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Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The objective of this project was to evaluate the environmental impacts of home-scale coal combustion on the Navajo Reservation and develop strategies to reduce adverse health effects associated with home-scale coal combustion. Principal accomplishments of this project were: 1) determination of the metal and gaseous emissions of a representative stove on the Navajo Reservation; 2) recognition of cyclic gaseous emissions in combustion in home-scale combustors; 3) 'back of the envelope' calculation that home-scale coal combustion may impact Navajo health; and 4) identification that improved coal stoves require the ability to burn diverse feedstocks (coal, wood, biomass). Ultimately the results of Navajo home-scale coal combustion studies will be extended to the Developing World, particularly China, where a significant number (> 150 million) of households continue to heat their homes with low-grade coal.

Background and Research Objectives

Pollutants derived from home-scale coal combustion are a significant health problem on the Navajo reservation. Residents of the Navajo Nation receive free coal from local mines, so this is the fuel of choice for many who live there. Outdoor air quality in the Shiprock, New Mexico, region is poor during the winter months because of emissions from power plants and home-coal stoves combined with a temperature inversion layer. In addition, indoor air quality throughout the reservation is poor because of leaking chimneys. More importantly, home-coal use on the Navajo reservation is analogous to home-scale coal use in the Developing World, particularly that in China, where more than thirty percent of Chinese households burn low-quality coal to heat their homes.

The objectives of this study were: (1) to evaluate whether environmental pollutants

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from home-coal use could negatively impact the health of residents of the Navajo reservation; (2) to evaluate the current 'state-of-the-art' in coal stove technology; and (3) to develop a work plan to continue investigating this important problem.

Importance to LANL's Science and Technology Base and National R&D Needs

The significance of the results derived from this study is threefold. First, the study validates the anecdotal information concerning pollutants from home-coal use on the Navajo reservation. Second, we have provided a roadmap to achieve further programmatic development in the field of home-coal combustion. Finally, we have supported LANL's educational mission — this project involved three Navajo students and a faculty member at Navajo Community College.

The results of this study support LANL's mission in 'Environmental Stewardship' and enhance LANL's core technical competencies in 'Earth and Environmental Systems', and 'Complex Experimentation and Measurements'. The research directly helps pursue LANL's newly-developed programmatic tactical goal in 'Environmental Science'.

Scientific Approach and Accomplishments

A. Overall Approach

This project was divided into six phases, each of which is described below: (1) obtaining general background information concerning environmental problems associated with coal use on the Navajo reservation; (2) analysis of types and sources of air pollutants from home-scale coal combustion on the Navajo reservation including a comparison of these data to Federal standards; (3) implementation of a survey of coal use on the Navajo reservation (with the help of students at Navajo Community College); (4) investigation of the current state-of-the-art in coal stove technology; (5) determination of needs for future studies of home-coal use on the Navajo reservation; and (6) development of a plan for further study. This report is a condensed version of a more comprehensive report describing this study in detail [1].

This report suggests a continuing program whose goals are reduction of outdoor pollution in the Shiprock area and indoor pollution everywhere on the Navajo reservation to Environmental Protection Agency (EPA) levels. The program would include creation of a pollution-free stove that can burn wood, coal, or other biomass effectively, and is affordable to residents of the Navajo Nation and industrializing nations. Meeting these goals ultimately requires that relative contributions of power plants and stoves to pollution

in the Shiprock area be determined, that stove-caused pollution effects on indoor air quality on the Navajo reservation be evaluated, and that an economical, pollution-free coal and biomass stove for space heating and cooking be designed. The report identifies actions required to implement such a program — funding sources may include the US Joint Implementation (JI) program, the EPA, and international development organizations such as the US Agency for International Development.

B. General Background

Quantitative studies of air quality on the Navajo reservation do not exist, so qualitative and anecdotal evidence are all that are available. One of the first steps in the proposed plan is the acquisition of more reliable and quantitative air-quality data. Air quality of the Shiprock area differs from the remainder of the Navajo reservation. The Shiprock region is in the valley of the San Juan River. Polluted air accumulates under atmospheric temperature inversions over the region. Inversion periods occur most frequently in the December-March interval. The remainder of the Navajo Nation does not experience such inversions, as prevailing winds throughout the remainder of the reservation tend to sweep away polluted air.

The Shiprock region can be regarded as representative of many urban areas with significant pollution problems caused by atmospheric temperature inversions. Well-known examples are Los Angeles, Denver, Mexico City, and Quito, Ecuador.

Types and Sources of Air Pollution on the Navajo Reservation.

There are two large coal-fired electricity generating stations in the Four Corners area. During the months December 1995 through March 1996, the two plants together burned slightly over four million tons of coal to generate electricity. If the two plants are regarded as a single entity, together they are the second largest consumer of coal in the nation.

Stoves, both coal- and wood-burning, are a source of air pollution in the Shiprock area during periods of temperature inversions. An order-of-magnitude calculation shows that these stoves can be a significant source. If the area population of 13,000 has 2,000 stoves that burn five pounds of coal per stove each day, and if this coal has 0.5% organic sulfur, then the 10,000 lbs of coal burned will contain 50 lbs of organic sulfur. If this sulfur is converted to sulfur dioxide, then about 1 lb-moles of SO_2 will be emitted. This 1 lb-moles of SO_2 will occupy approximately 500 cu ft of air space in the Shiprock region. If the region is about 30 sq mi in area, the inversion layer about 30 feet high, and one day's emission of SO_2 collects in the layer, then the SO_2 concentration is 0.02 ppm. This is $\frac{2}{3}$ of the EPA recommended standard for maximum SO_2 concentration in ambient air. This

amount leaves little margin for sulfur emissions from other sources, such as power plant or automobile emissions. Observed air quality in Shiprock during the winter months also suggests that home-scale wood and coal burning creates a health problem.

C. Emissions Study on the Navajo Reservation

Description of experiments. A series of tests was carried out to determine the orders of magnitude of pollutants in different fuels and emissions on the Navajo reservation. The tests sampled coal from the Shiprock area, stack gases from one of the power plants in the region, and off gases from a residential stove in Shiprock. On February 9, 1996, samples of coal being used at the San Juan Power Plant were taken and analyzed. On February 8, samples from both Stack 2 and Stack 3 from the San Juan Power Plant were taken and later analyzed. The study also analyzed samples of fly ash from the plant collected on February 6.

The stove tested was a "Warm Morning" cast iron stove, popular in the region. The stove is about 20 years old. A dark region on the ceiling above the stove indicated leaks in the system. On January 19, investigators from Los Alamos and NCC sampled the gas in the operating stove within the flame, 6 inches above the flame, and 18 inches above the flame. On March 21, the investigators operated the stove, intermittently placing coal on the fire. A portable Quintox detector analyzed 49 samples of the off gases from the stove. The Quintox detector analyzes for SO_x , NO_x , NO_2 , CO, and O, and can measure these substances at either low or high temperatures.

Results—coal analyses. The coals of the region are low-sulfur coals, averaging significantly less than 1% total sulfur. The sulfur analyses are consistent with this, showing about 0.4% sulfur in the coal. The other elements of interest are the toxic trace elements. Of the toxic trace elements proposed for regulation under the Clean Air Act Amendments, beryllium, cadmium, lead, and manganese contents are near the average for U.S. coals. The mercury content is higher, the selenium content is somewhat lower, and arsenic and nickel contents are much lower than U.S. coal averages.

Results—analyses of power plant stack gases and fly ash. The CO contents of the gas coming from Stack #2 averaged about 0.01%, while the CO content of the gas from Stack #3 averaged about 0.04%. The NO_x content of the gas coming from Stack #2 averaged about 0.04%, while the NO_x content of the gas from Stack #3 averaged about 0.02%. The SO_2 content of the gas from Stack #2 averaged about 0.01%, while the SO_2 content of the gas from Stack #3 averaged about 0.015%. The fly ash contains significant amounts of the toxic trace elements — in many cases at levels greater than EPA

risk-based levels for contaminants in soils. Arsenic and beryllium in particular are at levels of concern.

Results—analyses of stove gases. The March 21, 1996, test yielded analyses of 49 samples of gases within the coal stove. Table 1 gives the mean concentrations and standard deviations for the CO, NO_x, and SO₂ in the gases in the stove. A comparison of the CO, NO_x, and SO₂ contents of the gases in the stove shows that the amounts of all three drop significantly from the flame to the regions 6 inches and 18 inches above the flame.

Combustion of coal occurs in two stages, the first being the emission and combustion of volatile matter and the second the burning of char. During the test, whenever fresh coal was added to the fire, gases were emitted from the fresh lumps for a short period (< 15 minutes). This resulted in wide swings in the gases' abundances in the stove during the test. The large standard deviations reported in Table 1 reflect this temporal variability.

The abundances of CO, NO_x, and SO₂ in the coal stove study are significantly greater than OSHA and EPA air quality standards. The evidence of leaking chimneys in the home where the air samples were taken suggest a possible indoor air pollution concern.

Table 1. POLLUTANT CONTENTS IN GASES EMITTED FROM COAL-STOVE FIRE (data from 49 samples)

	mean content of gas in stove (ppm)	standard deviation (ppm)
CO	3346	6319
NO _x	62	48
SO ₂	72	123

D. Survey of Stoves on the Navajo Reservation

A survey was carried out by Navajo Community College (NCC) students to provide an approximate picture of the types and distributions of stoves in the Navajo Nation. Of the 42 valid replies to the survey, 9 respondents said they had no stove, and 33 said they possessed a stove. Many of the stoves were inherited or fabricated by relatives. Most stove users burned both wood and coal in their stoves; burning either only wood or only coal was unusual. Of the people who reported that they purchased their stove, most said that the seller did not specify the type of fuel. Thirteen reported costs ranging from \$120 to \$1200, with \$411 being the average.

Shiprock probably does not represent the reservation very well. As a border town, there are more people with jobs, hence the stoves will tend to be more costly and of higher quality than further out in the reservation. The population surveyed was small.

The survey leads to the conclusion that a large fraction of the Navajo Nation owns stoves, and that they burn both wood and coal within them.

E. State-of-the-Art in Coal Stove Technology

There has been an upsurge in interest in stove design and performance over the last 15 years. A majority of the interest has been directed toward wood stoves, however. The indexes of *Chemical Abstracts* from 1977 through 1995 list 119 articles treating wood stoves, and only sixteen treating coal stoves.

From 1940 to 1950, engineers at Battelle Memorial Institute in Columbus, Ohio, worked at creating a stove that would burn bituminous coal without emitting smoke. They succeeded. However, during the years immediately following World War II, pipelines snaked across the US, bringing the convenience of oil and gas to virtually the entire country. Sales of coal-burning heaters plummeted, and "commercial exploitation (of the smokeless bituminous-burning stoves) has not followed" [3].

In contrast to the forced evolution of wood stoves driven by EPA edict, a decision to exempt coal stoves from regulation combined with the low demand for coal stoves has discouraged progress in coal-stove design. Nevertheless, the principles developed by Landry and Sherman [3] have been and are being used in coal-stove design. Toynbee [4] mentions a South African coal-fired "Frifire" heater, implying that it has low emission of pollutants due to properly designed air flows and baffling. He also describes research aimed at developing an intermittently fed, coal-fired heater with low emission of pollutants. A 1990 model coal stove by a reputable US manufacturer (Buck Model 24 stove) upon

visual inspection has obvious baffling and directed air flows for the apparent purpose of reducing emission of pollutants.

Not all coal stoves exhibit such attributes, however. Without EPA standards, coal stoves of widely varying quality are available. Since no regulations exist, anybody with a welding torch and some heavy-gauge sheet metal can put together a device and call it a coal stove. Thus coal stoves range from simple home-made stoves constructed from welded sheet metal up to the Buck Model 24. The lack of demand for high-quality coal stoves has also discouraged development. The New Buck Corporation of Spruce Pine, North Carolina, a manufacturer of high-quality wood and gas stoves, ceased manufacturing coal stoves around 1990.

F. Technologies Needed

Necessity of coordinating new technologies with indigenous culture. Kammen [2] points out the necessity of coordinating new technologies with indigenous cultures. The new technologies must be employable by the intended users with a level of training appropriate to the culture. The new technologies must work in the field under less-than-ideal conditions. The new technologies must be repairable by local artisans and with locally available materials. The new technologies must be compatible with practices that the intended users will employ. If any of these conditions are not fulfilled, implementation of a new technology will likely fail.

Cultural aspects of Navajo use of stoves. The results of the survey carried out at NCC had a clear message. Irrespective of any instructions, the Navajos are going to burn both wood and coal in their stoves. This result was unexpected, but knowing this will help prevent failure of the continued project. It is likely that this result applies to home-scale coal combustion in the Developing World.

Other messages in the survey results were more predictable. For widespread use, economical stoves are almost certainly a necessity. The majority of stoves on the reservation are probably used for heating rather than for cooking, although the fraction used for cooking is not insignificant. Instructions supplied with the stoves by the sellers vary widely in quality and veracity.

Anecdotal evidence supplies other cautions. If the Navajos do not understand the necessity for particular facets of the stove, they may remove them for other uses. As an example, walkways composed of firebrick have been observed combined with stoves lacking firebrick.

Technologies needed to satisfy both cultural aspects and need to reduce harmful stove emissions. As pointed out earlier, wood and coal stoves have followed different evolutionary paths, and present stoves are suited for either one fuel or the other, but not both. Yet Navajos burn both in their stoves. Thus, any new technology must be able to accommodate both fuels, and perhaps other biomass materials as well. If the new technology is to be applicable to Developing Nations, then the ability to use other biomass materials is a necessity.

Other needs for any new technologies are perhaps obvious. Any new stoves must be affordable by the people who will use them. They must be simple to operate. Proper training, appropriate to the indigenous culture, must be provided. Finally, the level of emissions from any new stoves must be minuscule.

G. Proposed Activities

Goals of future efforts. The ultimate goals of future efforts on this project are 1) Reduction of outdoor air pollution in the Shiprock area to meet EPA-mandated levels, 2) Reduction of indoor air pollution on the Navajo reservation to everywhere meet EPA-mandated levels, and 3) Creation of a pollution-free coal and biomass stove that is affordable by residents of the Navajo Nation and residents of industrializing nations.

Meeting the ultimate goals requires fulfillment of the following series of intermediate goals:

- Quantitative determination of the relative contributions of power plants and stoves to outdoor air pollution in the Shiprock area.
- Quantitative determination of the extent of stove emissions in contaminating indoor air on the Navajo reservation.
- Design of an economical, pollution-free coal and biomass stove for space heating and cooking.

Actions needed to achieve future goals. The following series of actions are needed to achieve the future goals:

- Gathering samples of stack gas from power plants.
- Accurately determining extent of coal-stove usage in the Shiprock area.
- Gathering and analysis of chimney gas samples in the Shiprock area.

- Gathering and analysis of outdoor air samples in the Shiprock area during high-pollution occurrences.
 - Gathering and analysis of indoor air samples around the Navajo Nation.
 - Purchase and testing of a low-quality stove.
 - Purchase and testing of a high-quality stove.
 - Development of an economical, low-emission coal and biomass stove.
 - Development of devices for removal of noxious oxides in residential stoves.
- Specific funding sources to carry out these actions have not yet been identified..

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