Residential Wood Combustion— $PM_{2.5}$ Emissions

Prepared by:

James E. Houck and Paul E. Tiegs
OMNI Environmental Services, Inc.
5465 SW Western Avenue
Beaverton, Oregon 97005

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Woodstoves and Heaters

- Conventional Woodstoves

  40 year lifetime
  8.3 million in use or about 90% of total

- Certified Noncatalytic Woodstoves

  0.6 million in use
  Phase II, July 1990, 7.5 g/hr, 119 models

- Certified Catalytic Woodstoves

  0.4 million in use
  Phase II, 4.1g/hr, 83 models
  Durability, maintenance program

- Certified and Exempt Pellet Stoves

  0.3 million in use
  5 certified models
  35 to 1 air- to-fuel ratio (low burn rate)
  Suspected lower $PM_{2.5}$ to total ratio

- Masonry Heaters

  Higher cost, few in use, exempt from EPA certification
  High burn rate, lower emissions
  Colorado standard

- Fireplace Inserts (pellet, certified cordwood and gas)

  0.5 million certified cordwood inserts (27 million fireplaces)
  0.2 million pellet inserts
  4 catalytic and 6 non-catalytic models certified
  Gas inserts and fireplaces, natural gas and LPG
  Efficiencies lower than free standing

- Retrofit Catalysts

  Add-on stack and internal retrofits
  Late 80's research
  Currently not a viable technology

Fireplaces

- Zero-clearance Fireplaces

  Manufactured metal fireplaces
  27 million fireplaces, about 80% are zero-clearance
  3rd most popular household amenity
  46% of single family detached homes have a fireplace
  40 year lifetime
  About 0.4 million sold in 1998

- Masonry Fireplaces

  About 20% of total
  Indefinite lifetime

- "EPA Fireplaces"

  Two appliance types referred to as "EPA fireplaces". These are: zero clearance certified woodstoves and appliances with a single burn emission measurement.

- Older Emission Reducing Technologies and Accessories

  Convection shells and tubes
  Shaped masonry fire chambers
  Glass doors

- Gas Burning Fireplaces

  Up vent fireplaces
  Direct vent
  Vent free
  About 0.5 million sold in 1998

- Decorative Gas Logs

  Vented
  Vent free
  About 0.5 million sold in 1998

Cordwood Weight

Category	Pounds/dry cord
Deciduous — alder, apple, ash, aspen, beech, white birch, yellow birch, cherry, cottonwood, dogwood, elm, hickory, ironwood, black locust, madrone, red maple, sugar maple, red oak, white oak, poplar, sycamore, willow	mean = 2689 σ_{n-1} = 619 n = 22 range 1728 — 3520
Conifers— Western red cedar, Douglas fir, grand fir, hemlock, juniper, Western larch, lodgepole pine, ponderosa pine, white pine, yellow pine, redwood, Engelman spruce, Norway spruce, Stika spruce	mean = 2007 σ_{n-1} = 323 n = 14 range 1648 — 2664
DOE	2326

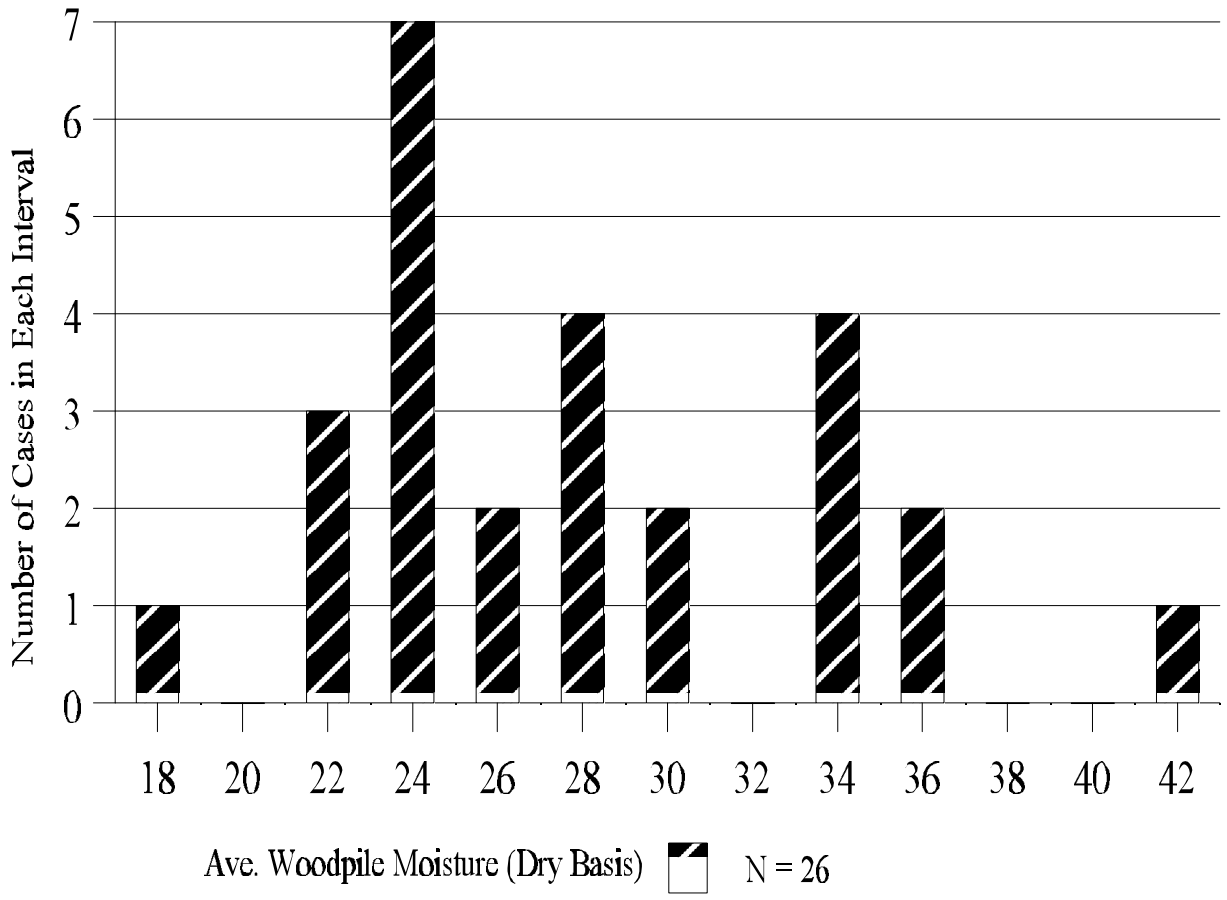
Heat Content of Cordwood

Category	Btu/pounds dry wood*
Deciduous — white ash, beech, white birch, elm, hickory, maple, black oak, red oak, white oak, poplar	mean = 8100 σ_{n-1} = 215 n = 10 range 7583 — 8315
Conifers — white cedar, cypress, Douglas fir, Western hemlock, pitch pine, white pine, yellow pine, redwood	mean = 8746 σ_{n-1} = 861 n = 8 range 7798 — 10,641
DOE	8875

* lower heating value

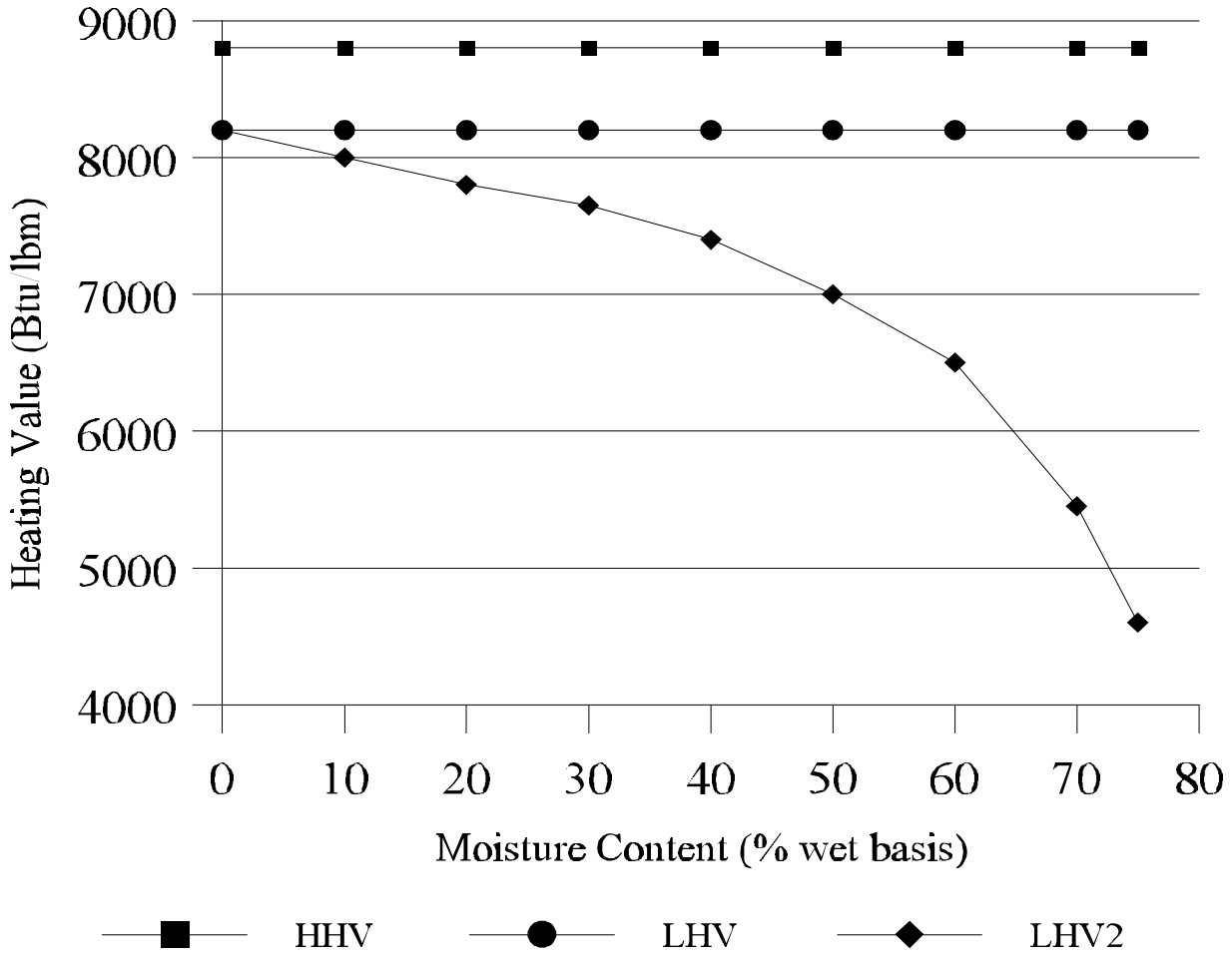
Distribution of Average Woodpile Moisture

Values (Dry Basis); 1988-89 NCWS



The Effect of Moisture on the Heating Value(s) of Wood Biomass.

Based on Douglas Fir with an Assumed Higher Heating Value of 8800 Btu/lbm.



Alternate Fuels

- Pellets

  Pellet Fuel Institute (PFI) fuel quality certification
  < 5% moisture

- Densified Logs

  Along with wax logs referred to as manufactured logs
  Woodstove and fireplace application
  Density of 1.1 to 1.3 g/cm^3 (cordwood 0.3 to 0.8 g/cm^3)
  < 10% moisture
  Lower emissions than cordwood
  Most brands 4 ½ inches in diameter
  Densified logs cost about 70% more than equivalent amount of cordwood

- Wax Firelogs

  Fireplace only application
  No kindling required
  60% wax and 40% sawdust
  100 million logs/year (0.8 million cord equivalents)
  Burned in 30% of fireplaces some of the time, exclusively in 12% of fireplaces
  Higher heating value 15,000 Btu/lb dry fuel as compared to 9050 for Douglas fir
  < 5% moisture
  Lower emissions than cordwood

- Gas

  17% of fireplaces use gas
  Liquified Petroleum Gas (LPG), 95% propane
  Natural gas, variable composition, 81% methane, 6% ethane, 2% propane, 9% nitrogen
  9.6 million gas hookups in homes in 1993 (8.8 million natural gas, 0.7 million LPG)
  Not renewable resource, fossil fuel

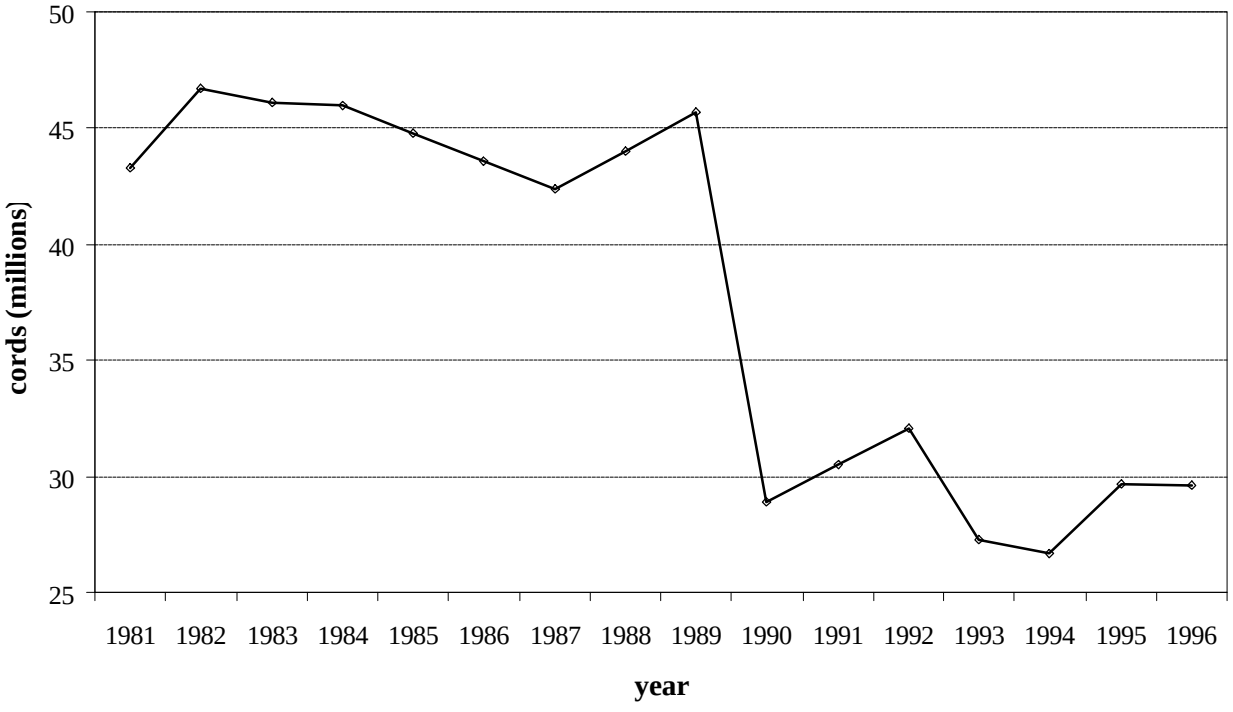
Home Heating by Energy Source (1993)

Energy Source	Quadrillion Btu	% of Total Energy	Millions of Households[b]	% of Total Households
Electricity	0.41[a]	7	37.1	38
Natural Gas	3.67	62	52.6	54
Fuel Oil	0.90	15	10.7	11
Kerosene	0.05	1	3.6	4
LPG	0.30	5	5.6	6
Wood	0.55	9	20.4	21
Total	5.88		96.6	

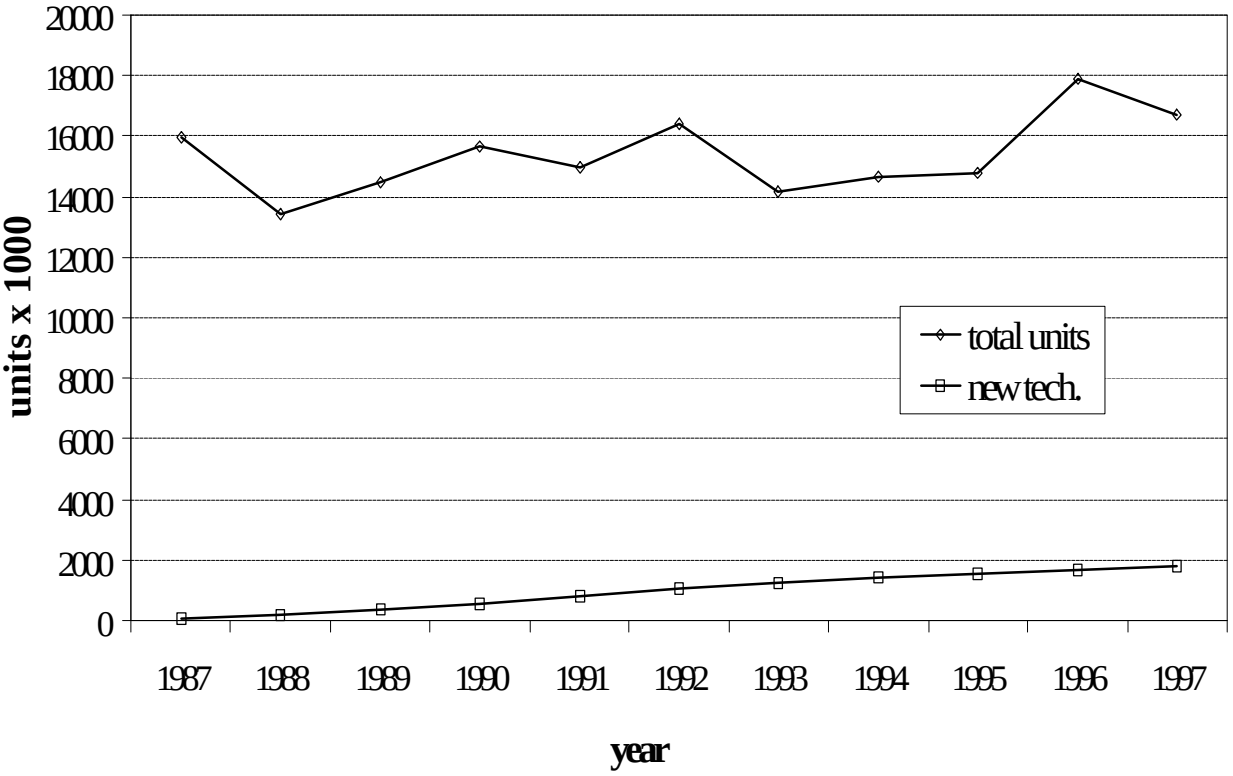
[a] 1.23 Btu required to produce 0.41 Btu at residences due to plant efficiencies and transmission line loses, 55% of electricity produced by coal.

[b] Many households have more than one type of heater

Cordwood Consumption by Year



Number of Total Units Compared to Number of Pellet and Certified Stoves and Inserts



Fireplace Use— Aesthetic and Heating

- Not Used or Not Used with Wood

  27 million fireplaces 20.4 million reported burning wood in last year (1993)

- Aesthetic and Minor Heating

  9.6 million <0.5 cord (1993)
  5.6 million < one hour per week (1993)

  17% once or twice a season (1994/1995)
  13% once or twice a month (1994/1995)
  18% once or twice a week (1994/1995)
  Sum 17%+13% + 18%, 13 million fireplaces

  Typical burn rate 6 lbs/hr

- Fireplaces Used as a Heat Source

  0.4 million used a fireplace as a primary heat source (1993)
  Efficiency for open radiant fireplace 7%
  Efficiency with doors and convection designs up to 40%
  7.1 million reported having inserts (1997)

Regional and HDD Correlations

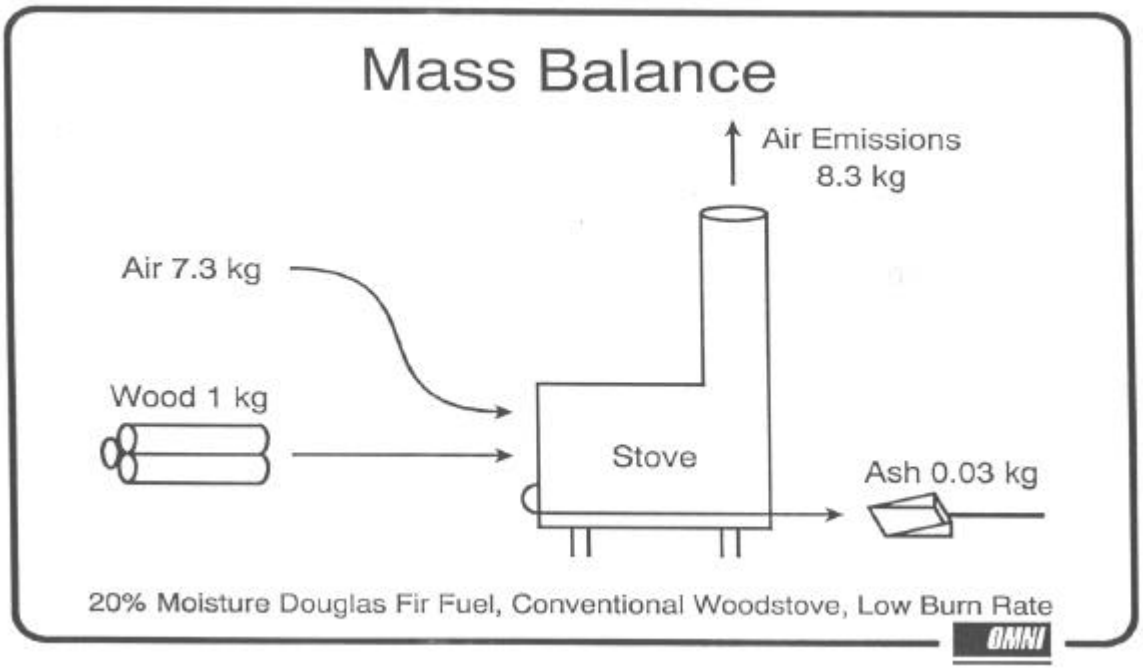
Average Cords per Wood Burning Household

Total U.S.		1.3		
By Region	Northeast	2.1		
	Midwest	1.4		
	South	1.2		
	West	1.1		
By Urban Status	Central City	0.6		
	Suburban	1.1		
	Rural	1.9		
By HDD	>7000	3.0	Flagstaff	7152
	5500-7000	1.2	Boise	5809
	4000-5499	1.3	Portland	4635
	<4000 (<2000 CDD)	1.1	Fresno	2611
	<4000 (>2000 CDD)	0.8	Phoenix	1765

Science (1983), v. 219, p. 1425

1978-79 heating year, 34.7×10^6 cords (29.6×10^6 cords 1997)
Cords per household = [3.087- 0.322 ln (pop. density per sq mile)] x [HDD x 10^{-4}]

Spokane County 1990 pop. 361,330, 1769 square miles, 6655 HDD
⇒ 1.5 cords per wood burning household


Mass Balance
Air Emissions
8.3 kg
Air 7.3 kg
Wood 1 kg
Stove
Ash 0.03 kg
20% Moisture Douglas Fir Fuel, Conventional Woodstove, Low Burn Rate
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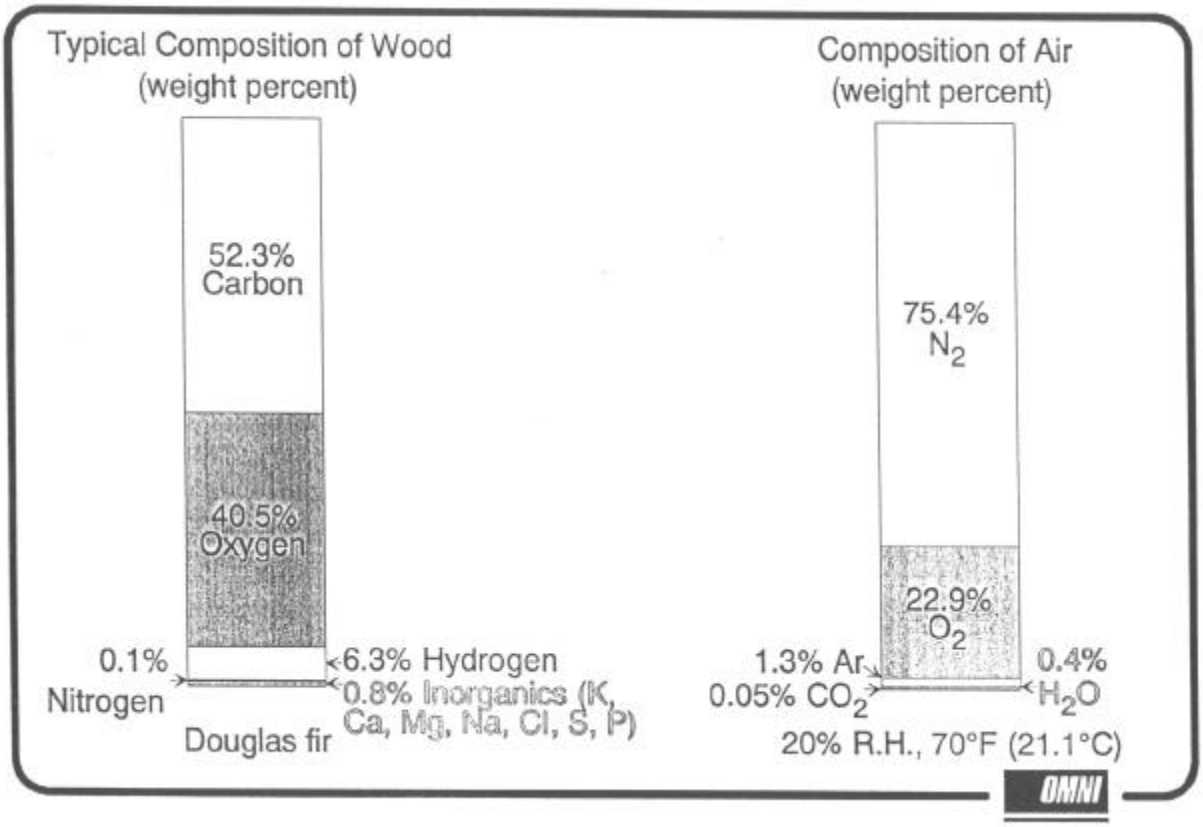
Typical Composition of Wood
(weight percent)
52.3%
Carbon
40.5%
Oxygen
0.1%
Nitrogen
6.3% Hydrogen
0.8% Inorganics (K, Ca, Mg, Na, Cl, S, P)
Douglas fir
Composition of Air
(weight percent)
75.4%
N_2
22.9%
O_2
1.3% Ar
0.05% CO_2
0.4%
H_2O
20% R.H., 70°F (21.1°C)
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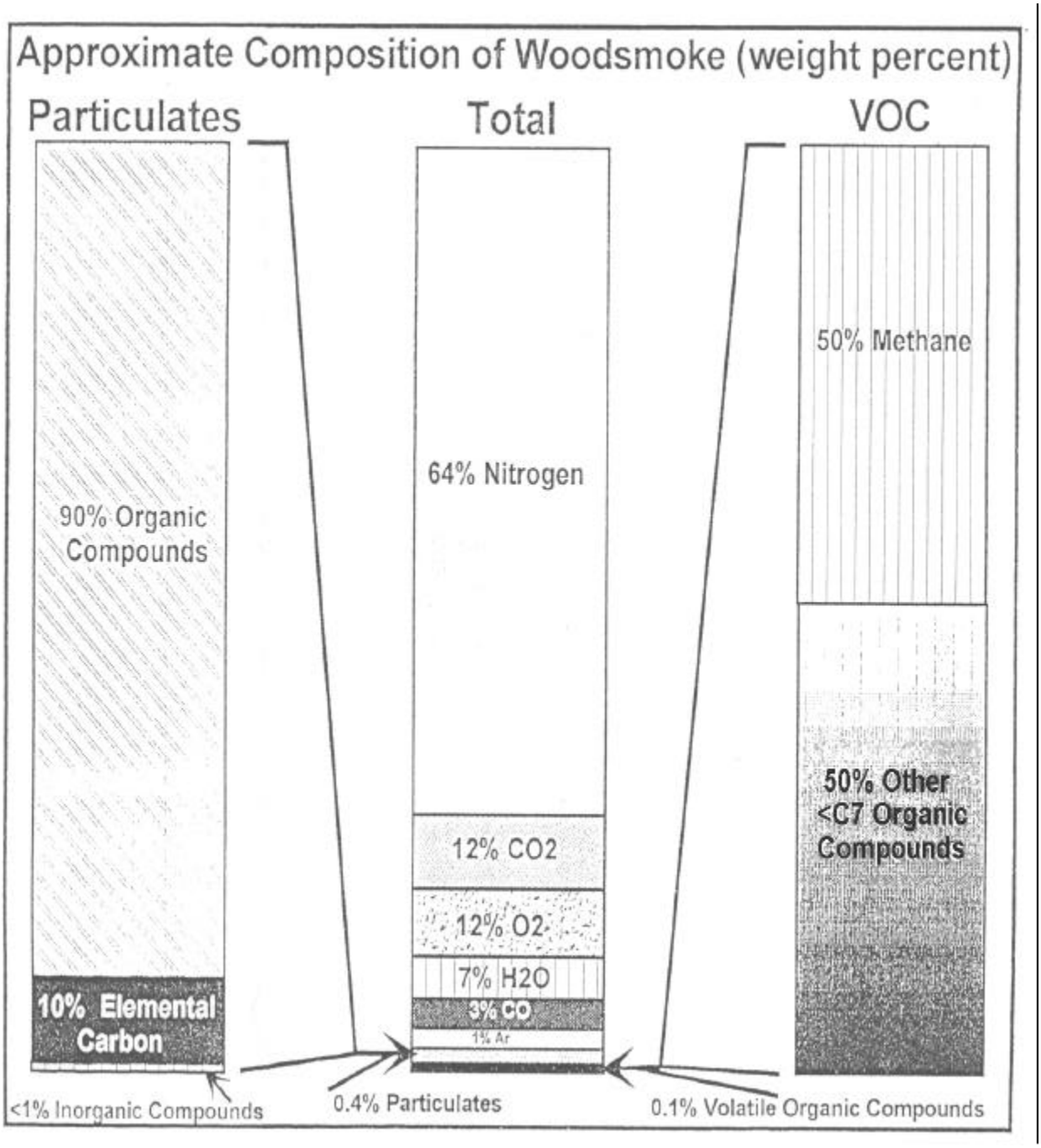
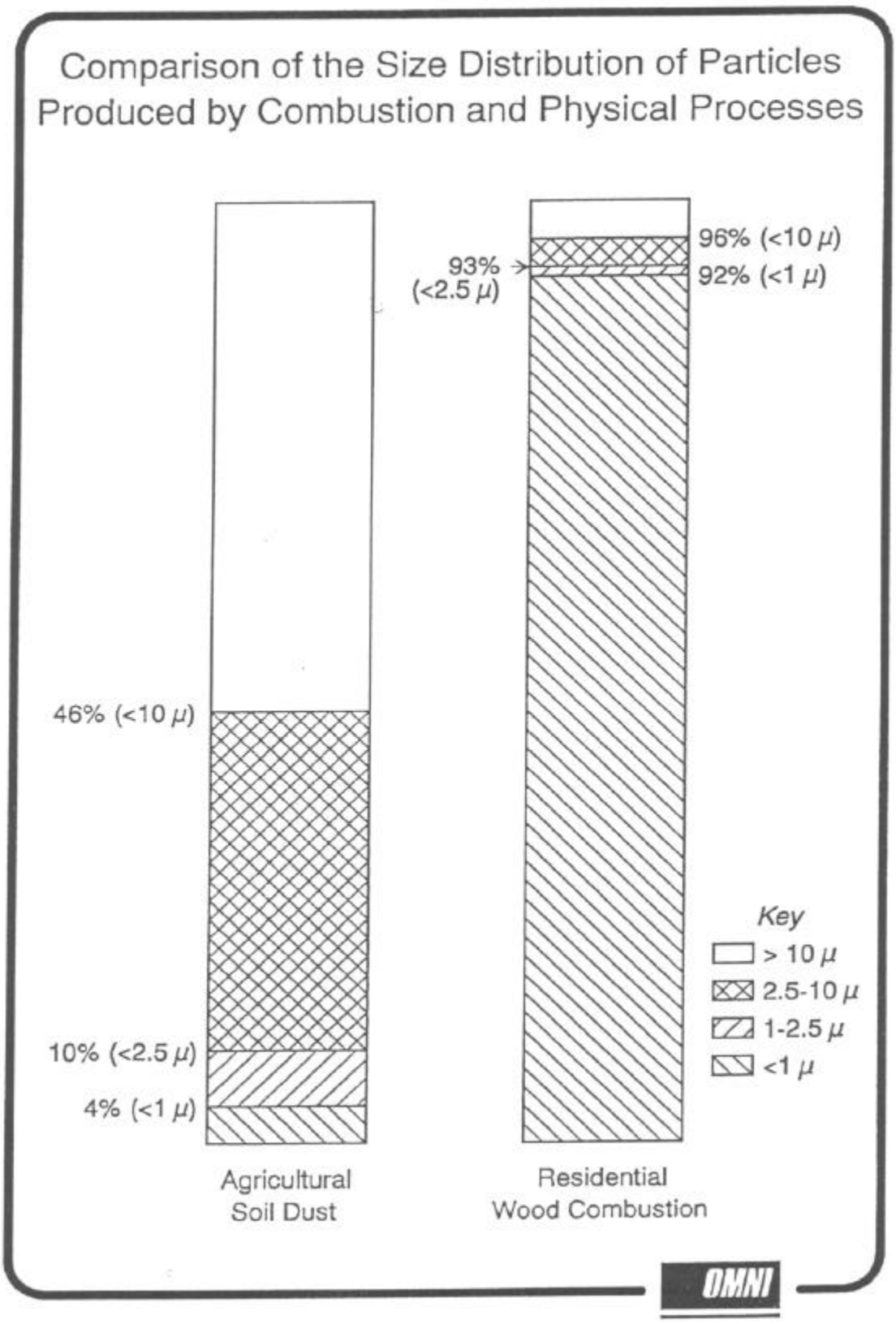

Approximate Composition of Woodsmoke (weight percent)
Particulates
Total
VOC
90% Organic Compounds
10% Elemental Carbon
64% Nitrogen
12% CO2
12% O2
7% H2O
3% CO
1% Ar
50% Methane
50% Other <C7 Organic Compounds
<1% Inorganic Compounds
0.4% Particulates
0.1% Volatile Organic Compounds


Comparison of the Size Distribution of Particles
Produced by Combustion and Physical Processes
46% (<10 μ)
10% (<2.5 μ)
4% (<1 μ)
Agricultural
Soil Dust
93%
(<2.5 μ)
96% (<10 μ)
92% (<1 μ)
Residential
Wood Combustion
Key
> 10 μ
2.5-10 μ
1-2.5 μ
<1 μ
OMNI

Emission Units

- Emission Factors

  g/kg or lb/ton
  PM_{10} in AP-42 by appliance type
  $PM_{2.5}/PM_{10}$ about 0.97 and $PM_{2.5}$/total PM about 0.93 except for pellet stoves & current EPA fireplace work
  Adjustment for efficiencies
  Temperature effect (e.g., 5G vs 5H)

- Emission Rates

  g/hr
  Stove certification values in g/hr — not representative of real world
  Emission rates useful for fireplace emission inventory and for comparison of alternatives to cord wood in fireplaces because of more or less fixed fireplace burn rate (about 3 kg/hr) and fixed burn rates of alternatives. (17.3 g/kg x 3 kg/hr = 51.9 g/hr)

- Mass of Emissions per Unit of Heat Delivered

  g/MJ or lb/million Btu
  Useful for comparison of wood heater alternatives because it takes efficiency into consideration, i.e, an effective emission reduction because less fuel is used

AP-42 PM_{10} Emission Factors (5H equivalent, g/kg)

Category	Wood Stoves			Pellet Stoves		Masonry Heaters	Fireplace
	Conv.	Non-cat.	Cat.	Certified	Exempt		
Pre-Phase I	15.3	12.9	12.1				
Phase I		10.0	9.8				
Phase II		7.3	8.1	2.1			
All	15.3	9.8	10.2	2.1	4.4	2.8	17.3

Comments on AP-42 Emission Factors

- Assumes all PM = PM_{10}
- $PM_{2.5}$ = 93% of PM for RWC, pellet stove $PM_{2.5}$ fraction smaller
- 89% of wood heaters are conventional wood stoves
- 8% of wood heaters are certified stoves
- 3% of wood heaters are pellet stoves
- Negligible number of masonry heaters
- Phase I certified woodstoves about 28% of the total number of certified stoves manufactured to date, if all in place about 2% of total number of wood heaters, all are 6 to 11 years old.
- Number of pre-phase I catalyst and high tech non-cat. (viz, Oregon certified) negligible, 8-13 years old.
- Ratio between the number of certified cat. and certified non-cat. stoves about 30:70.
- Phase II emission factors for cat. and non-cat. stoves based on 1990 or earlier field studies. New Phase II <u>at least</u> 1 g/kg less than older models, many are even better.
- Certified pellet stove emission factors are for phase I stoves tested in 1989 not phase II stoves as shown in AP-42. Emission factors for exempt pellet stoves based on 1990 field studies. Many early models of pellet stoves (89-90) had durability problems. These represented about 13% of the total number of pellet stoves manufactured to date, most of these are not now in use. New certified and exempt pellet stoves have about the same emissions which are lower than the old certified value. The 35:1 air to fuel ratio only needs to be shown at the low burn rate for exemption.
- Cat. stove emissions w/o cat. replacement equal to conventional stove emissions in 3 to 5 years depending on climate.
- Fireplace emission factor between 5G and 5H values depending on ambient temperature. The g/hr emission rate can be used for emission inventory due to typical mean burn rate of about 3 kg/hr.

A. CERTIFICATION PROGRAM TIMELINE

July 1, 1988

All wood heaters manufactured after July 1, 1988:

1) must meet Phase I emission limits
2) must have a temporary and permanent label

(NOTE: "Small" manufacturers (<2000 units) have a one-year extension for manufacturing until July, 1989.)

July 1, 1990

All wood heaters manufactured after July 1, 1990 must meet Phase II emission limits.

All wood heaters sold after July 1, 1990 must meet Phase I or II emission limits.

All wood heaters sold after July 1, 1992 must meet Phase II emission limits.

A "grandfathering" provision was included in the NSPS to allow manufacturers with models certified to the Oregon standards to be EPA Phase I certified without re-testing. Applications had to be submitted and approved by the EPA.

Development of Conventional Wood Stove Emission Factor

Study	Dates	Fuel	HDD	no. of runs	no. of stoves	burn rate (kg/hr)	5G emis. fac. (g/kg)	5H emis. fac. (g/kg)
VT & NY	85/86 & 86/87	Decid.	8269	14	6	1.65	8.50	10.70
Portland, OR	86/87	Mix	4635	12	4	1.19	12.05	15.14
Whitehorse, Yukon	86/87	Conif.	9545	53	16	1.45	10.56	13.11
Klamath Falls, OR	89/90	Conif.	6600	3	3	1.84	17.0	21.1
Crested Butte, CO	88/89 & 89/90	Conif.	11,500	59	11	1.48	14.91	17.88
AP-42								15.3
Weighted avg. by runs (n = 141)						1.46	12.3	15.2

Recommended Emission Factors for Wood Heaters (g/kg)

Percent in Use	Category	$PM_{2.5}$ Emission Factor
89	Conventional	.93 x 15.3 = 14.2
3	Pellet (exempt & certified)	.93 x 2 = 1.9
4	Phase II non-cat.	.93 x 6.3 = 5.8
1	Phase I non-cat.	.93 x 10.0 = 9.3
negligible	Pre-phase I non-cat.	.93 x 12.9 = 12.0
2	Phase II cat.	.93 x 6.3 = 5.8 (new) .93 x 15.3 = 14.2 (> 3 to 5 yrs).
1	Phase I cat.	.93 x 15.3 = 14.2*
negligible	Pre-phase I cat.	.93 x 15.3 = 14.2*
negligible	Masonry heater	.93 x 2.8 = 2.6

* Unless catalyst has been replace within the last 3 to 5 years

Recommended Emission Factors/Rates for Fireplaces

Method	Temperature	Emission Factor (g/kg)	Emission Rate at 3 kg/hr burn (g/hr)
5G	<90°F	13.7	41
5H	<32°F	17.3	52

- Extrapolate between 32°F and 90°F
- Emission rate and emission factor provide independent check for emission inventory

Example Relevant Surveys

- Klamath Falls Wood Heating Survey, 1991
- Oregon Wood Heating Survey for 1987, Klamath Falls Area
- Pocatello Air Quality RWC Device Usage, 1991
- Medford Area Wood Heating Survey, 1985
- Portland Area Wood Heating Survey, 1982
- Portland Area Wood Heating Survey, 1985
- Washington State Department of Ecology, Wood Smoke Pollution Survey, 1985
- Evaluation of Residential Wood Energy Use in Idaho, 1985
- 1983 Wood Cutting Permit Survey, Missoula, Montana
- 1986 Missoula Wood-Use Survey
- Study of Firewood Sources and Costs in Klamath Falls, Oregon and Sandpoint Idaho, 1992
- Developing a Residential Wood Combustion Emission Inventory and Profile of Wood Burning Practices for Fairbanks, Alaska 1984
- Portland, 1993 Oregon Woodheating Survey
- A Survey of Residential Combustion of Wood and Coal in Colorado, 1985
- Denver Metro Woodburning Survey, 1988

Survey Statistics

Number or responses needed given by:

$n = (Z_{1-\alpha/2}\ \eta/d_r)^2$, where,

$Z_{1-\alpha/2}$ = the standard normal deviate,

η = is the relative standard deviation, i.e., the true standard deviation of a population divided by the true population mean, and,

d_r = the relative error desired.

The relative standard deviation for wood usage in cord wood stoves and fireplaces must be estimated from other studies.

An example of the number of homes needed in Klamath Falls for a firewood use survey was 148. There were an estimated 9750 wood burning households (total number of households were 19,500) in Klamath Falls at the time of the study. 148 responses provided an estimated 10% relative error around the mean at a 95% confidence level.

Key Survey Questions/Pitfalls

- Number of Fireplaces and Wood Heaters and Wood Used in Them Recorded Separately
- Fireplace Inserts Often Confused with Zero-Clearance Fireplaces
- Age of Catalyst Stove, Catalyst Replaced?
- Species of Trees Used for Firewood
- Hours of Fireplace Operation as well as Cords Used in Them
- Information for Future SIP or Maintenance Plan

Residential Wood Combustion Tracers

- Levoglucosan
  - Thermal decomposition of cellulose
  - Anhydride of β-glucose

- Carbon-14
  - Modern carbon vs. fossil fuel
  - Other combustion sources, cooking, ethanol & methanol in gasoline

- Water Soluble Potassium
  - Mineral versus organic potassium
  - Marine aerosols and road salt

- Methoxylated Phenols
  - Some at percent level
  - Variable
  - Atmospheric lifetime?

- Methyl Chloride
  - OGI studies
  - Fraction of ppt level in atmosphere

- Retene
  - Incomplete product of combustion of coniferous tree resin

- PAH "Fingerprint"
  - Mobile, coal and RWC different relative proportions of specific PAH

- Chemical Mass Balance (CMB) Modeling Profile
  - Receptor modeling
  - Different sources have different source profiles
  - Key chemical profile species are OC,EC,K,Cl, $S0_4^{2-}$, Ca.
  - Some profiles have specific organic compounds

- Carbon Monoxide and Nephelometer Correlations
  - BPA and Oregon DEQ
  - RWC C0/particulate ratio 8:1, mobile 60:1

  CO 8 hr standard, 10,000 $\mu g/m^3$, $PM_{2.5}$ 24 hr standard 65 $\mu g/m^3$

Low Emission, New Technology Alternatives to Conventional Uncertified Stoves Burning Cordwood

Stove/Product	% Emissions Reduction Potential	Total Initial Cost*	Annual Costs Compared to Conventional Stoves Using Cordwood
Certified Non-Catalytic Stoves	71%	$2075	$67 less
Certified Catalytic Stoves	74%	$2425	$16 less
Pellet Stoves	92%	$2385	$145 more
Masonry Heaters	85%	$10,500	$109 less
Manufactures Densified Fuel	27%	$0	$ 291 more

* Includes unit, installation and chimney work costs

Lower Emission Alternatives Compared to Existing Zero-Clearance and Masonry Open Radiant Fireplaces Used as Supplemental or Primary Heat Sources

Stove/Product	% Emissions Reduction Potential	Total Initial Cost*	Annual Costs Compared to Conventional Stoves Using Cordwood
Certified Non-Catalytic Stoves	94%-98%	$1850	$11 less
Certified Catalytic Stoves	94%-98%	$2200	$52 more
Pellet Stoves	94%-98%	$2400	$53 more
Masonry Heaters	100%	$2300	$139 less
Manufactures Densified Fuel	100%	$2300	$102 less

* Includes unit, installation and chimney work costs

Lower Emission Alternatives Compared to Cordwood Used for Aesthetic and Minor Heating Purposes

Stove/Product	% Emissions Reduction Potential	Total Initial Cost*	Annual Costs Compared to Conventional Stoves Using Cordwood
Manufactured Wax Logs	68%	0	$166 more
Decorative Gas Logs Natural Gas	100%	$650	$15 less
Decorative Gas Logs LPG	100%	$650	$47 more