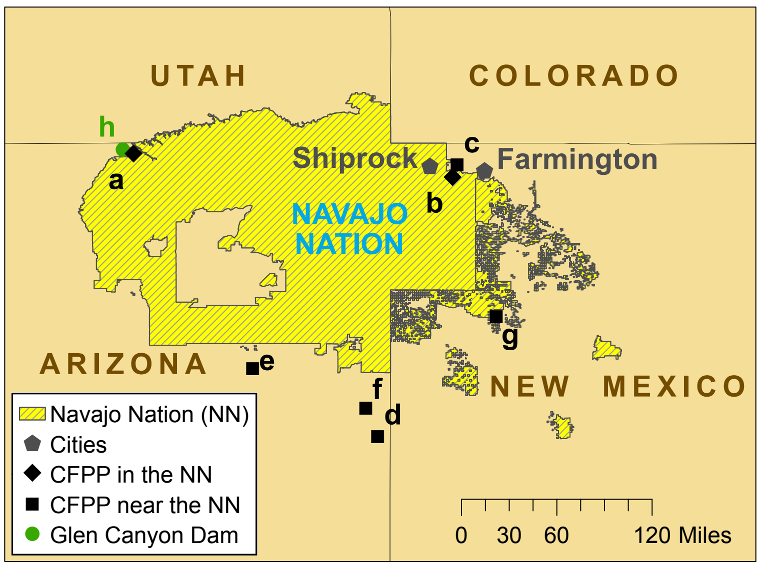


Figure 2-1. Map of the Navajo Nation and Four Corners Area (CFPP - Coal-fired Power Plants).

Dinétah (the Land of the People, in the Navajo language) is part of the Colorado Plateau at an altitude of 1,680 m. There are two coal-fired power plants (points a and b in Figure 2-1) within the boundaries of the NN, and five coal-fired power plants and a hydroelectric plant within 80 km of the NN border (points c-h in Figure 2-1), yet 20% of Navajo homes are off the grid/lack electricity (Navajo Housing Authority, 2011).

According to the US Census Bureau (2011), wood is the primary heating fuel in 62% of all Navajo homes, followed by natural gas (14%), propane (11%), electricity (11%), and kerosene, fuel oil, or other fuels (2%). The Navajo Housing Authority (NHA), however, reported that as many as 89% of rural Navajo homes use wood stoves for heating (NHA, 2011). While not identified in surveys by the US Census Bureau and NHA, unprocessed Black Mesa and Fruitland high-volatile bituminous coals (M. A. Kirschbaum, Roberts, and Biewick 2013), are distributed freely or at low cost and are widely used by NN residents to heat homes primarily at night (Hickmott et al. 1997; Bunnell et al. 2010).

Navajo dwellings include contemporary single family homes (59%), mobile homes (17%), multi-family attached housing (13%), and traditional *hogans* (eight sided homes with a wood burning stove and open roof in the center) (11%) (NHA, 2011). It is estimated that 63% of Navajo homes were built before 1990 (US Census Bureau, 2014e) and are probably in need of weatherization (e.g., caulking and weather stripping). Houses built by the NHA during the 1970's and 1980's often have no attic insulation, while newer NHA homes are more likely to include this feature. Eighty percent of Navajo homes are owned by the residents (Navajo Housing Authority 2011); however, home improvements done by owners may not follow housing codes, including insulation requirements.

2.2.2 Air Quality and Health in Shiprock, NM

Shiprock, NM is the largest city (population 8,300) in the NN, is located near the Four Corners Power Plant, and is part of the Farmington, NM Metropolitan Area (US Census Bureau, 2010). Farmington (population 45,900) lies 50 km east of Shiprock (Figure 2-1), just outside the NN border. Average daily high temperatures in the Shiprock-Farmington area range from 24°C in summer to -2°C in winter; average daily lows are below -1°C from November through March, reaching extremes as low as -37°C (NOAA 2011). Between 2005 and 2014, this region experienced an annual average of 139 days at or below freezing (0°C), 18 cm of rain, and 25 cm of snow (NOAA, 2015).

Heating Degree Days (HDD) are commonly used to assess heating demands and are defined as the difference between the daily mean ambient temperature (e.g., 30°F) and a defined indoor comfort temperature (e.g. 65°F). The HDD for this day (65-30) would be 35°F and then each day's difference is summed over a time period (e.g., if all days had a difference of 35 for a 30-day month, the monthly HDD would be 35 x 30 = 1,050). In the past 100 years (1915-2014), homes in the NN (New Mexico Climate, Division 1 and Arizona Climate, Division 2) have required 29% more heating than those in the contiguous U.S. annually (5,912 vs. 4,598 HDD) (NOAA, 2015). During the past ten years (2005-2014), homes in Shiprock have needed 17% more heating than those in the contiguous U.S. (5,064 vs. 4,322 HDD annually) (NOAA 2015a). Weatherizing Shiprock homes should reduce the energy required for heating and indoor air pollution.

Shiprock experiences low wintertime inversions that trap air pollution close to the ground, including combustion emissions from home heating (Hickmott et al. 1997). Wood and coal combustion produce a complex mixture of emissions (Gaston et al. 2016), including fine and ultrafine particulate matter (PM) (Schurman et al. 2015; McDonald et al. 2000; Tami C. Bond et al. 2002), polycyclic aromatic hydrocarbons (PAHs) (Samburova et al. 2016; Fine, Cass, and Simoneit 2004; Yingjun Chen et al. 2005), and carbon monoxide (CO) (Venkataraman and Rao 2001; Jaszczur et al. 1995). These components have been associated with adverse health effects (Butt et al., 2016; Solomon et al. 2012; Breysse et al., 2013). Correlations between higher outdoor concentrations of $PM_{2.5}$ and decreased life expectancy in the U.S. have been observed (Pope, Ezzati, and Dockery 2009; Fann et al. 2012). Barone-Adesi et al. (2012) correlated higher lung cancer mortality in China with domestic use of bituminous coal, the type mined at the Black Mesa coal field (M. A. Kirschbaum, Roberts, and Biewick 2013). Similar-rank coal from the Fruitland Formation in the San Juan Basin (M. A. Kirschbaum, Roberts, and Biewick 2013) is also used by Navajo residents living near the Broken Hill Proprietary (BHP) Billiton Navajo mine (Bunnell et al. 2010), posing similar health concerns. Recently, the World Health Organization (2014) strongly discouraged any unprocessed coal use indoors.

Bunnell et al. (2010) indicated that 77% of Shiprock residents surveyed (n=137) used an indoor stove for heating and 25% used coal in stoves not designed for that fuel. This use potentially results in increased indoor air pollution because the higher coal combustion temperatures promote cracking of the stove walls, allowing stove emissions to leak into the house (MacKay et al. 2003). Hickmott et al. (1997) observed that many stoves used by survey respondents were inherited or fabricated by relatives and most users burned a combination of wood and coal. They also determined that local stove retailers often did not specify what fuel should be used in the stove being purchased. Bunnell et al. (2010) observed over 100 times higher 24-hr average indoor concentrations of $PM_{2.5}$ (38 μg m^{-3}; n=19) in Shiprock homes heated with coal during winter months compared to one home heated with propane (0.29 μg m^{-3}) during the same period, exceeding the WHO recommended guideline of 25 μg m^{-3} (World Health Organization 2014). The study also observed three times higher indoor 24-hr $PM_{2.5}$ concentrations in those homes during winter (36 μg m^{-3}; n=20) compared to the summer when no coal was used (12 μg m^{-3}; n=8).

Bunnell et al. (2010) also observed higher rates of hospitalization due to respiratory conditions during the winter relative to summer and Shiprock ranked in the top 10 out of 37 surrounding communities for prevalence of the seven respiratory diseases studied. Past studies have found associations between wood stove use and increased respiratory illness. A study of Navajo homes in and near Ft. Defiance, AZ indicated that among Navajo children under 2 years old, increased prevalence of acute lower respiratory infection (ALRI) was associated with wood stove use (odds ratio, OR = 5.0) and high ($\geq 65\ \mu g\ m^{-3}$) 15-hr average PM_{10} indoor concentration (OR = 7.0) (Robin et al. 1996). Morris et al. (1990) examined respiratory illness among Navajo children of the same age group and of the ten factors studied, only wood stove use and recent respiratory illness exposure were independently associated with higher risk of ALRI.

2.2.3 The In-home Heating Alternatives Project (IHAP)

Motivated by these previous studies, the goals of the IHAP were to assess in-home heating alternatives for residents of the NN and provide recommendations for a stove replacement program that integrates the NN's unique culture and perception of the alternatives with infrastructure and availability limitations and a technical analysis of the alternatives. The IHAP is also responsive to a call by the WHO to develop research on indoor solid fuel use (World Health Organization 2014). Previously, Smith (2002) proposed that the adoption of any household device requires more than just technical and economic efforts, and relies upon social, cultural, and perceptual factors. Similarly, Heltberg (2005) identified taste of prepared meals and tradition as being more important factors than cost in fuel-switching in Guatemala. Patel et al. (2016) recognized that many market-based approaches to cook-stove intervention fail to account for critical factors including cultural structure. Troncoso et al. (2007) found that cooking with open fire was sometimes preferred in rural Mexican homes simply because it is customary. Person et al. (2012) observed that perception of neighbors and peers in rural Kenya strongly influenced the decision to purchase an improved cook-stove. None of these studies, however, proposed nor applied a methodology to integrate perception or culture on a technical solution.

Initially, the project convened stakeholders that included tribal, federal, academic, and private entities as well as NN residents and students. These stakeholders identified potential heating alternatives and established a framework for comparison that involved community members, NN cultural experts, and scientists. This community-science-based approach emphasized the integration of Navajo perception and culture with a technical analysis of heating alternatives, and may provide insight for similar issues in other communities with distinct cultural traditions.

2.3 Study Design and Methods

2.3.1 Diné Analytical Framework

Fundamental Navajo Law was integrated into this study and states that tradition is a resource for finding solutions. The Navajo are guided by the overarching philosophy of Sąʼah Naagháí Bikʼeh Hózhó (SNBH). Principles of SNBH are still relevant to modern environmental and health issues, such as those associated with indoor home heating practices within the NN. The esoteric knowledge contained in the Navajo philosophies were provided by experts within the Diné Policy Institute and integrated into the study. Specifics and details are maintained within the Navajo culture.

2.3.2 Study Design and Implementation

This study applied a parallel convergent mixed-methods approach (Creswell et al., 2011; Creswell, 2009; Johnson et al., 2007), which consisted of three parts: 1) gauging community perception of heating alternatives identified in the stakeholder's workshop and judged by community members; 2) identifying important cultural factors relevant to each alternative; and 3) conducting a limited technical assessment of environmental and health benefits associated with each alternative. Each assessment was conducted independently and then combined using concurrent triangulation.

In Navajo belief, restoration of environmental and public health (balance; *hozho*) requires partnership, community consensus, education, and critical thinking. The first step for the *Diné* (Navajo) People in problem solving is thinking (*Nitsáháskees*), followed by planning (*Nahat'á*), action (*Iiná*), and reflection (*Siihasin*) in a continuous cycle. This study followed these concepts to investigate how to address the heating needs of the NN and reduce the potential negative health effects caused by emissions from indoor solid fuel.

2.3.3 Selection of Heating Alternatives

Seven heating alternatives were selected by the IHAP stakeholders for assessment in the study: central furnaces that use 1) natural gas (NG), 2) propane gas (PG), or 3) electricity (EH); 4) wood pellet stoves (WP); 5) improvement to an existing wood stove (SI); 6) replacement with an improved wood or wood/coal stove (SR); and 7) passive solar heating (PS). Descriptions of each heating alternative follow and they assume a properly installed and operating system.

Natural Gas: Typically centralized units (furnaces) require utility gas and electricity for the blower as well as flue ducts and additional ductwork throughout the house. Maintenance needs include annual inspections and cleaning of the blower wheel, motor, combustion chamber, and air filter (Franklin 2000). Individual room heaters are not available for natural gas. Furnace emissions are low and emitted outdoors.

Propane Gas: Propane heating in this community is primarily by centralized units (selected for this assessment). Centralized propane furnaces require a large liquid propane gas (LPG) tank near the home and transfer pipe from the tank to the house. PG has similar infrastructure and maintenance requirements as NG.

Electrical Heating: Electric heaters are of two main types: centralized units and space heaters. Centralized furnaces using blowers (selected here for analysis) have similar infrastructure and maintenance requirements as centralized gas furnaces, excluding the gas transfer line or large outdoor tank. There are no indoor emissions; however, emissions depend on the pollution controls associated with the power plants. The emissions may have an impact regionally. Space heaters heat one or two rooms.

Wood Pellet: Most wood pellet stoves considered have combustion efficiencies between 58 and 75% (US EPA 1996), easy and automated loading mechanisms, and burn a waste product, such as wood, corn, or grass. Electricity is required to run the automated loading mechanism and blower, and wood pellets only may be accessible to residents in populated areas like Shiprock. Maintenance needs are similar to other wood burning devices and include annual stove and chimney cleaning (James E. Houck and Eagle 2006). Emissions are exhausted through a flue to the outdoors.

Stove Improvement: Stoves used in many Shiprock homes are old and the fuel used may not be appropriate for the stove type. Many have cracked or missing stove walls and flues and thus higher emissions indoors (Bunnell et al. 2010). In this option, stoves in reasonably good condition would be repaired but not replaced. Repairs included replacing gaskets and flue with new double-walled construction. Emissions are exhausted through the flue to the outdoors.

Stove Replacement: This option replaces old stove with non-catalytic US EPA-certified wood stoves with efficiencies of 66-73% (US EPA, 1996). Emissions are eliminated through a flue. Hickmott et al. (1997) suggested that Navajo residents are likely to continue mixed use of wood and coal due to the low cost of coal and its ability to heat the house all night long. Therefore, wood stoves should only be recommended for homes where coal will not be used. Dual wood/coal stoves are available but are not EPA certified, although EPA is in the process of evaluating and certifying dual wood/coal stoves (Stewart 2016).

Passive Solar: Passive solar heating uses sunlight to heat the home and does not require electricity. In this alternative, additional insulation, increased window area on the south-facing wall, and/or upgrade of existing windows would be used (NREL 1991), alongside the continued use of an old conventional wood stove that is properly functioning. An enclosed room extension or Trombe wall also may be added to the house (Balcomb and Mcfarland 1978). The Southwestern U.S. and the Colorado Plateau receive abundant solar radiation (Figure S2-1) for the efficient application of passive solar heating.

2.3.4 Community Perception Assessment

As part of a course, students at Diné College designed a project and obtained voluntary and basic information from their families regarding heating alternatives and how they rated these alternatives (Perry Charley, personal communication, April 1, 2014). This class project involved data gathering and analysis as part of the student learning strategies and their understanding of community-based projects. A total of 56 community members including students, their family members, and advising faculty participated in this class exercise. The criteria were described orally to the respondents and are included in Table S2-1A. The resulting secondary data formed the basis for the Perception Assessment performed by the IHAP. Refined descriptions used in the final assessment are included in Table S2-2. The difference between the two sets of descriptions highlights the importance for employing a framework that promotes early engagement of all relevant stakeholders, clear communication among them, and creation of instruments that use local language and perceptions yet reflect accepted scientific standard methods.

Community members assigned a score to each criterion for all seven heating alternatives. The scores used were:

5 – 'Very feasible'
4 – 'Highly feasible'
3 – 'May be feasible'
2 – 'May not be feasible'
1 – 'Not recommended'
0 – 'Not feasible'

A two-tailed Wilcoxon Signed-rank Test was applied to the perception data since it had a non-normal distribution. An alpha (α) value of 0.05 was used to determine if a perceived alternative was significantly different from all other alternatives for a given criterion. One-sided statements of significantly less (or least) feasible or significantly more (or most) feasible have α values of 0.025 and were derived from the two-tailed test, as recommended by the UCLA Statistical Consulting Group (2016). There were a total of 3,136 perception responses (56 respondents x 7 alternatives x 8 criteria).

2.3.5 Cultural Assessment

Diné fundamental law recognizes relationships between people, the sacred elements (land, air, water, and heat), Mother Earth, and Father Sky. *Diné* people understand that these entities each have rights and freedoms of their own and that the sacred elements are balanced only when natural resources are cared for (*baa aháyá*), valued (*baa háá hasin*), respected (*dílzin*), and cherished (*dóó baa ja' hóná*). The Diné Policy Institute (DPI) at Diné College, a research institute established to "mesh" Western research methods with Fundamental Navajo Law, determined cultural implications for each heating alternative by assessing its relationship with sacred elements and the preservation of balance attained through their use.

Results of this assessment were integrated into the Framework without further analysis to preserve its authenticity. In this study, its main role was to determine if strong limitations or motivations for a given alternative became apparent. A proper implementation of this Framework would emphasize a thorough cultural assessment such that a complete suite of both negative and positive cultural factors are identified.

2.3.6 Technical Assessment

A limited Technical Assessment was conducted using available modeling tools and had three main components. First, a Typical Navajo Home was modeled using Building Energy Optimization (BeOpt) software (v 2.3) (NREL 2014). The house was defined to have an area of 93 m^2 and be located in Shiprock, NM. The home was not weatherized and had significant air infiltration from the outside (see Tables S2-3 and S2-4 for BeOpt inputs and outputs) and used an inefficient wood stove for heating. Default BeOpt home values were used except for: R-values (i.e., capacity to resist heat flow) for wall and ceiling insulation, exterior finish, shingle color, exposed floor area, and window area (Table S2-3). These variations in input parameters were based on personal communication with Navajo residents, as well as an unpublished Navajo home modeling effort by the US EPA (Stewart 2014, personal communication). Second, a Baseline Home was defined as a Typical Home with standard weatherization (reducing its annual average air exchange per hour, AAACH, from 0.60 to 0.40) and modeled with BeOpt to determine the reduction in heating load. Third, each heating alternative was evaluated separately using the Baseline Home heating load and an in-house emissions model based on the US EPA Wood Stove and Fireplace Emission Calculator (US EPA, 2009). Results from this model (BeOpt and calculator) formed the basis of the technical evaluation.

The emissions model used mass emission factors of $PM_{2.5}$ and CO (Table S2-5) from the AP-42 Compilations (US EPA 1996; US EPA 1998; US EPA 2008) as well as US Department of Interior (USDOI 2014) emission estimates for local electricity generation, where applicable. All emissions were assumed to enter the ambient environment (e.g. no emissions entering the indoors). This step was necessary because there are no indoor emissions factors this model. Based on the heating load of the Baseline Home, quantities of fuel consumed annually for each alternative were estimated (Equations 1-19 in Tables S2-6 through S2-9) with assumed efficiencies (Table S2-10), electricity consumption (Table S2-11), fuel densities (Table S2-12), and heating values (Table S13). Annual emissions were calculated (Table S2-14) and net annual reductions (Tables S2-15A and S2-15B) and health benefits (Table S2-16) were compared to the Baseline Home. A summary of assumptions used in the technical assessment is presented in Table S2-17.

Multiple information sources were used to develop the costs and specifications of the options for each heating alternative and used as inputs for the emissions model (Table S2-18A). Each option, within an alternative, represented a different combination of necessary components (e.g. one furnace type and one type of ducting for Natural Gas). The initial (i.e. materials and labor) and long-term (i.e. operation and maintenance) costs were determined from a total of ten information sources:

1) RSMeans Online 2015 Estimating Handbook for Farmington, NM (Gordian Group 2015),

2) NREL BeOpt 2.3 Software Output for Farmington, NM (NREL 2014),

3) National Residential Efficiency Measures Database v 3.0.0 (NREL 2013),

4) NN Utility Costs (Navajo Tribal Utility Authority, 2007),

5) US EPA Burn Wise Online Air Quality Tools (US EPA 2013a),

6) United States Department of Energy Buildings Energy Databook (US DOE 2012),

7) Houck and Eagle (2006),

8) Franklin (2000),

9) Home Depot Online Catalog for Farmington, NM (Home Depot 2014), and

10) Personal communication with Shiprock vendors (Table S2-18B).

An example for Natural Gas follows: RSMeans Online (Gordian Group 2015) was used to estimate labor and capital costs for one furnace retrofit with installation of associated ducting (option 1). This labor cost was then used to create new options using other furnace models from a local retailer's online catalog, leading to options 2 through 5. Each of these options had a different capital cost but the same labor cost. Next, the NREL Database was used to determine 8 more options. Houck and Eagle (2006) suggested two additional potential options, and one option was obtained via personal communication with a local contractor. These represent a total of 16 options (n=16) for Natural Gas. Costs were annualized over the lifetime of each alternative (15-20 years).

Lastly, reductions in annual $PM_{2.5}$ emissions were translated into community health benefits (in US dollars) for the NN. The benefits-per-ton (BPT) values (Table S2-19) used were developed from existing residential wood combustion (RWC) emission inventories for the NN and EPA's Benefits Mapping and Analysis Software v 4.0.66 (BenMAP; US EPA, 2013). Emission (i.e. environmental) and health benefits were normalized to total net annualized costs (amortized initial cost + recurring heating and maintenance costs - wood fuel costs of Baseline Home) for each option of each alternative. This benefits analysis underestimates the benefits associated with RWC emissions reductions because: 1) it does not capture individual health impacts from indoor PM exposures, 2) it likely underestimates tribal RWC emissions inventories, and 3) it quantifies benefits from only a limited number of potential health effects (i.e., BenMAP considers 12 health effects).

2.4 Results and Discussion

2.4.1 Community Perception Assessment of Heating Alternatives

The seven home heating alternatives identified by the stakeholders were ranked by Navajo community members (Section 3.4) using a scale of 0-5, with 5 being "very feasible", applying the criteria listed in the footnote of Table S2-1A. Average total scores were calculated for each alternative resulting in the following order: Propane Gas (24.9), Electrical Heating (24.0), Passive Solar (23.6), Stove Replacement (22.8), Stove Improvement (22.5), Wood Pellet (21.4), and Natural Gas (18.8). Table S2-1B provides the results for each option and criteria listed in Table S2-1A. Only results of the Perception Assessment that reached statistical significance (and shown in bold in Table S2-1B) are discussed here. For a given criterion, an alternative perceived as significantly different and lower than the other 6 alternatives was identified as least feasible. Conversely, an alternative perceived as significantly different and higher than the other 6 alternatives, was identified as most feasible.

Results showed that Natural Gas and Passive Solar were perceived to be least feasible in terms of availability, while Propane Gas and Electrical Heating were both perceived to be most feasible for that criterion. Natural Gas was also perceived to be least feasible in terms of infrastructure already in place (only 14% of households presently use natural gas delivered through pipelines) and least feasible in terms of cultural considerations (there are some cultural taboos against using natural gas). Propane Gas was perceived to be most feasible in terms of initial costs. On the other hand, Passive Solar was perceived to be most feasible in terms of long-term costs, while Wood Pellets was perceived to be least feasible for that criterion. No alternatives were perceived to be different in terms of maintenance needs.

Stove Improvement was perceived to be the least feasible (least beneficial) alternative in terms of environmental benefits compared to all other alternatives, while both Natural Gas and Stove Improvement were perceived to be least feasible in terms health benefits compared to the rest. Passive Solar was the only alternative perceived most feasible in terms of environmental and health benefits. Overall, Propane Gas received the highest total score, which can be interpreted as being perceived as the most feasible and beneficial alternative for use in NN homes for heating whereas Natural Gas was perceived to be the least feasible alternative. Stove replacement ranked fourth in this analysis, with no major perceived drawbacks or disadvantages.

The above analysis ascribed equal weight to all criteria; however, in practice, some criteria would be more important to this community than others. This assessment could be improved by assigning different weights to each criterion, according to the perception results obtained from this community.

2.4.2 Cultural Assessment of Heating Alternatives

The Cultural Assessment was performed by the Diné Policy Institute (DPI) at Diné College. The goal of this assessment was for Navajo policy experts to identify potential barriers or incentives for the implementation of each of the 7 alternatives considered in this study. While the result of this process was not quantitative, it was critical for this Framework to generate recommendations.

Some relevant results and discussion are presented below. The descriptions closely reflect the language and views of the DPI and, therefore, may be less accessible to the regular reader;

however, it is included for fidelity purposes. This also underscores the need for community participation and engagement to secure a successful intervention.

2.4.2.1 Natural Gas and Propane Gas

Natural gas and propane are believed to be natural elements that originated from animals and plants that have decomposed over time and may not be seen as having negative effects on people. Appropriate protocol for accessing and utilizing them should be taken. Also, the blue flame created when combusted could be associated with a more dangerous form of fire, such as lighting. This flame is thought to burn hotter and could have negative effects on the body, such as gall bladder or lung related effects.

2.4.2.2 Electrical Heating

Electricity is linked to energy of lightning, and thus should be treated with utmost precaution. Particular caution should be given to electrical heating sources that heat through direct contact with the human body. Electric blankets as an example, have been cause for some individuals to require ceremonies that can counter the effects. Electric heaters may also have effects on people through drying of the air, including drying of the skin and nostrils.

2.4.2.3 Wood Pellet

According to *Diné* teachings, wood is the preferred method of heating dwellings and cooking food. However, since wood pellet stoves require electricity, this reliance on electricity may be viewed as endangering one’s well-being. Furthermore, some wood types are prohibited, such as Aspen and Cottonwood, since they belong to the snake family and produce a lot of smoke. If pellets were composed of these or other forms of prohibited wood, the effects could be negative for the person using the pellet stove.

2.4.2.4 Stove Improvement and Stove Replacement

From a cultural standpoint, naturally harvested cedar and oak are optimal for use in heating stoves, although pine and piñon are also acceptable. These woods produce red, yellow, or white fire flames, which are seen as the natural flames that represent Navajo sacred relative fires. The removal of coal from Mother Earth should be done with caution and proper protocols of respect and offering must be undertaken for accessing this element. Disregard for these protocols of respect and offering can lead to imbalance and negative effects to people who utilize coal.

2.4.2.5 Passive Solar

The Navajo maintain a strong relationship with the Sun, the father, as a holy being and sacred (*Diyin*). From this connection, the Navajo were given the power of sunlight (*sháńdíín*) to use. However, this use needs to be done with control and care (e.g., prevent overexposure to avoid overheating). In general, sunrays are good, exhibiting positive energy. There is not a taboo against using the sunlight for energy, but some protocols are to be observed. For people to subsist with this energy is a way of life and to access the sun to heat one's home is not restricted. The idea of building according to the Sun is an ancient concept for Diné people. Building a home to orient to the Sun, such as with passive solar, can actually be seen as building according to nature and the path of the Sun, as long as the doorway faces the East.

2.4.3 Technical Assessment of Individual Heating Alternatives

The Technical Assessment consisted of three steps: 1) defining a Typical Navajo Home using BeOpt, 2) defining a Baseline Navajo Home by applying basic weatherization to the Typical Home and reducing its AAACH, and 3) applying each individual alternative to the Baseline Home and using an in-house emissions model to determine the environmental and health benefits of that alternative relative to the Baseline Home. Figure 2-2 shows the three steps including key assumptions pertaining to home characteristics and household heating practices. Mean Initial Costs and Health Implications (benefits) are reported in the right-most column.

Table S2-20 summarizes the results of the Technical and Cultural Assessments for the heating alternatives on the basis of their availability (AV), infrastructure (IN), maintenance needs (MN), and cultural considerations (CC). Availability of Natural Gas was limited by access to gas pipelines, while Propane Gas, Electrical Heating, Wood Pellet, and Stove Replacement were limited by access to electricity. In this study, all the Stove Replacement options assessed had a built-in blower that requires electricity to improve combustion efficiency; however, they could be operated without the blower. Passive Solar is currently limited by access to affordable and effective technologies. Natural Gas, Propane Gas, and Electric Heating require the installation of ducting, a significant infrastructure change if not already in place in the home. Wood Pellet, Stove Improvement, and Stove Replacement are much simpler to retrofit and may utilize the existing flue. Infrastructure change for Passive Solar is extensive for an existing home, requiring installation of windows or construction of a Trombe wall. Maintenance needs vary between \$100-167 yr^{-1} for each alternative. Cultural Considerations include the blue flame color of gaseous fuels, the association of electricity with danger, the importance of wood type used in wood pellet production, the sustained dependence upon solid fuels, and the over-exposure to sunrays.

Table S2-21 summarizes the results of the Technical Assessment on the basis of their Initial Costs (IC), Long-term Costs (LC), Environmental Implications (EI), and Health Implications (HI). Mean values for each alternative as well as the standard deviation (SD) and number of options explored (n) are presented. In terms of Initial Costs, Stove Improvement was the least expensive and Passive Solar the most expensive. For Long-term Costs, Stove Replacement was least expensive and Propane Gas was the most expensive. Natural Gas provided the most environmental and health benefits per dollar, while Propane gas provided the least.

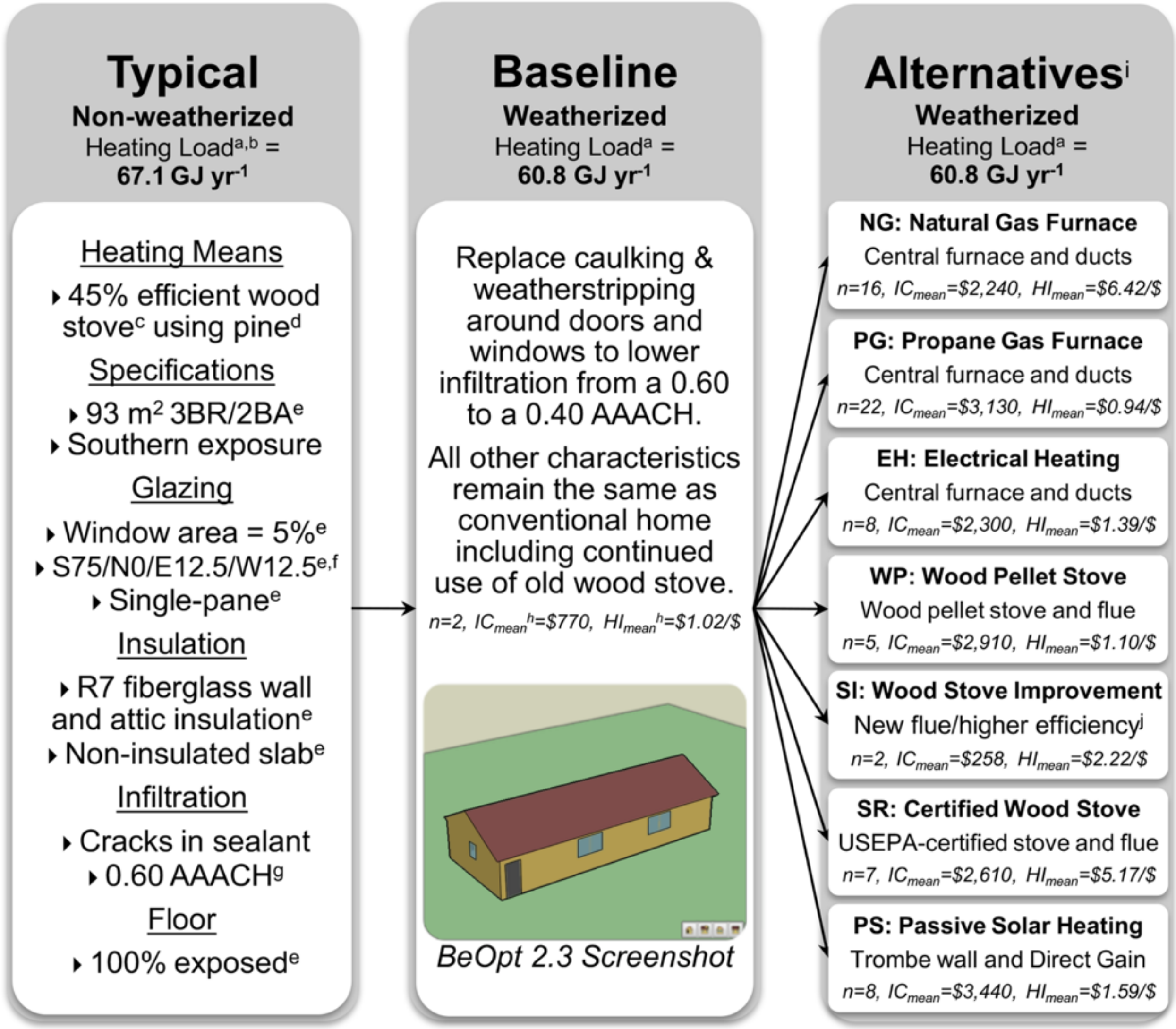
Figure 2-3 integrates the results from the Perception (Section 3.4 of this Chapter), Cultural (Section 3.5), and Technical (Section 3.6) Assessments to provide an overview of the results. Perception Assessment results were not normally distributed; thus, they are presented as boxplots. Discrepancies between the technical and perception assessments are indicated when the red diamond is outside interquartile range. Results from the combined assessments are as follows:

Natural Gas was perceived as less feasible in terms of availability, infrastructure, culture, and health implications. It provided the greatest benefits per dollar spent and had low long-term costs. Initial costs were comparable to other alternatives. Culturally, the blue flame often associated with gaseous fuels is believed to have negative effects on the body.

Propane Gas was perceived most feasible in terms of initial costs and availability. However, it provided the lowest benefits per dollar spent. Technically, Propane Gas had the highest initial and long-term costs. Culturally, there may be some concerns due to flame color.

Electrical Heating was perceived more feasible in terms of availability; however, it provided lower than average benefits per dollar spent. Initial costs were comparable to other alternatives, while long-term costs were higher than average. Culturally, heating with electricity is considered to have negative health effects on people.

Wood Pellet was perceived as least feasible in terms of long-term costs. It provided the second lowest benefits per dollar spent and the second highest long-term costs. Initial costs were comparable to other alternatives. Culturally, there may be concerns if pellets are made with unfavorable wood types or if wood type cannot be identified.



a. Heating load estimated by BeOpt 2.3 with a comfort temperature of 70°F.
b. Value agrees with USEIA (2005) estimate for the climate zone (CZ) in which the NN resides (CZ 2) (USEIA 2005b).
c. Low value (45.0%) from conventional wood stove range (41.7-63.1%) chosen (USEPA 1996). Characterization of typical Navajo stoves is recommended; Hickmott et al. (1997) reported CO, NO_x, and SO_2 concentrations from a coal stove (*Warm Morning* model) commonly used in the NN, but no efficiency value. Hickmott reported peaks in gas-phase pollutants in the 15 minutes following addition of coal to a burning stove, and highly recommended further study and improvement of coal stoves for residential heating.
d. Pine was most commonly used firewood in a survey of 45 Navajo homes near Ft. Defiance, AZ (Robin et al. 1996).
e. Defined as typical through personal communication with community leaders and brief visual inspection of Shiprock homes.
f. Percentages of window areas on (S)outh, (N)orth, (E)ast, and (W)est sides of home; Σ=100
g. AAACH defined as constant (A)nnual (A)verage (A)ir ex(C)hanges per (H)our. Value of 0.60 defined as "leaky" in BeOpt 2.0.
h. Alternatives defined in terms of number of options analyzed (n) and their efficiencies [$\varepsilon=1-([Heat_{in}-Heat_{out})/Heat_{in}]$ and heating capacities (BTU/time). Furnace and stove capacities are most often reported per hour, while passive solar model results (NREL 2014; Balcomb and Mcfarland 1978) are annual.
i. Efficiency of "typical" Navajo wood stove (45.0%) improved to average of conventional wood stoves (53.6%) as defined by USEPA (1996).

Figure 2-2. Summarized Methods and Results of Technical Assessment.

Stove Improvement was perceived as the least feasible in terms of both health and environmental implications. It provided lower than average benefits per dollar spent, but the initial costs were the lowest of all alternatives. Culturally, there were no apparent concerns, and wood fire is accepted as the traditional means of home heating.

There were no clear negative or positive perceptions regarding Stove Replacement. Stove Replacement provided the second highest benefits per dollar spent. Initial costs were comparable to other alternatives. Stove Replacement had the lowest long-term costs. Culturally, wood fire is the traditional Navajo method of home heating and is widely accepted in the NN.

Passive Solar was perceived as the most feasible in terms of long-term costs, and was the most feasible in terms of both health and environmental implications; however, it was perceived to be least feasible in terms of availability. PS had lower than average long-term cost, but the initial costs were the highest of any alternative. The idea of building according to the Sun is an ancient concept for Diné people, and therefore culturally valued.

According to these results, SI, SR, and PS are viewed most positively by the Navajo culture, but SR shows the best combined results.

2.5 Conclusions

This study applies a newly established framework that takes into account community perceptions, relevant cultural considerations, and technical factors to evaluate replacement alternatives for home heating stoves in NN houses that potentially produce high levels of indoor air pollution. Two out of these three analyses depend completely on the NN, highlighting the importance of engaging this community in the process.

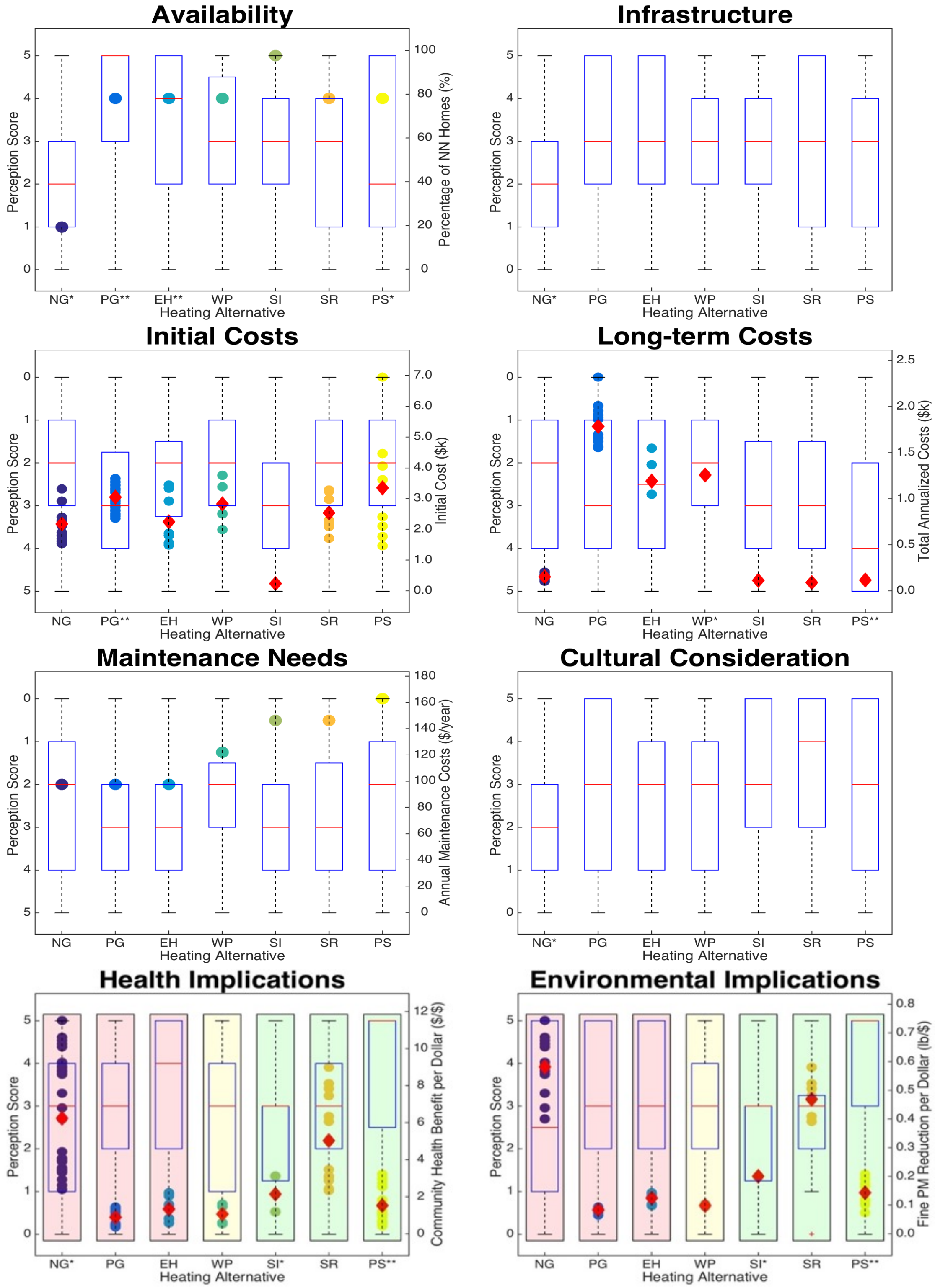


Figure 2-3. Integrated Results of Perception, Cultural, and Technical Assessments. The Perception Assessment is indicated as boxplots (y-axis) and a higher score is perceived as more feasible based on the criteria evaluated. The red line represents the median Perception score for that alternative, the bottom and top lines in the box represent the first and third quartiles representing the interquartile range (IQR), the whiskers represent 91%

and 10%. For the criteria quantified by cost (IC, LC, and MN), a higher perception score would be perceived as "more feasible" or less expensive; therefore, the left y-axis (and quartiles) are flipped for these alternatives. Alternatives perceived as least feasible are denoted with * next to their initials on the x-axis and those that are most feasible are denoted with **. Results of the Cultural Assessment were superimposed on the HI and EI sub-panels, where red, yellow, and green shading represent overall negative, neutral, or positive results from the Cultural Assessment, respectively. Results of the Technical Assessment are shown as dots. Dot colors represent a heating alternative, while each dot represents a different option (section 3.3). The red diamond is the mean technical assessment for all options for that alternative, also shown in Table S2-21. The right y-axis shows the results of the Technical Assessment, with the lower and upper limits of the y-axis defined as zero and approximately the maximum value for that criterion, respectively. The Technical Assessment did not include Infrastructure or Cultural Considerations because they were not defined in a manner that could be quantified.

The current project applied a parallel convergent mixed-methods approach to balance the goal of reducing health and environmental impacts from solid fuel heating in the NN with the unique cultural and perceived preferences of Navajo families with scientific analysis. To date, there exists no accepted framework to address environmental sustainability issues in communities with cultural and economic barriers to the adoption of cleaner technologies.

This assessment shows that weatherizing homes and replacing old stoves with cleaner more efficient models would be culturally acceptable, cost effective, and should reduce fuel use, improve indoor and outdoor air quality, and likely lead to improved health outcomes. To ensure that home heating stove changeout solutions are compatible with Navajo heating practices and traditions, it is critical to integrate the sustained involvement of Navajo leaders and community members in the process.

Due to varying levels of fuel availability and affordability, and to ensure cultural suitability, a successful intervention will require a mixture of approaches and should include freedom of choice for fuels and stove types. Attention must be paid to common heating practices, such as the use of both wood and coal in the same stove. In that regard, EPA is pilot testing new dual-fuel (wood and coal) stoves to see if a cleaner dual-fuel stove can be developed that meets wood stove emission standards. Educational initiatives should accompany any changeout program to explain the benefits and health implications of each heating alternative in a culturally relevant manner and to ensure proper operation of new stoves.

A settlement agreement between EPA and several electric utilities is providing funds for a stove change out and weatherization program in the NN for homes near the Four Corners Power Plant. To validate and communicate the anticipated improvements in air quality, indoor and outdoor air measurements should be undertaken before and after alternatives are instituted, and participants should be surveyed to assess satisfaction with their new stove. Stove replacement should lead to reductions in adverse health and air quality impacts from residential heating on the NN, as recommended by Bunnell et al. (2010).

This combined assessment helped uncover areas where community perception, culture, and the technical analysis align as well as where there are discrepancies that will necessitate increased dialogue regarding healthier heating methods. It is important that cultural experts in the community (e.g., here the Diné Policy Institute) write a thorough cultural assessment to achieve an effective integration of culture and science. The framework used for this study may be applicable for other Native American Nations, such as the nearby Hopi Nation, where climate conditions and coal use are similar to those of the NN (US Census Bureau, 2011).

2.6 Acknowledgments

Data used in the perception assessment were independently funded and independently collected by "in-kind" support of Diné College as a classroom project developed by the class teacher and without involvement from EPA or the University of Colorado. We thank A. Denny, J.

McKenzie, and Amber Crotty of the Diné College Policy Institute for their support on the Cultural Assessment and K. Davidson of US EPA for his support on the cost-benefit analysis. We also thank the Diné students and families who participated in the community Perception Assessment. This work was partially supported the National Science Foundation (award 0946502). EPA through its Office of Research and Development partially funded and collaborated in the research described here under assistance agreement by US EPA AE-83528101-0 to Dine College, Shiprock, NM. This manuscript has been subjected to Agency review and approved for publication. Mention of trade names or commercial products does not constitute endorsement, certification, or recommendation for use.

3. Emission Factors of Fine Particulate Matter, Organic and Elemental Carbon, Carbon Monoxide, and Carbon Dioxide for Four Solid Fuels Commonly Used in Residential Heating by the Navajo Nation

Champion, W.M.[1], Connors, L.[1], and Montoya, L.D.[1]

[1] University of Colorado Boulder, Civil, Environmental, and Architectural Engineering Department, Boulder, CO 80309

Graphical Abstract

3.1 Abstract

Most homes in the Navajo Nation (NN) use wood as their primary heating fuel, often in combination with locally-mined coal. Previous studies observed health effects linked to this solid-fuel use in several Navajo communities. Emission factors for common fuels used on the NN have not been developed using a representative stove type and community specific fuels and practices.

In this study, two softwoods (*Ponderosa Pine* and *Utah Juniper*) and two high-volatile bituminous coals (*Black Mesa* and *Fruitland*) commonly used were tested with an *in-use* residential wood stove and modified ASTM/EPA test protocols. Filter sampling quantified fine particulate matter ($PM_{2.5}$), and organic and elemental carbon (OCEC). Real-time monitoring measured total suspended particles (TSP), carbon monoxide (CO), and carbon dioxide (CO_2). Coal types compared to wood emitted significantly more $PM_{2.5}$, OC, and CO on both mass and energy normalized bases. Strong correlations between emission factors of $PM_{2.5}$ and CO for these fuels were developed. All fuels caused a rapid (<5 min) increase in TSP and CO following fuel addition. Between wood types specifically, *Ponderosa Pine* formed a hot charcoal bed with lower overall emissions compared to *Utah Juniper*. This study may be useful in future estimates of emissions-based benefits from a wood stove change-out program on the NN scheduled for 2017.

3.2 Introduction

Household air pollution (HAP) is the leading environmental health risk factor worldwide (World Health Organization, 2016) and responsible for 2.8 million premature deaths each year (Forouzanfar et al., 2015). Residential solid fuel combustion is the primary contributor to HAP (Smith et al., 2014) and the second largest contributor to ambient black carbon, an important climate forcer, (Bond et al., 2013). Solid fuels include a wide range of fuels, from agricultural and animal waste, to fossil fuels like coal. Their use is closely linked to socioeconomic status and the energy ladder (Smith, 1990). Acute and chronic exposures to wood and coal smoke are associated with adverse health impacts through a significant body of epidemiologic and toxicological evidence (Naeher et al., 2007). Use of unprocessed coal in homes has been strongly discouraged by the World Health Organization (2014) citing evidence of links to lung cancer (World Health Organization and International Agency for Research on Cancer, 2010).

Between 500,000 and 600,000 low-income Americans are exposed to HAP from solid-fuel use (Rogalsky et al., 2014), 12-15% of whom reside in the NN (NN) (U.S. Census Bureau, 2015; US Census Bureau, 2014). Wood is the most common heating fuel in the NN, used in 62% of all Navajo homes and 89% of those in rural areas (US Census Bureau, 2015; Arizona Rural Policy Institute, 2010). Wood is affordable, widely available within the reservation, and culturally significant to the Navajo (Champion et al., 2017). High-volatile bituminous coal (Kirschbaum and Biewick, 2000) is provided at no cost to residents near mines (Hickmott et al., 1997; Bunnell et al., 2010). Many Navajo homes burn wood and coal in combination using *homestoves* (i.e., residential wood stoves) that are old and/or leaky (Bunnell et al., 2010), impacting indoor air quality in many Navajo communities.

Bunnell et al. (2010) found that nineteen coal-burning homes in Shiprock, NM had a mean indoor 24 hr fine particulate matter ($PM_{2.5}$) concentration 130 times higher than a propane-burning home (38 vs. 0.29 $\mu g/m^3$). Previously, wood-burning Navajo homes had a nearly five times higher median indoor 15 hr (5:00 p.m. to 8:00 a.m.) PM_{10} concentration (101 $\mu g/m^3$) compared to homes that used gas or electric heating (22 $\mu g/m^3$) (Robin et al., 1996).

Studies in Tuba City, AZ (Morris et al., 1990) and Ft. Defiance, AZ (Robin et al., 1996) found *homestove* use to correlate with higher odds of acute lower respiratory illness (ALRI) among Navajo children below the age of two. Similarly, Bunnell et al. (2010) found higher hospitalization rates for respiratory illness in the winter compared to other seasons, likely due to indoor heating practices.

Wood and coal combustion in a *homestove* produces a complex mixture of health-damaging pollutants including carbon monoxide (CO) and $PM_{2.5}$ (Bäfver et al., 2011; Chen et al., 2005). This $PM_{2.5}$ is comprised mostly (>60% by mass) of organic and elemental carbon (OC and EC, respectively) (Chen et al., 2016; Obaidullah et al., 2014; Shen et al., 2014).

Emission factors (EF) of these pollutants are used to model environmental and health benefits from modifications in residential wood combustion practices in ambient regional (Reddy and Venkataraman, 2002) and global-scale applications (Junker and Liousse, 2006). Reported EF of particulate matter (PM) from conventional (non-certified) *homestoves* vary greatly among stove and fuel types, often ranging from 3 to 30 g/kg for wood (Houck et al., 2008). Data from bituminous coal combustion for residential heating is more limited, but previous studies reported EF for PM from coal stoves between 2 and 15 g/kg (Butcher and Ellenbecker, 1982; Zhi et al., 2008; Shen et al., 2014; Chen et al., 2016).

Improved indoor air quality in Native American homes using EPA-certified *homestoves* has been measured in Idaho, where 24-48 hr mean indoor $PM_{2.5}$ concentrations decreased from 39 to 19 $\mu g/m^3$ following a stove change-out program (Ward et al., 2011). Controlled emissions testing was not performed on the *homestoves* evaluated in that study; therefore, EF for representative stoves in that Native American community are unavailable. Currently, there are no published EF for *in-use* residential stoves (*homestoves*) in Native Nations, including the NN.

Variability in EF of PM from *homestoves* and *cookstoves* (i.e., cooking stoves) have been the primary source of uncertainty in emission inventories from these units (Bond et al., 2004; Streets et al., 2003). *Homestove* age (Houck et al., 2008), design (US EPA, 1986), and operation (i.e., burn rate) (Jordan and Seen, 2005) strongly affect PM emissions. Older conventional *homestoves* are less efficient, larger *homestoves* emit more PM, and a lower burn rate increases emissions. Many *homestoves* in the NN are old (Bunnell et al., 2010) or self-fabricated

(Hickmott et al., 1997), and their emissions (from the practice of combined wood and coal combustion) are largely uncharacterized.

In this study, EF for two wood types and two coal types commonly used in the NN were determined using an *in-use* Navajo *homestove*. Experiments were conducted at the University of Colorado Emissions Standardization and Testing (*CUEST*) facility. To the authors' best knowledge, there are no published EF for these fuels using a representative Navajo *homestove*.

3.3 Materials and Methods

3.3.1 Homestoves

A residential wood *homestove* (King Martin Stove and Range Company, Florence, AL) was used in this study (Figure 3-1). This cast iron unit was designed for wood combustion but had been used in Navajo homes to burn both wood and coal. This *homestove* was primarily used for heating, though some Navajo homes (Robin et al., 1996) use wood and coal for both heating and cooking. The firebox is 33 cm (13 in) tall, 51 cm (20 in) long, 24 cm (9.5 in) wide and had an internal firebox volume of 40 l (1.4 ft^3). The *homestove* weighs 45 kg (99 lbs). Cracks are visible on the sidewalls and likely affect its efficiency.

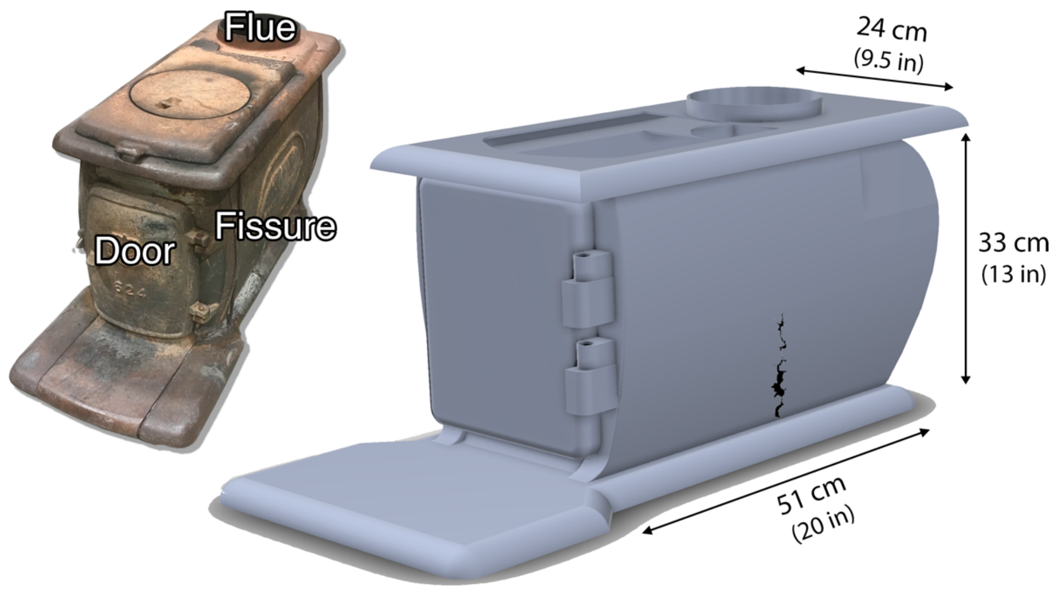


Figure 3-1.Navajo *Homestove* with Firebox Dimensions.

3.3.2 Fuels

A total of four fuels commonly used in the NN were included in this study. Two softwood types that are easily available to Navajo residents (Robin et al., 1996) were tested: *Ponderosa Pine* (*Pinus ponderosa*) and *Utah Juniper* (*Juniperus osteosperma*). In addition, two high-volatile bituminous coal types commonly distributed by coal mines in the NN (Brown et al., 1996; Hickmott et al., 1997) were tested: *Black Mesa* (*Grade C*) and *Fruitland* (*Grades B & C)*. Notably, some types of Juniper are referred to as "cedar" according to local growing and harvesting customs. Fuels were obtained from road-side vendors or delivery services in the NN. Proximate analysis of the fuels are presented in Table 3-1. The wood types compared to coal contain more volatile matter, and less fixed carbon and ash. Coal types compared to wood have roughly 25% higher energy content.

Table 3-1.Proximate Analysis and Higher Heating Value of Fuels Tested (% dry-basis and Btu/lb)

Fuel	Volatile Matter		Fixed Carbon		Ash		Higher Heating Value		Source
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Ponderosa Pine	82.2	0.42	16.8	0.64	1.0	1.0	8,630	26	(Gaur and Reed, 1998; Overend et al., 2012)
Utah Juniper	82.8	na	15.1	na	2.0	na	8,660	na	Chen et al. (2012)
Black Mesa	43.3	2.3	48.8	1.2	8.0	2.5	11,100	380	(Affolter, 2000; Arizona Bureau of Mines, 1977)
Fruitland	39.3	2.7	43.6	2.8	17.3	5.2	10,620	790	Affolter (2000)

Wood was cut into standard 1.5 x 1.5 x 36-40 cm pieces (Jetter and Kariher, 2009). The average dry-basis wood moisture content (MC) was determined with a resistance type moisture meter 15 min prior to each test. *Ponderosa Pine* MC was 12% (SD=3.5) and *Utah Juniper* 5.7% (SD=0.1). Coal was sorted into 2-4 cm in each dimension and the MC values were obtained from the literature: 11.5% for *Black Mesa* (Affolter, 2000) and 8.3% for *Fruitland* (Arizona Bureau of Mines, 1977).

3.3.3 Experimental Setup

The CUEST Facility (Figure 3-2) was designed for total-capture emissions testing of solid fuels. The closed test chamber was built with aluminum and glass and sealed with high-temperature resistant silicone (Rutland Fire Clay Company, Rutland, VA). Stove and fuel weight was measured throughout the test with an Accu-weigh scale (301TDX/A-54, Metro Equipment Corporation, Sunnyvale, CA) to determine the beginning and end of test phases. In-line isokinetic sampling was accomplished through three sampling ports located 241 cm (95 in) downstream of the test chamber, meeting EPA (1984) guidelines. Sampling lines were 0.64 cm (0.25 in) inside diameter (ID) Tygon tubing (Courbevoie, France). Lines leading to filter holders were 31 cm (12 in) long. A line leading to a Portable Emissions Monitoring System (PEMS) (Aprovecho Research Center, Cottage Grove, OR) was 305 cm (120 in); the additional length of sampling lien was needed to connect the PEMS to a computer. Temperatures in the firebox (labeled T_1 in Figure 3-2) and stove flue (T_2) were measured with K-type thermocouples, and in the exhaust flue (T_3) with an internal PEMS thermocouple. The PEMS was developed for field testing of *cookstoves* where generally higher magnitude and variability in emissions data are reported compared to laboratory results (Roden et al., 2009). It has been previously employed to report EF from a laboratory setting (Medina et al., 2016; MacCarty et al., 2010), as employed here.

3.3.4 Sampling

$PM_{2.5}$ was sampled with personal impactor filter packs (2000-25F-4-2.5, URG, Chapel Hill, NC) loaded with 25mm filters. One pack (labeled *A,* Figure 3-2) contained a Zeflour PTFE filter (Pall, Port Washington, NY) (0.5 μm pore size), selected for gravimetric and elemental analyses as well as in vitro studies (results not included here). Two packs in-series (labeled *B1 and B2,* Figure 3-2) contained single TissuQuartz quartz fiber filters (QFF) (Pall, Port Washington, NY), selected for analysis of organic and elemental carbons (OC and EC, respectively). Filter *B2* was used to quantify positive artifacts from adsorption of semi-volatile and volatile organics. Filter flow rate (4.0 lpm) was maintained with MOA diaphragm vacuum pumps (GAST, Benton Harbor, MI) and measured with FL-series rotameters (OMEGA, Stamford, CT); adjustments to filter flow rate were made every 5 min, if necessary. Following sampling, filters were transported in PTFE-sealed acid-washed Petri dishes on ice in a cooler and then stored at -20°C until analyses.

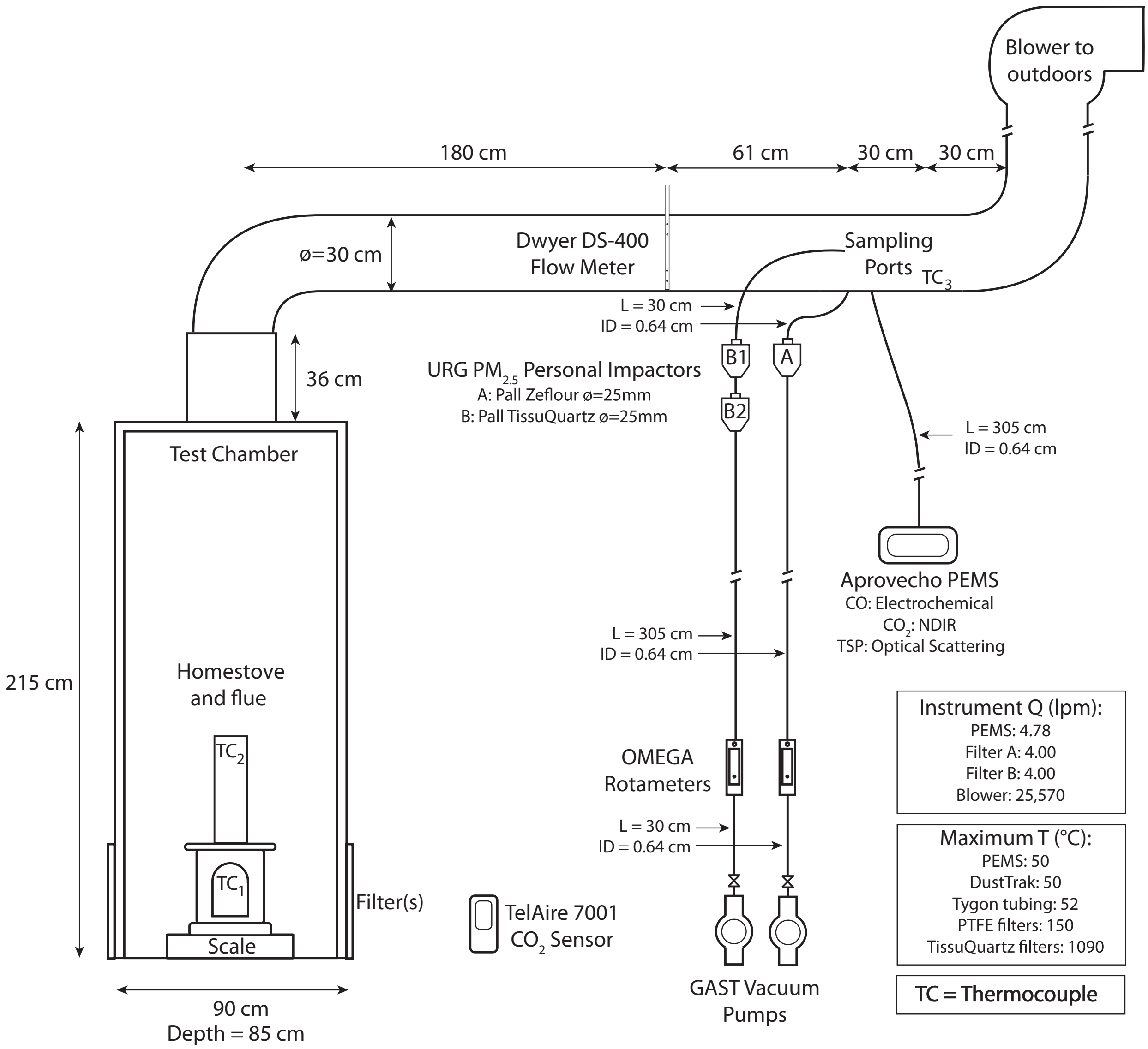


Figure 3-2. Schematic of *CUEST* Experimental Facility.

Mean air dilution ratios (by mass) were 869:1 (SD=231:1) for wood and 1680:1 (SD=339:1) for coal during *homestove* testing, and sampling temperatures were near ambient conditions [Table S3-1 in the Supplemental Information (SI)]. Lipsky and Robinson (2006) determined that a dilution ratio of 100:1 was sufficient to reduce *homestove* exhaust temperatures to ambient conditions, but may condense semi-volatile organics and over-estimate OC emissions

(Pankow, 1994). A previous *cookstove* study used dilution ratios as low as 24:1 (Roden et al., 2009), below the expected real-world conditions for combustion systems (Zhang and Wexler, 2004). High dilution ratio can affect air velocities near the combustion chamber of the stove and impact its performance, with higher velocities promoting convection but potentially increasing ignition time (Bilbao et al., 2001). Kortelainen et al. (2015) tested a wood chip burner at a dilution ratio of 2000:1. In this study, *homestove* testing utilized a closed door to minimize this effect.

Monitoring was conducted at 4.8 lpm using the PEMS for real-time (0.5 Hz) concentrations of CO, CO_2, and total suspended particles (TSP). PEMS sensor types are electrochemical for CO, non-dispersive infrared (NDIR) for CO_2, and optical light-scattering for TSP (MacCarty et al., 2010). Room CO_2 concentration was measured continuously (1 Hz) with a TelAire 7001 NDIR monitor (GE, Billerica, MA) correlated to the PEMS CO_2 sensor. Co-integration (i.e., ability of one time-series data set to predict another data set) was determined with the Engle-Granger test (Engle and Granger, 1987).

Prior to each test, filter packs and sampling lines were washed for organics analysis. PTFE filters and Petri dishes were washed for trace metals analysis (Majestic et al., 2012). Calibrations were performed every ten tests for filter flow rates, gas sensors, and thermocouples. Washing and calibration protocols are provided in the SI.

3.3.5 Filter Analyses

Gravimetric analysis ($PM_{2.5}$) was performed on the PTFE filters following conditioning for 24-36 hr at 75-81°F and 25-50% relative humidity (RH) based on published protocols (Dutton et al., 2009). $PM_{2.5}$ mass was determined using a LabServe microbalance with 10 ug precision (model BP210D, Sartorius Corporation, Germany).

Organic and elemental carbon content in $PM_{2.5}$ samples was determined using a Dual Optics OCEC Lab Instrument (Sunset Lab, Tigard, Oregon). Punches (1.5 cm^2) of QFF were analyzed using NIOSH870 (i.e., “NIOSH-like”) methods (Karanasiou et al., 2015) based on Birch and Cary (1996) with a maximum oven temperature of 870°C for OC and EC phases. Five distinct values for OC were reported by the instrument as OC1, OC2, OC3, OC4, and OCp, corresponding to temperature steps of 340, 500, 615, 870°C, and the pyrolized portion of OC, respectively. Each temperature increase represents decreased volatility of the OC.

3.3.6 Test Protocols

The *homestove* test protocol was based on the Cordwood Annex from the American Society for Testing and Materials E-2780 *Standard Test Method for Determining Particulate Matter Emissions from Wood Heaters* (ASTM, 2010). The ASTM test was based on EPA Method 28 using cribwood (i.e., standardized test loads of 2-4 in x 4 in nominal lumber nailed into a rectangular prism approximately 5/6th the length of the firebox) (US EPA, 1988); however, the ASTM test also includes an annex for testing cordwood, or split logs. The use of cordwood is considered more representative of real-world practices compared to cribwood. Consequently, the EPA is presently developing regulatory test methods based on the ASTM Cordwood Annex to be promulgated in 2018 (US EPA, 2016a). Currently, there exist no standardized protocols for testing coal in *homestoves*.

Figure 3-3 highlights the *homestove* testing phases utilized. In both ASTM and EPA methods, newspaper and kindling is used to ignite a *Pre-burn* load to bring the stove to operating temperature and establish a hot charcoal bed. In this study, the use of a propane torch was utilized for 30 s as opposed to a butane lighter. Coal testing was conducted with *Ponderosa Pine* as the *Pre-burn* fuel for two reasons: a) test protocols of current wood/coal combination stoves utilize a wood *Pre-burn* load (Bob Ferguson, Personal Communication), and b) establishing a wood charcoal bed prior to coal addition is common practice in the NN (Bunnell et al., 2010).

The *Pre-burn* is directly followed by the *Test*, wherein a *Test* load is added onto the hot charcoal bed and allowed to ignite with air controls fully open (5.0 min). The *Test* phase continues when air controls are lowered to maintain a fuel burn rate within a specified range (low = 0.60-1.15, medium=1.16-1.75, or maximum >1.75 kg-dry-fuel/h). Emissions from different burn rates are averaged to report EF, unless burn rate could not be controlled. The *Test* phase ends when the mass of the *Test* load was consumed (determined gravimetrically).

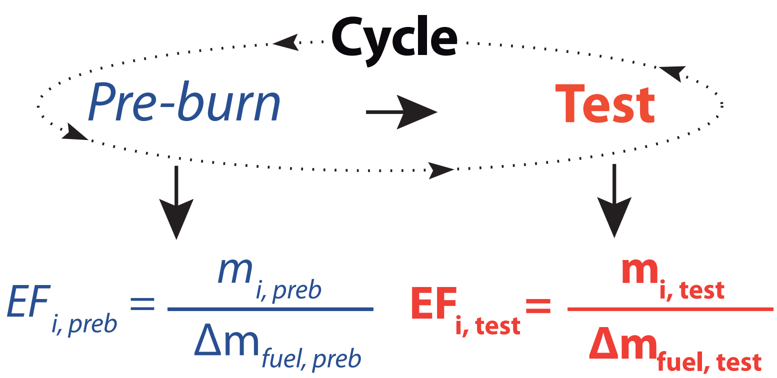


Figure 3-3. Overview of Phases and Equations for *mEF* and *eEF*, where i= $PM_{2.5}$, OC, EC, CO, and CO_2.

The *Cycle* shown in Figure 3-3 combines the *Pre-burn* and *Test* phases and is intended to represent one wood ignition event with a wood or coal addition to the hot charcoal bed. This protocol is similar to European standards for *homestove* testing (EN 13240:2001), wherein emissions are determined for a *Cycle* including both *Pre-burn* and *Test* phases (Ozgen et al., 2014).

Test phase conditions are listed in Table 3-2. Five individual *Pre-burn* and *Test* phases (i.e., 5 *Cycles*) were conducted for *Ponderosa Pine*, and four (n=4) for *Utah Juniper*, *Black Mesa*, and *Fruitland*. Mean mass fuel loading for the *Test* phase was 1.3 kg for wood and 0.65 kg for coal. This corresponds to 20% and 10% of the fuel loading as specified by the ASTM Cordwood Annex (162 kg per 1 m^3 of firebox volume). This was due primarily to limitations of CUEST to entirely evacuation emissions at full loading. Tissari et al. (2007) tested residential wood stove emissions using fuel loads similar to this study (20-30% of maximum firebox capacity, compared to 10-20% in this study).

Table 3- 2. *Test* phase conditions

	Ponderosa Pine		*Utah Juniper*		*Black Mesa*		*Fruitland*	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Replicates (#)	5	na	4	na	4	na	4	na
Fuel load (kg)	1.29	0.01	1.29	0.01	0.65	0.01	0.64	0.01
Duration (min)	28	6	44	10	98	20	77	19
Stove flue temperature (°C)	480	94	353	90	165	65	202	91
Fuel load remaining at end (%)	0	na	0	na	52	20	55	20

Mean *Test* phase duration was 35 min (SD=11) for wood and 87 min (SD=21). The *homestove* tested was leaky and burned wood at 2.2 kg-dry-fuel/h (SD=0.61) and coal at 0.26 kg-dry-fuel/h (SD=0.055) regardless of air control settings. Therefore EF are reported for the "maximum" rate category as defined by the protocols. Stove flue temperature (T_{flue}) measured at flue exit, was significantly higher for wood (424°C, SD=94) compared to coal (184°C, SD=41), though coal T_{flue} remained above the recommended value of 120°C to prevent formation of creosote (i.e. semi-volatile product of incomplete combustion) (Baker, 1993). The *Test* phase was deemed complete when two re-arrangements of the charcoal bed and coal (each 10 min apart) produced negligible fuel consumption (as defined in the Cordwood Annex). The *Test* load for wood was completely consumed, while approximately half remained for coal tests (Table 3-2).

3.3.7 Emission Factors

The "hood method" (Ballard-Tremeer and Jawurek, 1999; Butcher et al., 1984) was used in this study because it is common for controlled emissions testing; Jetter et al. (2012) reported 14 studies using it. In addition, this method does not require the measurement of methane and non-methane hydrocarbons to fulfill the "carbon balance" assumption (Roden et al., 2006; Zhang et al., 2000). Figure 3-3 shows the overall equations used to determine EF.

First, the flue volumetric flow rate (Q_{flue}) was multiplied by the mass concentration measured for each pollutant to determine an average mass flow rate of the pollutant ($\dot{m}_i$). This mass flow rate was then multiplied by the duration of the phase (e.g., *Pre-burn* or *Test*) to determine the mass of pollutant emitted during that phase. This mass was then divided by a) mass of fuel consumed during the *Test* phase or b) the amount of energy in the fuel (based on LHV) consumed during the *Pre-burn* and *Test* phases combined.

These values are reported as *mass EF* or *mEF* (g/kg) and *energy EF* or *eEF* (mg/MJ), respectively. The parameter *mEF* is useful to compare to previous studies and has been used to determine emissions limits by many entities including tribal agencies (US EPA, 2016b). All EF reported include ignition and wait periods, and were blank-corrected for $PM_{2.5}$, OC, and EC, and background-corrected for $PM_{2.5}$, OC, EC, and CO based on 45 min background sampling periods prior to each test. EF for CO_2 were corrected using real-time background measurements. EF were compared between fuel types (i.e., wood vs. coal) using a two-tailed Student's t-test at a significance level (α) of 0.10, therefore statements of significantly less or greater are at α=0.05.

3.3.8 Carbon Balance

Carbon balances ($C_{bal} = C_{fuel}/C_{emissions}$) were conducted for each trial [Figure S3-1 in the Supplemental Information (SI)] and included mass emissions of OC, EC, CO, and CO_2. Each of these terms are plotted in Figure S3-2 in the SI. Mean C_{bal} was 112% for the *Pre-burn* phase and 96% for the *Test* phase. Therefore, carbon emissions were under-sampled during the *Pre-burn* phase and over-sampled during the *Test* phase. Carbon balances were approximately normally distributed (Figure S3-3 in the SI) and no trials were eliminated due to C_{bal}. The carbon content of the fuels studied were estimated using published values (the same sources as those listed in Table 3-1), however it is likely that the actual values were lower from those in the literature. Additionally, methane and non-methane hydrocarbons were not measured and may account for roughly 3% of the carbon balance uncertainty (Smith et al., 1993).

3.4 Results and Discussion

3.4.1 Mass Emission Factors

Mass EF (*mEF*) for $PM_{2.5}$, OC, EC, CO, and CO_2 are presented in Table 3-3. Wood types had significantly lower ($p<0.05$) *mEF* for all pollutants. Fine particulate matter *mEF* ($mEF_{PM2.5}$) ranged from 1.09-1.68 g/kg) compared to 13.3-14.1 g/kg for coal. *Ponderosa Pine* had the lowest $mEF_{PM2.5}$ of all fuels and *Black Mesa* the highest.

Table 3-3.Mass Emission Factors (g/kg) for *Test* phase

Fuel	$PM_{2.5}$ Mean	SD	OC Mean	SD	EC Mean	SD	CO Mean	SD	CO_2 Mean	SD
Ponderosa Pine	1.09	0.578	0.538	0.325	0.206	0.178	27.2	13.1	1,470	234
Utah Juniper	1.68	0.207	1.04	0.278	0.183	0.072	40.4	10.9	1,540	131
Black Mesa	**14.1**	7.08	**9.30**	5.09	**0.471**	0.366	**226**	67.8	**2,424**	368
Fruitland	**13.3**	2.18	**7.07**	0.757	**0.451**	0.285	**204**	22.7	**2,484**	210

Bold indicates that fuel group (wood or coal) had significantly higher mEF_i (where i = $PM_{2.5}$, OC, EC, CO, and CO_2) at a significance level (α) of 0.05.

Previously, $mEF_{PM2.5}$ ranging from 2.0 to 18 g/kg have been reported for *Loblolly Pine* (Fine et al., 2004) and *Maritime Pine* (Alves et al., 2011; Gonçalves et al., 2011) combustion in *homestoves*. McDonald et al. (2000) determined $mEF_{PM2.5}$ for *Ponderosa Pine* combustion in a fireplace to range from 4.7-5.8 g/kg. $mEF_{PM2.5}$ for Juniper combustion in a *homestove* is unavailable, but was 4.6 g/kg from controlled open burning (i.e., without a stove) (McMeeking et al., 2009).

The lower $mEF_{PM2.5}$ for wood observed in this study is due potentially to several factors. First, different Pine species (e.g., *Loblolly*)can vary inherently in their composition and therefore emissions. Second, wood preparation in the *homestove* studies were different. Here, the wood was split into smaller pieces instead of whole logs (Fine et al., 2004). This did not necessarily affect wood moisture content (6-12% in this study vs. 8-9% in the *homestove* studies), but would likely improve the combustion process by increasing the surface area accessible to the combustion. Lastly, less wood was used here (1.3 kg) compared to 3-6 kg used in those studies.

Previous emissions testing of bituminous coal combustion in residential coal stoves (Chen et al., 2016; Shen et al., 2014) determined $mEF_{PM2.5}$ to range from 10-13 g/kg, therefore $mEF_{PM2.5}$ for coal types were slightly higher in this study. The *homestove* utilized here was old and improperly designed for coal combustion (i.e., no overfire air to promote combustion of devolatilization products). However, *Black Mesa* $mEF_{PM2.5}$ have been reported as high as 66 g/kg during controlled open burning (Simoneit et al., 2007). Shen et al. (2014) found bituminous coal $mEF_{PM2.5}$ to be seven fold higher compared to cordwood using similar residential stoves, agreeing closely with this study (ten fold higher).

$mEF_{PM2.5}$ variability observed in this study is common in *homestove* testing and within the ranges of previous work. An assessment of the EPA Accredited Laboratory Proficiency Test Program found that PM emission rates can vary up to ±112% between labs due to the "random nature of burning wood" (Curkeet and Ferguson, 2010). For residential coal stove testing, high variability (i.e., SD>mean) for *mEF* of $PM_{2.5}$, OC, and EC has been reported (Chen et al., 2016).

Table 3-3 includes mass EF of fine particulate OC and EC (mEF_{OC} *and* mEF_{EC}, respectively). Wood mEF_{OC} and mEF_{EC} were significantly lower than for coal. mEF_{OC} ranged from 0.54-1.0 g/kg for wood and 7.1-9.3 g/kg for coal. OC from all fuels were comprised mostly of high volatile organics (OC1): 37% and 45% for *Ponderosa Pine* and *Utah Juniper*, and 55% and 51% for *Black Mesa* and *Fruitland*. Mean mass fractions (for all fuels) of the other carbon volatility classes were: OC2 (17%, SD=2.6), OC3 (11%, SD=2.0), OC4 (12%, SD=6.3), and OCp (14%, SD=6.2). mEF_{EC} ranged from 0.18-0.21 g/kg for wood and 0.45-0.47 g/kg for coal. *Ponderosa Pine* had the lowest mEF_{OC}. *Utah Juniper* had the lowest mEF_{EC}. *Black Mesa* had the highest mEF_{OC} and mEF_{EC}.

Pine *homestove* mEF_{OC} and mEF_{EC} ranged previously from 0.87-6.8 g/kg and 0.27-0.71 g/kg, respectively (Fine et al., 2004; Alves et al., 2011). Those studies found that OC comprised between 44-49% of Pine $PM_{2.5}$, closely agreeing with the value of 50% for *Ponderosa Pine* in this study. From bituminous coal combustion in residential coal stoves, mean mEF_{OC} and mEF_{EC} ranged from 3.0-5.9 g/kg and 0.45-2.8 g/kg, respectively (Zhang et al., 2008; Shen et al., 2014).

Those studies found that OC comprised between 40-47% of $PM_{2.5}$, compared to 61% for the coal types tested here.

In this study, coal had eleven fold higher mEF_{OC} compared to wood, agreeing with Shen et al. (2014) who found bituminous coal to have seven fold higher mEF_{OC} than wood. That study however found that mEF_{EC} was much higher for coal compared to wood (eight fold). In this study, mEF_{EC} for coal was only three fold higher than wood. This discrepancy may be due to longer duration of flaming as opposed to smoldering combustion during the wood experiments, and subsequent higher emissions of EC (through graphitization of linked hydrocarbons in the flame) (Frenklach, 2002).

In this study, mEF_{CO} for wood types ranged from 27.2 to 40.4 g/kg; *Ponderosa Pine* had the lowest mEF_{CO} of all fuels. Reported average mEF_{CO} for Birch, Spruce, and Pine combustion in *homestoves* ranged from 21 to 137 g/kg, with increased air flow resulting in decreased emissions of CO (Pettersson et al., 2011). mEF_{CO} for coal types ranged from 204 to 226 g/kg in this study; *Black Mesa* had the highest mEF_{CO} of all fuels. Residential coal combustion data is limited, but Butcher and Ellenbecker (1982) observed a lower mEF_{CO} (116 g/kg) for bituminous coal in a residential coal stove designed with high underfire airflow to promote volatilization and mixing. In this study, coal mEF_{CO} were 6.5 fold higher compared to wood.

mEF_{CO2} for wood types ranged from 1470 to 1540 g/kg; *Ponderosa Pine* had the lowest mEF_{CO} of all fuels. $mEFCO_2$ for controlled open combustion of *Ponderosa Pine* were 1760 g/kg (Chen et al., 2007). mEF_{CO2} for coal types ranged from 2424 to 2484 g/kg in this study; *Fruitland* had the highest mEF_{CO} of all fuels tested.

During the *Pre-burn* phase, *Ponderosa Pine* compared to *Utah Juniper* had significantly lower ($p<0.05$) $mEF_{PM2.5}$ and mEF_{CO}. *Pre-burn* phase $mEF_{PM2.5}$ were 1.7 g/kg (SD=0.7) and 3.1

g/kg (SD=0.5) for *Ponderosa Pine* and *Utah Juniper*, respectively. *Pre-burn* phase mEF_{CO} were 26.5 (SD=8.8) and 39.6 (SD=15) for the two fuels, respectively. This suggests that for these two wood types, *Ponderosa Pine* provided a hot charcoal bed (for further fuel addition) with significantly lower $PM_{2.5}$ and CO emissions. *Pre-burn* EF are not reported for coal tests because *Ponderosa Pine* was used as the *Pre-burn* fuel load.

3.4.2 Energy Emission Factors

Energy EF (*eEF*) for $PM_{2.5}$, OC, EC, CO, and CO_2 from the *Cycle* (Figure 3-3) are presented in Table 3-4. Wood types had significantly lower ($p<0.05$) *eEF* for all pollutants expect EC. Fine particulate matter *eEF* ($eEF_{PM2.5}$) for wood ranged from 105-163 mg/MJ compared to 320-323 mg/MJ for coal. *Ponderosa Pine* had the lowest $eEF_{PM2.5}$ of all fuels and *Black Mesa* the highest.

Table 3-4. Energy Emission Factors (mg/MJ) for *Cycle*

Fuel	$PM_{2.5}$ Mean	SD	OC Mean	SD	EC Mean	SD	CO Mean	SD	CO_2 Mean	SD
Ponderosa Pine	105	50.3	54.5	28.5	15.5	8.8	2,108	897	105,710	8,760
Utah Juniper	163	12.5	100	10.8	11.6	3.1	2,849	567	105,040	6,660
Black Mesa	**320**	89.4	**201**	66.6	18.3	6.8	**5,195**	813	**117,740**	8,800
Fruitland	**323**	13.6	**174**	20.5	18.2	5.6	**5,123**	871	**122,860**	6,040

Bold indicates that fuel group (wood or coal) had significantly higher eEF_i (where i = $PM_{2.5}$, OC, EC, CO, and CO_2) at a significance level (α) of 0.05.

Previously, eEF_{TSP} ranged from 55 to 78 mg/MJ for cordwood combustion in a *homestove* (Bäfver et al., 2011). eEF_{CO} for wood types ranged from 2263 to 2821 mg/MJ; *Ponderosa Pine* had the lowest eEF_{CO} of all fuels. Previously published eEF_{CO} ranged from 1800 to 3200 mg/MJ for cordwood combustion in a conventional *homestove* (Bäfver *et al.,* 2011).

Similarly, eEF_{CO} for coal types ranged from 4679 to 4499 mg/MJ; *Black Mesa* had the highest eEF_{CO} of all fuels.

3.4.3 Correlation of $PM_{2.5}$ and CO Emission Factors

Using CO as a proxy for $PM_{2.5}$ emissions has been deemed acceptable in the evaluation of indoor air pollution from *cookstoves* burning wood (Northcross et al., 2010; Naeher et al., 2001). In a review of stove intervention programs in low and middle-income countries, CO was the most commonly measured pollutant (Thomas et al., 2015). No study has determined whether CO can be used as a proxy for $PM_{2.5}$ emissions from *homestoves*. In this study, correlations between these two pollutants were determined and are shown in Figure 3-4. *mEF* of $PM_{2.5}$ vs. CO from the *Test* phase are plotted in Figure 3-4a. Note that wood tests were below EPA *AP-42* suggested EF for conventional *homestoves* (shaded region), which are based on extensive testing by EPA Accredited labs. Most (88%) coal tests in this study were above EPA *AP-42* values.

Figure 3-4a also shows the range of $mEF_{PM2.5}$ from previous *homestove* tests as vertical dashed lines. The natural log-transformed linear relationship for $mEF_{PM2.5}$ vs. mEF_{CO} (calculated as $mEF_{PM2.5} = e^{(ln(EFCO)*1.17 - 3.74)}$) is plotted and shows a strong correlation ($r^2 = 0.94$). Indoor CO and $PM_{2.5}$ concentrations measured in Guatemalan homes burning wood were well-correlated using natural log-transformed linear (McCracken et al., 2013) and linear relationships ($\rho = 0.85$) (Naeher et al., 2001). These correlations support the use of CO monitoring as a proxy for $PM_{2.5}$ measurements. This relationship allows the estimation of $mEF_{PM2.5}$ using mEF_{CO}, but it is likely limited to the specific stove and fuel types studied here.

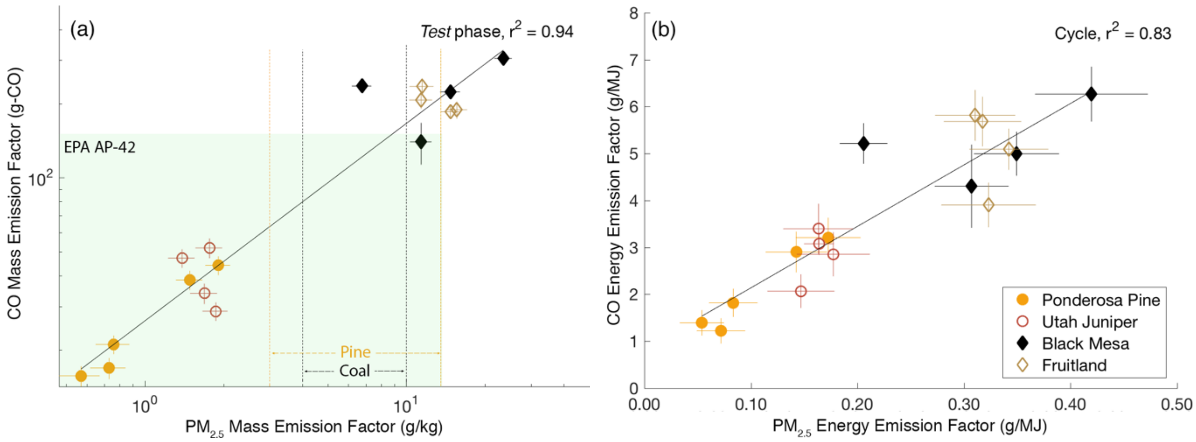


Figure 3- 4. $PM_{2.5}$ and CO EF for a) *Test* Phase with Natural Log-transform and Linear Fit for *mEF*, and b) *Pre-burn* and *Test* Phases Combined (*Cycle*) with Linear Fit for *eEF*. Light Dashed Lines Delineate the Range of Published $mEF_{PM2.5}$ for *Ponderosa Pine* (Fine et al., 2004; Alves et al., 2011; Gonçalves et al., 2011). Heavy Dashed Lines Delineate the Range of Published $mEF_{PM2.5}$ for Bituminous Coal (Chen et al., 2016; Shen et al., 2014).

Figure 3-4b shows the linear relationship for $eEF_{PM2.5}$ vs. eEF_{CO} (calculated as $eEF_{PM2.5} = 0.063*eEF_{CO} - 0.014; r^2 = 0.83$). $eEF_{PM2.5}$ and eEF_{CO} were also higher for coal compared to wood (2.5 and 2.2 fold higher); however, the difference between the fuels is less than on a mass basis (*mEF)*. This difference may be explained by two factors. First, coal types have 25% higher energy content compared to wood (Table 3-1), which resulted in lower differences of *eEF* between wood and coal types. Second, the *eEF* reported here for the *Cycle* include a *Ponderosa Pine Pre-burn* phase. Since this is a cleaner burning fuel compared to coal, it effectively lowers the total *Cycle* emissions.

3.4.4 Real-time conditions

Real-time CO and TSP concentrations, modified combustion efficiency (MCE), and combustion temperature during the *Test* phase (i.e., following fuel addition) are plotted in Figure 3-5. MCE is defined as $\Delta CO_2/(\Delta CO_2+\Delta CO)$, where ΔCO_2 and ΔCO are the increased concentrations (ppm) of CO_2 and CO above background levels (i.e., from emissions). Flue oxygen (O_2) concentration can be important for comparison between studies, however O_2 was not monitored in this study. McDonald et al. (2000) assumed 19% O_2 concentration for fireplace and residential wood stove emissions testing (without O_2 monitoring), with dilution ratios ranging from 20-70. Dilution ratios in this study were much higher and there O_2 concentrations would be expected to be more near ambient conditions (i.e., 20.9% v/v).

Test phase durations have relatively low variation within fuel types (Table 3-2), and therefore data are not normalized to a specific duration. The mean and standard deviation are presented for the instantaneous data (i.e., min elapsed following fuel addition) for all trials of the fuel (i.e., n=5 for *Ponderosa Pine*, and n=4 for all other fuels); no standard deviation is plotted where data is from only one *Test* for that fuel.

All fuels showed an initial peak in CO following fuel addition. CO emissions from *Ponderosa Pine* and *Utah Juniper* increased towards the end of the *Test* phase, typical of wood smoldering (Andreae and Merlet, 2001) when remaining char is incompletely oxidized (Turns, 1996). The same trend of increasing CO as smoldering proceeds has been observed in wood combustion in a *cookstove* (Roden et al., 2006) and wood-chip combustion (Kortelainen et al., 2015). *Ponderosa Pine* and *Utah Juniper* showed no significant co-integration for real-time CO concentration during the *Test* phase, suggesting the wood types. This suggests that the wood types emit CO at different levels during combustion.

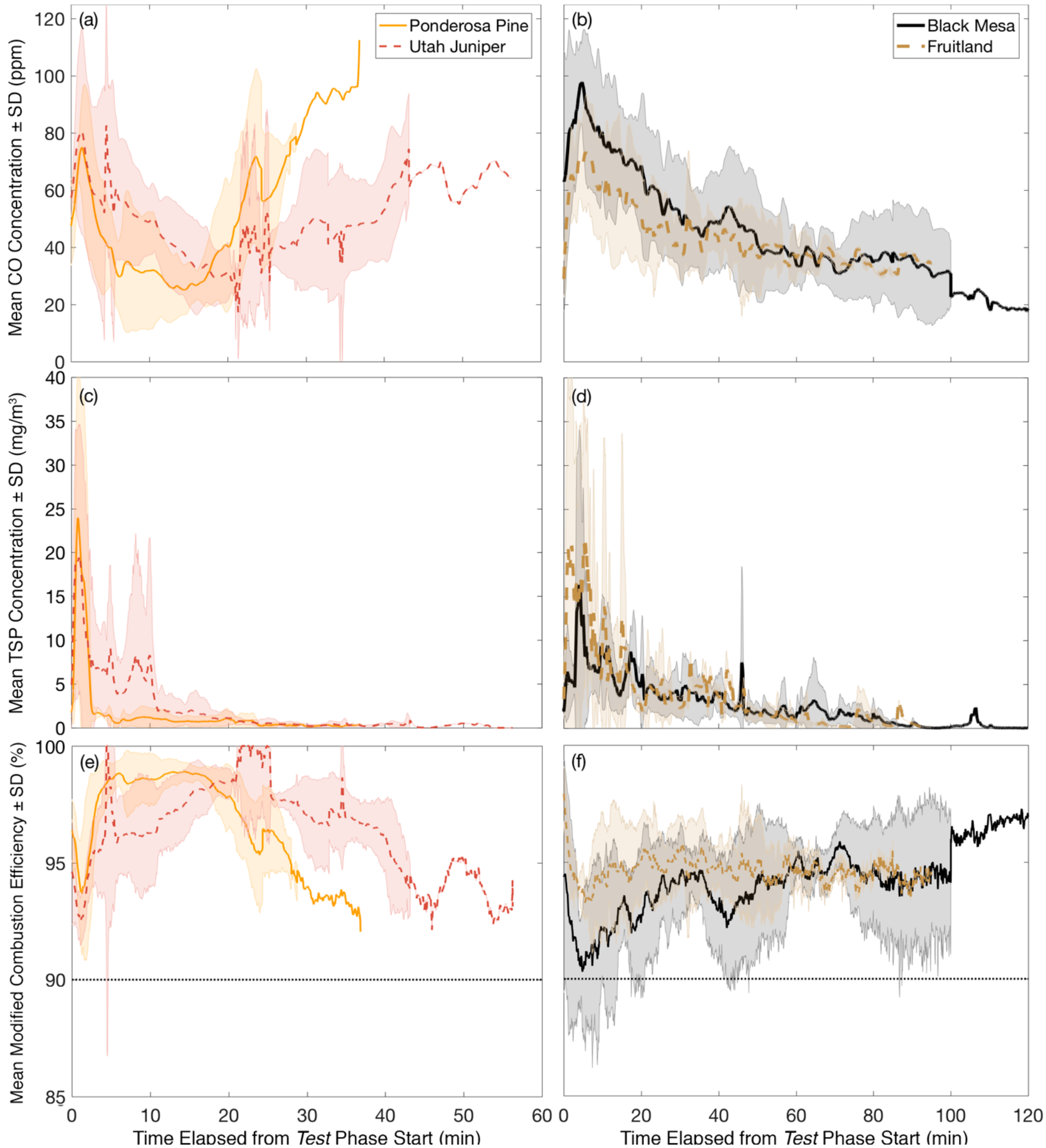


Figure 3-5. Real-time *Test* Phase (a,b) CO and (c,d) TSP Concentrations, and (e,f) MCE. Mean Concentration is Plotted as a Solid or Dashed Line. Standard Deviation of All *Test* Phases is Plotted as Shaded Region.

Conversely, the coal types showed a strong co-integration (p=0.0001) for real-time CO concentration, suggesting that CO emission rates do not vary significantly between the two coal types. CO concentration for all coals peaked following fuel addition, and then declined until the end of the *Test* phase, a trend observed by Shen et al. (2010) for coal combustion in residential stoves. The decay in CO concentration was modeled for *Black Mesa* ($CO_{ppm} = 83.5e^{-0.0121*t}$; $r^2 = 0.93$; t = min following fuel addition) and *Fruitland* ($CO_{ppm} = 61.8e^{-0.00785*t}$; $r^2 = 0.77$; t = min).

Similar to CO, all fuels exhibited a peak in TSP concentration following fuel addition. These peaks occurred while MCE was lowest during the *Test* phase (i.e., immediately following fuel addition). Butcher and Sorenson (1979) also observed TSP emissions to decrease rapidly following fuel ignition from *Eastern White Pine* combustion in a *homestove*. Zhi et al. (2008) observed similar trends where real-time black carbon (i.e., soot formed primarily during flaming combustion) concentrations peaked 5-15 min following addition of bituminous coal in Chinese residential stoves, and then decreased.

3.5 Conclusions

Four solid fuels commonly used for residential heating in the were tested using a representative Navajo stove. Of these fuels, *Ponderosa Pine* had the lowest *mEF* and *eEF* for $PM_{2.5}$, OC, CO and CO_2. *Ponderosa Pine* also developed a hot charcoal bed with lower emissions. *Black Mesa* coal had the highest *mEF* and *eEF* for $PM_{2.5}$, OC, and CO. Overall, coals produced higher mass emissions and more energy.

Additionally, it was determined that CO may be used as a proxy for $PM_{2.5}$ emissions for these fuels using a representative Navajo *homestove*. All fuels emitted the highest concentrations of TSP directly following fuel addition to the hot charcoal bed. This suggests that for a stove that is leaky or lacking proper exhaust, the minutes following fuel addition represent the most risk of personal exposure for residents using these fuels.

Tissari et al. (2007) notes the importance of accounting for the "habitual practices of operators" in residential wood stove testing, and found that field tests of heating stoves can result in three-fold higher emission factors of CO. The World Health Organization (2016) has acknowledged that household heating interventions "must take the whole picture into account." By using a representative stove and relevant fuels and practices, this study provided the first direct comparison of emissions from the combustion of wood and coal types relevant to the .

3.6 Acknowledgements

This work was partially supported by the National Science Foundation (award 0946502), the Discovery Learning Apprenticeship (DLA), and the CU Boulder Department of Civil, Environment, and Architectural Engineering's Dissertation Completion Fellowship. We thank the Mortenson Center for Engineering in Developing Communities for their assistance with facility funding. We are very grateful to Royce Brady and his family for providing the *homestove* and to Perry Charley and Dr. Donald Robinson for providing fuels used in this study.

4. Comparison of Field Determined $PM_{2.5}$, OC, EC, and CO Concentrations in Wood and Coal Burning Navajo Homes with Steady-state Concentrations Predicted by a Chemical Mass Balance Model

4.1 Abstract

A chemical mass balance model was used to predict steady-state indoor concentrations of fine particulate matter ($PM_{2.5}$), organic carbon (OC), elemental carbon (EC), and carbon monoxide (CO) in a representative Navajo single-family home burning wood and coal in a residential wood stove (i.e., *homestove*). Fuel types studied were two softwoods (*Ponderosa Pine* and *Utah Juniper)* and two high-volatile bituminous coals (*Black Mesa and Fruitland)*. Model inputs included the home characteristics and residential wood stove emission rates specific to this community and presented in Chapters 2 and 3 of this dissertation. The *model* predicted steady-state indoor concentrations were compared against *field* determined 79.5 hr mean indoor concentrations from a 2014 sampling campaign on the (Gordon et al. 2017). Errors between the *model* and *field* indoor concentrations of $PM_{2.5}$, OC, EC, and CO were determined using the Kolmogorov-Smirnov Goodness-of-Fit test and the model optimized by varying the assumed stove flue pollutant removal efficiency. For *wood-burning* homes, the model under-estimated $PM_{2.5}$ and CO concentrations, and over-estimated EC concentrations. For *coal-burning* homes, the *model* indoor concentrations were not significantly different than *field* measured indoor concentrations of $PM_{2.5}$, EC, and CO. This model may be useful to estimate emissions-based environmental and health benefits from an upcoming residential wood stove change-out program on the . With further validation, this model

may also be useful to estimate benefits from homes in other communities burning wood and coal in a conventional (i.e., non-catalytic) residential wood stove.

4.2 Introduction

Indoor air quality studies of Native American homes burning wood and coal have not related field measured indoor concentrations to data from controlled emissions tests (Bunnell et al., 2010; Ward, 2009). Residential wood stove emission factors can vary by more than an order of magnitude depending on their size and design (US EPA 1986), age (J E Houck, Pitzman, and Tiegs 2008), and operation (Jordan and Seen 2005). Hickmott et al. (1997) tested a coal-burning Navajo residential wood stove in a laboratory setting but did not compare results to field (i.e., actual home) indoor concentrations. Controlled emissions test data has under-estimated field test data by factors of two or more for *cookstoves* (Roden et al. 2009). This trend may be similar for residential wood stoves, though published comparisons between *field* measured and *model* predicted concentrations are limited.

Residential stove change-out programs in the US implement EPA-certified wood stoves that meet strict guidelines for emissions (2.5 g hr^{-1} of PM by the year 2020) as defined by New Source Performance Standards (US EPA 2016c). These guidelines are specific to devices that burn wood but not coal, though the EPA has sponsored the development and testing of a combination wood and coal *homestove* specific for use on the (Stewart 2016). To determine emissions-based benefits from an upcoming stove change-out program on the , exposures to health-damaging pollutants must be quantified.

Field filter particle sampling and gaseous pollutant monitoring can provide an accurate assessment of indoor air quality; however, validated modeling can be a powerful and affordable alternative. Indoor air quality models can be used to: 1) estimate health and environmental benefits from stove improvements or change-outs (i.e., monetized reduction in disease burden), 2) evaluate effects of specific stove, fuel and, operation parameters (e.g., flue height, fuel moisture content, and fuel load and burn rate), and 3) relate results of controlled emissions tests (i.e., emission factors in units of g kg^{-1}) to health-based metrics (i.e., regulatory standards in units of µg m^{-3} or ppm).

Indoor air quality models often apply conservation of energy and/or mass in a compartment, or zone (US EPA 1991). Johnson et al. (2011) employed a Monte Carlo simulation to estimate steady-state indoor concentrations of fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) in a 42 m^3 kitchen using *cookstoves*. Using emission factors from published literature, that study over-estimated indoor concentrations of both pollutants. Girman et al. (1982) under-estimated steady-state indoor CO concentrations from gas cooking and heating stoves. Nazaroff and Cass (1986) validated a model for the degradation of gaseous indoor pollutants, and noted the importance of heterogeneous chemistry (i.e., mixed-phase reactions) on air quality inside of homes burning solid fuels. These models were based on first-principles.

Fundamental models rely on accurate assumptions. According to Nagda et al. (1987), at least three parameters are required to estimate steady-state (i.e., dynamic equilibrium) indoor pollutant concentrations of a home using a well-mixed, single-source, single-compartment (WMSSSC) model. These parameters are: 1) indoor volume of the home (V, m^3), 2) air exchange rate of the home (v, hr^{-1}), and 3) pollutant indoor sources (S_i, g hr^{-1}). In this work, a WMSSSC chemical mass balance model was used to predict steady-state indoor concentrations of representative wood and coal burning Navajo homes.

4.3 Materials and Methods

4.3.1 Field Sampling

An air quality study was conducted at 46 homes in Tsaile, AZ and Shiprock, NM by the Hannigan research group (CU Boulder) during the spring of 2014. Homes included in the study utilized a variety of heating methods including gas and electricity; however only *wood-burning* (n=26) and *coal-burning* (n=9) homes were included in the present study. Mean indoor and outdoor concentrations of $PM_{2.5}$, organic carbon (OC), elemental carbon (EC), and CO were determined, and are herein referred to as *field* concentrations. Filter samples for $PM_{2.5}$ were collected for a mean duration of 79.5 hr (SD=18.6) using personal impactor filter packs (URG, 2000-25F-4-2.5, Chapel Hill, NC) loaded with 25mm Zeflour PTFE (0.5 μm pore size) and pre-baked (550°C for 8 hr) TissuQuartz filters (Pall Corp., Port Washington, NY).

PTFE and TissuQuartz filters were used for gravimetric and organic and elemental carbon analyses, respectively. Filters were located approximately 160 cm above the ground and 180 cm from the residential stove. CO levels were monitored using a collocated POD (Masson, Piedrahita, and Hannigan 2015). Field sampling was partial capture as opposed to the full capture utilized at *CUEST* (and in this model). Other sampling methods, and the analyses employed for the field study were the same as those at *CUEST* (Chapter 3, Section 2, in this dissertation).

4.3.2 Chemical Mass Balance Model

The steady-state chemical mass balance "box" model employed in this study (Nagda, Rector, and Koontz 1987; US EPA 1991) describes the generation and removal of pollutants in indoor air as:

Rate of accumulation = rate of [input + generation – output – sinks],

or,

Eq. 4-1

$$\frac{dm_i}{dt} = V\frac{dC_i}{dt} = \eta_i S_i + V(1 - F_b)vC_{0,i} - [C_{model}(Vv + v_{dep}A + qF) + \lambda_i]$$

Where:

dm_i	= Change in mass stock of pollutant *i* ($\mu g\ hr^{-1}$)
dt	= Change in time (hr)
V	= Volume indoors (m^3)
dC_i	= Change in concentration of pollutant *i* indoors ($\mu g\ m^{-3}$)
F_b	= Fraction of outdoor pollution intercepted by the building envelope (dimensionless)
v	= Air exchange rate (hr^{-1})
v_{dep}	= Velocity of particle deposition (i.e., terminal gravitational settling) ($m\ hr^{-1}$)
A	= Area of contact of particle deposition (m^2)
$C_{0,i}$	= Concentration of pollutant *i* outdoors ($\mu g\ m^{-3}$)
η_i	= *Homestove* flue removal efficiency of pollutant *i* (fractional)
S_i	= Source contribution of pollutant *i* ($\mu g\ hr^{-1}$), represented here with *Cycle* EF
$C_{model,i}$	= Concentration at steady-state of pollutant *i* ($\mu g\ m^{-3}$)
λ_i	= Decay rate of pollutant *i* ($\mu g\ hr^{-1}$)
q	= Flow rate through air cleaning device ($m^3\ hr^{-1}$)
F_i	= Fractional efficiency of the air cleaning device for pollutant *i* (dimensionless)

Terminal settling velocity of a particle decreases exponentially as a function of particle size according to Stokes' Law (Figure 4-1). Wood and coal combustion emits particles with a size distribution centered around a mean effective diameter of 100 nm (0.1 μm) (Tami C. Bond et al. 2002; Fine, Cass, and Simoneit 2004). The terminal settling velocity (v_{dep}) and hence deposition of $PM_{2.5}$ in the model was assumed to be negligible.

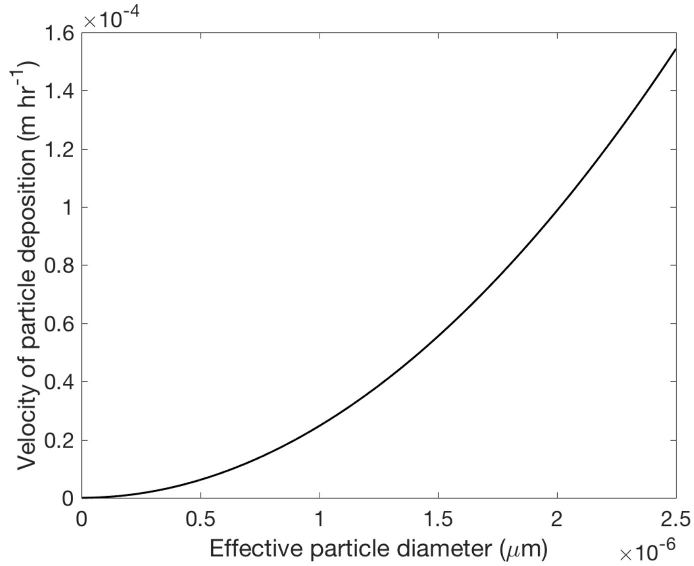


Figure 4-1. Terminal Velocity of Particle Deposition (v_{dep}) as a Function of Effective Particle Diameter (d). Unit Particle Density Assumed (i.e., ρ=1000 kg m^{-3}).

In this case, it was assumed there were no cleaning devices ($F_i = 0$), no capture by the building envelope ($F_B = 0$), and no decay of pollutants (e.g., devolatilization of volatile organics) ($\lambda_i = 0$). These were the same assumptions made by Johnson et al. (2011) in a cookstove modeling study. Equation 4-1 (Eq. 4-1) therefore becomes:

Eq. 4-2
$$\frac{dm_i}{dt} = V\frac{dC_i}{dt} = Vv\left(C_{0,i} - C_{model,i}\right) + \eta_i S_i$$

At steady-state (C_{model}, when $dC_i/dt = 0$), it reduces to:

Eq. 4-3
$$C_{model,i} = C_{0,i} + \frac{\eta_i S_i}{vV}$$

Outdoor concentrations of $PM_{2.5}$, OC, EC, and CO ($C_{0,i}$ in Eq. 4-3) were assumed to be zero in the model, thereby defining the residential wood stove as the only source of pollution. This assumption was primarily because the emission factors on which the model is based were background-corrected (i.e., subtracted) and intended to report only emissions from the *homestove*. Consequently, the *field* concentrations were corrected in the same manner by subtracting the corresponding mean outdoor concentration of each home for each pollutant.

Source contributions (S_i in Eq. 4-3) were based on emission rates for a representative Navajo residential wood stove (Champion et al., 2017) and are presented in Table 4-1. Based on a verbal questionnaire answered by the head of each household during the *field* study, the number of fires each day ranged between 0.33-and 2.0. Therefore, the model assumed that one (1.0) fire occurred each day for a duration of three days (i.e., the approximate duration of the *field* sampling). This daily fire was assumed in this study to consist of one *Pre-burn* phase (i.e., kindling and small wood load) and one *Test* phase (i.e., one *Cycle* as defined in Chapter 3, Section 2, in this dissertation).

The *model* also assumed a constant mass emission rate from the *homestove* even during low burn rates. To determine a constant mass emission rate (S_i), the mean mass emission rates from emissions testing (Table 4-1) were multiplied by an assumed burn frequency of one fire per day, and then divided by the mean sampling duration of the *field* study (79.5 hr). The purpose of this was to calculate a constant mass emission rate (S_i in Table 4-2) for use in the model.

The constant mass emission rates (S_i) equated to 3.4 – 7.7% of the mass emission rates observed during emissions testing. Therefore, the model assumes an emission rate at lower burn rates. This is not evident in the literature, however, as Jordan and Seen (2005) found that a residential wood stove had a 150% higher PM mass emission rate at a 73% lower burn rate.

.Table 4-1. Mean *Homestove Cycle* Burn Rate and Mass Emission Rates (During Testing)

Fuel	n	Burn rate	$PM_{2.5}$	OC	EC	CO
	#	*kg hr^{-1}*		*g hr^{-1}*		
Ponderosa Pine	5	2.6	3.3	0.7	0.29	66.6
Utah Juniper	4	1.6	3.7	1.3	0.19	63.5
Black Mesa	4	0.6	3.8	1.9	0.12	59.8
Fruitland	4	0.6	4.2	1.9	0.15	66.0

Table 4-2. Mean *Homestove* Mass Emission Rates (S_i) for $PM_{2.5}$, OC, EC, and CO in Units of mg hr^{-1} (Employed in the Model)

Fuel	$PM_{2.5}$	OC	EC	CO
Ponderosa Pine	11.6	2.5	1.0	233
Utah Juniper	19.7	6.7	1.0	345
Black Mesa	27.7	14.2	0.8	452
Fruitland	26.5	12.0	1.0	425

Finally, the internal volume of the home ($V=227\ m^2$) and air exchange rate (v=0.4 hr^{-1}) assumed were the same used in a previous energy model of a *Typical* non-weatherized 93 m^2 (1000 ft^2) Navajo home with 2.4 m (8.0 ft) ceilings (Champion et al., 2017b).

4.3.3 Fuel Grouping

Fuels were grouped by type (*wood* and *coal*) for two reasons: 1) to facilitate the comparison against *field* indoor concentrations from *wood-burning* and *coal-burning* Navajo homes, and 2) to increase the power of the statistical test employed. The second reason would also reduce Type II error (i.e., incorrectly retaining the null hypothesis), which would not be possible if each fuel was assessed individually. *Model* predicted steady-state concentrations for *Ponderosa Pine* and *Utah Juniper* were grouped as *wood* ($C_{model,\ wood}$) for comparison against *field* measured concentrations for *wood-burning* homes ($C_{field,\ wood}$). *Black Mesa* and *Fruitland* were grouped as *coal* for comparison of $C_{model,\ coal}$ against $C_{field,\ coal}$ for *coal-burning* homes.

The combined use of wood and coal was observed in the *field* study, as well as in previous air quality studies in Shiprock, NM (Hickmott et al. 1997; Bunnell et al. 2010). The emissions testing of *coal* conducted under this dissertation utilized *Ponderosa Pine* for the *Pre-burn* phase to establish a hot charcoal bed; therefore, the *Cycle* emission factors (i.e., *Pre-burn* + *Test* phases) include both *wood* and *coal* combustion and emissions. Additional details are included in Chapter 3 (Section 2).

4.3.4 Model Optimization

Homestove flue pollutant removal efficiency (η) was varied in order to minimize (i.e., optimize) the test statistic, *k*. Increasing η lowered the pollutant entering the home (i.e., is a source contribution). The parameter η was selected because all other terms in the steady-state equation (Eq. 4-3) were defined from previous studies (Chapters 2 and 3 of this dissertation). Additionally, estimates of η for a representative Navajo homestove flue was not available. It is noted that η remained the same for $PM_{2.5}$, OC, EC, and CO. The fit of *field* vs. *model* indoor concentrations *(C_{field} vs. C_{model})* of all pollutants was optimized by varying the pollutant removal efficiency of the *homestove* flue (η_i). Figure 4-2 shows this optimization process.

Since neither set of concentrations were normally distributed, the non-parametric two-sample Kolmogorov-Smirnov Goodness-of-Fit test was employed here for both optimization and comparison. The test statistic *k* was defined as the maximum absolute difference between the cumulative distribution functions of the datasets compared. Therefore, a smaller *k* represents a closer fit of *field* and *model* concentrations. As η increased, the fit between *model* and *field* concentrations improved. The optimized *model* value of η of 99.2% for all pollutants is shown in

Figure 4-2. Navajo homes can have cracked flues leaking into the home (Bunnell et al. 2010); this assumption is representative of homes with flues or stoves in poor condition.

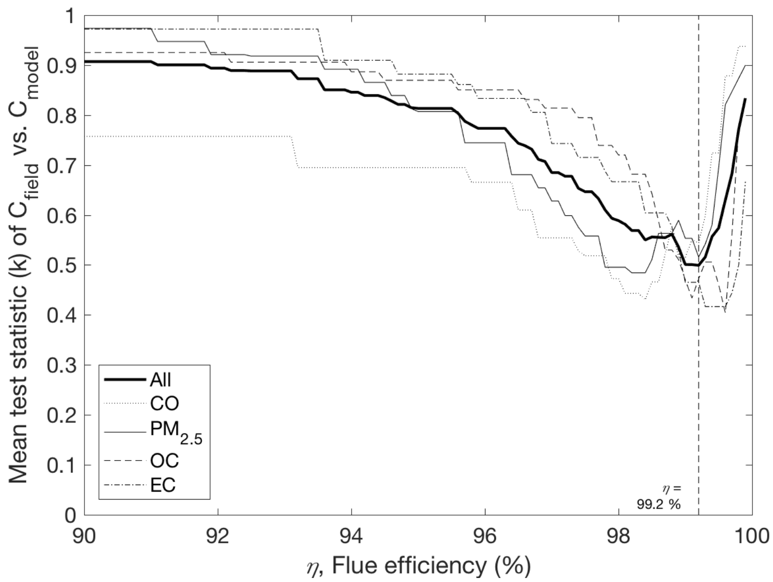


Figure 4-2. Optimization of Flue Efficiency to Fit *Model* Steady-state Concentrations (C_{model}) to *Field* Determined Concentrations (C_{field}) for $PM_{2.5}$, OC, EC, and CO Using Fuel Groupings.

4.4 Results and Discussion

Model predicted indoor steady-state and *field* determined indoor concentrations for $PM_{2.5}$, OC, EC, and CO are presented in Table 4-3. C_{field} of $PM_{2.5}$ and CO for both *wood-burning* and *coal-burning* homes were generally higher than C_{model}. Range of C_{model} vs. C_{field} for OC were similar (16 vs. 23 μg m^{-3}), suggesting that OC concentrations determined in the both the field and the lab were less than variable than the $PM_{2.5}$ concentrations.

Higher variability in the *field* compared to *model* concentrations were observed for $PM_{2.5}$ and CO, as expected. Emissions tests (i.e., model inputs) were controlled for stove, fuel, and practices (i.e., protocols), while *field* concentrations were not controlled and therefore had higher variability.

Table 4- 3. *Model* Predicted Steady-state and *Field* Determined Indoor Concentrations of $PM_{2.5}$, OC, EC, and CO.

Fuel Group	Concentration	$PM_{2.5}$ ($\mu g\ m^{-3}$)		OC (μg-C m^{-3})		EC (μg-C m^{-3})		CO (ppm)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	*Model*	19	33	5.3	3.8	1.2	0.78	0.30	0.10
Wood-burning	*Field*	34	24	5.2	4.5	0.6	0.90	0.88	1.1
Coal	*Model*	6.9	5.8	16	4.4	1.1	0.57	0.46	0.081
Coal-burning	*Field*	35	35	6.8	5.3	0.8	0.8	1.3	2.0

In Chapter 3, a strong correlation between CO and $PM_{2.5}$ emissions for the fuels tested was developed for the *Test* phase. It was expected that the *model* concentrations of CO and $PM_{2.5}$ would, therefore, correlate well in this exercise. Using C_{model} for all fuels, a linear correlation was observed between predicted concentrations of $PM_{2.5}$ and CO (R^2=0.90).

The test statistic, *k*, as determined by the Kolmogorov-Smirnov test for comparisons between *field* and *model* concentrations are presented as a heatmap in Figure 4-3. Darker areas on the heatmap represent lower k and closer fit of the sample probability distributions of *field* and *model* indoor concentrations. Additionally, a *p-value* approach was employed where the null hypothesis was rejected at a significance level (α) of 0.05 (labeled with asterisks in Figure 4-3).

The steady-state concentrations predicted by the *model* of $PM_{2.5}$, EC, and CO for *wood* ($C_{model,\ wood}$) were significantly different than the *field* measured concentrations for *wood-burning* homes ($C_{field,\ wood}$). The *model* under-estimated the steady-state $PM_{2.5}$ and CO concentrations, compared to *field* measurements. This discrepancy was likely due to differences in combustion processes during the controlled tests and the *field* measurements: in the *wood* tests, combustion was flaming and in the *field*, it included smoldering.

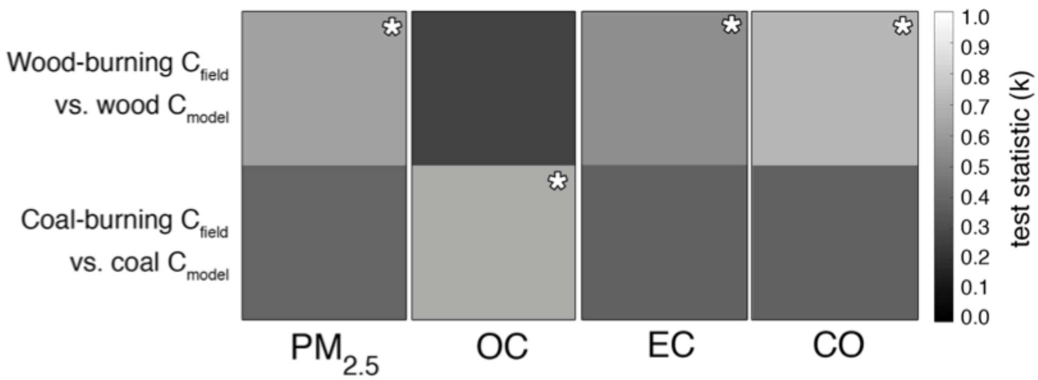


Figure 4-3. Test Statistic (k) from Two-sample Kolmogorov-Smirnov Goodness-of-Fit Test to Compare *Model* Predicted Steady-state Concentrations to *Field* Measured Concentrations for $PM_{2.5}$, OC, EC, and CO. Darker Areas Represent a Lower Value of *k* and Closer Fit of the Datasets Compared. Asterisks Represent a Significant Difference ($p<0.05$) Between the Sample Probability Distributions for C_{field} vs. C_{model}.

Flaming results in more complete combustion and lower emissions. Flaming combustion has been defined to have a modified combustion efficiency (MCE) greater than 90% (L. W. A. Chen et al. 2007). The mean MCE for *wood* tests was 96.7% (SD=1.6%), and combustion was entirely in the flaming phase. It is likely that the combustion in the *field* study included occasional or even extended periods of smoldering, resulting in higher *field* concentrations of $PM_{2.5}$ and CO.

Additionally, the burn rate of *wood* (2.1 ± 1.0 kg hr^{-1}) during the *Test* phase was defined as being the "maximum" burn rate category (Chapter 3, Section 2 of this dissertation). High burn rate of wood can result in production of devolatilization products exceeding the ability of the flame to combust them (Pettersson et al. 2011). Therefore, the higher $C_{model,wood}$ of CO compared to $C_{field,wood}$ may be explained, in part, by the higher burn rates observed during emissions testing.

The *model* over-estimated EC for *wood-burning* homes. EC is primarily a by-product of the flaming combustion phase. In this phase, the pyrolysed fuel produces aromatic compounds which grow in a planar and then spherical fashion, and ultimately oxidize to varying degrees (Leung, Lindstedt, and Jones 1991). The *model* predicted concentrations for OC that were not significantly different from those measured at *wood-burning* homes ($C_{field, wood}$).

In the case of *coal* combustion, the $C_{model, coal}$ for $PM_{2.5}$, EC, and CO were not significantly different from those measured at *coal-burning* homes ($C_{field, coal}$). Based on these results, the model seems adequate for estimating concentrations of these pollutants in *coal-burning* homes. The *model* did, however, over-estimate OC concentrations in *coal-burning* homes.

4.5 Conclusions

In this chapter, a first attempt was made at comparing pollutant concentrations measured in a *field* campaign to those predicted by a *model* based on data obtained in controlled experiments. This simple chemical mass balance *model* estimated steady-state indoor concentrations in a representative Navajo home *burning wood and coal*. For *wood-burning* homes, the model under-estimated indoor concentrations of CO and $PM_{2.5}$, but predicted mean OC concentrations within 5%. For *coal-burning* homes, model predictions for $PM_{2.5}$, EC, and CO were not significantly different than the concentrations measured in the *field*. Field determined concentrations were more variable than the *model* predicted concentrations and can vary spatially by orders of magnitude (Ezzati, Saleh, and Kammen 2000). This model can be refined by including more sources and sinks, as well as by adding more detailed home and stove characterization. In its present form, it may still be useful for modeling concentrations in *coal-burning* Navajo homes following a stove change-out program slated for 2017.

5. Fine Particulate Matter from the Combustion of Wood and Coal Types Commonly Used on the Navajo Nation Induce Oxidative Stress and Inflammatory Responses in Murine Macrophage Cells

Champion W.M.[1], Imam J.[2], Sidhu D.[3], Salazar, J. [4], Li N.[3], Majestic B.J. [4], Montoya L.D.[1]

[1] University of Colorado Boulder, Civil, Environmental, and Architectural Engineering Department, Boulder, CO 80309
[2] University of Colorado Boulder, Molecular, Cellular, and Developmental Biology Department, Boulder, CO 80309
[3] Michigan State University, Pathobiology and Diagnostic Investigation, East Lansing, MI 48824
[4] University of Denver, Department of Chemistry and Biochemistry, Denver, CO 80208

5.1 Abstract

Communities in the Navajo Nation face public health burdens caused in part by the combustion of wood and coal indoors. The residential heating stoves in many Navajo homes are old or damaged, and can emit health-damaging pollutants including fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) indoors. One of the recognized mechanisms by which particulate matter exerts its adverse health effects is the generation of reactive oxygen species (ROS) that leads to oxidative stress, inflammation, and cell death. In this study, we used murine macrophage cell line (RAW 264.7) to evaluate cellular responses induced by exposure to $PM_{2.5}$ sampled from emissions tests of common Navajo wood and coal types burned in a wood stove representative of this community. Our results showed that aqueous extracts of $PM_{2.5}$ of all fuels induced antioxidant enzyme heme oxygenase-1 (HO-1). Aqueous extracts of *Ponderosa Pine* and *Utah Juniper* wood,

and *Black Mesa* coal also increased the release of inflammatory cytokine tumor necrosis factor alpha (TNF-α). Content of low-volatile organic carbon (i.e., larger and more polar organics), elemental carbon, and soluble copper were positively correlated with both oxidative stress and inflammatory responses. Results of this study suggest that exposure to $PM_{2.5}$ emitted from combustion of common Navajo wood and coal types may be hazardous to the public health of Navajo communities.

5.2 Introduction

Household air pollution from solid fuel use indoors takes nearly three million lives around the world each year (Forouzanfar et al. 2015). Domestically, over a half million Americans living below the Federal Poverty Line are exposed to household air pollution (Rogalsky et al. 2014). Twelve to fifteen percent of these low-income Americans reside in the Navajo Nation (NN) (U.S. Census Bureau 2015; US Census Bureau 2014). Most Navajo homes burn wood (Bunnell et al. 2010; Arizona Rural Policy Institute 2010) or a combination of wood and coal together (Hickmott et al. 1997). Coal is distributed at no cost to residents living near mines and also sold by vendors at markets and roadside, making it a convenient heating alternative that burns longer than wood. Respiratory disease burdens from wood and coal use have been observed in several Navajo communities (Bunnell et al. 2010; Robin et al. 1996; Morris et al. 1990).

Coal and wood-smoke is a complex mixture of compounds possessing inflammatory and redox-active properties (Luke P. Naeher et al. 2007). Particulate matter (PM) has been shown to induce pulmonary inflammatory responses mediated through the generation of reactive oxygen species (ROS) (Breysse et al., 2013). The oxidative capacity (i.e., ability to generate ROS) of PM has been attributed to organic compounds including PAHs (Bae et al. 2010), their oxidized derivatives (e.g., quinones) (Squadrito et al. 2001), transition metals (González-Flecha, 2004; Prahalad et al., 1999), and endotoxins (Tao, Gonzalez-Flecha, and Kobzik 2003).

Decreasing particle size has been shown to have stronger inflammatory effect in the lung due to their large surface area to carry more hazardous materials, increased number of reaction sites, and great capability to penetrate deep in the lung (Oberdörster, Oberdörster, and Oberdörster 2005). $PM_{2.5}$ compared to PM_{10} induce greater oxidative stress and higher redox activity (Li et al. 2003). Residential stoves burning wood and coal emit PM in the fine fraction (i.e., < 2.5 μm) (Hueglin et al. 1997; Tami C. Bond et al. 2002). This $PM_{2.5}$ contains more than 60% carbon of ranging volatility, polarity, and solubility (Shen et al. 2014), and trace amounts (~0.01%) of transition and toxic metals (Fine, Cass, and Simoneit 2004).

Under homeostatic conditions, ROS are constantly generated and neutralized by the antioxidant defense system or enzymes whose primary function is to scavenge ROS. When ROS production overwhelms this defense, oxidative stress occurs causing damage to nucleic acids, proteins, and membrane lipids (Halliwell and Gutteridge 2015).

Based on cellular studies using diesel exhaust particles (DEP) (Xiao et al. 2003) and concentrated ambient particles (CAPs) (Li et al., 2003), a three-tier cellular oxidative stress response model has been proposed to explain the mechanisms by which PM exerts adverse health effects (Li et al., 2002). This model suggests that low levels of oxidative stress activate cellular antioxidant defense including antioxidant enzyme heme oxygenase-1 (HO-1) (Li et al., 2000). The failure to restore cellular redox balance leads to inflammatory responses characterized by increased cytokine production (e.g., tumor necrosis factor alpha, TNF-α) and upregulation of adhesion molecules (Sen and Packer 1996). Severe oxidative stress can interfere with mitochondrial function and cause cell death (Ott et al. 2007).

Macrophages (AM) are central for maintaining the delicate immune balance and cellular homeostasis of the lung (Lambrecht 2006). They are one of the first lines of defense in the respiratory system and also major sources of inflammatory mediators (Pozzi et al. 2003). Murine macrophage cell line RAW 264.7 has been widely and successfully used as a surrogate to assess the adverse cellular effects of oxidative PM (Hiura et al., 1999; Li et al., 2002).

In this study, we used RAW 264.7 to determine the oxidative, inflammatory and cytotoxic effects of $PM_{2.5}$ emitted from combustion of wood and coal types commonly used in Navajo homes based on the 3-tier stratified oxidative stress response paradigm. To our best knowledge, no previous *in vitro* study has applied this model to investigate the cellular effects of $PM_{2.5}$ emissions of the specific wood and coal species used in this work, nor from solid fuels burned in an aged residential wood stove.

5.3 Materials and Methods

5.3.1 Fuels

Two types of split softwood were tested: *Ponderosa Pine* (PP-wood, *Pinus ponderosa*) and *Utah Juniper* (UJ-wood, *Juniperus osteosperma*). These wood types were found to be the most commonly used in wood-burning Navajo homes in Ft. Defiance, AZ (Robin et al. 1996). These wood types have similar content (±10%) of volatile matter, fixed carbon, moisture, and energy (Gaur and Reed 1998; W. Chen et al. 2012). Additionally, two high-volatile bituminous coal types were tested: *Black Mesa* (BM-coal) and *Fruitland* (FR-coal). Compared to the wood types, these coals have roughly half the content of volatile matter, three times the fixed carbon, similar moisture, and 25% more energy (Affolter 2000; B. M. A. Kirschbaum and Biewick 2000). Wood fuels are central to Navajo culture, but coal is cheap and widely available (Champion et al., 2017).

5.3.2 Testing

Emissions testing was conducted at the University of Colorado Emissions Standardization and Testing (*CUEST*) facility. Details of the facility are described in Champion et al. (2017). Fuels were combusted using a cast iron wood-burning residential wood stove (King, Martin Stove and Range Company, Florence, AL) pictured in Figure 5-1. The stove was manufactured in 1912, had visible fissures on each side of the body, and was generously provided by a Navajo residence.

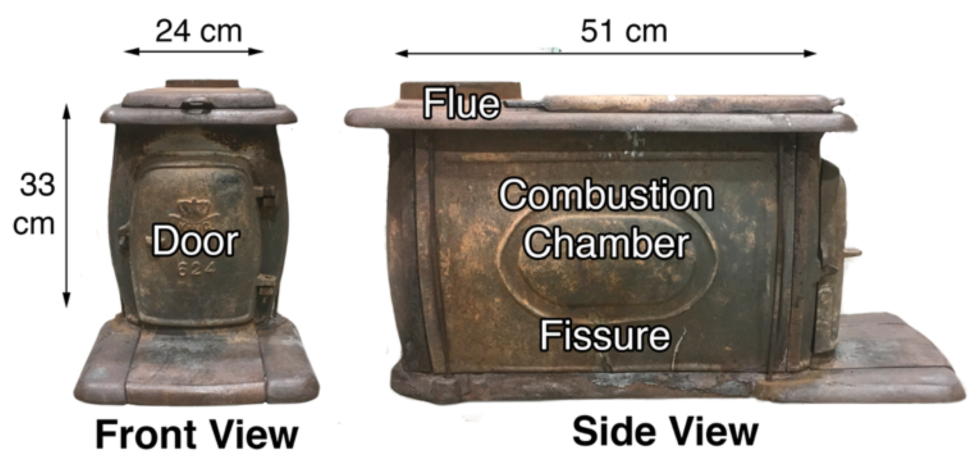


Figure 5-1. Residential Navajo Wood-burning Stove Used in this Study.

A modified certification test protocol for residential wood stoves (American Society for Testing and Materials 2010; USEPA 1991) was utilized and included a 45 min background sampling period followed by two phases: *Pre-burn* and *Test*. The ASTM method is currently being used as the basis for a new EPA cordwood stove certification test (US EPA 2016b). There is no current standard protocol for emissions testing of coal burning residential stoves, and the ASTM protocols for wood tests were adapted for the coal types in this study. Briefly, in the *Pre-burn* phase, a split log (i.e., cordwood) load was ignited to develop a hot charcoal bed and allow the stove to reach the operating temperature. Next, in the *Test* phase, a wood (1.3 kg) or coal (0.65 kg) load based on combustion chamber dimensions was added to the hot charcoal bed and ignited with the air control (i.e., door) fully open. The air control was then closed, but fissures in the stove body supplied enough air so that the burn rate was within the "maximum" category (>1.75 kg-dry-fuel/hr) as defined by the protocol.

The *Test* phase captured the three primary stages of combustion (ignition, flaming, and smoldering) and averaged 37 min for wood and 91 min for coal. The temperatures of the approximate centers of the top, front, and left and right side of stove body were measured from 25 cm away every five minutes during the *test* phase using an infrared thermometer to ensure thermal equilibrium was maintained. The *Test* phase is complete when the fuel load is consumed. The $PM_{2.5}$ collected during the *Test* phase were used to prepare extractions to be assessed in this study.

5.3.3 Sampling

Fine particulate matter was sampled onto acid-washed 25 mm polytetrafluouroethylene (PTFE, 0.5 μm pore size) (Zeflour, Pall Corporation, Port Washington, NY) and pre-baked quartz fiber filters (QFF) (TissuQuartz, Pall Corporation). The filters were loaded into pre-cleaned and solvent-washed personal impactors and filter holders (2000-25F-4-2.5, URG, Chapel Hill, NC). Flow rates through the filters were maintained at 4.0 lpm with diaphragm vacuum pumps and ball valves (MOA, GAST, Benton Harbor, MI) and measured with rotameters (OMEGA, Stamford, CT). Until analysis, filters were stored in acid-washed polystyrene Petri dishes (Pall Corp., # 7242, Port Washington, NY) at -20°C.

5.3.4 Gravimetric and Carbon Analyses

During the *Test* phase, $PM_{2.5}$ was sampled onto PTFE and QFF filters. The mass of $PM_{2.5}$ on PTFE filters was determined gravimetrically with a five-digit analytical scale (Sartorius Corp., LabServe, Germany) and following published protocols (Dutton et al. 2009). The mass of organic and elemental carbon (OCEC) in $PM_{2.5}$ on QFF was determined with a Dual Optics OCEC Lab Instrument (Sunset Laboratory, Tigard, OR), thermal optical transmission (TOT) protocols for DEP (NIOSH 5040, 2015), and 1.5 cm^2 filter punches. With the NIOSH method, the total OC (OC) is comprised of five volatility classes: OC1, OC2, OC3, OC4, and OCp.

The volatility classes OC1-OC4 are defined by the temperatures (340, 500, 615, 870°C, respectively) at which the carbonaceous $PM_{2.5}$ volatilizes from the solid-phase in a helium atmosphere at 0.5 atm. A higher number (i.e., OC4) represents lower volatility. The pyrolysed OC volatility class (OCp) is comprised of the elemental carbon formed from OC during analysis, and does not necessary represent that OCp is a lower volatility class than OC4. Lastly, elemental carbon (EC) is comprised of the insoluble and generally inert extended aromatics formed during the pyrolysis and subsequent combustion of the solid fuel during the original combustion processes (Fitzpatrick et al. 2008).

5.3.5 Sample Extractions

Fine particulate matter was extracted from the PTFE filters using cell culture grade (ccg) water (Gibco, ThermoFisher #A1287303, Waltham, MA). For a given fuel (i.e., PP-wood), the filters from all *Test* phases were extracted serially in the same solution, effectively “pooling” the samples of each fuel into one; PTFE filter count for each fuel ranged from 5 to 9, with coal fuels having more filter changes due to increased PM loading during testing. Briefly, filters were placed in a sterile 60 ml amber glass jar containing 5.0 ml of ccg water.

The filters were extracted by three steps: 1) shaking at 4°C for 1 hr, 2) vortexing at room temperature (RT) for 10 min, and 3) sonication at RT for 30 min. An additional 0.5 ml of ccg water was added with each filter addition, and the extraction repeated with the added filter. Final extract volumes were between 5.5-7.7 ml. Mean extraction efficiencies (i.e., mass yields from the PTFE filters) were 48% for wood and 16% for coal. The resulting particle suspensions were designated as aqueous extracts (AEs) and stored at -80°C until use (Prahalad et al. 1999).

5.3.6 Soluble Metal Analysis

Aqueous extracts were filtered with 0.45 µm pore size nitrocellulose filters (ThermoFisher, Fisher Scientific #SA1J791H5, Waltham, MA) that were pre-soaked in 2% trace-metal free hydrochloric acid (HCl) for 24 hr, and plastic syringes (ThermoFisher, National Scientific #S7515-20, Waltham, MA) washed with 2% HCl. Aqueous extracts were then acidified with 3% trace metal-free nitric acid (HNO_3) and analyzed using an intercoupled plasma mass spectrometry (ICP-MS) (Agilent Corp., 7700, Santa Clara, CA) following published protocols (Cartledge and Majestic 2015).

The soluble metals included in this analysis were of three classifications: 1) alkaline earth and alkali [magnesium (Mg), calcium (Ca), and potassium (K)], 2) transition [copper (Cu), zinc (Zn), iron (fe), nickel (Ni), chromium (Cr), and cadmium (Cd)], 3) metalloid and toxic [arsenic (As) and lead (Pb)]. Alkaline earth and alkali metals are reactive and electropositive and form alkaline oxides and peroxides (i.e., ROS). Transition metals have valence electrons in multiple shells and some (e.g., Cu, Fe, Cr) can undergo the Fenton reaction to form hydroxyl ion (^{-}OH) and radical ($^{\bullet}OH$) (Franco et al. 2009). Metalloids and toxic metals are less easily oxidized and thereby persist longer in their environment.

5.3.7 Endotoxin Assay

Endotoxin levels of the samples were evaluated with a chromogenic *limulus* amebocyte lysate (LAL) endotoxin quantitation kit (Pierce, ThermoFisher, Waltham, MA) following manufacturer's protocol.

5.3.8 Cell Culture and Stimulation

Murine alveolar macrophage cell line RAW 264.7 were obtained from American Type Culture Collection (Rockville, MD). Cells were maintained in Dulbecco's Modified Eagle Medium supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin (i.e., complete-DMEM) at 37°C in a humidified incubator supplemented with 5% CO_2 (Li et al., 2002). Cells passed between 4 and 14 generations were used for all experiments. Cells were plated in complete-DMEM in 12-well cell culture plates for HO-1 (0.5 x 10^6/well) and TNF-α (0.25 x 10^6/well) analysis, and in 96-well plates for cytotoxicity analysis (0.05 x 10^6/well). Cells rested 24 hr between plating and stimulation.

PM-containing complete DMEM for cellular stimulation were prepared using a previously published method (Li et al., 2003). The total stimulation volumes were 500 μl/well for HO-1, 350 μl/well for TNF-α, and 100 μl/well for cytotoxicity analyses. Cells were exposed for a period of 16 hr for all stimulations.

5.3.9 Western Blot of HO-1

Induction of HO-1 was determined by Western blot analysis. Briefly, cells were collected by gentle scraping, then washed with cold phosphate buffered saline (PBS), and re-suspended in cell lysis buffer (Cell Signaling Technology, Beverly, MA) containing a cocktail of protease inhibitors (Sigma Aldrich, St Louis, MI). Following ultra-sonication and centrifugation of the cell homogenate, the protein concentration of the supernatant was determined by Bradford assay (Bradford 1976). Western blot was performed as previously described (Li et al., 2003; Burnette, 1981). Briefly, one hundred (100) μg of total cellular protein from each sample was separated by polyacrylamide gel electrophoresis and then transferred to polyvinylidene fluoride (PVDF) membrane. Immunoblotting of HO-1 protein was performed using monoclonal anti-HO-1 antibody (1:1000), followed by an incubation with horseradish peroxidase (HRP)-linked sheep anti-mouse secondary antibody (1:1000). Enhanced chemiluminescence (ECL) western blotting substrate (Pierce-, Waltham, MA) was used to detect the signals on the membrane. (Li et al., 2000; Li et al., 2002). Semi-quantification of band density was conducted using ImageJ v1.51j (National Institute of Health, Bethesda, MD) and published methods (Ferreira et al. 2012).

5.3.10 Measurement of TNF-α in Cell Culture Media

TNF-α level in the culture media was determined by an enzyme-linked immunosorbent assay (ELISA) kit following manufacturer's instructions (BD Biosciences, San Jose, CA) using EON microplate spectrophotometer (BioTek, Winooski, VT) and GEN5 software.

5.3.11 Determination of Cell Viability

Cell membrane injury results in the release of lactate dehydrogenase (LDH) into the cell culture medium. Cytotoxicity of the PM samples was determined by the LDH assay using EON microplate spectrophotometer (BioTek, Winooski, VT) and GEN5 software (Promega, CytoTox 96, Madison, WI) were used.

5.3.12 Data Analysis

Data were processed in Excel and Matlab. Responses were compared against a cell control with a one-tailed Student's t-tests at a significance level (α) of 0.05. Errors are represented as standard error of the mean (SEM). Linear regressions between HO-1 and TNF-α responses were developed between particle components (i.e., carbon classes and soluble metals). Only components with a Pearson linear correlation coefficient (r) larger than 0.80 are discussed.

5.4 Results and Discussion

5.4.1 Organic and Elemental Carbon Content

Particle composition is plotted in Figure 5-2. The majority of $PM_{2.5}$ mass was carbon (56-73%). The remaining mass (labeled "Other" in Figure 5-2) is expected to be comprised of the carbon-bound oxygen, hydrogen, nitrogen, and sulfur (i.e., the non-carbonaceous fraction of OC), and low levels of salts and metals (0.01-0.1%) (Fine, Cass, and Simoneit 2004). The contribution of non-carbonaceous organic matter is expected to range between 29-50% of $PM_{2.5}$ mass, depending on the assumed organic matter to organic carbon ratio (OM/OC). This ratio is generally defined as 1.4 (White, Roberts, and Laboratories 1976), but is expected to be higher (~2.0) for wood and coal combustion emissions due to heavier oxidized compounds such as levoglucosan (Turpin and Lim 2001).

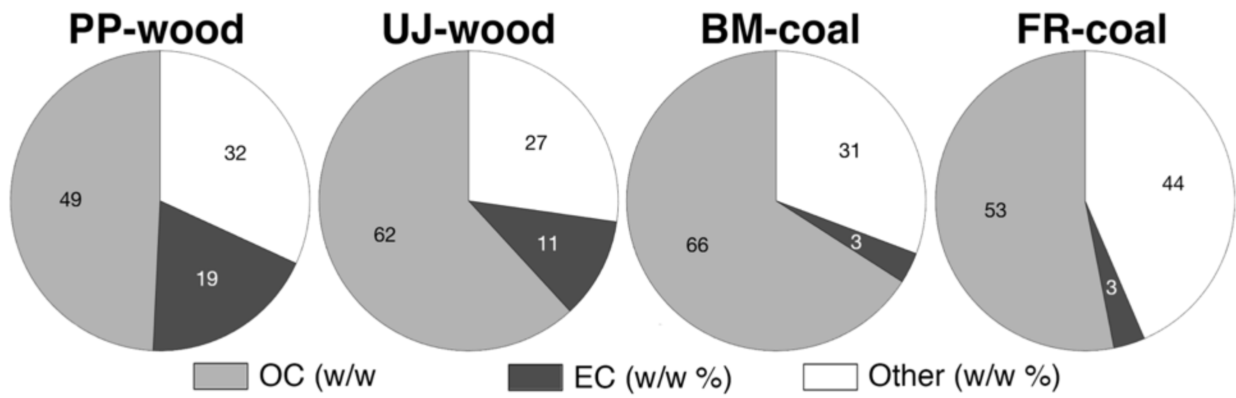


Figure 5-2. Composition of $PM_{2.5}$ from the Combustion of the Wood and Coal Types Tested. Particle Mass of All Fuels was Predominantly Carbon. BM-coal had the Highest OC Content. PP-wood $PM_{2.5}$ had the Highest EC content. Wood $PM_{2.5}$ Compared to Coal had Significantly ($p<0.05$) Higher EC Content.

PP-wood $PM_{2.5}$ was comprised on average of 49% OC and 19% EC. This composition is near that of Fine et al. (2004) who found $PM_{2.5}$ from *Loblolly Pine* combustion in a residential wood stove to be 44% OC and 13% EC. UJ-wood $PM_{2.5}$ compared to PP-wood contained higher a OC content (62%) with more volatile (i.e., less polar) compounds (e.g., volatility class OC1). The *Loblolly Pine* OC was primarily heavy long-chain branched hydrocarbons and polar sugar derivatives (e.g., levoglucosan) (Fine, Cass, and Simoneit 2004).

BM-coal and FR-coal OC content ranged from 53-66%, similar to that of the wood types tested. Simoneit et al. (2007) the determined OC fraction of $PM_{2.5}$ from a controlled open burn of BM-coal was comprised largely of long-chain hydrocarbons (similar to *Loblolly Pine*), and nonpolar alkanes. Therefore it is expected that OC from coal combustion will contain more nonpolar organics compared to wood.

Residential stoves in China burning bituminous coal (Zhang et al., 2008; Shen et al., 2014; Chen et al., 2016) found that OC comprised less of the $PM_{2.5}$ mass (27-47%) compared to the bituminous coal types in this study. This may be due in part to the high supply of dilution air and increased condensation of volatile and semi-volatile organics onto the QFF (Boman et al. 2005), though backup QFF determined this contribution to be small (<3%). Therefore the higher OC content for coal observed here may be due to difference in stove design. The studies in China utilized residential coal stoves that include “overfire” air entering above the fuel load to promote more complete combustion of organics formed during the devolatilization (i.e., pyrolysis) of the coal. Here, the residential wood stove tested did not include “overfire” air, and therefore higher OC emissions would be expected.

The EC content of $PM_{2.5}$ in the studies of Chinese residential coal stoves varied widely (1.1-37%), compared to low range of values determined here for BM-coal (3.4±2.3%) and FR-coal (3.5±2.2%). EC is formed primarily during flaming combustion, and the duration and properties of this combustion phase dictate the amount of EC formed.

5.4.2 Soluble Metals

Soluble metal concentrations for the $PM_{2.5}$ of all fuels are presented in Table 5-1. Soluble K was the most prevalent (0.25-0.58%), and is commonly used as a marker for wood combustion (Lee et al., 2010). A soluble K content (0.28%) within the range observed here was determined by Schauer et al. (2001) for $PM_{2.5}$ emitted by a fireplace burning *Loblolly Pine*. Hildemann et al. (1991) determined that $PM_{2.0}$ emitted by a fireplace burning an unspecified species of *Pine* had both similar magnitude and rank of concentrations of soluble K (0.47%), Mg (0.25%), Zn (0.017%), Cu (0.013%), and Ni (0.003%). That study however found higher levels of Pb (0.019%), Fe (0.009%), and Cr (0.001%) than observed here. Schauer et al. (2001) assessed the content of soluble metals [using x-ray fluorescence (XRF)] in the $PM_{1.8}$ emitted by combustion of *Loblolly Pine* in a fireplace and found similar potassium concentration (0.28%). The same study however found lower concentrations of all other metals assessed here [e.g., Cu, Ni, Pb, Cr, As, and Cd were below the lower detection limit (LDL) of that study]. The LDL from that study is expected to be much higher than this study, due to the different analytical technique employed (XRF vs. ICP-MS).

.Table 5-1. Soluble Metal Content of $PM_{2.5}$ (% w/w) Ranked by Mean Concentration.

Fuel Name	K	Mg	Zn	Cu	Ni	Pb	Cr	As	Cd	Fe
PP-wood	0.49	0.13	0.022	0.042	0.0027	nd	nd	nd	nd	nd
UJ-wood	0.25	0.09	0.033	0.034	0.0032	0.0001	nd	nd	nd	nd
Wood Mean	*0.37*	*0.11*	*0.028*	*0.038*	*0.0029*	*0.0001*	*nd*	*nd*	*nd*	*nd*
BM-coal	0.25	0.19	0.031	0.027	0.0018	nd	nd	nd	nd	nd
FR-coal	0.58	0.31	0.23	0.029	0.0019	0.0011	0.0002	0.0001	0.0001	nd
Coal Mean	*0.42*	*0.25*	*0.13*	*0.028*	*0.0019*	*0.0006*	*0.0001*	*0.0001*	*0.0001*	*nd*
LDL	0.0016	0.0002	0.00018	0.00002	0.00004	0.00001	0.00001	0.00001	0.00001	0.00004

nd = non-detect, or below detection limit of analysis. Assumed to be zero in calculation wood or coal mean. LDL = lower detection limits of ICP-MS analysis.

Raw BM-coal generally contains low total levels (<10 ppm) of the metals assessed here (Affolter 2000). Ge et al. (2004) found that $PM_{2.5}$ from anthracite honeycomb coal combustion in a residential coal stove contained low levels (<0.001%) of soluble arsenic and cadmium, agreeing with results from this study. However, levels of soluble Cr (0.3-0.5%) and Fe (0.02-0.2%) were much higher compared to this study.

5.4.3 Endotoxin

Studies have shown that endotoxin can activate macrophages and contribute to the inflammatory effects of ambient PM (Becker et al. 1996; S.-L. Huang et al. 2002). Endotoxin are the lipopolysaccharide (LPS) from Gram-negative bacteria and are the most potent natural stimulators of macrophage cytokine production (Becker et al. 1996). In order to determine whether the endotoxin in our samples had an impact on cellular responses we first measured the endotoxin content in each PM extract. The only fuel with $PM_{2.5}$ to have detectable levels of endotoxin was PP-wood (0.78 EU/ml).

5.4.4 Oxidative Stress Response

The mean relative scanning density for HO-1 induction is plotted in Figure 5-3 using data from two independent stimulations and Western blot analyses at high dose (50 µg/ml for PP-wood, UJ-wood, and BM-coal and 35 µg/ml for FR-coal). Fold change over the cell control ranged between 4 and 14. These values were similar to Li et al. (2003) who found HO-1 induction by exposure of RAW 264.7 cells to concentrated ambient $PM_{2.5}$ at 25–100 µg/ml to range from 3 and 17 fold. The AE of PP-wood caused the highest induction of HO-1 of all fuels. Additionally, wood types caused significantly higher HO-1 induction compared to coal types. The same trends were observed at low dose (25 µg/ml for all fuels) and this data is included in the Appendix (Chapter 8, Figure S5-1).

HO-1 is a highly sensitive marker for cellular oxidative stress including that induced by PM from various sources (Deng et al., 2013; Hirano et al., 2003; Li et al., 2002). Among all AEs tested, PP-wood was most potent in HO-1 induction. Between fuel types, wood compared to coal caused significantly higher HO-1 induction (Figure 5-3). Li et al. (2003) reported that HO-1 expression in both RAW 264.7 murine macrophages and BEAS-2B human bronchial epithelial cells was positively correlated with the particles' intrinsic oxidative potential as determined by the cell-free *dithiothreitol* (DTT) assay. Additionally, the formation of ROS in ambient $PM_{2.5}$ was correlated with content of high boiling-point PAHs and oxy-PAHs (Sklorz et al. 2007).

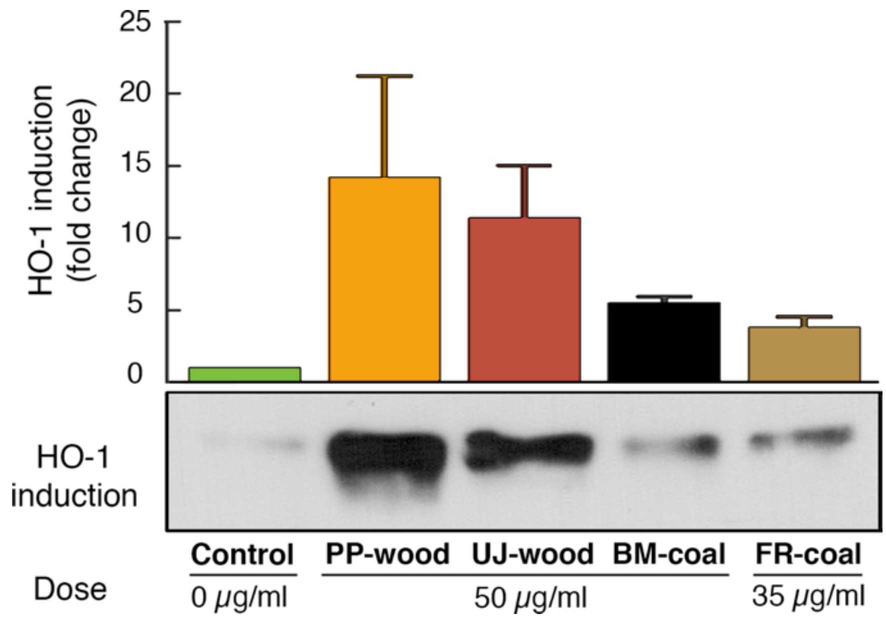


Figure 5-3. Induction of Heme Oxygenase 1 (HO-1) by Aqueous Extracts of Wood and Coals. Cells were Stimulated at Indicated Concentrations for 16 hr Before Collection for Western Blot Analysis. Bar Graph Shows Changes (fold) of HO-1 Protein Band Density over Untreated Control. Error Bars are SEM from Replicate Experiment (n=2) Data.

In previous studies of residential stove combustion emissions, PAHs and oxy-PAHs comprised a greater mass fraction of the OC for bituminous coal (13%) (Shen et al. 2013) compared to *Loblolly Pine* (2%) (Fine, Cass, and Simoneit 2004). The coal $PM_{2.5}$ assessed in this study (BM-coal and FR-coal) are therefore expected to contain a higher mass fraction of nonpolar and midpolarity OC. This OC includes PAHs and oxy-PAHs that are known to cause oxidative stress in RAW 264.7 (Kubátová et al. 2006) and human epithelial cells (Danielsen et al. 2011). However, PP-wood was the strongest inducer of HO-1, and is expected to have lower concentrations of these PAHs and oxy-PAHs. This suggests that the HO-1 induction observed here is due to different particle components. See below for further discussion.

5.4.5 Oxidative Stress Response and Particle Composition

The mass content of components that associated with HO-1 induction in this study are plotted in Figure 5-4. Total OC (i.e., sum of OC volatility class) did not correlate with HO-1 induction, though individual volatility classes (e.g., OC4) did. Total OC of all fuels was mainly comprised of OC1 (highest volatility) and OCp (pyrolysed OC), neither of which correlated with oxidative stress response (i.e., HO-1 induction). Mid-volatility fractions OC2 and OC3 (plotted in Chapter 8, Figure S5-2) correlated with HO-1 induction (r=0.96 and 0.82) at low dose but not at high dose.

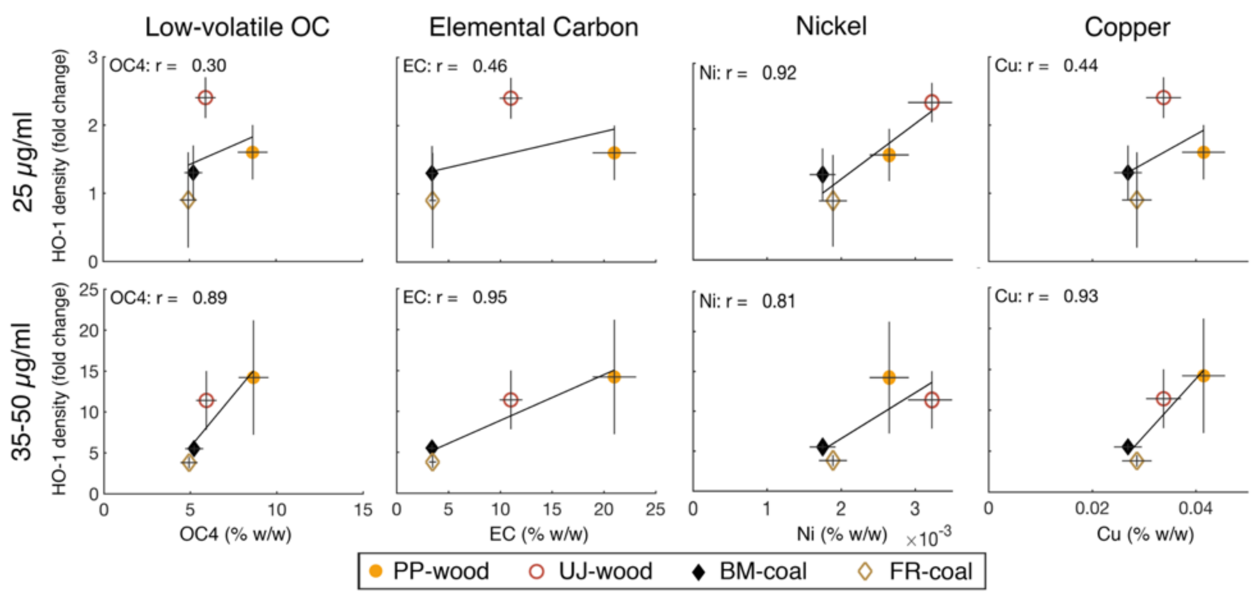


Figure 5-4. Correlations of Particle Components with HO-1 Induction. Low-volatile OC (i.e., OC4), EC, and Soluble Cu Correlated with HO-1 Induction at High Dose (50 µg/ml for PP-wood, UJ-wood, and BM-coal; 35 µg/ml for FR-coal). Soluble Ni Correlated with HO-1 Induction at Both Low (25 µg/ml) and High Dose.

Wood smoke OC consists of compounds ranging in volatility and polarity (e.g., oxygenation) (Rogge et al. 1998). Compared to wood, coal PM is expected to contain a higher fraction of nonpolar (i.e., more volatile) organics. Hong et al. (2009) found correlations between urinary biomarkers in humans for oxidative stress and exposure to both high volatile OC and PAHs (i.e., the volatility classes OC1 and OC2 in this study). Midpolarity (i.e., mid-volatile) and nonpolar organics in wood smoke has been shown to cause the most pronounced depletion of glutathione (GSH), an important anti-oxidant, in RAW 264.7 cells (Kubátová et al. 2006). The depletion of GSH by the midpolarity fraction was associated with content of oxy-PAHs, syringyls, disyringyls, and PAHs.

Quinonic oxy-PAHs induce ROS generation through redox cycling (Squadrito et al. 2001). The volatility class OC2 can include heavier PAHs (e.g., benzo[a]anthracene, benzo[a]pyrene, and benzo[bjk]flouranthene) that volatilize between 440-500°C (National Center for Biotechnology Information 2017), and that have been correlated with increased formation of free radicals in urban ambient $PM_{2.5}$ (Sklorz et al. 2007).

The lower volatility fractions OC4 and EC were correlated (r=0.89 and 0.95) at high dose (Figure 5-4). Both larger and more polar organics boil at higher temperatures (i.e., are less volatile) and are included in the volatility class OC4 (Karanasiou et al. 2015). EC is formed through the extension of relatively volatile and nonpolar compounds (e.g., PAHs) (Fitzpatrick et al. 2008). Ultrafine urban CAPs with significantly higher EC content were much more potent inducers of HO-1 in RAW 264.7 cells (Li et al., 2002).

EC content was also positively correlated with HO-1 induction (Figure 5-4). Elemental carbon is formed in flaming combustion by the planar extension of PAHs (Fitzpatrick et al. 2008). Therefore, though EC alone (i.e., graphitic chains of carbon) is understood to be relatively inert

(Nikula et al. 1995), the mass fraction of EC correlates with the concentration of particle-bound PAHs (Dachs and Eisenreich 2000).

Tian et al. (2009) showed a strong correlation between EC content and the intensity of redox activity of PM emitted from the combustion of both unspecified *Pine* and bituminous coal in a cooking stove; the *Pine* PM compared to coal caused twice the redox activity. Cho et al. (2005) found this same correlation in urban ambient $PM_{2.5}$. The increased redox activity of *Pine* (i.e., formation of radicals including hydroxide) may explain the higher response observed here by wood types compared to coal.

For soluble metals, mass content of soluble Ni correlated with HO-1 induction at both low (r=0.92) and high (r=0.81) doses. Soluble Cu content correlated with HO-1 induction at high dose only (r=0.93). No other metals correlated with HO-1 induction.

Soluble Ni exposure is known to cause formation of ROS in humans and animals (Das, Das, and Dhundasi 2008) and to deplete the antioxidant GSH (Franco et al. 2009). Dreher et al. (1997) determined that Ni content (among Fe and vanadium) of residual oil fly ash correlated with lung injury in rats due in part to it's bioavailability (i.e., water solubility).

Soluble Cu can undergo the Fenton reaction to generate ROS (•OH and OH^-) and subsequently induce oxidative stress (Perry et al. 2003) and HO-1 (González-Flecha 2004). Copper can also promote inflammation (Kennedy et al. 1998) and cause cell membrane injury (Ercal, Gurer-Orhan, and Aykin-Burns 2001).

5.4.6 Inflammatory Response

The levels of inflammatory cytokine TNF-α released into the cell culture media at a dose of 35 μg/ml are shown in Figure 5-5. This dose was chosen to provide the highest concentration available for side-by-side comparison of all fuels. At 35 μg/ml PP-wood, UJ-wood, and BM-coal significantly increased the release of TNF-α compared to the untreated control. PP-wood, UJ-wood, and BM-coal were also assessed at a higher dose. Our results show that at 75 μg/ml, PP-wood slightly increased TNF-α released compared with 35 μg/ml (20 vs. 17 fold change over control, respectively). Results from replicate stimulations and ELISA at low and high dose agree with trends in TNF-α production and are included in the SI (Figures S5-3 and S5-4, respectively). PP-wood was the only AS to caused significant release of TNF-α in all Tier-2 experiments.

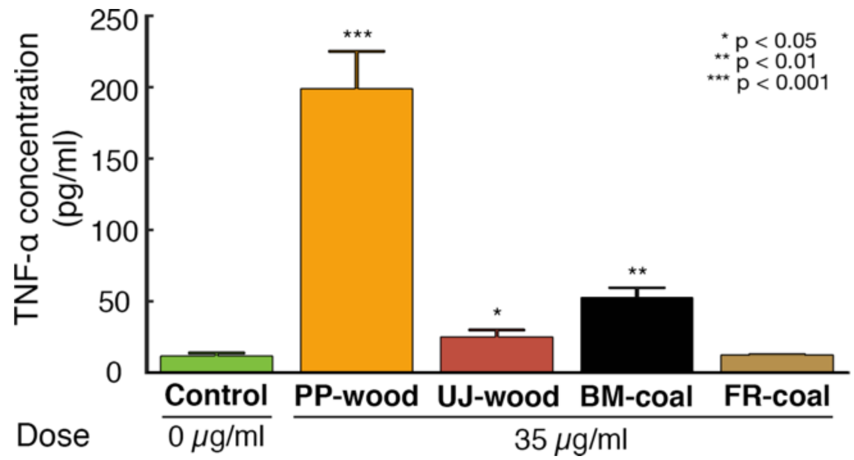


Figure 5-5. Concentration of TNF-α in the Cell Culture Media. RAW 264.7 Cells were Exposed to 35 μg/ml of Aqueous Extracts (AEs) for 16 hrs. This Experiment was Repeated Once (n=2) at Each Dose. PP-wood Caused the Highest Release of TNF-α of all AEs, though UJ-wood and BM-coal Also Caused Significant Release Compared to Untreated Control. Between Fuel Types, Wood Caused Significantly Higher TNF-α Release Compared to Coal.

Exposure to AE of PP-wood resulted in the strongest TNF-α response in this study, in conjunction with induction of HO-1. BM-coal also caused significant responses at Tier-1 (HO-1) and Tier-2 (TNF-α). Therefore, in this study, both PP-wood and BM-coal caused sufficient ROS formation to cause both an oxidative stress and inflammatory responses.

Similarly, Danielsen et al. (2011) found that AE prepared from $PM_{2.5}$ emitted by *beech* wood combustion in a residential wood stove caused significant induction of HO-1 along with the production TNF-α in human monocytic cells (i.e., progenitors to macrophages). In addition, Bolling et al. (2012) have demonstrated that AE from *birch* wood $PM_{2.5}$ could significantly increase TNF-α release from human monocytic cells. PP-wood observed the strongest inflammatory response, due potentially in part potentially to the presence of endotoxin, though the level of endotoxin in the AE was comparable to previous studies using AM cells (Soukup and Becker 2001; S. L. Huang, Hsu, and Chan 2003).

5.4.7 Inflammatory Response and Particle Composition

Figure 5-6 shows the correlations between particle weight percentages (% w/w) and TNF-α response. Low-volatility OC (i.e., OC4), and elemental carbon (EC) positively correlated with TNF-α at low (r=0.96 and 0.87) and high doses (r=0.98 and 0.89). There was no correlation between high volatile OC classes (i.e., OC1 and OC2), which composed the majority of $PM_{2.5}$ mass in this study, and TNF-α release. This may explain the lack of correlation between total OC (i.e., the sum of all OC volatility classes) and TNF-α release at either dose.

Muala et al. (2015) reported that PM with high PAH content from incomplete, high-temperature wood combustion in a *homestove* reduced cell metabolic activity and viability in RAW 264.7 cells, but did not cause an inflammatory response (i.e., TNF-α release). Prevalent PAHs in that study were benzo[a]pyrene, benzo[b]flouranthene, and benzo[a]anthracene, the same species observed in the highest concentrations in Navajo coal burning homes (Bunnell et al. 2010) and prevalent in $PM_{2.5}$ from BM-coal combustion (Simoneit et al. 2007). Retene, the most prevalent PAH in $PM_{2.5}$ from the combustion of *Pine* in a residential wood stove (Fine et al., 2004), has been shown to strongly activate transcription factor RelB, responsible for TNF-α production in murine macrophages following exposure to AE of softwood combustion in a residential wood stove (Migliaccio et al. 2013). Though PAH content of the $PM_{2.5}$ assessed in this study may have contributed to the observed TNF-α release, EC was also correlated at this endpoint. Urban ambient $PM_{2.5}$ with high EC content has caused significant TNF-α in RAW 264.7 cells previously (Steenhof et al. 2011; Pasi I. Jalava et al. 2008).

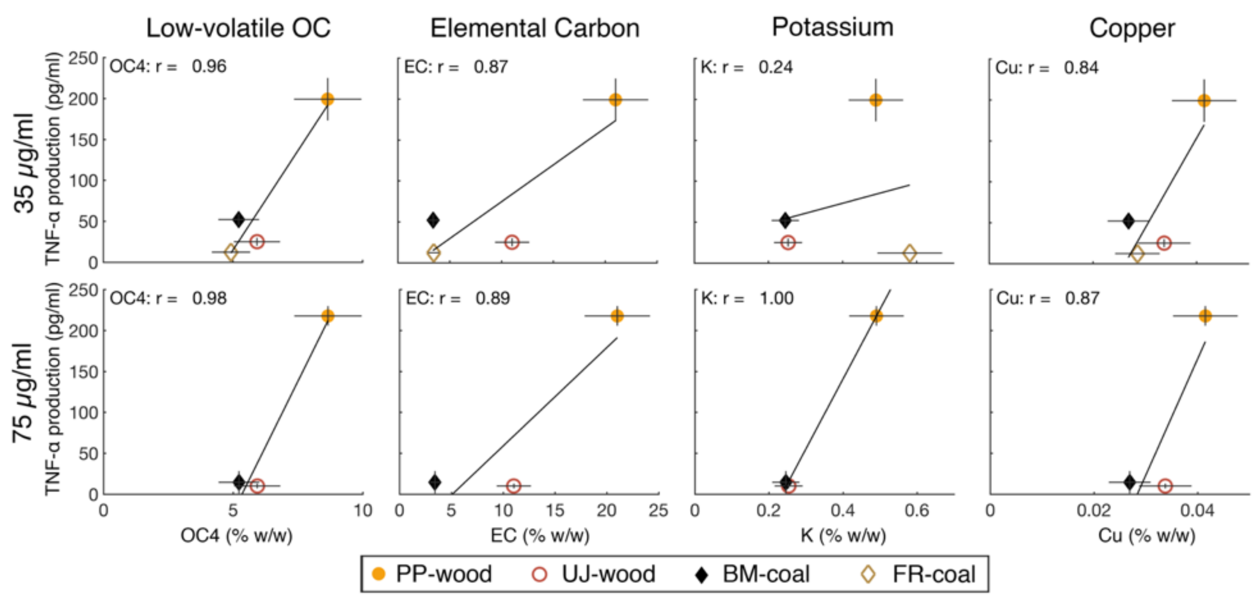


Figure 5-6. Correlations of Particle Components with TNF-α Production. Low-volatile OC, EC, and Copper Correlated with TNF-α Production at Low (35 µg/ml) and High Doses (75 µg/ml for PP-wood, UJ-wood, and BM-coal; FR-coal Not Assessed at High Dose). Soluble Potassium Correlated with TNF-α Production at High Dose.

While soluble K content positively correlated with TNF-α release at high dose only (r=1.00), soluble Cu correlated with this cytokine response at both low and high doses (r=0.84 and 0.87). No other metals were significantly correlated to TNF-α response. The oxidative potential of coal combustion-derived PM_{10} is largely due to the content of water soluble metals including K and C (Shao et al. 2016). Soluble Cu content on ambient PM has been associated with NF-κB activation and TNF-α production in human bronchial epithelial cells (Kennedy et al. 1998).

Soluble Ni content of urban ambient $PM_{2.5}$ positively correlated with a logarithmic fit of TNF-α release in RAW 264.7 cells at a dose 150 μg/ml (Jalava et al., 2009); the same particles caused significant TNF-α release at a dose of 50 μg/ml (Jalava et al., 2007).

5.4.8 Cytotoxicity

Cytotoxicity compared to the untreated controls was not significantly different at low (35 μg/ml) nor high (75 μg/ml for PP-wood, UJ-wood, and BM-coal, and 70 μg/ml for FR-coal) dose. Therefore, no increased cytotoxicity was caused by exposure to any of the AEs assessed in this study. Danielsen et al. (2011) also observed no significant increase in cytotoxicity of human monocytic cells from exposure from 2.5-100 μg/ml using AE prepared from $PM_{2.5}$ emitted from *beech* wood combustion in a residential stove. Oh et al. (2011) observed no significant and even reduced cytotoxicity in human bronchial BEAS-2B cells from exposure to traffic $PM_{2.5}$ at 50 μg/ml. Kasurinen et al. (2015) observed very low cytotoxicity (2%) from $PM_{2.5}$ sampled from wood pellet combustion only at 300 μg/ml. Findings of this work agreed with previously observed low cytotoxicity in mouse macrophages from the exposure to $PM_{2.5}$ of wood and coal combustion in a residential stove.

5.5 Conclusions

Based on the hierarchical cellular oxidative stress response model (Figure 5-7) we assessed the oxidative stress, inflammatory, and cytotoxic effects of $PM_{2.5}$ emitted by wood and coal species commonly used for residential heating in the . Induction of antioxidant enzyme HO-1, release of inflammatory cytokine TNF-α, and cytotoxicity (i.e., cell death) were used as the respective endpoint for each tier. AEs of all fuels studied induced HO-1 expression in RAW 264.7 cells, which was correlated to content of low-volatile OC, EC, and soluble nickel and copper. HO-1 induction was significantly greater for wood than coal, due potentially to the significantly higher EC content of wood $PM_{2.5}$. AEs of PP-wood, UJ-wood, and BM-coal also increased the release of inflammatory cytokine TNF-α, and this was positively correlated with the contents of low-volatile OC, EC, and soluble Cu and K. No aqueous extracts caused significant cytotoxicity.

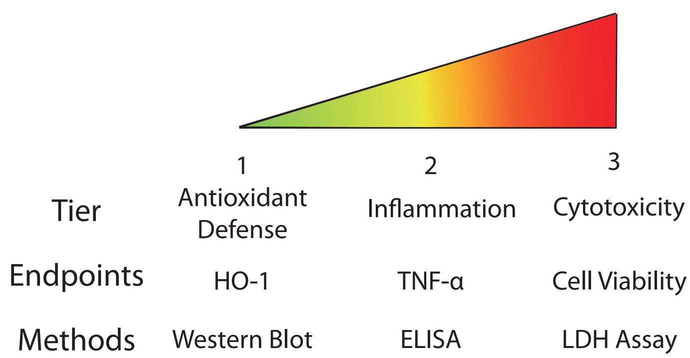


Figure 5-7. Three-tier Model for Oxidative Stress Response from Exposure to $PM_{2.5}$ (adapted from Li et al., 2002). Endpoints are HO-1, TNF-α, and Cytotoxicity for this Study.

This work included a limited dose-response study due to lack of available $PM_{2.5}$ mass. With additional emissions testing and more $PM_{2.5}$ sampled under similar test conditions, additional doses and exposure durations may be assessed. Additionally, the Tier-2 response is represented here with only one cytokine (TNF-α). Interleuken-6 (IL-6) was assessed, but no significant responses were observed. Additionally, the use of an antioxidant for the Tier-2 assessment can confirm the role of ROS formation and oxidative stress in the observed TNF−α response. This was beyond the scope of this work and may be investigated in future studies.

Taken together, our data indicates that exposure to $PM_{2.5}$ emitted by wood and coal types commonly burned in Navajo homes elicit cellular oxidative stress and potential inflammatory responses, which may be major contributing factors to public health burdens in the such as its higher death rates than the rest of the US due to cardiovascular and respiratory illness (Navajo Epidemiology Center 2009; Navajo Epidemiology Center 2013). This work provides key insights to the impact of household heating practices on the public health burden in and as well as developing preventive strategies to improve their indoor air quality.

6. Conclusions

6.1 Summary of Findings

This dissertation assessed the current issue of wood and coal use on the Navajo Nation (NN). First, a mixed-methods framework was developed to identify the most viable heating alternatives in terms of culture, community perception, and cost-normalized environmental and health benefits (Chapter 2). Benefit modeling was based on two conventional forms of environmental engineering: residential home energy modeling, and cost-normalized emissions rollback modeling. This project provided a characterization of a representative Navajo home, and a database of heating alternative costs and specifications specific to this community. Results from the study found that culture, perception, and science (i.e., engineering) independently supported a wood stove change-out program slated for approximately 1,000 residents of the NN in 2017 (Stewart 2016).

As part of this change-out program, the EPA has sponsored the development of a wood and coal combination stove specific for use in the NN. This development requires reliable test protocols for coal that currently do not exist. In this work, an *in-use* Navajo residential wood stove burning common wood and coal types was tested for emissions of key health-damaging pollutants. Coal compared to wood emitted significantly more fine particulate matter ($PM_{2.5}$), organic carbon (OC), and carbon monoxide (CO). Correlations between $PM_{2.5}$ and CO were developed and may be useful for future studies where filter sampling in wood and coal burning homes is cost-restrictive. In this vein, the emission factors developed were utilized in a chemical mass balance model to estimate steady-state concentrations in wood and coal burning Navajo homes.

Lastly, the $PM_{2.5}$ sampled during emissions testing were characterized for cellular responses in an oxidative stress model using well-established techniques. The mouse macrophage cells chosen represent one of the first lines of defense against airborne insults in mice. *Ponderosa Pine*, *Utah Juniper*, and *Black Mesa* induced the anti-oxidant enzyme hemeoxygenase-1 (HO-1). *Ponderosa Pine* and *Black Mesa* also caused significant release of the inflammatory cytokine tumor necrosis factor alpha (TNF-α). These responses with correlated with particle mass content of low volatile OC, elemental carbon (EC), and soluble copper. These preliminary toxicological results suggest that cellular responses from exposure to wood and coal may follow different pathways, but that both wood and coal $PM_{2.5}$ can elicit deleterious responses in mammalian cells.

6.2 Study Limitations

In the IHAP study (Chapter 2), some defined community perception criteria (i.e., infrastructure) were relatively ambiguous. Community perception surveys were conducted by students, and their verbal delivery and explanation of both assessment criteria and heating alternatives may have influenced perception results. Additionally, the availability of technical specifications and detailed costs was limited for this community, and hence the number of options varied widely between heating alternatives. Lastly, the existing emissions inventory of $PM_{2.5}$ from residential wood combustion in the NN is poorly defined (Section 7.1.3), and environmental and health benefits were likely under-estimated.

Emissions testing (Chapter 3) was limited in part by the ability of the *CUEST* facility to properly evacuate all emissions. This also resulted in the need for a relatively high dilution ratio, which may have resulted in an over-estimation of OC emissions. Additionally, the sample size was relatively small, but not uncommon for residential stove testing.

Field and laboratory comparison (Chapter 4) was limited by the assumption of steady-state conditions in the *model* predicted indoor concentrations. Real-time modeling of burn events would allow for more accurate assumptions of emission rates, and the ability of the model to predict peaks in pollutant concentrations (e.g., following an addition of fuel). Additionally, the limited sample size of the *field* determined indoor concentrations restricted further validation of the model.

Use of the oxidative stress model (Chapter 5) was limited by the availability of $PM_{2.5}$ mass stock. The relatively low solubility of filter bound carbon from both wood and coal resulted in low aqueous extraction efficiencies. Therefore, the assessment was limited to only two doses, a full dose-response relationship could not be developed, and only one endpoint was employed for each tier. Use of additional endpoints (i.e., proteins and cytokines) could substantiate the data from this study. Lastly, the use of an *in vitro* model with murine cells can limit the effectiveness of identifying mechanisms of cellular damage from $PM_{2.5}$ exposure in humans specifically.

6.3 Practical Implications

The framework developed and presented for the IHAP project (Chapter 2) may be useful to assess similar environmental and health issues in other communities with unique and important preferences (e.g., cultural considerations). Emissions test data (Chapter 3) can be used to inform both public and tribal policy, as well as to estimate emission reductions from the implementation of an upcoming wood stove change-out program on the NN. The comparison of *field* and *model* indoor concentrations (Chapter 4) further strengthens the usefulness of the emission factors developed, particularly for Navajo homes burning coal in a residential wood stove. Lastly, the toxicological assays conducted (Chapter 5) suggest that particle mass content of heavier, more polar organic carbon, elemental carbon, and soluble copper correlate with higher oxidative stress and inflammatory responses in murine macrophage cells.

6.4 Future Work

Importantly, the strong network of tribal colleges on the NN represent an opportunity for new and exciting forms of research. Further characterization of Navajo homes with energy auditing can refine assumptions made in Chapter 2. Emissions testing may be expanded by assessing the effects of varying burn rate, fuel load, and fuel cycles, as well as testing of other stove type. Further characterization of the $PM_{2.5}$ (e.g., organic speciation, redox activity) can help to further define the differences in emissions between the wood and coal types. For emissions testing, gas-phase monitoring for nitrogen and sulfur oxides would provide additional information on health-damaging pollutants from these fuels. Lastly, assessment of $PM_{2.5}$ emissions may be further explored with the use of oxidative stress and inflammatory endpoints in human bronchial epithelial cells.

7. References

Affolter, R H. 2000. “Quality Characterization of Cretaceous Coal from the Colorado Plateau Coal Assessent Area.” *Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah*. Vol. 1st. https://pubs.usgs.gov/pp/p1625b/.

Alves, Célia, Cátia Gonçalves, Ana Patrícia Fernandes, Luís Tarelho, and Casimiro Pio. 2011. “Fireplace and Woodstove Fine Particle Emissions from Combustion of Western Mediterranean Wood Types.” *Atmospheric Research* 101 (3). Elsevier B.V.: 692–700. doi:10.1016/j.atmosres.2011.04.015.

American Society for Testing and Materials. 2010. “Standard Test Method for Determining Particulate Matter Emissions from Wood Heaters,” no. C. ASTM International: 1–13. doi:10.1520/E2780-10.2.

Andreae, M.O., and P. Merlet. 2001. “Emission of Trace Gases and Aerosols from Biomass Burning.” *Global Biogeochemical CyclesBiogeochemistry* 15 (4): 955–66. doi:10.1029/2000GB001382.

Arizona Bureau of Mines. 1977. “Chemical Analyses of Coal Samples from the Black Mesa Field, Arizona.” http://repository.azgs.az.gov/uri_gin/azgs/dlio/1067.

Arizona Rural Policy Institute. 2010. “Demographic Analysis of the Navajo Nation Using 2010 Census and 2010 American Community Survey Estimates.” http://gotr.azgovernor.gov/sites/default/files/navajo_nation_0.pdf.

Arquette, Mary, Maxine Cole, Katsi Cook, Brenda Lafrance, Margaret Peters, James Ransom, Elvera Sargent, et al. 2002. “Holistic Risk-Based Environmental Decision Making : A Native Perspective.” *Environmental Justice* 110 (April): 259–64.

Bae, Sanghyuk, Xiao Chuan Pan, Su Young Kim, Kwangsik Park, Yoon Hee Kim, Ho Kim, and Yun Chul Hong. 2010. “Exposures to Particulate Matter and Polycyclic Aromatic Hydrocarbons and Oxidative Stress in Schoolchildren.” *Environmental Health Perspectives* 118 (4): 579–83. doi:10.1289/ehp.0901077.

Bäfver, Linda S., Bo Leckner, Claes Tullin, and Morten Berntsen. 2011. “Particle Emissions from Pellets Stoves and Modern and Old-Type Wood Stoves.” *Biomass and Bioenergy* 35 (8): 3648–55. doi:10.1016/j.biombioe.2011.05.027.

Balcomb, J D, and R D Mcfarland. 1978. “A Simple Technique of Estimating the Performance of Passive Solar Heating Systems.” *Proceedings from the 1978 ISES Conference, Denver, CO* 2.

Ballard-Tremeer, G., and H. H. Jawurek. 1999. “The ‘Hood Method’ of Measuring Emissions of Rural Cooking Devices.” *Biomass and Bioenergy* 16 (5): 341–45. doi:10.1016/S0961-9534(99)00012-4.

Barone-adesi, Francesco, Robert S Chapman, Debra T Silverman, Bofu Ning, Joseph F Fraumeni, and Nathaniel Rothman. 2012. “Risk of Lung Cancer Associated with Domestic Use of Coal in Xuanwei , China : Retrospective Cohort Study” 5414 (August): 1–10. doi:10.1136/bmj.e5414.

Becker, S, J M Soukup, M I Gilmour, and R B Devlin. 1996. “Stimulation of Human and Rat Alveolar Macrophages by Urban Air Particulates: Effects on Oxidant Radical Generation and Cytokine Production.” *Toxicology and Applied Pharmacology* 141: 637–48. doi:10.1006/taap.1996.0330.

Birch, M. E., and R. A. Cary. 1996. “Elemental Carbon-Based Method for Monitoring Occupational Exposures to Particulate Diesel Exhaust.” *Aerosol Science and Technology* 25 (3): 221–41. doi:10.1080/02786829608965393.

Bolling, Anette Kocbach, Annike Irene Totlandsdal, Gerd Sallsten, Artur Braun, Roger Westerholm, Christoffer Bergvall, Johan Boman, et al. 2012. “Wood Smoke Particles from Different Combustion Phases Induce Similar pro-Inflammatory Effects in a Co-Culture of Monocyte and Pneumocyte Cell Lines.” *Particle and Fibre Toxicology* 9: 45. doi:10.1186/1743-8977-9-45.

Boman, C., A. Nordin, R. Westerholm, and E. Pettersson. 2005. “Evaluation of a Constant Volume Sampling Setup for Residential Biomass Fired Appliances - Influence of Dilution Conditions on Particulate and PAH Emissions.” *Biomass and Bioenergy* 29 (4): 258–68. doi:10.1016/j.biombioe.2005.03.003.

Bond, T. C., S. J. Doherty, D. W. Fahey, P. M. Forster, T. Berntsen, B. J. DeAngelo, M. G. Flanner, et al. 2013. “Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment.” *Journal of Geophysical Research: Atmospheres* 118 (11): 5380–5552. doi:10.1002/jgrd.50171.

Bond, Tami C., David S. Covert, John C. Kramloch, Timothy V. Larson, and Robert J. Charlson. 2002. “Primary Particle Emissions from Residential Coal Burning: Optical Properties and Size Distributions.” *Journal of Geophysical Research* 107 (D21): 8347. doi:10.1029/2001JD000571.

Bond, Tami C., David G. Streets, Kristen F. Yarber, Sibyl M. Nelson, Jung Hun Woo, and Zbigniew Klimont. 2004. “A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion.” *Journal of Geophysical Research D: Atmospheres* 109 (14): 1–43. doi:10.1029/2003JD003697.

Bradford, M. 1976. “A Rapid and Sensitive Method for the quantiWcation of Microgram Quantities of Protein Utilizing the Principle of Protein– Dye Binding.” *Analytical Biochemistry* 72: 248–254. doi:10.1016/0003-2697(76)90527-3.

Breysse, Patrick N., Ralph J. Delfino, Francesca Dominici, Alison C. P. Elder, Mark W. Frampton, John R. Froines, Alison S. Geyh, et al. 2013. “US EPA Particulate Matter Research Centers: Summary of Research Results for 2005–2011.” *Air Quality, Atmosphere & Health* 6 (2): 333–55. doi:10.1007/s11869-012-0181-8.

Brown, Lee F, Donald D Hickmott, Robert P Currier, Steven C Semken, Terri Lameman, Suzette Martin, and Sonya Yazzie. 1996. “Reducing Adverse Health Effects and Improving Performance of Stoves on the Navajo Reservation - A Plan for Action.” Los Alamos National Laboratory.

Bunnell, Joseph E, Linda V Garcia, Jill M Furst, Harry Lerch, Ricardo A Olea, Stephen E Suitt, and Allan Kolker. 2010. “Navajo Coal Combustion and Respiratory Health near Shiprock, New Mexico.” *Journal of Environmental and Public Health*, January, 260525. doi:10.1155/2010/260525.

Burnette, W. Neal. 1981. “Electrophoretic Transfer of Proteins from Sodium Dodecyl Sulfate-Polyacrylamide Gels to Unmodified Nitrocellulose and Radiographic Detection with Antibody.” *Analytical Biochemistry* 112: 195–203. doi:10.1016/0003-2697(81)90281-5.

Butcher, S. S., U. Rao, K.R. Smith, J.F. Osborn, P. Azuma, and H. Fields. 1984. “Emission Factors and Efficiencies for Small-Scale Open Biomass Combustion: Towards Standard Measurement Techniques.” *Abstracts of Papers of the American Chemical Society* 188: 122–28.

Butcher, Samuel S., and Michael J. Ellenbecker. 1982. “Particulate Emission Factors for Small Wood and Coal Stoves.” *Journal of the Air Pollution Control Association* 32 (4): 380–84. doi:10.1080/00022470.1982.10465413.

Butcher, Samuel S., and Edmund M. Sorenson. 1979. “A Study of Wood Stove Particulate Emissions.” *Journal of the Air Pollution Control Association* 29 (7): 724–28. doi:10.1080/00022470.1979.10470854.

Cartledge, Benton T., and Brian J. Majestic. 2015. “Metal Concentrations and Soluble Iron Speciation in Fine Particulate Matter from Light Rail Activity in the Denver-Metropolitan Area.” *Atmospheric Pollution Research* 6 (3). Elsevier: 495–502. doi:10.5094/APR.2015.055.

Champion, W.M., P.H. Charley, B. Klein, K. Stewart, P.A. Solomon, and L.D. Montoya. 2016. “Perception, Cultural, and Technical Assessment of Heating Alternatives to Improve Indoor Air Quality in the Navajo Nation.” *Science of The Total Environment*.

———. 2017. “Perception, Culture, and Science: A Framework to Identify in-Home Heating Options to Improve Indoor Air Quality in the Navajo Nation.” *Science of The Total Environment* 580. Elsevier B.V.: 297–306. doi:10.1016/j.scitotenv.2016.11.053.

Champion, Wyatt M., Lea Connors, and Lupita D. Montoya. 2017. “Emission Factors of Fine Particulate Matter, Organic and Elemental Carbon, Carbon Monoxide, and Carbon Dioxide for Four Solid Fuels Commonly Used in Residential Heating by the Navajo Nation.” *Journal of the Air & Waste Management Association*.

Chen, L. W Antony, Hans Moosmüller, W. Patrick Arnott, Judith C. Chow, John G. Watson, Ronald A. Susott, Ronald E. Babbitt, Cyle E. Wold, Emily N. Lincoln, and Min Hao Wei. 2007. “Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and

Source Profiles." *Environmental Science and Technology* 41 (12): 4317–25. doi:10.1021/es062364i.

Chen, Wei, Kalyan Annamalai, R. James Ansley, and Mustafa Mirik. 2012. "Updraft Fixed Bed Gasification of Mesquite and Juniper Wood Samples." *Energy* 41 (1): 454–61. doi:10.1016/j.energy.2012.02.052.

Chen, Yingjun, Guoying Sheng, Xinhui Bi, Yanli Feng, Bixian Mai, and Jiamo Fu. 2005. "Emission Factors for Carbonaceous Particles and Polycyclic Aromatic Hydrocarbons from Residential Coal Combustion in China." *Environmental Science & Technology* 39 (6): 1861–67. doi:Chen, Y., Sheng, G., Bi, X., Feng, Y., Mai, B., Fu, J., 2005. Emission factors for carbonaceous particles and polycyclic aromatic hydrocarbons from residential coal combustion in China. Environ. Sci. Technol. 39, 1861–7.

Chen, Yuanchen, Guofeng Shen, Weijian Liu, Wei Du, Shu Su, Yonghong Duan, Nan Lin, et al. 2016. "Field Measurement and Estimate of Gaseous and Particle Pollutant Emissions from Cooking and Space Heating Processes in Rural Households, Northern China." *Atmospheric Environment* 125. Elsevier Ltd: 265–71. doi:10.1016/j.atmosenv.2015.11.032.

Cho, Arthur K., Constantinos Sioutas, Antonio H. Miguel, Yoshito Kumagai, Debra a. Schmitz, Manisha Singh, Arantza Eiguren-Fernandez, and John R. Froines. 2005. "Redox Activity of Airborne Particulate Matter at Different Sites in the Los Angeles Basin." *Environmental Research* 99 (1): 40–47. doi:10.1016/j.envres.2005.01.003.

Curkeet, Rick, and Robert Ferguson. 2010. "EPA Wood Heater Test Method Variability Study: Analysis of Uncertainty , Repeatability and Reproducibility Based on the EPA Accredited Laboratory Proficiency Test Database," 1–43. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&ved=0ahUKEwiEqsWnstbPAhXpylQKHXcCCfYQFgg4MAQ&url=http://www.hpba.org/government-affairs/nsps-members/Wood-Heater-Emission-Test-Method-Variability-Paper.pdf/at_download/file&usg=AFQjCNElr1GG5j.

Dachs, Jordi, and Steven J. Eisenreich. 2000. "Adsorption onto Aerosol Soot Carbon Dominates Gas-Particle Partitioning of Polycyclic Aromatic Hydrocarbons." *Environmental Science and Technology* 34 (17): 3690–97. doi:10.1021/es991201+.

Danielsen, Pernille Høgh, Peter Møller, Keld Alstrup Jensen, Anoop Kumar Sharma, Håkan Wallin, Rossana Bossi, Herman Autrup, et al. 2011. "Oxidative Stress, DNA Damage, and Inflammation Induced by Ambient Air and Wood Smoke Particulate Matter in Human A549 and THP-1 Cell Lines." *Chemical Research in Toxicology* 24 (2): 168–84. doi:dx.doi.org/10.1021/tx100407m.

Das, K K, S N Das, and S a Dhundasi. 2008. "Nickel, Its Adverse Health Effects & Oxidative Stress." *The Indian Journal of Medical Research* 128 (4): 412–25.

Deng, Xiaobei, Wei Rui, Fang Zhang, and Wenjun Ding. 2013. "PM2.5 Induces Nrf2-Mediated Defense Mechanisms against Oxidative Stress by Activating PIK3/AKT Signaling

Pathway in Human Lung Alveolar Epithelial A549 Cells." *Cell Biology and Toxicology* 29 (3): 143–57. doi:10.1007/s10565-013-9242-5.

Dreher, Kevin L., James R. Lehmann, Judy H. Richards, John K. McGee, Andrew J. Ghio, Daniel L. Costa, and Richard H Jaskot. 1997. "Soluble Transition Metals Mediate Residual Oil Fly Ash Induced Acute Lung Injury." *Journal of Toxicology and Environmental Health* 50 (3): 285–305. doi:10.1080/009841097160492.

Dutton, Steven J, James J Schauer, Sverre Vedal, and Michael P Hannigan. 2009. "PM2.5 Characterization for Time Series Studies: Pointwise Uncertainty Estimation and Bulk Speciation Methods Applied in Denver." *Atmospheric Environment* 43 (5). Elsevier Ltd: 1136–46. doi:10.1016/j.atmosenv.2008.10.003.PM.

Engle, Robert F, and C W J Granger. 1987. "Co-Integration and Error Correction : Representation , Estimation , and Testing." *Econometrica* 55 (2): 251–76. doi:10.2307/1913236.

Ercal, Nuran, Hande Gurer-Orhan, and Nukhet Aykin-Burns. 2001. "Toxic Metals and Oxidative Stress Part I: Mechanisms Involved in Metal Induced Oxidative Damage." *Current Topics in Medicinal Chemistry* 1: 529–39.

Ezzati, M., H. Saleh, and D.M. Kammen. 2000. "The Contribution of Emission and Spatial Microenvironments to Exposure to Indoor Air Pollution from Biomass Combustion in Keny." *Environmen. Health Persp* 108 (9): 833–39. doi:10.1289/ehp.00108833.

Fann, Neal, Amy D Lamson, Susan C Anenberg, Karen Wesson, David Risley, and Bryan J Hubbell. 2012. "Estimating the National Public Health Burden Associated with Exposure to Ambient PM2.5 and Ozone." *Risk Analysis : An Official Publication of the Society for Risk Analysis* 32 (1): 81–95. doi:10.1111/j.1539-6924.2011.01630.x.

Ferreira, Tiago, Tiago Ferreira, Wayne Rasband, and Wayne Rasband. 2012. "ImageJ User Guide," 1–198.

Fine, Philip M., Glen R. Cass, and Bernd R.T. Simoneit. 2004. "Chemical Characterization of Fine Particle Emissions from the Wood Stove Combustion of Prevalent United States Tree Species." *Environmental Engineering Science* 21 (6): 705–21. doi:10.1089/ees.2004.21.705.

Fitzpatrick, E M, J M Jones, M Pourkashanian, A B Ross, A Williams, and K D Bartle. 2008. "Mechanistic Aspects of Soot Formation from the Combustion of Pine Wood," no. 14: 3771–78.

Forouzanfar, Mohammad H., Lily Alexander, H. Ross Anderson, Victoria F. Bachman, Stan Biryukov, Michael Brauer, Richard Burnett, et al. 2015. "Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990-2013: A Systematic Analysis for the Global Burden of Disease Study 2013." *The Lancet* 386 (10010): 2287–2323. doi:10.1016/S0140-6736(15)00128-2.

Franco, Rodrigo, Roberto S??nchez-Olea, Elsa M. Reyes-Reyes, and Mihalis I. Panayiotidis. 2009. “Environmental Toxicity, Oxidative Stress and Apoptosis.” *Mutation Research - Genetic Toxicology and Environmental Mutagenesis* 674 (1–2): 3–22. doi:10.1016/j.mrgentox.2008.11.012.

Franklin, Robert. 2000. “Service Contracts for Residential Furnaces.” https://www.cpsc.gov//PageFiles/97048/annual_service_contracts_furnaces.pdf.

Gaston, Cassandra J., Felipe D. Lopez-Hilfiker, Lauren E. Whybrew, Odelle Hadley, Fran McNair, Honglian Gao, Daniel A. Jaffe, and Joel A. Thornton. 2016. “Online Molecular Characterization of Fine Particulate Matter in Port Angeles, WA: Evidence for a Major Impact from Residential Wood Smoke.” *Atmospheric Environment* 138: 99–107. doi:10.1016/j.atmosenv.2016.05.013.

Gaur, Siddhartha, and Thomas B Reed. 1998. *Thermal Data for Natural and Synthetic Fuels*. Marcel Dekker. http://drtlud.com/BEF/proximat.htm.

Ge, Su, Xu Xu, Judith C. Chow, John Watson, Qing Sheng, Weili Liu, Zhipeng Bai, Tan Zhu, and Junfeng Zhang. 2004. “Emissions of Air Pollutants from Household Stoves: Honeycomb Coal versus Coal Cake.” *Environmental Science and Technology* 38 (17): 4612–18. doi:10.1021/es049942k.

Girman, J. R., M. G. Apte, G. W. Traynor, J. R. Allen, and C. D. Hollowell. 1982. “Pollutant Emission Rates from Indoor Combustion Appliances and Sidestream Cigarette Smoke.” *Environment International* 8 (1–6): 213–21. doi:10.1016/0160-4120(82)90030-7.

Gonçalves, Cátia, Célia Alves, Ana Patrícia Fernandes, Cristina Monteiro, Luís Tarelho, Margarita Evtyugina, and Casimiro Pio. 2011. “Organic Compounds in PM2.5 Emitted from Fireplace and Woodstove Combustion of Typical Portuguese Wood Species.” *Atmospheric Environment* 45 (27). Elsevier Ltd: 4533–45. doi:10.1016/j.atmosenv.2011.05.071.

González-Flecha, Beatriz. 2004. “Oxidant Mechanisms in Response to Ambient Air Particles.” *Molecular Aspects of Medicine* 25 (1–2): 169–82. doi:10.1016/j.mam.2004.02.017.

Gordian Group. 2015. “Building Construction Cost Data.” www.rsmeansonline.com.

Gordon, Joanna C., Evan Coffey, Mingjie Xie, Holly Flinchpaugh, Wyatt M. Champion, John Ortega, Lupita D. Montoya, and Mike P. Hannigan. 2017. “A Study of Indoor Air Quality in 46 Homes on the Navajo Nation.” *In-Preparation*.

Grinde, Donald A, and Bruce E Johansen. 1995. “Ecocide of Native America: Environmental Destruction of Indian Lands and Peoples.”

Halliwell, Barry, and John M C Gutteridge. 2015. *Free Radicals in Biology and Medicine*. Oxford University Press, USA.

Hickmott, Donald D, Lee F Brown, Robert P Currier, Steven C Semken, Terri Lameman, Martin Suzette, and Sonya Yazzie. 1997. “Environmentally Conscious Coal Combustion.” *Los Alamos National Laboratory*. http://www.osti.gov/scitech/servlets/purl/516052.

Hildemann, Lynn M, Gregory R Markowski, and Glen R Cass. 1991. “Chemical Composition of Emissions from Urban Sources of Fine Organic Aerosol.” *Environmental Science & Technology* 25 (2): 744–59. doi:10.1021/es00016a021.

Hirano, Seishiro, Akiko Furuyama, Eiko Koike, and Takahiro Kobayashi. 2003. “Oxidative-Stress Potency of Organic Extracts of Diesel Exhaust and Urban Fine Particles in Rat Heart Microvessel Endothelial Cells.” *Toxicology* 187 (2–3): 161–70. doi:10.1016/S0300-483X(03)00053-2.

Hiura, T S, M P Kaszubowski, N Li, and A E Nel. 1999. “Chemicals in Diesel Exhaust Particles Generate Reactive Oxygen Radicals and Induce Apoptosis in Macrophages.” *Journal of Immunology* 163 (10): 5582–91.

Home Depot. 2014. “Heating Appliance Catalog for Farmington, NM Store.”

Hong, Yun-chul, Eun-young Park, Min-seon Park, Jeong Ah, Se-young Oh, Ho Kim, Kwan-hee Lee, Jong-han Leem, and Eun-hee Ha. 2009. “Community Level Exposure to Chemicals and Oxidative Stress in Adult Population” 184: 139–44. doi:10.1016/j.toxlet.2008.11.001.

Houck, J E, L Y Pitzman, and P Tiegs. 2008. “Emission Factors for Aged Uncertified Residential Cordwood Heaters.” *Inventory Evolution - Portal to Improved Air Quality*. http://search.proquest.com/docview/19587803?accountid=171201.

Houck, James E., and Brian N. Eagle. 2006. “Control Analysis and Documentation for Residential Wood Combustion in the MANE-VU Region.” Vol. 4.

Huang, Song-Lih, Wen-Ling Cheng, Chung-Te Lee, Hsin-Cheng Huang, and Chang-Chuan Chan. 2002. “Contribution of Endotoxin in Macrophage Cytokine Response to Ambient Particles in Vitro.” *Journal of Toxicology and Environmental Health. Part A* 65 (17): 1261–72. doi:10.1080/152873902760125741.

Huang, Song Lih, Miao Kan Hsu, and Chang Chuan Chan. 2003. “Effects of Submicrometer Particle Compositions on Cytokine Production and Lipid Peroxidation of Human Bronchial Epithelial Cells.” *Environmental Health Perspectives* 111 (4): 478–82. doi:10.1289/ehp.5519.

Hueglin, Ch, Ch Gaegauf, S. Künzel, and H. Burtscher. 1997. “Characterization of Wood Combustion Particles: Morphology, Mobility, and Photoelectric Activity.” *Environmental Science and Technology* 31 (12): 3439–47. doi:10.1021/es970139i.

Jalava, P I, M R Hirvonen, M Sillanp, A S Pennanen, M S Happo, R Hillamo, F R Cassee, et al. 2009. “Associations of Urban Air Particulate Composition with Inflammatory and

Cytotoxic Responses in RAW 246.7 Cell Line." *Inhalation Toxicology* 21 (12): 994–1006. doi:http://dx.doi.org/10.1080/08958370802695710.

Jalava, Pasi I., Raimo O. Salonen, Arto S. Pennanen, Mikko S. Happo, Piia Penttinen, Arja I. Hälinen, Markus Sillanpää, Risto Hillamo, and Maija Riitta Hirvonen. 2008. "Effects of Solubility of Urban Air Fine and Coarse Particles on Cytotoxic and Inflammatory Responses in RAW 264.7 Macrophage Cell Line." *Toxicology and Applied Pharmacology* 229 (2): 146–60. doi:10.1016/j.taap.2008.01.006.

Jalava, Pasi I, Raimo O Salonen, Arto S Pennanen, Markus Sillanpää, Arja I Hälinen, Mikko S Happo, Risto Hillamo, et al. 2007. "Heterogeneities in Inflammatory and Cytotoxic Responses of RAW 264.7 Macrophage Cell Line to Urban Air Coarse, Fine, and Ultrafine Particles from Six European Sampling Campaigns." *Inhalation Toxicology* 19 (3): 213–25. doi:10.1080/08958370601067863.

Jaszczur, Tadeusz, Maciej Lewandowski, Witold Sxewcryk, Andrzej Zaczkowski, and Thomas Butcher. 1995. "Coal-Fired Tile Stoves - Efficiency and Emissions."

Jetter, James J., and Peter Kariher. 2009. "Solid-Fuel Household Cook Stoves: Characterization of Performance and Emissions." *Biomass and Bioenergy* 33 (2). Elsevier Ltd: 294–305. doi:10.1016/j.biombioe.2008.05.014.

Jetter, James, Yongxin Zhao, Kirk R. Smith, Bernine Khan, Tiffany Yelverton, Peter Decarlo, and Michael D. Hays. 2012. "Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards." *Environmental Science and Technology* 46 (19): 10827–34. doi:10.1021/es301693f.

Johnson, Michael, Nick Lam, Simone Brant, Christen Gray, and David Pennise. 2011. "Modeling Indoor Air Pollution from Cookstove Emissions in Developing Countries Using a Monte Carlo Single-Box Model." doi:10.1016/j.atmosenv.2011.03.044.

Jordan, Timothy B., and Andrew J. Seen. 2005. "Effect of Airflow Setting on the Organic Composition of Woodheater Emissions." *Environmental Science and Technology* 39 (10): 3601–10. doi:10.1021/es0487628.

Junker, C., and C. Liousse. 2006. "A Global Emission Inventory of Carbonaceous Aerosol from Historic Records of Fossil Fuel and Biofuel Consumption for the Period 1860-1997." *Atmospheric Chemistry and Physics Discussions* 6 (3): 4897–4927. doi:10.5194/acpd-6-4897-2006.

Karanasiou, A, M C Minguillón, M Viana, A Alastuey, J.-P Putaud, W Maenhaut, P Panteliadis, G Močnik, O Favez, and T A J Kuhlbusch. 2015. "Thermal-Optical Analysis for the Measurement of Elemental Carbon (EC) and Organic Carbon (OC) in Ambient Air a Literature Review." *Atmos. Meas. Tech. Discuss* 8: 9649–9712. doi:10.5194/amtd-8-9649-2015.

Kasurinen, Stefanie, Pasi I. Jalava, Maija Tapanainen, Oskari Uski, Mikko S. Happo, Jorma Mäki-Paakkanen, Heikki Lamberg, et al. 2015. “Toxicological Effects of Particulate Emissions – A Comparison of Oil and Wood Fuels in Small- and Medium-Scale Heating Systems.” *Atmospheric Environment* 103: 321–30. doi:10.1016/j.atmosenv.2014.12.055.

Kennedy, T., A. J. Ghio, W. Reed, J. Samet, J. Zagorski, Quay., J. Carter, L. Dailey, J. R. Hoidal, and R. B. Devlin. 1998. “Cooper-Dependent Inflammation and Nuclear Factor-kB Activation by Particulate Air Pollution.” *Am. J. Respirology* 19 (15): 366–78.

Kirschbaum, By Mark A, and Laura R H Biewick. 2000. “A Summary of the Coal Deposits in the Colorado Plateau : Arizona , Colorado , New Mexico , and Utah.” *USGS Professional Paper Series*, no. U.S. Geological Survey Professional Paper 1625–B*.

Kirschbaum, M.A., L.N.R. Roberts, and L.R.H. Biewick. 2013. “Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah, U.S. Geological Survey Professional Paper 1625–B*.”

Kortelainen, Aki, Jorma Joutsensaari, Liqing Hao, Jani Leskinen, Petri Tiitta, Antti Jaatinen, Pasi Miettinen, et al. 2015. “Real-Time Chemical Composition Analysis of Particulate Emissions from Woodchip Combustion.” *Energy and Fuels* 29 (2): 1143–50. doi:10.1021/ef5019548.

Kubátová, Alena, Laura C Dronen, Matthew J Picklo, and Steven B Hawthorne. 2006. “Midpolarity and Nonpolar Wood Smoke Particulate Matter Fractions Deplete Glutathione in RAW 264.7 Macrophages.” *Chem. Res. Toxicol.* 19 (2): 255–61. doi:10.1021/tx050172f.

Lambrecht, Bart N. 2006. “Alveolar Macrophage in the Driver’s Seat.” *Immunity* 24 (4): 366–68. doi:10.1016/j.immuni.2006.03.008.

Lamlom, S. H., and R. A. Savidge. 2003. “A Reassessment of Carbon Content in Wood: Variation within and between 41 North American Species.” *Biomass and Bioenergy* 25 (4): 381–88. doi:10.1016/S0961-9534(03)00033-3.

Lee, Taehyoung, Amy P. Sullivan, Laura Mack, Jose L. Jimenez, Sonia M. Kreidenweis, Timothy B. Onasch, Douglas R. Worsnop, et al. 2010. “Chemical Smoke Marker Emissions During Flaming and Smoldering Phases of Laboratory Open Burning of Wildland Fuels.” *Aerosol Science and Technology* 44 (9): i–v. doi:10.1080/02786826.2010.499884.

Leung, K M, R P Lindstedt, and W P Jones. 1991. “A Simplified Reaction-Mechanism for Soot Formation in Nonpremixed Flames.” *Combustion and Flame* 87 (3–4): 289–305.

Li, Ning, Seongheon Kim, Meiying Wang, John Froines, Constantinos Sioutas, and Andre Nel. 2002. “Use of a Stratified Oxidative Stress Model To Study the Biological Efects of Ambient Concentrated and Diesel Exhaust Particulate Matter.” *Inhalation Toxicology* 14 (5): 459–86. doi:10.1080/089583701753678571.

Li, Ning, Constantinos Sioutas, Arthur Cho, Debra Schmitz, Chandan Misra, Joan Sempf, Meiying Wang, Terry Oberley, John Froines, and Andre Nel. 2002. "Ultrafine Particulate Pollutants Induce Oxidative Stress and Mitochondrial Damage." *Environmental Health Perspectives* 111 (4): 455–60. doi:10.1289/ehp.6000.

———. 2003. "Ultrafine Particulate Pollutants Induce Oxidative Stress and Mitochondrial Damage." *Environmental Health Perspectives* 111 (4): 455–60. doi:10.1289/ehp.6000.

Li, Ning, M. Indira Venkatesan, Antonio Miguel, Roman Kaplan, Chandrasekhar Gujuluva, Jawed Alam, and Andre Nel. 2000. "Induction of Heme Oxygenase-1 Expression in Macrophages by Diesel Exhaust Particle Chemicals and Quinones via the Antioxidant-Responsive Element." *The Journal of Immunology* 165 (6): 3393–3401. doi:ji_v165n6p3393 [pii].

Lipsky, Eric M, and Allen L Robinson. 2006. "Effects of Dilution on Fine Particle Mass and Partitioning of Semivolatile Organics in Diesel Exhaust and Wood Smoke." *Environmental Science & Technology* 40 (1): 155–62. doi:10.1021/es050319p.

MacCarty, Nordica, Dean Still, and Damon Ogle. 2010. "Fuel Use and Emissions Performance of Fifty Cooking Stoves in the Laboratory and Related Benchmarks of Performance." *Energy for Sustainable Development* 14 (3). Elsevier Inc.: 161–71. doi:10.1016/j.esd.2010.06.002.

MacKay, Susan, L. Dale Baker, John W. Bartok, and James P. Lassoie. 2003. "Heating with Wood and Coal."

Majestic, Brian J, Joseph A Turner, and Aurelie R Marcotte. 2012. "Respirable Antimony and Other Trace-Elements inside and Outside an Elementary School in Flagstaff, AZ, USA." *The Science of the Total Environment* 435–436. Elsevier B.V.: 253–61. doi:10.1016/j.scitotenv.2012.07.020.

Masson, Nicholas, Ricardo Piedrahita, and Michael Hannigan. 2015. "Quantification Method for Electrolytic Sensors in Long-Term Monitoring of Ambient Air Quality." *Sensors (Switzerland)* 15 (10): 27283–302. doi:10.3390/s151027283.

McCracken, John P., Joel Schwartz, Anaite Diaz, Nigel Bruce, and Kirk R. Smith. 2013. "Longitudinal Relationship between Personal CO and Personal PM2.5 among Women Cooking with Woodfired Cookstoves in Guatemala." *PLoS ONE* 8 (2): 3–6. doi:10.1371/journal.pone.0055670.

McDonald, JD, B Zielinska, Eric M Fujita, John C Sagebiel, Judith C Chow, and John G Watson. 2000. "Fine Particle and Gaseous Emission Rates from Residential Wood Combustion." *Environmental Science and Technology*, no. 775: 2080–91. http://pubs.acs.org/doi/abs/10.1021/es9909632.

McMeeking, Gavin R., Sonia M. Kreidenweis, Stephen Baker, Christian M. Carrico, Judith C. Chow, Jeffrey L. Collett, Wei Min Hao, et al. 2009. "Emissions of Trace Gases and

Aerosols during the Open Combustion of Biomass in the Laboratory." *Journal of Geophysical Research: Atmospheres* 114 (19): 1–20. doi:10.1029/2009JD011836.

Migliaccio, Christopher T, Emily Kobos, Quinton O King, Virginia Porter, Forrest Jessop, and Tony Ward. 2013. "Adverse Effects of Wood Smoke PM(2.5) Exposure on Macrophage Functions." *Inhalation Toxicology* 25 (2): 67–76. doi:10.3109/08958378.2012.756086.

Morris, K, Marcia Morganlander, John L. Coulehan, Sheila Gahagen, and Vincent C. Arena. 1990. "Wood-Burning Stoves and Lower Respiratory Tract Infection in American Indian Children." *American Journal of Diseases of Children* 144 (1): 105–8. doi:10.1001/archpedi.1990.02150250117047.

Muala, Ala, Gregory Rankin, Maria Sehlstedt, Jon Unosson, Jenny A. Bosson, Annelie Behndig, Jamshid Pourazar, et al. 2015. "Acute Exposure to Wood Smoke from Incomplete Combustion - Indications of Cytotoxicity." *Particle and Fibre Toxicology* 12 (1). Particle and Fibre Toxicology: 33. doi:10.1186/s12989-015-0111-7.

Naeher, L. P., K. R. Smith, B. P. Leaderer, L. Neufeld, and D. T. Mage. 2001. "Carbon Monoxide as a Tracer for Assessing Exposures to Particulate Matter in Wood and Gas Cookstove Households of Highland Guatemala." *Environmental Science and Technology* 35 (3): 575–81. doi:10.1021/es991225g.

Naeher, Luke P., Michael Brauer, Michael Lipsett, Judith T. Zelikoff, Christopher D. Simpson, Jane Q. Koenig, and Kirk R. Smith. 2007. "Woodsmoke Health Effects: A Review." *Inhalation Toxicology* 19 (1): 67–106. doi:10.1080/08958370600985875.

Nagda, N.L., H.E. Rector, and M.D. Koontz. 1987. *Guidelines for Monitoring Indoor Air Quality*. New York, NY: Hemisphere Publishing Corporation.

National Center for Biotechnology Information. 2017. "PubChem Compound Database." https://pubchem.ncbi.nlm.nih.gov.

Navajo Epidemiology Center. 2009. "Navajo Nation Mortality Report 2006-2009." http://www.nec.navajo-nsn.gov/Portals/0/Reports/Vital Statistics Report 2006 to 2009 FINAL.pdf.

———. 2013. "Navajo Mortality 2010-2013 New Mexico Portion of the Navajo Nation."

Navajo Housing Authority. 2011. "Phase II Housing Needs Assessment Demographic Analysis."

Navajo Tribal Utility Authority. 2014. "Utility Rates." http://www.ntua.com/utility_rate.html.

Nazaroff, W W, and G R Cass. 1986. "Mathematical Modeling of Chemically Reactive Pollutants in Indoor Air." *Environmental Science & Technology* 20 (9): 924–34. doi:10.1021/es00151a012.

Nikula, K J, M B Snipes, E B Barr, W C Griffith, R F Henderson, and J L Mauderly. 1995. "Comparative Pulmonary Toxicities and Carcinogenicities of Chronically Inhaled Diesel

Exhaust and Carban Black in F344 Rats." *Toxicological Sciences* 25 (1). Soc Toxicology: 80–94.

NIOSH. 2015. "Diesel Particulate Matter (as Elemental Carbon): Method 5040." *Manual for Occupational Safety and Health*. https://www.cdc.gov/niosh/docs/2014-151/pdfs/methods/5040.pdf.

NOAA. 2011. "Temperature ; Extreme Minimum ; By Month Climate Data Online Extremes Products." http://www7.ncdc.noaa.gov/CDO.

———. 2015a. "Annual Climatological Summary - Farmington, NM." ncdc.noaa.gov.

———. 2015b. "Farmington NM Ten Year HDD and Summary Annual Averages 2005-2014." https://www.ncdc.noaa.gov/cag/time-series.

Northcross, Amanda, Zohir Chowdhury, John McCracken, Eduardo Canuz, and Kirk R Smith. 2010. "Estimating Personal PM2.5 Exposures Using CO Measurements in Guatemalan Households Cooking with Wood Fuel." *Journal of Environmental Monitoring : JEM* 12 (4): 873–78. doi:10.1039/b916068j.

NREL. 1991. "Passive Solar Design Strategies: Guidelines for Home Building (Northwest NM)."

———. 2013. "National Residential Efficiency Measures Database v 3.0.0." http://www.nrel.gov/ap/retrofits/.

———. 2014. "Building Energy Optimization (BeOpt v 2.3) Software." *BeOpt Ver. 2.3*. https://beopt.nrel.gov/.

O'Sullivan, Robert B. 1958. "Summary of Coal Resources in the Black Mesa Coal Field, Arizona." In *Guidebook of the Black Mesa Basin, Northern Arizona: New Mexico Geological Society, 9th Field Conference*, 169–71.

Obaidullah, M., I. V. Dyakov, J. D. Thomassin, T. Duquesne, S. Bram, F. Contino, and J. De Ruyck. 2014. "CO Emission Measurements and Performance Analysis of 10 kW and 20 kW Wood Stoves." *Energy Procedia* 61. Elsevier B.V.: 2301–6. doi:10.1016/j.egypro.2014.12.443.

Oberdörster, Günter, Eva Oberdörster, and Jan Oberdörster. 2005. "Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles." *Environmental Health Perspectives* 113 (7): 823–39. doi:10.1289/ehp.7339.

Oh, Seung Min, Ha Ryong Kim, Yong Joo Park, Soo Yeun Lee, and Kyu Hyuck Chung. 2011. "Organic Extracts of Urban Air Pollution Particulate Matter (PM2.5)-Induced Genotoxicity and Oxidative Stress in Human Lung Bronchial Epithelial Cells (BEAS-2B Cells)." *Mutation Research - Genetic Toxicology and Environmental Mutagenesis* 723 (2). Elsevier B.V.: 142–51. doi:10.1016/j.mrgentox.2011.04.003.

Ott, Martin, Vladimir Gogvadze, Sten Orrenius, and Boris Zhivotovsky. 2007. “Mitochondria, Oxidative Stress and Cell Death.” *Apoptosis* 12 (5): 913–22. doi:10.1007/s10495-007-0756-2.

Overend, Ralph P, T Milne, and L Mudge. 2012. *Fundamentals of Thermochemical Biomass Conversion*. Springer Science & Business Media.

Ozgen, Senem, Stefano Caserini, Silvia Galante, Michele Giugliano, Elisabetta Angelino, Alessandro Marongiu, Francesca Hugony, Gabriele Migliavacca, and Carmen Morreale. 2014. “Emission Factors from Small Scale Appliances Burning Wood and Pellets.” *Atmospheric Environment* 94. Elsevier Ltd: 144–53. doi:10.1016/j.atmosenv.2014.05.032.

Pankow, James F. 1994. “An Absorption Model of Gas/particle Partitioning of Organic Compounds in the Atmosphere.” *Atmospheric Environment* 28 (2): 0–3. doi:10.1016/1352-2310(94)90093-0.

Patel, Sameer, Anish Khandelwal, Anna Leavey, and Pratim Biswas. 2016. “A Model for Cost-Benefit Analysis of Cooking Fuel Alternatives from a Rural Indian Household Perspective.” *Renewable and Sustainable Energy Reviews* 56. Elsevier: 291–302. doi:10.1016/j.rser.2015.11.047.

Perry, George, Marta A. Taddeo, Robert B. Petersen, Rudy J. Castellani, Peggy L R Harris, Sandra L. Siedlak, Adam D. Cash, et al. 2003. “Adventiously-Bound Redox Active Iron and Copper Are at the Center of Oxidative Damage in Alzheimer Disease.” *BioMetals* 16 (1): 77–81. doi:10.1023/A:1020731021276.

Pettersson, Esbjörn, Christoffer Boman, Roger Westerholm, Dan Boström, and Anders Nordin. 2011. “Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion, Part 2: Wood Stove.” *Energy and Fuels* 25 (1): 315–23. doi:10.1021/ef1007787.

Pope, C Arden, Majid Ezzati, and Douglas W Dockery. 2009. “Fine-Particulate Air Pollution and Life Expectancy in the United States.” *The New England Journal of Medicine* 360 (4): 376–86. doi:10.1056/NEJMsa0805646.

Pozzi, Roberta, Barbara De Berardis, Luigi Paoletti, and Cecilia Guastadisegni. 2003. “Inflammatory Mediators Induced by Coarse (PM2.5-10) and Fine (PM2.5) Urban Air Particles in RAW 264.7 Cells” 183: 243–54.

Prahalad, Agasanur K, Joleen M Soukup, Jefferson Inmon, Robert Willis, Andrew J Ghio, Susanne Becker, and Jane E Gallagher. 1999. “Ambient Air Particles: Effects on Cellular Oxidant Radical Generation in Relation to Particulate Elemental Chemistry.” *Toxicology and Applied Pharmacology* 158 (2): 81–91. doi:http://dx.doi.org/10.1006/taap.1999.8701.

Reddy, M.Shekar, and Chandra Venkataraman. 2002. “Inventory of Aerosol and Sulphur Dioxide Emissions from India: I—Fossil Fuel Combustion.” *Atmospheric Environment* 36 (4): 677–97. doi:10.1016/S1352-2310(01)00463-0.

Robin, Laura F., Peter S.J. Lees, Marcy Winget, Mark Steinhoff, Lawrence H. Moulton, Mathuram Santosham, and Adolfo Correa. 1996. “Word-Burning Stoves and Lower Respiratory Illnessess in Navajo Children.” *The Pediatric Infectious Disease Journal* 15 (10): 859–65. doi:10.1097/00006454-199610000-00006.

Roden, Christoph A., Tami C. Bond, Stuart Conway, and Anibal Benjamin Osorto Pinel. 2006. “Emission Factors and Real-Time Optical Properties of Particles Emitted from Traditional Wood Burning Cookstoves.” *Environmental Science and Technology* 40 (21): 6750–57. doi:10.1021/es052080i.

Roden, Christoph A., Tami C. Bond, Stuart Conway, Anibal Benjamin Osorto Pinel, Nordica MacCarty, and Dean Still. 2009. “Laboratory and Field Investigations of Particulate and Carbon Monoxide Emissions from Traditional and Improved Cookstoves.” *Atmospheric Environment* 43 (6). Elsevier Ltd: 1170–81. doi:10.1016/j.atmosenv.2008.05.041.

Rogalsky, Derek K., Pauline Mendola, Tricia A. Metts, and William J. Martin. 2014. “Estimating the Number of Low-Income Americans Exposed to Household Air Pollution from Burning Solid Fuels.” *Environmental Health Perspectives* 122 (8): 806–10. doi:10.1289/ehp.1306709.

Rogge, Wolfgang F., Lynn M. Hildemann, Monica A. Mazurek, Glen R. Cass, and Bernd RT Simoneit. 1998. “Sources of Fine Organic Aerosol. 9. Pine, Oak, and Synthetic Log Combustion in Residential Fireplaces.” *Environmental Science & Technology* 32 (1): 13–22. doi:10.1021/es960930b.

Samburova, Vera, Jessica Connolly, Madhu Gyawali, Reddy L N Yatavelli, Adam C Watts, Rajan K Chakrabarty, Barbara Zielinska, Hans Moosmüller, and Andrey Khlystov. 2016. “Science of the Total Environment Polycyclic Aromatic Hydrocarbons in Biomass-Burning Emissions and Their Contribution to Light Absorption and Aerosol Toxicity.” *Science of the Total Environment* 568. Elsevier B.V.: 391–401. doi:10.1016/j.scitotenv.2016.06.026.

Schauer, James J., Michael J. Kleeman, Glen R. Cass, and Bernd R T Simoneit. 2001. “Measurement of Emissions from Air Pollution Sources. 3. C1-C29 Organic Compounds from Fireplace Combustion of Wood.” *Environmental Science and Technology* 35 (9): 1716–28. doi:10.1021/es001331e.

Schurman, M. I., T. Lee, Y. Desyaterik, B. A. Schichtel, S. M. Kreidenweis, and J. L. Collett. 2015. “Transport, Biomass Burning, and in-Situ Formation Contribute to Fine Particle Concentrations at a Remote Site near Grand Teton National Park.” *Atmospheric Environment* 112. Elsevier Ltd: 257–68. doi:10.1016/j.atmosenv.2015.04.043.

Sen, Chandan K., and Lester Packer. 1996. “Antioxidant and Redox Regulation of Gene Transcription.” *The FASEB Journal* 10 (7): 709–20.

Shao, Longyi, Cong Hou, Chunmei Geng, Junxia Liu, Ying Hu, Jing Wang, Tim Jones, Chengmei Zhao, and B Kelly. 2016. “The Oxidative Potential of PM 10 from Coal , Briquettes and Wood Charcoal Burnt in an Experimental Domestic Stove." *Atmospheric Environment* 127: 372–81. doi:10.1016/j.atmosenv.2015.12.007.

Shen, Guofeng, Shu Tao, Siye Wei, Yuanchen Chen, Yanyan Zhang, Huizhong Shen, Ye Huang, et al. 2013. "Field Measurement of Emission Factors of PM, EC, OC, Parent, Nitro-, and Oxy- Polycyclic Aromatic Hydrocarbons for Residential Briquette, Coal Cake, and Wood in Rural Shanxi, China." *Environmental Science and Technology* 47 (6): 2998–3005. doi:10.1021/es304599g.

Shen, Guofeng, Miao Xue, Yuanchen Chen, Chunli Yang, Wei Li, Huizhong Shen, Ye Huang, et al. 2014. "Comparison of Carbonaceous Particulate Matter Emission Factors among Different Solid Fuels Burned in Residential Stoves." *Atmospheric Environment* 89. Elsevier Ltd: 337–45. doi:10.1016/j.atmosenv.2014.01.033.

Shen, Guofeng, Yifeng Yang, Wei Wang, Shu Tao, Chen Zhu, Yujia Min, Miao Xue, et al. 2010. "Emission Factors of Particulate Matter and Elemental Carbon for Crop Residues and Coals Burned in Typical Household Stoves in China." *Environmental Science and Technology* 44 (18): 7157–62. doi:10.1021/es101313y.

Simoneit, Bernd R T, Xinhui Bi, Daniel R Oros, Patricia M Medeiros, Guoying Sheng, and Jiamo Fu. 2007. "Phenols and Hydroxy-PAHs (Arylphenols) as Tracers for Coal Smoke Particulate Matter: Source Tests and Ambient Aerosol Assessments." *Environmental Science and Technology* 41 (21): 7294–7302. doi:10.1021/Es071072u.

Sklorz, Martin, Jacob-Jan Briedé, Jürgen Schnelle-Kreis, Yongbo Liu, Josef Cyrys, Theo M de Kok, and Ralf Zimmermann. 2007. "Concentration of Oxygenated Polycyclic Aromatic Hydrocarbons and Oxygen Free Radical Formation from Urban Particulate Matter." *Journal of Toxicology and Environmental Health. Part A* 70 (21): 1866–69. doi:10.1080/15287390701457654.

Sly, Peter D, and Felicity Flack. 2008. "Susceptibility of Children to Environmental Pollutants." *Annals of the New York Academy of Sciences* 1140 (October): 163–83. doi:10.1196/annals.1454.017.

Smith, K R. 1990. "Indoor Air Quality and the Pollution Transition." In *Indoor Air Quality*, edited by H. Kasuga. Berlin.

Smith, K R, M A K Khalil, R A Rasmussen, S A Thorneloe, F Manegdeg, and M Apte. 1993. "Greenhouse Gases from Biomass and Fossil-Fuel Stoves in Developing-Countries - a Manila Pilot-Study." *Chemosphere* 26: 479–505. doi:10.1016/0045-6535(93)90440-G.

Smith, Kirk R, Nigel Bruce, Kalpana Balakrishnan, Heather Adair-Rohani, John Balmes, Zoë Chafe, Mukesh Dherani, et al. 2014. "Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution." *Annual Review of Public Health* 35 (January): 185–206. doi:10.1146/annurev-publhealth-032013-182356.

Soukup, J M, and S Becker. 2001. “Human Alveolar Macrophage Responses to Air Pollution Particulates Are Associated with Insoluble Components of Coarse Material, Including Particulate Endotoxin.” *Toxicology and Applied Pharmacology* 171: 20–26. doi:10.1006/taap.2000.9096.

Squadrito, Giuseppe L., Rafael Cueto, Barry Dellinger, and William A. Pryor. 2001. “Quinoid Redox Cycling As a Mechanism for Sustained Free Radical Generation By Inhaled Airborne Particulate Matter.” *Fr* 31 (9): 1132–38.

Steenhof, Maaike, Ilse Gosens, Maciej Strak, Krystal J Godri, Gerard Hoek, Flemming R Cassee, Ian S Mudway, et al. 2011. “In Vitro Toxicity of Particulate Matter (PM) Collected at Different Sites in the Netherlands Is Associated with PM Composition, Size Fraction and Oxidative Potential--the RAPTES Project.” *Particle and Fibre Toxicology* 8 (1): 26. doi:10.1186/1743-8977-8-26.

Stewart, Kathleen. 2016. “The View from Two Feet on the Ground,” June.

Streets, D. G., T. C. Bond, G. R. Carmichael, S. D. Fernandes, Q. Fu, D. He, Z. Klimont, et al. 2003. “An Inventory of Gaseous and Primary Aerosol Emissions in Asia in the Year 2000.” *Journal of Geophysical Research* 108 (D21): 8809. doi:10.1029/2002JD003093.

Tao, Florence, Beatriz Gonzalez-Flecha, and Lester Kobzik. 2003. “Reactive Oxygen Species in Pulmonary Inflammation by Ambient Particulates.” *Free Radical Biology and Medicine* 35 (4): 327–40. doi:10.1016/S0891-5849(03)00280-6.

Thomas, Emma, Kremlin Wickramasinghe, Shanthi Mendis, Nia Roberts, and Charlie Foster. 2015. “Improved Stove Interventions to Reduce Household Air Pollution in Low and Middle Income Countries: A Descriptive Systematic Review.” *BMC Public Health* 15 (1): 650. doi:10.1186/s12889-015-2024-7.

Tian, Linwei, Catherine P Koshland, Junko Yano, Vittal K Yachandra, Ignatius T S Yu, S C Lee, and Donald Lucas. 2009. “Carbon-Centered Free Radicals in Particulate Matter Emissions from Wood and Coal Combustion.” *Energy & Fuels : An American Chemical Society Journal* 23 (5): 2523–26. doi:10.1021/ef8010096.

Turns, Stephen. 1996. *An Introduction to Combustion: Concepts and Applications*. Edited by McGraw-Hill. New York, NY.

Turpin, Barbara J., and Ho-Jin Lim. 2001. “Species Contributions to PM2.5 Mass Concentrations: Revisiting Common Assumptions for Estimating Organic Mass.” *Aerosol Science and Technology* 35 (February): 602–10. doi:10.1080/02786820119445.

U.S. Census Bureau. 2015. “Navajo Nation House Heating Fuel 2011 - 2015 American Community Survey Estimate.” https://factfinder.census.gov/bkmk/table/1.0/en/ACS/15_5YR/B25040/2500000US2430.

UCLA: Statistical Consulting Group. 2016. “IBM Statistical Package for the Social Sciences (SPSS) Frequently Asked Questions.”

United States Census Bureau. 2010. “American Community Survey Results: Navajo Nation Year Home Built.”

US Census Bureau. 2010a. “American Community Survey Results: Navajo Nation Children.”

———. 2010b. “Profile of General Population and Housing Characteristics for Shiprock, NM.”

———. 2011. “American Community Survey Results: Navajo Nation House Heating Fuel.”

———. 2012. American Community Survey Results: Navajo Nation Total Population, issued 2012.

———. 2013a. “2009-2013 American Community Survey 5-Year Estimates: Navajo Nation.”

———. 2013b. “2009-2013 American Community Survey 5-Year Estimates: United States.”

———. 2014. “ACS Navajo Nation Demographic and Housing.”

US DOE. 2012. “Buildings Energy Data Book: 2.5 Residential Construction and Housing Market” 45: 501–501. doi:10.1162/LEON_r_00465.

US EPA. 1984. “Guidelines on Preferred Location and Design of Measurement Ports for Air Pollution Control.” https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=50000KW3.TXT.

———. 1986. “Effects of Design Factors on Emissions from Non-Catalytic Residential Wood Combustion Appliances.” http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9100J6Q5.TXT.

———. 1988. “Method 28 - Certification and Auditing of Wood Heaters,” 1–15. https://www.epa.gov/sites/production/files/2016-06/documents/m-28.pdf.

———. 1991. “Introduction to Indoor Air Quality: A Reference Manual.” *Office of Air and Radiation*. Vol. EPA/400/3. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=000000S0.txt.

———. 1996. “AP-42, Fifth Edition, Chapter 1: External Combustion Sources, Residential Wood Stoves” 1 (10): 1–10. http://www.epa.gov/ttn/chief/ap42/ch01/index.html.

———. 1998. “AP-42 Fifth Edition, Chapter 1: External Combustion Sources, Natural Gas Combustion,” no. 5.

———. 2008. “AP-42, Sixth Edition, Chapter 1: External Combustion Sources, Liquified Petroleum Gas Combustion” 1 (6): 8–11. http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s05.pdf.

———. 2013a. “Burn Wise Resources: Air Quality Tools.” https://www.epa.gov/burnwise/burn-wise-additional-resources.

———. 2013b. “Technical Support Document Estimating the Benefit per Ton of Reducing PM2.5 Precursors from 17 Sectors,” 1–107.

———. 2016a. “Basic Information of Air Emissions Factors and Quantification.” https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification.

———. 2016b. “Process for Developing Improved Cordwood Test Methods for Wood Heaters,” no. March. https://www.epa.gov/sites/production/files/2016-03/documents/discussion_paper_-_process_for_dev_imp_cwtm_030916.pdf.

———. 2016c. “Summary of Requirements for Woodstoves and Pellet Stoves.” https://www.epa.gov/residential-wood-heaters/fact-sheet-summary-requirements-woodstoves-and-pellet-stoves.

USDOI. 2014. “Four Corners Power Plant and Navajo Mine Energy Project: Draft Environmental Impact Statement” 1 (March).

USEIA. 2005a. “Average Consumption for Space Heating by Main Space Heating Fuel Used, 2005 Million British Thermal Units per Household.”

———. 2005b. “Residential Energy Consumption Survey (RECS) - AIA Climate Zones.” http://www.eia.gov/consumption/residential/maps.cfm.

USEPA. 1991. “STANDARDS OF PERFORMANCE FOR NEW STATIONARY SOURCES.” http://www.deq.state.or.us/aq/forms/sourcetest/appendix_a1.pdf.

———. 1996. “AP-42, Fifth Edition, Chapter 1: External Combustion Sources, Residential Wood Stoves Background Document.”

Venkataraman, Chandra, and G. Uma Maheswara Rao. 2001. “Emission Factors of Carbon Monoxide and Size-Resolved Aerosols from Biofuel Combustion.” *Environmental Science & Technology* 35 (10): 2100–2107. doi:10.1021/es001603d.

Ward, Tony, Johna Boulafentis, Julie Simpson, Carolyn Hester, Tui Moliga, Kayla Warden, and Curtis Noonan. 2011. “Lessons Learned from a Woodstove Changeout on the Nez Perce Reservation.” *Science of The Total Environment* 409 (4). Elsevier B.V.: 664–70. doi:10.1016/j.scitotenv.2010.11.006.

Ward, Tony J. 2009. “Measurable Outcomes of a Woodstove Changeout on the Nez Perce Reservation Final Report,” no. 406.

White, W H, P T Roberts, and W M Keck Laboratories. 1976. “On the Nature and Origins of Visibility-Reducing Aerosols in the Los Angeles Air Basin.” doi:10.1016/0004-6981(77)90042-7.

World Health Organization. 2014. “WHO Guidelines for Indoor Air Quality: Household Fuel Combustion.”

———. 2016. “Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children.” http://apps.who.int/iris/bitstream/10665/204717/1/9789241565233_eng.pdf?ua=1.

World Health Organization, and International Agency for Research on Cancer. 2010. “Household Use of Solid Fuels and High-Temperature Frying.” *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*. Vol. 95. http://monographs.iarc.fr/ENG/Monographs/vol95/mono95.pdf.

Xiao, G. G., M. Wang, N. Li, J. A. Loo, and A. E. Nel. 2003. “Use of Proteomics to Demonstrate a Hierarchical Oxidative Stress Response to Diesel Exhaust Particle Chemicals in a Macrophage Cell Line.” *Journal of Biological Chemistry* 278 (50): 50781–90. doi:10.1074/jbc.M306423200.

Zhang, J, K.R Smith, Y Ma, S Ye, F Jiang, W Qi, P Liu, M.A.K Khalil, R.A Rasmussen, and S.A Thorneloe. 2000. “Greenhouse Gases and Other Airborne Pollutants from Household Stoves in China: A Database for Emission Factors.” *Atmospheric Environment* 34 (26): 4537–49. doi:10.1016/S1352-2310(99)00450-1.

Zhang, K. Max, and Anthony S. Wexler. 2004. “Evolution of Particle Number Distribution near Roadways - Part I: Analysis of Aerosol Dynamics and Its Implications for Engine Emission Measurement.” *Atmospheric Environment* 38 (38): 6643–53. doi:10.1016/j.atmosenv.2004.06.043.

Zhang, Yuanxun, James Jay Schauer, Yuanhang Zhang, Limin Zeng, Yongjie Wei, Yuan Liu, and Min Shao. 2008. “Characteristics of Particulate Carbon Emissions from Real-World Chinese Coal Combustion.” *Environmental Science and Technology* 42 (14): 5068–73. doi:10.1021/es7022576.

Zhi, Guorui, Yingjun Chen, Yanli Feng, Shengchun Xiong, L. I. Jun, G. A N Zhang, Guoying Sheng, and Jiamo Fu. 2008. “Emission Characteristics of Carbonaceous Particles from Various Residential Coal-Stoves in China.” *Environmental Science and Technology* 42 (9): 3310–15. doi:10.1021/es702247q.

8. Appendix

8.1 Chapter 2: Perception, Culture, and Science: A Framework to Identify In-home Heating Options to Improve Indoor Air Quality in the Navajo Nation

A total of 23 Tables, 1 Figure and 2 Attachments are included which provide detailed information used by the mixed-methods Navajo Framework. Each component is mentioned in the main text of Chapter 2 as needed.

Table S2-1A. Community Perception Survey Form.

HEATING ALTERNATIVE OPTIONS: In-Home Stove Coal Use Project: ISCUP

	CRITERION AND EVALUATION FACTORS								
OPTIONS IDENTIFIED	AVAILABILITY	INFRA-STRUCTURE	INITIAL COSTS	LONG TERM COST	MAINTENANCE NEEDS	CULTURAL CONSIDERATION	HEALTH IMPLICATIONS	ENVIRONMENTAL IMPLICATIONS	SCORE
NATURAL GAS									
PROPANE GAS									
ELECTRICAL STOVES									
PELLET STOVES									
IMPROVING EXISTING STOVES									
REPLACEMENT STOVES									
PASSIVE SOLAR									

Availability: are options & models readily available on the market and/or through existing sources, styles/models (aesthetics)
Infrastructure: design, multi-fuel capacity, safety factors/features/training, EPA certified, fuel/energy efficiency/effectiveness/capacity (BTUs), installation restrictions/codes
Initial Costs: initial purchasing availability, affordable costs & ease of installation
Long Term Costs: average life expectancy, fuel/energy efficiency
Long Term Maintenance: replacement part availability, maintenance of system, durability
Cultural considerations: acceptable to local populace, no cultural restrictions/taboos, remoteness vs. availability
Health Implications: adequate ventilation/installation/construction, BTU efficiency, stove types, ash traps, design/operations/maintenance, fuel curing
Environmental Implications: EPA certified, wood vs. coal use; stove exchange; maintenance, long term durability, fuel type use/level of dependency/emissions

Table S2-1B. Community Perception Survey Results (Means and Standard Deviations shown).

	CRITERION AND EVALUATION FACTORS								
OPTIONS IDENTIFIED	AVAILABILITY	INFRA-STRUCTURE	INITIAL COSTS	LONG TERM COST	MAINTENANCE NEEDS	CULTURAL CONSIDERATION	HEALTH IMPLICATIONS	ENVIRONMENTAL IMPLICATIONS	SCORE
NATURAL GAS	**2.10 (1.45)**	**2.27 (1.55)**	2.04 (1.56)	2.54 (1.78)	2.50 (1.86)	**2.21 (1.78)**	**2.57 (1.66)**	2.79 (1.80)	19.0 (10.8)
PROPANE GAS	**3.80 (1.59)**	3.21 (1.52)	**2.81 (1.65)**	2.73 (1.63)	3.02 (1.46)	2.96 (1.99)	2.99 (1.50)	3.19 (1.62)	24.7 (10.1)
ELECTRICAL STOVES	**3.38 (1.75)**	3.21 (1.52)	2.51 (1.46)	2.54 (1.67)	3.08 (1.33)	2.49 (1.75)	3.36 (1.73)	3.36 (1.61)	23.9 (9.55)
PELLET STOVES	3.11 (1.60)	2.88 (1.62)	2.01 (1.39)	**2.30 (1.55)**	2.44 (1.38)	2.54 (1.79)	2.70 (1.65)	2.95 (1.54)	20.9 (8.95)
IMPROVING EXISTING STOVES	2.84 (1.45)	2.92 (1.35)	2.67 (1.47)	2.71 (1.47)	2.84 (1.11)	3.21 (1.82)	**2.56 (1.34)**	**2.62 (1.40)**	22.4 (7.59)
REPLACEMENT STOVES	2.74 (1.69)	3.02 (1.80)	2.38 (1.38)	2.77 (1.49)	2.89 (1.63)	3.21 (1.86)	2.94 (1.45)	2.72 (1.36)	22.7 (10.0)
PASSIVE SOLAR	**2.44 (1.93)**	2.59 (1.69)	2.02 (1.57)	**3.38 (1.85)**	2.45 (1.75)	2.91 (1.98)	**3.80 (1.82)**	**3.91 (1.72)**	23.5 (9.65)

Bolded scores indicate statistical significance of the heating alternative compared to all other heating alternatives for the given criterion.

Table S2-2. Revised Community Perception Criteria.

Criteria	Description
Availability	Are options and models readily available on the local market?
Infrastructure	Is the needed infrastructure available? Include fuel access, safety factors, training, EPA certification, and installation restrictions/codes.
Initial Costs	Initial purchasing and installation costs.
Long-term Costs	Operating and maintenance costs and average life of product, accounting for fuel and energy efficiency.
Maintenance Needs	Availability of replacement parts and skilled labor for inspections and repairs. Also considers durability.
Cultural Consideration	Is the alternative acceptable to local populace, with no cultural restrictions or taboos?
Health Implications	Have health effects been linked to the use of this technology? Is adequate ventilation/installation/construction, efficiency, etc. available?
Environmental Implications	Does this technology reduce emissions? EPA certified, wood vs. coal use, stove exchange, maintenance, long-term durability, fuel type use/level of dependency.

Table S2-3. Typical Navajo and BeOpt v2.3 Default Home Characteristics.

Group Name	Category Name	Typical Navajo Home (Non-weatherized)	BeOpt v2.3 Defaults
Building	Orientation	South	North
	Neighbors	None	None
Operation	Heating Set Point	70 F	71 F
	Cooling Set Point	76 F	76 F
	Humidity Set Point	60% RH	60% RH
	Misc Electric Loads	1	1
	Misc Gas Loads	0	1
	Misc Hot Water Loads	Benchmark	Benchmark
	Natural Ventilation	Benchmark	Benchmark
Walls	Wood Stud	R7 Batt-Gr 3 2x4 16"o.c.	R13 Batt-Gr 1 2x4 16"o.c.
	Exterior Finish	Gray Wood Siding	Stucco
Ceilings/Roofs	Unfinished Attic	Ceiling R7 Fiberglass Blown-In Vented	Ceiling R30 Cellulose Blown-In Vented
	Roofing Material	Asphalt Shingles Medium	Asphalt Shingles Dark
	Radiant Barrier	None	None
Foundation/Floors	Slab	Uninsulated	Uninsulated
	Exposed Floor	100% Exposed	20% Exposed
Thermal Mass	Ext Wall Mass	1/2" Drywall	1/2" Drywall
	Partition Wall Mass	1/2" Drywall	1/2" Drywall
	Ceiling Mass	1/2" Ceiling Drywall	1/2" Ceiling Drywall
Windows & Shading	Window Areas	5.0% F75 B0 L12.5 R12.5	15.0% F20 B40 L20 R20
	Window Type	1-Pane Clear NM	2-Pane Low-e NM Air Med.-SHGC
	Interior Shading	Benchmark	Benchmark
	Eaves	1 ft	2 ft
	Overhangs	None	None
Airflow	Infiltration	0.60 ACH Annual Average	0.28 ACH Annual Average (**from BeOpt v1.6**). BeOpt v2.3 uses 15 ACH50 as "typical".
	Mechanical Ventilation	None	Exhaust 100% of A-62.2
Major Appliances	Refrigerator	Old Top Mount Freezer	Standard Top Mount Freezer
	Cooking Range	Gas Conventional	Electric Conventional
	Dishwasher	None	Standard
	Clothes Washer	None	Standard
	Clothes Dryer	None (Clothes Line)	Electric
Lighting	Lighting	B10 Benchmark	B10 Benchmark
Space Conditioning	Air Conditioner	None	SEER 13
	Furnace	Gas AFUE 78%	Gas AFUE 78%
	Ducts	Leaky R6 Insulation	Typical R6 Insulation
	Ceiling Fans	Benchmark	Benchmark
	Dehumidifier	None	None
Water Heating	Water Heater	Gas Standard	Gas Standard
	Distribution	Uninsulated TrunkBranch Copper	Uninsulated TrunkBranch Copper
	Solar DHW	None	None
	SDHW Azimuth	Back Roof	Back Roof
	SDHW Tilt	Roof Pitch	Roof Pitch
Power Generation	PV System	0 kW	0 kW
	PV Azimuth	Back Roof	Back Roof
	PV Tilt	Roof Pitch	Roof Pitch
HVAC Sizing	Cooling Capacity	0.0 tons	1.5 tons
	Heating Capacity	30 kBtu/hr	30 kBtu/hr

Table S2-4. Typical Home Heating Load Assumptions.

Assumption	Value	Units	Source
Climate Zone for Navajo Nation*	2	n/a	(USEIA, 2005a)
Average Annual Household Heating Load for Initial Home (Non-weatherized)	63.6	million BTU (mmBTU)/year	(USEIA, 2005b)
Average Annual Household Heating Load for Initial Home (Non-weatherized)	63.6	million BTU (mmBTU)/year	(NREL, 2014a)
Annual firewood use for Navajo conventional wood stove in Typical Home	3.9	air-dried-cord/yr	Equation 1
Average Annual Household Heating Load for Baseline Home (Weatherized)	57.6	mmBTU/year	(NREL, 2014a)
Annual firewood use for Navajo conventional wood stove in Baseline Home	3.5	air-dried-cord/yr	Equation 2

* Climate zone 2 corresponds to regions where less than 2,000 cooling degree-days (CDD) and between 5,500 and 7,000 HDD are required annually.

Table S2-5. Emission Factors* (EFs) of Heating Alternatives.

Assumption	Value	Units	Source
$PM_{2.5}$ Emission Factor ($EF_{PM2.5}$) for Navajo Conventional and Conventional Wood Stove**	30.6	lb-$PM_{2.5}$/ton-wood	(USEPA, 1996a)
PM_{10} Emission Factor (EF_{PM10}) for Navajo Conventional and Conventional Wood Stove**	30.6	lb-PM_{10}/ton-wood	(USEPA, 1996a)
Carbon Monoxide Emission Factor (CO) (EF_{CO}) for Navajo Conventional and Conventional "Improved" Wood Stove**	231	lb-CO/ton-wood	(USEPA, 1996a)
$EF_{PM2.5}$ for Natural Gas Furnace	7.60	lb-$PM_{2.5}$/10^6*scf-natural-gas	(US EPA, 1998)
EF_{PM10} for Natural Gas Furnace	7.60	lb-PM_{10}/10^6*scf-natural-gas	(US EPA, 1998)
EF_{CO} for Natural Gas Furnace	40.0	lb-CO/10^6*scf-natural-gas	(US EPA, 1998)
$EF_{PM2.5}$ for Propane Gas Furnace	0.700	lb-$PM_{2.5}$/10^3*gal-propane	(US EPA, 2008)
EF_{PM10} for Propane Gas Furnace	0.700	lb-PM_{10}/10^3*gal-propane	(US EPA, 2008)
EF_{CO} for Propane Gas Furnace	7.50	lb-CO/10^3*gal-propane	(US EPA, 2008)
$EF_{PM2.5}$ for Electricity Consumption	$1.64*10^{-4}$	lb-$PM_{2.5}$/kW-hr	(USDOI, 2014)
EF_{PM10} for Electricity Consumption	$1.23*10^{-4}$	lb-PM_{10}/kW-hr	(USDOI, 2014)
EF_{CO} for Electricity Consumption	$2.82*10^{-4}$	lb-CO/kW-hr	(USDOI, 2014)
$EF_{PM2.5}$ for Pellet Stove	4.20	lb-$PM_{2.5}$/ton-pellets	(USEPA, 1996a)
EF_{PM10} for Pellet Stove	4.20	lb-PM_{10}/ton-pellets	(USEPA, 1996a)
EF_{CO} for Pellet Stove	39.4	lb-CO/ton-pellets	(USEPA, 1996a)
$EF_{PM2.5}$ for USEPA-certified Non-catalytic Wood Stove	14.6	lb-$PM_{2.5}$/ton-wood	(USEPA, 1996a)
EF_{PM10} for USEPA-certified Non-catalytic Wood Stove	14.6	lb-PM_{10}/ton-wood	(USEPA, 1996a)
EF_{CO} for USEPA-certified Non-catalytic Wood Stove	141.8	lb-CO/ton-wood	(USEPA, 1996a)

*Outdoor emissions are used for three reasons: i) EFs from the USEPA *AP-42* compilations are defined as such, ii) variability of stove and flue condition between homes makes indoor estimates difficult, and iii) community health benefits are based on existing inventories of outdoor emissions from residential wood combustion (RWC).
**Assumed to be the same.

8.1.1 Technical Assessment Equations

Non-bolded items are calculated. Bolded items require assumptions and these are listed in Table S22 following all equations. Italicized items are considered model inputs are defined by the heating alternative options and their values are listed in Table S23.

Table S2-6. Equations: Firewood Burn Rates for Typical and Baseline Homes.

Equation 1	typlburn = **typlload** / (**typlstef** * **woodheat** * **woodens**)
Equation 2	baseburn = **baseload** / (**typlstef** * **woodheat** * **woodens**)

Where:

Typlburn	= Annual firewood use for Navajo conventional wood stove in Typical Home (air-dried-cord/yr)
typlload	= Annual heating load of Typical Home (10^6*BTU/yr)
baseburn	= Annual firewood use for Navajo conventional wood stove in Baseline Home (air-dried-cord/yr)
baseload	= Annual heating load of Baseline Home (10^6*BTU/yr)
typlstef	= Efficiency of "typical" Navajo conventional wood stove (fractional)
woodheat	= Heat density of firewood (10^6*BTU/ton)
wooddens	= Cord density of firewood (ton/air-dried-cord)

Table S2-7. Equations: Annual Fuel Use of All Heating Alternative Options.

Equation 3	NGfuel = **baseload** * 10^6 / (**NGgrheat** * *optneff*)
Equation 4	PGfuel = **baseload** * 10^6 / (**PGgrheat** * *optneff*)
Equation 5	EHfuel = **baseload** * 10^6 / (*EHoptnout* * *EHoptnin*)
Equation 6	WPfuel = **baseload** * 10^6 / (**WPgrheat** * *optneff*)
Equation 7	SIfuel = **baseload** / (*optneff* * **woodheat** * **wooddens**)
Equation 8	SRfuel = **baseload** / (*optneff* * **woodheat** * **wooddens**)
Equation 9	PSfuel = (**baseload** - *PSoptnout*) / (**typlstef** * **woodheat** * **wooddens**)

Where:

NGfuel	= Annual natural gas use for NG option in Baseline Home (scf/yr)
PGfuel	= Annual propane gas use for PG option in Baseline Home (gal/yr)
EHfuel	= Annual electricity use for EH option in Baseline Home (kW-hr/yr)
WPfuel	= Annual wood pellet use for WP option in Baseline Home (ton/yr)
SIfuel	= Annual firewood use for SI option in Baseline Home (air-dried-cord/yr)
SRfuel	= Annual firewood use for SR option in Baseline Home (air-dried-cord/yr)

PSfuel	= Annual firewood use for PS option in Baseline Home (air-dried-cord/yr)
Baseload	= Annual heating load of Baseline Home (10^6*BTU/yr)
NGgrheat	= Natural gas gross heating value (BTU/scf)
PGgrheat	= Propane gas gross heating value (BTU/gal)
EHoptnout	= EH option heat output (BTU/hr)
EHoptnin	= EH option electrical input (kW)
WPgrheat	= Wood pellet gross heating value (BTU/ton)
optneff	= Efficiency of option heating device (fractional)
woodheat	= Heat density of firewood (10^6*BTU/ton)
wooddens	= Cord density of firewood (ton/air-dried-cord)
PSoptnout	= Solar gain provided by PS option in Baseline Home (10^6*BTU/yr)
typlstef	= Efficiency of "typical" Navajo conventional wood stove (fractional)

Table S2-8. Equations: Annual Use of NG, PG, WP, and SR Options.

Equation 10	NGonhour = (**baseload** * 10^6) / (*optnin* * *optneff*)
Equation 11	PGonhour = (**baseload** * 10^6) / (*optnin* * *optneff*)
Equation 12	EHonhour = (**baseload** * 10^6) / (*optnout*)
Equation 13	WPonhour = (**baseload** * 10^6) / (*optnin* * *optneff*)
Equation 14	SRonhour = (**baseload** * 10^6) / (*optnin* * *optneff*)

Where:

NGonhour	= Annual use of NG option in Baseline Home (hrs/yr)
PGonhour	= Annual use of PG option in Baseline Home (hrs/yr)
EHonhour	= Annual use of EH option in Baseline Home (hrs/yr)
WPonhour	= Annual use of WP option in Baseline Home (hrs/yr)
SRonhour	= Annual use of SR option in Baseline Home (hrs/yr)
Baseload	= Annual heating load of Baseline Home (10^6*BTU/yr)
optnin	= Option heat input (BTU/hr)
optneff	= Efficiency of option heating device (fractional)

Table S2-9. Equations: Annual Electricity Consumption of Furnace or Stove Blower and Controls for NG, PG, WP, and SR Options.

Equation 15	NGelec = NGonhour * (**furnwatt** / 1000)
Equation 16	PGelec = PGonhour * (**furnwatt** / 1000)
Equation 17	EHelec = EHonhour * (**furnwatt** / 1000)
Equation 18	WPelec = WPonhour * (**blowwatt** / 1000)
Equation 19	SRelec = SRonhour * (**blowwatt** / 1000)

Where:

NGelec	= Annual electricity consumption of NG option blower and controls in Baseline Home (kW-hr/yr)

PGelec	= Annual electricity consumption of PG option blower and controls in Baseline Home (kW-hr/yr)
EHelec	= Annual electricity consumption of EH option blower and controls in Baseline Home (kW-hr/yr)
WPelec	= Annual electricity consumption of WP option blower and controls in Baseline Home (kW-hr/yr)
SRelec	= Annual electricity consumption of SR option blower and controls in Baseline Home (kW-hr/yr)
NGonhour	= Annual use of NG option in Baseline Home (hr/yr)
PGonhour	= Annual use of PG option in Baseline Home (hr/yr)
EHonhour	= Annual use of EH option in Baseline Home (hr/yr)
WPonhour	= Annual use of WP option in Baseline Home (hr/yr)
SRonhour	= Annual use of SR option in Baseline Home (hr/yr)
furnwatt	= Assumed electricity consumption of furnace blower and controls (W)
blowwatt	= Assumed electricity consumption of stove blower and controls (W)

Table S2-10. Efficiencies of Wood and Wood Pellet Stoves.

Assumption	Value	Units	Source
Efficiency of Navajo Conventional Wood Stove	45.0	%	*
Efficiency of Conventional “Improved” Wood Stove	53.6	%	(USEPA, 1996a)
Efficiency of USEPA-certified Wood Stove	68.3	%	(USEPA, 1996a)
Efficiency of USEPA-certified Wood Pellet Stove	67.5	%	(USEPA, 1996a)

* Value chosen from low end of range of 41.6 – 63.1% (USEPA, 1996b).

Table S2-11. US EPA-certified Wood and Wood Pellet Stove and Furnace Electricity Assumptions.

Assumption	Value	Units	Source
Electricity Consumption of USEPA-certified Wood or Wood Pellet Stove Blower and Controls	75	W	(I. S. Walker et al., 2010)
Electricity Consumption of Furnace Blower and Controls	500	W	(Walker, nd)

Table S2-12. Fuel Densities.

Assumption	Value	Units	Source
Average Cord Density of Pinyon Pine	1.65	tons/air-dried-cord	(Bureau of Land Management, 2012)

Table S2-13. Fuel Heating Values.

Assumption	Value	Units	Source
Average Heating Value of Pinyon Pine	22.2	mmBTU/ton-air-dried-wood	(Bureau of Land Management, 2012)
Pellet Gross Heating Value	16.5	mmBTU/ton-pellets	(Reeb, 2009)
Natural Gas Gross Heating Value	1,020	BTU/scf-natural-gas	(US EPA, 1998)
Liquefied Petroleum Gas (HD-5 consumer grade) Gross Heating Value	90,500	BTU/gallon	(US EPA, 2008)

Table S2-14. Equations: Emission Inventories for Typical and Baseline Homes and All Heating Alternative Options.

Equation 20	typlemis = typlburn * **wooddens** * **EFconv**
Equation 21	baseemis = baseburn * **wooddens** * **EFconv**
Equation 22	NGemis = NGfuel * **EFNG** * 10^{-6} + NGelec * **EFEH**
Equation 23	PGemis = PGfuel * **EFPG** * 10^{-3} + PGelec * **EFEH**
Equation 24	EHemis = (EHfuel + EHelec) * **EFEH**
Equation 25	WPemis = WPfuel * **EFWP** + WPelec * **EFEH**
Equation 26	SIemis = SIfuel * **wooddens** * **EFconv**
Equation 27	SRemis = SRfuel * **wooddens** * **EFcert** + SRelec * **EFEH**
Equation 28	PSemis = PSfuel * **wooddens** * **EFconv**

Where:

Typlemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from Navajo conventional wood stove in Typical Home from fuel use (lbs/yr)
Baseemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from Navajo conventional wood stove in Baseline Home from fuel use (lbs/yr)
NGemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from NG option in Baseline Home from fuel and electricity use (lbs/yr)
PGemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from PG option in Baseline Home from fuel and electricity use (lbs/yr)
EHemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from EH option in Baseline Home from electricity use (lbs/yr)
WPemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from WP option in Baseline Home from fuel and electricity use (lbs/yr)
SIemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from SI option in Baseline Home from fuel use (lbs/yr)
SRemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from SR option in Baseline Home from fuel and electricity use (lbs/yr)
PSemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from PS option in Baseline Home from fuel use (lbs/yr)
Typlburn	= Annual firewood use for Navajo conventional wood stove in Typical Home (air-dried-cord/yr)

baseburn	= Annual firewood use for Navajo conventional wood stove in Baseline Home (air-dried-cord/yr)
NGfuel	= Annual natural gas use for NG option in Baseline Home (scf/yr)
PGfuel	= Annual propane gas use for PG option in Baseline Home (gal/yr)
EHfuel	= Annual electricity use for EH option in Baseline Home (kW-hr/yr)
EHelec	= Annual electricity consumption of EH option blower and controls in Baseline Home (kW-hr/yr)
WPfuel	= Annual wood pellet use for WP option in Baseline Home (ton/yr)
SIfuel	= Annual firewood use for SI option in Baseline Home (air-dried-cord/yr)
SRfuel	= Annual firewood use for SR option in Baseline Home (air-dried-cord/yr)
PSfuel	= Annual firewood use for PS option in Baseline Home (air-dried-cord/yr)
wooddens	= Cord density of firewood (ton/air-dried-cord)
EFconv	= Emission factors (EFs) of $PM_{2.5}$, PM_{10}, and CO for conventional wood stove (lbs/ton-wood)
EFNG	= Emission factors (EFs) of $PM_{2.5}$, PM_{10}, and CO for natural gas furnace wood stove (lbs/10^6*scf)
EFPG	= Emission factors (EFs) of $PM_{2.5}$, PM_{10}, and CO for propane gas furnace (lbs/10^3*gal)
EFEH	= Emission factors (EFs) of $PM_{2.5}$, PM_{10}, and CO for electricity production (lbs/kW-hr)
EFWP	= Emission factors (EFs) of $PM_{2.5}$, PM_{10}, and CO for wood pellet stove (lbs/ton)
EFconv	= Emission factors (EFs) of $PM_{2.5}$, PM_{10}, and CO for conventional wood stove (lbs/ton-wood)
EFcert	= Emission factors (EFs) of $PM_{2.5}$, PM_{10}, and CO for USEPA-certified wood stove (lbs/ton-wood)

Table S2-15. Equations: Environmental Benefits from Weatherization and All Heating Alternative Options.

Equation 29	WZredc = typlemis - baseemis
Equation 30	HAredc = baseemis – HAemis

Where:

WZredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from weatherization of Typical Home (lbs/yr)
HAredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from Heating Alternative (NG, PG, EH, WP, SI, SR, or PS) option in Baseline Home (lbs/yr)
PGredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from PG option in Baseline Home (lbs/yr)
EHredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from EH option in Baseline Home (lbs/yr)
WPredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from WP option in Baseline Home (lbs/yr)
SIredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from SI option in Baseline Home (lbs/yr)
SRredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from SR option in Baseline Home (lbs/yr)
PSredc	= Reduction in emissions of $PM_{2.5}$, PM_{10}, and CO from PS option in Baseline Home (lbs/yr)
Typlemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from Navajo conventional wood stove in Typical Home from fuel use (lbs/yr)
baseemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from Navajo conventional wood stove in Baseline Home from fuel use (lbs/yr)
NGemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from NG option in Baseline Home from fuel and electricity use (lbs/yr)
PGemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from PG option in Baseline Home from fuel and electricity use (lbs/yr)
EHemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from EH option in Baseline Home from electricity use (lbs/yr)
WPemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from WP option in Baseline Home from fuel and electricity use (lbs/yr)
SIemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from SI option in Baseline Home from fuel use (lbs/yr)
SRemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from SR option in Baseline Home from fuel and electricity use (lbs/yr)
PSemis	= Annual emissions of $PM_{2.5}$, PM_{10}, and CO from PS option in Baseline Home from fuel use (lbs/yr)

Table S2-16. Summary of Technical Assessment for Emission Reductions.

	Units	Alternative	Mean	SD	n
		NG	176	0.077	16
		PG	176	0.070	22
		EH	173	0.521	8
$PM_{2.5}$	lbs-$PM_{2.5}$/yr	WP	155	0.004	5
		SI	28.3	0.000	2
		SR	121	0.007	7
		PS	43.3	1.80	8
		NG	1328	0.338	16
		PG	1325	0.626	22
		EH	1325	0.894	8
CO	lbs-CO/yr	WP	1127	0.007	5
		SI	214	0.000	2
		SR	792	0.012	7
		PS	327	13.6	8

Table S2-17. Equations: Health Benefits from Weatherization and All Heating Alternative Options.

Equation 31	WZbptl = WZredc(PM25) * (**bptlow**/2000)
Equation 32	WZbpth = WZredc(PM25) * (**bpthigh**/2000)
Equation 33	HAbptl = HAredc(PM25) * (**bptlow**/2000)
Equation 34	HAbpth = HAredc(PM25) * (**bpthigh**/2000)

Where:

WZbptl	= Low-estimated health benefits for the Navajo Nation from reduction in $PM_{2.5}$ emissions from residential wood use from weatherization option of Typical Home ($/yr)
WZbpth	= Low-estimated health benefits for the Navajo Nation from reduction in $PM_{2.5}$ emissions from residential wood use from weatherization option of Typical Home ($/yr)
HAbptl	= Low-estimated health benefits for the Navajo Nation from reduction in $PM_{2.5}$ emissions from residential wood use from Heating Alternative (NG, PG, EH, WP, SI, SR, or PS) option in Baseline Home ($/yr)
HAbpth	= Low-estimated health benefits for the Navajo Nation from reduction in $PM_{2.5}$ emissions from residential wood use from Heating Alternative (NG, PG, EH, WP, SI, SR, or PS) option in Baseline Home ($/yr)
WZredc(PM25)	= Reduction in emissions of $PM_{2.5}$ from weatherization of Typical Home (lbs/yr)
HAredc(PM25)	= Reduction in emissions of $PM_{2.5}$ from Heating Alternative (NG, PG, EH, WP, SI, SR, or PS) option in Baseline Home (lbs/yr)
bptlow	= Low-estimated benefit-per-ton (BPT) figure of health benefits for the Navajo Nation from reduction in $PM_{2.5}$ emissions from residential wood use ($/ton-$PM_{2.5}$)
bpthigh	= High-estimated benefit-per-ton (BPT) figure of health benefits for the Navajo Nation from reduction in $PM_{2.5}$ emissions from residential wood use ($/ton-$PM_{2.5}$)

Table S2-18. Technical Assessment Assumptions Summarized.

Assumption	Value	Units	Source	Table #
typlload	63.6	million BTU (mmBTU)/year	(USEIA, 2005b)	S2-3
baseload	57.6	mmBTU/year	(NREL, 2014a)	S2-3
EFconv	30.6 / 30.6 / 231	lb/ton-wood	(USEPA, 1996a)	S2-4
EFNG	7.60 / 7.60 / 40.0	lb/10^6*scf-natural-gas	(US EPA, 1998)	S2-4
EFPG	0.700 / 0.700 / 7.50	lb/10^3*gal-propane	(US EPA, 2008)	S2-4
EFEH	$1.64*10^{-4}$ / $1.23*10^{-4}$ / $2.82*10^{-4}$	lb/kW-hr	(USDOI, 2014)	S2-4
EFWP	4.20 / 4.20 / 39.4	lb/ton-pellets	(USEPA, 1996a)	S2-4
EFcert	14.6 / 14.6 / 141.8	lb/ton-wood	(USEPA, 1996a)	S2-4
typlstef	45.0	%	*	S2-5
woodheat	22.2	mmBTU/ton-air-dried-wood	(Bureau of Land Management, 2012)	S2-6
wooddens	1.65	ton/air-dried-cord	(Bureau of Land Management, 2012)	S2-6
WPgrheat	16.5	mmBTU/ton-pellets	(Reeb, 2009)	S2-6
NGgrheat	1,020	BTU/scf-natural-gas	(US EPA, 1998)	S2-7
PGgrheat	90,500	BTU/gallon	(US EPA, 2008)	S2-7
furnwatt	75	W	(I. S. Walker et al., 2010)	S2-8
blowwatt	500	W	(Walker, nd)	S2-8
bptlow	12,000	\$/$ton_{PM2.5}$-year	(US EPA, 2013)	S2-9
bpthigh	31,000	\$/$ton_{PM2.5}$-year	(US EPA, 2013)	S2-9

Table S2-19A. Technical Assessment Model Inputs.

		optnin (BTU/hr)	*EHoptnin (kW)*	*optneff (fractional)*	*EHoptnout (BTU/hr)*	*PSoptnout (BTU/yr)*
WZ	0a	n/a	n/a	0.450	n/a	n/a
	0b	n/a	n/a	0.450	n/a	n/a
NG	1	75,000	n/a	0.900	n/a	n/a
	2	60,000	n/a	0.800	n/a	n/a
	3	60,000	n/a	0.800	n/a	n/a
	4	80,000	n/a	0.955	n/a	n/a
	5	80,000	n/a	0.955	n/a	n/a
	6	38,290	n/a	0.780	n/a	n/a
	7	38,290	n/a	0.780	n/a	n/a
	8	38,290	n/a	0.800	n/a	n/a
	9	38,290	n/a	0.800	n/a	n/a
	10	38,290	n/a	0.900	n/a	n/a
	11	38,290	n/a	0.900	n/a	n/a
	12	38,290	n/a	0.980	n/a	n/a
	13	38,290	n/a	0.980	n/a	n/a
	14	60,000	n/a	0.650	n/a	n/a
	15	60,000	n/a	0.750	n/a	n/a
	16	60,000	n/a	0.800	n/a	n/a
PG	17	75,000	n/a	0.900	n/a	n/a
	18	60,000	n/a	0.800	n/a	n/a
	19	60,000	n/a	0.800	n/a	n/a
	20	80,000	n/a	0.955	n/a	n/a
	21	80,000	n/a	0.955	n/a	n/a
	22	38,290	n/a	0.780	n/a	n/a
	23	38,290	n/a	0.780	n/a	n/a
	24	38,290	n/a	0.800	n/a	n/a
	25	38,290	n/a	0.800	n/a	n/a
	26	38,290	n/a	0.820	n/a	n/a
	27	38,290	n/a	0.820	n/a	n/a
	28	38,290	n/a	0.900	n/a	n/a
	29	38,290	n/a	0.900	n/a	n/a
	30	38,290	n/a	0.920	n/a	n/a
	31	38,290	n/a	0.920	n/a	n/a
	32	38,290	n/a	0.940	n/a	n/a
	33	38,290	n/a	0.940	n/a	n/a
	34	38,290	n/a	0.980	n/a	n/a
	35	38,290	n/a	0.980	n/a	n/a
	36	60,000	n/a	0.650	n/a	n/a
	37	60,000	n/a	0.750	n/a	n/a
	38	60,000	n/a	0.800	n/a	n/a
EH	39	n/a	15	1.000	34,100	n/a
	40	n/a	15	1.000	49,147	n/a
	41	n/a	15	1.000	49,147	n/a
	42	n/a	25	1.000	81,912	n/a
	43	n/a	25	1.000	81,912	n/a
	44	n/a	15	1.000	38,290	n/a
	45	n/a	15	1.000	38,290	n/a
	46	n/a	15	1.000	49,147	n/a

Table S2-19A continued.

		optnin (BTU/hr)	*EHoptnin (kW)*	*optneff (fractional)*	*EHoptnout (BTU/hr)*	*PSoptnout (BTU/yr)*
WP	47	35,000	n/a	0.675	n/a	n/a
	48	50,000	n/a	0.675	n/a	n/a
	49	45,000	n/a	0.675	n/a	n/a
	50	47,300	n/a	0.675	n/a	n/a
	51	35,000	n/a	0.675	n/a	n/a
SI	52	n/a	n/a	0.536	n/a	n/a
	53	n/a	n/a	0.536	n/a	n/a
SR	54	89,000	n/a	0.683	n/a	n/a
	55	112,000	n/a	0.683	n/a	n/a
	56	40,000	n/a	0.683	n/a	n/a
	57	40,741	n/a	0.683	n/a	n/a
	58	55,600	n/a	0.683	n/a	n/a
	59	56,000	n/a	0.683	n/a	n/a
	60	89,000	n/a	0.683	n/a	n/a
PS	61	n/a	n/a	0.450	n/a	13.6
	62	n/a	n/a	0.450	n/a	13.6
	63	n/a	n/a	0.450	n/a	13.6
	64	n/a	n/a	0.450	n/a	13.6
	65	n/a	n/a	0.450	n/a	14.7
	66	n/a	n/a	0.450	n/a	14.7
	67	n/a	n/a	0.450	n/a	14.7
	68	n/a	n/a	0.450	n/a	14.7

Table S2-19B. List of Vendors Contacted via Telephone.

Vendor and Contact Info	Heating Alternative(s)	Description	Cost ($)
Four States Equipment & Services (505) 327-1617 714 West Main St. Farmington, NM 87401	NG, PG, EH	Retrofit of centralized furnace	3000
White Desert Construction (505) 516-3337 3001 Northridge Dr. Farmington, NM 87401	PS	Replacement of single-pane window	500
Country Gas (505) 327-0595 4400 W Main St. Farmington, NM 87401	PG	200 gallon tank Tank annual rental Piping and connections Regulator Taxes State inspection	360 48 140 58 44.69 20

Table S2-20. Community Health Benefit-per-ton (BPT) Figures.

Assumption	Value	Units	Source
Low Estimated Health BPT for Navajo Community from $PM_{2.5}$ Reduction	12,000	$/ton$_{PM2.5}$-year	(US EPA, 2013)
High Estimated Health BPT for Navajo Community from $PM_{2.5}$ Reduction	31,000	$/ton$_{PM2.5}$-year	(US EPA, 2013)

Table S2-21. Summary of Availability (AV), Infrastructure (IN), Maintenance Needs (MN) and Cultural Considerations (CC).

Criteria	Alternative	% of homes[A]	Pros	Cons
AV	NG	20	More available in population centers, used in 14% of homes currently[1]. No direct estimate of percentage of Navajo residents with access available and the value of 20% was assumed.	Limited by access to natural gas lines and need for electricity[2].
	PG	80	Widely available, used in 11% of homes currently[1]; furnace, fuel, and labor available	Limited by need for electricity[2].
	EH	80	Widely available, used in 11% of homes currently[1]; furnace and labor available.	Limited by need for electricity[2].
	WP	80	Widely available, estimated that 89% of rural NN homes use wood or wood pellet stoves currently[2]. Stove, fuel, and labor available	Limited by need for electricity[2].
	SI	100	Universally available, used in 62% of homes currently[3] with likely higher usage in rural areas[2]. Materials, fuel, and labor available.	n/a
	SR	80	Widely available, used in 62% of homes currently[3] with likely higher usage in rural areas[2]. Stoves, fuel, and labor available.	Stoves with fan for improved efficiency limited by need for electricity[2].
	PS	80	Materials and labor available; solar radiation high in the region (61% higher than national average)[4].	Accessible solar designs not presently available; not used currently in NN.

A) Availability refers to potential for use, as opposed to current use.
1) US Census Bureau (2011); 2) Navajo Housing Authority (2011); 3) US Census Bureau (2009); 4) NREL (2014b); 5) Franklin (2000); 6) Houck and Eagle (2006); 7) USDOI (2014)

Criteria	Alternative	Required	Cons
IN	NG	Electricity, access to natural gas pipeline, dedicated ducts in house.	Flue from existing wood stove is inappropriate.
	PG	Electricity, propane tank, line from tank to house, dedicated ducts in house.	Flue from existing wood stove is inappropriate.
	EH	Electricity, dedicated ducts in house.	Flue from existing wood stove is inappropriate.
	WP	Electricity, flue; existing flue may be used if inspected and repaired.	n/a
	SI	Flue; existing flue may be used if inspected and repaired.	n/a
	SR	Electricity, flue; existing flue may be used if inspected and repaired.	n/a
	PS	PS side of house facing south; most cost effective for new construction.	Provides only 25% of heat required so in-home heating stove still required; major construction for existing house.

Criteria	Alternative	Yearly Cost ($)	Required	Cons
MN	NG, PG, EH	100[5]	Annual furnace inspection[5].	Inspections not offered by NTUA.
	WP	125[6]	Annual chimney cleaning[6].	Cleaning not offered by NTUA.
	SI, SR	150[6]	Annual chimney cleaning[6].	Cleaning not offered by NTUA.
	PS	167	Replacement of caulking every five years; annual chimney cleaning with continued use of conventional stove[6].	Cleaning not offered by NTUA.

Criteria	Alternative	Pros	Cons
CC	NG, PG	Use of gaseous fuels acceptable if done carefully.	Blue flame from combustion of natural gas is associated with danger and poor health.
	EH		Considered dangerous if in direct contact with people or air molecules. Pollution from coal-fired power production on air quality a concern[7].
	WP	Burns a waste product.	Some wood types should not be used, and since wood pellets are conglomerates of different saw dust, it is not always possible to know their composition.
	SI, SR	Does not disrupt current heating practices. Culturally appreciated means of heating.	Sustained dependence on wood use is a concern for some members of the community.
	PS	Use of solar energy is respected and appreciated.	n/a

Table S2-22. Summary of Technical Assessment for Initial Costs (IC), Long-term Costs (LC), Environmental Implications (EI), and Health Implications (HI) .

	Units	Alternative	Mean	SD	n
IC	$	NG	2,243	581	16
		PG	3,134	410	22
		EH	2,304	866	8
		WP	2,907	734	5
		SI	258	12	2
		SR	2,605	637	7
		PS	3,443	1862	8
LC	$/yr	NG	159	29	16
		PG	1,831	197	22
		EH	1,224	208	8
		WP	1,291	2	5
		SI	122	0	2
		SR	98	3	7
		PS	124	2	8
EI	lb-$PM_{2.5}$-reduced/$ / lb-CO-reduced/$	NG	0.60 / 4.5	0.09 / 0.69	16
		PG	0.09 / 0.66	0.01 / 0.06	22
		EH	0.13 / 0.99	0.02 / 0.16	8
		WP	0.10 / 0.75	0.00 / 0.03	5
		SI	0.21 / 1.6	0.00 / 0.01	2
		SR	0.48 / 3.2	0.08 / 0.49	7
		PS	0.15 / 1.1	0.05 / 0.37	8
HI	$/$	NG	6.4	3.1	16
		PG	0.94	0.43	22
		EH	1.4	0.68	8
		WP	1.1	0.52	5
		SI	2.2	1.1	2
		SR	5.2	2.5	7
		PS	1.6	0.91	8

Table S2-23. Proposed Educational Components to Improve Indoor Air Quality in the NN.

Category	Stakeholder Group	Educational Components Focusing on: *Environment*	*Society and Community*	*Local Economy*
Environmental/ Regulatory	Navajo Nation EPA	Awareness events (with food, music, dance, and local key community members) focused on replacement of outdated solid-fuel stoves and reduced use of coal indoors.	Offer seminars or free clinics for residents with outdated stoves. The discontinued use of coal MUST be a priority also.	Provide emissions and health benefit information on each stove and furnace available from local vendors.
	US EPA	Extension of BurnWise program into the Navajo Nation, including translation of educational documents and small-scale stove subsidy programs	Integration of Navajo culture into existing forms of public health educational materials (especially w.r.t. particulate matter). Can include color themes, Navajo actors/actresses, Navajo characters, and Diné philosophy.	Vouchers towards new wood stoves and natural gas furnaces, along with simple pamphlets on their benefits (compare and contrast these two options). Same can be done for passive solar retrofits.
Utility	Navajo Tribal Utility Authority	Report figures on emissions reductions with the use of electrical or gaseous heating, compared to conventional wood stoves.	Provide the estimated health benefits (from not using a conventional wood stove) reported with each monthly bill if the resident uses electrical or natural gas heating.	Build relationships with local Navajo-owned businesses to promote use of natural gas furnaces for residents on the network.
	Navajo Weatherization Program	Report estimated emission reductions from decreased energy demand from household weatherization.	Provide estimated health benefits versus cost of home weatherization.	Pamphlets describing available weatherization materials and their costs/benefits; potentially collaboration with local businesses to provide discounted prices.
Government	Navajo Tribal Council	Discuss environmental benefits of heating alternatives.	Emphasize and discuss health effects of indoor wood and coal use.	Highlight opportunities for major Navajo businesses to offer weatherization and retrofit services at high volumes (entire communities).
	Chapter Meetings	Same as Navajo Tribal Council but more small-scale and community oriented.	Same as Navajo Tribal Council but more small-scale and community oriented.	Highlight opportunities for local business-people to make money while helping the community in terms of improving home quality and reducing solid fuel use indoors.

Community	Navajo Hour (radio)	Discuss estimated public health benefits from the retrofit of just one conventional wood stove; provide advice for listeners as far as assessing their own stove's condition (eg. check for smoke and cracks).	Broadcast results of research focused on Navajo public health, including past and current work.	Provide information about availability and costs of weatherization and most viable alternatives.
	Community Socials and Dinners	Speakers from NNEPA and Diné College to discuss environmental impacts of wood and coal use.	Speakers from Indian Health Services to discuss observed health impacts in the Navajo Nation; plays or performances with Navajo characters telling a modern story of health concerns from wood and coal use indoors.	Speakers from local Navajo business-people working with home improvement, clean heating alternatives, and passive solar technologies.
Business	Local Stove and Furnace Companies	Provide complete data on efficiencies, emissions, and estimated long-term costs for available models.	Offer trainings on proper operation of stoves and furnaces, as well as firewood curing.	Seek to increase volume of affordable, efficient stoves and reduce capital costs for local residents.
	Local Contractors and Solar Installers	Develop modular and affordable passive solar retrofits for typical Navajo homes and provide attractive marketing.	Beyond retrofits, offer educational packages to homeowners explaining benefits associated with the heating alternative chosen.	Volume discounts on weatherization and retrofit services.
Education	Local Schools (K-12)	STEM workshops offering simple passive solar design projects for younger grades, and more intensive work with energy modeling software for higher grades.	Surveying of community members to gauge perception of public health issues of the Navajo Nation.	Call local businesses to determine costs of heating alternatives.
	Diné College	Incorporate design-based projects into the curricula based on reducing the amount of pollutants entering the environment.	Energy audit training for students by assessing local Navajo homes; surveying of residents to gauge common heating and cooking practices	Help develop small-scale business opportunities based on design-based curricula.

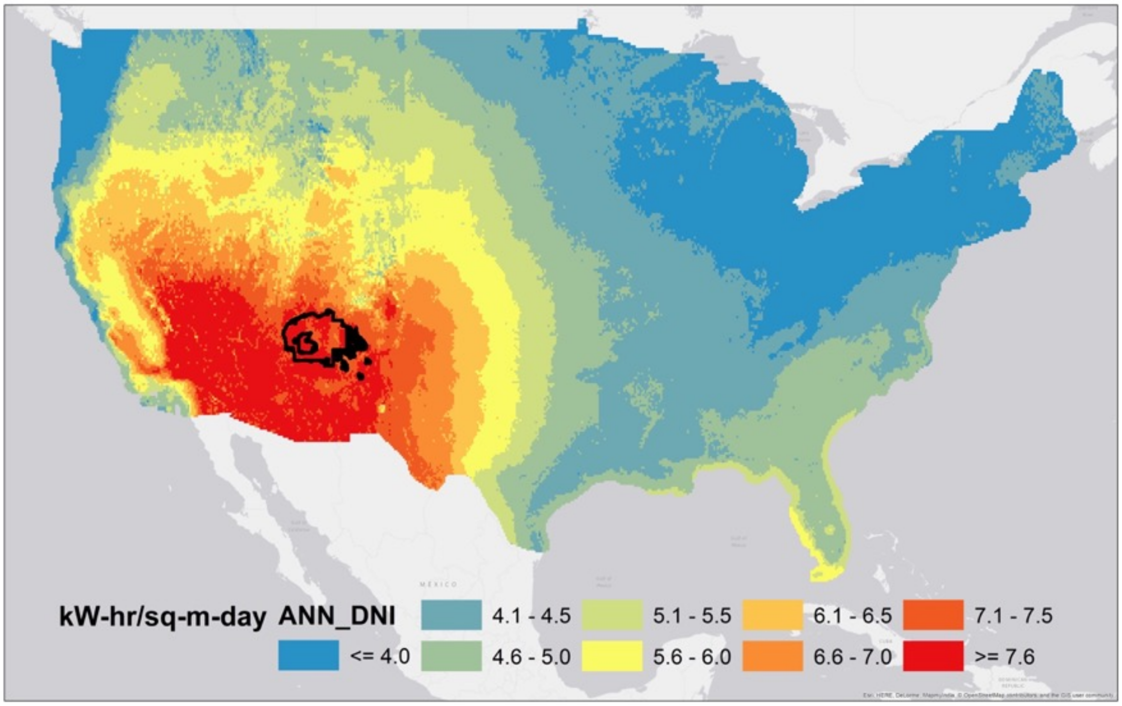


Figure S2-1. Annual Average Direct Normal Solar Radiation in the US (Navajo Nation Outlined in Black).

8.1.2 Cost Details and Methodologies

The following sources were used to determine a price range for the installation, maintenance, and use of the heating alternatives:

1. RSMeans 2015 for Farmington, NM (capital costs of all alternatives including overhead and profit)
2. National Renewable Energy Laboratory (NREL) BeOpt 2.3 Software Output for Farmington, NM (capital cost of passive solar direct gain retrofit)
3. NREL National Residential Efficiency Measures Database 3.0.0
4. Navajo Tribal Utility Authority (NTUA) (recurring utility costs of electricity and natural gas)
5. USEPA BurnWise Program Website (capital cost of wood stove retrofit)
6. United States Department of Energy (capital cost of gas furnace retrofit)
7. Houck and Eagle, 2006 (capital costs, and recurring costs and frequency of wood stove and wood pellet stove chimney cleaning)
8. Franklin, 2000 (recurring costs and frequency of gas furnace inspection)
9. Home Depot Online Catalog for Farmington, NM (capital costs of furnaces and stoves including local sales tax)
10. Personal Communication (fuel costs of wood and propane, capital costs of all retrofits)

8.1.2.1 Cost Annualization

One goal of the technical assessment was to determine the annual cost of implementing the heating alternatives after performing a baseline weatherization. Capital costs of retrofits were determined using a variety of sources, as explained below, and then annualized over the expected lifetime of the technology using equation C1 (Watts and Chapman, 2004) and an inflation rate of 1.5% [the 2013 national average (United States Bureau of Labor Statistics, 2014)]. This annualized capital cost was added to recurrent costs (or savings) such as fuel use and maintenance (e.g., inspections and chimney cleanings) to determine a total annualized cost for each alternative.

Equation C 1

$$A = P * \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

Where:

A = Annualized Cost, \$/year
P = Present value (capital cost), \$
i = Interest (inflation) rate, %
n = Lifetime of the alternative, years

8.1.2.2 Typical Home: Non-weatherized Navajo

There were no capital costs associated with the Typical Home, and the only recurring cost was fuel use (air-dried firewood, ponderosa pine). Cords of wood burned annually were determined using equation C2 and annual wood fuel cost for the Typical Home was determined using equation C3. Firewood costs associated with the Typical Home are shown in Table C1. No annual chimney cleaning is assumed for the Typical Home.

Equation C 2

$$Wood\ use = \frac{Heating\ load}{Wood\ heat\ content * Wood\ stove\ efficiency}$$

Where:

Wood use	= air-dried-cords/year
Heating load	= mmBTU/year
Wood heat content	= mmBTU/air-dried-cord
Wood stove efficiency	= fractional

Equation C 3

$$Wood\ fuel\ cost = Wood\ use * Wood\ cost$$

Where:

Annual firewood cost	= \$/year
Wood use	= air-dried-cords/year
Wood cost	= \$/air-dried-cord

Table C1. Initial Home Costs

Cost	Value	Units	Source
Firewood cost	50.00	$/air-dried-cord	(Personal Communication, 2014)
Annual wood fuel cost, initial home (63.6 mmBTU/year heating load using a 45% efficient stove)	192.92	$/year	Equation C3

8.1.2.3 Baseline Home: Weatherized Navajo

A Baseline Home was determined by applying a basic weatherization (WZ) to the Typical Navajo home. The infiltration rate for the “leaky” (as defined by BeOpt) Typical Navajo Home was reduced from 0.60 Annual Average Air Exchanges per Hour (AAACH) to 0.40 AAACH (the value for a “typical” home, also defined by BeOpt). Annual wood fuel costs of the Baseline Home were calculated similarly to the Typical Home and are lower due to decreased heating demand (57.6 mmBTU/year for the weatherized Baseline Home compared to 63.6 mmBTU/year for the non-weatherized Typical Home, a 9.4% reduction). Weatherization capital costs were determined using RSMeans 2015 for Farmington, NM (Gordian Group, 2015), as well as NREL’s National Residential Efficiency Measures Database (NREL, 2013). RSMeans line-item searches were performed using the keywords “caulking”, “weatherstripping”, and “sealant.” The line-items selected and their material (Mat.) and labor (Lab.) costs are listed in Table C2. RSMeans equipment (Eq.) cost values are denoted $0.00 when reported as such by RSMeans, and exc. when excluded; for excluded costs it was assumed that contractors would own the equipment necessary. NREL options are in Table C3 and n/a denotes no discrete material or labor cost reported, only the total. The quantity of each item was calculated from assumptions and values in Table C4 defining the Typical Home. No other cost estimates were available outside of RSMeans Data. Recurring costs for the Baseline Home are shown in Table C5 and include annual wood stove chimney cleaning, a cost not included for the Typical Home. The Index denotes the weatherization or heating alternative option; n/a for Index signifies an incomplete cost needed for a total estimate.

Table C2. WZ Capital Costs: RSMeans

Description	Index	Unit/ Quantity*	Cost Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Selective demolition, thermal and moisture protection, caulking/sealant, to 1" x 1" joint	n/a	*Linear feet*	*0.00*	*0.40*	*0.00*	*0.40*
		84[1]	0.00	33.60	0.00	33.60
Joint sealants, caulking and sealants, bulk acrylic latex, 3/8" x 3/8", in place	n/a	*Linear feet*	*0.22*	*1.12*	*0.00*	*1.34*
		84[1]	18.48	94.08	0.00	112.56
Weatherstripping, doors, wood frame, interlocking, zinc, for 3' x 7' door	n/a	*Opening*	*50.25*	*99.52*	*0.00*	*149.77*
		1[2]	50.25	99.52	0.00	149.77
Weatherstripping, for thresholds, door sweep, flush mounted, aluminum	n/a	*Each*	*21.76*	*11.95*	*0.00*	*33.71*
		1[2]	21.76	11.95	0.00	33.71
Weatherstripping, window, double hung, zinc, for 3' x 5' window	n/a	*Opening*	*22.79*	*41.64*	*0.00*	*64.43*
		4[3]	91.16	166.56	0.00	257.72
Total	0a	n/a	181.65	405.71	0.00	587.36

*Superscripts correspond to values in Table C4.

Table C3. WZ Capital Costs: NREL

Description	Index	Unit/ Quantity*	Total Cost ($)		
			Low Estimate	High Estimate	Average
Improvement of Air Leakage (Sealing); 10 ACH50 to 8 ACH50	n/a	*Square feet*	*0.22*	*0.82*	*0.52*
		1000[4]	220.00	820.00	520.00
Improvement of Air Leakage (Sealing); 15 ACH50 to 8 ACH50	n/a	*Square feet*	*0.66*	*2.50*	*1.58*
		1000[4]	660.00	2,500.00	1,580.00
Improvement of Air Leakage (Sealing); 12 ACH50 to 8 ACH50**	0b	*Square feet*	*0.40*	*1.49*	*0.95*
		1000[4]	400.00	1,490.00	945.00

*Superscripts correspond to values in Table C4
**The proposed weatherization resulted in a reduction in infiltration from 0.60 AAACH to 0.40 AAACH. The commonly used metric for leakage (induced by an artificial pressure decrease, “blower door test”) is ACH50 (Air Exchanges per Hours at 50 Pascals Pressure). The two units have been related by the Kronvall-Persily (K-P)

relationship, described by (Sherman, 1987), where AAACH is simply ACH50 divided by 20. Therefore, the proposed weatherization resulted in a reduction in leakage from 12 ACH50 to 8 ACH50. Since NREL had no cost estimate available for this exact scenario, the costs were assumed to be linear with respect to the starting condition.

Table C4.WZ Assumptions and Calculations

Home Characteristic	Quantity	Unit	Superscript from Table C2	Calculation (if applicable)
Home length (L)	50	Linear feet	n/a	n/a
Home width (W)	20	Linear feet	n/a	n/a
Home height (H)	8	Linear feet	n/a	n/a
Home area (A)	1000	Square feet	4	A=L*W
Exterior wall area (A_E)	1,120	Square feet	n/a	A_E = (2L+2W)*H
Number of doors (N_D)*	1	# doors	2	n/a
Door height (H_D)	7	Linear feet	n/a	n/a
Door width (W_D)	3	Linear feet	n/a	n/a
Total door perimeter (P_D)	20	Linear feet	n/a	$P_D = N_D*(2H_D+2W_D)$
Fractional total window area (f_W)**	0.05	Unitless	n/a	n/a
Total window area (A_W)	56	Square feet	n/a	$A_W = A_E*f_W$
Number of windows (N_W)	4	# windows	3	n/a
Window height (H_W)	3	Linear feet	n/a	n/a
Window width (W_W)	5	Linear feet	n/a	n/a
Total window area estimate ($A_{W,est}$)***	60	Square feet	n/a	$A_{W,est} = N_W*(H_W*W_W)$
Total window perimeter (P_W)	64	Linear feet	n/a	$P_W = N_W*(2H_W+2W_W)$
Total door and window perimeter to be sealed (P_{Tot})	84	Linear feet	1	$P_{Tot} = P_D+P_W$

*Number of doors is not an input of Beopt, and the default value of 1 door was used.
**This was an important assumption used in BeOpt determined from personal communication with community members after brief characterization of Shiprock home exteriors.
***It was necessary to assume a number of windows (3'x'5) to determine window perimeter and material costs. The value using number of windows and area (Aw,est) was 7.1% higher than AW (BeOpt input) and deemed acceptable.

Table C5. WZ Recurring Costs and Assumptions

Assumption	Value	Unit	Source
Lifespan of weatherization materials	20	Years	(Berry et al., 1997)
Firewood cost	50.00	$/air-dried-cord	(Personal Communication, 2014)
Annual wood fuel cost, baseline home (57.6 mmBTU/year heating load)	174.72	$/year	*Calculation*
Wood stove chimney cleaning cost*	150.00	$	(Houck and Eagle, 2006)
Wood stove chimney cleaning frequency*	1	1/year	(Houck and Eagle, 2006)

*Baseline home assumes same chimney cleaning cost and frequency as home with EPA-certified stove.

8.1.2.4 NG: Natural Gas Furnace

Capital cost of a natural gas furnace retrofit was determined using RSMeans and NREL estimates, as well as the Home Depot catalog for Farmington, NM (Home Depot, 2014), estimates from Houck and Eagle (2006), as well as estimates from local vendor through personal communication. RSMeans line-item searches were performed using the keywords "furnace", "stove", and "duct" and the items selected and their costs are shown in Table C6. Furnace selective demolition was selected to estimate the cost of removal of the old wood stove (wood stove selective demolition was not available). The 75 MBH (MBH is the unit used by RSMeans, and is equivalent to kBTU/hr, the unit used in this document) input furnace was chosen as this was the smallest available in RSMeans and the heating load for the baseline home estimated by BeOpt was 38.3 MBH. Installation of insulated 8" ducting was chosen. Natural gas furnace capital costs from Home Depot and RSMeans estimates are shown in Table C7, while NREL options are in Table C8. Houck and Eagle and personal communication values are shown in Table C9. Recurring costs and assumptions for natural gas furnace use are shown in Table C10.

Table C6. NG Capital Costs: RSMeans

Description	Index	Unit/ Quantity	Cost Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Furnace, gas or oil, under 120 MBH, selective demolition	n/a	*Each*	*0.00*	*153.18*	*0.00*	*153.18*
		1	0.00	153.18	0.00	153.18
Furnace, gas, upflow, direct drive model, intermittent pilot, 75 MBH input, AGA certified, includes standard controls, excludes gas, oil or flue piping; *Assumed 90% efficient*	n/a	*Each*	*636.27*	*169.69*	*0.00*	*805.96*
		1	636.27	169.69	0.00	805.96
Ductwork, flexible coated fiberglass fabric on corrosion resistant metal helix, insulated, P.E. jacket, 1" thick, 8" diameter, pressure to 12"(WG) UL-181	n/a	*Linear feet*	*3.84*	*3.23*	*0.00*	*7.07*
		100*	384.00	323.00	0.00	707.00
Index/Total	1	n/a	1,020.27	645.87	0.00	1,666.14

*The value of 100 linear feet of ducting was derived from a case-study of a larger home (US DOE, 2012) by assuming that length of ducting correlates linearly with home size.

Table C7. NG Capital Costs: Home Depot & RSMeans

Description	Index	Cost Including Local Sales Tax, Overhead and Profit/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Furnace: Winchester 60 kBTU/hr 80.0% Efficient); Duct: Insulated, R-6, 8” diameter, 100’, Master Flow	2	943.49	645.87*	exc.	1,589.36
Furnace: Winchester 60 kBTU/hr 80.0% Efficient); Duct: Insulated, R-8, 8” diameter, 100’, Master Flow	3	1,005.32	645.87*	exc.	1,651.19
Furnace: Winchester 80 kBTU/hr 95.5% Efficient; Duct: Insulated, R-6, 8” diameter, 100’, Master Flow	4	1,533.09	645.87*	exc.	2,178.96
Furnace: Winchester 80 kBTU/hr 95.5% Efficient; Duct: Insulated, R-8, 8” diameter, 100’, Master Flow	5	1,594.92	645.87*	exc.	2,240.79

*Labor cost from RSMeans 2015 (Table C6)

Table C8. NG Capital Costs: NREL

Description*	Index	Unit/ Quantity	Total Cost ($) Low Estimate	High Estimate	Average
Individual Components (Furnace and Duct individually)					
Upgrade of Natural Gas Furnace; None to 78% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*6.40* 245.06	*13.00* 497.77	*9.70* 371.42
Upgrade of Natural Gas Furnace; None to 80% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*8.40* 321.64	*16.00* 612.64	*12.20* 467.14
Upgrade of Natural Gas Furnace; None to 90% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*15.00* 574.35	*29.00* 1,110.41	*22.00* 842.38
Upgrade of Natural Gas Furnace; None to 98% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*17* 650.93	*34* 1,301.86	*25.50* 976.40
Installation of Ducts; None to 15% leakage with R6 duct insulation	n/a	*Square feet duct surface* 209***	*5.70* 1,191.30	*8.30* 1,734.70	*7.00* 1,463.00
Installation of Ducts; None to 7.5% leakage with R8 duct insulation	n/a	*Square feet duct surface* 209***	*5.80* 1,212.20	*8.40* 1,755.60	*7.10* 1,483.90
Total Installation (Furnace and Duct)					
Upgrade of Natural Gas Furnace; None to 78% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation	6	38.29 kBTU/hr; 209 ft^2	n/a	n/a	1,750.82
Upgrade of Natural Gas Furnace; None to 78% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation	7	38.29 kBTU/hr; 209 ft^2	n/a	n/a	1,855.32
Upgrade of Natural Gas Furnace; None to 80% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation	8	38.29 kBTU/hr; 209 ft^2	n/a	n/a	1,846.54
Upgrade of Natural Gas Furnace; None to 80% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation	9	38.29 kBTU/hr; 209 ft^2	n/a	n/a	1,951.04
Upgrade of Natural Gas Furnace; None to 90% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation	10	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,221.78
Upgrade of Natural Gas Furnace; None to 90% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation	11	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,326.28
Upgrade of Natural Gas Furnace; None to 98% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation	12	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,355.80
Upgrade of Natural Gas Furnace; None to 98% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation	13	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,460.30

*All available natural gas furnace options were selected. For ducting, 30% leakage and non-insulated ducts were available, but were not selected due to their lower efficiencies.

**The value for heating demand of 38.29 kBTU/hr was determined with BeOpt.
***The value of 209 square feet of ducting surface was calculated by multiplying the circumference of the ducting (8” diameter, 25.1” or 2.09’ circumference) by the linear feet of ducting (100’).

Table C9. NG Capital Costs: Houck and Eagle & Personal Communication

Description	Index	Cost Including Local Sales Tax, Overhead and Profit/Total Cost ($)				Source
		Mat.	Lab.	Eq.	Tot.	
Gas Stove-Natural Gas, B Vent; 65% efficient; *Assumed 60 kBTU/hr*	14	n/a	n/a	n/a	3,400.00	(Houck and Eagle, 2006)
Gas Stove-Natural Gas, Direct Vent; 75% efficient; *Assumed 60 kBTU/hr*	15	n/a	n/a	n/a	3,400.00	(Houck and Eagle, 2006)
Natural Gas Furnace (Assume 80% efficient; *Assumed 60 kBTU/hr*	16	n/a	n/a	n/a	3,000.00	(Personal Communication, 2015a)

Table C10. NG Recurring Costs and Assumptions

Description	Value	Unit	Source
Natural Gas Utility Cost	0.257	$/therm	(Navajo Tribal Utility Authority, 2014)
Electricity Cost	0.0740	$ per kilowatt-hour ($/kWh)	(Navajo Tribal Utility Authority, 2014)
Lifespan of Natural Gas Furnace	18	Years	(Houck and Eagle, 2006)
Natural Gas Furnace Inspection Cost	150.00	$	(Franklin, 2000)
Natural Gas Furnace Inspection Frequency	1	1/year	(Franklin, 2000)

8.1.2.5 PG: Propane Gas Furnace

Propane gas furnace capital costs were determined using the same protocol as with natural gas furnace capital costs, since the same furnace and ducting are used, with the addition of tank and yardline installation (Personal Communication, 2013a).Propane gas furnace line-items and capital costs from RSMeans are shown in Table C11, furnaces and capital costs from Home Depot and in addition to RSMeans labor estimates are shown in Table C12. NREL options in addition to tank and yardline cost are shown in Table C13. Houck and Eagle and personal communication value are in Table C14. Recurring costs and assumptions for propane gas furnace use are shown in Table C15.

Table C11. PG Capital Costs: RSMeans and Personal Communication

Description	Index	Unit/ Quantity	Cost Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Furnace, gas or oil, under 120 MBH, selective demolition	n/a	*Each*	*0.00*	*153.18*	*0.00*	*153.18*
		1	0.00	153.18	0.00	153.18
Furnace, gas, upflow, direct drive model, intermittent pilot, 75 MBH input, AGA certified, includes standard controls, excludes gas, oil or flue piping	n/a	*Each*	*636.27*	*169.69*	*0.00*	*805.96*
		1	636.27	169.69	0.00	805.96
Ductwork, flexible coated fiberglass fabric on corrosion resistant metal helix, insulated, P.E. jacket, 1" thick, 8" diameter, pressure to 12"(WG) UL-181	n/a	*Linear feet*	*3.84*	*3.23*	*0.00*	*7.07*
		100	384.00	323.00	0.00	707.00
Index/Total	17	n/a	1,020.27	645.87/ 1,490.87*	0.00	2,511.14

*Labor cost ($1,490.87) from sum of RSMeans 2015 average ($645.87; Table C11) and tank and yardline cost ($845.00).

Table C12. PG Capital Costs: Home Depot, RSMeans, and Personal Communication

Description	Index	Cost Including Local Sales Tax/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Individual Components (Tank and yardline from Personal Communication)					
Propane Gas Tank and Yardline Installation (includes materials)	n/a	n/a	845.00		n/a
Total Installation (Furnace and duct materials from Home Depot; labor including tank and yardline from RSMeans and Personal Communication)					
Furnace: Winchester 60 kBTU/hr 80.0% Efficient; Duct: Insulated, R-6, 8” diameter, 100’, Master Flow; Tank and Yardline	18	943.49	1,490.87*	n/a	2434.36
Furnace: Winchester 60 kBTU/hr 80.0% Efficient); Duct, Insulated, R-8, 8” diameter, 100’, Master Flow; Tank and Yardline	19	1,005.32	1,490.87*	n/a	2496.19
Furnace: Winchester 80 kBTU/hr 95.5% Efficient; Duct: Insulated, R-6, 8” diameter, 100’, Master Flow; Tank and Yardline	20	1,533.09	1,490.87*	n/a	3,023.96
Furnace: Winchester 80 kBTU/hr 95.5% Efficient; Duct, Insulated, R-8, 8” diameter, 100’, Master Flow; Tank and Yardline	21	1,594.92	1,490.87*	n/a	3,085.79

*Labor cost ($1,490.87) from sum of RSMeans 2015 average ($645.87; Table C11) and tank and yardline cost ($845.00).

Table C13. PG Capital Costs: NREL and Personal Communication

Description*	Index	Unit/ Quantity	Total Cost ($) Low Estimate	High Estimate	Average
Individual Components (Furnace and duct from NREL;, tank, and yardline from Personal Communication)					
Upgrade of Propane Gas Furnace; None to 78% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*6.30* 241.23	*12.00* 459.48	9.15 350.36
Upgrade of Propane Gas Furnace; None to 80% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*8.40* 321.64	*16.00* 612.64	12.20 467.14
Upgrade of Propane Gas Furnace; None to 82% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*10.00* 382.90	*21.00* 804.09	15.50 593.50
Upgrade of Propane Gas Furnace; None to 90% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*19.00* 727.51	*37.00* 1,416.73	28.00 1,072.12
Upgrade of Propane Gas Furnace; None to 92% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*21.00* 804.09	*41.00* 1,569.89	31.00 1,186.99
Upgrade of Propane Gas Furnace; None to 94% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*23.00* 880.67	*45.00* 1,723.05	34.00 1,301.86
Upgrade of Propane Gas Furnace; None to 98% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*25.00* 957.25	*49.00* 1,876.21	37.00 1,416.73
Installation of Ducts; None to 15% leakage with R6 duct insulation	n/a	*Square feet duct surface* 209***	*5.50* 1,149.50	*7.70* 1,609.30	6.60 1,379.40
Installation of Ducts; None to 7.5% leakage with R8 duct insulation	n/a	*Square feet duct surface* 209***	*5.80* 1,212.20	*8.40* 1,755.60	7.10 1,483.90
Propane Gas Tank and Yardline Installation including Materials	n/a	1	n/a	n/a	845.00
Total Installation (Furnace and duct costs from NREL; tank and yardline costs from Personal Communication)					
Upgrade of Propane Gas Furnace; None to 78% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation; Tank and yardline	22	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,574.76
Upgrade of Propane Gas Furnace; None to 78% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation; Tank and yardline	23	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,679.26
Upgrade of Propane Gas Furnace; None to 80% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation; Tank and yardline	24	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,691.54
Upgrade of Propane Gas Furnace; None to 80% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation; Tank and yardline	25	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,796.04
Upgrade of Propane Gas Furnace; None to 82% Efficient Furnace; Installation of	26	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,817.90

Ducts; None to 15% leakage with R6 duct insulation; Tank and yardline					
Upgrade of Propane Gas Furnace; None to 82% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation; Tank and yardline	27	38.29 kBTU/hr; 209 ft^2	n/a	n/a	2,922.40
Upgrade of Propane Gas Furnace; None to 90% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation; Tank and yardline	28	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,296.52
Upgrade of Propane Gas Furnace; None to 90% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation; Tank and yardline	29	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,401.02
Upgrade of Propane Gas Furnace; None to 92% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation; Tank and yardline	30	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,411.39
Upgrade of Propane Gas Furnace; None to 92% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation; Tank and yardline	31	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,515.89
Upgrade of Propane Gas Furnace; None to 94% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation; Tank and yardline	32	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,526.26
Upgrade of Propane Gas Furnace; None to 94% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation; Tank and yardline	33	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,630.76
Upgrade of Propane Gas Furnace; None to 98% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation; Tank and yardline	34	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,641.13
Upgrade of Propane Gas Furnace; None to 98% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation; Tank and yardline	35	38.29 kBTU/hr; 209 ft^2	n/a	n/a	3,745.63

*All available propane gas furnace options were selected. For ducting, 30% leakage and non-insulated ducts were available, but were not selected.

**The value for heating demand of 38.29 kBTU/hr was determined with BeOpt.

***The value of 209 square feet of ducting surface was calculated by multiplying the circumference of the ducting (8” diameter, 25.1” or 2.09’ circumference) by the linear feet of ducting (100’).

Table C14. PG Capital Costs: Houck and Eagle and Personal Communication

Description	Index	Cost Including Local Sales Tax, Overhead and Profit/Total Cost ($)*				Source
		Mat.	Lab.	Eq.	Tot.	
Gas Stove-LPG, B Vent; 65% efficient; *Assumed 60 kBTU/hr*	36	n/a	n/a	n/a	3,367.00	(Houck and Eagle, 2006)
Gas Stove-LPG, B Vent; 75% efficient; *Assumed 60 kBTU/hr*	37	n/a	n/a	n/a	3,367.00	(Houck and Eagle, 2006)
Propane Gas Furnace ; *Assumed 60 kBTU/hr and 80% efficient*	38	n/a	n/a	n/a	3,000.00	(Personal Communication, 2015a)

Table C15. PG Recurring Costs and Assumptions

Description	Value	Unit	Source
Propane Gas Cost 1	1.80	$/gal	(Personal Communication, 2015b)
Propane Gas Cost 2	2.94	$/gal	(Personal Communication, 2013b)
Average Propane Gas Costs 1 and 2	2.37	$/gal	*Calculation*
Propane Gas Tank Rental Cost	75.00	$/year	(Personal Communication, 2013a)
Electricity Cost	0.0740	$ per kilowatt-hour ($/kWh)	(Navajo Tribal Utility Authority, 2014)
Lifespan of Propane Gas Furnace	18	Years	(Houck and Eagle, 2006)
Propane Gas Furnace Inspection Cost	150.00	$	(Franklin, 2000)
Propane Gas Furnace Inspection Frequency	1	1/year	(Franklin, 2000)

8.1.2.6 EH: Electrical Heating

Capital costs of an electric furnace retrofit were determined using RSMeans, the Home Depot catalog, estimates from NREL as well as from local vendors. RSMeans line-item searches were performed using the keywords “electric”, “electrical”, “furnace”, “stove”, and “duct” and the items selected and their costs are shown in Table C16. Furnace selective demolition was used to estimate the cost of removal of the old wood stove (wood stove selective demolition was not available). The 34.1 MBH furnace was the only residential electric furnace option available though the heating load for the baseline home estimated using BeOpt was 38.3 MBH (kBTU/hr), 12% higher than the furnace heat capacity. Installation of insulated 8” ducting was assumed and the value of 100 linear feet of ducting was derived from a case-study of a larger home (US DOE, 2012) by assuming that length of ducting correlates linearly with home size. Electric heating capital costs from the Home Depot catalog are shown in Table C17. Electrical furnaces chosen from the catalog range between 49.1 and 81.9 MBH, sufficient for the heating load estimated by BeOpt. Electric furnace options from NREL are listed in Table C18, and from personal communication in Table C19. Electrical heating recurring costs and assumptions are shown in Table C20.

Table C16. EH Capital Costs: RSMeans

Description	Index	Unit/ Quantity	Cost Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Furnace, gas or oil, under 120 MBH, selective demolition	n/a	*Each*	*0.00*	*153.18*	*0.00*	*153.18*
		1	0.00	153.18	0.00	153.18
Furnace, hot air heating, blowers, electric, 34.1 MBH, U.L. listed, includes standard controls, excludes gas, oil or flue piping	n/a	*Each*	*501.00*	*175.87*	*0.00*	*676.87*
		1	501.00	175.87	0.00	676.87
Ductwork, flexible coated fiberglass fabric on corrosion resistant metal helix, insulated, P.E. jacket, 1" thick, 8" diameter, pressure to 12"(WG) UL-181	n/a	*Linear feet*	*3.84*	*3.23*	*0.00*	*7.07*
		100	384.00	323.00	0.00	707.00
Index/Total	39	n/a	885.00	652.05	0.00	1,537.05

Table C17. EH Capital Costs: Home Depot and RSMeans

Description	Index	Cost Including Local Sales Tax/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Furnace: Winchester WMA36-15 49,147 BTU 15 kW); Duct, Insulated, R-6, 8" diameter, 100', Master Flow	40	889.89	652.05*	0.00	1,541.94
Furnace: Winchester WMA36-15 49.147 kBTU/hr 15 kW; Duct: Insulated, R-8, 8" diameter, 100', Master Flow	41	951.72	652.05*	0.00	1,603.77
Furnace: Winchester WMA60-25 81.912 kBTU/hr 25 kW; Duct: Insulated, R-6, 8" diameter, 100', Master Flow	42	1,211.49	652.05*	0.00	1,863.54
Furnace: Winchester WMA60-25 81.912 BTU 25 kW; Duct: Insulated, R-8, 8" diameter, 100', Master Flow	43	1,273.32	652.05*	0.00	1,925.37

*Labor cost from RSMeans (Table C17).

Table C18. EH Capital Costs: NREL

Description*	Index	Unit/ Quantity	Total Cost ($)		
			Low Estimate	High Estimate	Average
Individual Components (Furnace and duct)					
Upgrade of Electric Furnace; None to Electric 100% Efficient Furnace	n/a	*kBTU/hr* 38.29**	*36.00* 1,378.44	*71.00* 2,718.59	*53.50* 2,048.52
Installation of Ducts; None to 15% leakage with R6 duct insulation	n/a	*Square feet duct surface* 209***	*5.50* 1,149.50	*7.70* 1,609.30	*6.60* 1,379.40
Installation of Ducts; None to 7.5% leakage with R8 duct insulation	n/a	*Square feet duct surface* 209***	*5.80* 1,212.20	*8.40* 1,755.60	*7.10* 1,483.90
Total Installation (Furnace and duct)					
Upgrade of Electric Furnace; None to Electric 100% Efficient Furnace; Installation of Ducts; None to 15% leakage with R6 duct insulation	44	n/a	n/a	n/a	3,427.92
Upgrade of Electric Furnace; None to Electric 100% Efficient Furnace; Installation of Ducts; None to 7.5% leakage with R8 duct insulation	45	n/a	n/a	n/a	3,532.42

*There was only one available electric furnace option. For ducting, 30% leakage and non-insulated ducts were available, but were not selected.
**The value for heating demand of 38.29 kBTU/hr was determined with BeOpt.
***The value of 209 square feet of ducting surface was calculated by multiplying the circumference of the ducting (8" diameter, 25.1" or 2.09' circumference) by the linear feet of ducting (100').

Table C19. EH Capital Costs: Personal Communication

Description	Index	Cost Including Local Sales Tax, Overhead and Profit/Total Cost ($)				Source
		Mat.	Lab.	Eq.	Tot.	
Electric Furnace *Assumed 49,147 kBTU/hr 15 kW*	46	n/a	n/a	n/a	3,000.00	(Personal Communication, 2015a)

Table C20. EH Recurring Costs and Assumptions

Description	Value	Unit	Source
Electricity Cost	0.0656	$ per kilowatt-hour ($/kWh)	(Navajo Tribal Utility Authority, 2014)
Lifespan of Electric Furnace*	18	Years	(Houck and Eagle, 2006)
Electric Furnace Inspection Cost*	100.00	$	(Franklin, 2000)
Electric Furnace Inspection Frequency*	1	1/year	(Franklin, 2000)

*Assumed to be same as gas furnace.

8.1.2.7 WP: Wood Pellet Stove

Capital costs of wood pellet stove retrofit were determined using RSMeans 2015, the Home Depot catalog, and the BurnWise program. RSMeans line-item searches were performed using the keywords “wood”, “pellet”, “stove” and “flue” and the items selected and their costs are shown in Table C21. Furnace selective demolition option was chosen to estimate the cost of removal of the old wood stove (wood stove selective demolition was not available). Unfortunately there were no appropriate wood pellet stove (or wood stove) options available in RSMeans, as the only solid-fuel heating options available were centralized wood burning furnaces with a minimum furnace cost of $4,308 (not including overhead and profit). Labor costs for installation of a wood pellet stove were however derived from the installation of a centralized wood burning furnace. The smoke pipe kit was chosen to represent replacement of the current flue. Selected low and high cost wood pellet stoves from the Home Depot catalog and estimated average installation costs from the USEPA BurnWise program and RSMeans are shown in Table C22. The heating load for the baseline home estimated using BeOpt was 38.3 MBH (kBTU/hr), and wood pellet stoves chosen from the Home Depot catalog range between 35.0 and 50.0 MBH. Wood pellet stove total costs from Houck and Eagle are shown in Table C23. Wood pellet stove recurring costs and assumptions are shown in Table C24.

Table C21. WP Labor: RSMeans

Description	Index	Unit/ Quantity	Cost Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Furnace, gas or oil, under 120 MBH, selective demolition	n/a	*Each* 1	*0.00* 0.00	*153.18* 153.18	*0.00* 0.00	*153.18* 153.18
Furnaces, solid fuel fired, hot air heating, blowers, wood fired, 24" long firebox, includes hot water coil, thermostat and auto draft control, excludes gas, oil or flue piping	n/a	*Each* 1	*n/a** n/a*	*169.69* 169.69	*0.00* 0.00	*169.69* 169.69
Furnaces, solid fuel fired, wood fired hot water furnace, optional accessory, smoke pipe kit	n/a	*Each* 1	*n/a** n/a*	*152.51* 152.51	*0.00* 0.00	*152.51* 152.51
Total	n/a	n/a	0.00	475.38	0.00	475.38

*Only the labor costs for solid fuel furnace install was derived from the available RSMeans data, in the attempt to compile complete labor costs (ie. not missing components of required labor).

Table C22. WP Capital Costs: BurnWise, RSMeans, and Home Depot

Description	Index	Cost Including Local Sales Tax/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Retrofit labor from Burnwise and RSMeans					
Burnwise; Low Estimated Wood Pellet Stove Installation Cost**	n/a	n/a	600.00		n/a
Burnwise; High Estimated Wood Pellet Stove Installation Cost**	n/a	n/a	1,200.00		n/a
RSMeans; Stove demolition, stove install, flue install	n/a	n/a	475.38		n/a
Average Estimated Wood Pellet Stove Installation Cost (from above 3)	n/a	n/a	758.46		n/a
Flue material from Home Depot					
Flue: Double-walled PelletVent, 3” diameter x 72” length	n/a	114.55	n/a	n/a	n/a
Total Installation (Stove and flue from Home Depot, and labor from Burnwise and RSMeans)					
Stove: Pleasant Hearth PH35PS 35 kBTU/hr 68% efficient; Flue: Double-walled PelletVent, 3” diameter x 72” length	47	1,293.75	758.46*	n/a	2,052.21
Stove: Pleasant Hearth PH50CABPS 50 kBTU/hr 68% Efficient; Flue: Double-walled PelletVent, 3” diameter x 72” length	48	1,829.75	758.46*	n/a	2,588.21
Stove: MF3800 45 kBTU/hr 68% Efficient; Flue: Double-walled PelletVent, 3” diameter x 72” length	49	1,814.55	758.46*	n/a	2,573.01
Stove: Classic Bay 1200 47.3 kBTU/hr 68% efficient; Flue: Double-walled PelletVent, 3” diameter x 72” length	50	2,713.55	758.46*	n/a	3,472.01

**Assumed to be same as installation cost of new USEPA-certified wood stove.

Table C23. WP Capital Costs: Houck and Eagle

Description	Index	Cost Including Local Sales Tax, Overhead and Profit/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Pellet Stove; Assumed 35,000 kBTU/hr 68% efficient	51	n/a	n/a	n/a	3,850.00

Table C24. WP Recurring Costs and Assumptions

Description	Value	Unit	Source
Electricity Cost	0.0740	$ per kilowatt-hour ($/kWh)	(Navajo Tribal Utility Authority, 2014)
Pellet Fuel Cost	257.28	$/ton	(Home Depot, 2014)
Lifespan of Pellet Stove	15	Years	(Houck and Eagle, 2006)
Pellet Stove Chimney Cleaning Cost*	125.00	$	(Houck and Eagle, 2006)
Pellet Stove Chimney Cleaning Frequency*	1	1/year	(Houck and Eagle, 2006)

*Assumed to be same as for USEPA-certified wood stove.

8.1.2.8 SI: Wood Stove Improvement

Capital costs of wood stove improvement were determined using RSMeans. Line-item searches were performed using the keywords “wood”, “stove”, “flue” and “piping” and the items chosen are shown in Table C25. The smoke pipe kit was chosen to represent replacement of the current flue. While clay flue lining was available, this option was not chosen as the sizes available (smallest was 8”x12” flue) were deemed inappropriate. Wood stove repair cost using material costs from Home Depot and labor costs from RSMeans is shown in Table C26. Wood stove repair recurring costs and assumptions are shown in Table C27. Annual wood fuel costs are lower with the improved Navajo wood stove due to the increased efficiency compared to the conventional Navajo wood stove.

Table C25. SI Capital Costs: RSMeans

Description	Index	Unit/ Quantity	Cost Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Furnaces, solid fuel fired, wood fired hot water furnace, optional accessory, smoke pipe kit	52	*Each*	*97.19*	*152.51*	*0.00*	*249.70*
		1	97.19	152.51	0.00	249.70

Table C26. SI Capital Costs: Home Depot and RSMeans

Description	Index	Cost Including Local Sales Tax/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Flue: Double-walled PelletVent, 3" diameter x 72" length	53	114.55	152.51*	0.00	267.06

*Labor cost from RSMeans (Table C25).

Table C27. SI Recurring Costs and Assumptions

Assumption	Value	Unit	Source
Lifespan of wood stove repair materials*	20	Years	(Berry et al., 1997)
Firewood cost	50.00	$/air-dried-cord	(Personal Communication, 2014)
Annual firewood cost, Typical Home	289.59	$/year	*Calculation*
Annual firewood cost, Typical Home with improved Navajo wood stove	241.33	$/year	*Calculation*
Wood stove chimney cleaning cost**	150.00	$	(Houck and Eagle, 2006)
Wood stove chimney cleaning frequency**	1	1/year	(Houck and Eagle, 2006)

*Assumed to be same as for weatherization materials.
**Home with improved Navajo stove assumes same chimney cleaning cost and frequency as home with EPA-certified stove.

8.1.2.9 SR: Wood Stove Replacement

Wood stove replacement capital costs were determined using RSMeans, the Home Depot catalog, and the BurnWise program. RSMeans line-item searches were performed using the keywords “wood”, “stove”, “furnace” and “flue” and the items selected and their costs are shown in Table C28 (these are the same line-items selected for wood pellet stove). Furnace selective demolition option was chosen to estimate the cost of removal of the old wood stove (wood stove selective demolition was not available). Unfortunately there were no appropriate wood stove options available in RSMeans, as the only solid-fuel heating options available were centralized wood burning furnaces with a minimum furnace cost of $4,308 (not including overhead and profit). Labor costs for installation of a wood stove were however derived from the installation of a centralized wood burning furnace. The smoke pipe kit was chosen to represent replacement of the current flue. Selected low and high cost USEPA-certified wood stoves from the Home Depot catalog and average estimated installation costs from the USEPA BurnWise program and RSMeans are shown in Table C29. The heating load for the baseline home estimated using BeOpt was 38.3 MBH (kBTU/hr), and USEPA-certified wood stoves chosen from the Home Depot catalog range between 89.0 and 112.0 MBH; smaller heating capacity stoves were unavailable. Wood stove replacement costs from Houck and Eagle are shown in Table C30. Wood stove replacement recurring costs and assumptions are shown in Table C31

Table C28. SR Capital Costs: RSMeans

Description	Index	Unit/ Quantity	Cost Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Furnace, gas or oil, under 120 MBH, selective demolition	n/a	*Each* 1	*0.00* 0.00	*153.18* 153.18	*0.00* 0.00	*153.18* 153.18
Furnaces, solid fuel fired, hot air heating, blowers, wood fired, 24" long firebox, includes hot water coil, thermostat and auto draft control, excludes gas, oil or flue piping	*n/a*	*Each* 1	*n/a** n/a*	*169.69* 169.69	*0.00* 0.00	*169.69* 169.69
Furnaces, solid fuel fired, wood fired hot water furnace, optional accessory, smoke pipe kit	n/a	*Each* 1	*n/a** n/a*	*152.51* 152.51	*0.00* 0.00	*152.51* 152.51
Total	n/a	n/a	0.00	475.38	0.00	0.00

*Only the labor costs for solid fuel furnace was derived from the available RSMeans data, in the attempt to compile complete labor costs (ie. not missing components of required labor).

Table C29. SR Capital Costs: Home Depot, BurnWise, and Personal Communication

Description	Index	Cost Including Local Sales Tax/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Retrofit labor from Burnwise and RSMeans					
Burnwise; Low Estimated USEPA-certified Wood Stove Installation Cost	n/a	n/a	600.00	n/a	n/a
Burnwise; High Estimated USEPA-certified Wood Stove Installation Cost	n/a	n/a	1,200.00	n/a	n/a
RSMeans; Stove demolition, stove install, flue install	n/a	n/a	475.38	n/a	n/a
Average Estimated Wood Pellet Stove Installation Cost (from above 3)	n/a	n/a	758.46	n/a	n/a
Flue material from Home Depot					
Flue: Double-walled PelletVent, 3" diameter x 72" length	n/a	114.55	n/a	n/a	n/a
Total Installation (Stove and flue from Home Depot, and labor from Burnwise and RSMeans)					
Stove: USEPA-certified US Stove Model 2000 89 kBTU/hr; Flue: Double-walled PelletVent, 3" diameter x 72" length	54	1,007.68	758.46	0.00	1,766.14
Stove: USEPA-certified US Stove Model 2500 112 kBTU/hr; Flue: Double-walled PelletVent, 3" diameter x 72" length	55	1,393.60	758.46	0.00	2,152.06
Stove: USEPA-certified Princess Model 1006 40 kBTU/hr; Flue: Double-walled PelletVent, 3" diameter x 72" length	56	2,300.00	758.46	0.00	3,058.46
Stove: USEPA-certified Royal Guardian Model 40.7 kBTU/hr; Flue: Double-walled PelletVent, 3" diameter x 72" length	57	1,599.00	758.46	0.00	2,357.46
Stove: USEPA-certified WS22 55.6 kBTU/hr; Flue: Double-walled PelletVent, 3" diameter x 72" length	58	1,449.00	758.46	0.00	2,207.46
Stove: USEPA-certified Step Top Series 56 kBTU/hr; Flue: Double-walled PelletVent, 3" diameter x 72" length	59	2,567.00	758.46	0.00	3,325.46

Table C30. SR Capital Costs: Houck and Eagle

Description	Index	Cost Including Local Sales Tax, Overhead and Profit/Total Cost ($)			
		Mat.	Lab.	Eq.	Tot.
Certified NSPS Non-Catalytic Cordwood Stove; *Assumed 89 kBTU/hr*	60	n/a	n/a	n/a	3,367.00

Table C31. SR Recurring Costs and Assumptions

Description	Value	Unit	Source
Electricity Cost	0.0740	$ per kilowatt-hour ($/kWh)	(Navajo Tribal Utility Authority, 2014)
Wood cost	50.00	$/air-dried-cord	(Personal Communication, 2014)
Lifespan of USEPA-certified Wood Stove	19	Years	(Houck and Eagle, 2006)
USEPA-certified Wood Stove Chimney Cleaning Cost	150.00	$	(Houck and Eagle, 2006)
USEPA-certified Wood Stove Chimney Cleaning Frequency	1	1/year	(Houck and Eagle, 2006)

8.1.2.10 PS: Passive Solar Heating

Passive solar heating retrofit capital costs were determined using RSMeans for both direct gain and Trombe wall options, and NREL for direct gain only. BeOpt cost estimates were not available for either option. Optimization results from BeOpt guided the selection of RSMeans line-items for the direct gain option. Specifically the window area (10.0% was preferred by BeOpt during optimization over 12.0% and 15.0%), and choice of single-pane glass (preferred over double-pane by BeOpt) for the low-cost direct gain option. The low-cost direct gain option includes removal of old attic insulation and installation of higher R-value attic insulation, and the addition of new single-pane windows and overhangs to the southern side of the home. The high-cost direct gain option includes removal of old attic insulation and installation of higher R-value attic insulation, the removal of old single-pane windows, and the installation of new double-pane windows in both the old locations and additionally to the southern side of the home (including overhangs on the southern side). In the passive solar Navajo home, continued use of the conventional Navajo wood stove is assumed, as to highlight the costs and benefits of passive solar only. It is important to note that continued use of a dirty stove in a weatherized home is not recommended.

RSMeans line-item searches were performed using the keywords “window”, “windows”, “insulation”, “overhang”, and “weatherstripping” for the direct gain option, and “concrete”, “curing”, “paint”, “caulking”, “wood”, “framing”, “window”, and “glass” for the Trombe Wall option. The items selected and their costs are shown in Tables C32 (includes estimate from personal communication) and C33 for the single-pane window direct gain options, and Table C34 and C35 for the double-pane window options. Assumptions and calculations relevant to the single and double pane window direct gain options are shown in Table C36. Costs for the four different Trombe wall options are shown in Tables C37 - C40. Assumptions and calculations relevant to the single and double pane window direct gain options are shown in Table C41. Passive solar recurring costs and assumptions are listed in Table C42.

Table C32. PS Low-cost Single-pane Direct Gain Capital Costs: RSMeans and Personal Communication

Description	Index	Unit/ Quantity*	Cost Per Unit Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Selective demolition, thermal and moisture protection, insulation, foamed or sprayed	n/a	*Board feet*	*0.00*	*0.49*	*0.00*	*0.49*
		1000[1]	0.00	490.00	0.00	490.00
Fiberglass insulation, ceilings, with open access, 20" thick, R49, blown-in	n/a	*Square feet*	*0.94*	*0.73*	*exc.*	*1.67*
		1000[2]	940.00	730.00	exc.	1,670.00
Window install, material and labors; *Assumed single-pane 3’x5’****	n/a	*Each*	*500.00*			*500.00*
		4[3]	2000.00			2,000.00
Index/Total	61	n/a	2,940.00	1,220.00	0.00	4,160.00

*Superscripts correspond to values in Table C36.

Table C33. Passive Solar High-cost Single-pane Direct Gain Capital Costs: RSMeans

Description	Index	Unit/ Quantity*	Cost Per Unit Including Overhead and Profit/Total Cost ($)			
			Mat.	Lab.	Eq.	Tot.
Selective demolition, thermal and moisture protection, insulation, foamed or sprayed	n/a	*Board feet*	*0.00*	*0.49*	*0.00*	0.49
		1000[1]	0.00	490.00	0.00	490.00
Fiberglass insulation, ceilings, with open access, 20" thick, R49, blown-in	n/a	*Square feet*	*0.94*	*0.73*	*0.53*	2.20
		1000[2]	940.00	730.00	exc.	1,670.00
Windows, aluminum, commercial grade, stock units, sliding, standard glass, 5'-0" x 3'-0" opening, incl. frame and glazing	n/a	*Each*	*378.14*	*79.89*	*0.00*	458.03
		4[3]	1,512.56	319.56	0.00	1,832.12
Windows, solid vinyl replacement, silicone caulking at perimeter	n/a	*Linear feet*	*0.19*	*0.37*	*0.00*	0.56
		128[4]	24.32	47.36	0.00	71.68
Weatherstripping, window, double hung, zinc, for 3' x 5' window	n/a	*Opening*	*22.79*	*41.64*	*0.00*	64.43
		8[5]	182.32	333.12	0.00	515.44
Index/Total	62	n/a	2,659.20	1,920.04	0.00	4,579.24

*Superscripts correspond to values in Table C36.

Table C34. Passive Solar Low-cost Double-pane Direct Gain Capital Costs: NREL

Description*	Index	Unit/ Quantity**	Total Cost ($)		
			Low Estimate	High Estimate	Average
Upgrade of Attic Insulation; R11 Fiberglass Vented to R49 Fiberglass Vented	n/a	*Square feet ceiling*	*1.20*	*2.50*	1.85
		1000[1]	1,200.00	2,500.00	1,850.00
Double-Pane, Clear, Metal Frame, Air Fill	n/a	*Square feet window*	*21.00*	*41.00*	31.00
		60[7]	1,260.00	2,460.00	1,860.00
Index/Total	63	n/a	n/a	n/a	3,710.00

*The lowest R-value option (R11) of existing attic insulation was chosen. Additional upgrade options included R19, R21, and R25 fiberglass, and numerous R-value cellulose and closed spray foam options.
**Superscripts correspond to values in Table C36.

Table C35. Passive Solar High-cost Double-pane Direct Gain Capital Costs: RSMeans

Description	Index	Unit/ Quantity*	Cost Per Unit Including Overhead and Profit/Total Cost ($) Mat.	Lab.	Eq.	Tot.
Window demolition, wood, to 25 S.F., remove old window	*n/a*	*Each*	*0.00*	*12.36*	*0.00*	*12.36*
		4[6]	0.00	49.44	0.00	49.44
Selective demolition, thermal and moisture protection, insulation, foamed or sprayed	*n/a*	*Board feet*	*0.00*	*0.49*	*0.00*	*0.49*
		1000[1]	0.00	490.00	0.00	490.00
Fiberglass insulation, ceilings, with open access, 20" thick, R49, blown-in	*n/a*	*Square feet*	*0.94*	*0.73*	*n/a*	*1.67*
		1000[2]	940.00	730.00	n/a	1,670.00
Windows, wood, double hung, vinyl clad, premium, double insulated glass, 3'-0" x 5'-0" high, incl. frame, screens and grilles	*n/a*	*Each*	*502.46*	*37.24*	*0.00*	*539.70*
		8[5]	4,019.68	297.92	0.00	4,317.60
Windows, solid vinyl replacement, silicone caulking at perimeter	*n/a*	*Linear feet*	*0.19*	*0.37*	*0.00*	*0.56*
		128[4]	24.32	47.36	0.00	71.68
Weatherstripping, window, double hung, zinc, for 3' x 5' window	*n/a*	*Opening*	*22.79*	*41.64*	*0.00*	*64.43*
		8[5]	182.32	333.12	0.00	515.44
Index/Total	64	n/a	5,166.32	1,947.84	0.00	7,114.16

*Superscripts correspond to values in Table C36.

Table C36. Home Assumptions and Calculations for Passive Solar Direct Gain

Home Characteristic	Quantity	Unit	Superscript from Table C23	Calculation (if applicable)
Home length (L)	50	Linear feet	n/a	n/a
Home width (W)	20	Linear feet	n/a	n/a
Home height (H)	8	Linear feet	n/a	n/a
Home area (A_H)	1000	Square feet	2	$A_H = L*W$
Exterior wall area (A_E)	1,120	Square feet	n/a	$A_E = (2L+2W)*H$
Fractional total window area of baseline home (f_W)*	0.05	Unitless	n/a	n/a
Fractional total window area of direct gain home ($f_{W,dir}$)**	0.10	Unitless	n/a	n/a
Total window area of baseline home (A_W)	56	Square feet	n/a	$A_W = A_E*f_W$
Total window area of baseline home ($A_{W,Direct}$)	112	Square feet	n/a	$A_{W,dir} = A_E*f_{W,dir}$
Number of windows of baseline home (N_W)	4	# windows	6	n/a
Number of windows of direct gain home ($N_{W,dir}$)	8	# windows	5	n/a
Number of windows added to direct gain home ($N_{W,diradd}$)	4	# windows	3	$N_{W,diradd} = N_{W,dir}-N_W$
Window height (H_W)	3	Linear feet	n/a	n/a
Window width (W_W)	5	Linear feet	n/a	n/a
Total window area estimate for baseline home ($A_{W,est}$)***	60	Square feet	7	$A_{W,est} = N_W*(H_W*W_W)$
Total window area estimate for direct gain home ($A_{W,est,dir}$)***	120	Square feet	n/a	$A_{W,est,dir} = N_{W,dir}*(H_W*W_W)$
Assumed baseline insulation thickness (D_{ins})	1	Linear inch	n/a	n/a
Quantity of insulation removed from baseline home ($V_{ins,rem}$)	1000	Board feet	1	$V_{ins,rem} = A_H*D_{ins}$
Total window perimeter of direct gain home ($P_{W,dir}$)	128	Linear feet	4	$P_{W,dir} = N_{W,dir}*(2H_W+2W_W)$

*An important assumption used in BeOpt determined from personal communication with community members after brief characterization of Shiprock home exteriors.
**Determined from BeOpt Optimization with Window Area options of 7.0, 10.0, 12.0, and 15.0%.
***It was necessary to assume a number of windows (3'x'5) to determine window perimeter. With these nominally sized windows (3'x5'), the value of $A_{w,est}$ and $A_{w,est,dir}$ were 7.1% higher than A_W and $A_{W,dir}$ (BeOpt inputs) and deemed acceptable.

Table C37. Passive Solar Low-cost Adobe Trombe Wall Capital Costs: RSMeans and Home Depot

Description	Unit/ Quantity*	Cost Per Unit Including Overhead and Profit/Total Cost			
		Mat.	Lab.	Eq.	Tot.
*Adobe (materials assumed to be free; labor and equipment assumed to be same as hand mix concrete using gas power mixer option shown in Table C39)***	*Cubic Foot*	*0.00*	*1.71*	*0.00*	*1.71*
	88[1]	0.00	150.48	0.00	150.48
Curing, burlap, 7.5 oz., 4 uses assumed	*Square Foot*	*0.14*	*0.08*	*0.00*	*0.22*
	96[2]	13.44	7.68	0.00	21.12
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, latex, roller	*Square Foot*	*0.10*	*0.17*	*0.00*	*0.27*
	96[2]	9.60	16.32	0.00	25.92
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, waterproof sealer, roller	*Square Foot*	*0.29*	*0.15*	*0.00*	*0.44*
	96[2]	27.84	14.40	0.00	42.24
Joint sealants, caulking and sealants, bulk acrylic latex, 1/2" x 1/2", in place	*Linear Foot*	*0.39*	*1.15*	*0.00*	*1.54*
	62[3]	24.18	71.30	0.00	95.48
Wood framing, partitions, standard & better lumber, 2" x 4" studs, 12" O.C., 8' high, includes single bottom plate and double top plate, excludes waste	*Linear Foot*	*5.20*	*7.25*	*0.00*	*12.45*
	62[3]	322.40	449.50	0.00	771.90
Clear acrylic, 1/8”	*48”x96” sheet*	*105.01****	*n/a*	*n/a*	*n/a*
	3[4]	315.03	96.00****	0.00	411.03
Index/Total	65	712.49	805.68	0.00	1,518.17

*Superscripts correspond to values in Table C41.
**Adobe is readily available and excellent for use as thermal mass, requiring less volume than concrete [6-10” inch recommended thickness (average=8”) for adobe compared to 10-16” (average=13”) recommended thickness for concrete thermal walls] (Lechner, 2008).
***Cost from Home Depot. 1/8” acrylic is comparable to 3/16” glass in terms of solar transmittance (89% vs 84%), infrared transmittance (<5% vs <3%), estimated lifetime (20+ years vs 25+ years); one downside is the maximum temperature of 200°F for acrylic compared to 400°F for the glass (Wilson, 1979).
****Labor cost from RSMeans for 96 sq. ft. 3/16” window glass installation.

Table C38. Passive Solar High-cost Adobe Trombe Wall Capital Costs: RSMeans

Description	Unit/ Quantity*	Cost Per Unit Including Overhead and Profit/Total Cost			
		Mat.	Lab.	Eq.	Tot.
*Adobe (materials assumed to be free; labor and equipment assumed to be same as hand mix concrete using gas power mixer option shown in Table C39)***	*Cubic Foot*	*0.00*	*1.71*	*n/a*	*1.71*
	88[1]	0.00	150.48	n/a	150.48
Curing, burlap, 7.5 oz., 4 uses assumed	*Square Foot*	*0.14*	*0.08*	*0.00*	*0.22*
	96[2]	13.44	7.68	0.00	21.12
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, latex, roller	*Square Foot*	*0.10*	*0.17*	*0.00*	*0.27*
	96[2]	9.60	16.32	0.00	25.92
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, waterproof sealer, roller	*Square Foot*	*0.29*	*0.15*	*0.00*	*0.44*
	96[2]	27.84	14.40	0.00	42.24
Joint sealants, caulking and sealants, bulk acrylic latex, 1/2" x 1/2", in place	*Linear Foot*	*0.39*	*1.15*	*0.00*	*1.54*
	62[3]	24.18	71.30	0.00	95.48
Wood framing, partitions, standard & better lumber, 2" x 4" studs, 12" O.C., 8' high, includes single bottom plate and double top plate, excludes waste	*Linear Foot*	*5.20*	*7.25*	*0.00*	*12.45*
	62[3]	322.40	449.50	0.00	771.90
Window glass, clear float, stops, putty bed, 3/16" thick***	*Square Foot*	*6.40*	*1.00*	*0.00*	*7.40*
	96[2]	614.40	96.00	0.00	710.40
Index/Total	66	1,011.86	805.68	0.00	1,817.54

*Superscripts correspond to values in Table C41.
**Adobe is readily available and excellent for use as thermal mass, requiring less volume than concrete [6-10" inch recommended thickness (average=8") for adobe compared to 10-16" (average=13") recommended thickness for concrete thermal walls] (Lechner, 2008).
***The Trombe wall model utilized (Balcomb and Mcfarland, 1978) assumed double-glazing, but the 3/16" thick flat glass option from RSMeans 2015 was chosen over individual double-pane windows due to the unreasonably high cost of the latter.

Table C39. Passive Solar Low-cost Concrete Trombe Wall Capital Costs: RSMeans

Description	Unit/ Quantity*	Cost Per Unit Including Overhead and Profit/Total Cost			
		Mat.	Lab.	Eq.	Tot.
Concrete, hand mix, for small quantities or remote areas, 3000 psi, using gas powered cement mixer, includes local bulk aggregate & sand, bagged Portland cement (Type I) and water, excludes, forms, reinforcing, placing & finishing	*Cubic Foot*	*3.87*	*1.71*	*n/a*	*5.58*
	144[5]	557.28	246.24	n/a	803.52
Curing, burlap, 7.5 oz., 4 uses assumed	*Square Foot*	*0.14*	*0.08*	*0.00*	*0.22*
	96[2]	13.44	7.68	0.00	21.12
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, latex, roller	*Square Foot*	*0.10*	*0.17*	*0.00*	*0.27*
	96[2]	9.60	16.32	0.00	25.92
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, waterproof sealer, roller	*Square Foot*	*0.29*	*0.15*	*0.00*	*0.44*
	96[2]	27.84	14.40	0.00	42.24
Joint sealants, caulking and sealants, bulk acrylic latex, 1/2" x 1/2", in place	*Linear Foot*	*0.39*	*1.15*	*0.00*	*1.54*
	62[3]	24.18	71.30	0.00	95.48
Wood framing, partitions, standard & better lumber, 2" x 4" studs, 12" O.C., 8' high, includes single bottom plate and double top plate, excludes waste	*Linear Foot*	*5.20*	*7.25*	*0.00*	*12.45*
	62[3]	322.40	449.50	0.00	771.90
Clear acrylic, 1/8”	*48”x96” sheet*	*105.01***	*n/a*	*0.00*	*n/a*
	3[4]	315.03	96.00***	0.00	411.03
Total/Index	67	1,269.77	901.44	0.00	2,171.21

*Superscripts correspond to values in Table C41.
**Cost from Home Depot. 1/8” acrylic is comparable to 3/16” glass in terms of solar transmittance (89% vs 84%), infrared transmittance (<5% vs <3%), estimated lifetime (20+ years vs 25+ years); one downside is the maximum temperature of 200°F for acrylic compared to 400°F for the glass (Wilson, 1979).
***Labor cost from RSMeans for 96 sq. ft. 3/16” window glass installation.

Table C40. Passive Solar High-cost Concrete Trombe Wall Capital Costs: RSMeans

Description	Unit/ Quantity*	Cost Per Unit Including Overhead and Profit/Total Cost			
		Mat.	Lab.	Eq.	Tot.
Concrete, hand mix, for small quantities or remote areas, 3000 psi, using gas powered cement mixer, includes local bulk aggregate & sand, bagged Portland cement (Type I) and water, excludes, forms, reinforcing, placing & finishing	*Cubic Foot*	*3.87*	*1.71*	*exc.*	*5.58*
	144^5	557.28	246.24	exc.	803.52
Curing, burlap, 7.5 oz., 4 uses assumed	*Square Foot*	*0.14*	*0.08*	*0.00*	*0.22*
	96^2	13.44	7.68	0.00	21.12
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, latex, roller	*Square Foot*	*0.10*	*0.17*	*0.00*	*0.27*
	96^2	9.60	16.32	0.00	25.92
Paints & coatings, walls, concrete masonry units (CMU), smooth surface, first coat, waterproof sealer, roller	*Square Foot*	*0.29*	*0.15*	*0.00*	*0.44*
	96^2	27.84	14.40	0.00	42.24
Joint sealants, caulking and sealants, bulk acrylic latex, 1/2" x 1/2", in place	*Linear Foot*	*0.39*	*1.15*	*0.00*	*1.54*
	62^3	24.18	71.30	0.00	95.48
Wood framing, partitions, standard & better lumber, 2" x 4" studs, 12" O.C., 8' high, includes single bottom plate and double top plate, excludes waste	*Linear Foot*	*5.20*	*7.25*	*0.00*	*12.45*
	62^3	322.40	449.50	0.00	771.90
Window glass, clear float, stops, putty bed, 3/16" thick**	*Square Foot*	*6.40*	*1.00*	*0.00*	*7.40*
	96^2	614.40	96.00	0.00	710.40
Total/Index	68	1569.14	901.44	0.00	2,470.58

*Superscripts correspond to values in Table C41.
**The Trombe wall model utilized (Balcomb and Mcfarland, 1978) assumed double-glazing, but the 3/16" thick flat glass option from RSMeans was chosen over individual double-pane windows due to the unreasonably high cost of the latter.

Table C41. Home Assumptions and Calculations for Passive Solar Trombe Wall

Home and Trombe Wall Characteristic	Quantity	Unit	Superscript from Table C23	Calculation (if applicable)
Home Length (L)	50	Linear feet	n/a	n/a
Home Width (W)	20	Linear feet	n/a	n/a
Home Height (H)	8	Linear feet	n/a	n/a
Home Area (A_H)	1000	Square feet	n/a	$A_H = L*W$
Thickness of Trombe Wall Concrete Thermal Wall ($D_{thrm,c}$)	18*	Linear inches	n/a	n/a
Thickness of Trombe Wall Adobe Thermal Wall ($D_{thrm,a}$)	11*	Linear inches	n/a	n/a
Height of Trombe Wall Concrete or Adobe Thermal Wall (H_{thrm})	6**	Linear feet	n/a	n/a
Length of Trombe Wall Concrete or Adobe Thermal Wall (L_{thrm})	16**	Linear feet	n/a	n/a
Volume of Concrete for Trombe Wall Thermal Wall ($V_{thrm,c}$)	144	Cubic feet	5	$V_{thrm,c} = D_{thrm,c}*H_{thrm}*L_{thrm}$
Volume of Adobe for Trombe Wall Thermal Wall ($V_{thrm,a}$)	88	Cubic feet	1	$V_{thrm,a} = D_{thrm,a}*H_{thrm}*L_{thrm}$
Area of Trombe Wall Concrete Thermal Wall and Glazing (A_{thrm})	96	Square feet	2	$A_{thrm} = H_{thrm}*L_{thrm}$
Length of 2”x4” Wood Framing for Trombe Wall Air Space and Glazing (L_{frm})***	62	Linear feet	3	$L_{frm} = 2*L_{thrm} + 5*H_{thrm}$
Width of 2”x4” Wood Framing (W_{frm})	1.5	Linear inches	n/a	n/a
Area of 2”x4” Wood Framing Exposed (A_{frm})	7.75	Square feet	n/a	$A_{frm} = L_{frm}*W_{frm}$
Solar aperature of Trombe Wall (Ap)****	88.25	Square feet		$Ap = A_{thrm}-A_{frm}$
Number of sheets of 4’x8’ acrylic (N_{acr})	3	Number	4	$N_{acr} = A_{thrm}/(32 \text{ sq. ft.})$

*As specified in (Wilson, 1979; Balcomb and Mcfarland, 1978). Adobe wall uses relationship (8” average recommended thickness for adobe compared to 13” average recommended thickness for concrete) (Lechner, 2008).
**Selected for ease of use of commonly available windows (Four 48”x72” windows).
***Frame designed for use of four 48”x72” windows, requiring five vertical and two horizontal braces.
****An important input for the Trombe wall model (Wilson, 1979; Balcomb and Mcfarland, 1978).

Table C42. Passive Solar Recurring Costs and Assumptions

Assumption	Value	Unit	Source
Lifespan of passive solar materials*	20	Years	(Berry et al., 1997)
Wood cost	50.00	$/air-dried-cord	(Personal Communication, 2014)
Wood stove chimney cleaning cost**	150.00	$	(Houck and Eagle, 2006)
Wood stove chimney cleaning frequency**	1	1/year	(Houck and Eagle, 2006)

*Assumed to be same of weatherization materials.
**Passive solar home with conventional Navajo stove assumes same chimney cleaning cost and frequency as home with EPA-certified stove.

Table C43: Summary Table: Capital and Annualized Total, Capital, Fuel, and Maintenance Costs of All Heating Alternative Options

Weatherization/ Heating Alternative	Index	Retrofit Capital Costs ($)*			Capital Cost Source(s)**	Annualized Costs ($/year)				
		Tot.	Mat.	Lab.		Total Net***	Total Gross****	Capital	Fuel	Main.
WZ	0a	587.36	181.65	405.71	1	184.21	358.93	34.21	174.72	150.00
	0b	945.00	n/a	n/a	3	205.04	379.76	55.04	174.72	150.00
NG	1	1,666.14	1,020.27	645.87**	1	231.18	405.90	106.31	164.52	100.00
	2	1,589.36	943.49	645.87**	1,9	259.67	434.39	101.41	185.08	100.00
	3	1,651.19	1,005.32	645.87**	1,9	263.62	438.34	105.36	185.08	100.00
	4	2,178.96	1,533.09	645.87**	1,9	250.75	425.47	139.03	155.04	100.00
	5	2,240.79	1,594.92	645.87**	1,9	254.70	429.42	142.98	155.04	100.00
	6	1,750.82	n/a	n/a	3	301.68	476.40	111.71	189.83	100.00
	7	1,855.32	n/a	n/a	3	308.35	483.07	118.38	189.83	100.00
	8	1,846.54	n/a	n/a	3	301.26	475.98	117.82	185.08	100.00
	9	1,951.04	n/a	n/a	3	307.93	482.65	124.49	185.08	100.00
	10	2,221.78	n/a	n/a	3	296.91	471.63	141.76	164.52	100.00
	11	2,326.28	n/a	n/a	3	303.57	478.29	148.43	164.52	100.00
	12	2,355.80	n/a	n/a	3	286.98	461.70	150.31	151.09	100.00
	13	2,460.30	n/a	n/a	3	293.65	468.37	156.98	151.09	100.00
	14	3,400.00	n/a	n/a	7	428.16	602.88	216.94	227.80	100.00
	15	3,400.00	n/a	n/a	7	390.50	565.22	216.94	197.42	100.00
	16	3,000.00	n/a	n/a	10	349.68	524.40	191.42	185.08	100.00
PG	17	3,531.14	1,020.27	1,490.87***	1,10	1933.18	2107.90	225.31	1676.02	100.00
	18	2,434.36	943.49	1,490.87***	1,9,10	2085.53	2260.25	155.33	1885.52	100.00
	19	2,496.19	1,005.32	1,490.87***	1,9,10	2089.48	2264.20	159.27	1885.52	100.00
	20	3,023.96	1,533.09	1,490.87***	1,9,10	1800.62	1975.34	192.95	1579.50	100.00
	21	3,085.79	1,594.92	1,490.87***	1,9,10	1804.56	1979.28	196.89	1579.50	100.00
	22	2,574.76	n/a	n/a	3,10	2169.79	2344.51	164.28	1933.87	100.00
	23	2,679.26	n/a	n/a	3,10	2176.46	2351.18	170.95	1933.87	100.00
	24	2,691.54	n/a	n/a	3,10	2127.11	2301.83	171.74	1885.52	100.00
	25	2,796.04	n/a	n/a	3,10	2133.78	2308.50	178.40	1885.52	100.00
	26	2,817.90	n/a	n/a	3,10	2087.49	2262.21	179.80	1839.54	100.00
	27	2,922.40	n/a	n/a	3,10	2094.16	2268.88	186.47	1839.54	100.00
	28	3,296.52	n/a	n/a	3,10	1948.48	2123.20	210.34	1676.02	100.00
	29	3,401.02	n/a	n/a	3,10	1955.15	2129.87	217.00	1676.02	100.00
	30	3,411.39	n/a	n/a	3,10	1918.03	2092.75	217.67	1639.59	100.00
	31	3,515.89	n/a	n/a	3,10	1924.70	2099.42	224.33	1639.59	100.00
	32	3,526.26	n/a	n/a	3,10	1889.19	2063.91	225.00	1604.70	100.00
	33	3,630.76	n/a	n/a	3,10	1895.86	2070.58	231.66	1604.70	100.00
	34	3,641.13	n/a	n/a	3,10	1828.60	2003.32	232.33	1539.20	100.00
	35	3,745.63	n/a	n/a	3,10	1835.27	2009.99	238.99	1539.20	100.00
	36	3,367.00	n/a	n/a	7	2590.41	2765.13	214.83	2320.65	100.00
	37	3,367.00	n/a	n/a	7	2273.70	2448.42	214.83	2011.23	100.00
	38	3,000.00	n/a	n/a	10	2121.62	2296.34	191.42	1885.52	100.00
EH	39	1,537.05	885.00	652.05**	1	1685.48	1860.20	98.07	1662.12	100.00
	40	1,541.94	889.89	652.05**	1,9	1176.91	1351.63	98.38	1153.24	100.00
	41	1,603.77	951.72	652.05**	1,9	1180.85	1355.57	102.33	1153.24	100.00
	42	1,863.54	1,211.49	652.05**	1,9	1197.42	1372.14	118.90	1153.24	100.00
	43	1,925.37	1,273.32	652.05**	1,9	1201.37	1376.09	122.85	1153.24	100.00
	44	3,427.92	n/a	n/a	3	1624.24	1798.96	218.72	1480.24	100.00
	45	3,532.42	n/a	n/a	3	1630.91	1805.63	225.39	1480.24	100.00
	46	3,000.00	n/a	n/a	10	1269.94	1444.66	191.42	1153.24	100.00

Table C43 Continued.

Weatherization/ Heating Alternative	Index	Retrofit Capital Costs ($)*			Capital Cost Source(s)**	Annualized Costs ($/year)				
		Tot.	Mat.	Lab.		Total Net***	Total Gross****	Capital	Fuel	Main.
WP	47	2,052.21	1,293.75	758.46***	1,5,9	1446.74	1621.46	153.80	1329.13	125.00
	48	2,588.21	1,829.75	758.46***	1,5,9	1482.85	1657.58	193.97	1329.13	125.00
	49	2,573.01	1,814.55	758.46***	1,5,9,10	1482.77	1657.49	192.83	1329.13	125.00
	50	3,472.01	2,713.55	758.46***	1,5,9,10	1549.63	1724.35	260.21	1329.13	125.00
	51	3,850.00	n/a	n/a	7	1581.48	1756.20	288.54	1329.13	125.00
SI	52	249.70	97.19	152.51**	1	136.51	311.23	14.54	146.69	150.00
	53	267.06	114.55	152.51**	1,9	137.52	312.24	15.56	146.69	150.00
SR	54	1,766.14	1,007.68	758.46***	1,5,9	203.17	377.89	107.52	115.12	150.00
	55	2,152.06	1,393.60	758.46***	1,5,9	225.59	400.31	131.01	115.12	150.00
	56	3,058.46	2,300.00	758.46***	1,5,9,10	288.29	463.01	186.19	115.12	150.00
	57	2,357.46	1,599.00	758.46***	1,5,9,10	245.40	420.12	143.52	115.12	150.00
	58	2,207.46	1,449.00	758.46***	1,5,9,10	233.20	407.92	134.39	115.12	150.00
	59	3,325.46	2,567.00	758.46***	1,5,9,10	301.20	475.92	202.45	115.12	150.00
	60	3,367.00	n/a	n/a	7	300.63	475.35	204.98	115.12	150.00
PS	61	4,160.00	2,940.00	1,220.00	1	367.76	542.49	242.30	133.47	166.72
	62	4,579.24	2,659.20	1,920.04	1,10	392.18	566.90	266.72	133.47	166.72
	63	3,710.00	n/a	n/a	1	341.55	516.27	216.09	133.47	166.72
	64	7,114.16	5,166.32	1,947.84	3	539.83	714.55	414.37	133.47	166.72
	65	1,518.17	712.49	805.68	1,9	210.55	385.27	88.43	130.13	166.72
	66	1,817.54	1,011.86	805.68	1	227.99	402.71	105.86	130.13	166.72
	67	2,171.21	1,269.77	901.44	1,9	248.59	423.31	126.46	130.13	166.72
	68	2,470.58	1,569.14	901.44	1	266.03	440.75	143.90	130.13	166.72

* Tot. = Total, Mat. = Materials, Lab. = Labor. Equipment is not included as all values were either $0.00 or n/a.
** 1=RSMeans 2015 for Farmington, NM, 2=National Renewable Energy Laboratory (NREL) BeOpt 2.3 Software Output for Farmington, NM, 3=NREL National Residential Efficiency Measures Database 3.0.0, 4=Navajo Tribal Utility Authority (NTUA), 5=USEPA BurnWise Program Website, 6=United States Department of Energy, 7=Houck and Eagle, 2006, 8=Franklin, 2000, 9=Home Depot Online Catalog for Farmington, NM, 10=Personal Communication
*** Total Net represents how much more the homeowner would spend relative to their current fuel use. Total Net is the fuel cost of the Baseline Home ($174.72) subtracted from the sum of the: 1) annualized capital, 2) annual fuel cost, 3) annual electricity (except EH where fuel is the electricity cost) cost, 4) annual maintenance needs, 5) service fee for natural gas ($3.50/yr), and 6) tank rental fee for propane gas ($75.00/yr).
**** Total Gross represents how much the homeowner would spend in total, and is again the sum of: 1) annualized capital, 2) annual fuel cost, 3) annual electricity (except EH where fuel is the electricity cost) cost, 4) and annual maintenance needs, 5) service fee for natural gas, and 6) tank rental fee for propane gas

8.1.3 Memo from Ken Davidson (USEPA) to Katie Stewart (USEPA). Residential Wood Combustion (RWC) Benefits-per-ton (BPT) Values for the Navajo Nation. 06/19/2014

Residential Wood Combustion (RWC) Benefits-per-ton (BPT) Values for the Navajo Nation

The procedure for calculating national average BPT coefficients follows three steps (described more fully in the Technical Support Document: Estimating the Benefit per Ton of Reducing $PM_{2.5}$ Precursors from 17 Sectors):

- Use air quality modeling to predict ambient concentrations of primary $PM_{2.5}$, nitrate and sulfate across the contiguous U.S. that are attributable to a particular sector.
- Estimate the health impacts, and the economic value of these impacts, associated with the attributable ambient concentrations of primary $PM_{2.5}$, sulfate and nitrate $PM_{2.5}$ using the environmental Benefits Mapping and Analysis Program (BenMAP v4.0.66) 110 (Abt Associates, Inc, 2012).
- Divide the $PM_{2.5}$-related health impacts attributable to each type of $PM_{2.5}$, and the monetary value of these impacts, by the level of associated precursor emissions. That is, primary $PM_{2.5}$ benefits are divided by direct $PM_{2.5}$ emissions, sulfate benefits are divided by SO_2 emissions, and nitrate benefits are divided by NO_x emissions.

The approach for generating regional benefit-per-ton estimates for $PM_{2.5}$ from RWC emissions in the Navajo Nation is a modification of the approach described above from the BPT TSD. Use the same air quality modeling from the national sector analysis, which includes the ambient $PM_{2.5}$ attributable to the RWC sector in the six-county Navajo area.

The six counties include: Apache, Coconino and Navajo in AZ; and McKinley, Rio Arriba, Sandoval and San Juan in NM

- Use this data to estimate the $PM_{2.5}$ benefits in 2016 and aggregate the benefits results across the six-county Navajo area
- Calculate the benefit-per-ton estimates by dividing the regional benefits estimates by the corresponding emissions (underlying "platform" emissions derived from the NEI)

The baseline emissions inventory for directly-emitted $PM_{2.5}$ from the RWC sector in the Navajo region is 831 tons. This is likely an underestimate. From Alexis Zubrow (OAQPS): "For the 2011 modeling platform, we drop the tribal emissions for all area sources b/c we don't have a good spatial surrogate and it is difficult to know to what degree these emissions are accounted for in the state estimates for those areas." The BPT for direct $PM_{2.5}$ emissions range from about \$12,000 to \$31,000.

- Using an example from an email chain with Wyatt a while back, replacing 1000 woodstoves would lead to a 12.4% decrease of 399 tons of PM decrease (~49 tons). Benefits would from \$590,000 to \$1,500,000
- This method measures the health benefits from a reduction in annual average ambient PM exposures related to a reduction in annual residential wood combustion PM emissions in the six-county Navajo region.
- It does not capture individual health impacts from indoor PM exposures.
- Because this method estimates the health impacts from ambient $PM_{2.5}$ exposures in the region, we can expect the values to be low because of a low population density (compared to areas with a high population density).

That said, the probable exclusion of a more refined Navajo inventory means the air quality and health impacts modeled by the underlying sector analysis are likely underestimated.

8.2 Chapter 3: Emission Factors of Fine Particulate Matter, Organic and Elemental Carbon, Carbon Monoxide, and Carbon Dioxide for Four Solid Fuels Commonly Used in Residential Heating by the Navajo Nation

Table S1. *Test* Phase Dilution Ratio and Sampling Temperature

	Ponderosa Pine		*Utah Juniper*		*Black Mesa*		*Fruitland*	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dilution ratio	716	143	1,061	165	1,813	370	1,444	217
Sampling temperature (°C)	41	4	35	4	27	3	29	4

8.2.1 Washing and Calibration Protocols

Washing

- Filter packs and sampling lines were washed with Alconox soap and warm tap water, rinsed with Milli-Q (18.2 MΩ•cm) water, and then lab-grade isopropanol.
- Metal components were also rinsed with lab-grade hexanes and dichloromethane.
- PTFE filters and Petri dishes were washed in 3% nitric acid (HNO_3), rinsed with Milli-Q water, washed in 10% hydrochloric acid (HCl), and then rinsed once more with Milli-Q water, following published protocols for trace metals analysis (Majestic et al., 2012).

Calibrations

- All calibrations conducted every ten *Test* phases.
- Filter flows were calibrated with a Gilian Gilibrator-2 Primary Flow Calibrator (Sensidyne, St. Petersburg, FL).

- PEMS gas sensors were calibrated following manufacturer protocols using zero (particle free, 99.999% N_2) and span (particle free, 300 ppm CO / 2900 ppm CO_2 / balance N_2) gases (AirGas, Radnor, PA).
- The TelAire CO_2 monitor was calibrated with a one-point calibration and zero gas following manufacturer protocols.
- The flue (duct) thermocouple was calibrated against three thermometers at 10, 20, 30, 35, and 40°C, and the stove flue thermocouple at 0, 50, 75, 90, and 95.5°C.

8.2.2 Carbon Balances

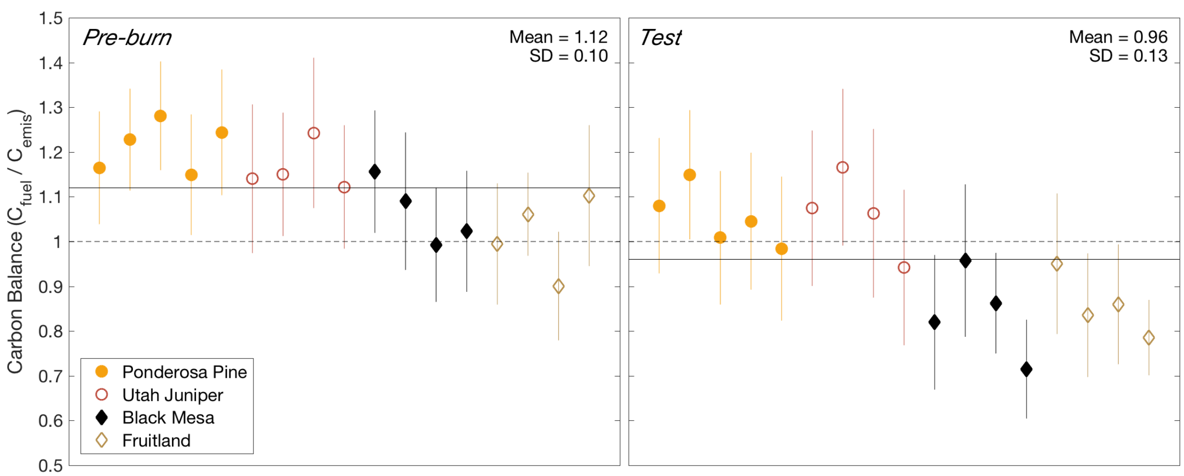


Figure S3-1. Carbon Balances ($C_{balance}$) for *Pre-burn* and *Test* Phases. Fuel Carbon (C_{fuel}) was Based on Fuel Consumption During Each Phase and the Assumed Carbon Content Based on Ultimate Analyses from the Literature. Emissions Carbon ($C_{emissions}$) was Determined during Testing, and Included Organic and Elemental carbon (OC and EC) in the $PM_{2.5}$, and Carbon Monoxide (CO) and Carbon Dioxide (CO_2). A Value of $C_{balance}$ Greater than 1.0 Indicates that C_{fuel} Exceeded $C_{emissions}$. On average, the *Pre-burn* Compared to *Test* Phase had Higher $C_{balance}$. Additionally, Wood Compared to Coal Fuels had Higher $C_{balance}$.

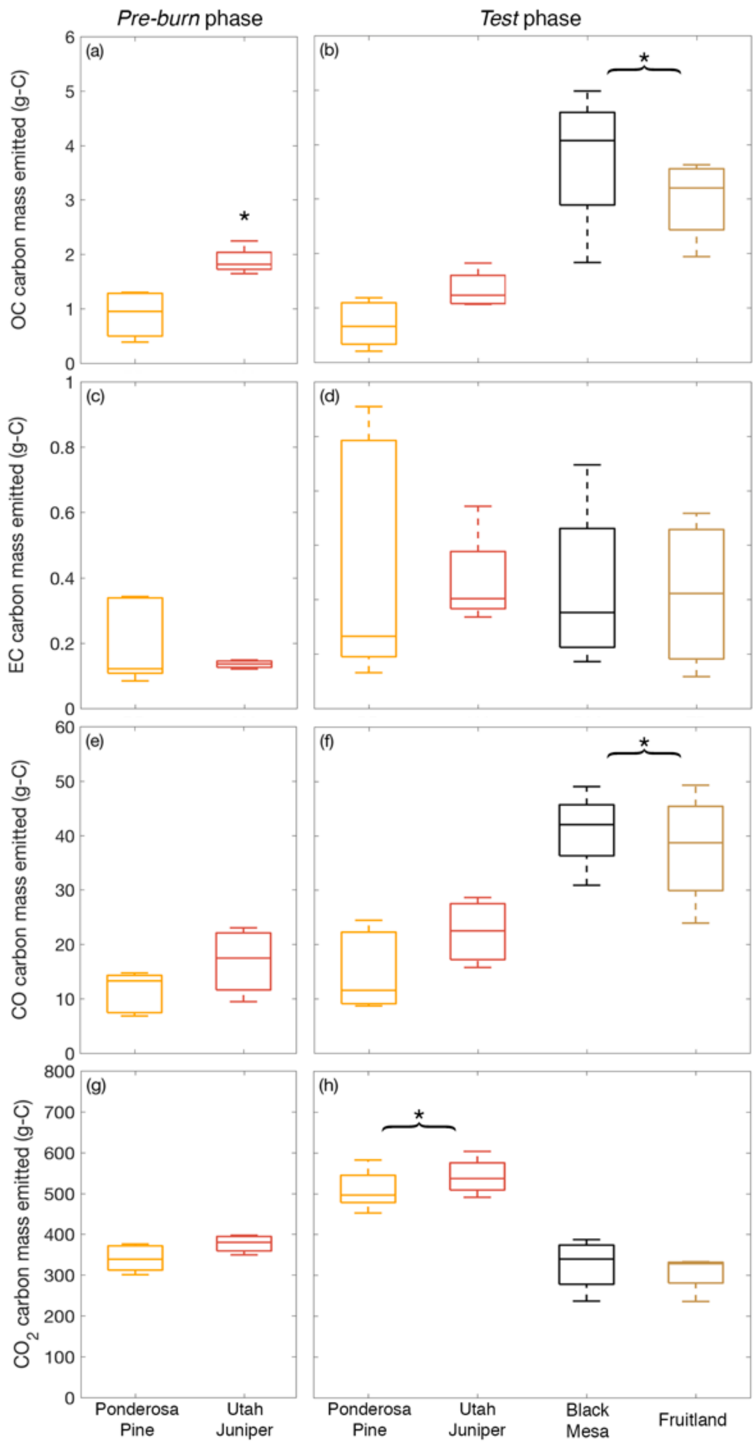


Figure S3-2. Boxplots of Carbon Balance Terms for *Pre-burn* and *Test* Phases. *Pre-burn* Data for *Black Mesa* and *Fruitland* are Not Presented, since *Ponderosa Pine* was Used as the *Pre-burn* Fuel Load for Coal Tests. For the *Pre-burn* Phase, *Utah Juniper* Compared to *Ponderosa Pine* Emitted Significantly ($p<0.05$, * in the Figure) More Organic Carbon (OC).

For the *Test* phase, Coal Compared to Wood Emitted Significantly More OC and Carbon Monoxide (CO), and Significantly Less Carbon Dioxide (CO_2).

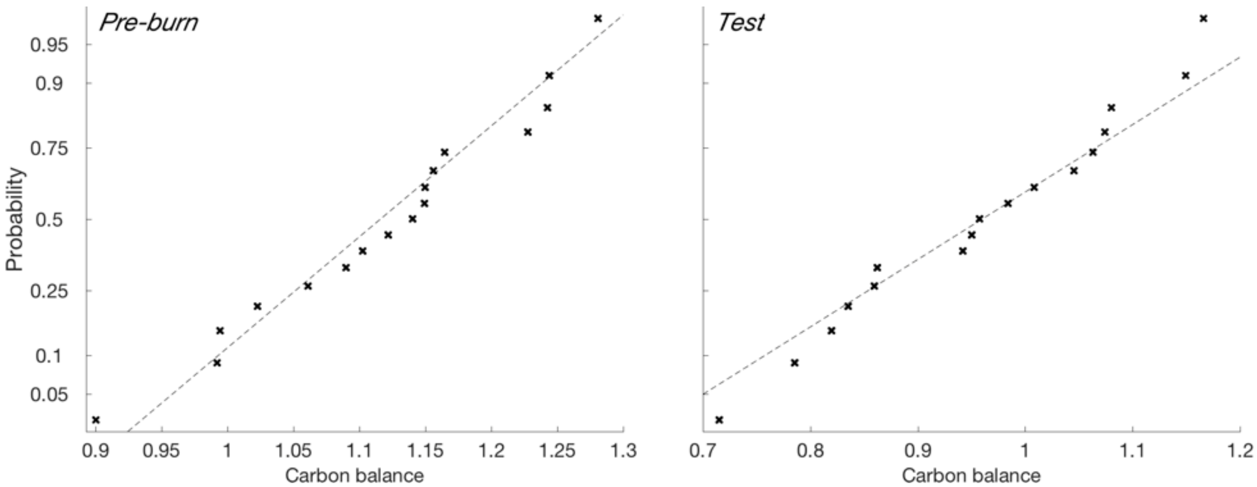


Figure S3-3. Normal Distribution Probability Plots for Carbon Balances ($C_{balance}$) for *Test* and *Pre-burn* Phases. No *Pre-burn* nor *Test* Phases were Excluded Based on $C_{balance}$.

8.2.3 Error propagation for $PM_{2.5}$ Mass Emission Factors

$$EF_{PM} = \frac{m_{PM} * Q_{flue}}{m_{fuel} * Q_{filter}}$$

Where:

EF_{PM}	= Mass emission factor of $PM_{2.5}$ from PTFE filters (g/kg)
m_{PM}	= Mass of sampled $PM_{2.5}$ (g)
m_{fuel}	= Mass of fuel consumed (kg)
Q_{flue}	= Mean flow rate of flue (lpm)
Q_{filter}	= Mean flow rate through filter (lpm)

Therefore, uncertainty in mass emission factor (EF_{PM}) is:

$$s_{EF_{PM}}{}^2 = [\frac{\partial EF_{PM}}{\partial m_{PM}}]^2 * s_{m_{PM}}{}^2 + [\frac{\partial EF_{PM}}{\partial Q_{flue}}]^2 * s_{Q_{flue}}{}^2 + [\frac{\partial EF_{PM}}{\partial m_{fuel}}]^2 * s_{m_{fuel}}{}^2 + [\frac{\partial EF_{PM}}{\partial Q_{filter}}]^2 * s_{Q_{filter}}{}^2$$

and

$$\left[\frac{\partial EF_{PM}}{\partial m_{PM}}\right] = \frac{Q_{flue}}{m_{fuel} * Q_{filter}}$$

$$\left[\frac{\partial EF_{PM}}{\partial Q_{flue}}\right] = \frac{m_{PM}}{m_{fuel} * Q_{filter}}$$

$$\left[\frac{\partial EF_{PM}}{\partial m_{fuel}}\right] = \frac{m_{PM} * Q_{flue}}{{m_{fuel}}^2 * Q_{filter}}$$

$$\left[\frac{\partial EF_{PM}}{\partial Q_{filter}}\right] = \frac{m_{PM} * Q_{flue}}{m_{fuel} * {Q_{filter}}^2}$$

Where:

S_{EFPM}	= Uncertainty in $PM_{2.5}$ mass emission factor (g/kg)
$\partial EF_{PM}/\partial m_{PM}$	= Partial derivative of EF_{PM} with respect to mass of sampled $PM_{2.5}$ (1/kg)
s_{mPM}	= Uncertainty in mass of sampled $PM_{2.5}$ (g)
	= Standard deviation of masses of filter blanks (g)
$\partial EF_{PM}/\partial Q_{flue}$	= Partial derivative of EF_{PM} with respect to flue flow rate (g/kg-lpm)
s_{Qflue}	= Uncertainty in flue flow rate (lpm)
	= Standard deviation of flue flow rate (lpm)
$\partial EF_{PM}/\partial m_{fuel}$	= Partial derivative of EF_{PM} with respect to mass of fuel consumed (g/kg^2)
s_{mfuel}	= Uncertainty in mass of fuel consumed (kg)
	= Error associated with scale (kg)
$\partial EF_{PM}/\partial Q_{filter}$	= Partial derivative of EF_{PM} with respect to flow rate through filter (g/kg-lpm)
$s_{Qfilter}$	= Uncertainty in filter flow rate (lpm)
	= Error associated with rotameter (lpm)

8.3 Fine Particulate Matter from the Combustion of Wood and Coal Types Commonly Used on the Navajo Nation Induce Oxidative Stress and Inflammatory Responses in Murine Macrophage Cells

8.3.1 Results and Discussion

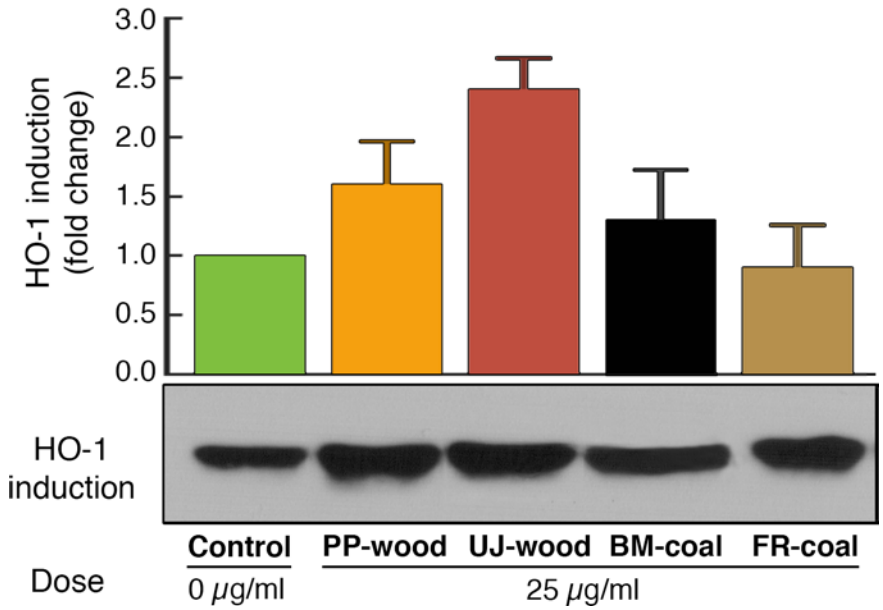


Figure S5-1. Induction of Heme Oxygenase 1 (HO-1) by Aqueous Extracts (AEs) of Wood and Coals. Cells were Stimulated at Indicated Concentrations for 16 hr Before Collection for Western Blot Analysis. Bar Graph Shows Changes (fold) of HO-1 Protein Band Density over Untreated Control. Error Bars are SEM from Replicate Experiment (n=2) Data at this Dose.

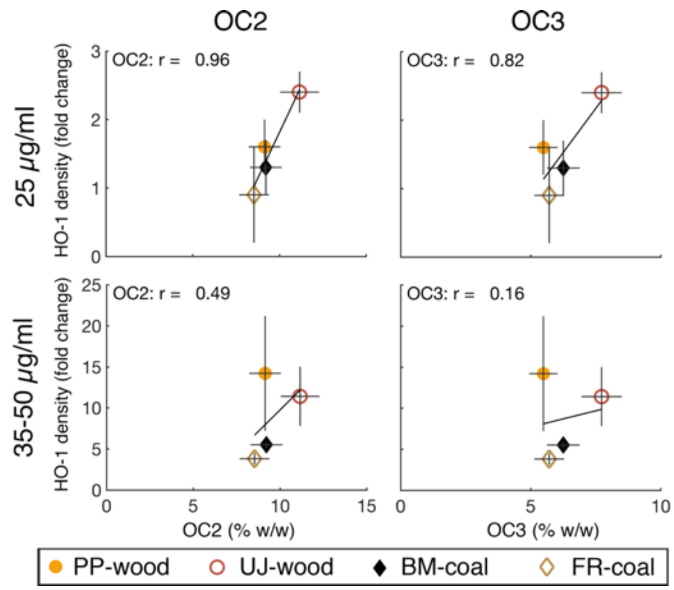


Figure S5-2. Correlations of Mid Volatile Organic Carbon (OC2 and OC3) with HO-1 Induction. OC2 and OC3 Correlated with HO-1 Induction at Low dose (25 µg/ml) but Not High Dose (50 µg/ml for PP-wood, UJ-wood, and BM-coal; 35 µg/ml for FR-coal).

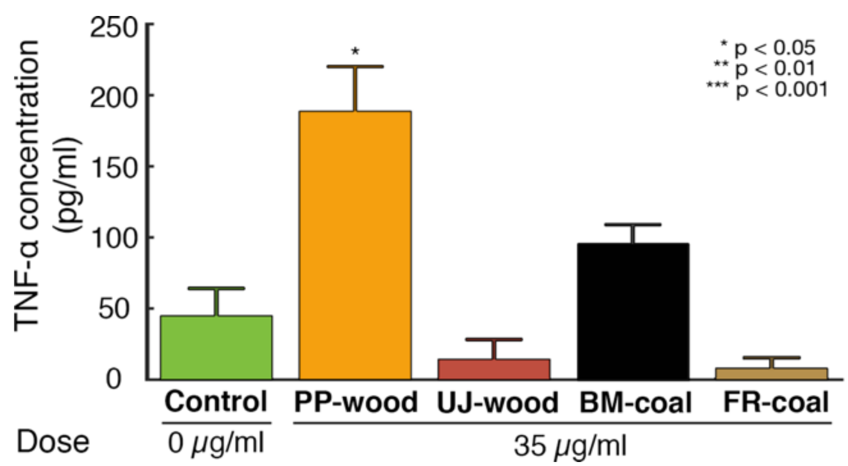


Figure S5-3. Concentration of TNF-α in the Cell Culture Media as Determined by the Replicate Experiment. RAW 264.7 Cells were Exposed to 35 µg/ml of Aqueous Extracts (AEs) for 16 hr. PP-wood Caused the Highest Production of TNF-α of all AEs. Between Fuel Types, Wood Caused Significantly Higher TNF-α Production Compared to Coal.

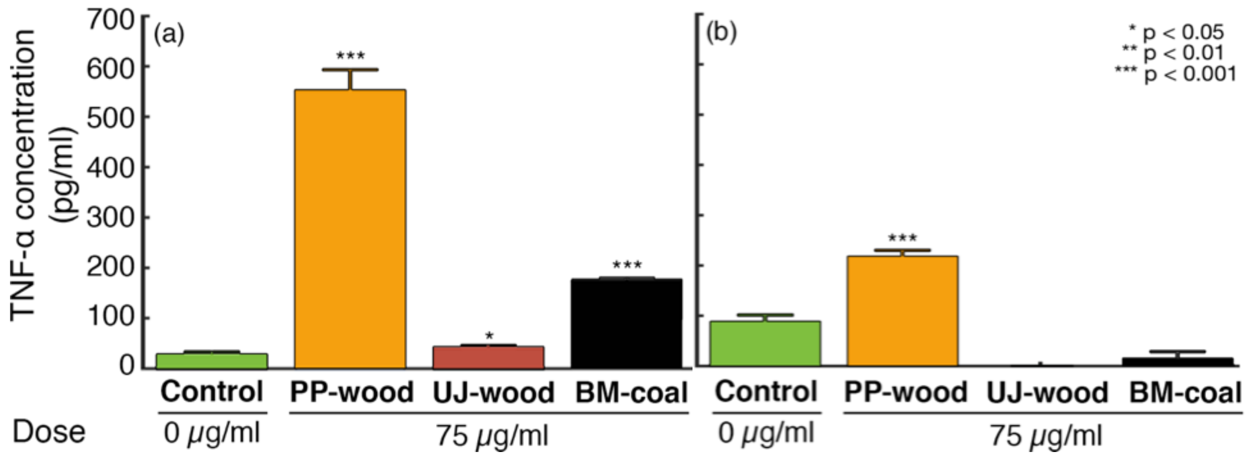


Figure S5-4. Concentration of TNF-α in the Cell Culture Media. RAW 264.7 Cells Were Exposed to 75 µg/ml Of Aqueous Extracts (AEs) For 16 Hr. This Experiment Was Repeated Once, with Data from Each Replicate Plotted as (A) And (B). PP-Wood Caused the Highest Release Of TNF-A of all AEs, And Caused Significant Release Compared to the Untreated Control.

Table S5-1. Rationale for Presentation of Cellular Response Data.

HO-1:	At each dose, correlations were based on mean HO-1 induction from two independent stimulations and Western blot analyses (n=2). Since Western blot results in one data point for HO-1 induction from each experiment, the fold change (over untreated control) was utilized to present the mean induction from both experiments.
TNF-α:	At each dose, correlations were based on mean TNF-α release from one stimulation and ELISA using independent triplicate determinations (n=3). Since ELISA results in three data points for TNF-α release from each experiment, the mean release in pg/ml is presented from one experiment at each dose. This is opposed to the fold change approach used for HO-1 (i.e., to present data from multiple experiments).

Table S5-2. Summary of Pierson Correlation Coefficients for Cellular Responses and Particle Carbon Mass Concentrations. Mid-volatile Carbon (OC2) and Elemental Carbon (EC) were Significantly Correlated with HO-1 Induction. Low Volatile Carbon (OC4) was Significantly Correlated with TNF-α Release.

	HO-1		**TNF-α**			
Carbon Class	**Low Dose** 25 μg/ml	**High Dose** 35-50 μg/ml	**Low Dose** 35 μg/ml		**High Dose** 75 μg/ml	
	Stim 1/2	*Stim 1/2*	*Stim 1*	*Stim 2*	*Stim 1*	*Stim 2*
OC	0.26	-0.40	-0.66	-0.47	-0.91	-0.97
OC1	-0.16	-0.71	-0.71	-0.47	-0.74	-0.86
OC2	**0.96**	0.49	-0.21	-0.28	-0.73	-0.58
OC3	0.82	0.16	-0.52	-0.55	-0.90	-0.80
OC4	0.30	0.89	**0.95**	0.84	0.90	0.97
OCp	0.60	-0.15	-0.73	-0.71	-0.98	-0.93
EC	0.46	**0.95**	0.87	0.71	0.76	0.87

Bold indicates $p<0.10$ for linear regression of particle mass component (e.g., OC) and cellular response (e.g., HO-1 induction).

Table S5-3. Summary of Pierson Correlation Coefficients for Cellular Responses and Particle Soluble Metal Mass Concentrations. Soluble Nickel (Ni) and Copper (Cu) were Significantly Correlated with HO-1 Induction. Soluble Potassium (K) was Significantly Correlated with TNF-α Release.

	HO-1		**TNF-α**			
Soluble Metal	**Low Dose** 25 µg/ml	**High Dose** 35-50 µg/ml	**Low Dose** 35 µg/ml		**High Dose** 75 µg/ml	
	Stim 1/2	*Stim 1/2*	*Stim 1*	*Stim 2*	*Stim 1*	*Stim 2*
Mg	**-0.91**	-0.83	-0.39	-0.35	0.20	0.01
K	-0.62	-0.12	0.24	0.09	0.96	**1.00**
Cr	-0.50	-0.62	-0.58	-0.69	-0.70	-0.55
Ni	**0.92**	0.81	0.20	0.00	-0.13	0.07
Cu	0.44	**0.93**	0.84	0.65	0.73	0.85
Zn	-0.66	-0.69	-0.50	-0.58	**-1.00**	-0.98
As	-0.21	-0.49	-0.68	-0.83	-0.70	-0.55
Cd	-0.56	-0.64	-0.54	-0.65	-0.70	-0.55
Pb	-0.65	-0.69	-0.52	-0.60	-0.96	-0.89

Bold indicates $p<0.10$ for linear regression of particle mass component (e.g., Mg) and cellular response (e.g., HO-1 induction). Soluble Fe was below detection limit for all fuels and was not included here.