Background File

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COLORADO FIREPLACE REPORT

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ABSTRACT

A wide range of open and closed fireplace designs was investigated for the ability to reduce carbon monoxide (CO) and particulate matter (PM) emissions. Three fireplace design types yielded emissions reductions for PM and CO of between 40 and 80%. Two of the designs had open doors; one involved catalytically assisted combustion and the other featured a deep, small firebox. The third design type involved closed doors and featured insulation and/or convection. Emissions of polycyclic organic matter (POM) were also measured for selected designs. Suggested modifications are made to adapt existing woodstove emissions test methods to fireplaces.

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1. INTRODUCTION

Colorado Air Quality Control Act, Colorado Revised Statutes, Section 1, Article 7, Title 25, Part 4, 25-7-406, requires the Air Pollution Control Division to establish a program to study the ways different fireplace designs affect emissions of particulates and CO.

With the input of the Commission's Subcommittee on Fireplaces, the Division developed an RFP which required:

a) A development of test method for fireplaces based on stove test methods.

b) Development of baseline data on emission factors for particulate matter (PM), carbon monoxide (CO), and polycycle organic material (POM).

c) Development of a technical definition of fireplaces.

d) Investigatation of various designs and methods to reduce PM and CO from both masonry and factory-built fireplaces.

Very little research on emissions aspects of fireplaces has been previously conducted. In particular, there was no significant data suggesting what design approaches might be most successful. Thus the overall approach was to investigate a wide range of design concepts.

2. TESTING METHODOLOGY

2.1. INSTALLATION

All factory-built fireplaces and their modifications were installed using the associated factory-built chimney normally supplied with such fireplaces. The deep fireplace was vented using 6 inch stovepipe. In all cases, including the masonry fireplace, the flues extended to between 14 and 16 feet above the bottom of the unit as is standard practice in emissions testing of stoves (Figure 2.1).

All fireplaces were installed free-standing in a laboratory with a 25 feet high ceiling. Ambient temperature was typically between 70 and 90 degrees Fahrenheit. Ambient pressure was typically between 580 and 610 mm of mercury. Relative humidity was typically between 20 and 50%. With no fire in the fireplaces, air velocities within 2 feet of the fireplace were less than 50 feet per minute.

2.2. FUELING PROTOCOL

For the cold-start tests, sampling began before the fire was ignited. The fuel configuration consisted of a 3-standard-log load on top of a standard safety-testing firebrand on top of 4 inch andirons. Balled newspaper was placed under the andirons.

The standard logs were Douglas fir nominal 4x4s with a moisture content of 16 to 20% (moist basis). The piece lengths were 5/6 of the average of the front and rear widths of the hearth. Two pieces were placed on the firebrand and the third was placed centrally on top of the other two. The spacers resulted in 1.5 inch spacing between pieces horizontally and vertically.

The safety firebrand consisted of 3/4 X 3/4 inch Douglas fir strips on one inch centers with a second layer at 90 degrees to the first. The moisture content of the brands used here was 16 to 20% (moist basis, the same as the 4x4's).

The cold-to-cold start test cycles lasted for approximately 1 hour. During the cycle, additional 4x4s were added based primarily on the appearance of the fire. For medium burn rate tests, the pieces were added when the operators felt a typical homeowner would have added a piece. Higher and lower burn rates were achieved based on similarly subjective judgements.

Each hot-to-hot test cycle started just before a single log reload. The duration of these tests was also approximately 1 hour and always involved an integral number of single-log mini-cycles.

There was no monitoring of performance during the final cool-down or charcoal phase.

The fire was typically poked just before each single-log reload and once during each single-log mini-cycle.

2.3. CARBON MONOXIDE

The concentration of carbon monoxide in the tunnel was monitored continuously during every run using a non-dispersive infrared analyzer (Horiba PIR-2000, full scale signal for 0.5% CO). The analyzer was zeroed and spanned before each set of tests using a calibration gas accurate to within 1%. The sample gas stream was conditioned by filtration and drying with Drierite.

The signal was integrated automatically over the period of the test using a Spectra-Physics 4290 integrator. Total carbon monoxide (in grams) was then obtained by multiplying with the appropriate sensitivity and tunnel mass flow factors.

2.4. PARTICULATE MATTER

Particulate matter was measured in the tunnel using two identical sampling trains as described in Appendix B of the Colorado Woodstove Regulation. Each sampling train consisted of a stainless steel probe, two filter holders, 1/4 inch teflon tubing, pump, rotameter, and two pressure gauges. Pressure-side leak checks were conducted before and after every test. Vacuum-side leak checks were conducted whenever a change was made in the system.

To conserve project resources, dry gas meters were not used. Hundreds of tests at SRI using both rotameters and dry gas meters have indicated very close agreement (to within a few percent).

Before use, glass filters (Gelman AE, 47mm) were desiccated and weighed twice. After use they were desiccated between 24 and 72 hours and weighed once.

Total particulate matter was calculated as the product of the catch and the ratio of the (nearly constant) mass flow in the tunnel and the mass flow in the sampling system.

2.5. POM (POLYCYCLIC ORGANIC MATTER)

The sampling procedure for POMs was essentially the same as for particulate matter, with the differences that:

1) The POM was trapped in an assembly consisting of a single Gelman 47mm AE glass filter followed by two XAD-2 adsorption tubes (SKC, Eighty-Four, PA), and

2) only one sampling train was used.

The glass adsorption tubes were covered with black plastic during sampling. A constant sampling rate was chosen such that the total volume sampled fell within the 200 - 1000 liter range specified in NIOSH (National Institute of Occupational Safety and Health) Method 5506.

The collection of tubes was made of 6mm (i.d.) glass tubing and contained two sections of Amberlite XAD-2. The purpose of the second section (50 mg) was to detect compounds not fully retained in the first section (100 mg).

After each test the filter and tubes were stored at 0 degrees C in darkness until four or five sets had accumulated. These were then packed in an insulating box along with one or more U-Tek Refrigerant Packs (Polyfoam Packers Corp.) and shipped by overnight express to the University Analytical Center (Tucson, Arizona).

Analysis of the sixteen POMs designated in EPA Method 610 was carried out using high performance liquid chromatography in accordance with NIOSH Method 5506.

2.6. TOTAL GASEOUS COMBUSTIBLES

The total amount of incompletely oxidized matter in the smoke was determined by continuous calorimetry of a gas sample drawn from the tunnel. The instrument used is called a combustibles meter and was developed especially for determining the calorific value of wood smoke in a project at Shelton Research Inc. sponsored by the U.S. Department of Energy.

The instrument is constructed of a 8.5 kg block of heavily insulated aluminum maintained at 350 degrees C. A sample stream passes through the hollow center containing catalytic pellets. The temperature rise of the gas stream is measured across the pellet bed with two platinum resistance thermometers. This temperature rise is proportional to the lower heating value of the gas in the dilution tunnel. Total chemical energy in the dilution tunnel gases (and therefore flue gases) was obtained by integration of the signal from the combustibles meter over the period of a test and multiplication by appropriate calibration and tunnel mass flow factors.

Zero drift in the combustibles meter resulted in significant scatter in the data for the cleaner burning systems. All data is reported in Appendix 5 and used in obtaining the changes in combustibles emissions in Table 4-1 (see Section 4). However, both because of the scatter in the data and because combustibles emissions are not regulated in Colorado, only PM and CO results are used in Table 4-1 for ranking the fireplace designs. In essentially all cases, the combustibles results support the conclusions drawn from the CO and PM results.

2.7. FLUE FLOW

The velocity of gases in the flue was measured directly using an S-type Pitot tube and a liquid manometer with a resolution of 0.0002 inch of water (Dwyer "Microtector"). The flue calibration factor (converting the central velocity determined by the Pitot tube to the average flue velocity) was established by injecting carbon monoxide at a metered rate, monitoring the CO concentration in the flue, and utilizing a mass balance relationship, namely:

$$\dot{N}co_{\text{metered}} = \dot{N}co_{\text{flue}} = \frac{Pco\ \dot{V}}{RT} = \frac{Pco \cdot A \cdot v}{RT}$$

$$= \frac{Pco \cdot A \cdot F \cdot vPitot}{RT}$$

where F is the desired calibration factor.

$\dot{N}co$ = molar flow rate of carbon monoxide
Pco = partial pressure of carbon monoxide in the flue

$\dot{V}$ = volumetric flow rate in the flue

A = area of flue

v = average velocity in the flue

R = ideal gas constant

T = absolute temperature

v Pitot = measured central velocity

2.8. SENSIBLE ENERGY LOSS

The heat carried away by flue gases was determined by evaluating the integral $\int \dot{m} \cdot C \cdot \Delta T \, dt$

where $\dot{m}$ = mass flow rate in the flue

C = the heat capacity of flue gases

ΔT = temperature rise above ambient

The heat capacity of the flue gases was approximated by that of dry air.

2.9. AIR-TO-FUEL RATIO

The air-to-fuel ratio as used in the woodstove industry is commonly defined in terms of dry air and dry fuel.

$$A/F = \frac{\left[\int \dot{M}st \, dt - \text{mass fuel (wet)}\right] \cdot Ya}{\text{mass fuel (dry)}}$$

where: $\dot{M}st$ = stack mass flow (wet)

Ya = mass fraction of dry air

In this project the flue mass flow was approximately:

$$\dot{M}st = \frac{29 \cdot P \cdot \dot{V}st}{RT}$$

where 29 is the molecular weight of dry air and Vst is the flue volumetric flow rate measured as described. The mass fraction of dry air, Ya, was approximated by (1 - X H2O) where X H2O is the mole fraction of water in ambient air, measured by the wet bulb/dry bulb method.

2.10. DIAGNOSTIC MEASUREMENTS

As an aid to understanding the performance of selected designs and hence to point the way towards design improvements, diagnostic measurements were made. The measurements consisted of various combinations of CO2, CO and temperature. A long sampling probe connected to the gas analyzers could be positioned anyplace within the firebox. In the case of selected catalytic designs, access holes were provided to allow the gas probe and a thermocouple to be positioned over a variety of positions just above the catalyst.

2.11. HEAT OUTPUT AND ENERGY EFFICIENCY

There are several different legitimate heat output and energy efficiency concepts for fireplaces. All fireplaces have frontal heat output, usually mostly radiant, which should be counted as useful output. Fireplaces may also emit or lose heat through the side, back and top, as well as from the sides of the flue. These heat fluxes do not normally contribute to useful heat output. (An exception is a masonry fireplace with all surfaces of the fireplace and its flue exposed to the heated spaces of the house.) Thus accurate measurements of fireplace efficiencies and heat outputs must be tailored to individual systems.

Since heat outputs and efficiencies were not primary objectives in this study, measurement methods were selected for their simplicity and low cost only. The objective was to be able to detect major effects on heat output and efficiency due to fireplace design.

Radiant heat out the front of the fireplaces was measured using an array of 5 full spectrum radiometers.

A flue loss efficiency was calculated wherein all energy not passing up the flue itself (8 feet above the floor) was taken as output. For a masonry fireplace this is a useful concept applicable to interior exposed installations. However this method yields an overestimate for most factory-built fireplaces.

Specifically, the total heat (energy, not power) output, HO, was calculated as follows:

HO = WE - SL - LL - CL

where WE = wood energy input
SL = sensible heat loss
LL = latent heat loss
CL = chemical heat loss

The wood energy was computed as the higher heating value of the fuel (8700 BTU/lb) times the dry mass of the fuel. Computation of the sensible heat loss was described above. The latent loss was computed as the maximum latent loss assuming 100% combustion efficiency. The latent loss was approximately 9.5% for all tests. The maximum error in this computation is estimated to be 2 percentage points. The chemical loss was computed as the sum of the gaseous combustibles loss (measured directly using a combustibles meter) and the energy loss in particulate matter (assuming a heating value of 30,000 joules/gram).

Overall energy efficiency in percent was computed as total heat output (energy) divided by wood energy input, times 100.

3. BASELINE DATA

3.1 COMPARISON BASIS FOR EXPERIMENTAL DESIGNS:

The bulk of the design development work was performed using a medium size factory-built fireplace of typical construction. This fireplace also served as the primary baseline fireplace against which performance the experimental designs were compared. It had an opening height of 20 inches and a hearth of 13 inches in depth and front and back widths of 30 inches and 22 inches. A refractory liner approximately 1 inch thick covered the hearth and all 3 walls up to a height of about 18 inches. Although a throat damper is standard with the unit, it was removed for most of the testing (and, in any case, was used full open when in place). The fireplace was used with 4 inch high andirons as used in safety testing to Underwriters Laboratories Standard 127. Tests involving this fireplace as manufactured (no modifications) with its doors open are designated "M" for medium size in graphs.

Two other fireplaces also served to provide baseline data as well as an exploration of size effects - a very small and a very large fireplace.

The small fireplace, designated "S" on graphs, consisted of a Franklin fireplace stove with an added refractory liner of the sort found in many factory-built fireplaces. A baffle at the top of the firebox was removed and the unit was operated with its doors open. The firebox itself was 21" wide and 18" high at the front, 17" x 10" in the rear and had a depth of 11". The inside diameter of the flue was 8". The large (designated "B" for Big in graphs) fireplace had a front opening 36" wide by 28" high and a depth of 24". The inside diameter of the flue was 10".

Substantially more effort was spent establishing the performance of the medium size factory-built baseline fireplace than had been originally intended. Some of the design modifications resulted in burn rates which were higher or lower than our original set of baseline data. Thus we extended the baseline data to cover a broader burn rate range.

Comparisons of designs at equal burn rates is not a necessity. If a fireplace design tends to operate at an unusual burn rate but does so cleanly, it is a design of merit. Yet burn rate is not exclusively a property of fireplace design. Operator variables such as fuel moisture, piece size and load size can all have a large effect on burn rate. Thus it is important to examine the performance of each design over a range of burn rates.

Specifically, for all quantitative comparisons (such as Table 4-1 in the next Section) of fireplace designs against baseline performance, the baseline data is an average of all tests conducted using the standard 4x4 Douglas fir fuel in the medium size factory-built fireplace described above operated with its doors open.

However, in graphical comparisons of various designs against baseline performance the small ("S" in graphs) and big ("B" in graphs) factory-built fireplaces operated with doors open are treated as baseline data. (See Section 4 for descriptions of these fireplaces.) In order to improve the clarity of the graphs, baseline data is represented as a curve rather than individual test points. These curves (Figures 3-1 and 3-2) do not represent mathematical best fits to the "M", "S" and "B" data, but rather a qualitative approximate fit. Most weight is given to the performance of the medium factory-built fireplace but for very low and particularly very high burn rates, the performance of the small and big factory-built fireplaces is used to help extend the burn rate range. Since some of the design modifications had very high burn rates, this extension of the baseline data provides better perspective for design evaluation.

3.2 BASELINE EMISSION RATES AND FACTORS:

All results in this report are given as measured in Shelton Research Inc.'s laboratory in Santa Fe, New Mexico, at 6900 feet, without any correction to Colorado's stove-regulation reference altitude of 5000 feet. (See Appendix 3.)

Using standard test fuel, baseline PM emission rates were typically between 15 and 30 g/hr. The PM rate appears to have a slight burn rate dependence, being higher at lower burn rates. Using realistic fuel (R) yielded an average PM rate of nearly 50 g/hr in a burn rate region (low) where standard fuel yielded about 30 g/hr. (See Section 5.8.)

PM emission factors (grams of PM per dry kg of fuel burned) were very sensitive to burn rate, with higher burn rates resulting in lower factors (Figure 3-3). Because of the strong burn rate dependence, an average of all PM factors is not necessarily meaningful. The results using realistic fuel are probably most closely related to field practice and other research efforts. The average PM factor for realistic fuel in the baseline fireplace was 14.4 g/kg.

Most CO rates at all burn rates and for both fuels burned in the baseline factory-built fireplaces were between 200 and 300 g/hr. CO factors were highest at the lowest burn rates (Figure 3-4). For realistic fuel burned in the baseline fireplace, the average emission factor was 76 g/kg.

These measured emission factors of 14.4 g/kg and 76 g/kg for PM and CO are not inconsistent with U. S. Environmental Protection Agency (EPA) recommended emission factors (Emission Factor Documentation for AP-42: Section 1.9, Residential Fireplaces, EPA-450/482-004). EPA's average factors are 13.6 and 85 g/kg for PM and CO. As has been pointed out, both factors have a strong burn rate dependence. Thus small differences in burn rates among studies can explain significant differences in emissions factors. The PM test method also influences the PM factor. EPA's number is based primarily on EPA Method 5. This study used a dilution tunnel method as in Colorado Appendix B. There is no direct fireplace data available, but wood stove data suggests EPA Method 5 might yield up to twice the PM emissions compared to the dilution tunnel method. Finally, there may be an air pressure effect due to altitude difference which, again based on stove data, might result in PM and CO emission factors approximately twice as high as measured in this study compared to near sea level (the altitude for most of the EPA data). When all these possible mechanisms for differences are taken into consideration, the results from this study and EPA are remarkably close.

POM data was obtained only from selected tests (see Section 6.8). For the Ponderosa pine burned in the baseline factory-built fireplace, the average emission rate for this case was 6.3 g/hr and the average emission factor was 1.7 g/kg, all at an average burn rate of 3.7 kg/hr.

The emission rates and factors for the masonry (MA) fireplace were slightly higher for PM and substantially higher for CO than for the factory-built fireplaces operated at the same burn rates (Figures 3-1 through 3-4). However we do not feel any general conclusions can be drawn concerning relative emissions from masonry and factory-built fireplaces due to the limited amount of data.

4. EXPERIMENTAL LOW-EMITTING FIREPLACE DESIGNS AND RESULTS

4.1. INSULATED DESIGNS

A few of the designs throughout this project were intentionally extreme without regard for practicality. The intent was to quickly establish whether certain design parameters were important. If there is no effect on peformance between designs representing the two extremes of a design parameter, it is probably not worth further effort. If the effect of a design parameter is important but not extremely large, this is more likely to be revealed if the designs represent extremes of the parameter.

One such extreme design involved insulation. The combustion chamber was hot due to a large amount of insulation and relatively low excess air. The combustion chamber shape was a vertical cylinder. The walls consisted of 2 inch thick ceramic fiber blanket. Air entered through many small holes around the circumference at the hearth level and in a tangential direction so as to induce a helical flame path in the combustion chamber (Figure 4-1). The diameter and height of the combustion chamber were approximately 27" and 17", respectively. Two inch thick ceramic fiber blanket insulation was used to insulate the collection hood. The lower side of a baffle at the top of the firebox was insulated with 1/2 inch thick ceramic fiberboard. The system was operated with its door closed. It is designated "K" (kiln) in graphs.

Primary measured emittants (PM and CO) were reduced by approximately 50 to 65% compared to baseline factory-built performance (Figures 4-2 and 4-3 and Table 4-1). Also see Figures 4-4 and 4-5 for a comparison of emissions rates for all designs tested. Although capable of very high burn rates in excess of 10 kg/hr, the cleanest performance occurred at lower burn rates of 4 to 5 kg/hr for the kiln design. Since this design was closed and had a relatively low average air-to-fuel ratio of 13, it was in fact more like a stove than a fireplace. However, the low emissions and simplicity of the design concept justified further exploration of more practical and fireplace-like insulated designs.

Just applying a one inch layer of ceramic fiberboard insulation to all surfaces inside the firebox of the baseline fireplace and using the same fiberboard material as a door (to further retain heat) resulted in the highest emissions observed - an average for PM and CO of 152% higher than the baseline fireplace. (This design is designated "I" for insulated in the graphs.) Overall, the design was not air starved. The air-to-fuel ratio was 50. Thus the high emissions were likely to have been caused by poorer mixing - the fit of the door was significantly tighter than the standard glass doors.

This result suggested that insulation alone was not the key to the clean performance of the kiln design, but that mixing of air with smoke was also critical. Adding an air injection grate system ("IA", insulated, air) to the closed insulated fireplace helped but still resulted in substantially worse performance than from the baseline fireplace.

Admitting extra air (to the same insulated fireplace with fiberboard door) at three or all four corners at hearth level helped. The air was introduced such as to induce a helical flow pattern in the fireplace (Figure 4-6). This insulated and closed design is designated "I3" (insulated, 3-corner air) in the graphs. Although this system is capable of very high burn rates (over 10 kg/hr), it remains a relatively clean burning system when fueled at lower rates (around 4 to 5 kg/hr).

Adding an opening for direct fire viewing to design "I3" could only be done in moderation before emissions performance suffered. A small horizontal 3" x 20" opening near the top of the fireplace face still yielded significant emissions reductions ("IS", insulated, small opening). However, increasing the opening size to a larger 9" x 20" horizontal opening or a nearly full 20" x 24" opening ("IL", insulated, large opening) resulted in performance essentially the same as the baseline fireplace. The loss of good emissions performance with large openings may be caused by substantial reduction in air drawn in the hearth-level corner air inlets and hence less turbulence.

4.2. AIR INJECTION DESIGNS

Three factory-built designs involved forced combustion air. In all cases a blower forced air through 1 to 2 inch diameter tubes with small holes. In the three designs, the tubes were: 1) part of the grate ("AG",air, grate), 2) located at the base of the back wall ("AL", air, low), and 3) located midway up the back wall ("AH", air, high). The back wall locations were intended to correct a degree of air starvation observed in the flames rising up the center of the back wall.

The results were not encouraging for any of these designs. Average performance was approximately unchanged compared to baseline performance (Figures 4-7 and 4-8).

In a previous privately funded study, the grate-level air injection system appeared to be helpful in reducing emissions. We have no certain explanation for the difference in results between that study and this one. Two possibilities are 1) that the earlier study used split oak logs instead of the 4x4 Douglas fir lumber with 1-1/2 inch spacing used in this study and 2) differences in average burn rates between the two studies (higher in the present study than in the previous one).

4.3. GLASS DOORS AND OUTSIDE AIR

Use of glass doors and standard outside air in baseline factory-built fireplace ("O", outside air) did not have a significant impact on emissions (Figures 4-9 and 4-10). In the fireplace tested, the outside air system consisted of a 1-3/4 inch diameter port located in the rear of the left side on the outside of the fireplace. The air then moved around (mostly up and over) the refractory liner to enter the firebox. Since the liner height was about 18 inches, it is plausible that most of the outside air did not contribute to combustion but became dilution air.

There appears to be some potential for glass doors and outside air which enters at hearth level. Air introduced at three of the four corners and directed so as to induce a helical flow pattern in the firebox resulted in a substantial reduction PM emissions (about 50%). However, CO emissions appeared not to be reduced.

Glass doors by themselves ("GL") without outside air were more effective than with outside air; average emissions were reduced by roughly 35%. This may be attributable to higher turbulence in the absence of outside air. The outside air was primarily dilution air; hence its presence did not contribute to combustion and resulted in less air entering through the doors. This could mean lower velocity air entering through the doors and hence less turbulence in the combustion zones of the fireplace.

If the effectiveness of glass doors with or without outside air is related primarily to turbulence, then it is related to details of how much air enters through inlets and cracks in particular locations and hence is likely to depend on individual fireplace designs.

4.4. SIZE EFFECTS

If combustion efficiency were approximately the same for all conventional open fireplaces, then emission rates would be less for smaller fireplaces because of the lower burn rate.

This possibility was explored by including both a very small ("S") and a very big ("B") factory-built fireplace. The small fireplace had an opening width and height of 21 and 18 inches, and a depth of 11 inches. The large fireplace had an opening of 36 inches x 26 inches, and a depth of 24 inches.

The results do not indicate that smaller fireplaces have lower emission rates (Figures 3-1 and 3-2). Clearly combustion emission rates are roughly the same independent of fireplace size. In contrast, emissions factors are not uniform as a function of fireplace size (Figures 3-3 and 3-4). Rather, bigger fires tend to be cleaner burning, probably because of the higher temperatures. Based on this limited data, controlling fireplace size does not appear to be a reliable way to assure low emission rates.

4.5. FIREPLACE SHAPE

One radically different fireplace shape was explored, consisting of a relatively deep ("D") but narrow firebox open at the front (Figure 4-11). For convenience, a wood stove without its door was used. The entire combustion chamber (region below the baffle) was lined with one inch of ceramic fiber insulating board. The firebox under the baffle was 16 inches deep and approximately 14 inches high and 13 inches wide (inside the liner). Since the baffle did not extend all the way forward, fuel longer than 16 inches could be used without smoke spillage. Three fuel configurations were tested: 1) full length 20 inch pieces which forward ends extended forward of the baffle, 2) shorter 14 inch pieces located entirely under the baffle, and 3) still shorter 11 inch pieces oriented crosswise (parallel to the door opening) as is conventional in fireplaces.

All fuel configurations resulted in approximately the same performance. The relatively small scale of the design resulted in relatively low burn rates of 2 to 4 kg/hr. All three measured emittants were reduced with the reduction in PM being the largest (59%),(Figures 4-12 and 4-13.)

The reduced emission rates from this design were not just due to its low burn rate; it had substantially lower emissions factors than most other designs operated at the same burn rates (Figures 4-14 and 4-15). Thus, although the tested fireplace was very small compared to typical fireplaces, there is a reasonable chance that performance will remain attractive if the size were scaled. (Emission rates equal the product of emission factors and dry burn rates.)

Because this was one of the more technically promising designs, its performance was also measured using realistic fuel (Ponderosa pine split logs). As was true for the primary baseline fireplace, use of Ponderosa pine resulted in higher emissions than did use of standard test fuel. However, comparing both designs using the realistic fuel, the reductions in both PM and CO rates were at least as high as with both designs using standard fuel (Figures 4-16 and 4-17, and Table 4-2).

Because the scale of the design was significantly smaller than what is accepted as being a fireplace, a logical next step would be to scale up the design to a more typical fireplace size and determine if the performance is still improved.

4.6 OTHER NON-CATALYTIC DESIGNS

As part of the initial exploration of extreme designs, an open campfire was tested - an open fire ("F" in Figures 4-12 and 4-13 and Table 4-1) with only a collection hood above it. CO emissions were roughly comparable to those from the baseline factory-built fireplace. PM emissions were significantly higher - on the order of 50%. Since the performance was not spectacularly better or worse than the baseline case, mechanisms to explain the difference in emissions reduction were not investigated.

A circular ("C") fireplace was tested. Air entered tangentially at one vertical slot so as to induce a helical flame path. The results (Figures 4-12 and 4-13) did not merit further development of the design concept.

The original version of the simulated small factory-built fireplace ("SB") had a cast iron baffle in the top of the combustion chamber. Its apparently inconsistent performance (high PM and low CO) and the fact that the baffle was uncharacteristic of fireplaces resulted in repeating the tests with baffle absent. (This unbaffled design was the small baseline fireplace.) We did not pursue the baffled design because its performance was not promising.

A test was conducted on the baseline fireplace without andirons ("N", no andirons) to investigate the contribution of the grate to air/fuel mixing. Emissions were apparently slightly reduced, but by an amount possibly attributable to data scatter.

4.7. CATALYTIC DESIGNS

Four catalytic designs were investigated. All were intended primarily to determine if catalytic reduction of emissions in an open fireplace was technically feasible.

None of the designs included bypass mechanisms.

None of these designs involved any significant changes to the shape or components of the original fireplace, only the addition of a combustor. Thus negligible retooling would be necessary on the basic fireplace - the expense would be primarily the combustor itself.

The four designs were given the abbreviated names Liner, Thin, Thick and Stack. All involved a catalytic coating (composition and loading) identical to that commonly used in wood stove combustors. In all cases the combustors were assembled from two basic 4 x 4 x 1/2 inch catalytic building blocks with a cell density of either approximately 16 or 4 cells per square inch.

LINER ("CL"), Catalyst Liner

The objective in this design was to avoid undue flow resistance and hence smoke spillage. A total of 512 square inches of 16 cell material was used primarily as a firebox liner in the baseline fireplace. One layer was applied flat to all surfaces starting approximately 1 foot above the hearth. Roughly 256 square inches of the same material was suspended in the throat of the fireplace in a vertical configuration such that smoke flow was predominantly parallel to the plane of the thin honeycomb slabs. Thus no smoke was forced to pass through the cells of the honeycomb.

THIN ("CT", Catalyst, Thin)

The "thin" catalyst design consisted of 16 cell material placed on a horizontal grate support in the throat of the baseline fireplace (Figure 4-18). The bed was approximately 12" x 18" and was 1 inch thick. It filled the fireplace throat so that all smoke from the fire had to pass through the cells.

THICK ("CT", Catalyst, Thick)

The "thick" catalyst also utilized the 16 cell material. The size of this bed was approximately 12" x 18" at the bottom tapering to approximately 8" x 10" at the top and 5" in thickness.

STACK ("CS", Catalyst, Stack)

This design was installed as an add-on. It was located in a 12 x 12 inch rectangular segment of flue located, with appropriate round-to-square adaptors, immediately above the fireplace (Figure 4-18). It consisted of a 12 x 12 inch bed, 5 inches in thickness of 4 cell material.

All of the above four designs were tested in the baseline factory-built fireplace. The catalytic designs with the best performance were the thick catalyst bed in the throat and the catalyst in the stack, which was also thick (Figures 4-19 and 4-20). Both designs resulted in over 50% reductions in PM and CO emissions. The thin catalyst averaged a 38% reduction in CO and PM. The catalytic liner was less, but still apparently slightly effective. The masonry fireplace was also catalyzed with a 4 inch thick bed in the throat using the 4 cell material in the center back of the bed where the most concentrated products of combustion are located. A 3 inch thickness of the 16 cell material was used for all other portions of the bed. PM and CO reductions were both about 40%. Thus, the catalytic approach was also effective in a masonry fireplace.

Realistic fuel was also used in the factory-built fireplace with the stack catalyst. An average (PM and CO) emissions reduction of 51% was observed compared to use of the same realistic fuel in the baseline fireplace.

For some of the catalytic designs there was slight smoke spillage at the beginning of the kindling phase. In no catalytic design was there smoke spillage during the hot-to-hot test cycles.

4.8 POM RESULTS FOR LOW-EMITTING FIREPLACE DESIGNS

POM was measured for selected tests only. The detailed results are given in Table 4-3 and in Appendix 5. The data in Appendix 5 represent the total of the sixteen compounds covered in EPA Method 610.

Three pairs of compounds were not resolved and are given in Table 4-3 as the sums of both compounds.

Lower molecular weight compounds dominate as has been found to be the case for woodstove POM (see Shelton Research Inc.'s

California Air Resources Board report "Evaluation of Low-Emission Wood Stoves", June 23, 1986).

For some tests results appear to be inconsistent. For example, the relatively large amount of dibenzo(a)anthracene in Test No. 146 appears to be anomolous, as do the very low amounts of napthalene in Test Nos. 109, 143, 144 and 146. Since these tests are not unique with respect to fireplace design or burn rate, we suspect these results reflect noise, not reality. We are particularly suspicious that the total emission rates and factors for Test Nos. 143 and 144 are inconsistent with each other (both represent the same design at approximately the same burn rate).

There was no specific analysis for breakthrough in this project. Previous research using this POM method (see Shelton Research Inc.'s report for California Air Resource Board, "Evaluation of Low-Emission Wood Stoves", June 23, 1986) indicated very small, if any, breakthrough when sampling a similar volume of similarly diluted woodstove smoke.

Table 4-4 contains average POM emission rates and factors for those designs which were represented by 3 or more tests with POM analysis. Both the deep and catalytic designs burning standard fuel had substantially reduced POM emissions relative to the baseline fireplace burning Ponderosa pine. But for these two designs the emissions factors are substantially higher than for clean-burning stoves burning the same standard fuel by on the order of a factor of 10. POM production from primary pyrolysis products requires threshold temperatures, which are more often and uniformly achieved in flaming fireplace fires than in smoldering woodstove fires. Even in wood stoves, POM production increases with increasing burn rate (higher combustion temperatures).

4.9 HEAT OUTPUT AND EFFICIENCY RESULTS

Radiant heat output was measured for selected tests. The results are shown graphically in Figure 4-21. Two trends are apparent.

1. Radiant heat output increases with burn rate.

2. Glass doors suppress heat output.

The tests designated "GL" and "O" both involved closed doors.

An approximate overall efficiency is shown in Figure 4-22. Because the efficiency is computed as wood energy input minus flue losses as explained in Section 2.11, it is an overestimate for appliances with losses other than up the flue. Side, back and top losses as well as losses up the air spaces in non-solid-pack flues are all counted as gains. Thus the results are overestimates for most tested designs. Since heat storage was not taken into account, the results for the masonry fireplace are distorted upwards additionally.

Nonetheless, some useful trends are revealed. For any given design, efficiency tends to increase with burn rate. The kiln (super-insulated design, designated "K") had high efficiency despite the insulation because of its relatively low air-to-fuel ratio and because of heat transfer through the single wall flue used.

The deep fireplace ("D") also had high overall efficiency in part because of its single-wall construction and its single wall flue.

The insulated factory-built fireplace with a closed insulated door ("I"on the graphs) had low efficiency since the design forced most of the heat up the flue.

These trends are further revealed in flue flow and flue temperature data (Figures 4-22 and 4-23).

5. TEST METHOD DEVELOPMENT

It was the intent in this project to use existing test methods as far as is practical. The primary reference test method was that described in Appendix B of "Colorado Department of Health Regulation No. 4", i.e., the Colorado dilution tunnel method. The Oregon stack-sampling method described in Appendix A of Regulation No. 4 is not suitable when flue gases are too dilute, as is the case with most open fireplaces.

Although the Colorado Appendix B test method is the primary reference method for testing fireplaces this project, the U. S. Environmental Protection Agency (EPA) methods for wood stoves have also been under development during the course of this project (EPA proposed test methods 28, 28A, 5G and 5H). In most respects, the EPA methods represent technical improvements over the Colorado methods, having been written more recently. Methods 28, 28A and 5G contain some features which are useful for testing fireplaces even though they were designed for stoves. In addition, the Colorado Appendix B method has been evolving. Some equivalent techniques are now permitted which are applicable to fireplace testing. Thus useful test method features were drawn from these sources as well as Colorado Appendix B.

It was found that test method modifications were necessary or advisable in areas relating to dilution tunnel parameters, CO and PM sampling, fuel load and fueling protocol, and distribution of tests. Problems and suggested solutions in each of these areas are given in this chapter of the report.

Neither Colorado nor EPA requires efficiency measurements in their stove emissions programs.

5.1. DILUTION TUNNEL PARAMETERS

The Colorado Appendix B test method places two constraints on dilution tunnel parameters:

1. The tunnel temperature may not exceed 51.7 degrees C (125 degrees F) at any time during a test.

2. The ratio of the average tunnel flow to the average fuel burn rate (moist basis) must be between 100 and 400.

At the outset of this project, there was concern that the average air-to-fuel ratio of some fireplaces might exceed 400 to 1. If this were the case, the tunnel-flow to burn rate ratio would have to exceed 400 to 1 in order to entrain all the flue gas (as is required). In actuality, the air-to-fuel ratio never exceeded 400 during any test in this project, and was typically under 100.

Nevertheless, there are advantages to changing the tunnel flow specification to the spirit of EPA's tunnel flow specification. A single uniform tunnel flow for all tests eliminates dilution as a variable and thus should improve precision and reproducibility.

Thus we suggest the following tunnel flow specification for fireplace testing:

> Dilution tunnel flow shall be 1500 +/- 150 kg/hr for all tests with average dry burn rates under 15 kg/hr, and the tunnel diameter in the measurement section shall be 12 inches. For burn rates greater than 15 kg/hr, larger tunnel flows and diameters may be used to avoid condensation and to maintain the tunnel-to-burn-rate ratio above 100. However, this ratio must be kept below 400.

These proposed tunnel flow limits and ratios are shown in Figure 5-1 along with test data for this project.

The instantaneous tunnel temperature limit of 51.7 degrees C now in Colorado Appendix B is not practically achievable when testing most fireplaces. The low heat transfer efficiency of most fireplaces results in very large heat flows up the flue and consequently high tunnel temperatures when using ambient temperature dilution air at the tunnel entrance. In this project, the 51.7 degrees C instantaneous tunnel temperature limit was exceeded in virtually every test and, in fact, the average tunnel temperature in well over half the tests exceeded 51.7 degrees C (Figure 5-2).

This is not now considered a serious problem in itself. When the first draft of the American Society for Testing and Materials (ASTM) tunnel method was written, it was assumed that filtration temperature would closely correlate with tunnel temperature and hence that tunnel temperature must be constrained. (This ASTM draft method was the basis for both Colorado Appendix B and EPA Method 5G.) In fact, filtration temperature is what is critical. It is virtually always less than tunnel temperature and it has its own limits in Colorado Appendix B and in EPA Method 5G. Thus the tunnel temperature limit is not needed and, in fact, is no longer required by the Colorado Department of Health or the Oregon Department of Environmental Quality. The draft EPA test methods also have no limits on tunnel temperature.

Thus we recommend that tunnel temperature have no constraints in a fireplace test method.

5.2. PM SAMPLING TRAIN

One aspect of the particulate matter (PM) sampling method which may need modification concerns the filtration temperature. The present Colorado Appendix B instantaneous range limit of 21 to 32 degrees C and the draft EPA upper limit of 32 degrees C were exceeded in well over half of the tests in this project. Even the average filtration temperature exceeded these limits in many tests (Figure 5-3). The PM sample stream cooling achieved with maximum length probes (12 inches), wet cloths on the probes and filter holders and a fan were not adequate to maintain filtration temperatures below 32 degrees C, even with an ambient temperature close to the minimum allowed of 65 degrees F. A maximum average filtration temperature of 45 degrees C was observed.

For direct comparability with stove emissions, it is desirable that laboratories be required to do whatever is necessary to maintain filtration temperatures below the present 32 degrees C limit if reasonably practical. This may require one or more of the following changes:

1. Use of larger length and/or diameter PM probes to provide more surface area for cooling (the current length limit is 24 inches; diameter limits vary);

2. use of larger filters and filter holders (present limits vary;

3. lowering the minimum ambient temperature from 65 degrees F to 55 degrees F;

4. allowing colder-than-ambient air to be added to tunnel flow upstream of the 2 mixing baffles. (These mixing baffles are an EPA addition to the method; Colorado Appendix B does not require them.)

A second issue concerns the use of dual PM sampling trains. Colorado Appendix B requires dual trains. EPA Method 5G requires them in some circumstances and not in others. We recommend that dual trains be required. Use of dual trains improve precision and prevents certain kinds of errors from passing undetected.

5.3. CO MEASUREMENT

Since energy efficiency determinations are not part of the contemplated fireplace test method, Carbon Monoxide (CO) emission rates are not a byproduct of flue gas measurements.

We suggest that CO emissions be determined by measuring the CO concentration continuously in the dilution tunnel and integrating the results to obtain total grams of CO emitted from each test. This method is now an approved equivalent for Colorado Department of Health. An NDIR CO analyzer with 1% of full scale accuracy and a full scale response for 0.2% CO is usually adequate.

5.4. DOOR CONFIGURATION

The largest single probable cause of the apparent lack of realism (much greater emissions in the field than in laboratory testing) in the wood stove program is the fact that in the field bypass dampers in catalytic stoves are too often open. Reasons include the desire to operate with doors open for direct viewing of the fire, desire for higher heat outputs and forgetfulness.

Preventing similar problems in fireplace programs is important. Early in the program it was decided to emphasize open-door fireplace designs, recognizing that if closed-door operation were essential to clean combustion, there would inevitably be higher emissions in the field due to user desire for open-door operation. The assumption was that open door configuration is the more challenging one for achieving emissions reductions. However, this assumption may not always be valid. Thus we recommend that a fireplace which has, or reasonably could have, doors be tested both with and without doors.

It should be noted that if a bypassless design is developed for fireplaces, it might also be applicable to stoves and hence be a solution to the problem of open bypass operation of stoves in the field.

5.5. CHARCOAL BED WEIGHT MONITORING

All extant stove testing methods prescribe a charcoal bed weight of 20 to 25% of the test load weight. Tests begin and end at the same charcoal bed weight.

Charcoal bed weights are determined by monitoring the weight of the appliance, its contained fuel and (usually) the chimney. Thus a fundamental assumption is that the initial empty weight of the appliance plus flue does not change during a test.

This assumption is questionable. Many fireplaces (and stoves) contain firebricks and other refractory material. Poured refractory can contain very large amounts of moisture until heated in use. We observed a one time loss of 12 kg of moisture from the refractory in the largest fireplace tested. As a consequence of this and other observations, EPA's draft test method for stoves requires at least 10 hours of "aging" of all stoves before testing in order to drive out moisture.

Unfortunately, refractory materials also regain some of their lost moisture when they cool. We have seen weight gains as high as .35 kg. This constitutes on the order of 10% of the specified charcoal bed size for typical fireplaces. Larger distortions in charcoal bed size are no doubt possible. If the effect can indeed be larger than 20% of the charcoal bed size, corrective action is probably appropriate. (It should be noted that this potential problem applies to stove as well as fireplace testing.)

Our suggested solution is to adopt a fueling protocol that does not involve the need to measure charcoal bed weight. This is discussed in the next few Sections.

5.6. CHARCOAL BED SIZE

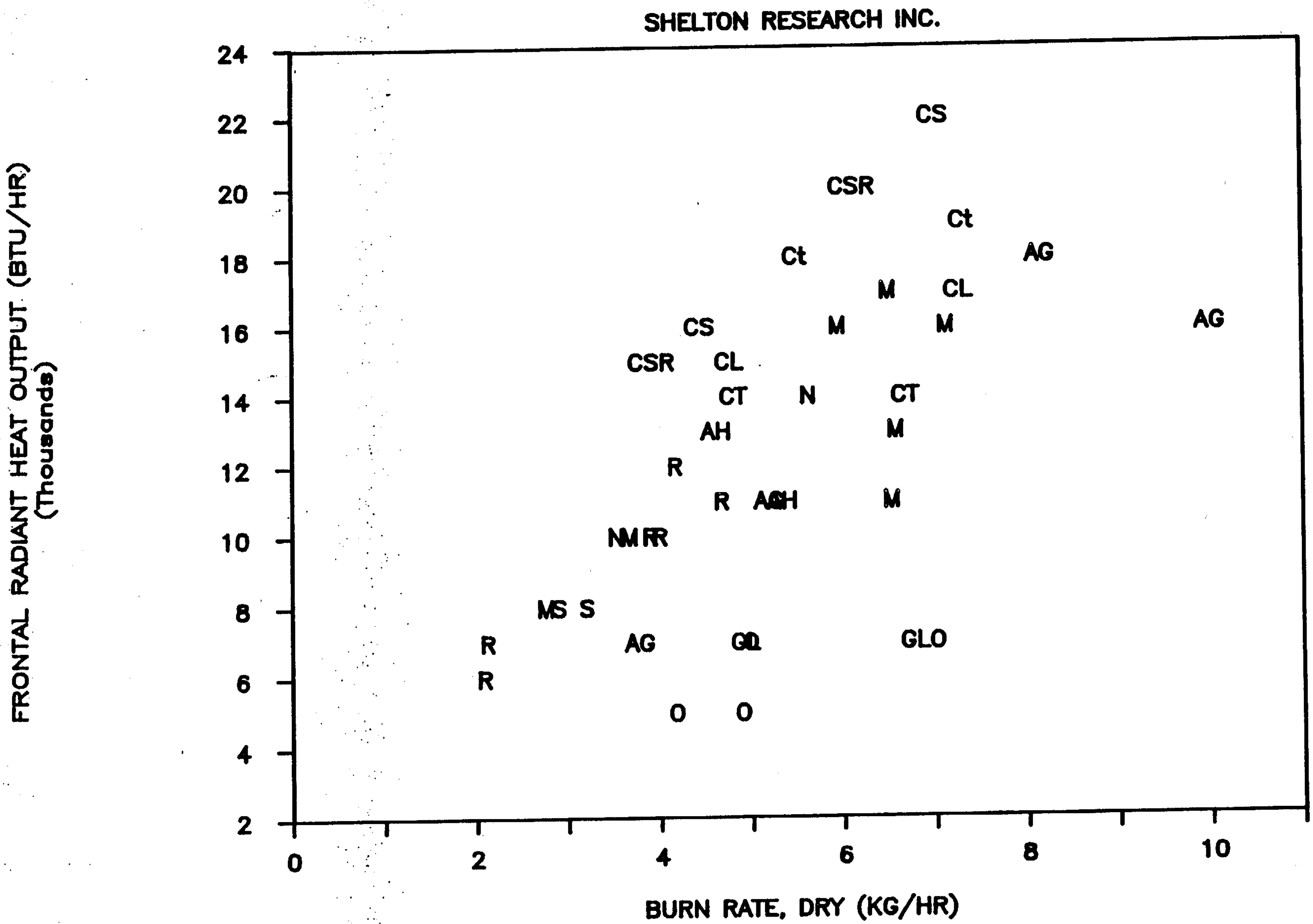
One reason the standard fuel loads burn at such a high rate is that the standard charcoal bed (20 to 25% of the fuel load by weight) is very big and hot relative to typical home use of fireplaces. The charcoal bed typically covers the entire hearth to a depth of 5 to 6 inches. The bed is also red hot when it is established following the standard pre-test protocols. Such a charcoal bed causes fuel loads to burn uncharacteristically fast and is thus felt to be unsuitable for a fireplace emissions test.

5.7. FUEL LOAD SIZE

The test fuel load size specified in Colorado Appendix B and in both Oregon and EPA standards is not appropriate to use for fireplace emissions testing. Particularly in larger fireplaces the load is unrealistically large, dangerous and impractical.

The degree of realism can be a subjective judgement. However, few will quarrel that the fire illustrated in Figure 5-4 is uncharacteristic of typical home fireplace use. The Colorado Appendix B load for this 36" x 28" x 24" (width x height x depth) fireplace consists of 10 4x4s, 27 inches long, with a total weight of about 34 kg (75 lb), (moist basis). The resulting burn rate is about 37 kg/hr (82 lb/hr, moist basis).

FIGURE 4–21. FRONTAL RADIANT OUTPUT.



starts or kindling phases. Thus this project included measurements of emissions over both the kindling phase and main load hot-to-hot phases for most designs. The objective was to determine if serious rating reversals would occur if only hot-to-hot test cycles were used to certify designs compared to using cold-start cycles or a combination.

The results (Figure 5-5) do not indicate any convincing inadequacy of using only hot-to-hot test cycles. The cleanest-burning designs for the hot-to-hot test cycles are at the left side of the graph. They also tend to have the lowest emissions during the kindling phase. The designs with higher emissions during main load phases also tend to have higher kindling phase emissions. Thus focusing on main load performance is unlikely to yield misleading results when all phases are taken into account.

The two instances where a cold-start cycle was cleaner than the average of the hot-to-hot test cycles almost certainly represent scatter in the data and irregularities in how solid fuel burns, not some characteristic of the fireplace designs.

5.10. RECOMMENDED FUELING PROTOCOL FOR FIREPLACES

Faced with all the fuel and charcoal bed issues just discussed, we developed an alternative which deviates significantly from the stove fueling protocol but in our opinion is necessary for a meaningful fireplace test method and has some substantial benefits in addition to its improved realism.

The key element is single log fuel additions at a rate to match a predetermined fueling rate. Preconditioning consists of approximately 90 minutes of fueling at the target rate. The test then consists of approximately 90 minutes of fueling at the same rate.

Three tests at 3 different fueling rates are required for each appliance configuration. (Open and closed doors are different configurations.) The medium fueling rate is determined by hearth area; the medium burn rate (dry basis) in kg/hr is approximately twice the hearth area in square feet. (See Section 8 for a more complete description of this proposed fueling protocol.)

This particular fueling protocol was only used for a few tests at the end of the project. Most of the tests used fueling rates which made the fires look realistic - a subjective judgement. A number of tests used higher and lower fueling rates to achieve higher and lower burn rates. The suggested scheme for determining the required medium fueling rate is based on burn rates achieved during the project wherein the fire looked realistic.

The particular proposed relation between hearth area and medium fueling rate is a very rough estimate based on limited data

(Figure 5-6). Further research is appropriate (see Appendix 2). The 50% margin for the low and high burn rates is also only a rough estimate of what might be reasonable.

The proposed fueling protocol has the significant advantage that the appliance need not be weighed. "Charcoal bed" weights are established as a consequence of a fixed fueling rate. Test duration is based on time or number of single log additions, not weight. Thus the fueling protocol is equally applicable to factory-built fireplaces and masonry fireplaces. Some masonry fireplaces are essentially unweighable with the accuracy required by the stove fueling protocol (0.1 lb).

6. DEFINITIONS OF FIREPLACES

At present there is no consistent and practical definition of a fireplace. Colorado's fireplace definition involves subjective judgements and is thus difficult to work with. Colorado's stove and fireplace definitions are inconsistent with each other and EPA's stove definition is different from Colorado's stove definition. If Colorado is to have separate emissions regulations for stoves and fireplaces, it is important to have definitions which unambiguously place appliances in either or neither category, but not both.

The present Colorado stove regulation (and Section 25-7-402(3) of the Act) defines a stove as follows:

"Woodstove" means a wood-fired appliance, including a fireplace insert, with a closed fire chamber which maintains an air-to-fuel ratio of less than 30 during the burning of 90 percent or more of the fuel mass consumed in the low-firing cycle. The low-firing cycle means less than or equal to 25% of the maximum burn rate achieved with doors closed or the minimum burn rate achievable.

Section 25-7-402(2) of the Act defines a fireplace as follows:

"Fireplace" means a structure designed for the burning of wood which is an integral part of the construction of a building and which would commonly be considered a fireplace.

The proposed EPA wood stove regulation defines a stove as follows:

" 'Wood Heater' means an enclosed woodburning appliance capable of and intended for space heating, domestic water heating, or indoor cooking, that meets all of the following criteria:

a) air-to-fuel ratio in the combustion chamber averaging less than 35-to-1 as determined by the test procedure prescribed in 60.534;
b) a usable firebox volume of less than 20 cubic feet;

c) a minimum burn rate of less than 5 kg/hr; and

d) a maximum weight of 800 kg.

In addition to this definition of wood heater, EPA excludes from its proposed regulation coal-only heaters, central heaters (furnaces and boilers) and open masonry fireplaces constructed on site.

Since these definitions were written (particularly the Colorado definitions), more has been learned about how woodburning systems perform under standard testing conditions. As part of this project, air-to-fuel ratios were measured for a few fireplaces using standard test methods as specified by the Colorado Regulation (essentially the same testing specified in EPA Method 28A).

The results indicate that most fireplaces are stoves! Air-to-fuel ratios of fireplaces are less than 30 in standard laboratory testing (EPA Method 28A) even with their doors open (Figure 6-1). Using realistic fuel and firing conditions, air-to-fuel ratios of most fireplaces are greater than 35 (Figure 6-2). However, the large size of the "standard" fuel load specified in existing standards and the very large and hot charcoal bed on which this load is placed results in an extremely large fire. This, in turn, tends to lower the air-to-fuel ratio. Thus present Colorado definitions are contradictory - fireplaces are both fireplaces and stoves.

A partial resolution would be to adopt EPA's definition of a wood stove. This requires, among other things, a minimum burn rate of under 5 kg/hr. Most fireplaces would then not be stoves because their minimum burn rates are greater than 5 kg/hr.

Fireplaces could then be defined as systems with minimum burn rates greater than 5 kg/hr or air-to-fuel ratios greater than 35-to-1 plus additional attributes to distinguish fireplaces from other high minimum-burn-rate or high air-to-fuel ratio appliances.

Specifically, for the sake of national uniformity, we recommend that Colorado adopt EPA's definition of wood stoves. We further recommend that a fireplace be defined as a wood-burning appliance satisfying all of the following:

1. Combustion chamber volume (EPA definition) is less than 20 cubic feet.

2. Either A) the air-to-fuel ratio (EPA Method 28A) is greater than 35-to-1, or B) the minimum burn rate is greater than or equal to 5 dry kg/hr (EPA Method 28A), or both.

3. An intended normal operating configuration is without doors or with doors open.
4. Fuel is fed into the combustion chamber by hand, not by an auger or by gravity-feed from a hopper.

5. The unit is not a central heater (EPA definition, which requires among other things that the appliance be listed to a nationally recognized central heater standard).

6. The unit is not a barbecue.

Finally, we recommend that Colorado's stove and fireplace definitions be designed to be responsive to changes in EPA's stove definition. For example, EPA may make adjustments to the 35-to-1 air-to-fuel ratio and to the 5 kg/hr minimum burn rate. EPA developed these cutoffs when little data was available. It now appears that some adjustments may be necessary to assure that some fireplaces are not accidentally caught in the stove net. As illustrated in Figure 4-1, some medium size fireplaces even without doors are not very far from being stoves.

7. DISCUSSION OF THE MOST PROMISING DESIGNS TESTED

Among the designs investigated, there are three general design types which emerge as having significant potential for reducing emissions. Two are open designs and one is closed.

The promising open designs are the deep firebox and the catalytic approach. The closed design is characterized by turbulence and/or insulation.

7.1. DEEP FIREBOX

The open, deep firebox design exhibited an average PM and CO emissions reduction of 50%. Comparing realistic fuel results in both the deep and baseline fireplaces, the reduction averaged 52%. Thus there seems to be no doubt about the reality of the beneficial effect on emissions.

If its size were scaled up, would its performance continue to be good? One can be hopeful since the emissions factors (grams per kilogram of fuel, Figures 4-14 and 4-15) were relatively low compared to other designs tested at the same burn rate. However, the question can only be answered with certainty experimentally.

The unit tested does not look like a fireplace. When scaled up and fitted with a front whose area is larger than the combustion chamber cross-sectional area, the aesthetics would be more conventional. The flame path and pattern would still be unusual.

Since only one design of this type was tested, it may be that other proportions or shapes would work as well or better. The importance of the insulation ceramics board is also not established. It may be unnecessary or performance might be improved by increasing the amount of insulation.

Although unconventional in shape, the design is simple, durable and needs no operator participation (there are no dampers or other controls). There are also no anticipated unusual safety problems.

Overall, the only significant liability appears to be the size of the firebox, and it is not certain if this is a necessary liability.

7.2 CATALYTIC DESIGNS

Catalytic combustion using traditional honeycomb (or equivalent small passageway) geometry substrates is one technology which is known to be very effective in laboratory testing in stoves.

Catalyzing open fireplaces is more challenging than catalyzing stoves for a number of reasons:

1. The high excess air levels in traditional fireplaces result in lower temperatures. This inhibits both light-off and sustained operation of combustors.

2. The high excess air levels in traditional fireplaces, and their relatively high combustion efficiencies, result in lower concentrations of combustibles. This hurts sustained operation since less heat is generated in the combustor and lower combustor temperatures result. Temperature rises of only a few tens of degrees can be expected rather than the 100's of degrees in stoves.

3. The high excess air levels in traditional fireplaces and their high burn rates result in higher volume flows. To achieve the same degree of conversion (of combustibles) that is achieved with stoves requires more total catalyzed surface area or smaller cells. To the extent that velocities are higher, catalyst abrasion is worse.

4. Traditional fireplaces have a very delicate balance between draft, flow resistance and flow. Most fireplaces need all the draft they have to prevent smoke spillage. If a combustor is added to a traditional fireplace, it must present <u>very</u> little resistance to flow or smoke spillage will result.

5. Two ways to reduce flow resistance are to decrease cell length or increase cell diameter. Both of these approaches result in a combustor with higher thermal losses; this inhibits sustained operation. Both these approaches also reduce surface area if overall volume remains the same; this also is detrimental to performance.

6. The plugging of honeycomb combustors with ash is more of a problem with higher velocities, as are found in fireplace combustion. However, this potential problem could be solved through use of larger cell sizes in the combustor.

The thick-bed and stack catalytic designs exhibited similar emissions reductions - 65% to 60% (average of PM and CO) compared to the baseline fireplace using the Douglas fir 4x4 fuel, 51% using realistic fuel, and 40% in the masonry fireplace using Douglas fir 4x4s.

These reductions were achieved with no attempt to optimize the catalytic combustion. The combustor materials (shapes and coatings) were what was available on short notice. It is likely that performance could be much better, or the amount of catalytic material much less, or both.

Probing of the gas chemistry just above the combustor indicated poor mixing. During the peak of each 1 log cycle the mixture was fuel-rich near the center of the combustor (for all horizontal or bed-type geometries). There was also a peak in the emissions at the same time. Hence some precombustor mixing should improve performance.

Combustor temperatures were clearly adequate to achieve substantial catalytic combustion, but the margin was slim. During most of each 1-piece mini-cycle, temperatures in the center back of the combustor were roughly 100 to 300 degrees F above combustor light-off temperature. Towards the end of each single log cycle, the instantaneous CO emissions increased as combustor temperatures cooled.

This has some important implications. A slight increase in temperatures could improve performance significantly. A slight decrease in temperatures could increase emissions substantially. Thus one can expect burn rate to be an important variable.

Standard emissions testing must cover a full range of realistic burn rates. It would not be surprising if use of green fuel would result in poor combustor performance due to lower burn rate and hence lower temperatures.

As combustors age, performance might degrade more than in stoves because of marginal temperatures (as combustors age, light-off temperatures become higher). On the other hand, hours of use are so much less for fireplaces that aging may be relatively slow.

Given all these sensitivities to temperature, fireplace designs which tend to have higher temperatures would be desirable for emissions reduction. The most obvious way to achieve this is to lower the air-to-fuel ratio by reducing the size of the fireplace opening relative to the hearth area. Design shifts in this direction may increase fireplace costs but need not restrict the fire view if, for instance, some fixed glass is used. On the other hand, higher temperatures will make it more difficult (but not impossible) to pass safety standards.

The amount of catalytic material was very large. However most of it was not in fact being utilized. The gas concentrations in the horizontal bed combustors were non-uniform, especially the combustors located in the fireplace throats. The combustion products rising up from a fire in an open fireplace are concentrated centrally and against the back wall. The forward and side portions of the flow are predominantly air. Thus only the central back portion of the full throat combustor was in use. The rest of the combustor could be replaced with uncatalyzed substrate or perhaps even cheaper materials which would let the air pass through.

Normally (in the case of stoves) catalytic designs have bypasses to provide adequate venting during startup, reloading and direct fire viewing. The catalytic fireplace designs investigated had no bypass. This was done primarily for research simplicity. However if a no-bypass system can be made to work, it has the advantage that the emissions reducing technology cannot be bypassed intentionally or unintentionally. This should result in field performance which more closely resembles laboratory performance.

If a bypassless combustion system is developed for fireplaces, it might find application in stoves. This could solve a major design problem - the leakiness of bypass dampers. It would also substantially reduce emissions at times when, in an ordinary catalytic stove, the bypass is open.

Whether such a design can be made practical is as yet unknown. The challenge is to avoid smoke spillage at start-up without sacrificing performance when the fireplace warms up, and to minimize the probability of combustor plugging during operation.

Combustor durability is important. Flame impingement needs to be minimized. This will require more remote locations or baffling. Baffling, of course, increases the tendency for smoke spillage. Remote (high) locations make combustors and related mechanisms such as bypass dampers less accessible for maintenance. Combustor poisoning could be more of a problem with fireplaces than stoves because of the stronger tendency to use a fireplace as a trash burner. Ash plugging of the leading face and abrasion are also likely to be more serious problems in fireplaces than stoves.

On the other hand, the potential for emissions reduction is very high. If a first-guess system results in 50% reduction, higher reductions are certainly possible with design optimization. This is in contrast to the deep fireplace design where there is more uncertainty if higher reductions are possible because the mechanisms for that design's success are not as well understood.

7.3. INSULATION AND/OR TURBULENCE

The closed design concept with potential involves a combination of insulation and/or turbulence. The kiln was an impractical extreme case. The insulated fireplace with 3-corner hearth-level air did nearly as well. Other promising essentially closed designs with one or both of the design elements were the insulated fireplace with 4-corner air and a very small door, ("IS"), the baseline fireplace with glass doors and 3-corner air ("GL3"), and the baseline fireplace just with glass doors ("GL").

These designs tend to have relatively high burn rates and hence short burn times - a disadvantage. They also all involve closed doors or a very small door - also a disadvantage. The insulation and admission of extra combustion air at hearth level will raise temperatures and may require some redesign to pass safety standards. However the concepts are simple and can be implemented in a rugged, durable and probably relatively inexpensive system. It is our feeling that further research on these design concepts would produce positive results, perhaps even in an open-door mode.

8. CONCLUSIONS

8.1 TEST METHODS

One of this project's objectives was to consider modifications to wood stove emissions test methods to create a test method applicable to fireplaces. Our specific suggestions follow:

Base Method

Both for the sake of national uniformity and because the method incorporates some minor improvements over Colorado Appendix B, we suggest EPA Methods 28 and 5G as the stove testing methods to be adapted to fireplaces.

Changes in Dilution Tunnel Construction and Operation

Dilution tunnel flow shall be 1500 +/- 150 kg/hr for all tests with average dry burn rates under 15 kg/hr, and the tunnel diameter in the measurement section shall be 12 inches. For burn rates greater than 15 kg/hr, larger tunnel flows and diameters may be used to avoid condensation and to maintain the tunnel-to-burn-rate ratio above 100. However this ratio must be kept below 400. Cool air may be introduced into the tunnel through a tee upstream of the mixing plates if desired to help maintain the filtration temperature below 32 degrees C.

PM Measurement

Some changes may be necessary to assure filtration temperatures can be maintained below 32 degrees C.

The current dual PM train and precision requirements in Colorado Appendix B (but not in all aspects of EPA Method 5G) should be maintained.

CO Measurement

Add to EPA 5G the dilution-tunnel-based CO measurement now approved for Colorado.

Door Configuration

A fireplace which has, or reasonably could have, doors shall be tested at the three required burn rates both with and without doors open.

Preload and Test Load Fuel: Species, grade and moisture content as described in current Colorado and proposed EPA standards. Piece lengths: 3/4 of the average of the hearth width in the back and front of the fireplace.

Piece Size: We suggest that piece size (cross-sectional dimensions) be a function of piece length as defined above. For piece lengths less than 1 foot, use 2"x4" dimensional lumber. For piece lengths between 1 and 3 feet, use 4"x4" lumber. For piece lengths more than 3 feet, use 6"x6" lumber.

Spacing: 3/4 inch for 6"x6" lumber, 1-1/2 inch otherwise.

Note: With this definition of the fuel very nearly all fireplaces would be tested using 4"x4" pieces, spaced 1-1/2 inches.

Kindling: No constraints.

Initial Preload: 3 standard (usually 4x4) pieces.

Subsequent Preloads: Single log loads. The first is added 20 to 40 minutes after ignition of the fire. Subsequent single log preload additions are at precisely timed intervals to achieve the desired fueling rate.

Start of Test: Immediately preceding the fourth (or later) single log load. Note: Consecutive tests may be conducted as long as each test is preceded by a minimum of at least one hour of fueling the fireplace at the new rate.
During Test: Single log additions at timed intervals which achieve the desired fueling rate.

End of Test: At A single log loading time which occurs more than 90 minutes after the beginning of the test; a minimum of 4 logs must be burned during a test. More logs may be burned to achieve a larger PM filter catch to improve precision.

Fire Poking: Using a poker for up to 15 seconds immediately before each loading is permitted as well as one other time during each single log cycle.

Determination of Fueling Rates

Tests at 3 fueling rates in both open and closed door (if applicable) modes are required. These fueling rates are based on hearth area as defined in UL 127. The medium fueling rate in kg/hr (dry basis) shall be twice the hearth area expressed in square feet. The low and high fueling rates are 50% lower and higher than the medium fueling rate.

Test Results Averaging

Ordinary linear averages of the emission rates for each series of 3 tests are to be computed.

Altitude

Because of potential conflict of interest, we are not making a recommendation for how Colorado should deal with altitude. Among the options are:

1. No correction factor and no constraint on altitude (air pressure) of testing laboratories;

2. the present Colorado wood stove correction factor (and no constraint on altitude of testing laboratories);

3. constraints on altitude of testing laboratories; and

4. a combination of a correction factor and constraints on altitude of testing laboratories.

See Appendix 3 for further discussion.

8.2 FIREPLACE DEFINITION

The second objective of this project was to develop a reasonable and practical definition of a fireplace which will unambiguously place any wood-burning device in only one of the following categories: stove, fireplace and neither stove nor fireplace. An additional objective was to make this fireplace definition consistent with EPA's stove definition in the sense that a Colorado fireplace should not also be an EPA stove. Our suggested definition of a fireplace is as follows:

1. Combustion chamber volume (EPA definition) is less than 20 cubic feet.

2. Either A) the air-to-fuel ratio (EPA Method 28A) is greater than 35-to-1, or B) the minimum burn rate is greater than or equal to 5 kg/hr (EPA Method 28A), or both.

3. An intended normal operating configuration is without doors or with doors open.

4. Fuel is fed into the combustion chamber by hand, not by an auger or by gravity from a hopper.

5. The unit is not a central heater (EPA definition, which requires among other things that the appliance be listed to a nationally recognized central heater standard).

6. The unit is not a barbecue.

We further recommend that these definitions automatically accomodate changes in EPA's definitions specifically with respect to the air-to-fuel ratio and burn rate limits.

8.3 EMISSION RATES AND FACTORS

The third objective of this project was to develop emission rates and factors applicable to Colorado fireplace use.

Since use of realistic fuel (split Ponderosa pine logs) resulted in significantly different emissions than use of standard test fuel, the results given in Table 8-1 below are for Ponderosa pine. Emission factors are very sensitive to burn rate, thus the average burn rate is also given. The results have not been corrected to Colorado's reference elevation of 5000 feet from 6900 feet (the elevation of the Shelton Research Inc. laboratory in Santa Fe, New Mexico) because of uncertainty concerning appropriate correction for fireplaces (see Appendix 3). All of these results were obtained using a typical medium size factory-built fireplace.

TABLE 8-1

AVERAGE EMISSIONS FACTORS AND RATES. Ponderosa pine in a conventional open factory-built fireplace:

	BURN RATE (dry) kg/hr	EMISSION FACTOR g/kg	EMISSION RATE g/hr	NUMBER OF TESTS
PM	3.5	14.4	47	6
CO	3.5	76	256	6
POM	3.7	1.7	6.3	4

8.4 LOW EMISSION FIREPLACE DESIGNS

The fourth objective of this project was to investigate and develop fireplace designs applicable to both masonry and factory-built fireplaces which result in reduced emissions.

Three fireplace design types yielded emission reductions for PM and CO of approximately 40 to 80%. The two open designs were 1) catalytic and 2) a deep, small firebox. The closed designs involved insulation and/or turbulence. Thus the technical feasibility of reducing fireplace emissions through fireplace design has been demonstrated.

APPENDIX 1

DESIGN SPECIFICATION APPROACH ISSUES

It is not our responsibility as the research laboratory in this project to recommend a performance approach, a design specification approach or both. However, if a design approach is considered, we feel that attention to the issues discussed below is vital.

> More research is needed covering a broader range of realistic fuels, fueling protocols, and chimney heights to be sure laboratory and field performance will correspond. (This applies equally to the performance approach.)
>
> It is critical to be sure that a specified design is not outrightly incompatible with safety standards. There is potential for such a conflict between catalytic combustion and smoke spillage, although we believe that further development work would result in a solution to this potential conflict. If masonry designs are not to be tested and listed for safety, it is even more critical that the State be sure a specified design is safe. It would be inappropriate for there to be any chance that a State-specified emissions-reducing design be even a contributing cause to house fires.
>
> Only those features which are known to be critical to emissions reductions should be specified. All features and tolerances which do not impact emissions should be unconstrained. At this point it is not known which aspects of the designs are necessary and which are not critical.
>
> It is advisable to conduct research on whether or not a proposed design specification increases smoke spillage under any circumstances, since regardless of actual causes the design specification will be blamed. The State may need a technically sound defense against such complaints.

The safety issue deserves further discussion. It was the intent in this project to develop at least two designs to the point where necessary and sufficient design specifications could be justified. Preliminary safety testing would then have been conducted on these designs to indicate any likely safety concerns. In fact, no design reached the point where explicit safety testing was justified.

Our society has very different approaches for handling safety of factory-built versus masonry fireplaces. The safety of factory-built fireplaces is ascertained through testing at an independent laboratory using nationally recognized test methods and acceptance criteria. The safety of most masonry fireplaces is handled through building code specifications concerning dimensions, materials, wall thicknesses and clearances. These specifications are based primarily on a combination of field practice and field fire safety records.

If a radically new fireplace design were to be required, the safety of conforming factory-built fireplaces would be checked through the existing testing and listing procedures. It is conceivable that a specified emissions-reducing design could be fundamentally incompatible with safety requirements. This is why adequate research on safety is important before specifying a design.

The verification of safety for radically new masonry fireplace designs is not such a clear process. Existing code requirements might be adequate to deal with safety. However, to assume this without confirmation testing involves some risk. Since there are so many variations of masonry fireplaces, confirming the safety of emissions-reducing design features would require testing in a variety of fireplaces. An alternative which has been adopted by some manufacturers of masonry fireplace systems (and some foreign countries) is to obtain a listing via laboratory testing. In this case, fireplaces would no longer be as free-form; there would be a set of specific designs among which masons could choose.

Are there any anticipated safety problems associated with the clean burning designs investigated in this project? For the catalytic designs the primary concern is smoke spillage since all the tested designs obstructed smoke flow to some extent. Although smoke spillage did not occur during the hot-to-hot test cycle, some did during many of the cold starts. (There was no bypass in the tested designs.) Thus these designs might fail the smoke spillage part of the standard safety test (Underwriters Laboratories Standard No. 127 - (UL127)). If a smaller fireplace opening relative to hearth area is part of a catalytic design, then firebox and flue temperatures can be expected to rise. This is not a fundamental problem but may require some redesign of fireplaces and their chimneys.

The deep firebox design does not appear to have any fundamental incompatibilities between safety and performance. However it is such a radically different fireplace design that some effort would be required to assure safety.

The designs based on convection and/or insulation may have higher firechamber and flue temperatures because of the introduction of extra hearth-level combustion air in some of the designs.

APPENDIX 2

FUEL AND FUELING RATE REALISM

It is vital for any emissions control program based on laboratory testing to be as certain as practical that there is a correspondence between laboratory results and field practice. The actual emissions rates need not be identical, but the ranking of emissions based on laboratory testing should correspond to the ranking of field performance.

There are two overall approaches to building assurance that this correspondence exists. One is direct field measurement of performance and the other is laboratory testing and research directed at realism issues. Ultimately, field verification is the best approach. However at this time, new clean-burning fireplace designs are not in the field. In addition, field studies rarely have the detailed information on emissions and fireplace use which are important at this stage to contribute to our understanding of fireplace emissions - an understanding which is vital for the current need of designing appropriate test methods.

What are the major realism issues needing further effort at this time? They concern fuel and fueling protocol. Fuel realism was given considerable attention in this project but deserves still more. Because of limited resources, only one realistic fuel was investigated - Ponderosa pine split logs with a moisture content of about 18%, i.e., one species, one moisture content, one piece size and one refueling protocol. Further research including a wider variety of realistic fuels and refueling habits is essential. Testing must be done both in a variety of conventional fireplaces and in the most practical clean-burning designs to determine the performance correlation with standard laboratory fuel and burn rates.

Probably the most important aspect of the fueling protocol in laboratory testing is the specified fueling rates. It is likely that the emissions rates for at least some designs are very sensitive to fueling rate. Thus the fueling rates used in laboratory testing must cover the bulk of the field range.

Our proposals to key the fueling rates to hearth area needs further research. An insufficient range of fireplace designs and sizes was included to provide an adequate predictive data base. In addition, it must be realized that the fueling rates used in the bulk of this project were those that yielded what subjectively appeared to be typical fires. Additional opinions on this subjective judgement would be useful.

Once these additional data on baseline fireplace performance are gathered, a curve will need to be fitted that defines a medium burn rate as a function of hearth area. Finally, the factors used to determine low and high burn rates can be selected.

APPENDIX 3

ALTITUDE - AIR PRESSURE

If Colorado selects a performance standard as part of its fireplace emissions control program, the issue of air pressure (altitude and weather) effects on emissions will have to be addressed.

Colorado's (and Oregon's) stove regulation takes into account that stoves have higher emissions of PM and CO at higher altitudes, specifically a factor of 2 higher for each 6600 feet increase in elevation. Colorado's emissions levels for stoves are expressed at an equivalent altitude of 5000 feet. Thus if tests are conducted at sea level, the measured emissions are increased by 76% before submission to Colorado for certification. The assumption is that the altitude effect is known and that it is the same for all kinds of stoves.

Can Colorado derive fireplace emissions at 4000 to 10,000 feet from data measured near sea level? There is no air-pressure-effect data on fireplaces. Thus any conversion formula is a guess. On theoretical grounds fireplace emissions must increase with altitude. However, the increase need not be the same for different designs, different burn rates and different fuels. The factor also need not be the same as for stoves.

The U. S. Environmental Protection Agency (EPA) has chosen to ignore the altitude issue for purposes of EPA certification of stoves. EPA does not permit use of any altitude correction factor. This was done, in part, because of EPA's very tight time schedule for creating the regulation and, in part, because EPA did not find the available data sufficiently convincing.

The consequences of ignoring air pressure effects are generally undesirable. For purposes of this discussion, let us assume that there is a significant altitude effect on fireplace emissions, and further, that the altitude effect is significantly different for different designs. Further assume that no new altitude data is forthcoming so that the size of the average altitude effect remains somewhat uncertain and the design dependence is not fully understood.

What would be the consequence of ignoring altitude in a Colorado fireplace performance regulation?

1) Since there would be little doubt in anyone's mind that emissions increase with elevation, a lack of recognition of this in the regulation would result in virtually all emissions testing being done near sea level.

2) Therefore, Colorado would be forced to accept a higher uncertainty in estimating actual emissions from the test results since the average altitude factor has not been

accurately determined. This lowers the accuracy with which they could estimate relative emissions from different sources (e.g., stoves vs. automobiles).

3) Ranking reversals would occur. Fireplace A could be 50% cleaner than Fireplace B when tested in New England, but 50% dirtier when used in Colorado.

4) Colorado would be accepting a variety of fireplaces under the impression they are all equally clean-burning when in fact they would not be (due to ranking reversals).

5) Manufacturers who develop designs that are especially effective at higher elevations would not get any credit within the context of the regulation and thus would have little incentive to develop such designs.

6) Consumers at higher elevations who attempt to select the lowest emitting fireplace may be misled. Fireplace A's label may say it is 50% cleaner than Fireplace B, but the opposite could be true.

7) In addition to these large effects, there are smaller distortions and sources of scatter which could be eliminated if the effect of air pressure were understood and used. Barometric pressure variations of +/- one inch of mercury (29 to 30 inches) would result in a 14% change of emissions if the altitude effect is as now assumed by Oregon and Colorado. This source of random variations in the results could be eliminated if the air pressure correction factor were used.

8) There is also potential for consistent discrepancies between laboratories even if all laboratories were within 1000 feet of sea level. Presently available stove data suggests that laboratories at the two limits of even this small range of elevations would produce results consistently 15% different.

9) In the worst case, the combined effects merely of barometric pressure fluctuation and altitude could cause a discrepancy in test results of nearly 30% among laboratories within 1000 ft of sea level. Again, use of an air pressure correction factor would eliminate most of this kind of discrepancy.

What can Colorado do to avoid these problems? The simplest and most technically sound solution for any one state is to require that testing be done over a restricted range of altitudes around a median altitude of fireplace use in that state. This obviates the need for researching the air pressure effect and guarantees the applicability of the results without danger of ranking reversals.

An alternative technically sound approach is to is conduct research into the air pressure effect over a full range of fireplace designs and burn rates. If the air pressure effect is essentially uniform, testing could then be performed at any elevation and converted to the equivalent at any other elevation. If the air pressure effect has a clean and simple design-type dependence, different conversions could be used for the different design types. If the air pressure effect were both significant and without a simple correlation with design type, the only possibilities would be to restrict testing to the elevations of interest or to accept the ranking reversals etc. which would result if testing were conducted at significantly different altitudes.

At this point in time, there is essentially no data of the air pressure effect on emissions from fireplaces, much less on any design dependence. Until such data becomes available, Colorado will not have an easy decision on how to handle altitude in a performance regulation.

APPENDIX 4. CHRONOLOGICAL LISTING AND IDENTIFICATION OF TESTS.

TEST NO	GRAPH SYMBOL	TEST CYCLE	BASE FIREPLACE	DOORS	FIREBOX MODIFICATION	COMBUSTION AIR MODIFICATION	OTHER MODIFICATIONS	FUEL
13	SB	COLD-TO-HOT	SMALL	OPEN	REFRACTORY		BAFFLE	D. FIR 4X4
14	SB	HOT-TO-HOT	SMALL	OPEN	REFRACTORY		BAFFLE	D. FIR 4X4
15	SB	HOT-TO-HOT	SMALL	OPEN	REFRACTORY		BAFFLE	D. FIR 4X4
16	SO	EPA 28A	SMALL	OPEN	REFRACTORY		BAFFLE	FULL OREG
19	B	COLD-TO-HOT	BIG	OPEN				D. FIR 4X4
20	B	HOT-TO-HOT	BIG	OPEN				D. FIR 4X4
21	B	HOT-TO-HOT	BIG	OPEN				D. FIR 4X4
22	BO	EPA 28A	BIG	OPEN				FULL OREG
23	BC	EPA 28A	BIG	OPEN				FULL OREG
25	F	COLD-TO-HOT	CAMPFIRE	NA				D. FIR 4X4
26	F	HOT-TO-HOT	CAMPFIRE	NA				D. FIR 4X4
27	F	HOT-TO-HOT	CAMPFIRE	NA				D. FIR 4X4
28	CIRC	COLD-TO-HOT	CIRCULAR	CLOSED, GLASS				D. FIR 4X4
29	CIRC	HOT-TO-HOT	CIRCULAR	CLOSED, GLASS				D. FIR 4X4
30	CIRC	HOT-TO-HOT	CIRCULAR	CLOSED, GLASS				D. FIR 4X4
31	CIRCC	EPA 28A	CIRCULAR	CLOSED, GLASS				FULL OREG
32	K	COLD-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
33	K	HOT-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
34	K	HOT-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
35	M	COLD-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
36	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
37	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
38	AL	COLD-TO-HOT	MEDIUM	OPEN		INJECTED AIR, LOW BACK		D. FIR 4X4
39	AL	HOT-TO-HOT	MEDIUM	OPEN		INJECTED AIR, LOW BACK		D. FIR 4X4
40	AL	HOT-TO-HOT	MEDIUM	OPEN		INJECTED AIR, LOW BACK		D. FIR 4X4
41	IL	COLD-TO-HOT	MEDIUM	24X20 OPENING	INSULATION		20% FRONT CLOSURE	D. FIR 4X4
42	IL	HOT-TO-HOT	MEDIUM	24X20 OPENING	INSULATION		20% FRONT CLOSURE	D. FIR 4X4
43	IL	HOT-TO-HOT	MEDIUM	24X20 OPENING	INSULATION		20% FRONT CLOSURE	D. FIR 4X4
44	M	COLD-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
45	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
46	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
47	MO	EPA 28A	MEDIUM	OPEN				FULL OREG
48	MC	EPA 28A	MEDIUM	CLOSED, GLASS				FULL OREG
49	M	COLD-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
50	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
51	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
52	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
53	N	COLD-TO-HOT	MEDIUM	OPEN	NO ANDIRONS			D. FIR 4X4
54	N	HOT-TO-HOT	MEDIUM	OPEN	NO ANDIRONS			D. FIR 4X4
55	N	HOT-TO-HOT	MEDIUM	OPEN	NO ANDIRONS			D. FIR 4X4
56	O	COLD-TO-HOT	MEDIUM	CLOSED, GLASS		OUTSIDE AIR		D. FIR 4X4
57	O	HOT-TO-HOT	MEDIUM	CLOSED, GLASS		OUTSIDE AIR		D. FIR 4X4
58	O	HOT-TO-HOT	MEDIUM	CLOSED, GLASS		OUTSIDE AIR		D. FIR 4X4
59	AH	COLD-TO-HOT	MEDIUM	OPEN		INJECTED AIR, HIGH BACK		D. FIR 4X4
60	AH	HOT-TO-HOT	MEDIUM	OPEN		INJECTED AIR, HIGH BACK		D. FIR 4X4
61	AH	HOT-TO-HOT	MEDIUM	OPEN		INJECTED AIR, HIGH BACK		D. FIR 4X4
62	K	COLD-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4

APPENDIX 4. CHRONOLOGICAL LISTING AND IDENTIFICATION OF TESTS.

TEST NO	GRAPH SYMBOL	TEST CYCLE	BASE FIREPLACE	DOORS	FIREBOX MODIFICATION	COMBUSTION AIR MODIFICATION	OTHER MODIFICATIONS	FUEL
63	K	HOT-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
64	K	HOT-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
65	K	COLD-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
66	K	HOT-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
67	K	HOT-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
68	K	HOT-TO-HOT	KILN	CLOSED, INSULATION				D. FIR 4X4
69	F	COLD-TO-HOT	CAMPFIRE	NA				D. FIR 4X4
70	F	HOT-TO-HOT	CAMPFIRE	NA				D. FIR 4X4
71	F	HOT-TO-HOT	CAMPFIRE	NA				D. FIR 4X4
72	S	COLD-TO-HOT	SMALL	OPEN	REFRACTORY		NO BAFFLE	D. FIR 4X4
73	S	HOT-TO-HOT	SMALL	OPEN	REFRACTORY		NO BAFFLE	D. FIR 4X4
74	S	HOT-TO-HOT	SMALL	OPEN	REFRACTORY		NO BAFFLE	D. FIR 4X4
75	AG	COLD-TO-HOT	MEDIUM	OPEN		INJECTED AIR, GRATE		D. FIR 4X4
76	AG	HOT-TO-HOT	MEDIUM	OPEN		INJECTED AIR, GRATE		D. FIR 4X4
77	AG	HOT-TO-HOT	MEDIUM	OPEN		INJECTED AIR, GRATE		D. FIR 4X4
78	MO	EPA 28A	MEDIUM	OPEN				FULL OREG
79	MC	EPA 28A	MEDIUM	CLOSED, GLASS				FULL OREG
80	BO	EPA 28A	LARGE	OPEN				FULL OREG
81	BC	EPA 28A	LARGE	CLOSED, GLASS				FULL OREG
82	I	COLD-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION			D. FIR 4X4
83	I	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION			D. FIR 4X4
84	I	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION			D. FIR 4X4
85	IA	COLD-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	INJECTED AIR, GRATE		D. FIR 4X4
86	IA	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	INJECTED AIR, GRATE		D. FIR 4X4
87	IA	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	INJECTED AIR, GRATE		D. FIR 4X4
88	I3	COLD-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	3 CORNER AIR		D. FIR 4X4
89	I3	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	3 CORNER AIR		D. FIR 4X4
90	I3	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	3 CORNER AIR		D. FIR 4X4
91	I3	COLD-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	3 CORNER AIR		D. FIR 4X4
92	I3	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	3 CORNER AIR		D. FIR 4X4
93	I3	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	3 CORNER AIR		D. FIR 4X4
94	I3	HOT-TO-HOT	MEDIUM	CLOSED, INSUL	INSULATION	3 CORNER AIR		D. FIR 4X4
95	GL3	COLD-TO-HOT	MEDIUM	CLOSED, GLASS		3 CORNER AIR		D. FIR 4X4
96	GL3	HOT-TO-HOT	MEDIUM	CLOSED, GLASS		3 CORNER AIR		D. FIR 4X4
97	GL3	HOT-TO-HOT	MEDIUM	CLOSED, GLASS		3 CORNER AIR		D. FIR 4X4
98	GL3	HOT-TO-HOT	MEDIUM	CLOSED, GLASS		3 CORNER AIR		D. FIR 4X4
99	AG	COLD-TO-HOT	MEDIUM	OPEN		INJECTED, GRATE		D. FIR 4X4
100	AG	HOT-TO-HOT	MEDIUM	OPEN		INJECTED, GRATE		D. FIR 4X4
101	AG	HOT-TO-HOT	MEDIUM	OPEN		INJECTED, GRATE		D. FIR 4X4
102	R	COLD-TO-HOT	MEDIUM	OPEN				PONDEROSA
103	R	HOT-TO-HOT	MEDIUM	OPEN				PONDEROSA
104	R	HOT-TO-HOT	MEDIUM	OPEN				PONDEROSA
105	R	HOT-TO-HOT	MEDIUM	OPEN				PONDEROSA
106	R	COLD-TO-HOT	MEDIUM	OPEN				PONDEROSA
107	R	HOT-TO-HOT	MEDIUM	OPEN				PONDEROSA
108	R	HOT-TO-HOT	MEDIUM	OPEN				PONDEROSA
109	R	HOT-TO-HOT	MEDIUM	OPEN				PONDEROSA

APPENDIX 4. CHRONOLOGICAL LISTING AND IDENTIFICATION OF TESTS.

TEST NO	GRAPH SYMBOL	TEST CYCLE	BASE FIREPLACE	DOORS	FIREBOX MODIFICATION	COMBUSTION AIR MODIFICATION	OTHER MODIFICATIONS	FUEL
110	D	COLD-TO-HOT	DEEP	OPEN				D. FIR 4X4
111	D	HOT-TO-HOT	DEEP	OPEN				D. FIR 4X4
112	D	HOT-TO-HOT	DEEP	OPEN				D. FIR 4X4
113	IS	COLD-TO-HOT	MEDIUM	3X20 OPENING	INSULATION	4 CORNER AIR		D. FIR 4X4
114	IS	HOT-TO-HOT	MEDIUM	3X20 OPENING	INSULATION	4 CORNER AIR		D. FIR 4X4
115	IS	HOT-TO-HOT	MEDIUM	3X20 OPENING	INSULATION	4 CORNER AIR		D. FIR 4X4
116	IL	COLD-TO-HOT	MEDIUM	9X20 OPENING	INSULATION	4 CORNER AIR		D. FIR 4X4
117	IL	HOT-TO-HOT	MEDIUM	9X20 OPENING	INSULATION	4 CORNER AIR		D. FIR 4X4
118	IL	HOT-TO-HOT	MEDIUM	9X20 OPENING	INSULATION	4 CORNER AIR		D. FIR 4X4
119	CL	COLD-TO-HOT	MEDIUM	OPEN			CATALYST, LINER	D. FIR 4X4
120	CL	HOT-TO-HOT	MEDIUM	OPEN			CATALYST, LINER	D. FIR 4X4
121	CL	HOT-TO-HOT	MEDIUM	OPEN			CATALYST, LINER	D. FIR 4X4
122	Ct	COLD-TO-HOT	MEDIUM	OPEN			CATALYST, THIN	D. FIR 4X4
123	Ct	HOT-TO-HOT	MEDIUM	OPEN			CATALYST, THIN	D. FIR 4X4
124	Ct	HOT-TO-HOT	MEDIUM	OPEN			CATALYST, THIN	D. FIR 4X4
125	CT	COLD-TO-HOT	MEDIUM	OPEN			CATALYST, THICK	D. FIR 4X4
126	CT	HOT-TO-HOT	MEDIUM	OPEN			CATALYST, THICK	D. FIR 4X4
127	CT	HOT-TO-HOT	MEDIUM	OPEN			CATALYST, THICK	D. FIR 4X4
128	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
129	M	HOT-TO-HOT	MEDIUM	OPEN				D. FIR 4X4
130	D	COLD-TO-HOT	DEEP	OPEN				D. FIR 4X4
131	D	HOT-TO-HOT	DEEP	OPEN				D. FIR 4X4
132	D	HOT-TO-HOT	DEEP	OPEN				D. FIR 4X4
133	D	HOT-TO-HOT	DEEP	OPEN				D. FIR 4X4
134	D	HOT-TO-HOT	DEEP	OPEN				D. FIR 4X4
135	CS	COLD-TO-HOT	MEDIUM	OPEN	INSULATION		CATALYST, STACK	D. FIR 4X4
136	CS	HOT-TO-HOT	MEDIUM	OPEN	INSULATION		CATALYST, STACK	D. FIR 4X4
137	CS	HOT-TO-HOT	MEDIUM	OPEN	INSULATION		CATALYST, STACK	D. FIR 4X4
138	CR	HOT-TO-HOT	MEDIUM	OPEN	INSULATION		CATALYST, STACK	PONDEROSA
139	CR	HOT-TO-HOT	MEDIUM	OPEN	INSULATION		CATALYST, STACK	PONDEROSA
140	GL	COLD-TO-HOT	MEDIUM	CLOSED, GLASS				D. FIR 4X4
141	GL	HOT-TO-HOT	MEDIUM	CLOSED, GLASS				D. FIR 4X4
142	GL	HOT-TO-HOT	MEDIUM	CLOSED, GLASS				D. FIR 4X4
143	O	HOT-TO-HOT	MEDIUM	CLOSED, GLASS		OUTSIDE AIR		D. FIR 4X4
144	O	HOT-TO-HOT	MEDIUM	CLOSED, GLASS		OUTSIDE AIR		D. FIR 4X4
145	DR	COLD-TO-HOT	DEEP	OPEN				PONDEROSA
146	DR	HOT-TO-HOT	DEEP	OPEN				PONDEROSA
147	DR	HOT-TO-HOT	DEEP	OPEN				PONDEROSA
149	MA	HOT-TO-HOT	MASONRY	OPEN				D. FIR 4X4
150	MA	HOT-TO-HOT	MASONRY	OPEN				D. FIR 4X4
151	MAC	HOT-TO-HOT	MASONRY	OPEN			CATALYST, THICK	D. FIR 4X4
152	MAC	HOT-TO-HOT	MASONRY	OPEN			CATALYST, THICK	D. FIR 4X4

APPENDIX 5. TEST DATA.

TEST NO	GRAPH SYMBOL	DURAT MIN	FUEL MOISTURE (DRY) PCNT	FUEL MASS (MOIST) KG	FUEL MASS (DRY) KG	BURN RATE (MOIST) KG/HR	BURN RATE (DRY) KG/HR	PM G/HR	PM G/KG	CO G/HR	CO G/KG	PAH G/HR	PAH G/KG	FLUE TEMP C	FLUE FLOW KG/HR	RATIO AIR/FUEL	FRONT RADIANT OUTPUT BTU/HR
XXXXXXXXXXX		XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX						XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX						XXXXXXXXXXXXXXXXXXXXXXXXXXXX			
13	SB	60	25	4.8	3.8	4.8	3.8	62	16.1	295	77			99	226	58	
14	SB	40	25	2.6	2.1	3.9	3.2	53	16.9	298	95			118	237	74	
15	SB	40	25	2.8	2.2	4.2	3.4	61	18.0	300	89			134	243	71	
16	SO	75	25	6.5	5.2	5.2	4.1	37	9.1	301	73			162	234	55	
19	B	65	25	19.5	15.6	18.0	14.4	83	5.7	360	25			226	404	27	
20	B	51	25	10.3	8.2	12.1	9.7	25	2.6	304	31			234	418	42	
21	B	50	25	10.0	8.0	12.0	9.6	23	2.4	222	23			219	408	41	
22	BO	55	25	34.1	27.3	37.2	29.8			286	10			594	403	12	
23	BC	77	25	33.9	27.1	26.4	21.1			311	15			583	360	16	
25	F	108	25	12.9	10.3	7.2	5.7	58	10.1	386	67			62	651	112	
26	F	39	25	4.6	3.7	7.1	5.7	37	6.5	279	49			100	674	117	
27	F	41	25	4.4	3.5	6.4	5.1	42	8.1	371	72			73	631	122	
28	CIRC	66	25	10.4	8.3	9.4	7.5	46	6.1	637	85			251	236	30	
29	CIRC	60	25	7.1	5.7	7.1	5.7	32	5.6	663	117			278	202	34	
30	CIRC	63	25	7.0	5.6	6.6	5.3	25	4.7	771	145			302	221	40	
31	CIRCC	80	25	20.1	16.1	15.1	12.0			622	52			467	219	17	
32	K	36	25	11.7	9.4	19.6	15.7	34	2.2	184	12			467	142	8	
33	K	62	25	10.9	8.7	10.5	8.4	31	3.7	122	14			655	87	9	
34	K	47	25	6.2	4.9	7.9	6.3	3	0.5	71	11			491	103	15	
35	M	70	25	13.6	10.8	11.6	9.3	63	6.8	465	50			201	318	33	11000
36	M	55	25	8.2	6.5	8.9	7.1	19	2.6	214	30			253	320	44	16000
37	M	61	25	8.3	6.6	8.1	6.5	18	2.8	198	31			248	322	48	17000
38	AL	52	25	8.2	6.6	9.5	7.6	80	10.5	540	71			214	308	40	
39	AL	50	25	8.1	6.5	9.7	7.8	20	2.5	303	39			273	332	41	
40	AL	56	25	8.2	6.5	8.7	7.0	22	3.1	299	43			262	334	47	
41	IL	52	25	8.7	7.0	10.1	8.1	77	9.5	511	63			238	294	35	
42	IL	44	25	7.9	6.3	10.7	8.6	25	2.9	251	29			307	307	35	
43	IL	62	25	8.2	6.6	7.9	6.3	24	3.8	274	43			245	305	47	
44	M	54	25	5.5	4.4	6.1	4.8	70	14.3	421	87			194	313	63	
45	M	60	25	7.7	6.2	7.7	6.2	18	3.0	276	45			223	323	51	
46	M	70	25	7.6	6.1	6.5	5.2	22	4.3	311	60			217	321	60	
47	MO	57	25	11.7	9.3	12.3	9.8			399	41			277	300	29	
48	MC	55	25	11.9	9.5	13.0	10.4			440	42			239	298	27	
49	M	64	25	8.4	6.7	7.8	6.3	80	12.8	506	81			171	300	47	8000
50	M	38	25	5.2	4.2	8.2	6.6			300	46			214	317	47	13000
51	M	57	25	7.8	6.2	8.2	6.5	22	3.3	266	41			247	313	47	11000
52	M	59	25	7.3	5.8	7.4	5.9	24	4.0	255	43			233	309	51	16000
53	N	59	25	5.2	4.2	5.3	4.3	44	10.3	265	62			174	303	70	7000
54	N	68	25	8.0	6.4	7.0	5.6	17	3.1	184	33			204	324	55	14000
55	N	114	25	8.4	6.7	4.4	3.5	19	5.3	269	76			142	301	84	10000
56	O	74	25	8.7	7.0	7.1	3.5	70	12.4	473	84			190	274	77	3000
57	O	85	25	8.7	6.9	6.1	4.9	34	6.9	269	55			223	254	51	5000
58	O	99	25	8.6	6.9	5.2	4.2	19	4.5	287	69			203	254	60	5000
59	AH	57	25	8.1	6.5	8.5	6.8	86	12.7	486	71			174	298	43	7000
60	AH	72	25	8.0	6.4	6.7	5.3	24	4.4	279	52			206	316	58	11000
61	AH	84	25	8.1	6.5	5.8	4.6	25	5.3	363	79			186	314	67	13000
62	K	53	25	8.3	6.6	9.4	7.5	20	2.7	165	22			329	121	15	

APPENDIX 5. TEST DATA.

TEST NO	GRAPH SYMBOL	DURAT	FUEL MOISTURE (DRY)	FUEL MASS (MOIST)	FUEL MASS (DRY)	BURN RATE (MOIST)	BURN RATE (DRY)	PM	PM	CO	CO	PAH	PAH	FLUE TEMP	FLUE FLOW	RATIO AIR/ FUEL	FRONT RADIANT OUTPUT
		MIN	PCNT	KG	KG	KG/HR	KG/HR	G/HR	G/KG	G/HR	G/KG	G/HR	G/KG	C	KG/HR		BTU/HR
63	K	45	25	10.1	8.1	13.5	10.8	23	2.1	71	7			616	95	8	
64	K	62	25	11.1	8.9	10.7	8.6	8	1.0	47	5			617	96	10	
65	K	40	25	4.1	3.3	6.1	4.9			135	27			360	134	26	
66	K	60	25	8.6	6.8	8.6	6.8	8	1.2	49	7			526	91	12	
67	K	65	25	6.0	4.8	5.5	4.4	2	0.5	109	25			471	85	18	
68	K	115	25	8.4	6.7	4.4	3.5	5	1.5	195	55			399	73	20	
69	F	91	25	7.7	6.1	5.0	4.0	75	18.7	469	116			60	681	168	
70	F	128	25	8.1	6.4	3.8	3.0	32	10.6	338	112			57	676	223	
71	F	127	25	5.5	4.4	2.6	2.1	31	15.2	320	155			46	656	316	
72	S	73	27	4.4	3.5	3.6	2.8	43	15.3	238	83			150	246	85	6000
73	S	76	27	5.1	4.1	4.1	3.2	33	10.2	236	74			148	253	78	8000
74	S	83	27	5.1	4.0	3.7	2.9	29	9.9	194	67			137	249	84	8000
75	AG	53	25	8.0	6.4	9.0	7.2	11	1.5	204	28			226	285	38	7000
76	AG	37	25	7.7	6.2	12.5	10.0			168	17			334	283	27	16000
77	AG	50	25	8.5	6.8	10.2	8.1	29	3.6	166	20			318	281	33	18000
78	MO	72	26	11.4	9.1	9.5	7.6			414	55			246	285	36	
79	MC	76	26	11.4	9.1	9.0	7.2			637	89			278	243	33	
80	BO	113	26	34.4	27.4	18.3	14.5			615	42			319	239	15	
81	BC	88	26	35.1	27.9	23.9	19.0			305	16			522	226	11	
82	I	46	26	8.8	7.0	11.4	9.1	38	4.2	673	74			394	283	30	
83	I	60	26	8.4	6.6	8.4	6.6	60	9.0	648	98			311	299	44	
84	I	65	26	5.4	4.3	5.0	3.9	75	18.9	533	135			180	269	67	
85	IA	35	24	8.6	6.9	14.7	11.9	71	6.0	627	53			361	351	28	
86	IA	39	24	8.3	6.7	12.8	10.3	28	2.8	366	35			527	291	27	
87	IA	52	24	8.9	7.2	10.2	8.3	39	4.7	669	81			360	304	36	
88	I3	35	24	8.6	6.9	14.7	11.9	22	1.9	165	14			514	168	13	
89	I3	41	24	10.4	8.4	15.2	12.3	18	1.4	56	5			763	135	10	
90	I3	49	24	11.7	9.4	14.3	11.5	22	1.9	90	8			774	130	10	
91	I3	37	24	8.6	7.0	14.0	11.3			82	7			540	137	11	
92	I3	60	24	10.1	8.1	10.1	8.1	9	1.1	48	6			624	128	15	
93	I3	55	24	5.2	4.2	5.7	4.6	11	2.5	220	48			395	137	29	
94	I3	60	24	3.9	3.1	3.9	3.1	7	2.1	231	74			343	173	54	
95	GL3	49	24	9.1	7.4	11.2	9.0			433	48			244	172	19	
96	GL3	59	24	8.3	6.7	8.4	6.8	11	1.7	200	29			343	179	25	
97	GL3	46	24	5.6	4.5	7.3	5.9	11	1.8	265	45			376	179	29	
98	GL3	40	24	2.5	2.0	3.7	3.0	13	4.2	340	113			254	170	56	
99	AG	38	24	6.0	4.8	9.4	7.6	38	5.0	220	29			235	262	33	9000
100	AG	53	24	5.7	4.6	6.4	5.2	17	3.3	294	57			225	256	50	11000
101	AG	34	24	2.6	2.1	4.7	3.8	27	7.3	423	112			225	292	76	7000
102	R	54	23	6.9	5.6	7.7	6.2	99	15.9	331	53	2.9	0.47	159	260	41	8000
103	R	104	23	8.5	6.9	4.9	4.0	49	12.2	289	72	9.5	2.37	165	266	65	10000
104	R	40	23	1.7	1.4	2.6	2.1	37	17.3	186	88	3.8	1.81	107	229	107	7000
105	R	81	23	6.9	5.6	5.1	4.2	35	8.4	256	62	8.0	1.93	172	264	62	12000
106	R	45	23	8.9	7.2	11.8	9.6	84	6.8	347	36			269	289	29	14000
107	R	70	23	5.6	4.5	4.8	3.9	56	14.4	305	79			160	275	70	10000
108	R	45	23	1.9	1.6	2.6	2.1	42	20.0	194	93			90	244	116	6000
109	R	105	23	10.1	8.2	5.8	4.7	66	14.1	303	65	4.0	0.86	173	272	57	11000

APPENDIX 5. TEST DATA.

TEST NO	GRAPH SYMBOL	DURAT	FUEL MOISTURE (DRY)	FUEL MASS (MOIST)	FUEL MASS (DRY)	BURN RATE (MOIST)	BURN RATE (DRY)	PM	PM	CO	CO	PAH	PAH	FLUE TEMP	FLUE FLOW	RATIO AIR/ FUEL	FRONT RADIANT OUTPUT
		MIN	PCNT	KG	KG	KG/HR	KG/HR	G/HR	G/KG	G/HR	G/KG	G/HR	G/KG	C	KG/HR		BTU/HR
110	D	52	24	5.8	4.7	6.7	5.4	18	3.3	151	28			20	113	20	
111	D	58	24	6.0	4.8	6.2	5.0	12	2.4	183	37			296	115	22	
112	D	64	24	4.9	3.9	4.6	3.7	10	2.8	176	48	1.4	0.38	257	113	29	
113	IS	45	25	8.8	7.0	11.8	9.4	40	4.3	243	26			291	236	24	
114	IS	47	25	5.9	4.7	7.6	6.0	11	1.8	132	22			261	235	38	
115	IS	63	25	6.1	4.8	5.8	4.6	13	2.8	194	42	4.0	0.87	233	231	49	
116	IL	59	25	8.2	6.6	8.4	6.7	49	7.3	267	40			215	257	37	
117	IL	41	25	5.5	4.4	8.1	6.5	21	3.2	217	34			250	265	40	
118	IL	62	25	5.7	4.5	5.5	4.4	21	4.7	288	66	2.5	0.58	191	254	57	
119	CL	51	25	7.8	6.3	9.2	7.4	46	6.2	257	35			242	254	33	11000
120	CL	51	25	7.7	6.2	9.1	7.3	24	3.3	158	22			263	267	36	17000
121	CL	54	25	5.3	4.3	5.9	4.8	21	4.5	191	40	2.0	0.42	194	259	53	15000
122	Ct	47	25	8.3	6.6	10.6	8.5	35	4.2	190	22			291	261	30	14000
123	Ct	51	25	7.8	6.2	9.1	7.3	18	2.5	107	15			326	266	35	19000
124	Ct	67	25	7.7	6.1	6.9	5.5	19	3.5	133	24	1.5	0.28	256	279	50	18000
125	CT	58	28	10.5	8.2	10.8	8.5	31	3.7	152	18			294	192	21	9000
126	CT	58	28	8.2	6.4	8.5	6.7	14	2.1	36	5			358	190	27	14000
127	CT	58	28	5.9	4.6	6.1	4.8	9	2.0	74	16	1.0	0.21	278	197	40	14000
128	M	68	28	5.3	4.2	4.7	3.7	31	8.4	295	81			160	256	69	10000
129	M	55	28	3.2	2.5	3.5	2.8	33	12.1	315	114	1.1	0.41	139	242	67	9000
130	D	48	27	4.2	3.3	5.2	4.1	25	6.0	256	62			222	126	29	
131	D	55	27	4.3	3.4	4.6	3.7	12	3.2	153	42			255	127	33	
132	D	73	27	4.4	3.4	3.6	2.8	6	2.1	99	35	0.7	0.26	201	120	41	
133	D	46	27	3.2	2.5	4.2	3.3	9	2.7	199	60			236	125	37	
134	D	53	27	2.9	2.3	3.3	2.6	8	3.2	143	55	1.2	0.45	207	126	47	
135	CS	46	23	7.7	6.2	10.0	8.1	33	4.0	130	16			312	224	26	16000
136	CS	60	23	8.6	7.0	8.6	7.0	11	1.5	60	9	0.8	0.11	339	237	33	22000
137	CS	65	23	5.9	4.8	5.4	4.4	11	2.4	124	28	0.8	0.18	254	241	53	16000
138	CR	60	22	7.5	6.1	7.5	6.1	22	3.6	115	19	1.2	0.20	314	241	38	20000
139	CR	65	22	5.2	4.2	4.8	3.9	20	5.1	160	41	0.7	0.17	238	243	61	15000
140	GL	55	24	10.7	8.6	11.7	9.4	49	5.2	219	23			263	262	27	4000
141	GL	42	24	5.9	4.7	8.4	6.8	19	2.8	142	21	1.3	0.19	296	257	37	7000
142	GL	54	24	5.5	4.4	6.1	4.9	16	3.2	163	33	0.9	0.17	255	255	51	7000
143	O	51	24	7.4	6.0	8.7	7.0	17	2.4	151	21	3.7	0.53	306	273	38	7000
144	O	76	24	7.8	6.3	6.2	5.0	15	3.0	191	38	0.4	0.07	263	265	52	7000
145	DR	43	24	2.4	1.9	3.3	2.7	28	10.4	203	75			150	117	42	
146	DR	52	24	2.8	2.3	3.2	2.6	12	4.7	135	52	0.7	0.26	192	123	46	
147	DR	70	24	2.9	2.3	2.5	2.0	11	5.3	126	63	0.5	0.24	176	118	57	
149	MA	60	23	10.9	8.9	10.9	8.9	28	3.1	363	41	0.2	0.03	156	622	69	
150	MA	60	23	7.4	6.0	7.4	6.0	30	4.9	436	72			107	647	106	
151	MAC	60	23	10.8	8.8	10.8	8.8	21	2.4	193	22			179	554	62	
152	MAC	60	23	7.2	5.9	7.2	5.9	15	2.6	216	37			176	543	91	

APPENDIX 6. GRAPH SYMBOL KEY.

GRAPH SYMBOL	DESIGN TYPE SHORT NAME	OPEN OR CLOSED DESIGN
AG	INJECTED AIR, GRATE	OPEN
AH	INJECTED AIR, HIGH	OPEN
AL	INJECTED AIR, LOW	OPEN
B	BIG	OPEN
CIRC	CIRCULAR	CLOSED
CL	CATALYST, LINER	OPEN
CR	CAT,REALISTIC FUEL	OPEN
CS	CATALYST, STACK	OPEN
Ct	CATALYST, THIN	OPEN
CT	CATALYST, THICK	OPEN
D	DEEP	OPEN
DR	DEEP, REALISTIC FUEL	OPEN
F	CAMPFIRE	OPEN
GL	GLASS DOORS	CLOSED
GL3	GLASS DOORS, CORNER AIR	CLOSED
I	INSULATED, CLOSED	CLOSED
I3	INSUL, CORNER AIR	CLOSED
IA	INSUL, INJECTED AIR	CLOSED
IL	INSUL, LARGE DOOR	OPEN
IS	INSUL, SMALL DOOR	OPEN
K	KILN	CLOSED
M	MEDIUM	OPEN
MA	MASONRY	OPEN
MAC	MASONRY, CAT	OPEN
N	NO GRATE	OPEN
O	OUTSIDE AIR	CLOSED
R	REALISTIC FUEL	OPEN
S	SMALL	OPEN
SB	SMALL, BAFFLE	OPEN
BC	BIG, EPA 28A	CLOSED
BO	BIG, EPA 28A	OPEN
CIRCC	CIRCULAR, EPA 28A	CLOSED
MC	MEDIUM, EPA 28A	CLOSED
MO	MEDIUM, EPA 28A	OPEN
SO	SMALL, EPA 28A	OPEN

INDEX OF FIGURES

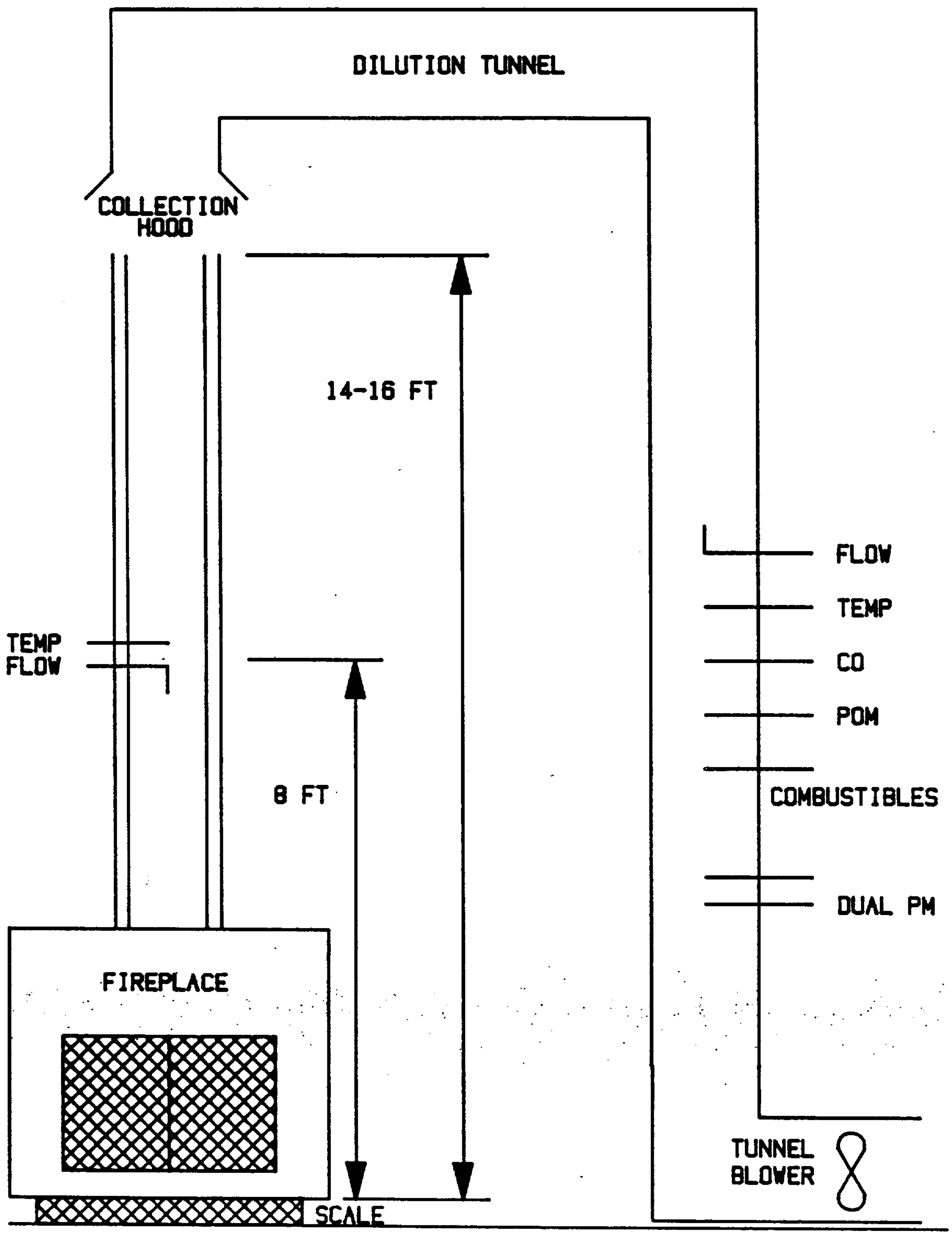


FIGURE 2-1. INSTALLATION.

FIGURE 3–1. BASELINE PM RATE.

SHELTON RESEARCH INC.

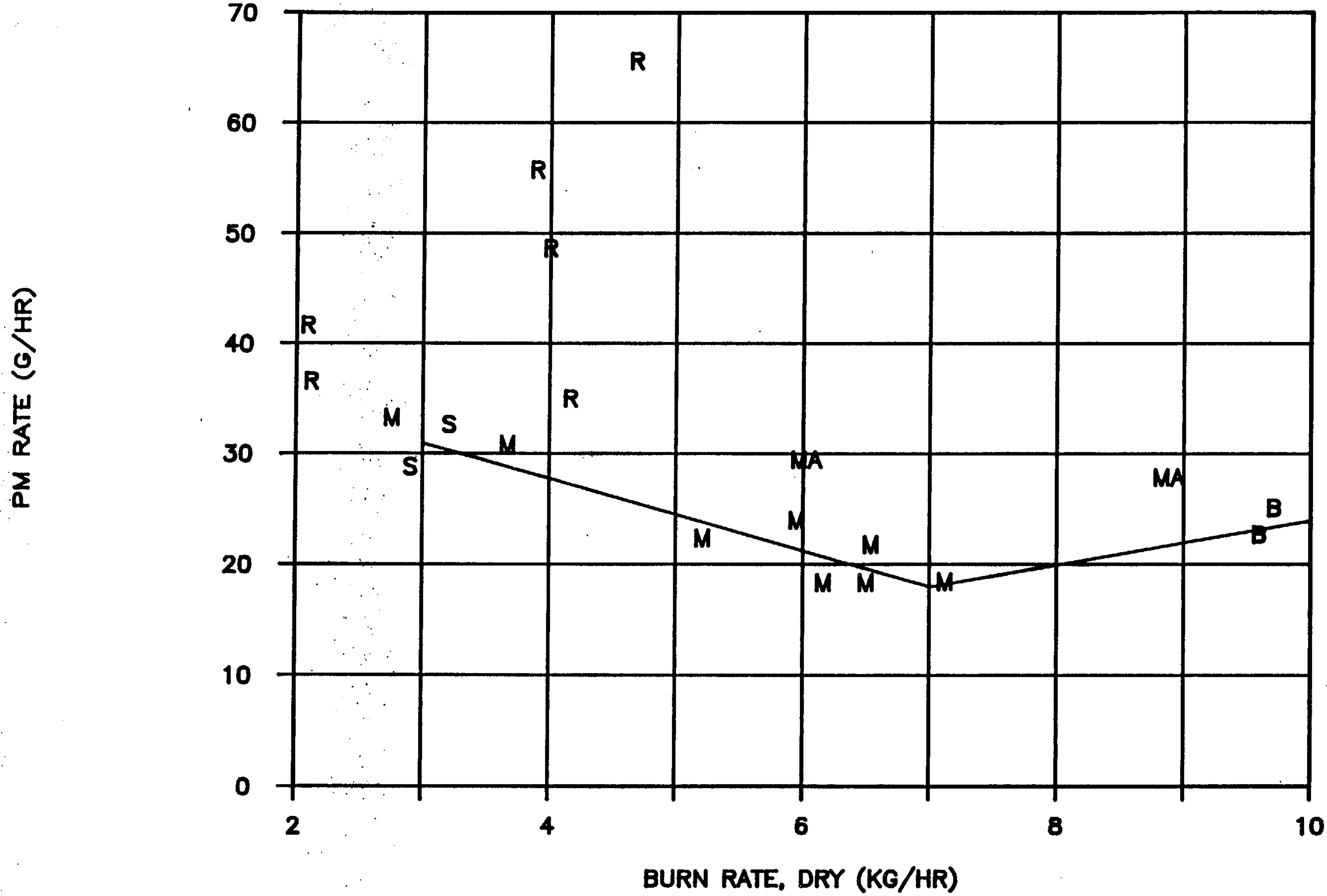


FIGURE 3–2. BASELINE CO RATE.

SHELTON RESEARCH INC.

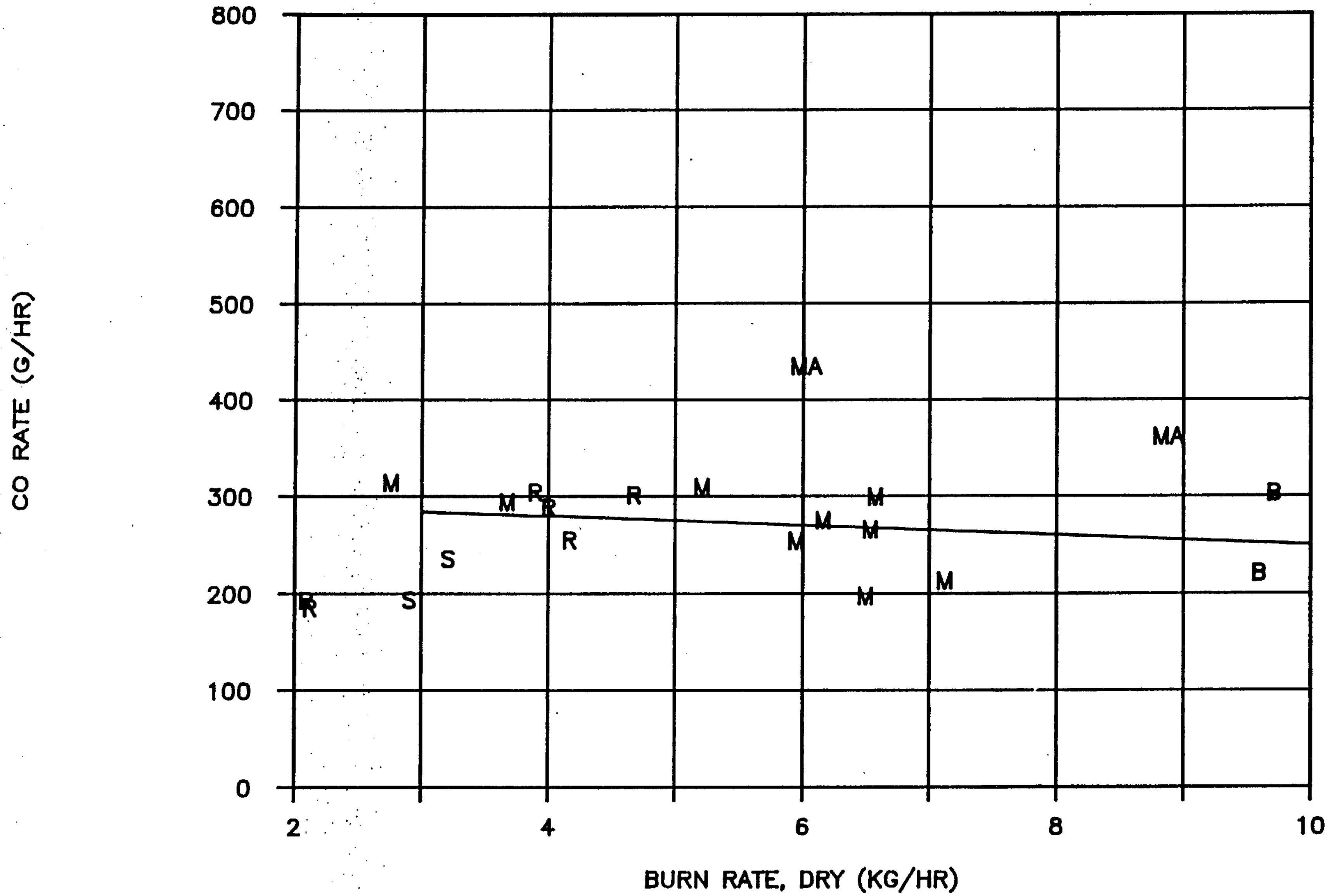


FIGURE 3-3. BASELINE PM FACTOR.

SHELTON RESEARCH INC.

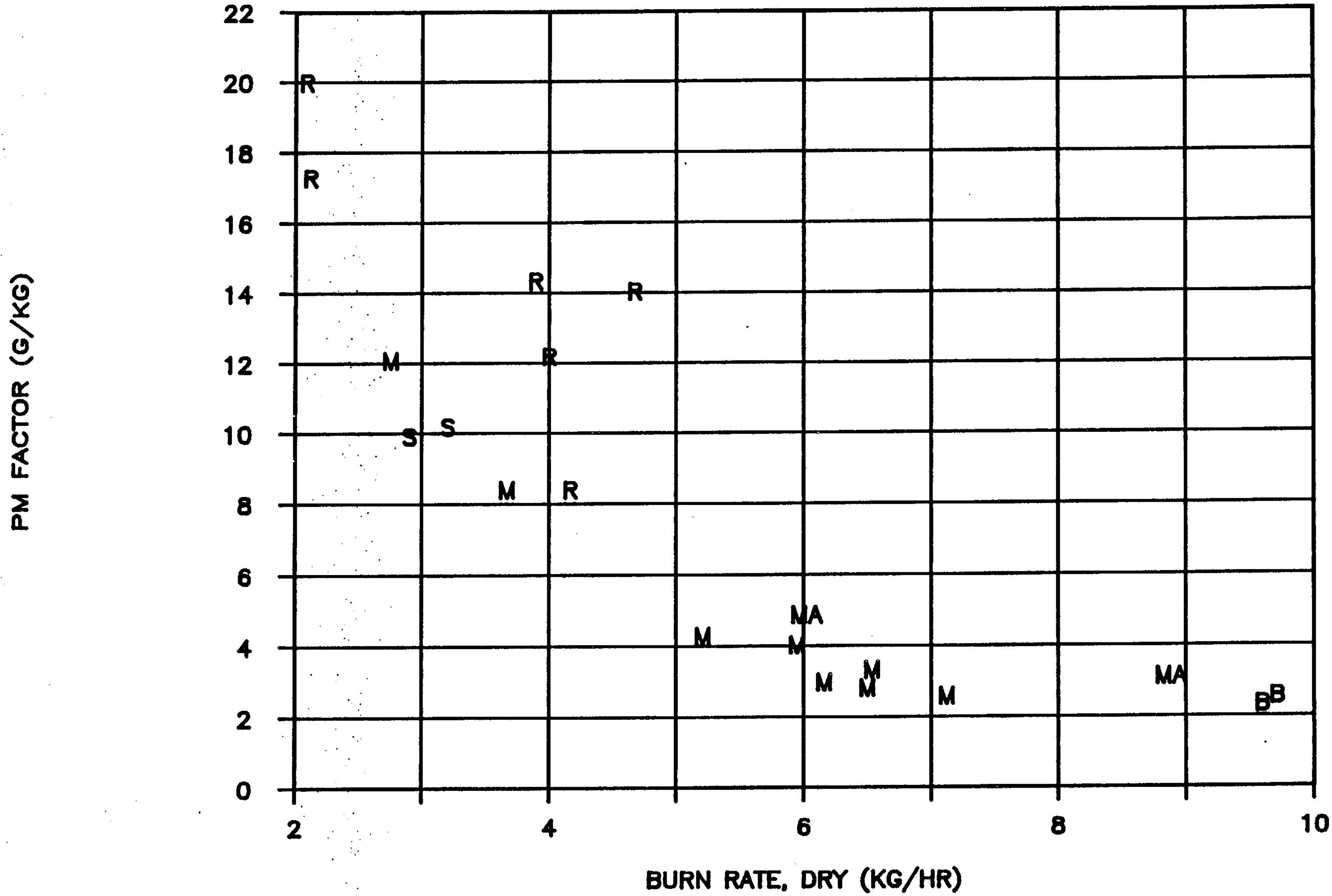
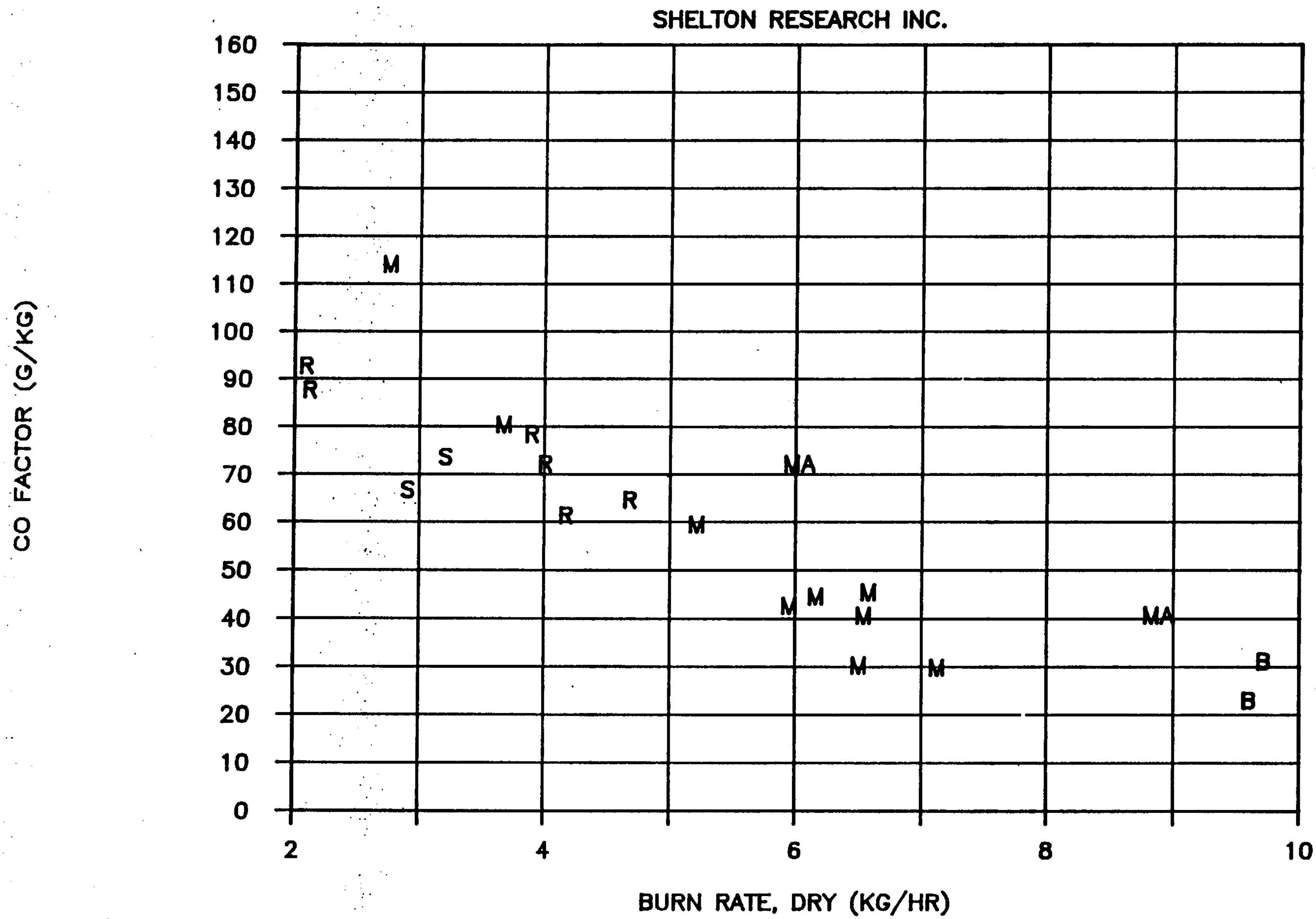


FIGURE 3–4. BASELINE CO FACTOR.



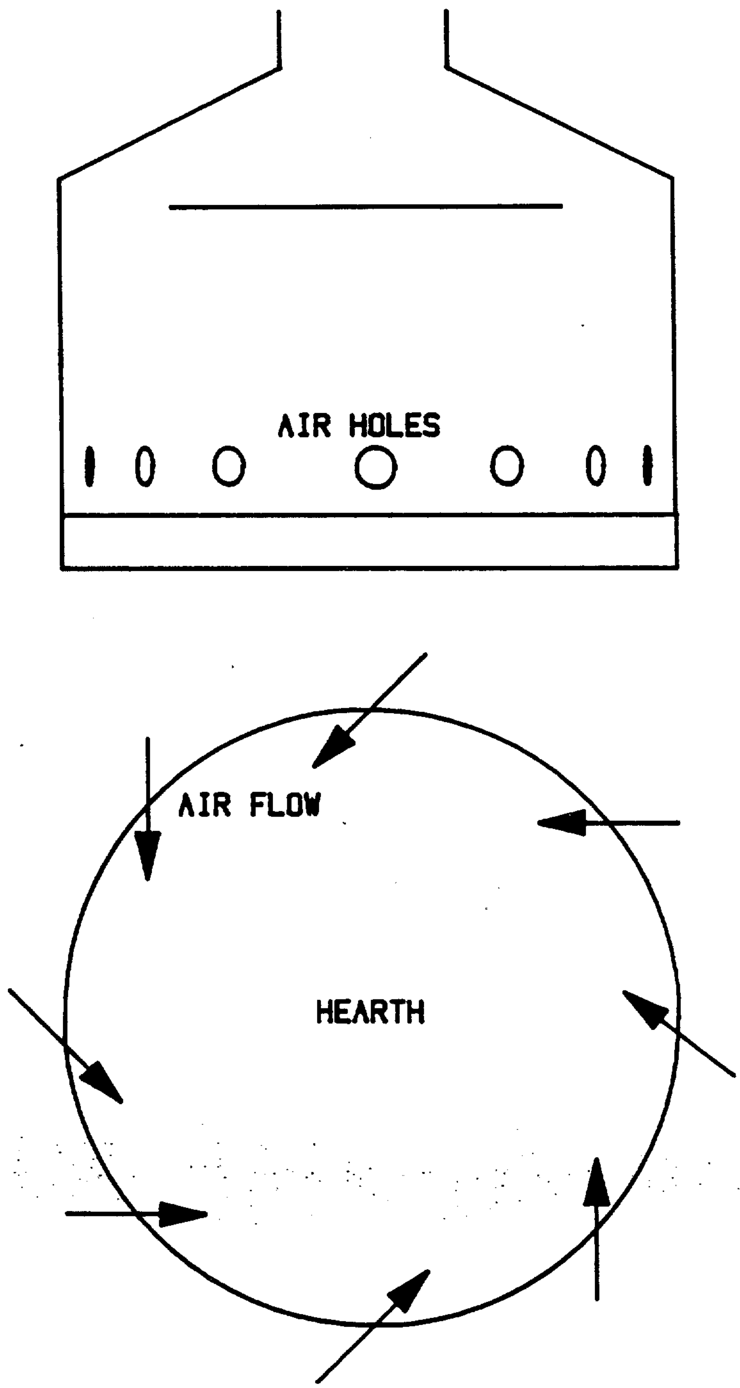


FIGURE 4-1. KILN DESIGN. INSULATION NOT SHOWN. NOT TO SCALE.

FIGURE 4—2. PM FOR INSULATED DESIGNS.

SHELTON RESEARCH INC.

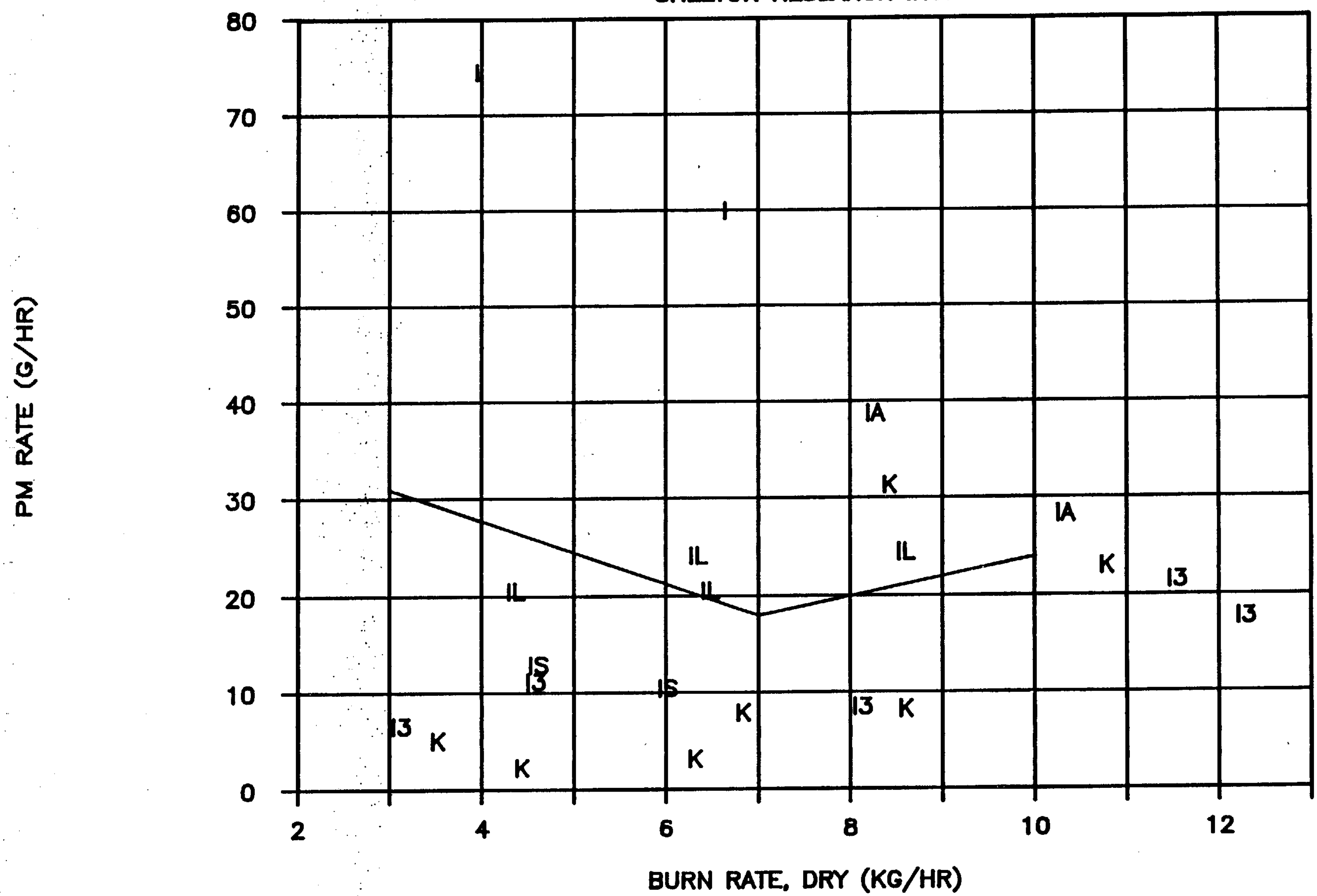


FIGURE 4—3. CO FOR INSULATED DESIGNS.

SHELTON RESEARCH INC.

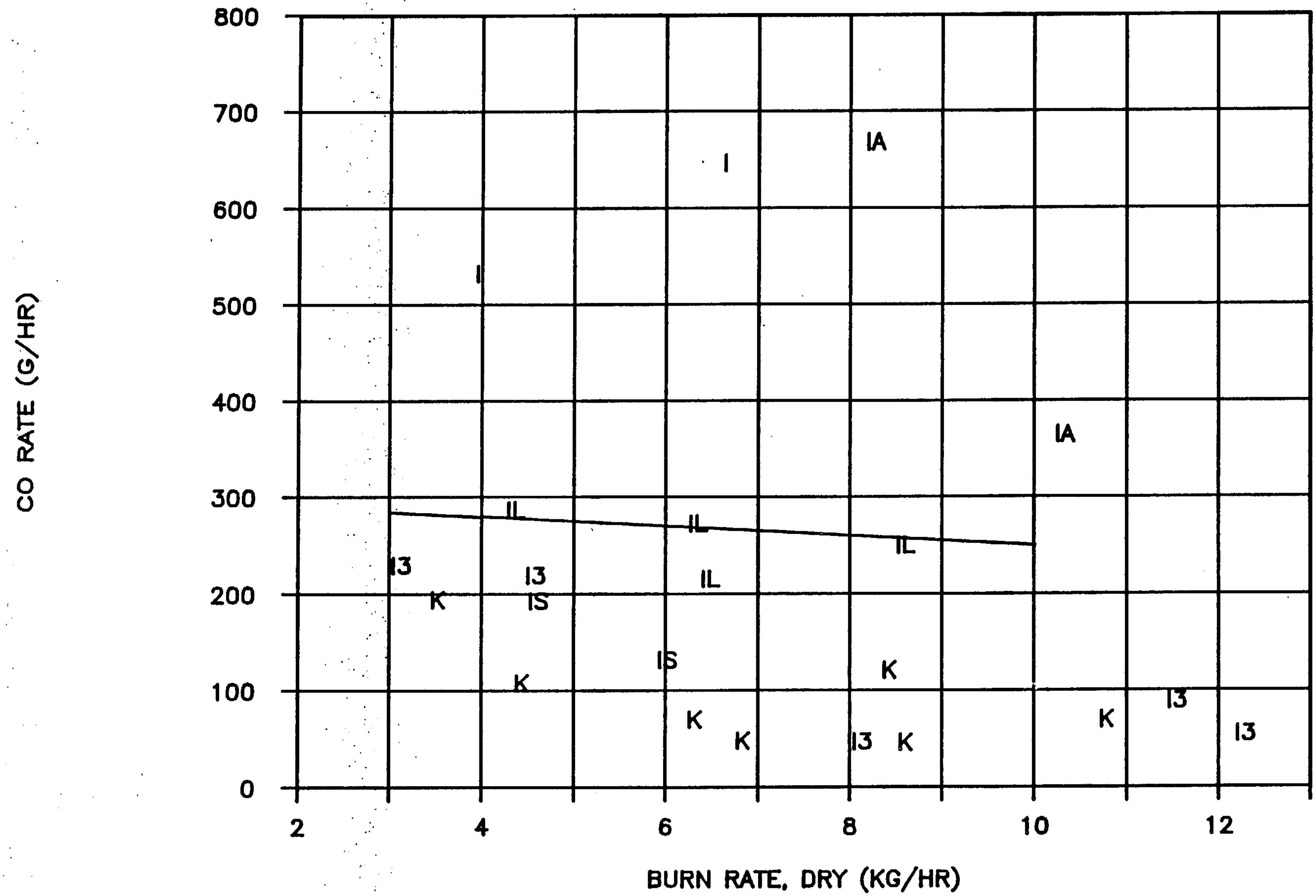


FIGURE 4–4. PM RATE.

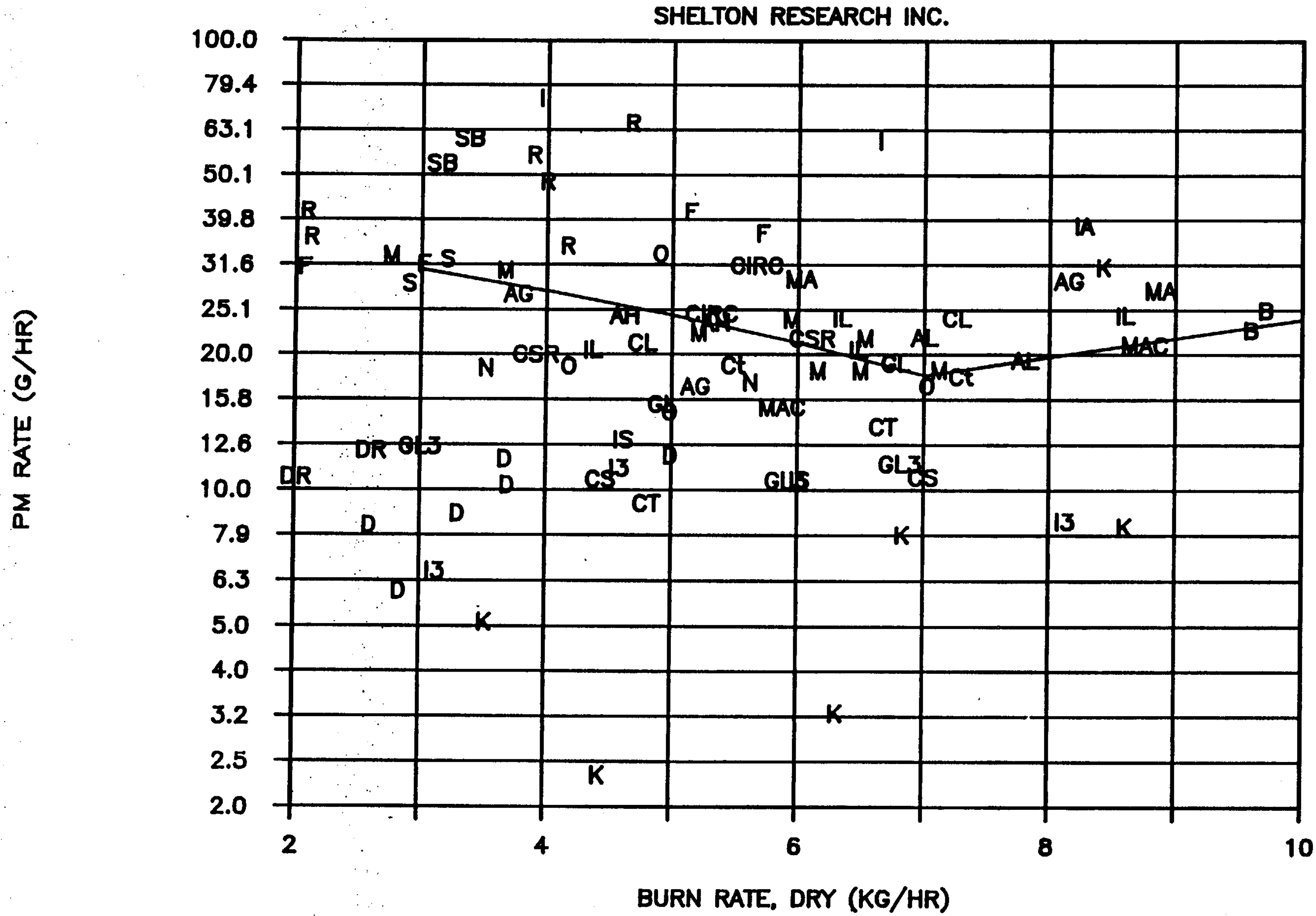
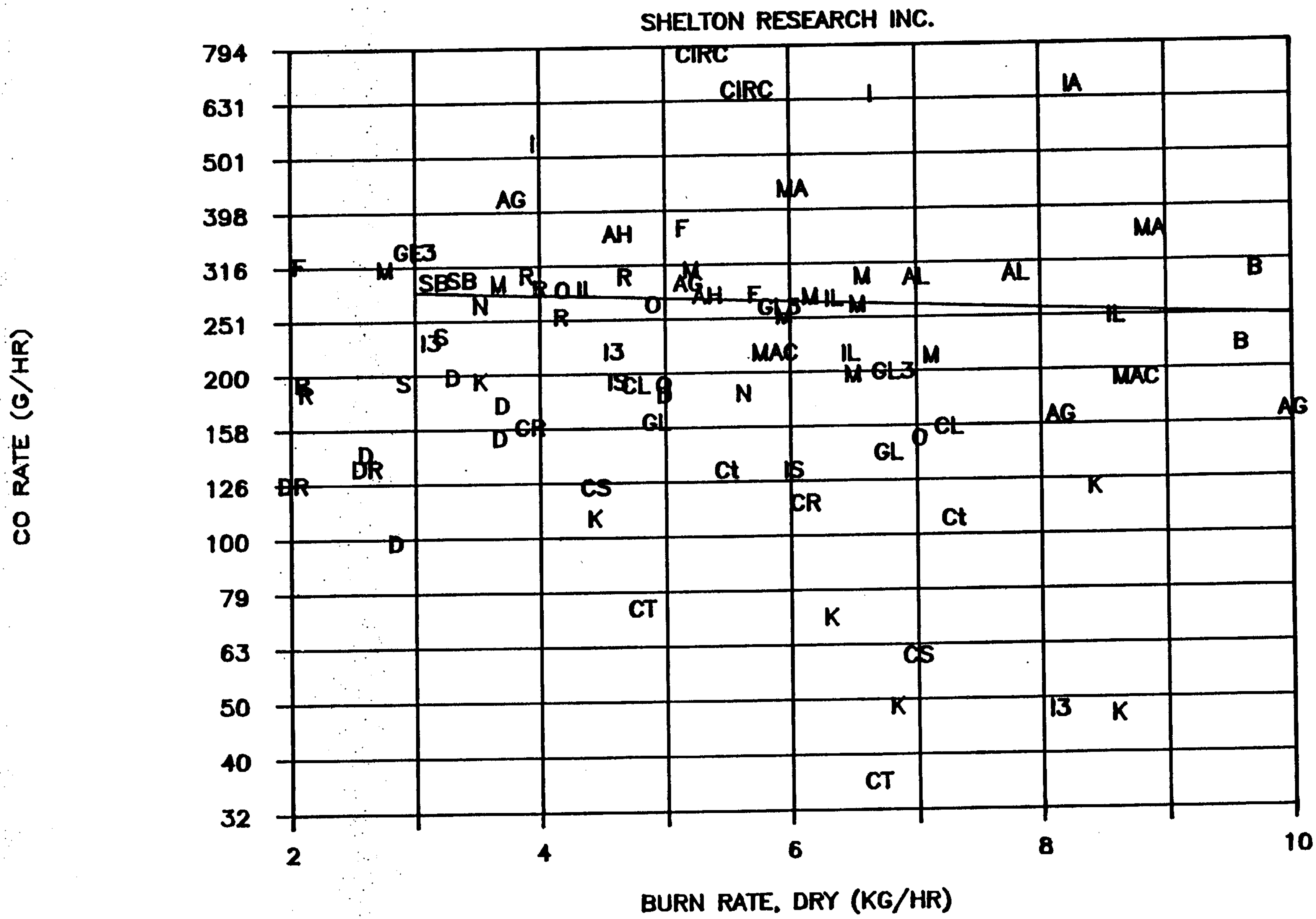


FIGURE 4–5. CO RATE.



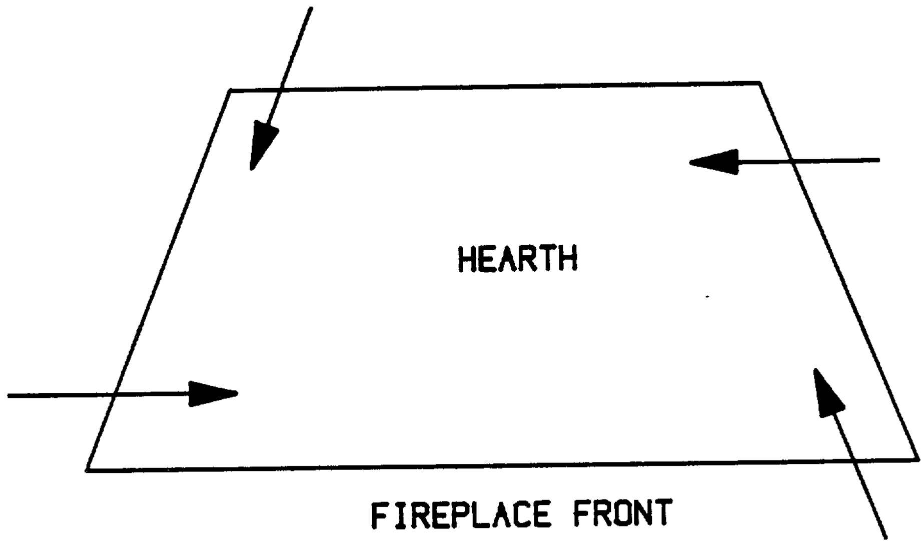


FIGURE 4-6. FOUR-CORNER AIR DESIGN.

FIGURE 4—7.. PM, AIR INJECTION DESIGNS.

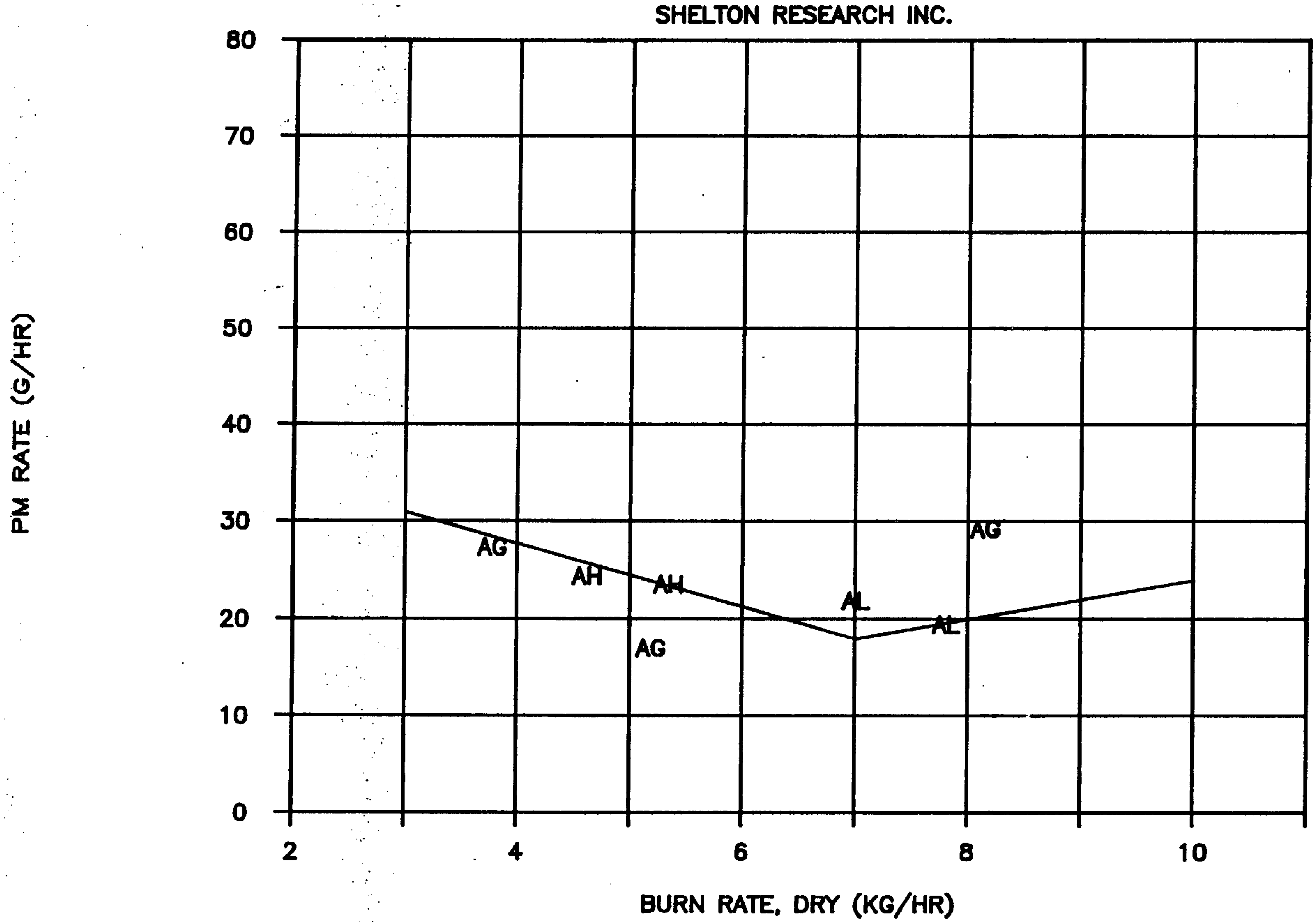


FIGURE 4–8. CO, AIR INJECTION DESIGNS.

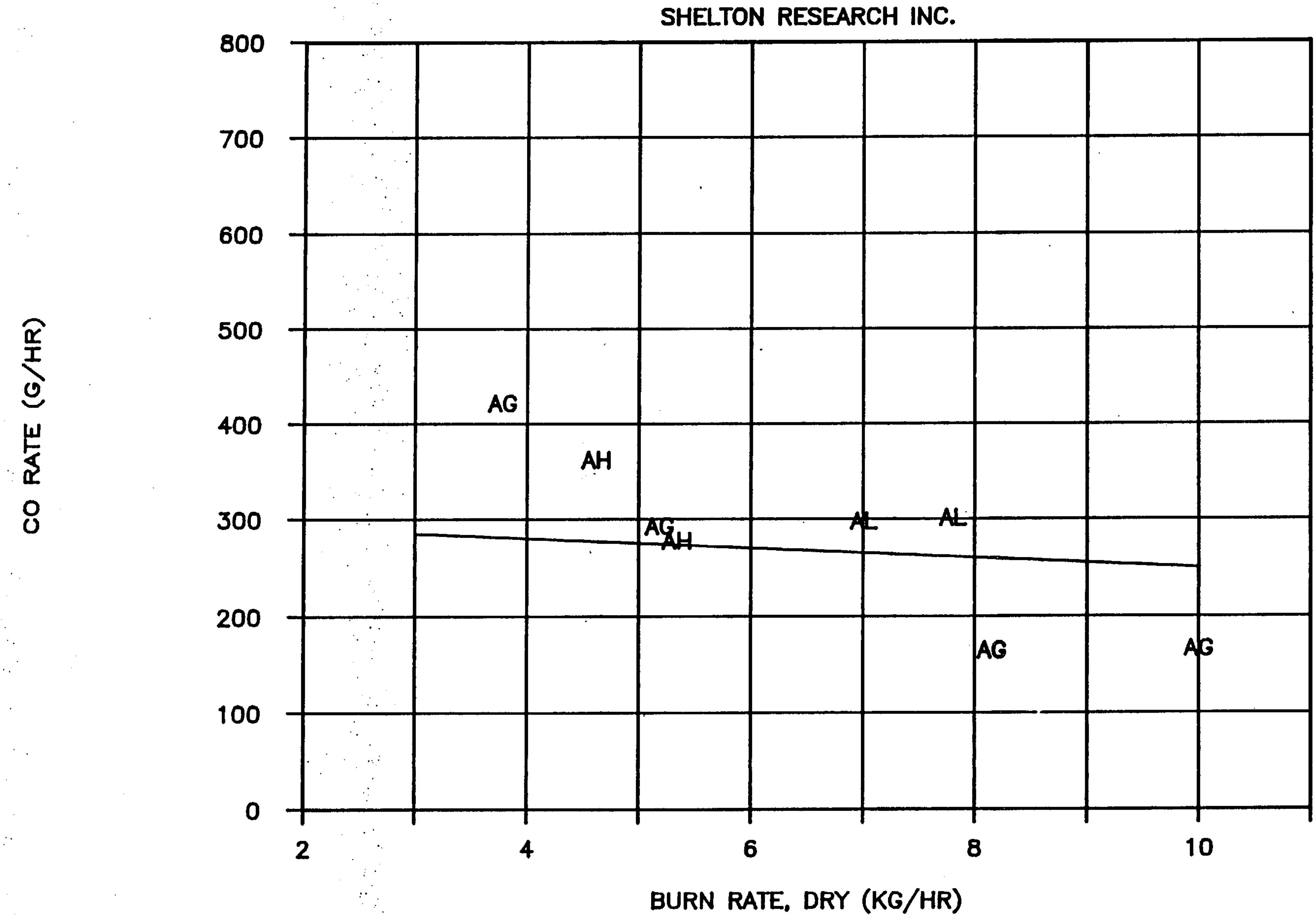


FIGURE 4–9. PM, CLOSED–DOOR DESIGNS.

SHELTON RESEARCH INC.

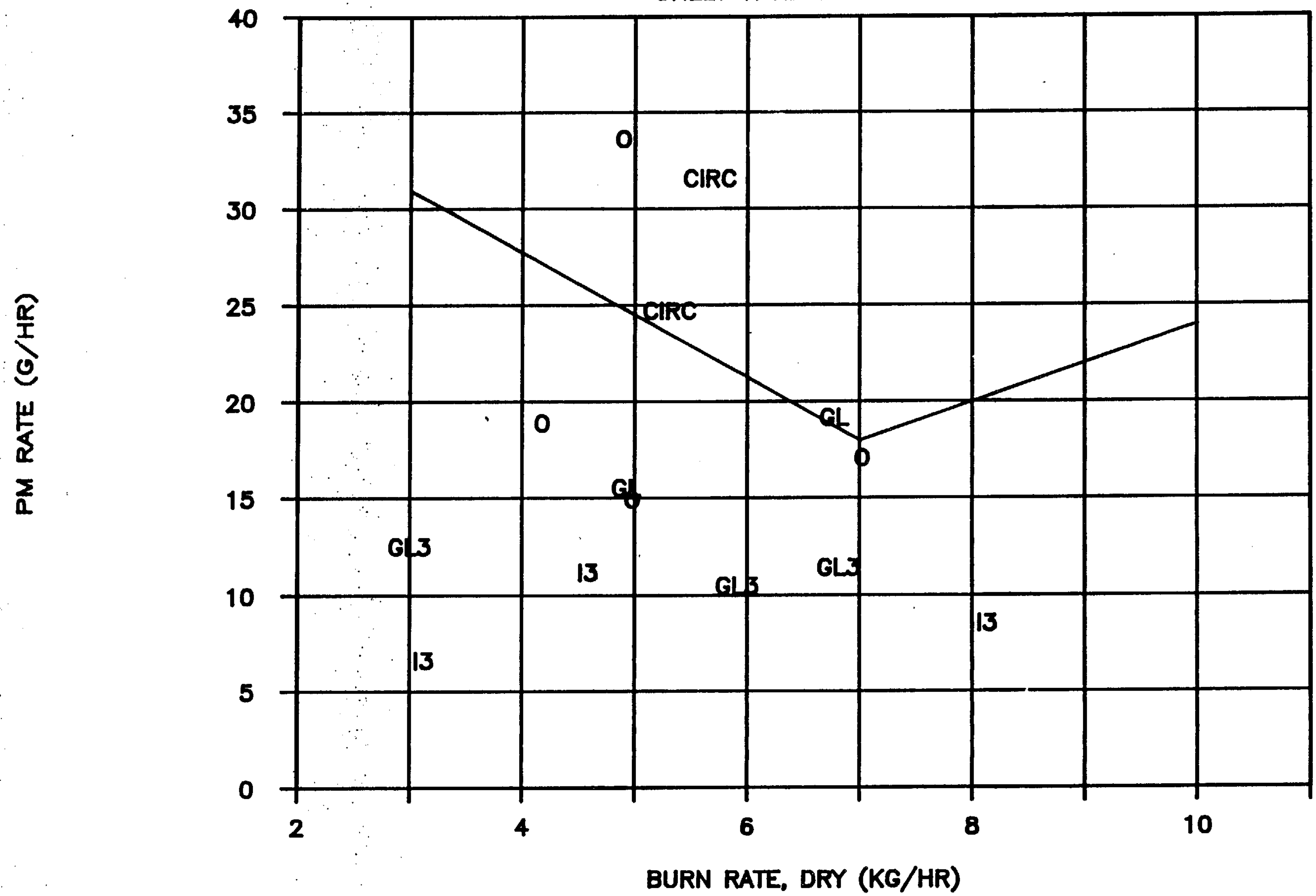
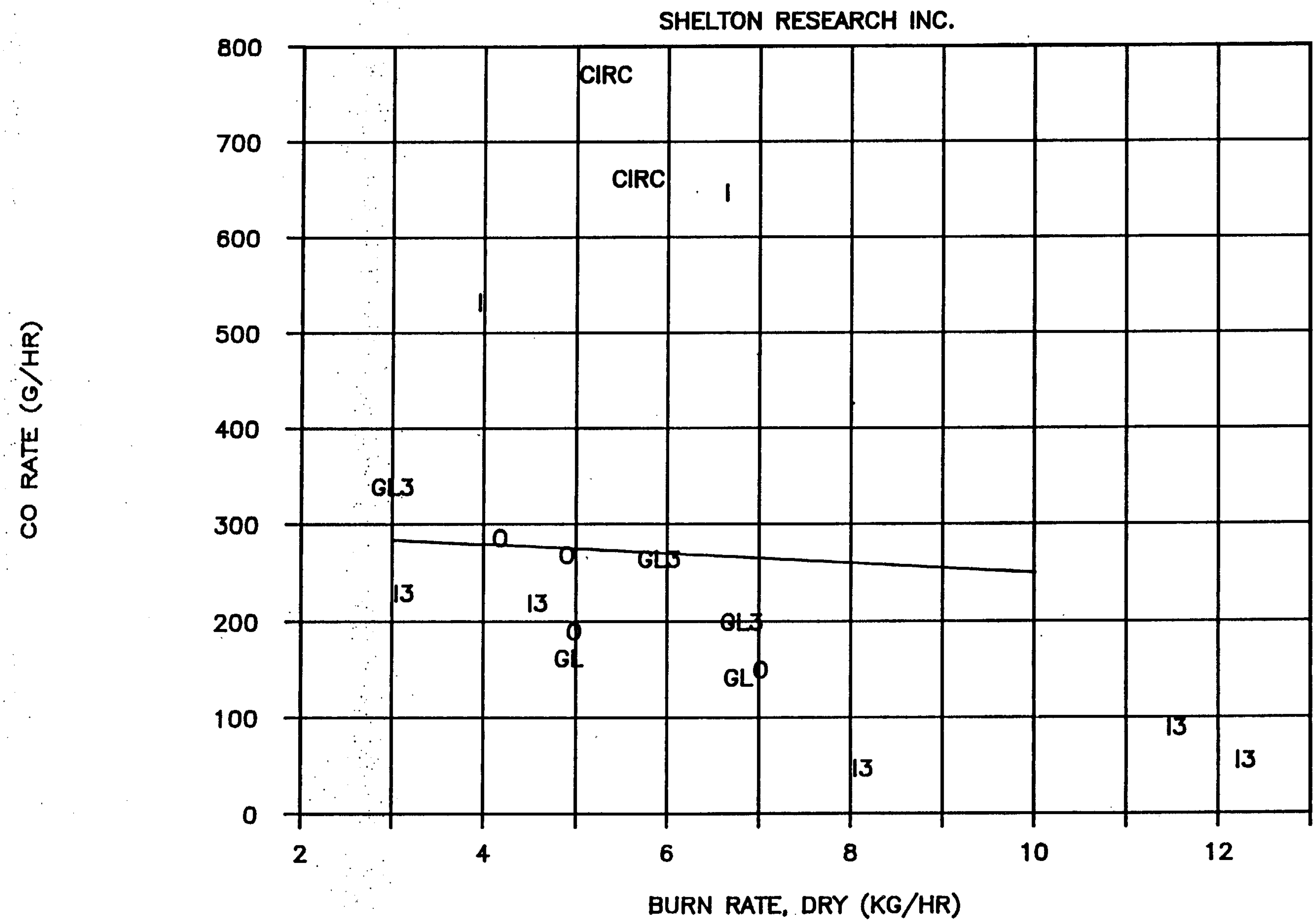


FIGURE 4–10. CO, CLOSED–DOOR DESIGNS.



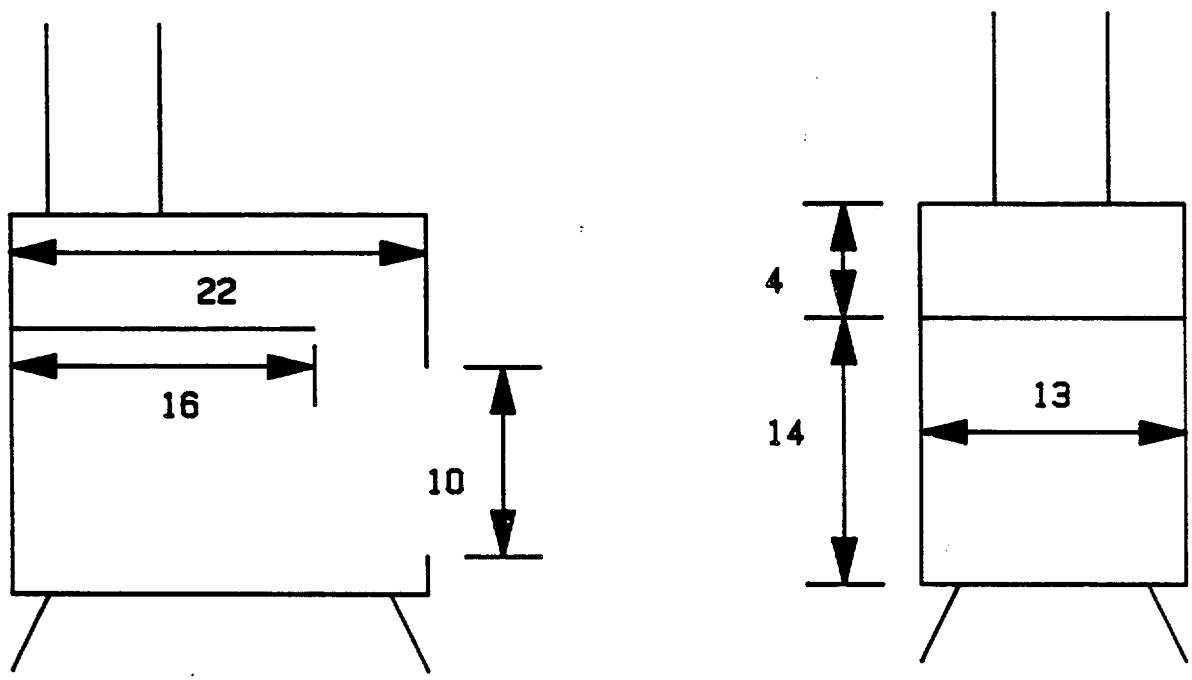


FIGURE 4-11. DEEP FIREBOX INSIDE DIMENSIONS (INCHES).

FIGURE 4–12. PM FOR OTHER DESIGNS.

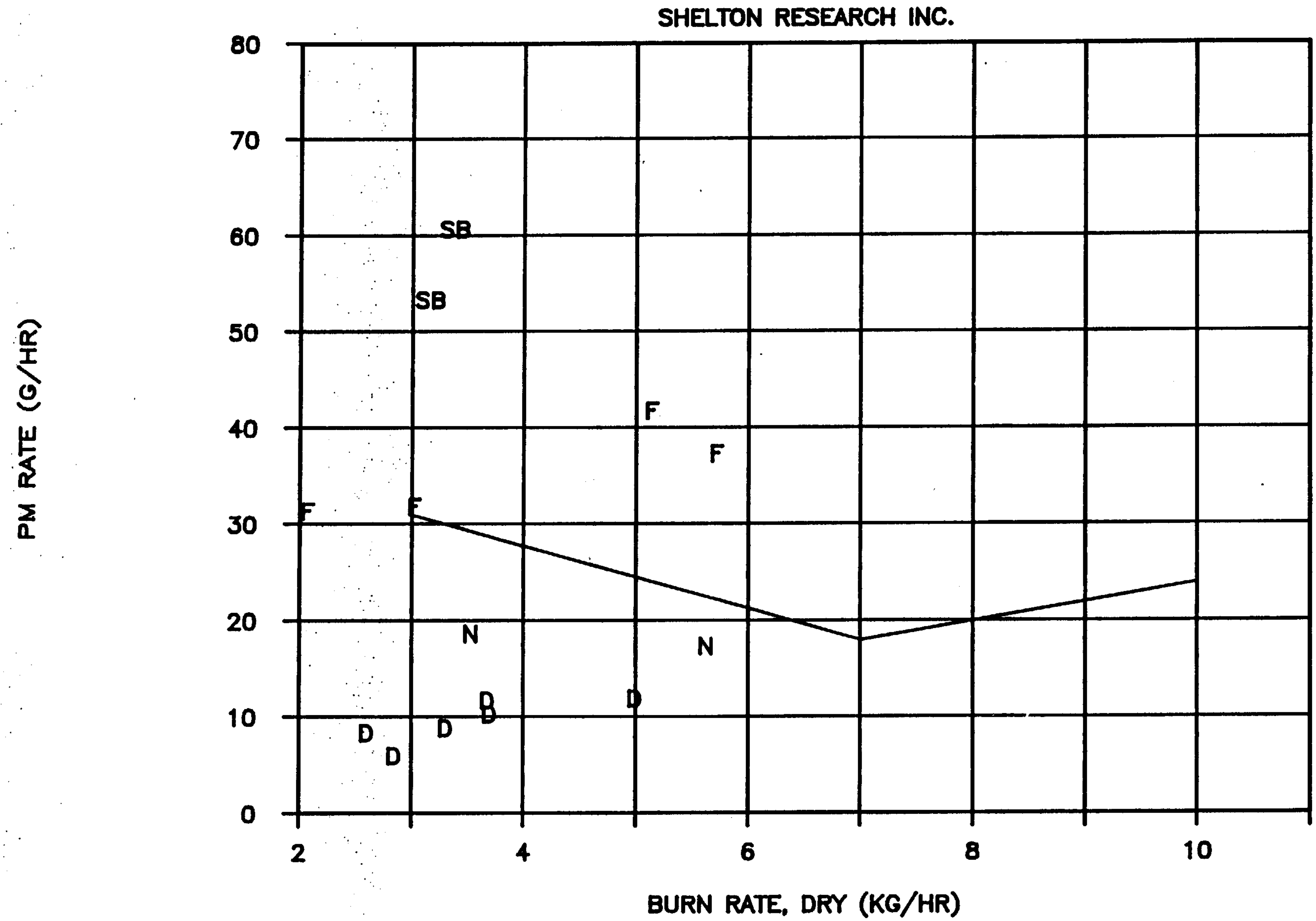


FIGURE 4–13. CO FOR OTHER DESIGNS.

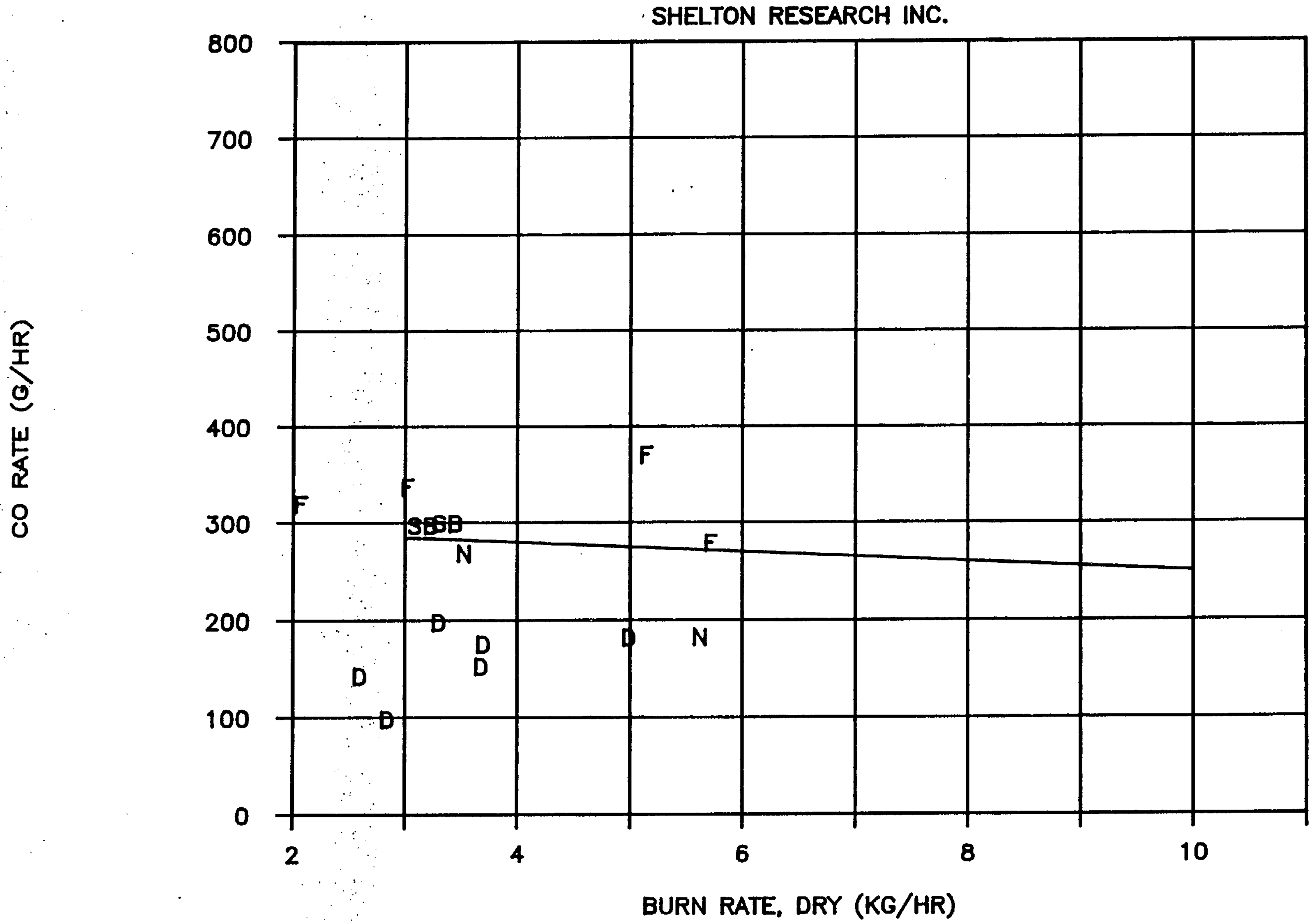


FIGURE 4-14. PM FACTOR.

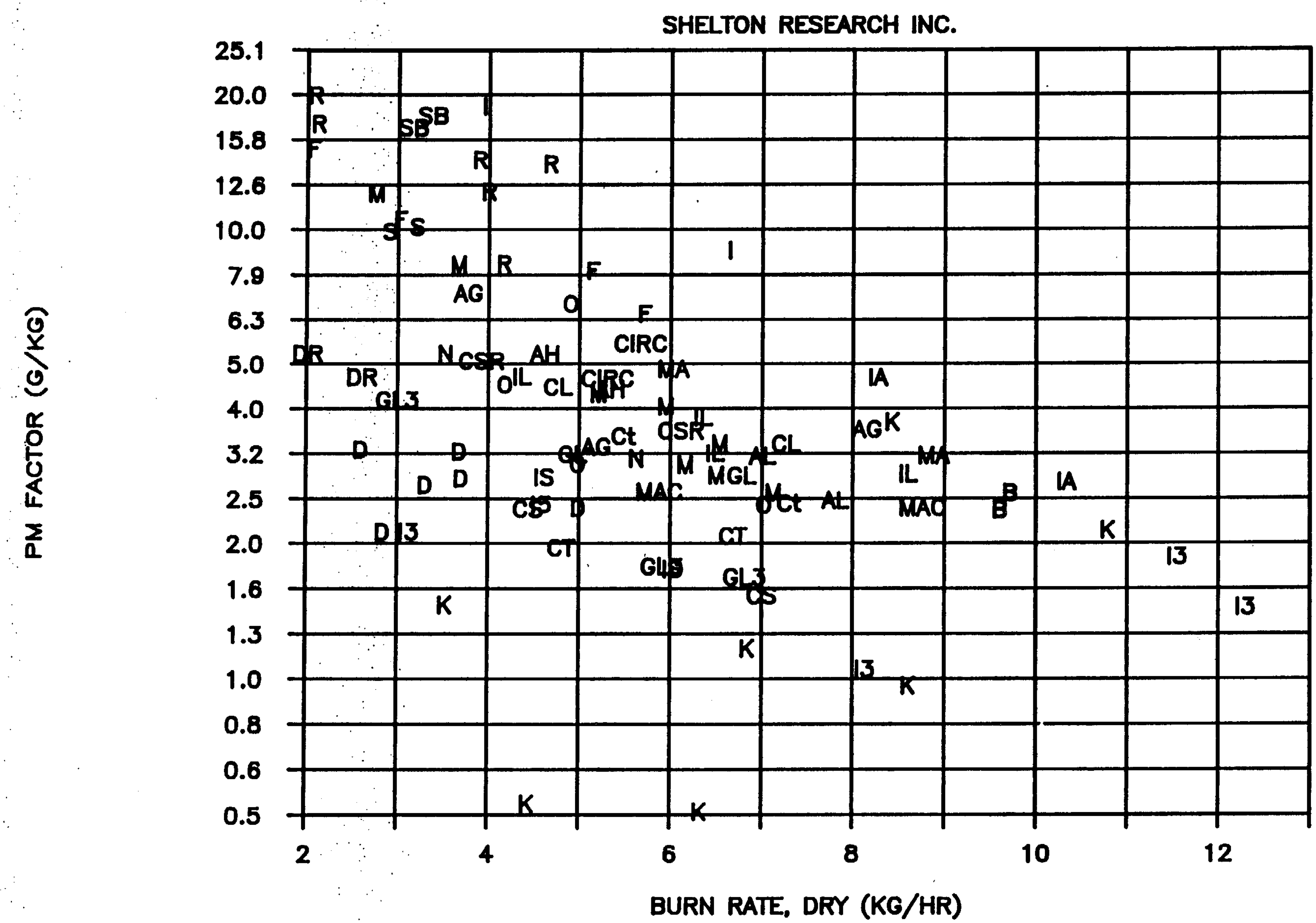


FIGURE 4–15. CO FACTOR.

SHELTON RESEARCH INC.

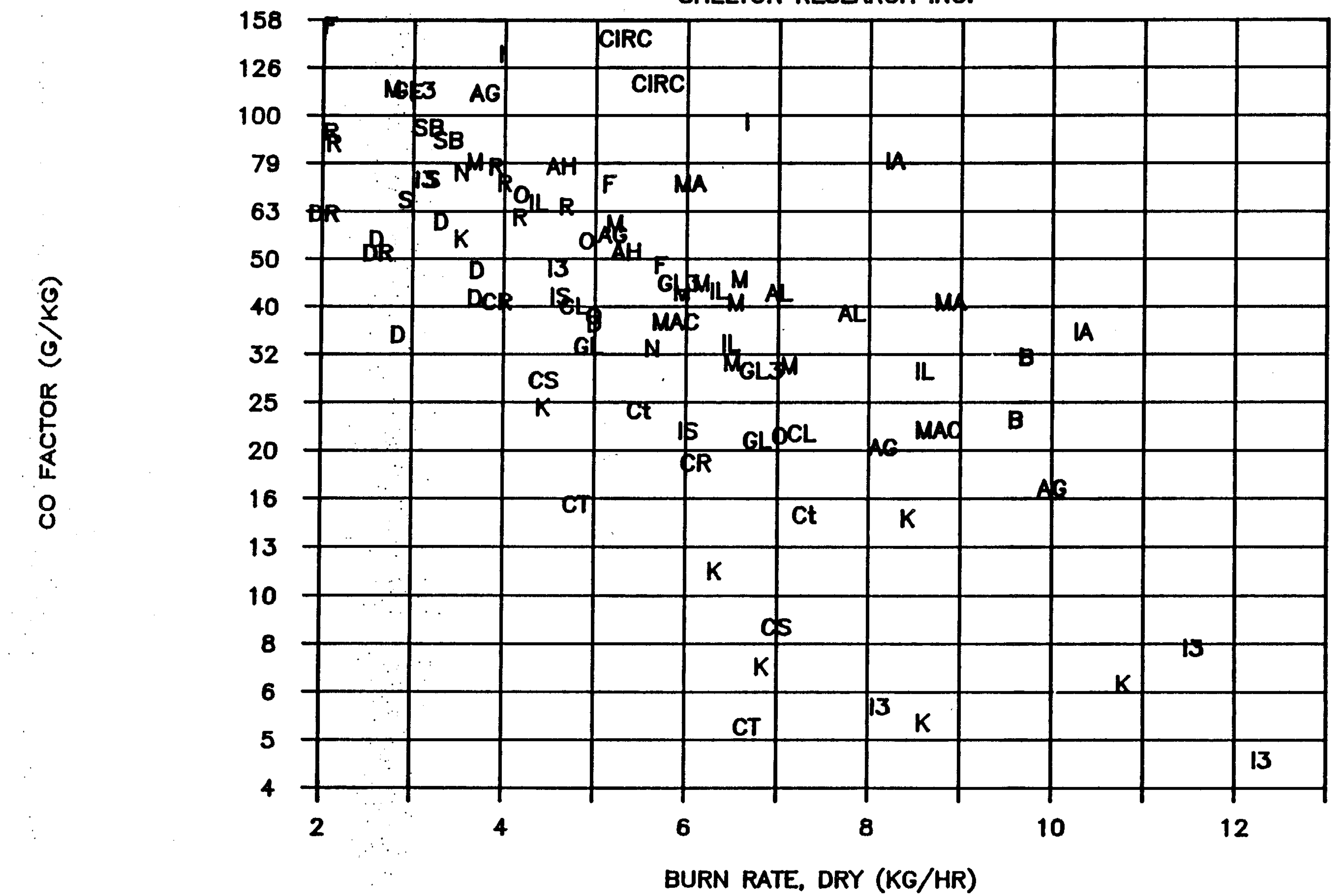


FIGURE 4–16. PM FOR REALISTIC FUEL.

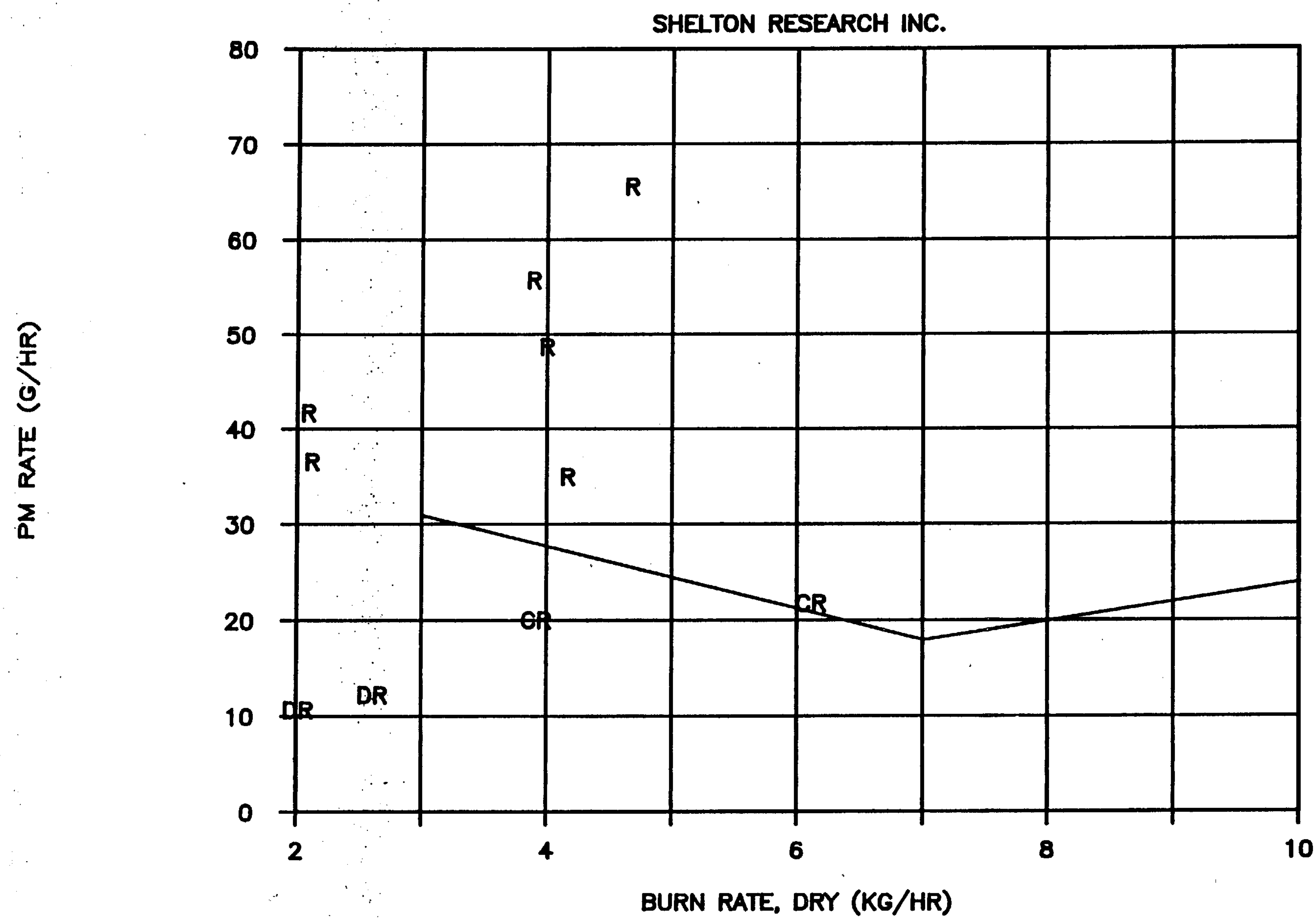
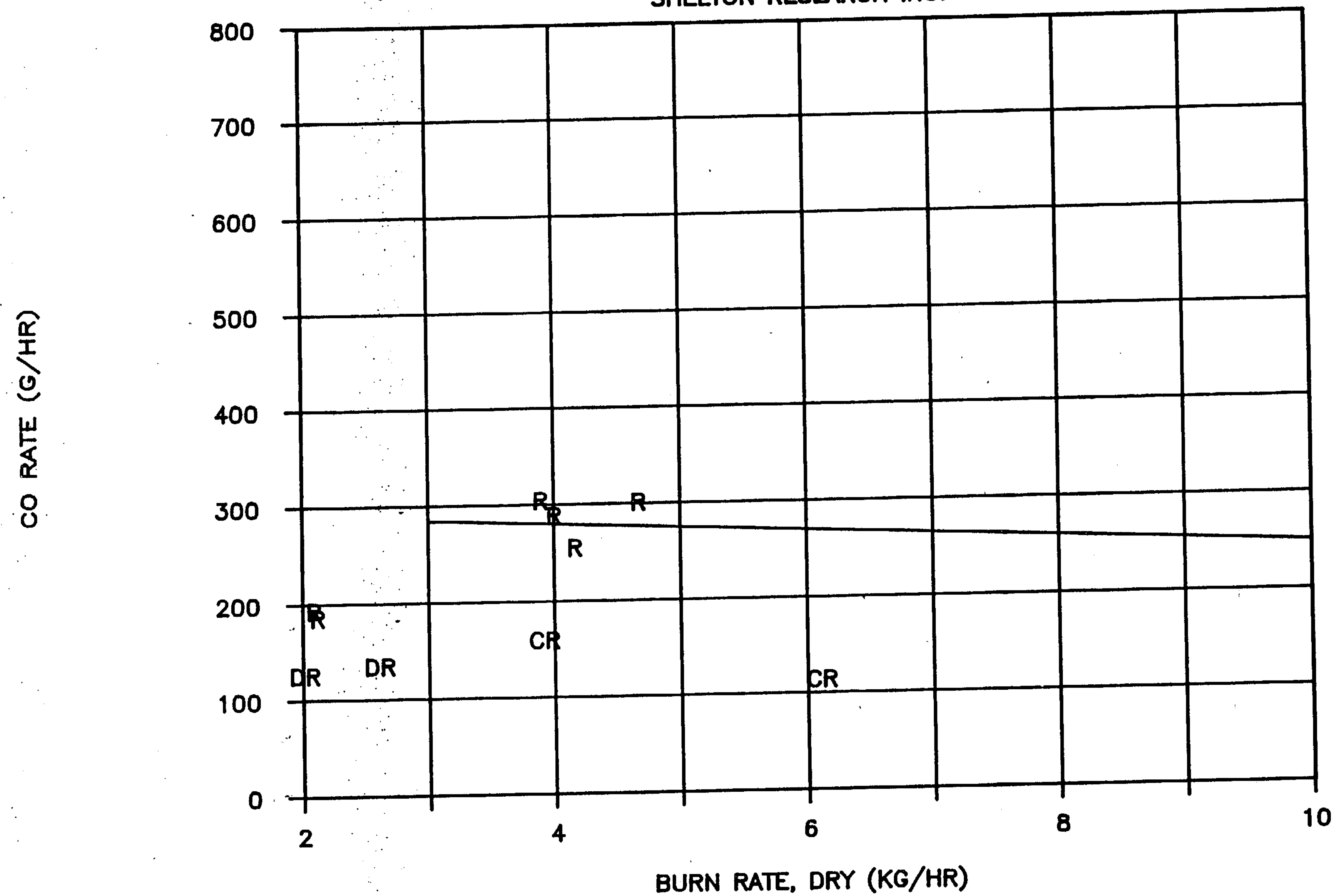


FIGURE 4–17. CO FOR REALISTIC FUEL.

SHELTON RESEARCH INC.



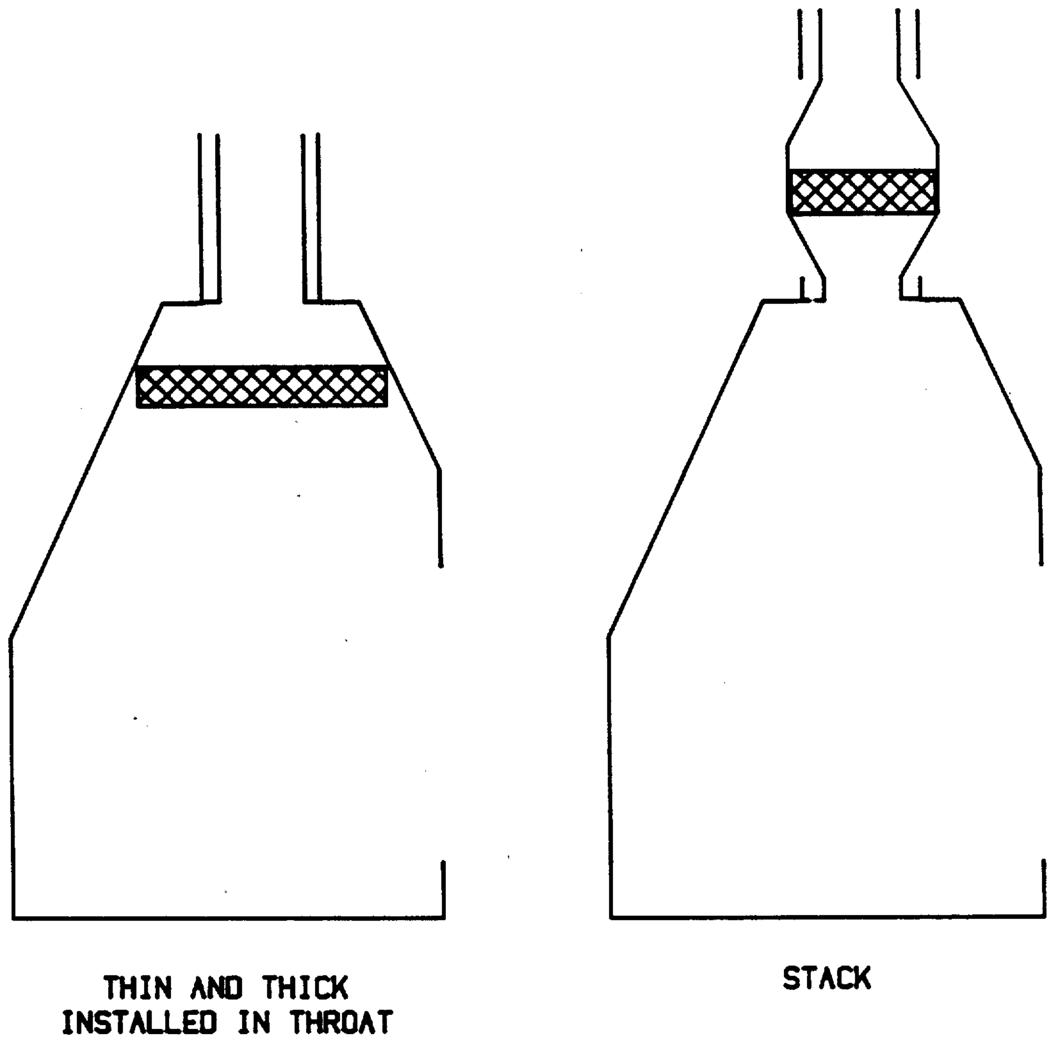


FIGURE 4-18. CATALYTIC FIREPLACE CONFIGURATIONS (NOT TO SCALE).

FIGURE 4–19. PM FOR CATALYTIC DESIGNS

SHELTON RESEARCH INC.

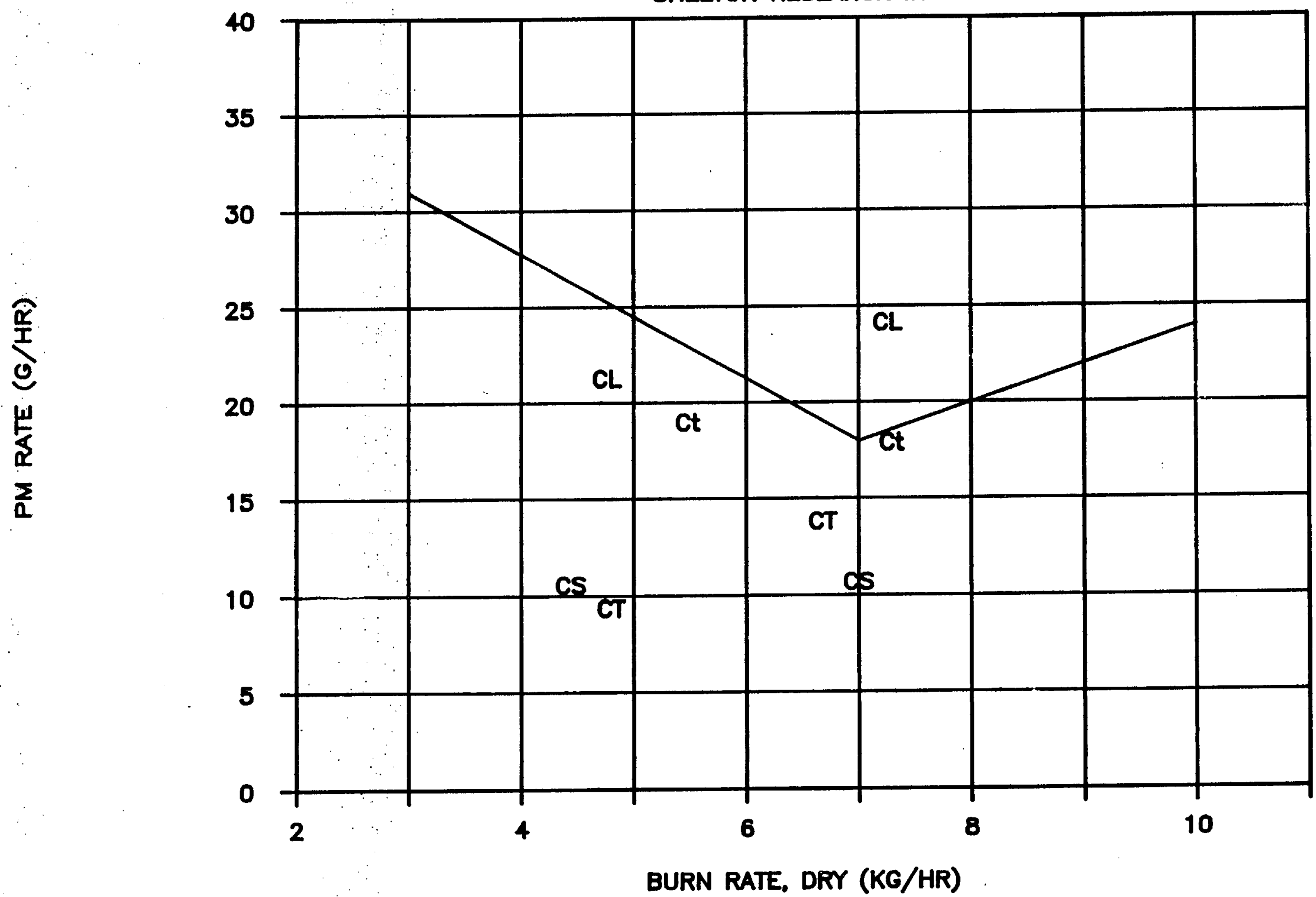


FIGURE 4–20. CO FOR CATALYTIC DESIGNS

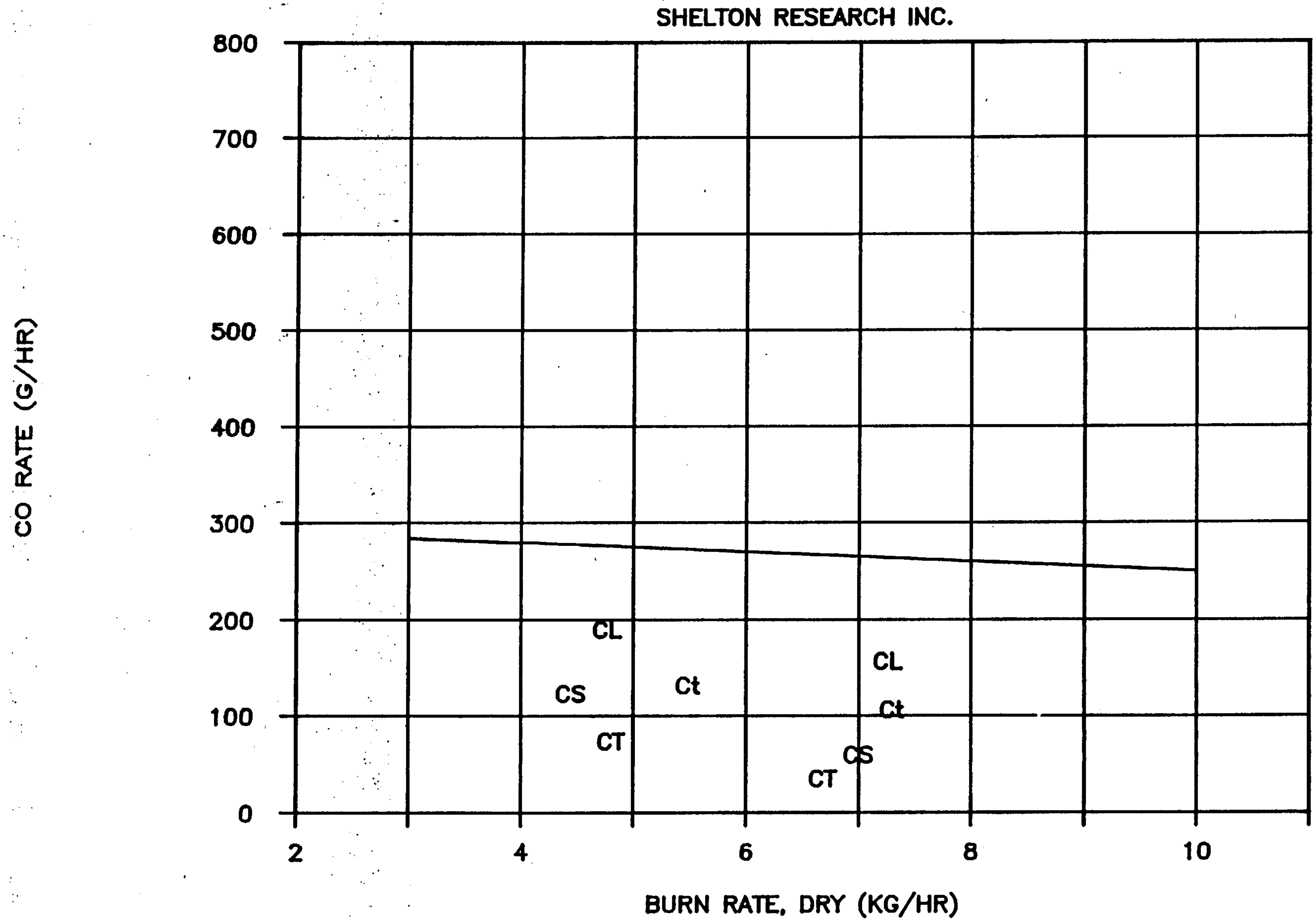


FIGURE 4–21. FRONTAL RADIANT OUTPUT.

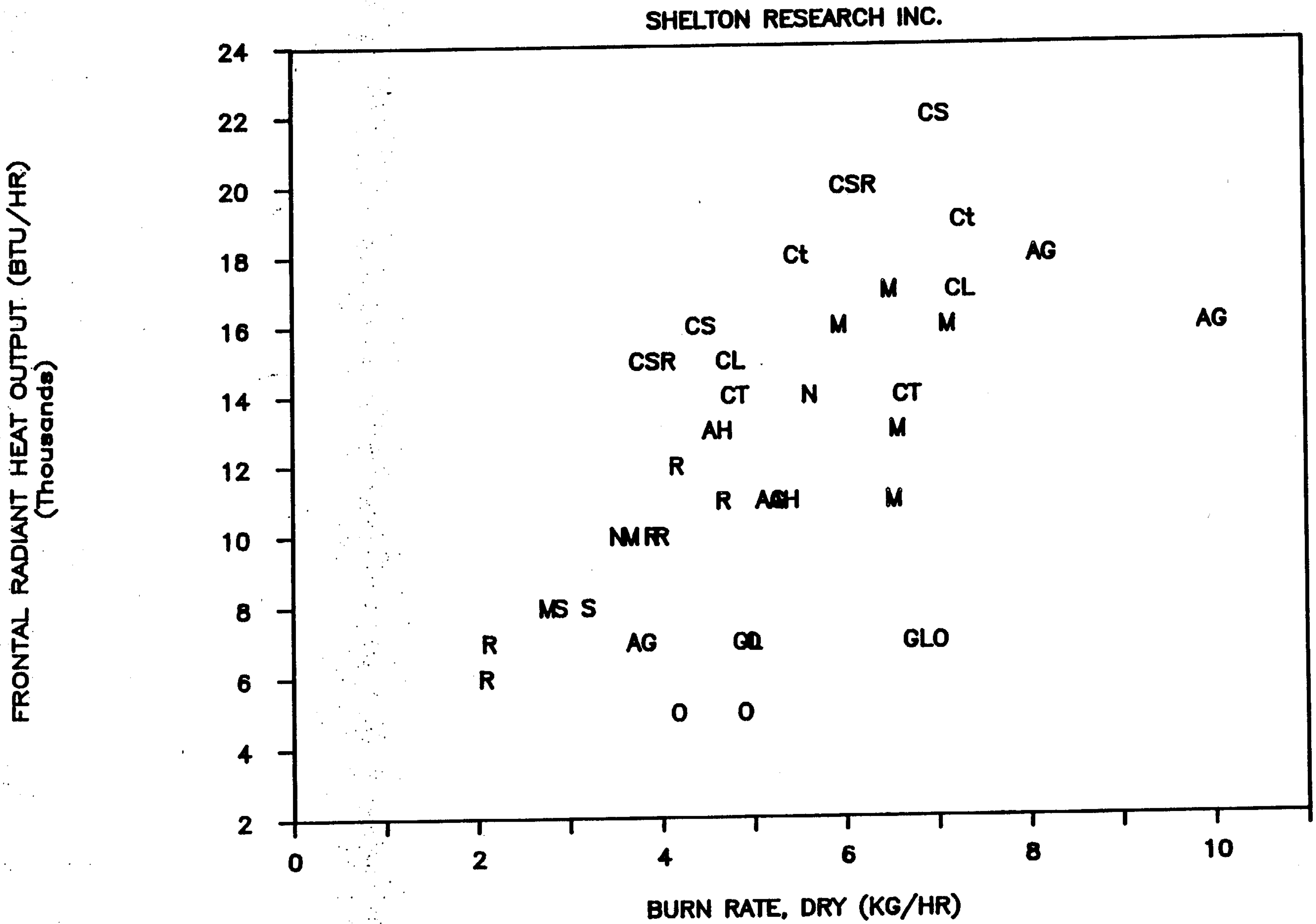


FIGURE 4–22. INPUT MINUS LOSSES.

SHELTON RESEARCH INC.

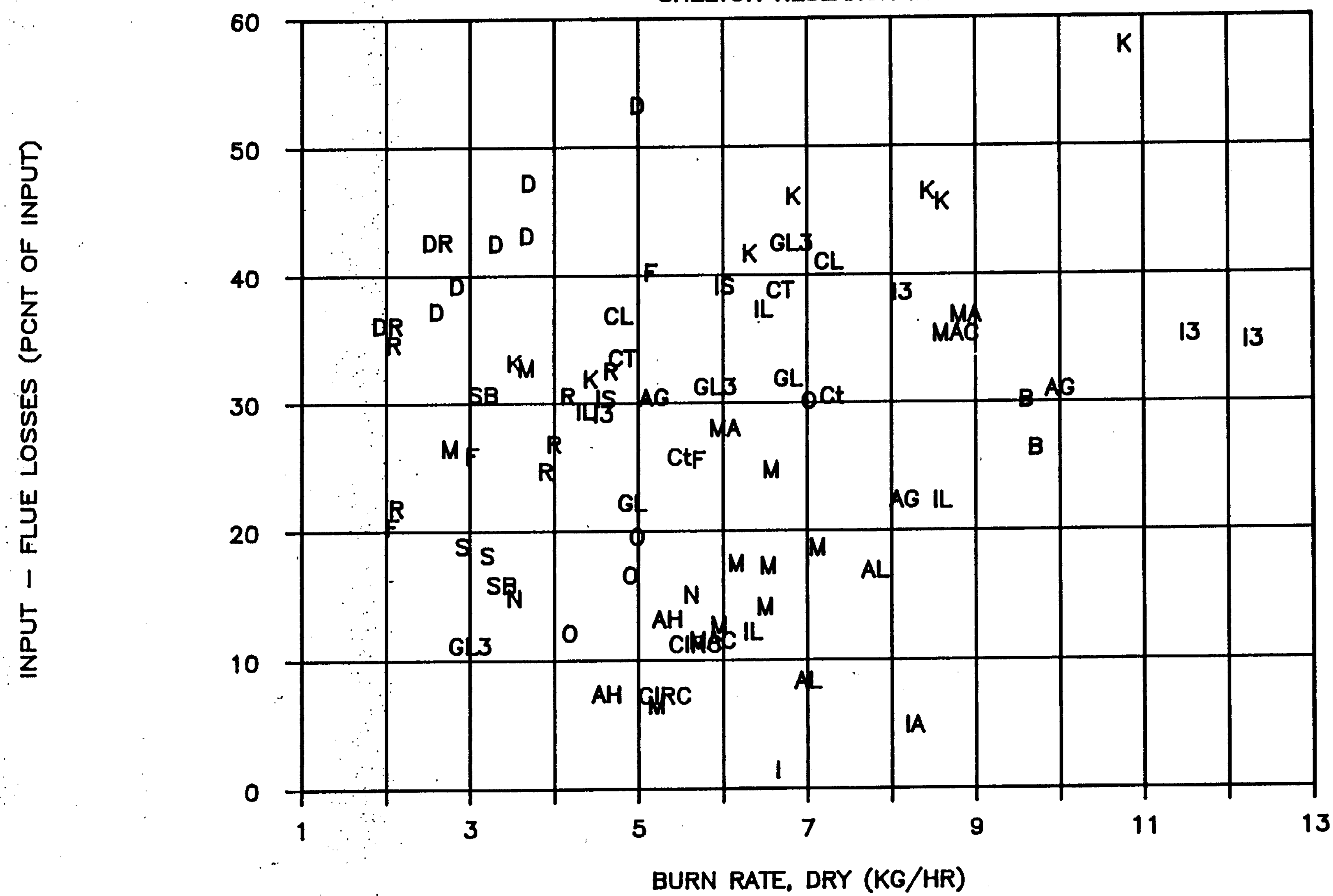


FIGURE 4–23. FLUE FLOW.

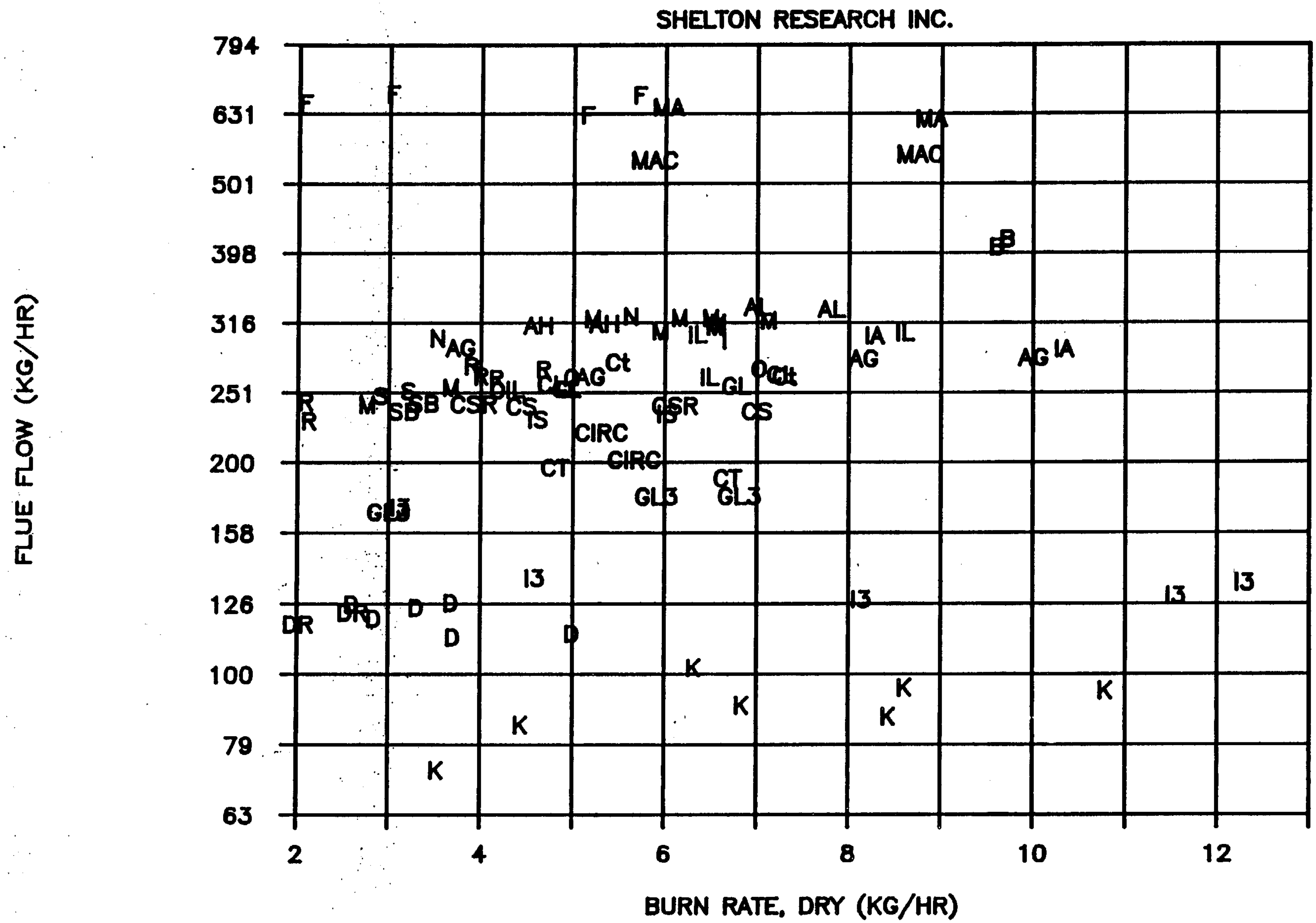


FIGURE 4–24. FLUE TEMPERATURE.

SHELTON RESEARCH INC.

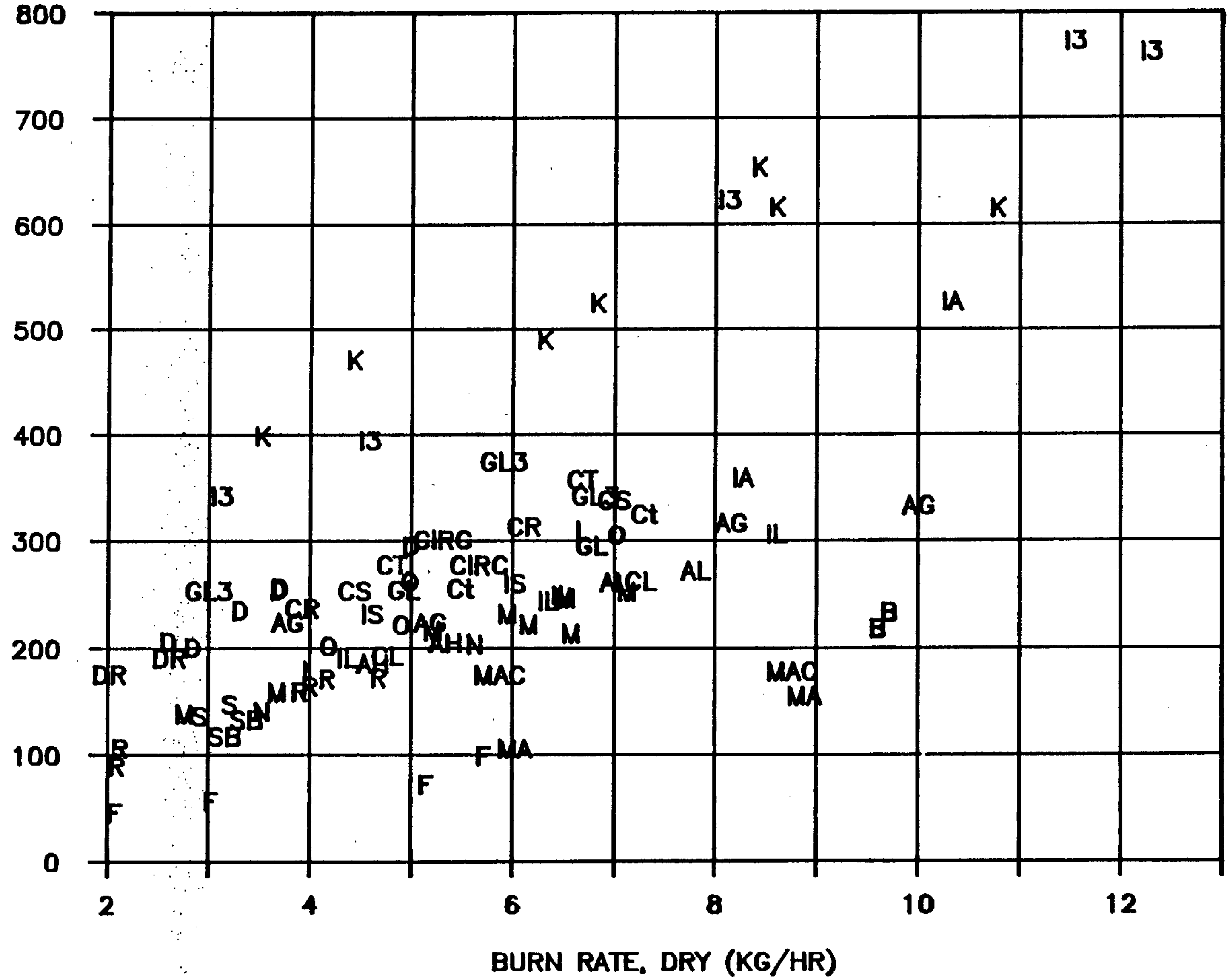
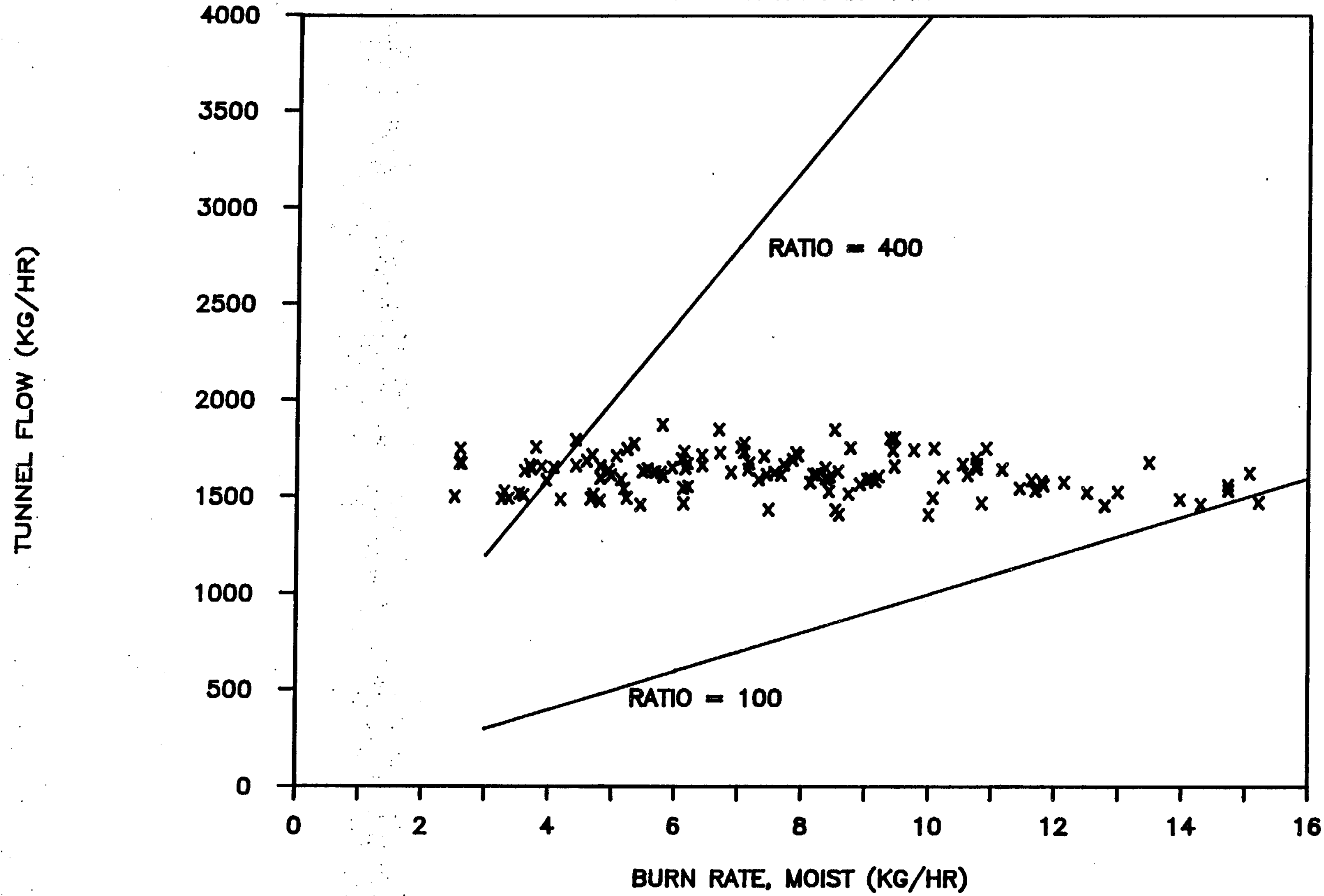


FIGURE 5–1. TUNNEL FLOW.

SHELTON RESEARCH INC.



5–2. TUNNEL TEMPERATURE.

SHELTON RESEARCH INC.

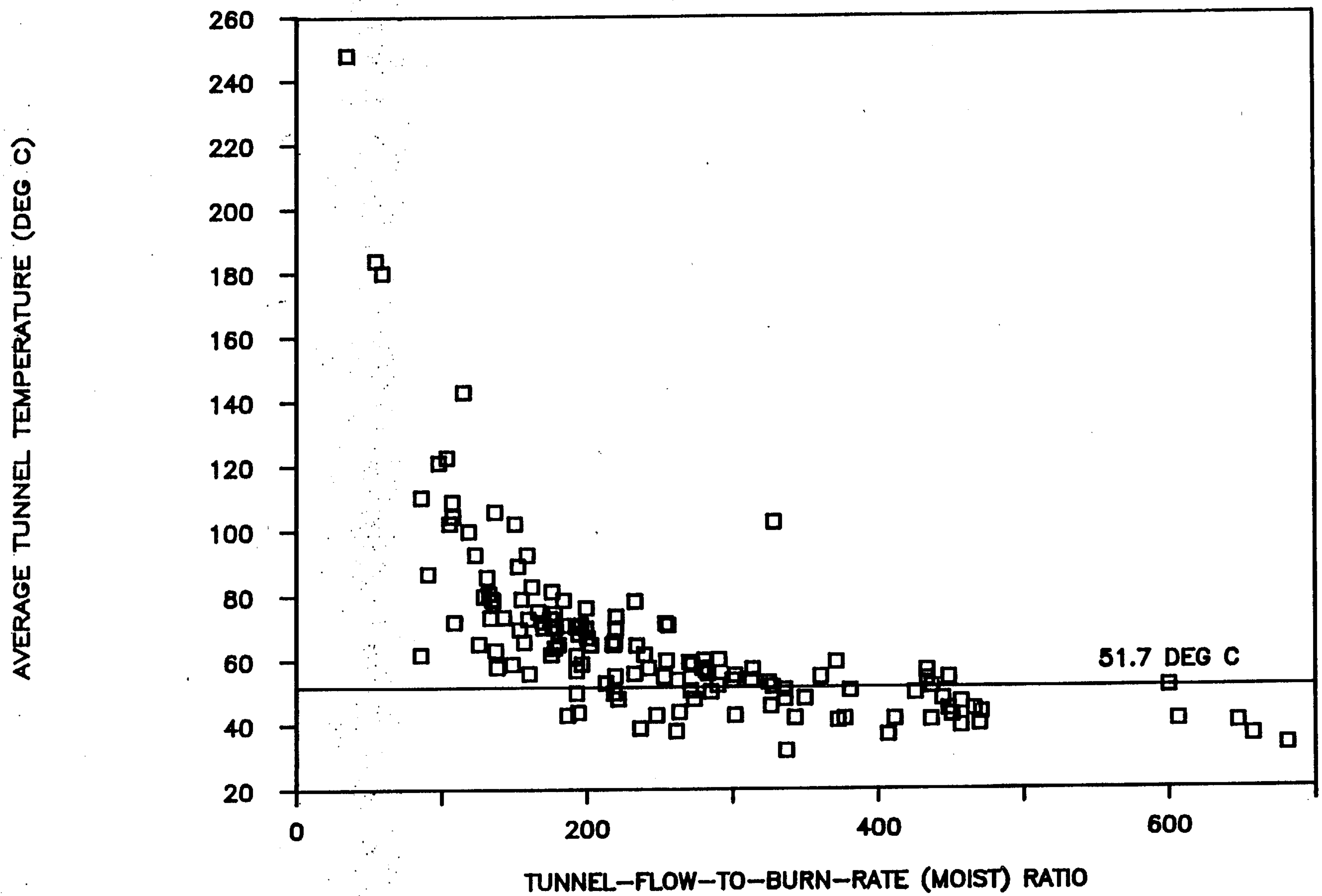
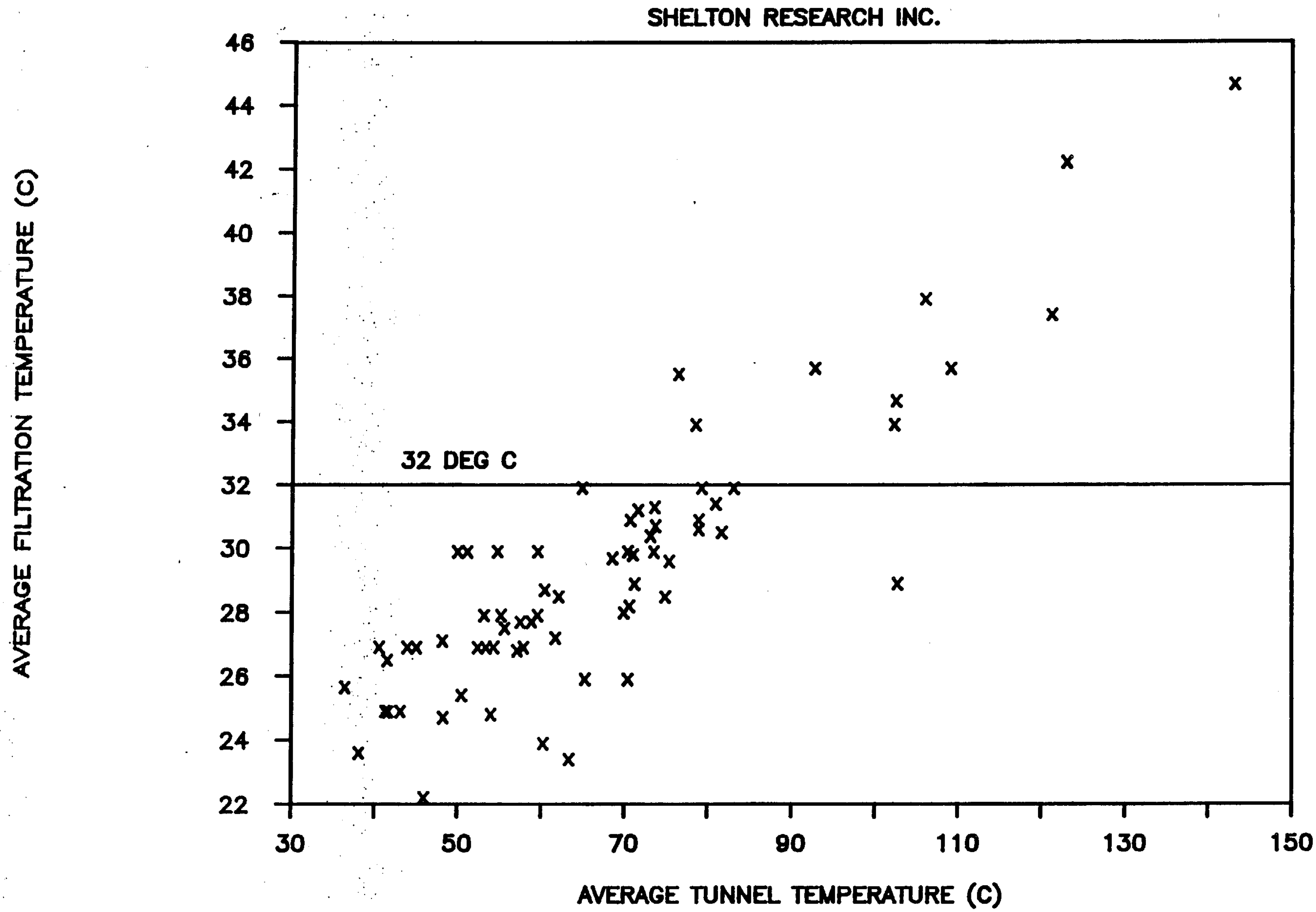


FIGURE 5–3. AVERAGE FILTRATION TEMP.



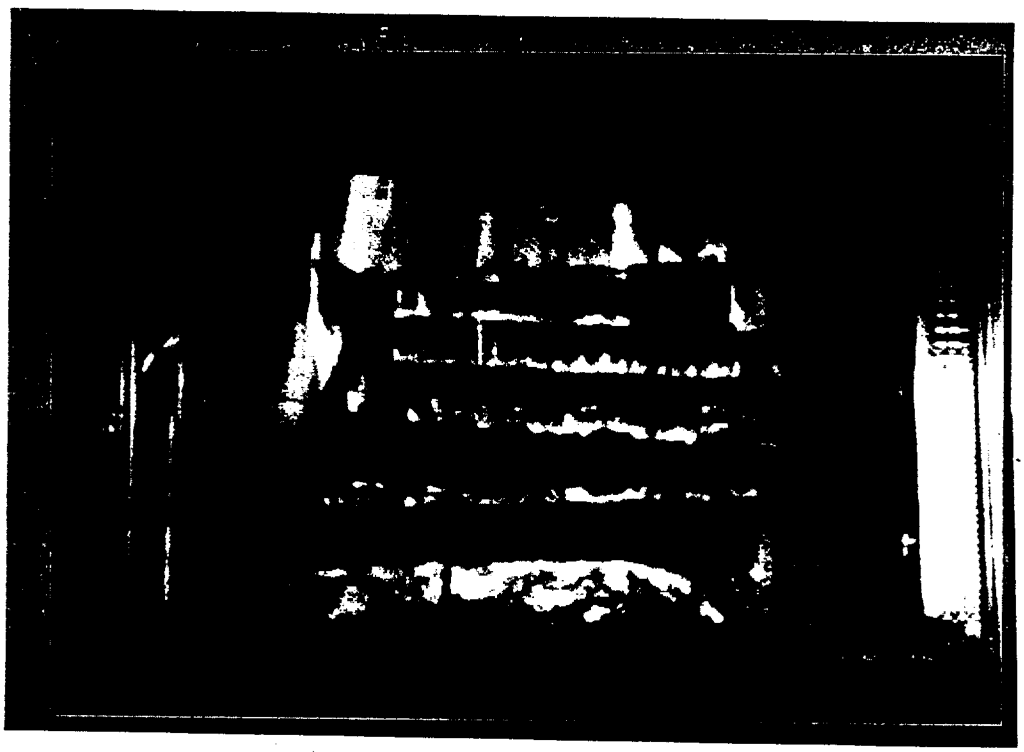


FIGURE 5-4 Air-to-Fuel Test using EPA Method 28A

FIGURE 5-5. PM PHASE DEPENDENCE.

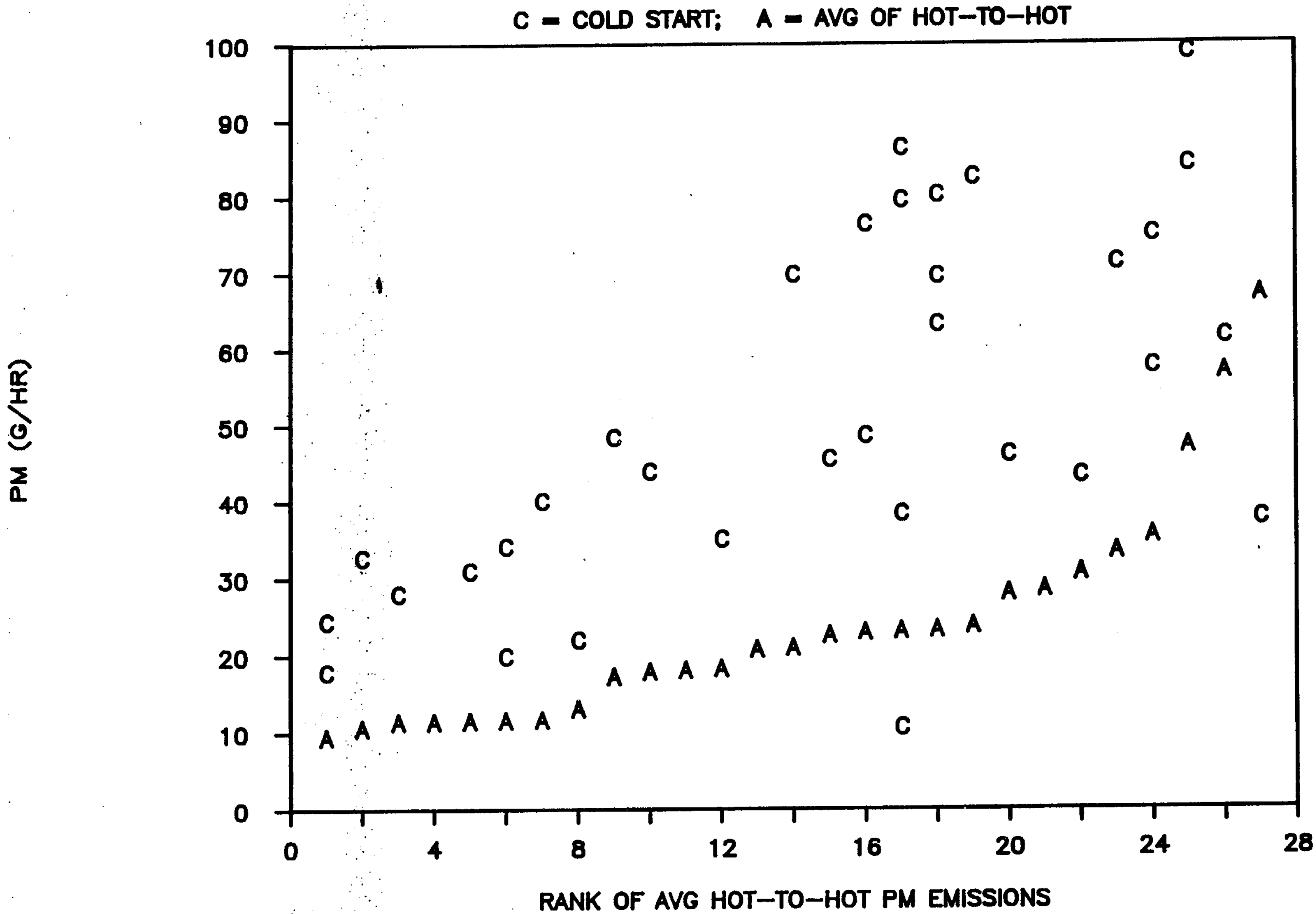


FIGURE 5–6. BURN RATE VS HEARTH AREA.

SHELTON RESEARCH INC.

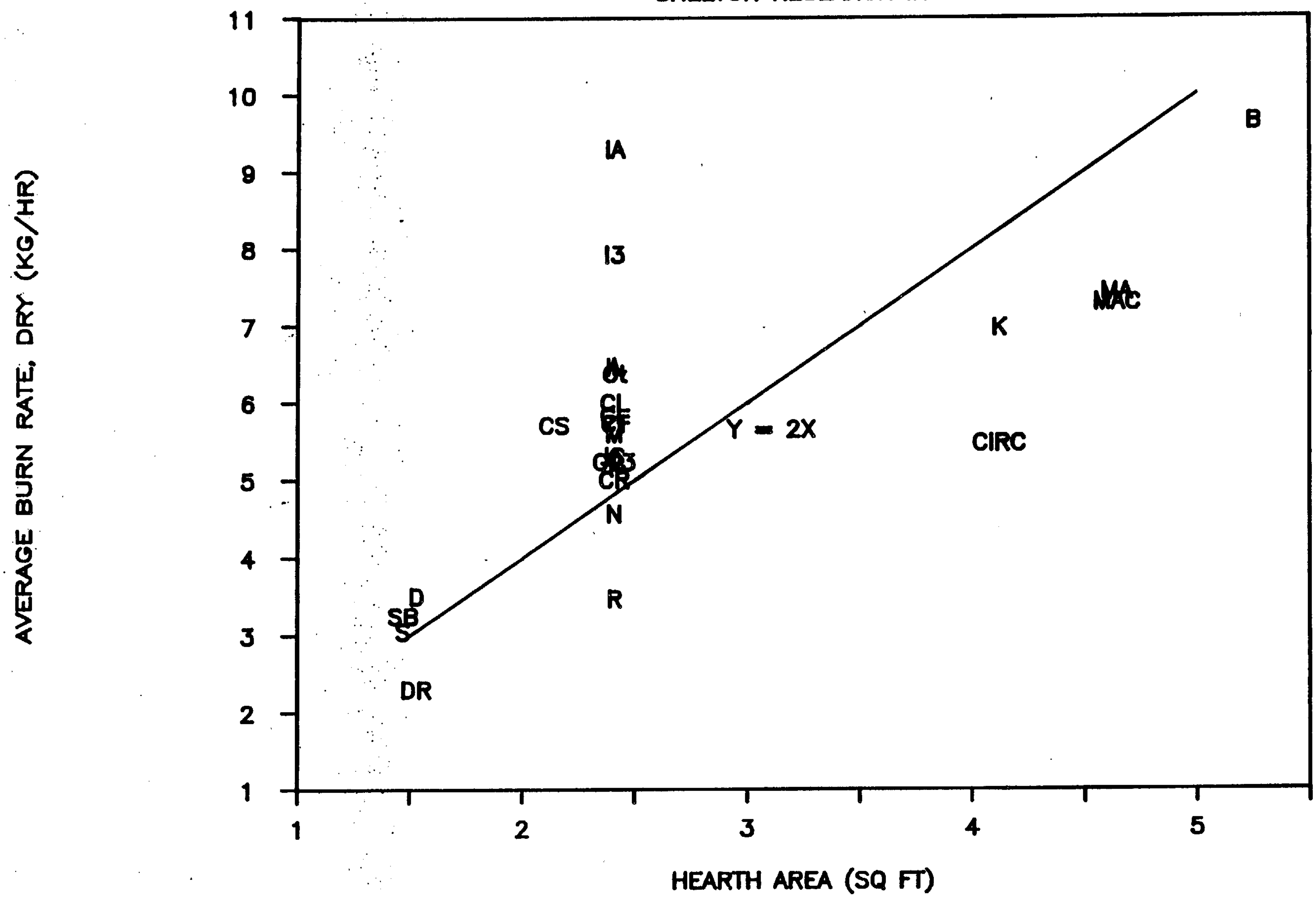


FIGURE 6-1. AIR-TO-FUEL RATIO

EPA METHOD 28G

SHELTON RESEARCH INC.

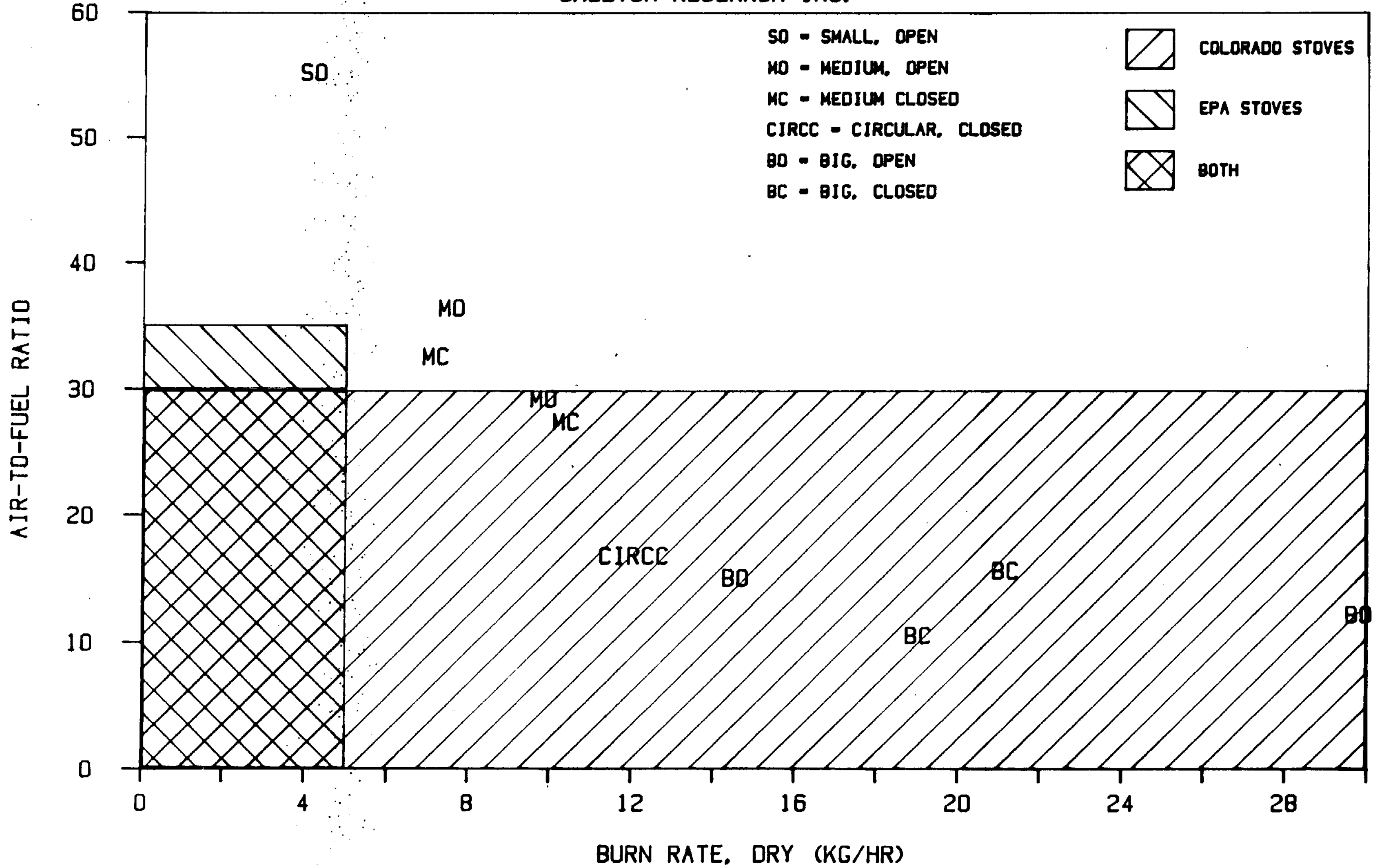
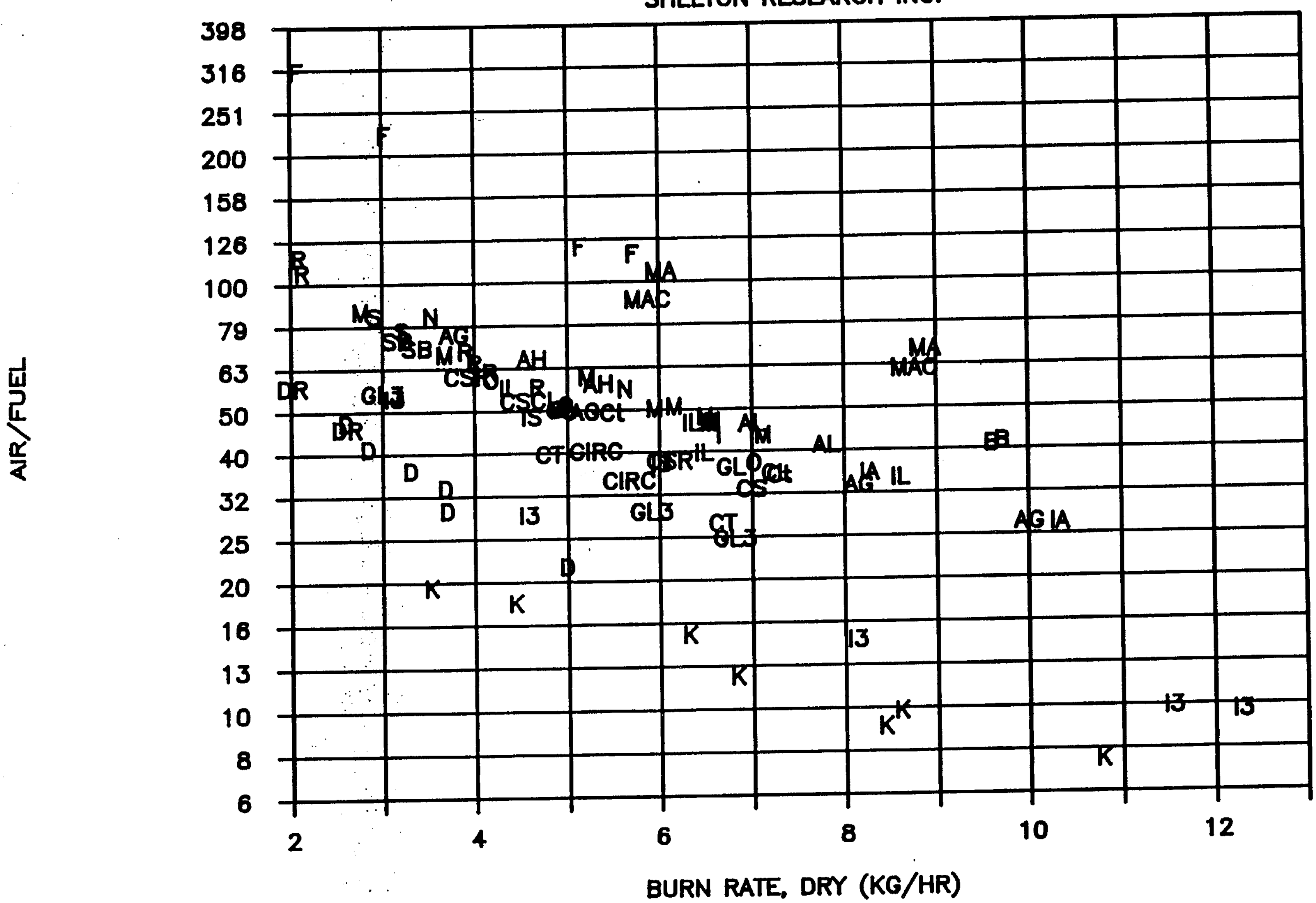


FIGURE 6-2. AIR-TO-FUEL RATIO.

SHELTON RESEARCH INC.



INDEX OF TABLES

COMB AND CO

TABLE 4-1. SUMMARY OF DESIGN EFFECTS ON EMISSIONS.

OPEN OR CLOSED DESIGN	DESIGN TYPE SHORT NAME	DESIGN TYPE ABBR	PERCENTAGE CHANGE RELATIVE TO BASELINE FIREPLACE USING STANDARD FUEL: AVG EFFECTS ON PM & CO RATES (PCNT)	EFFECT ON PM RATE (PCNT)	EFFECT ON CO RATE (PCNT)	EFFECT ON COMB RATE (PCNT)	PM (G/HR)	CO (G/HR)	BURN RATE (DRY) (KG/HR)	PM (G/KG)	CO (G/KG)	RATIO AIR/ FUEL	NUMBER OF TESTS
O	CATALYST, THICK	CT	-65	-51	-80	-84	12	55	5.7	2.0	10	34	2
O	CATALYST, STACK	CS	-60	-54	-66	-	11	92	5.7	1.9	18	43	2
C	KILN	K	-58	-50	-65	-54	12	95	7.0	1.5	18	13	7
O	DEEP	D	-50	-59	-41	-16	10	159	3.5	2.7	46	35	6
C	INSUL, CORNER AIR	I3	-48	-44	-52	-40	13	129	7.9	1.8	28	23	5
O	DEEP, REALISTIC FUEL	DR	-51	-51	-51	1	12	131	2.3	5.0	57	52	2
O	INSUL, SMALL DOOR	IS	-45	-50	-40	-52	12	163	5.3	2.3	32	43	2
O	CATALYST, THIN	Ct	-38	-21	-56	-83	18	120	6.4	3.0	19	42	2
C	GLASS DOORS	GL	-35	-26	-43	-35	17	153	5.8	3.0	27	44	2
C	GLASS DOORS, CORNER AIR	GL3	-26	-51	-1	23	12	268	5.2	2.6	63	37	3
O	CAT,REALISTIC FUEL	CR	-30	-11	-49	-	21	138	5.0	4.3	30	49	2
O	NO GRATE	N	-20	-23	-16	-36	18	226	4.6	4.2	55	70	2
O	MASONRY, CAT	MAC	-23	-23	-24	-57	18	206	7.3	2.5	30	77	2
O	CATALYST, LINER	CL	-19	-3	-36	-42	23	174	6.0	3.9	31	44	2
C	OUTSIDE AIR	O	-13	-10	-17	-33	21	224	5.3	4.2	46	50	4
O	BIG	B	0	2	-3	37	24	263	9.6	2.5	27	42	2
O	INSUL, LARGE DOOR	IL	-5	-4	-5	-26	23	257	6.4	3.6	43	45	4
O	MEDIUM	M	0	0	0	0	24	270	5.6	5.1	54	56	9
O	INJECTED AIR	A	3	-1	6	3	23	287	6.5	4.2	52	50	8
O	SMALL	S	5	31	-20	3	31	215	3.1	10.1	70	81	2
O	CAMPFIRE	F	36	51	21	70	36	327	4.0	10.1	97	195	4
O	MASONRY	MA	35	22	48	-33	29	399	7.4	4.0	57	88	2
O	REALISTIC FUEL	R	48	101	-5	29	47	256	3.5	14.4	76	80	6
C	INSUL, INJECTED AIR	IA	67	43	92	18	34	518	9.3	3.7	58	31	2
C	CIRCULAR	CIRC	93	20	166	49	28	717	5.5	5.1	131	37	2
O	SMALL, BAFFLE	SB	77	143	11	216	57	299	3.3	17.5	92	72	2
C	INSULATED, CLOSED	I	152	186	119	154	67	590	5.3	14.0	116	55	2

TABLE 4-2. EFFECTINESS OF CATALYTIC AND DEEP DESIGNS USING REALISTIC FUEL.

OPEN OR CLOSED DESIGN	DESIGN TYPE SHORT NAME	DESIGN TYPE ABBR	PERCENTAGE CHANGE RELATIVE TO BASELINE FIREPLACE USING PONDEROSA PINE: AVG EFFECTS ON PM & CO RATES	EFFECT ON PM RATE	EFFECT ON CO RATE	EFFECT ON COMB RATE	PM	CO	BURN RATE (DRY)	PM	CO	RATIO AIR/ FUEL	NUMBER OF TESTS
			PCNT	PCNT	PCNT	PCNT	G/HR	G/HR	KG/HR	G/KG	G/KG		
O	DEEP, REALISTIC FUEL	DR	-62	-76	-49	-22	12	131	2.3	5.0	118	52	2
O	CAT,REALISTIC FUEL	CR	-51	-56	-46	-	21	138	5.0	4.3	54	49	2
O	BASELINE, REALISTIC FUEL	R	0	0	0	0	47	256	3.5	14.4	113	80	6

TABLE 4-3. POM RESULTS. SPECIATION IN PERCENT.

TEST NO.	102	103	104	105	109	112	115	118	121	124	127	129	132	134
DESIGN ABBREVIATION	R	R	R	R	R	D	IS	IL	CL	Ct	Ct	CT	M	D
NAPTHALENE	14.0	38.9	20.6	35.1	3.5	31.3	13.3	13.1	37.3	29.4	23.8	41.5	47.3	24.1
ACENAPHTHYLENE	48.9	49.9	57.0	59.8	88.9	36.8	71.0	53.5	28.2	44.9	37.7	16.3	18.6	0.0
ACENAPHTHENE ¦ FLUORENE ¦	15.2	5.2	14.0	2.8	2.5	24.1	14.7	31.0	32.1	23.3	31.5	30.6	31.0	65.3
PHENANTHRENE	0.6	0.1	0.4	0.6	0.2	5.0	0.2	0.6	1.5	0.9	1.4	6.1	1.2	4.8
ANTHRACENE	0.5	1.1	0.4	0.1	0.2	1.3	0.2	0.8	0.9	0.9	5.3	5.2	1.8	1.9
FLUORANTHENE	2.6	0.6	.0	0.2	.0	0.3	0.2	0.2	.0	0.3	0.1	0.1	.0	1.0
PYRENE	11.7	2.5	3.2	.0	.0	.0	0.2	0.4	0.0	.0	0.0	0.0	0.0	0.0
BENZO(A)ANTHRACENE ¦ CHRYSENE ¦	1.6	0.4	0.3	0.3	1.0	0.1	.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
BENZO(B)FLUORANTHENE ¦ BENZO(K)FLUORANTHENE ¦	0.2	.0	0.0	.0	0.1	0.2	.0	.0	0.0	0.1	0.0	0.2	0.0	0.0
BENZO(A)PYRENE	1.1	0.0	0.0	0.4	0.6	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	.0
DIBENZO(A,H)ANTHRACENE	0.0	1.0	2.5	0.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0
BENZO(GHI)PERYLENE	3.2	0.1	1.6	0.1	3.0	0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0
INDENO(1,2,3-CD)PYRENE	0.4	0.1	0.1	0.4	.0	0.0	0.1	0.1	0.0	0.0	0.2	0.0	0.0	0.0
TOTALS	100	100	100	100	100	100	100	100	100	100	100	100	100	100
TOTAL G/KG	0.5	2.4	1.2	1.9	0.9	0.4	0.9	0.6	0.4	0.3	0.2	0.4	0.25	0.45

TEST NO.	136	137	138	139	141	142	143	144	146	147	149	AVERAGE
DESIGN ABBREVIATION	D	CS	CS	CSR	CSR	GL	GL	O	O	DR	DR	
NAPTHALENE	13.8	21.8	28.0	43.0	22.7	14.6	1.6	0.5	1.9	12.8	16.5	22.0
ACENAPHTHYLENE	29.4	25.2	24.2	21.2	45.4	47.8	2.4	16.1	32.5	24.6	25.9	36.3
ACENAPHTHENE ¦ FLUORENE ¦	51.0	47.0	34.1	29.8	22.7	29.2	89.7	71.3	32.5	38.6	51.9	33.0
PHENANTHRENE	4.6	2.6	7.5	1.3	3.2	6.9	2.5	5.8	8.1	10.5	2.6	3.2
ANTHRACENE	.0	2.9	6.2	4.2	4.8	.0	1.0	5.6	2.4	9.6	3.1	2.4
FLUORANTHENE	1.2	0.4	.0	0.3	1.0	1.2	0.8	0.3	5.1	1.6	0.0	0.7
PYRENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.8
BENZO(A)ANTHRACENE ¦ CHRYSENE ¦	0.0	0.0	.0	0.0	0.0	.0	0.0	0.1	0.0	0.1	0.0	0.2
BENZO(B)FLUORANTHENE ¦ BENZO(K)FLUORANTHENE ¦	0.0	.0	0.0	.0	0.1	0.0	0.2	0.1	2.1	0.3	0.0	0.2
BENZO(A)PYRENE	.0	0.1	.0	0.1	0.1	0.1	0.0	0.2	0.0	0.4	0.0	0.1
DIBENZO(A,H)ANTHRACENE	.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	15.4	0.0	0.0	1.3
BENZO(GHI)PERYLENE	0.0	0.0	.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.4
INDENO(1,2,3-CD)PYRENE	0.0	0.0	.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
TOTALS	100	100	100	100	100	100	100	100	100	100	100	100
TOTAL G/KG	0.11	0.18	0.2	0.17	0.19	0.17	0.53	0.07	0.26	0.24	0.03	2.2

TABLE 4-4

POM AVERAGES

DESIGN	FUEL	BURN RATE kg/hr	POM RATE g/hr	POM FACTOR g/kg	NUMBER OF TESTS
Baseline	Ponderosa Pine	3.7	6.3	1.7	4
Deep	Standard	3.0	1.1	0.4	3
Catalytic	Standard	4.9	1.2	0.3	6

TABLE 5-1

STANDARD AND REALISTIC FUELS

CHARACTERISTIC	STANDARD TEST FUEL	REALISTIC FUEL IN COLORADO
Shape (cross-section)	rectangular	round and split
Spacing	1.5 inch	much less, appx. 0.5 inch
Moisture Content	16-20%	20-35%
Species	Douglas fir	Ponderosa, Aspen, Cotton-wood...
Size - Cross-Sectional area	5 - 12 sq. in.	5 - 30 sq. in.

Realistic fuel properties are estimates, not based on any careful survey or measurements.

TABLE 8-1

AVERAGE EMISSIONS FACTORS AND RATES. Ponderosa pine in a conventional open factory-built fireplace:

	BURN RATE (dry) kg/hr	EMISSION FACTOR g/kg	EMISSION RATE g/hr	NUMBER OF TESTS
PM	3.5	14.4	47	6
CO	3.5	76	256	6
POM	3.7	1.7	6.3	4