RESIDENTIAL WOOD BURNING AND NATIONAL PARKS-- AN OVERVIEW OF AIR POLLUTION ASPECTS

David B. Joseph
Air & Water Quality Division
National Park Service
Denver, CO 80225

There is concern in some national parks that local air pollution problems are being created by the use of wood in campfires and residential stoves and fireplaces. This paper describes which pollutants are of concern in residential woodburning; the magnitude of their emissions; monitoring and receptor modeling that can be used to determine the extent that residential woodburning emissions are impacting a local airshed; what options are available for mitigating the problem; and a recommended course of action for the Air and Water Quality Division of the National Park Service.

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INTRODUCTION

Burning wood in a fireplace, stove or campfire is appealing to people for many reasons. The warmth, the smell, the sound of the fire, the independence from fossil fuels such as oil and natural gas, and the relative cheapness of wood versus these other fuels have all contributed to the great acceptance and increase in the use of wood by individuals as fuel for heating. However, there are environmental tradeoffs that we must face when we burn wood. Smoke from the combustion of wood typically contains many air pollutants such as carbon monoxide (CO), particulate matter and organic compounds.

Carbon monoxide and particulate matter are two pollutants for which the Environmental Protection Agency (EPA) has established National Ambient Air Quality Standards (NAAQS) to protect human health. Organic compounds can react in the atmosphere to form ozone--another NAAQS pollutant that can be injurious to human health. Several of these organic compounds, albeit emitted in lesser amounts, are known human carcinogens such as benzo(a)pyrene. Wood smoke is also generally released at ground level (as with a campfire) or from a relatively short chimney (less than 10 meters in height) where humans can be exposed to it with little atmospheric dilution.

Furthermore, over eighty percent of the mass of wood smoke emissions are in the particle size range of 0.1 to 1.0 micrometers (um) --sizes that are both easily ingested into the thoracic region (including both the tracheobronchial and alveolar regions) of the human body and highly efficient at scattering light which can produce local visible hazes. Wood burning emissions may become a more significant source of pollution with respect to air quality management programs in light of EPA's recent efforts to propose a National Ambient Air Quality Standard for particulate matter less than 10 micrometers in size; and also the Agency's efforts at studying the origins and solutions to local and regional visibility problems.

Lastly, under certain conditions, the odors of wood smoke may be unpleasant and a nuisance to some people.

To date, the air pollution resulting from residential wood combustion has generally been addressed in urban areas where the problems are most pronounced. For example, in 1979-80, in Medford, Oregon, woodsmoke contributed 86 percent to the worst case 24-hour fine particulate mass pollutant levels and 47 percent to the annual fine particulate mass levels.[1]

The National Park Service (NPS) is concerned that in some of the areas it manages, wood smoke from campfires, and residential fireplaces and woodstoves may produce air pollution problems that will have to be addressed and corrected. Yosemite National Park is one such Park Service unit, for example. Yosemite National Park has approximately one thousand campsites and several hundred wood burning stoves. Emissions from these sources can create hazes during the summer, fall and winter months.

Presently, the National Park Service does not have any control program to address these wood burning emissions. This paper briefly explores what the NPS (or any other agency) can do to quantitatively determine if a residential wood combustion problem exists in a local airshed and what can be done to manage and control this type of problem. This paper will discuss wood combustion and emissions of pollutants; health effects of these pollutants; ambient monitoring and modeling to quantify the woodburning emissions contribution to overall pollution levels; strategies and tactics for controlling these emissions; and a recommended course of action for the NPS to address this potential problem.

WOOD COMBUSTION AND AIR POLLUTANT EMISSIONS

Wood is composed mostly of carbon (about 50% by weight), oxygen (about 44% by weight) and hydrogen (about 6% by weight) with minor amounts of ash, sulfur and nitrogen.[2] Wood combustion has been categorized to occur in four stages.[3] In the first stage, with temperatures in the range of 200-250°F, water in the wood vaporizes. As temperatures increase to 500-750°F, the second stage of wood pyrolysis (or thermal degradation) occurs. Gaseous, volatile and tarry products as well as charcoal are produced. These two first stages are endothermic and require energy to be added to sustain the reactions. The gaseous and volatile components begin burning above 1100°F (the third stage) while charcoal burns in air between 1200-1800°F (the fourth stage). The third and fourth stages are exothermic and liberate energy, which provides heat and energy to sustain the combustion process.

The compounds formed during combustion are a function of the available air and temperature. Carbon dioxide and water are the major products of complete combustion (along with some minor components such as ash, sulfur oxides and nitrogen oxides). However, should the temperature and available air in the combustion region fall below the level required for complete combustion, unoxidized volatile organic compounds and aerosols are emitted as smoke. It is this incomplete combustion that produces the air pollutants and associated health and welfare problems. The unburned organic compounds also represent a waste of the chemical energy stored in the wood. When these compounds condense on the walls of a chimney they create the potential for creosote chimney fires. Thus, health, energy efficiency and safety are major issues associated with wood combustion pollutants.

Table I summarizes the emission factors for various pollutants.[4] The numbers represent the mass of the pollutant emissions per unit mass of wood burned. Carbon monoxide (CO), volatile organic compounds, and particulate matter are the pollutants emitted in greatest quantities from fireplaces and wood stoves. Emissions from campfires can be approximated by using the fireplace emission factors. Actual campfire emissions are higher than the corresponding fireplace factors because campfires lack the fireplace's enclosure which reradiates heat and maintains a higher temperature promoting more complete combustion.

Furthermore, the moisture content of campfire wood may be much higher than that of fireplace fuel. Higher fuel moisture content produces greater emissions during combustion. The U.S. Forest Service has estimated that particulate emissions from campfires are more in the range of 20-30 grams per kilogram of fuel burned.[5]

Polycyclic organic material (POM) is a minor yet important, component of wood smoke. POM is a group of organic compounds which includes recognized human carcinogins such as benzo(a)pyrene (B(a)P). POM is a product of incomplete combustion and is often found on or in suspended smoke particulate matter.

Campfire, fireplace and wood stove emissions are quite variable and are a function of the stages of combustion during the burn cycle; the burn rate (i.e., mass of wood fuel burned per hour); wood type; wood moisture content; wood burning appliance type; log size; and the operating practices of the person using the stove, fireplace or campfire. The emissions vary with the above parameters generally in the following way:

<u>Burn Cycle</u> - Emissions are generally greater during the early stages of combustion during pyrolysis when the volatile organic matter is being driven off. The charcoal stage of the burn cycle is characterized by relatively clean emissions.

<u>Burn Rate</u> - Emissions are generally greater at the lower burn rates. The increase in emissions can be very significant when burn rates for stoves approach 2-3 kg/hr.[6] The burn rate can be controlled by varying the amount of wood used and, in the case of an airtight wood stove, by regulating the supply of combustion air to the stove's firebox. Thus, stopping down the stove's air supply to prolong the burning time of a load of wood can drastically increase the amount of air pollutants generated.

<u>Wood Type</u> - Hardwoods generally burn cleaner than softwoods because they contain less organic resins.

<u>Wood Moisture Content</u> - Burning very wet wood creates more emissions because pyrolysis and combustion are retarded until the water is evaporated. The smoldering conditions encourages incomplete combustion and the formation of unburned organic compounds. The moisture content of wood is a function of the wood type and amount of time it has been allowed to season (i.e., to dry).

<u>Appliance Type</u> - Table I indicates this variation in emissions. Each appliance has features that vary the time-temperature-and-turbulence factors that affect the efficiency of combustion and air pollutant generation.

Log Size - The wood piece size affects the burn rate. Small pieces of wood will generally increase the burn rate and reduce emissions.

Operator Practices - The person controlling the wood burn can affect the emissions by controlling the burn rate, moisture content, log size, etc.

HEALTH EFFECTS

Emissions from residential wood burning sources represent a potential threat to public health because of their small particle size which makes them respirable; the chemical composition of the emissions which include carbon monoxide, particulate matter, and organic compounds, some of which are known carcinogens and toxic substances; and lastly because the emissions are released at low levels in residential areas where public exposure is great.

Carbon monoxide (CO) is a chemical asphyxiant which interfers with oxygen dissolution in the blood. Persons with existing heart disease are at greatly enhanced risk when exposed to CO. Particulate matter produces short term irritation to chronic diseases depending on the chemical composition, concentration and exposure. The organic compounds are irritants and precursors to the pollutant ozone which is formed in the atmosphere. A small portion of the organic wood burning emissions are carcinogenic, cilia toxic, mucus coagulating, co-carcinogenic, toxic and noxious.[7] However, more animal cancer and human epidemiology studies need to be undertaken to better quantify the human health risks of wood smoke.[8]

HOW TO DETERMINE IF RESIDENTIAL WOODBURNING EMISSIONS ARE IMPACTING A LOCAL AIRSHED

Many urban areas such as Portland, Eugene and Medford, Oregon; Missoula, Montana; Chattanooga, Tennessee; Bangor, Maine;[9] Denver and Vail, Colorado and Alburquerque, New Mexico[10] have undertaken ambient air monitoring and modeling analyses to quantify the impact residential woodburning emissions have on the area's air pollution levels. These urban studies are of use to the National Park Service if and when the woodburning contribution to air pollution must be determined within any given NPS unit.

The ambient air quality analyses often involve a combination of ambient air quality monitoring and analytic and/or statistical methods commonly referred to as "receptor models".[10, 11, 12, 13, 14, 15, 16, 17] Based on the data collected at air quality monitoring sites (or receptors), receptor models can quantify a source's contribution (such as woodburning) to the measured air quality and also indicate the importance of that source relative to the others producing an impact at the monitoring sites.

First, a suggested monitoring approach for collecting the ambient data required by the receptor models will be discussed. Next, an assortment of receptor models of use in woodburning air quality impact studies will be summarized and last, other approaches such as surveys and diffusion models will be addressed.

Ambient Air Monitoring

Dr. Robert Stevens has outlined a collection of ambient air quality monitors and measurements of use in assessing residential woodburning impacts on air pollution levels.[10] This collection is illustrated in Figure 1 and includes:

1. Fine Particle Monitors

   Two samplers, such as dichotomous samplers, would be used to collect fine particles (less than 2.5 um in diameter). One sampler would collect fine particles on Teflon filters and the other simultaneously would collect the fine particles on quartz filters. The fine particle total mass; the elemental composition of the fine particles (as determined, for example by X-ray flourescence analysis); sulfate and nitrate levels; and light absorption coefficient (Babs) of the aerosols are determined by analysis of the Teflon filters. Organic and elemental carbon measurements can be obtained by analysis of the matter collected on the quartz filters. The fine particle mass measurements correlate with visual range and visibility degradation. The elemental composition of the aerosol is used in receptor models, such as chemical mass balance, to distinguish the woodburning contribution from that of automobiles and other pollution sources. Analyzing the filter material for anions and cations such as sulfates and nitrates helps account for the origin of all the fine particle mass on the filters. Light absorption coefficient measurements correlate well with the fine black carbon soot collected on the Teflon filters.

   Last, the organic and elemental carbon measurements help distinguish between the filter material caused by woodburning and automotive sources.

2. Carbon Monoxide (CO) Monitoring

   Measurements of CO concentrations indicate whether campfire and wood space heating emissions may produce CO emissions in excess of unhealthy levels. Furthermore, comparing CO data with nephelometer measurements (below) collected during the same time period assists in determining whether woodburning is the principle source of CO emissions.

3. Integrating Nephelometer

   The nephelometer measures the light scattering caused by fine particles. Wood burning emissions are characterized by fine particles and the increase in fine particles caused by wood burning would be reflected in the nephelometer data. Such data is also relevant to the variation in visual range and visibility.

4. Source Signature Monitoring

   The above measurements characterize the properties of the ambient aerosol. Receptor models also require source emission characteristics data that define the chemical composition and variability of the source's emissions to the atmosphere. These data define the source's emission "signature" and much fireplace and woodstove source monitoring data are presently available for use in receptor modeling studies.[10, 12] Thus, source monitoring may not have to be performed because of the existing source emissions data base. However, because source signatures are highly dependent on combustion temperature, it may be necessary to make such measurements for typical campfires.

Receptor Models

Receptor models estimate source contributions given ambient observations made at the sampling (or receptor) site. A variety of receptor model source apportionment techniques have been employed to identify the ambient air impacts from residential wood burning.[10, 11, 12, 13, 14, 15, 16, 17, 18] The following are among the most useful tools for a woodburning impact analysis:

1. Chemical Mass Balance (CMB)

   This technique compares the elemental composition of the particulate matter collected by the ambient air sampler with elemental contributions from various air pollution sources and estimates the sources' contribution to the collected ambient particle mass. CMB attempts to match the sources chemical "signature" or "fingerprint" of those measured at the receptor. By superimposing source emission fingerprints one can generate a profile that resembles the ambient aerosol fingerprint. The types and relative mix of sources are thus identified during this superposition. CMB can be applied to data from a single sample and to data collected from a short term (less than 24 hour) sample. Thus, CMB can be applied to analyze source contributions to actual worst case 24 hour or air pollution episode conditions.

2. Multivariate Techniques

   These techniques include factor analysis, regression methods, target transformation factor analysis and cluster and principle component analyses. These methods investigate the variability of chemical elements or species as measured on a large number of particulate filters. The underlying assumption is that the time and spatial variations of chemical species concentrations measured at the receptor and attributed to a specific source will be similar. Source identity is determined by comparing species of similar variability to the chemical emission signatures of specific sources.[19] This family of techniques has the advantage of being able to include other measurements such as light scattering, meteorology, and gaseous pollutants.

3. Radiocarbon (^{14}C) Dating Techniques

   Carbonaceous material much older than the ^{14}C half life of 5730 years, such as fossil fuels (and the particulates resulting from fossil fuel combustion), contain essentially no ^{14}C. All living material and matter that has been dead for a short time contain an equilibrium amount of ^{14}C. Therefore, ^{14}C is an unique tracer of carbonaceous aerosols emitted from modern sources such as woodburning. Dr. L. Currie, et.al.,[18] have developed a ^{14}C analytical technique that can be used to determine how much carbon has its origin in fossil fuel versus wood and vegetative burning sources.

4. Enrichment Factor Models

This model considers ambient aerosol chemical element composition data to provide an estimate of how a specific element has been "enriched" by an air pollution source's emissions relative to some reference material. In the case of woodburning, the potassium to iron (K/Fe) ratio measured from the chemical composition of collected aerosol particles has been compared to the corresponding ratio in crustal material. This technique can estimate the average fine particle wood smoke impact.[20]

5. Elemental and Organic Carbon Measurements

Elemental (soot) and organic (non-soot) carbon measurements can be used to distinguish woodburning sources from automotive sources such as diesel exhaust.[15, 21]

6. Pattern Recognition Using Nephelometer Data

Nephelometers record the light scattering caused by fine particles. Because most of the particules emitted in wood smoke are less than 2.5 um in size, the nephelometer can qualitatively be used to document wood burning impacts. Kowalczyk and Green reported that the key signs indicating wood smoke impacts are increasing nephelometer readings beginning about 4:00 p.m. and peaking in the 7:00 to 11:00 p.m. time period.[22]

Other Approaches

1. Surveys

Surveys of people who burn wood can be very important in order to determine the amount of emissions resulting from residential wood combustion. The following types of information can be requested during the survey of stoves, fireplaces or campfires: Type of wood used, wood moisture content, refueling frequency, total amount of wood consumed, number of stoves, fireplaces, campfires, method of operation (i.e., how the individual operates the stove), supplier of the wood, how wood is stored, etc. The states of Oregon and Colorado have used surveys to collect these woodburning data.[23, 24] The survey data can be used to generate an emissions inventory which in turn can be used as input to an air quality dispersion model.

2. Source Oriented Dispersion Models

Air quality dispersion models simulate the transport and diffusion of air pollutants emitted from a source. These models start with source emissions and meteorological data and predict ambient pollutant concentrations at selected receptors.

This approach is useful for evaluating the benefits of alternative air pollution control strategies, new source growth and predicting future air quality. However, for woodburning sources and other area and fugitive emissions, predicting variation of emissions with time and the usual uncertainties in air quality models make this approach valuable only if used with care.[25]

TACTICS AND STRATEGIES FOR REDUCING RESIDENTIAL WOOD COMBUSTION EMISSIONS

Many state and local governments are developing strategies and tactics to reduce the air pollution problems caused by residential wood burning.[26, 27, 28, 29, 30] The National Park Service will benefit from their experiences because some of these control approaches are relevant to the situations found in the Parks. A summary of the relevant tactics and strategies are presented below.

1. Wood Burning Stoves

Emissions from stoves vary strongly with the manner in which they are operated. State and local authorities have instituted campaigns to educate the public on how to operate stoves (and other appliances) to minimize the formation of air pollutants and at the same time, to burn wood more efficiently, economically and safely. These educational programs recommend that the stove operator burn hardwoods rather than softwoods; burn dry, seasoned wood rather than wet, green wood; burn smaller loads of wood in a hotter fire; and finally, not burn garbage or coal (in some areas).

In response to emerging state regulations that will require new stoves to meet clean burning emissions standards, stove manufacturers are developing a new generation of woodstoves that promises to be less polluting, more heat efficient, and safer. In Oregon, it has been reported that a new high efficiency woodstove (70% efficient) will use 20% less wood than the average airtight wood stove (50-55% efficient) and produce the same heat output. The emission rates from these new design stoves can be 70-80% lower than those from average wood stoves. Consequently, the emissions per heat output of a new design wood stove is 75-80% lower than the average stove.[31]

The new stove designs[32, 33] employ both catalyst and non-catalyst technology to more completely combust the wood smoke. The catalyst technology, as in the schematic design of Figure 2, uses a ceramic honeycomb substrate coated with a platinum and/or palladium metal catalyst. This ceramic honeycomb catalyst causes unburned gases leaving the primary combustion zone to undergo a secondary combustion at a lower temperature. Equipment manufacturers are also in the process of developing catalyst devices capable of being retrofitted to existing stoves to reduce pollution emissions and boost heat output.[34] The issue of the level of effectiveness of these add-on catalytic devices to existing stoves is still under debate.

The advanced non-catalyst stove designs achieve secondary combustion by using smaller fireboxes, providing a source of secondary combustion air and insulating the secondary combustion chamber as illustrated in Figure 3.

2. Fireplaces

The above recommended operator practices for burning wood better in stoves also applies to fireplaces. Furthermore, there are design changes to fireplaces that can make them more efficient space heaters, such as glass doors, outside combustion air and fan assisted circulation. Open hearth fireplaces can use 20 times more air than is necessary for the complete combustion of the wood. This excess air is pulled from the room and drawn up the chimney. Glass doors limit the heat loss of warm room air up the chimney and are most effective when the fire is burning slowly or out. Using outside air as the combustion air source rather than room air and a fan to increase hot air circulation can increase the fireplace's efficiency. Using the above three design changes can increase fireplace efficiencies from -10% to 15-35%.[35] One last tactic worth mentioning is the use of wood stove inserts in fireplaces. Such inserts have efficiencies in the range of 35-55%.[35]

The above control tactics for stoves and fireplaces will result in less emissions to the atmosphere, less wood burned to produce a given heat output, and reduce the buildup of creosote and corresponding chance for chimney fires and property damage.

3. Campfires

The practices for burning wood better in stoves are applicable to campfires too. Other approaches that would reduce campfire emissions include the prohibition of campfires during episodes of high air pollution levels, limiting the number of campfires allowed in campgrounds, allowing campfires in selected campgrounds on a rotating basis, charging fees for campfires or wood, burning seasoned dry firewood and covering stored wood.

4. Regulatory Strategies

States such as Oregon and Colorado, and cities such as Missoula, Montana, and Aspen and Vail, Colorado, have developed regulatory strategies designed to control pollution from wood burning. These strategies include requirements for:

a. Public education programs that instruct individuals on the how and why of burning wood better,

b. The weatherization of residences to reduce space heating fuel consumption. (Less fuel consumed means less air pollution.)

c. The establishment of new stove emission standards and a program that certifies which specific wood stove models meet these emission limitations. (These emission standards create a market for low polluting stoves and force the technology to be developed to meet these requirements.)

d. New wood stoves to be labeled with information on the appliance's emissions and efficiency, thus providing the consumer with valuable information prior to the purchase,

e. Development of design criteria for new less polluting, more efficient fireplaces,

f. Voluntary and/or mandatory curtailment of wood burning during episodes of high air pollution levels, and

g. The limiting of the number of new fireplaces and stoves in new buildings.

The above strategies could be adopted in part by the National Park Service if needed. Public and employee education campaigns, energy conservation initiatives, purchase of newer low polluting wood burning appliances that meet strict State emission limitations, and curtailments of woodburning during air pollution episodes all appear feasible if the need for such measures is warranted.

A RECOMMENDED COURSE OF ACTION FOR THE NATIONAL PARK SERVICE

The Air and Water Quality Division of the NPS should survey individual park units to identify areas with potential woodburning problems caused by campfires and residential stoves and fireplaces. Information on the number, type and location of wood smoke sources, type and amount of wood burned, and the manner in which the fire is tended would be collected during this survey.

Based on the results of the survey and discussions with Park Superintendents and staff, a limited monitoring program should be implemented by the Air and Water Quality Division at one park during the wood smoke season. Such monitoring data would quantify the seriousness of the air pollution problem and the wood smoke contribution to this problem.

The Air and Water Quality Division and park units affected by wood smoke should develop a feasibile strategy for mitigating the emissions.

The Air and Water Quality Division should develop detailed guidance documents for all NPS staff on burning wood more efficiently, available air pollution control technology, applicable control strategies, etc.

Conclusion

A significant body of knowledge exists on the air pollution aspects of woodburning. The National Park Service can benefit from the combined experience of many states and localities should the NPS decide that a program to control wood smoke is warranted.

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TABLE I. EMISSION FACTORS FOR FIREPLACES, WOOD STOVES AND CAMPFIRES.

Pollutant	Fireplaces[a] g/kg	Wood Stoves[b] g/kg	Campfires[c] g/kg
Particulate	14[d]	21[e,f]	20-30
Carbon Monoxide	85	130[f]	
Volatile Organic Compounds (VOC)			
Methane	-[g]	0.5	
Nonmethane	13	51	
Sulfur Oxides	0.2	0.2	
Nitogen Dioxide	1.7	1.4	

[a] Reference 4, p.1.9-3. Based on tests burning primarily oak, fir or pine, with moisture content ranging from 15-35%.

[b] Reference 4, p.1.10-5. Based on tests burning primarily oak, fir or pine, with moisture content ranging from 15-35%.

[c] Reference 5. Campfire emissions can be approximated by using fireplace emission factors.

[d] Polycyclic Organic Matter (POM) is carried by suspended particulate matter and has been found to range from 0.017-0.044 g/kg which may include benzo(a)pyrene [B(a)P] of up to 1.7 mg/kg

[e] POM has been found to range from 0.19-0.37 g/kg which may include B(a)P of up to 1.4 mg/kg.

[f] Emissions were determined at burn rates of 3 kg/hr or less. If greater than 3 kg/hr, emissions may decrease by as much as 55-60% for particulates and VOC, and 25% for carbon monoxide.

[g] Dash = no data available.

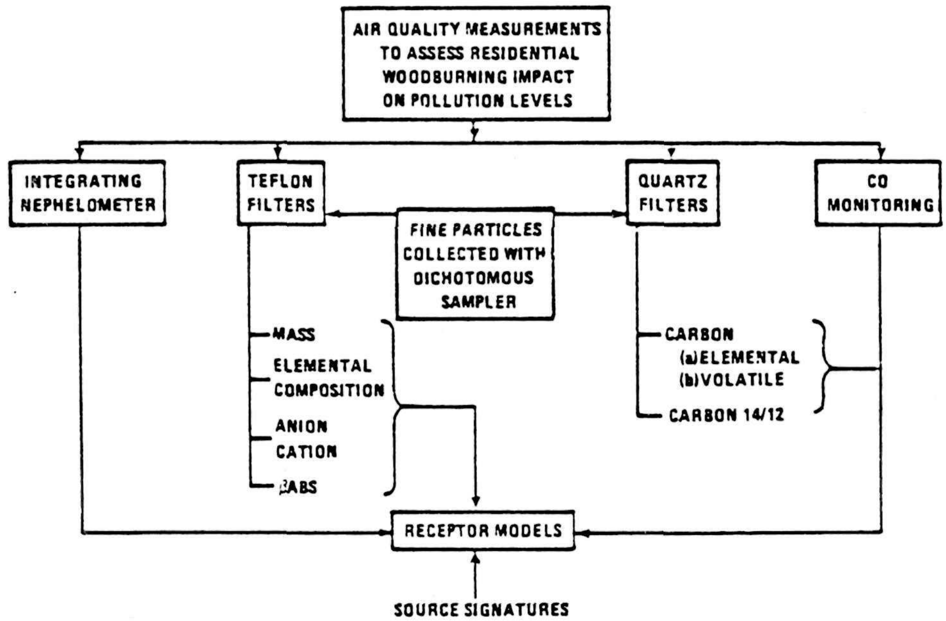

Figure 1. Flow diagram of sampling and analysis needed to support receptor modeling related to residential wood burning. (R. K. Stevens - Reference 10).

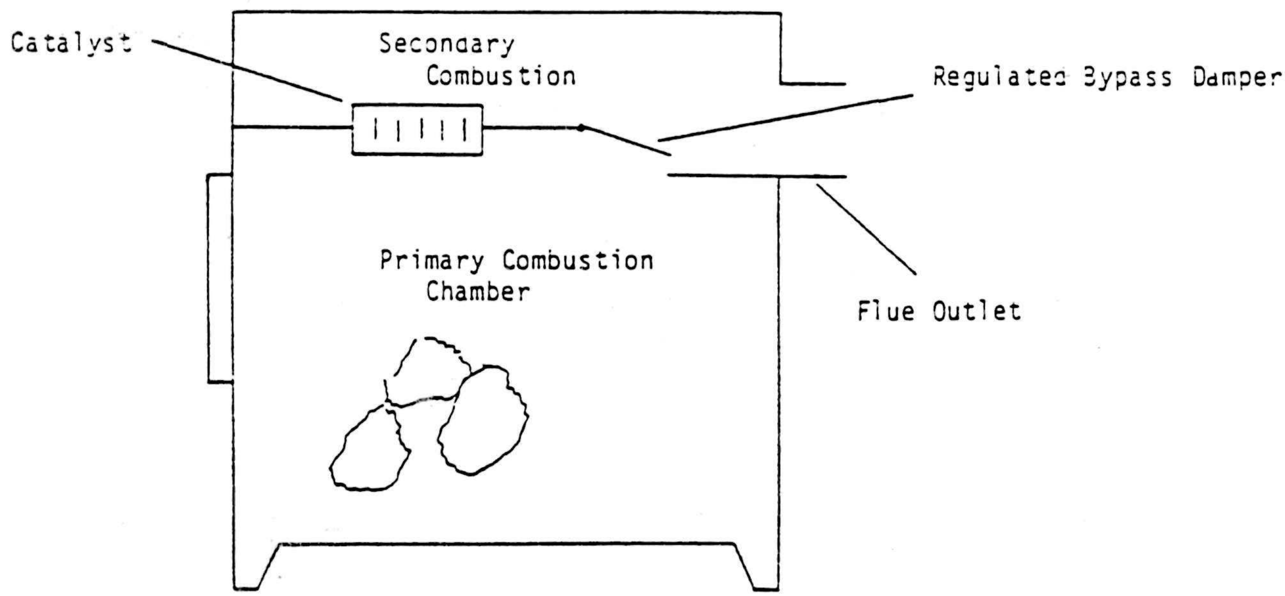

Figure 2. Catalyst design wood stove.
(Reference 3.)

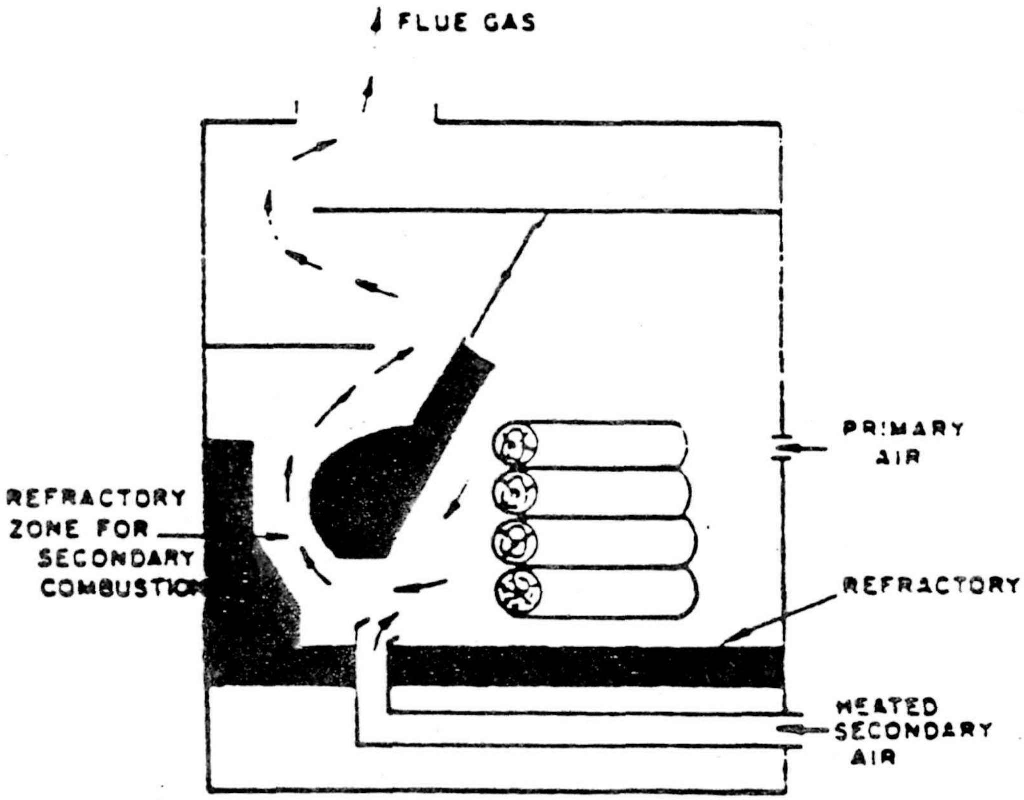

Figure 3. Non-catalyst design wood stove.
(A.C.S. Hayden and R. W. Bratten - Reference 2.)