Note: This is a reference cited in *AP 42, Compilation of Air Pollutant Emission Factors, Volume I Stationary Point and Area Sources.* AP42 is located on the EPA web site at www.epa.gov/ttn/chief/ap42/

The file name refers to the reference number, the AP42 chapter and section. The file name "ref02_c01s02.pdf" would mean the reference is from AP42 chapter 1 section 2. The reference may be from a previous version of the section and no longer cited. The primary source should always be checked.

AP-42, Section 1.10, Ref. 23

EFD, Ch. 4, Ref. 13

In-Home Evaluation of Emissions from a Tulikivi KTU 2100 Masonry Heater

Prepared for: The Tulikivi Group

Prepared by: Stockton G. Barnett
OMNI Environmental Services, Inc.
10950 SW Fifth Street, Suite 160
Beaverton, Oregon 97005-3400

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Executive Summary

Particulate (PM) and carbon monoxide (CO) emissions were measured using two of OMNI's Automated Woodstove Emissions Sampler (AWES) systems operating simultaneously on a one-year-old Tulikivi KTU 2100 masonry heater located in Sauvie Island, Oregon in February, 1992. The heater was operated by the homeowner in his normal fashion using Douglas fir cordwood with 20% moisture. The unit was fired seven times during the week-long test. Average daily burn rate was 0.41 kg/hr.

PM emissions averaged 5.7 g/kg, 2.3 average daily g/hr, and 5.7 normalized average daily g/hr. These PM values are comparable to those obtained from Phase II noncatalytic woodstoves in the field.

CO emissions averaged 107 g/kg, 44 average daily g/hr, and 107 normalized daily g/hr. These values are somewhat higher than Phase II EPA certified noncatalytic woodstoves.

The average net delivered efficiency was 59%, which is in between conventional and Phase II certified stoves. Average heat output was 4541 BTU/hr.

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Introduction

There has been increased tightening of emissions regulations on residential woodburning devices in recent years. In 1986, the EPA established a woodstove certification program that went into effect in two stages in 1988 and 1990. Masonry heaters, which essentially function as high-mass rapidly burning woodstoves, were exempted from this program by virtue of their large mass.

In more recent years, certain heavy woodburning areas of the west have been declared by the EPA to be in nonattainment for airborne particulate matter of less than 10 microns in diameter (PM_{10}). State Implementation Plans (SIPs) have been written to develop strategies for reducing air pollution to bring these areas into compliance. Measures beyond the EPA woodstove certification process have been needed. Among other things, a need for woodburning devices that are cleaner-burning than certified woodstoves has developed. One such device that has attracted attention has been the masonry heater, a European technology that has existed for several centuries.

The current project has been designed to evaluate the in-home emissions and efficiency performance of a potentially clean-burning heater, the Finnish-designed Tulikivi KTU 2100. A Tulikivi KTU 2100 heater that has been burned for one year in a home on Sauvie Island, Oregon was evaluated over a one-week period in February, 1992. The heater was operated by the homeowner as he normally did. Since the heater was the only source of heat, the homeowner burned wood at a loading frequency needed to meet the home's heat demand. The homeowner was supplied with 16-inch long Douglas fir cordwood averaging 20% moisture. During the week the homeowner loaded the heater seven times. Photographs of the Tulikivi KTU 2100 appear in Figures A-1 through A-4 of Appendix A.

OMNI's Automated Woodstove Emissions Sampler (AWES) and datalogger were used to conduct the sampling. By doing so, a direct comparison can be made to numerous published studies on woodstoves, fireplaces, masonry heaters, and pellet stoves. This system collected samples for PM_{10} and carbon monoxide (CO) determinations. In addition to producing emissions results, the AWES uniquely collects real-time temperature information on the home's ambient temperature and the stack temperature above the flue damper. Real-time data on stack oxygen content and fuel loading patterns were also collected. Results for the Tulikivi KTU 2100 are shown in Figures A-5 and A-6 of Appendix A. During this test two AWES were operated simultaneously. The average of both samples is reported in the text.

The AWES was specially modified for masonry heater sampling. Due to the anticipated low concentration of emissions in masonry heater flue gases, a large volume of these gases had to be sampled in order to collect an adequate amount of particulate catch. In this project, about 900 liters were collected. This meant that the AWES was operated one minute on and two minutes off throughout the sampling period. Additionally, a Tedlar bag was used to collect an integrated flue gas sample for the week-long sample period so that CO and carbon dioxide (CO_2) could be measured. More details of how procedures were modified for masonry heaters are provided in the Methodology section.

Two masonry heaters, a Contraflow kit heater and a locally designed and built "Russian" heater, were evaluated by Barnett (1990) in the Western States Clay Products fireplace and masonry heater project. The issue of how to present emissions results for masonry heaters was discussed at length in that report. Because masonry heaters are only burned for short periods, the emissions rate concept used for woodstoves of grams per hour is not appropriate. Instead, the concept of average daily grams per hour was adopted. Emissions values were also normalized to a 1 kg/hr burn rate, the average Phase II EPA woodstove rate, and presented as normalized average daily grams per hour. The normalized value (which

equals the g/kg value) is the most appropriate way to express emissions since it eliminates burn rate as a variable, placing all heaters and Phase II woodstoves on a "level playing field". Additionally, the efficiencies of all of these burning devices are very similar, further supporting the use of this approach. This procedure is followed in this report.

Methodology

Emissions Sampling

The Modified AWES Emission Sampling System for Masonry Heaters

Figure 1 shows a schematic of the AWES/data logger system as modified for masonry heater sampling. For the Tulikivi KTU 2100, the AWES unit draws flue gases through a 38 cm (15 in.) long, 1.0 cm ($^3/_8$ in.) O.D. stainless steel probe which samples from the center of the flue about 305 cm (10 ft) above the base of the firebox. This location is above the flue damper. The sample then travels through a 1.0 cm O.D. Teflon line, and a heated U.S. EPA Method 5-type filter for collection of particulate matter, followed by a sorbent resin (XAD-2) trap for semi-volatile hydrocarbons. Water vapor is removed by a silica gel trap. Flue gas oxygen concentrations, which are used to determine flue gas volume, were measured by an electrochemical cell manufactured by Lynn Instruments. The AWES uses a critical orifice (Millipore #XX500001) to maintain a nominal sampling rate of 1.0 liters per minute (0.035 cfm). The flow rate through each AWES critical orifice is measured with a bubble flow meter to determine the exact sampling rate.

The AWES unit returns particle-free exhaust gas to the flue via a 0.6 cm ($^1/_4$ in.) Teflon line and a 38 cm (15 in.) stainless steel probe inserted in the flue. Some flue gas exiting the AWES is pumped into a 22-liter Tedlar bag (for later gas analysis) under positive pressure, since the inlet to the bag is on the positive pressure side of the pump. The flow to the bag was controlled by a solenoid valve connected to the pump circuit and a rotameter with a flow-controlling orifice. The solenoid valve is open only when the pump is activated. Thus the bag receives effluent gas at all times when the AWES pump is on. The rate of flow into the bag is controlled by a fine metering valve which was adjusted to acquire the optimum amount of gas over the entire test without over-pressurizing the bag. Flow is measured using a bubble flow meter.

The Data Logger System

The data logger system, known as the CONLOG data logger system, is a second-generation data logging and emission sampler controlling system developed in 1990 by OMNI. The system (Figure 2) consists of a host personal computer (PC) containing a data processing board, a terminal box, and specialized data acquisition software.

The CONLOG software is written in a high-level programming language (C) and can be programmed to control, collect, and store the following software settings and data:

- Establish starting and ending date and length of sampling period
- Establish pump cycle length and thermocouple (TC) cycle recording interval
- Record date and time at pre-selected intervals
- Record up to eight temperatures, including flue gas temperature, averaged over pre-selected intervals

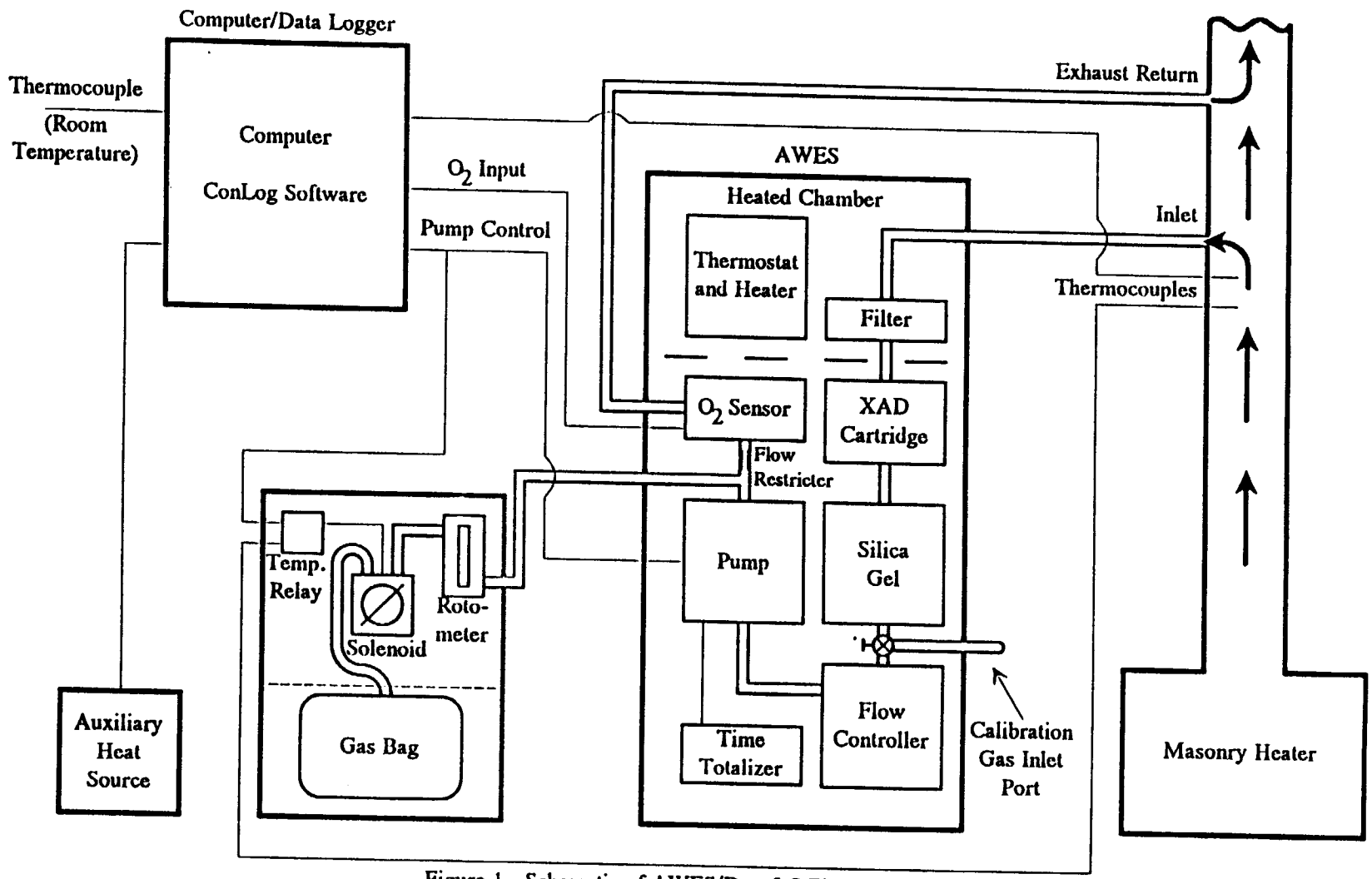

Figure 1. Schematic of AWES/Data LOG'r system.

OMNI Environmental Services, Inc.	Not to Scale	Project No.: 80119.01
		Date: February 19, 1992
		Drawing: 80119-01.DRW

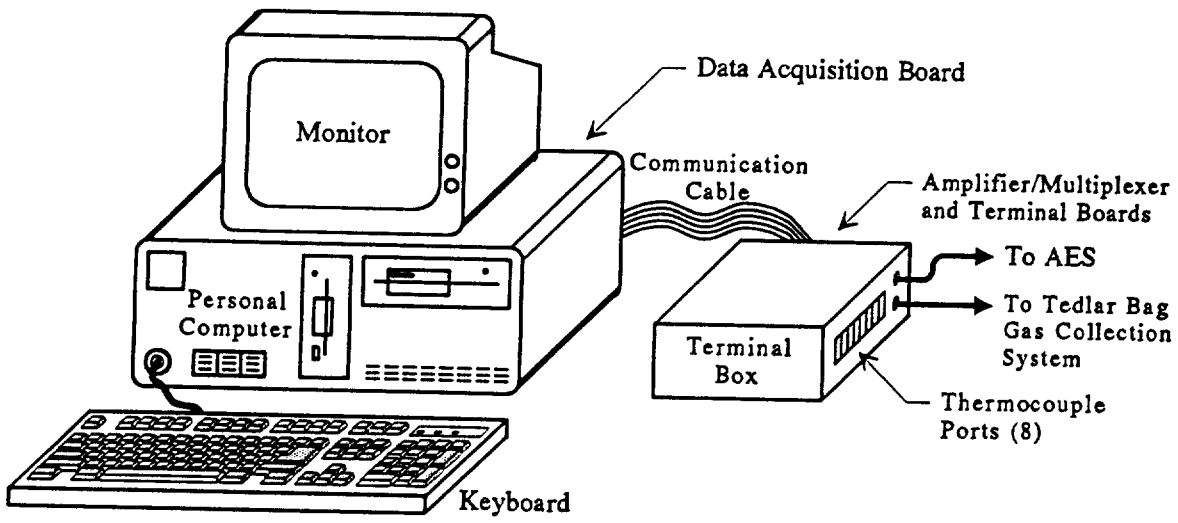

Figure 2. The ConLog data logger system.

- Record ambient temperature (room temperature), averaged over pre-selected intervals
- Record flue gas oxygen measurements, averaged over pre-selected intervals
- Save file as an ASCII file with PRN suffix on 3.5" disk

Instantaneous readings of real-time data are also displayed on the system status screen of date, time, temperature for TCs 1 through 8, and flue gas oxygen percent. The most recent 15 sets of recorded data are also displayed.

For masonry heaters, temperature, etc. are recorded at five-minute intervals. The sampling pump is operated for one minute on followed by two minutes off. This procedure ensures the sample of about 1,000 liters during burning periods, which is needed for clean-burning devices.

The CONLOG system uses external sensors which generate analog voltages that are processed by the PC microprocessor's data acquisition board. For this project, a type K ground-isolated, stainless-steel-sheathed TC (Pyrocom 1K-27-5-U) was used to monitor flue gas temperature at 213 cm (7 ft) above the base of the firebox in the center of the flue gas stream.

The keyboard and screen were left installed in the home during the sample period. The presence of the display screen's real-time data generated considerable interest on the part of the participants in the project and was a positive experience. The CONLOG program was software-locked to prevent possible interference. However, historically, on a few occasions homeowners have been given the password and "walked through" minor program modifications over the telephone to solve a problem that may have occurred during a sampling period. This proved successful and saved considerable field technician time.

Equipment Preparation and Sample Processing Procedures

Prior to emissions testing, the AWES unit was cleaned and prepared with a new fiberglass filter and XAD-2 sorbent resin cartridge. This was done in OMNI's laboratory facility at Beaverton, Oregon. After the sampling period, the stainless steel sampling probe, Teflon sampling line, filter holder, and XAD-2 cartridges were removed from the home and transported to OMNI's laboratory for processing. The components of the AWES sampler were processed as follows:

1. Filters: The glass fiber filter (102 mm in diameter) was removed from the AWES filter housings and placed in a petri dish for desiccation and gravimetric analysis for particulate catch.

2. XAD-2 sorbent resin: The sorbent resin cartridge was extracted in the Soxhlet extractor with dichloromethane for 24 hours. The extraction solvent was transferred to a tared glass beaker. The solvent was evaporated in an ambient air dryer, the beaker and residue were desiccated, and the extractable residue was weighed on a Mettler AE160 balance.

3. AWES hardware: All hardware which was in the sample stream (stainless steel probe, Teflon sampling line, stainless steel filter housing, and all other Teflon and stainless steel fittings) through the base of the sorbent resin cartridge was rinsed with a 50/50 mixture of dichloromethane and methanol solvents. The solvents were placed in tared glass beakers. The solvents were evaporated in an ambient air dryer, desiccated, and weighed to determine the residue fraction weight.

EPA Method 5 procedures for desiccation and the weighing time schedule were followed for 1 through 3 above.

OMNI personnel serviced the sampling equipment at the start and end of the sampling period. At the start of each sampling period, the AWES unit was installed; leak checks were performed; the thermocouples, scale unit, and oxygen cell were calibrated; and the data logger was programmed with the proper sampling interval and start/stop times. The data logger was programmed to activate the AWES units for one minute on and two minutes off for seven consecutive days. At the end of the sampling period, final calibration, and leak-check procedures were performed, and the AWES, sampling line, filter housing, XAD-2 cartridge, sampling probe, and Tedlar bag were removed and sent to the lab.

Data Processing and Quality Assurance

The data file stored on the data logger's 3.5" computer diskette was sent to OMNI's lab for computer analysis. The data file was reviewed immediately to check for proper equipment operation. The data logger data files, log books, and records maintained by field staff were reviewed to ensure sample integrity, which was excellent for this project.

The data logger file was used in conjunction with the AWES particulate sample to calculate particulate emission rates, daily temperature profiles of the flue temperatures, heater operation time, burn rates, etc. In addition, the computer program output for each file includes graphical representations of parameters and parameter interrelationships (see Figures A-5 and A-6).

Particulate Emissions Calculations

The basic particulate emissions equation produces grams per dry kilogram of fuel burned (g/kg). The basic g/kg equation includes the following components:

1. Particulate mass: The total mass, in grams, of particulate caught on the filter, XAD-2 resin trap, and in the probe rinse. Particulate mass averages about 0.040 grams but varies considerably.

2. Sample time: The number of minutes the sampler operated during the sampling week when the stack oxygen was less than 20.6%.

3. Sampler's flow rate: This is controlled by the critical orifice in the sampler. Flow values vary slightly for the various samplers and average about one liter per minute.

4. Stoichiometric volume: The volume of smoke produced by combusting one dry kilogram of wood. This value is calculated using a carbon balance for each sample but averages about 4,900-5,000 liters at standard temperature and pressure for masonry heaters.

5. Dilution factor: The degree to which the sampled combustion gases have been diluted in the stack by the presence of excess air. The dilution factor is obtained by using the sample period's average oxygen value in the following equation. Dilution factors range from about 2 to 5.

$$\text{Dilution Factor} = ((20.9/(20.9 - \text{Average oxygen}))$$

$$\text{Emissions (g/kg)} = \frac{(\text{Particulates})(\text{Stoich. Vol.})(\text{Dilution Factor})}{(\text{Sample Time})(\text{Sampler Flow})}$$

Uncertainty in Emissions Results

Particulate emissions values are presented along with associated uncertainty levels. Each measurement used in the emissions calculations has some degree of uncertainty associated with it, and these uncertainties are propagated to determine the amount of uncertainty attached to each calculated particulate emission rate. Criteria, procedures, and calculations used in evaluating uncertainty are summarized in a previous report (Barnett and Fields, 1991). Within the low range of emissions values encountered in this project, uncertainty is generally about 20% of the stated value. This is consistent with data gathered independently during a similar pellet stove project (Barnett and Roholt, 1990) by operating five AWES sampling systems simultaneously while burning a pellet stove.

The issue of sample-blank-induced error was previously investigated at length by Barnett (1990). The values determined in that study have been used here. They include a probable error at the 95% confidence level of ±4.88 mg and an average blank value of 3.9 mg.

Oxygen-cell-induced error was also investigated by Barnett (1990). The 95% confidence level of the probable error contribution to emission values of ±7% is used in this study.

For a detailed treatment of these and other sources of uncertainty and QA procedures utilized, see Appendix C of Barnett and Fields (1991).

Efficiency Calculations

Woodstove efficiency was determined using the "Condar method" described by Barnett (1985). This method uses CO and PM emissions, stack dilution (based on excess air), stack temperature, wood type, and wood moisture to calculate combustion, heat transfer, and overall efficiencies, as well as net output in BTU/hr.

This method has been used in all previous field studies of woodstoves, masonry fireplaces, pellet stoves, and masonry heaters. The stack temperature probe was placed in the masonry heater's flue immediately above the flue damper near the home's exit location for the flue, so the measured efficiency included essentially all of the heat energy that the heater contributed to the home.

AWES Modifications for Masonry Heater Emissions Testing

A modification in data reduction procedures has been made for masonry heaters. All previous AWES sampling of woodstoves used 100 °F stack temperature as the cutoff point to mark the start and end of a combustion cycle. Since masonry heaters maintain high stack temperatures long after combustion ceases, this procedure could not be used. Review of the stack temperature-stack oxygen regression results from computer files of the noncatalytic stoves in the 1988-1989 Northeast Cooperative Woodstove Study (Barnett, 1990) and the 1990 Klamath Falls Pacific Energy Project (Barnett, 1990a) indicated that 100° stack temperature at the end of a burn cycle was associated with 20.6% oxygen in the stack. Therefore, the masonry heater computer program was modified to separate burning from nonburning periods using the 20.6% oxygen criterion rather than 100° stack temperature. A sensitivity analysis using 0.1% increments from 20.5% to 21.5% indicated a low sensitivity to the cutoff setting. All results (g/kg and average daily g/hr) were within a 5% range. Grams per hour were significantly affected, of course, because g/hr = g/kg × burn rate (kg/hr). Grams per hour, however, is not considered to be a very suitable form for presenting emissions results for masonry heaters (Barnett, 1991).

The sampling period was modified to accommodate the low emissions of masonry heaters. A sampling frequency of one minute of sampling out of every fifteen minutes at a flow rate of one liter per minute has been found to provide optimal sample catches for analysis from clean-burning cordwood stoves during a one-week period. A shorter sampling frequency of one minute out of three minutes at the same flow rate was selected to obtain optimal sample catch from one week of masonry heater sampling. For example, this provided for a particulate catch of 0.034 g from a 900-liter sample for the Tulikivi KTU 2100, rather than only 0.004 g per 100-liter sample volume.

The final modification was the addition of a flue gas Tedlar bag collection system (Figure 3). Carbon dioxide, carbon monoxide, and oxygen data are generated from this collection system, allowing for calculation of carbon monoxide emission factors. Tedlar bag gases were measured using an NDIR analyzer. For the Tulikivi KTU 2100 test, the Tedlar bag collection system was left on for the entire test. Every three minutes it operated for one minute. This causes the collected gases to be more dilute than those emitted during the combustion phase. Thus, in Tables 1 and 2, the O_2 values are artificially high and the CO and CO_2 values low. This method of gas collection does not affect the calculated CO emissions values at all, however.

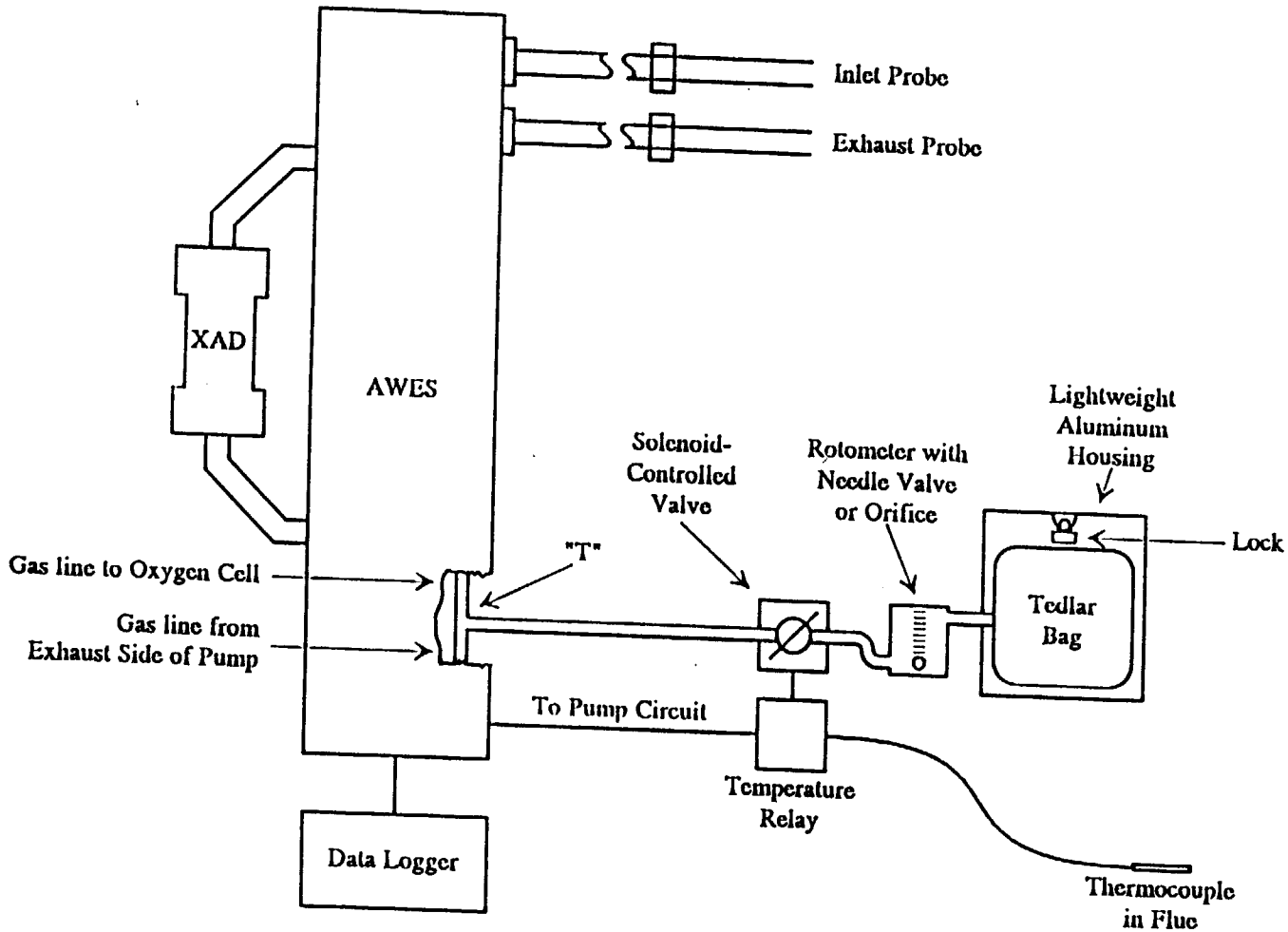

Figure 3. Schematic of AWES system modified for masonry heater application.

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Emissions Results

PM emissions averaged 5.7 g/kg and 2.3 average daily g/hr for both samples. Tables 1 and 2 show the results from each simultaneous emissions test. The 95% confidence limit for the g/kg value is ±0.85 g/kg. Normalizing the grams per hour emissions to a 1 kg/hr burn rate as described in Barnett (1991) yields 5.7 average daily g/hr. The average daily burn rate was 0.41 dry kg/hr.

Average CO emissions were 107 g/kg, 44 average daily g/hr, and 107 normalized average daily g/hr.

Comparatively, the PM emissions were comparable to Phase II EPA certified noncatalytic woodstoves as tested in homes. Figure 4 indicates that Tulikivi KTU 2100 emissions are about 62% lower than the EPA's AP-42 emissions value of 14.9 g/kg for conventional woodstoves.[a]

CO emissions are comparatively not as low as PM emissions. They are somewhat higher than Phase II certified noncatalytic woodstoves but significantly lower than conventional stoves.

Efficiency

The average net delivered efficiency of the Tulikivi KTU 2100 was 59%. This efficiency is about midway between the 50-55% average of conventional woodstoves and the 65-70% average for Phase II woodstoves as measured in homes (References 1,6,10,11). The average heat output was 4541 BTU/hr.

The design of the heat transfer system is moderately effective (Figure 5). Improvement could be made by both reducing the excess air so that stack oxygen averaged about 16% and reducing stack temperature somewhat.

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[a] The woodstove values in this figure are from the summary paper by McCrillis and Jaasma, 1991. The Certified pellet stove values are from Barnett and Roholt, 1990, and the exempt pellet stove values are from Barnett and Fields, 1991.

MASONRY HEATER EMISSIONS RESULTS

HOUSE AND RUN:	TULIKIVI A
SAMPLE DATES:	2/12-18/92
HEATER TYPE:	TULIKIVI 2100
FUEL TYPE:	DOUGLAS FIR

TOTAL STOVE BURNING HOURS=	11.58 HOURS	
% OF TIME FIREPLACE BURNED=	7.04 PERCENT	
AVE. STACK TEMP=	339.10 DEGREES F.	
* AVE OXYGEN (STACK)=	16.75 PERCENT	
* AVE. OXYGEN (BAG)=	20.63	*****
TOTAL WOOD USED, WET LBS.=	179.0	
WOOD MOISTURE (DRY BASIS %)=	19.7	*****
AWES FLOW RATE(L./MIN)=	0.909	*****
LENGTH OF SAMPLE CYCLE (MIN.)=	3	*****
AVERAGE CO % (BAG)=	0.0234	*****
AVERAGE CO2 % (BAG)=	0.31	*****
VOC, PPM (BAG)=		*****
TOTAL PARTICULATES IN MG.		
RINSE=	31.1 ****	
XAD=	8 ****	
FILTER=	10.5 ****	
MINUS AVE BLANK	3.9	
TOTAL PARTICULATES=	0.046 GM.	
TOTAL DRY WOOD USED=	67.97 KG.	
* BURN RT (DRY KG/H) DURING BURN=	5.87 KG/HR	
AVE DAILY BURN RT (DRY KG/H)=	0.41 KG/HR	
AIR TO FUEL RATIO=	34.53	

*** PARTICULATE EMISSIONS:**

* GM/KG=	5.38
GM/KG UNCERTAINTY=	0.86
* GM/HR=	31.59
Ave. daily g/hr=	2.22

*** CO EMISSIONS:**

GM/KG=	103.86 AVE OF A-1 AND A-2
GM/HR=	609.44
Ave. daily g/hr=	42.91

ADDITIONAL ITEMS:

AVE WOOD LOAD (WET LB.)=	25.57
AVE. WOOD USAGE/DAY (WET LB.)=	26.12
# TIMES LOADED/DAY=	1.02
AVE. AMBIENT TEMP=	73.09

NET EFFICIENCY:

COMBUSTION EFFIC.=	92.36
HEAT TRANS. EFFIC=	63.98
NET EFFICIENCY=	59.09
NET OUTPUT (BTU/HR)=	4566

Table 1

MASONRY HEATER EMISSIONS RESULTS

HOUSE AND RUN:	TULIKIVI B
SAMPLE DATES:	2/12-18/92
HEATER TYPE:	TULIKIVI 2100
FUEL TYPE:	DOUGLAS FIR

TOTAL STOVE BURNING HOURS=		11.75 HOURS	
% OF TIME FIREPLACE BURNED=		7.11 PERCENT	
AVE. STACK TEMP=		340.50 DEGREES F.	
* AVE OXYGEN (STACK)=		16.74 PERCENT	
* AVE. OXYGEN (BAG)=		20.57	*****
TOTAL WOOD USED, WET LBS.=		179.0	
WOOD MOISTURE (DRY BASIS %)=		19.7	*****
AWES FLOW RATE(L./MIN)=		1.102	*****
LENGTH OF SAMPLE CYCLE (MIN.)=		3	*****
AVERAGE CO % (BAG)=		0.0289	*****
AVERAGE CO2 % (BAG)=		0.35	*****
VOC, PPM (BAG)=			*****
TOTAL PARTICULATES IN MG.			
RINSE=	38.4 ****		
XAD=	14.6 ****		
FILTER=	13.7 ****		
MINUS AVE BLANK	3.9		
TOTAL PARTICULATES=		0.063 GM.	
TOTAL DRY WOOD USED=		67.97 KG.	
* BURN RT (DRY KG/H) DURING BURN=		5.78 KG/HR	
AVE DAILY BURN RT (DRY KG/H)=		0.41 KG/HR	
AIR TO FUEL RATIO=		34.41	

*** PARTICULATE EMISSIONS:**

* GM/KG=	5.98
GM/KG UNCERTAINTY=	0.84
* GM/HR=	34.61
Ave. daily g/hr=	2.46

*** CO EMISSIONS:**

GM/KG=	109.67 AVE OF A-1 AND B-2
GM/HR=	634.46
Ave. daily g/hr=	45.11

ADDITIONAL ITEMS:

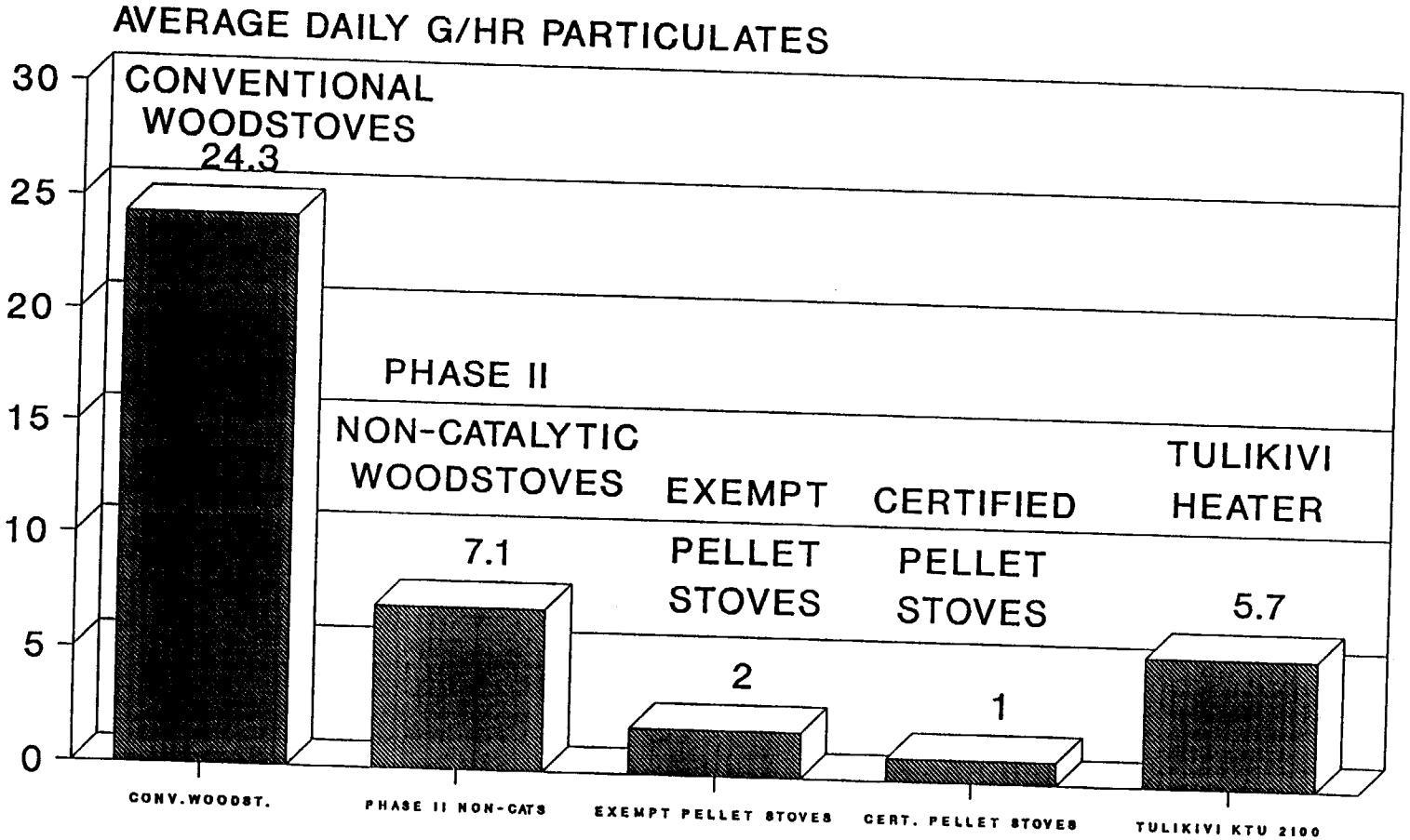
AVE WOOD LOAD (WET LB.)=	25.57
AVE. WOOD USAGE/DAY (WET LB.)=	26.00
# TIMES LOADED/DAY=	1.02
AVE. AMBIENT TEMP=	72.20

NET EFFICIENCY:

COMBUSTION EFFIC.=	91.81
HEAT TRANS. EFFIC=	63.93
NET EFFICIENCY=	58.70
NET OUTPUT (BTU/HR)=	4515

Table 2

AVERAGE DAILY G/HR PARTICULATES FOR WOODSTOVES, PELLET STOVES AND THE TULIKIVI KTU 2100 MASONRY HEATER

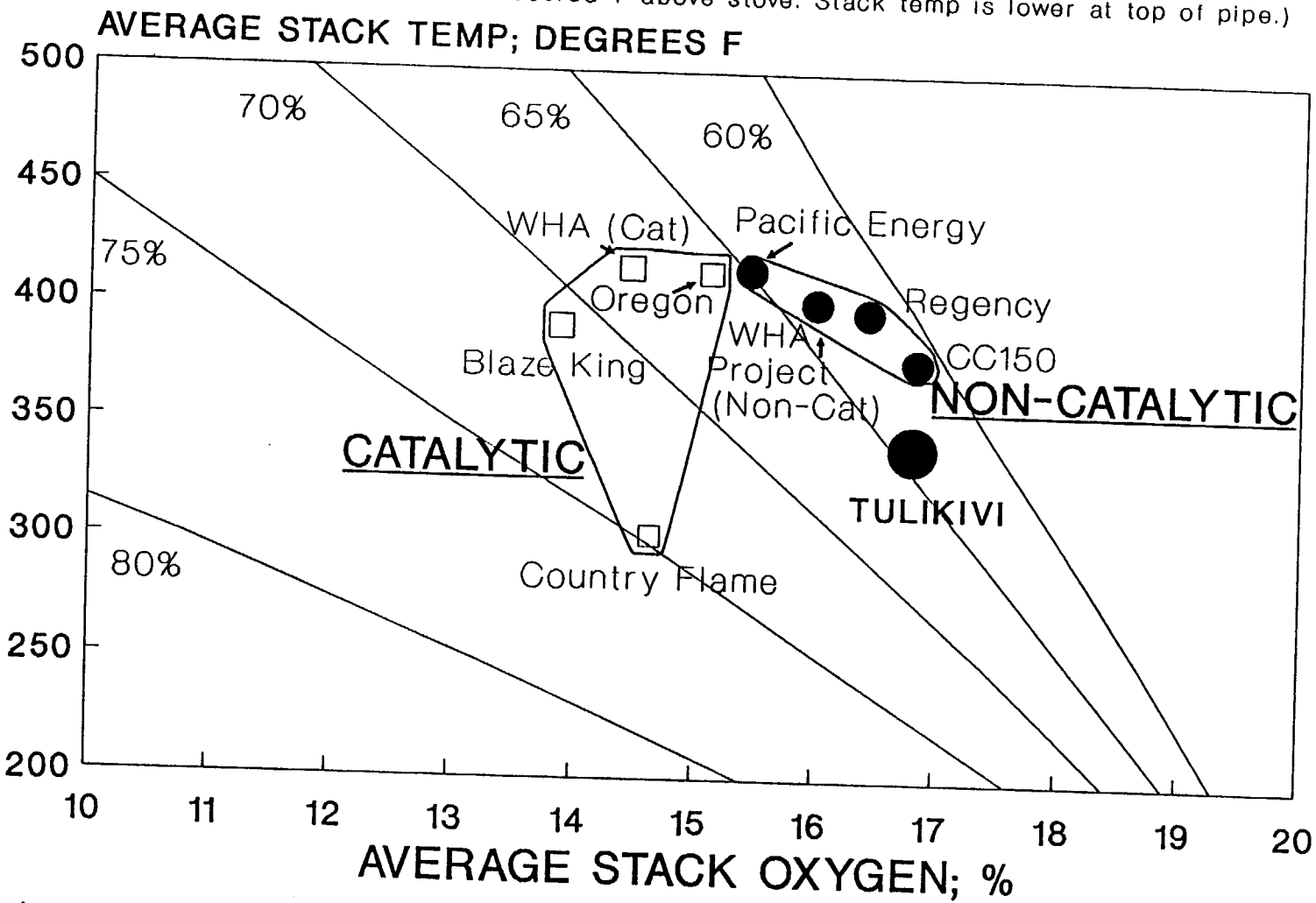


Masonry heater values normalized to a 1.0 kg/hr burn rate, the Phase II woodstove field average.

Figure 4

HEAT TRANSFER EFFICIENCY DIAGRAM: FIELD STUDIES: CAT, NON-CAT STOVES & TULIKIVI

(Stack temp for woodstoves measured 1' above stove. Stack temp is lower at top of pipe.)



Woodstove studies: 1989 NCWS, 1990 WHA.

Figure 5

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