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THE PERFORMANCE OF A DOUBLE-WALL PREFABRICATED METAL CHIMNEY FOR OIL-FIRED RESIDENTIAL HEATING APPLICATIONS

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by

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ABSTRACT

The overall heat transfer coefficient of a double-wall prefabricated metal chimney has been measured under experimental conditions duplicating those occurring in residential practice. Calculations using the measured U-value of 0.46 Btu/ft^{2}hr°F show that the thermal and draft performance of the chimney will be substantially the same for chimneys erected inside a building or on the outside wall.

The maximum chimney capacity at internal wall temperatures above the acid dewpoint is above 1 US gph for chimney heights greater than 10 ft and diameters larger than 6 in.;for chimney dimensions greater than these minimum values a draft of 0.04 in. WC (or higher) can be achieved at furnace efficiencies of 79%.

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INTRODUCTION

The design of natural draft chimneys for use with oil-fired domestic heating appliances involves balancing the force which tends to produce flow against those which tend to retard flow. The force producing flow is a buoyancy due to the density difference between the hot flue gases and the ambient air; the forces retarding flow are the fractional forces between the flue gases and the walls of the chimney. Calculation of the buoyancy force or theoretical draft demands a knowledge of the mean flue-gas temperature within the chimney which, in turn, requires that the inlet gas temperature, the overall heat transfer coefficient of the chimney structure and the chimney dimensions are known.

As part of an investigation of oil-fired domestic heating systems at the Canadian Combustion Research Laboratory the thermal performance characteristics of a prefabricated double-wall chimney (Figure 1) were measured. An empirical equation was developed from measured data to allow prediction of chimney performance in terms of internal and external metal temperatures as well as maximum chimney capacity.

OBJECTIVES

The overall heat transfer coefficient or "U" value of a prefabricated double-wall chimney is an essential parameter in the calculation of chimney performance and is usually the least well-defined. The 1972 ASHRAE Equipment Guide and Data Book quotes a range of "U" values for this type of chimney construction.

Double Wall Gas Vent ¼ in. air gap	$U = 0.15$ to 0.86 Btu/ft^{2}hr°F
Double Wall Gas Vent ½ in. air gap	$U = 0.37$ to 1.04 Btu/ft^{2}hr°F

Data presented by Gills and Etoc[1] on the performance of aluminum clad chimneys (Figure 2) suggest that the U-value lies between 0.4 and 0.6 Btu/ft^{2}hr°F depending on the flue gas velocity. At a normal flue gas velocity of 5 ft/sec, encountered in residential heating where the chimney diameter is normally less than eight inches, a typical U-value is 0.4 Btu/ft^{2}hr°F as shown in Figure 2. The range of U-values quoted in the literature indicated that the primary objective was to measure a U-value for the chimney under conditions representative of residential operation.

The use of prefabricated double-wall chimneys with stainless-steel inner surfaces is at present limited (for oil-fired applicances) to 6 in. diameter or less and to flue gas temperatures below 575°F; there is limited experience of the durability of these chimneys under a variety of operating conditions. The reason for the temperature and diameter restrictions is not apparent when the inner wall is stainless steel, unless the manufacturer is concerned about heat conduction through the inner wall. A secondary objective of the investigation was to accumulate some information on the durability of these chimneys over a range of flue gas temperatures and over a prolonged period of time.

THE EXPERIMENTAL CHIMNEY

Instruments capable of continuously monitoring flue gas composition, temperature and mass flow rate were installed on an experimental chimney at the locations illustrated in Figure 3. Throughout the course of a three-year program a total of 24 oil-fired heating systems were vented through the chimney, one at a time,over a period of 2500 hours which is considered equivalent to approximately 5000 hours of regular cyclic operation in a home.

1/ Design and Performance of Aluminum-Clad Chimneys. P. Etoc and B. G. Gills J. Inst Fuel 1969 42 104-111.

THE OVERALL HEAT-TRANSFER COEFFICIENT (U-VALUE)

The chimney U-value can be calculated with a sufficient degree of accuracy by the equation derived in Appendix A.

$$U = \frac{W \cdot C_p \cdot \left(Tx - Ty\right)}{A \cdot \left(\frac{Tx + Ty}{2}\right) - T_{amb}}$$

Where

W = Mass flow rate of flue gas, lb/hr

A = Exposed surface area of chimney between locations x and y, ft^2

Tx = Flue gas temperature at location x, °F

Ty = Flue gas temperature at location y, °F

Cp = Mean specific heat of flue gas at a mean temperature given by: $\left(\frac{Tx + Ty}{2}\right)$, Btu/lb

T_{amb} = Ambient air temperature, °F

U-values may be calculated by applying measured data of flue gas composition, firing rate and gas temperature to this equation.

The data from a series of tests were used to calculate the U-values given in Table 1. In the calculations, no attempt was made to accommodate differences in heat transfer due to the off-vertical angle of some sections of the chimney; errors attributed to this omission will be less than 5%.

The mean value of the overall heat-transfer coefficient was found to be 0.46 $Btu/ft^2hr°F$.

EXTERNAL AND INTERNAL METAL TEMPERATURES

U-values determined above were used to predict external and internal metal temperatures along the chimney using the numerical procedure described in Appendix A-3. The results of this calculation are presented in Figures 4 and 5 where a comparison is shown with measurements of external wall temperature made with an Alnor surface thermocouple. The predicted outside metal temperatures are consistently 20°F above the measured values and the downstream gas temperatures predicted from known input conditions are consistently 15°F higher than the measured gas temperatures. Figure 6 shows a comparison of measured internal and external metal temperatures with a correlation derived from the experimentally determined U-value.

The experimentally determined U-value can be used to predict the temperatures of the inner and outer metal walls of the chimney to within 20°F.

CHIMNEY DESIGN CALCULATIONS

Internal Wall Metal Temperatures

The internal wall temperatures for a range of flue-gas temperatures are shown in Figure 7. These were calculated as described in Appendix A-2. The correlation shown is for a normal flow velocity of 5 ft/sec in a 6 in. diam chimney but will not change significantly as the velocity changes within the range normally encountered in domestic practice.

When a metal temperature of 300°F is necessary to prevent acid condensation on the inner wall, the gas temperature must be maintained above 375°F throughout the chimney. For all subsequent calculations of chimney performance an exit gas temperature of 375°F was selected as a standard. Figure 8 shows the gas temperatures at the chimney base which will meet this condition for a range of chimney heights.

Current CSA standards for oil-fired equipment require that the flue gas temperature at the chimney base shall be above 350°F when less than 40% of the chimney is external and above 400°F when more than 40% of the chimney is external.

Chimney Draft

For natural-draft chimneys the available draft at the chimney base may be calculated from a general formula[2/].

$$\Delta h = \frac{1}{5.2} \cdot H.(\rho a - \rho m) - (1 + 0.09 \frac{H}{D}) \frac{V^2 \rho m}{2g}$$

where

	h	=	Available draft, in. WC
	ΔH	=	Chimney height, ft
	D	=	Internal chimney diameter, ft
	ρa	=	Density of ambient air, lb/ft^3
	ρm	=	Density of chimney gas at the mean chimney temperature; lb/ft^3
	V	=	Velocity of chimney gas at density ρm, ft/sec
	g	=	Gravitational constant; 32.2 ft/sec

This formula was used to calculate the theoretical draft that is available from internal and external double-wall chimneys under different mass flow conditions. The flue gas entry temperature that would maintain the inner metal temperature above 300°F was incorporated into the calculation. The results of this calculation, presented in Table 2, show that an inlet gas temperature of 470°F will maintain an available draft at the chimney base of 0.05 in. WC and that the differences due to location of the chimney (internal or external) are small. The available draft at the chimney base must be modified to take account of bends in the flue pipe between the appliance and the chimney base. This can be done by subtracting from the calculated Δh, a flow loss term equal to $\frac{k\ V}{5.2(2g)}$ where k is a resistance coefficient (velocity heads, dimensionless) taken from Table 3.

When three right angle bends are included in the flue pipe between the furnace outlet and the chimney base then the available draft at the appliance is reduced to the levels presented in Table 4 and illustrated in Figure 9. Figure 9 has

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[2/] Technical Data on Fuel: Ed H.M. Speirs. Pub World Power Conference 1962.

been used to specify a maximum chimney capacity by selecting a minimum acceptable available draft of 0.04 in. WC. The chimney capacity in lb/hr can be read directly from this figure for chimney heights of 10, 16, 20 and 30 ft; the chimney capacity for intermediate heights can be determined by interpolation.

Mass flow is a function of the firing rate and excess-air level and it determines the lower limit of flue-gas temperature. If an allowance is made for a temperature drop of the flue gas between the appliance and the chimney base, these same gas properties define the maximum furnace efficiency which must not be exceeded if the chimney design conditions are to be met.

Table 5 presents the maximum chimney capacities and maximum furnace efficiencies that meet all the chimney design criteria for a range of chimney diameters with the same construction as the one used in this investigation. It can be seen that this chimney structure is capable of providing a draft greater than 0.04 in. WC at a moderate gas temperature, thereby accommodating high furnace operating efficiency.

Chimney Durability

The chimney showed no signs of physical deterioration on either the internal or external surfaces over a period of three years despite unusual experimental conditions when flue gas temperature reached as high as 700°F although, for the major proportion of operating time, the flue gas temperature was below 600°F. At least one oil spillage occurred in an experimental furnace which produced a flue-gas temperature in the order of 1000°F for a period of 20 seconds.

CONCLUSIONS

The overall heat transfer coefficient of a 6 in. diam double-wall prefabricated metal chimney having a ½ in. air gap between walls is 0.46 Btu/ft^{2}hr°F.

The low overall heat-transfer coefficient of the chimney indicates that its thermal and draft performance are only marginally affected by installation inside or outside a heated building.

Rational selection of diameter and height will permit this type of chimney structure to be used in the majority of residential applications where a draft capacity of 0.04 in. WC is required. For furnaces having inputs below 300,000 Btu/hr this can be achieved with a flue-gas temperature below 500°F.

TABLE 1

Overall Heat-Transfer Coefficients

Mass Flow lb/hr	Mean Gas Temperature °F	Overall Heat Transfer Coefficient (U) Btu/ft^{2}hr°F
278	317	.56
	301	.39
	301	.43
	301	.42
	307	.43
	290	.24
210	424	.38
	428	.47
	403	.29
	386	.56
	391	.56
	388	.48
	380	.61
	384	.58
	383	.52

Mean U-Value 0.46

TABLE 2

The Maximum Available Draft From the Experimental Chimney

Mass Flow In Chimney lb/hr		Chimney Dimensions Height ft	Chimney Dimensions Diameter ft	Minimum Internal Wall Temperature °F	Gas Temperature Inlet °F	Gas Temperature Exit °F	Temperature Surrounding Chimney °F	External Temperature °F	Maximum Available Draft in. WC
	A			300	462	375	70	32	0.069
100	B	10	0.5	300	488	375	32	32	0.071
	C			294	462	359	32	32	0.069
	A	20	0.5	300	585	375	70	32	0.151
100	B			300	632	375	32	32	0.155
	C			287	585	351	32	32	0.147
	A	30	0.5	300	713	375	70	32	0.239
100	B			300	805	375	32	32	0.260
	C			275	713	335	32	32	0.239
	A		0.5	300	408	375	70	32	0.055
200	B	10		300	429	375	32	32	0.055
	C			294	408	360	32	32	0.053
	A		0.5	300	510	375	70	32	0.187
200	B	30		300	550	375	32	32	0.193
	C			290	510	354	32	32	0.187
	A		0.5	300	394	375	70	32	0.033
300	B	10		300	412	375	32	32	0.036
	C			297	394	364	32	32	0.033
	A		0.5	300	457	375	70	32	0.137
30	B	30		300	485	375	32	32	0.145
	C			292	457	357	32	32	0.137

A is an internal chimney with all metal temperatures above 300°F
B is an external chimney with all metal temperatures above 300°F
C is an external chimney with the same chimney base temperature as A

TABLE 3

Resistance-Loss Coefficients k Values

Component	Resistance Loss Coefficient (Velocity Heads) Suggested Design Value	Estimated Span and Notes
Inlet--Acceleration		
Gas vent with draft hood	1.5	1.0 to 3.0
Barometric regulator	0.5	0.0 to 0.5
Direct connection	0.0	Also dependent on blocking damper position
Round elbow, 90°	0.75	0.5 to 1.5
Round elbow, 45°	0.3	
Tee or 90° breeching	1.25	1.0 to 4.0
Y breeching	0.75	0.5 to 1.5

TABLE 4

The Effect of Three Right-Angle Bends On Available Draft at the Appliance

Mass Flow in Chimney lb/hr	Chimney Dimensions Height ft	Chimney Dimensions Diameter ft	Maximum Available Draft, in. WC At Chimney Base	Maximum Available Draft, in. WC At Appliance
100	10	0.5	0.069	.063
	16	0.5	0.117	.111
	20	0.5	0.151	.145
	30	0.5	0.239	.233
200	10	0.5	0.055	.034
	16	0.5	0.092	.071
	20	0.5	0.120	.099
	30	0.5	0.187	.166
300	10	0.5	0.033	-0.012*
	16	0.5	0.065	0.020
	20	0.5	0.084	0.039
	30	0.5	0.137	0.092

*Of the examples quoted this is the only condition which will result in a pressure at the appliance outlet.

TABLE 5

Maximum Chimney Capacities, Firing Rates and Furnace Efficiencies

Chimney Height ft	Chimney Diameter ft	Acceptable Maximum Chimney Flow Rates lb/hr	Furnace Operation: Maximum* Firing Rate US gph	Furnace Operation: Maximum** Furnace Efficiency %
10	6	180	1.11	82
16	6	270	1.67	81
20	6	300	1.86	80
30	6	350	2.17	79
10	7	380	2.35	79
16	7	480	2.97	79
20	7	520	3.22	78
30	7	590	3.65	77
10	8	400	2.48	79
16	8	560	3.47	79
20	8	640	3.96	78
30	8	750	4.64	77

*This has been calculated at a CO_2 level of 10% (v/v;dry)

**This has been calculated to meet the requirements of the external chimney with a minimum internal wall temperature of 300°F; it has been assumed that the temperature drop between the furnace outlet and the chimney base is 50°F and that the indoor air temperature is 70°F.

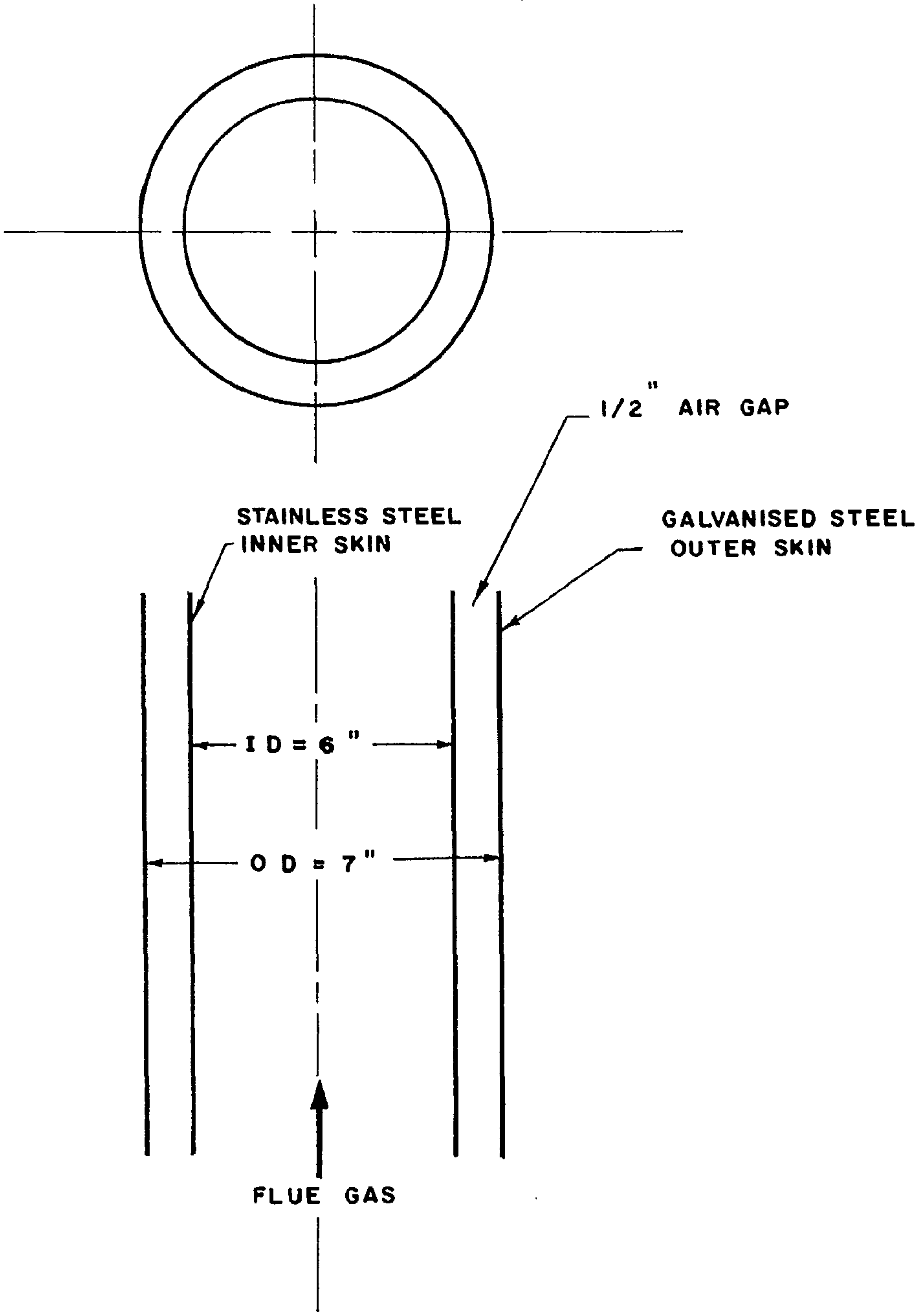

Figure 1. Construction of the double-skin prefabricated chimney.

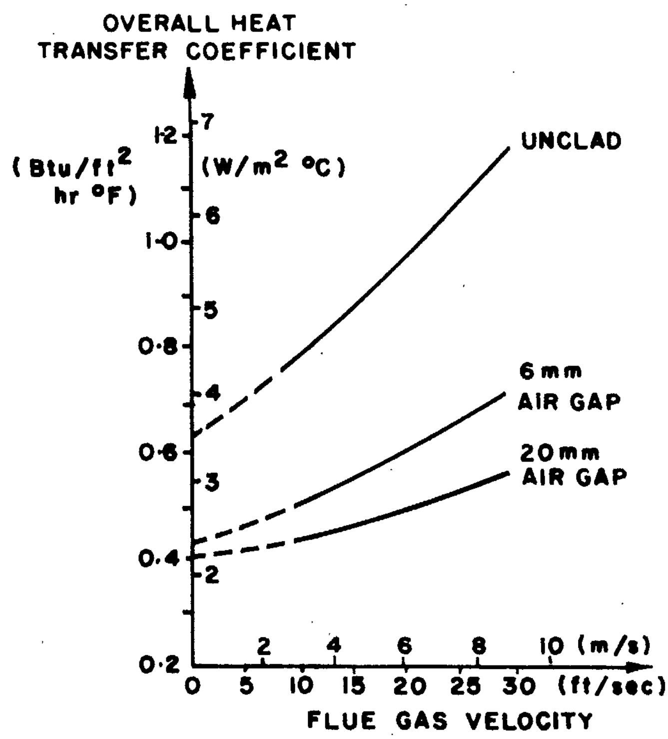

Figure 2. Overall heat-transfer coefficients plotted against flue gas velocities (after Gills and Etoc;Reference 1).

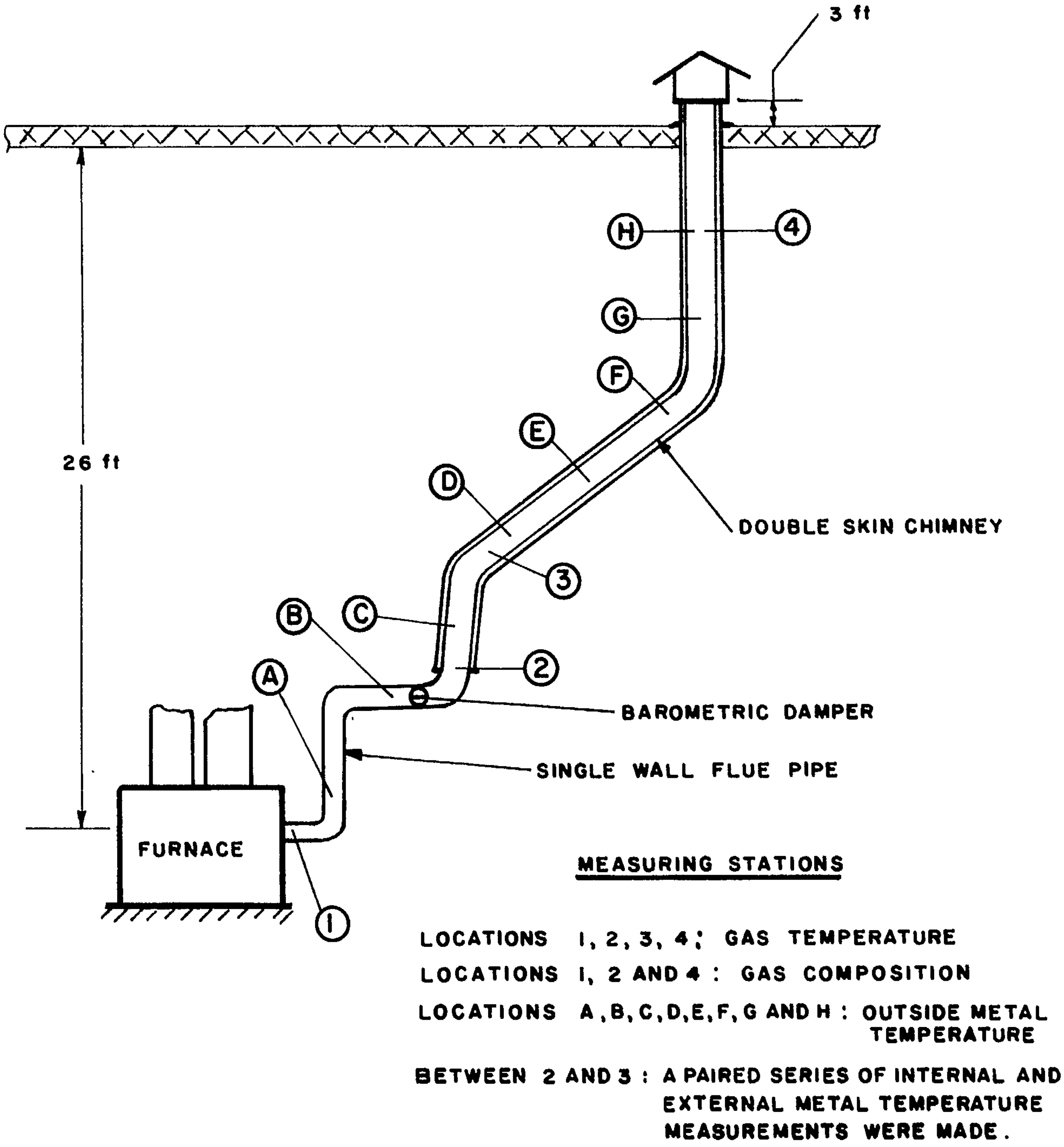

Figure 3. Measuring locations on the experimental double-skin chimney system.

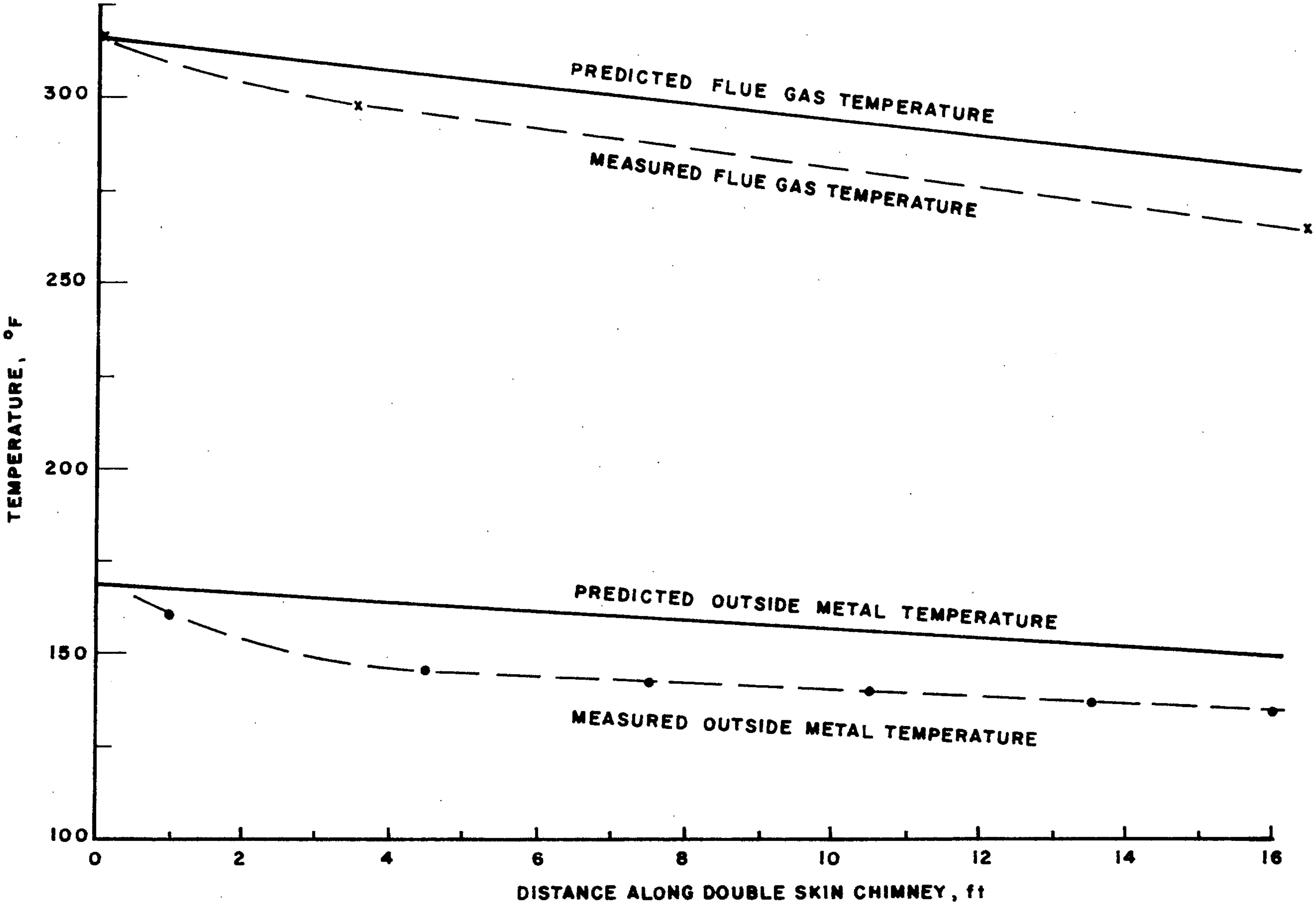

Figure 4. A comparison of predicted and measured flue-gas temperatures and external metal surface temperatures. Mass flow rate 210 lbs/hr.

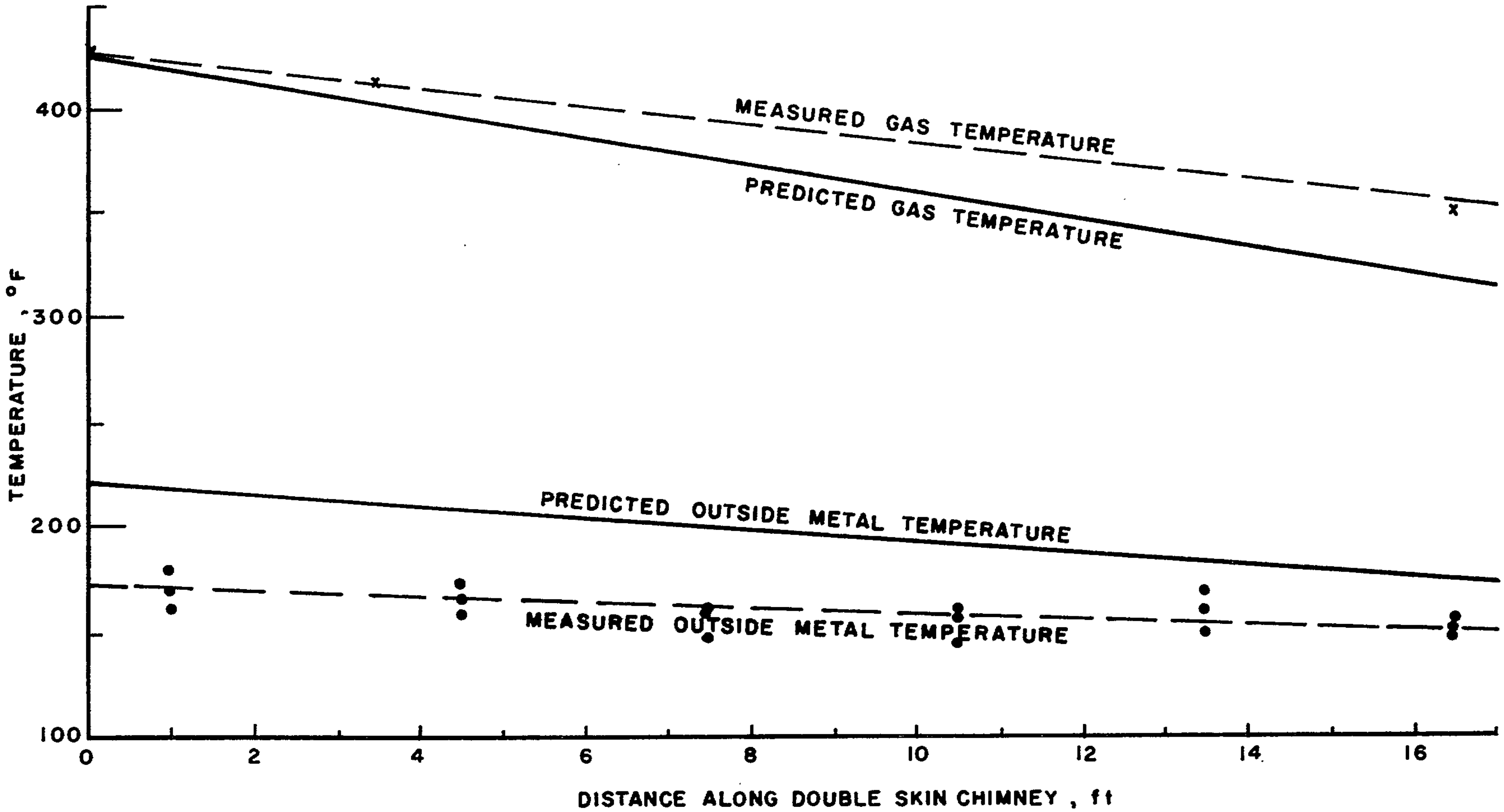

Figure 5. A comparison of predicted and measured flue-gas temperatures and external metal surface temperatures. Mass flow rate 280 lbs/hr.

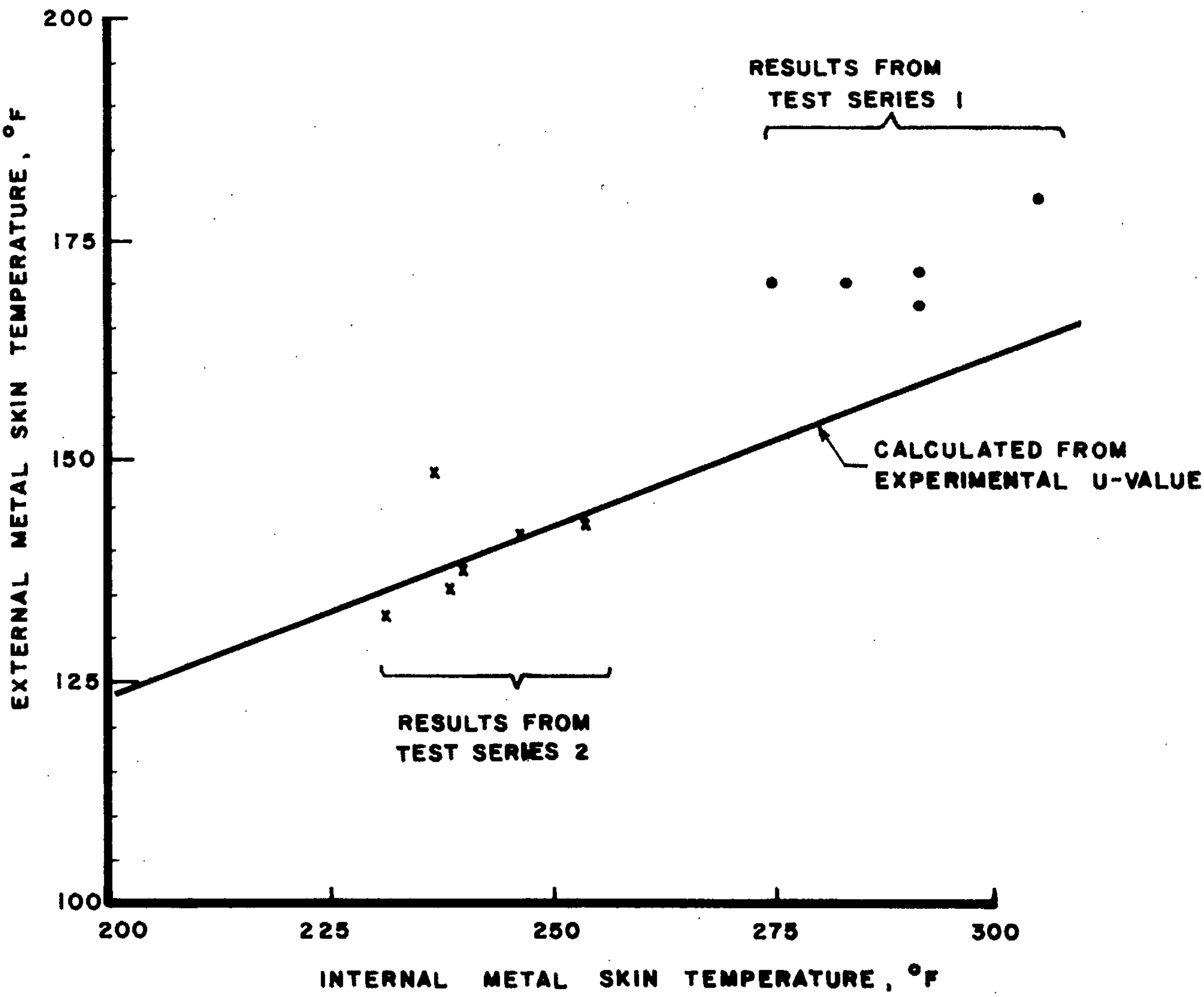

Figure 6. A comparison of predicted and measured internal and external metal skin temperatures.

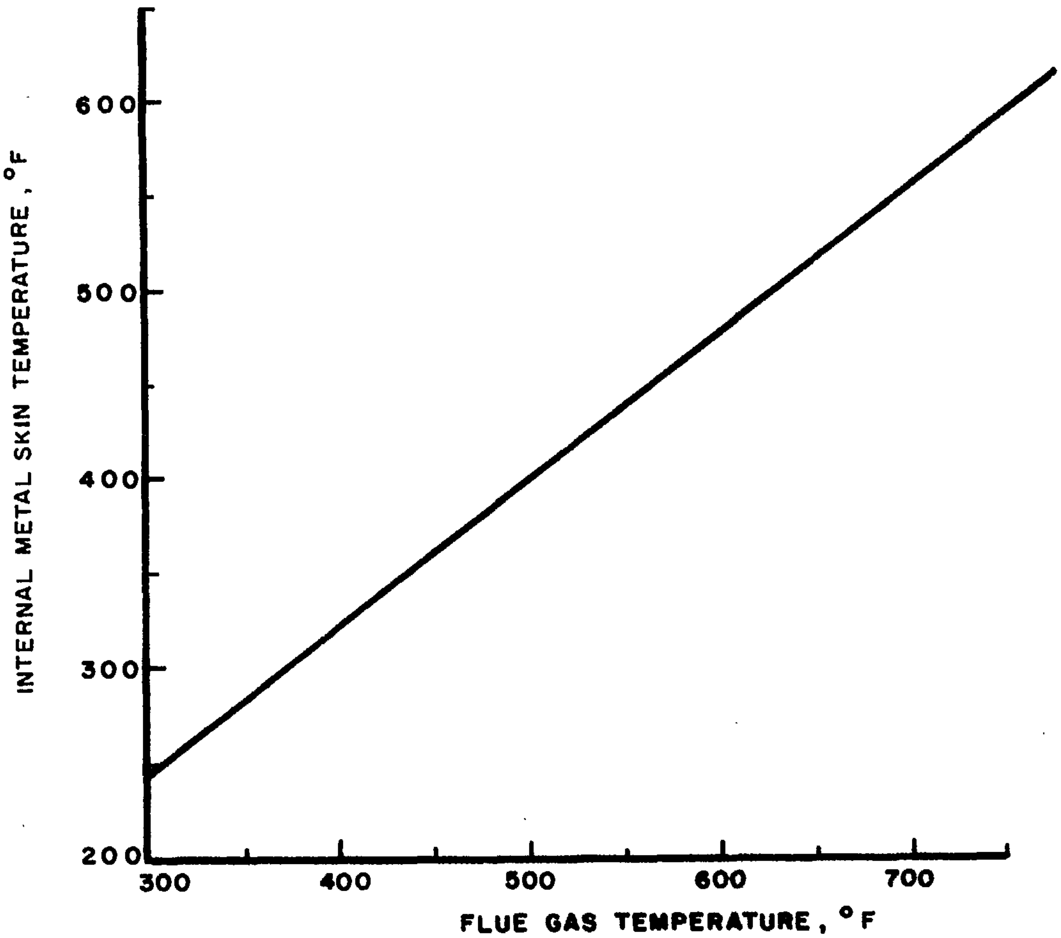

Figure 7. The effect of flue gas temperature on internal metal skin temperature. Mass flow rate 250 lbs/hr, equivalent to 1.25 US gph at 8% CO_2 no dilution.

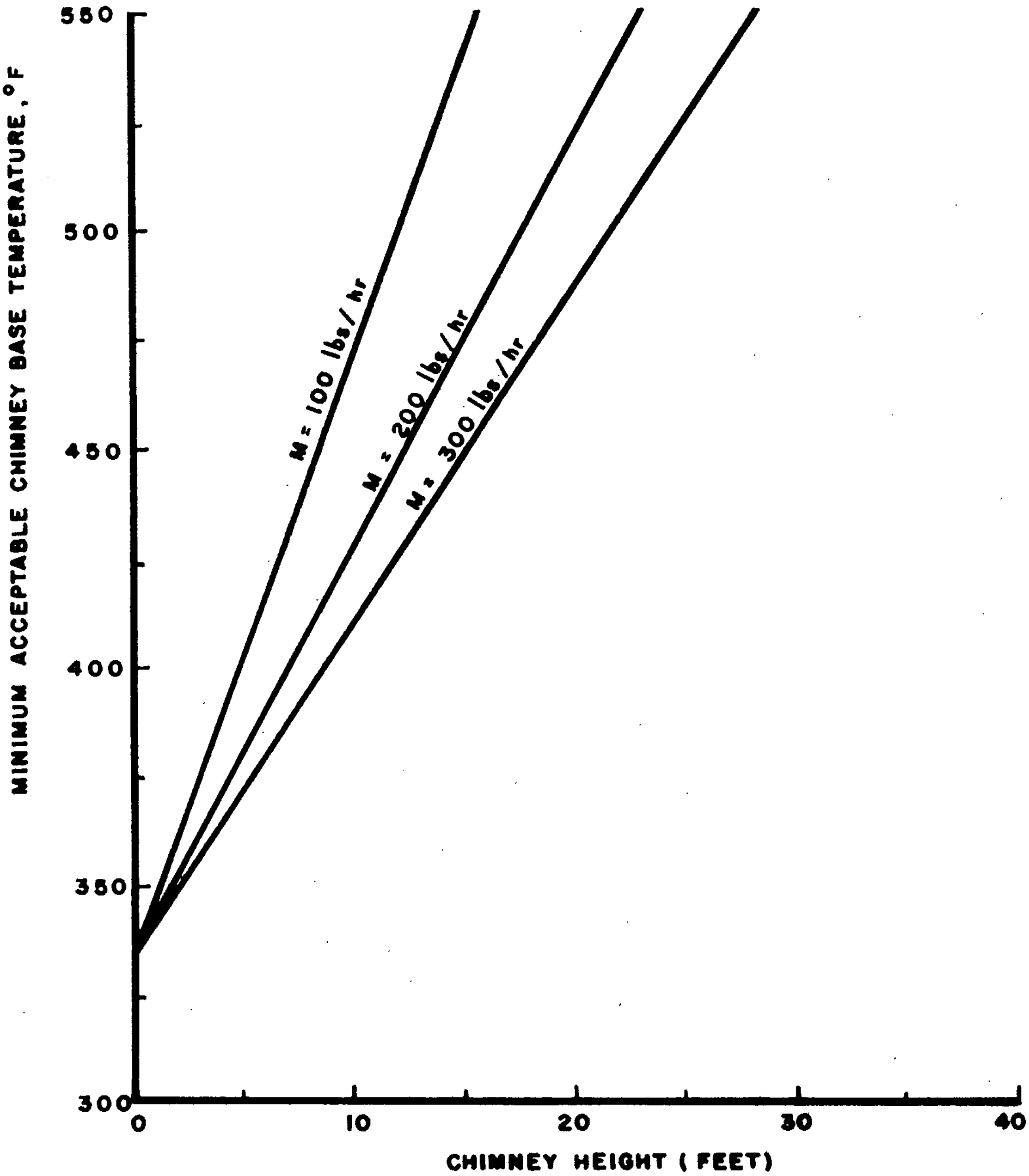

Figure 8. The effect of chimney height on the minimum acceptable entry gas temperature.

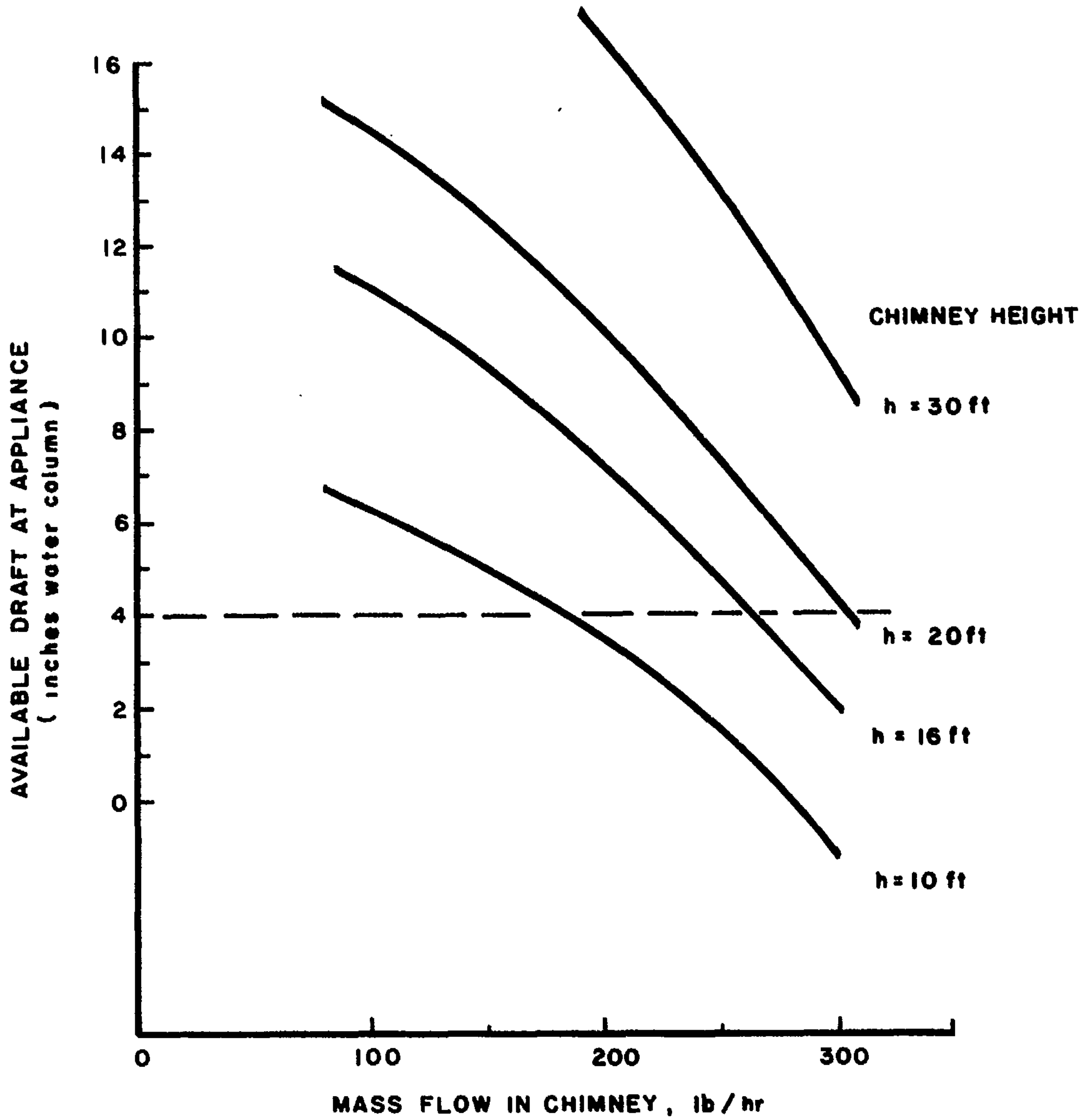

Figure 9. The effects of mass flow and chimney height on available draft (chimney diameter 6 in., 3 right-angle bends between chimney base and appliance).

APPENDIX A

Calculation Procedures

In the treatment of the experimental data to calculate the overall heat transfer coefficient and surface metal temperatures it was assumed that:

a) No air infiltration occurred after the barometric damper.

b) Arithmetic mean temperature differences could be used for heat-transfer calculations with a sufficient degree of accuracy.

A-1 Nomenclature

U = Overall heat-transfer coefficient of the chimney structure.

L = Length of chimney pipe.

A = Area per foot run of chimney.

W = Mass flow rate of combustion products in the chimney.

C_p = Specific heat of combustion products.

h_o = External surface heat-transfer coefficient.

h_i = Internal surface heat-transfer coefficient.

h_c = External surface convective heat-transfer coefficient.

h_r = External surface radiant heat-transfer coefficient.

k = Thermal conductivity of combustion products.

T_{amb} = Ambient external air temperature.

T_g = Temperature of combustion products.

T_{mi} = Internal surface metal temperature.

T_{mo} = External surface metal temperature.

T_x, T_y = Temperature of combustion products at location x, y respectively.

σ = Stefan Boltzman constant.

ξ_{mo} = Surface emissivity of the external chimney surface.

ξ_{surr} = Emissivity of the surroundings of the chimney.

A-2 Calculation of the Overall Heat-Transfer Coefficient

The heat lost by the combustion products (Q_1) during their movement between two planes x and y separated by a distance L is given by:

$$Q_1 = W. C_p. (T_x - T_y)$$

The heat lost from the external surface of the chimney (Q_2) between the same two planes is given by:

$$Q_2 = \left[U.L.A. \left(\frac{T_x + T_y}{2}\right)\right] - T_{amb}$$

Under steady conditions $Q_1 = Q_2$

$$U = \frac{W. C_p. (T_x - T_y)}{A. \left(\frac{T_x + T_y}{2}\right) - T_{amb}}$$

This equation was used to calculate the U value from experimental measurements of T_x, T_y, T_{amb} and W.

A-3 Calculation of Internal and External Wall Temperatures of the Chimney Structure

a) Internal Wall Temperature

If we consider a short element of a chimney ΔL the combustion product temperature difference between the exit and entry planes can be neglected, the heat loss from the element (Q_3) is given by

$$Q_3 = U.A.\Delta L. (T_g - T_{amb})$$

The heat transferred from the combustion products to the internal wall (Q_4) is given by:

$$Q_4 = h_i . A . \Delta L . (T_g - T_{mi})$$

Under steady conditions $Q_3 = Q_4$ and

$$T_{mi} = T_g - \frac{U}{h_i} . (T_g - T_{amb})$$

The value of h_i may be calculated from the flow conditions

$$h_i = \frac{0.02.k.}{D} (Re)^{0.8}$$

when $Re > 3000$

Under these experimental conditions h_i has a value of 1.9 $Btu/ft^2hr°F$.

$$T_{mi} = T_g - \frac{U}{1.9} . (T_g - T_{amb})$$

b) <u>External Wall Temperature</u>

In an analogous way to that described above for the internal wall temperature, the external wall temperature can be calculated by equating the total heat lost through a chimney element (Q_3) with the heat lost from the external surface (Q_5).

$$Q_3 = U.A.\Delta L . (T_g - T_{amb})$$

$$Q_5 = h_o.A.\Delta L . (T_{mo} - T_{amb})$$

$$T_{mo} = \frac{U}{h_o} . (T_g - T_{amb}) + T_{amb}$$

The external surface coefficient has a radiant and a convective component (h_r and h_i respectively) which may be calculated as follows:

$$h_r = \left[\frac{\sigma T_{mo}^4 - \sigma T_{amb}^4}{T_{mo} - T_{amb}}\right]\left[\frac{1}{\frac{1}{\xi_{mo}} + \frac{1}{\xi_{surr}} - 1}\right]$$

For the range of conditions used in these experiments

$$h_r = 0.1 \quad Btu/ft^2hr^\circ F$$

$$h_c = \frac{0.3(c)(T_{mo} - T_{amb})^{1.25}}{T_{mo} - T_{amb}}$$

For vertical surfaces (c) is equal to unity; and for the range of conditions used in these experiments $(T_{mo} - T_{amb})$ is close to 100 F.

$$h_c = 0.95 \quad Btu/ft^2hr^\circ F$$

The external surface coefficient (h_o) is the sum of radiant and convective components.

$$h_o = 1.05 \quad Btu/ft^2hr^\circ F$$

and the external wall temperature is therefore given by

$$T_{mo} = \frac{U}{1.05}(T_g - T_{amb}) + T_{amb}$$

A-4 Minimum Internal Metal Temperature

The minimum internal metal surface temperature occurs at the chimney outlet. The metal surface temperature distribution throughout the chimney length can be calculated by considering heat balances over consecutive chimney sections such that the surface area of each section is 1 sq ft. The outlet conditions for the first element become the inlet conditions for the second element and the procedure is repeated until the number of elements has reached the chimney height.

The calculation can also be carried out in reverse, i.e. from the chimney outlet towards the chimney base, with the advantage that a minimum internal metal surface temperature of 300°F can be imposed. When this is done the output from the calculation is the minimum acceptable gas temperature at the chimney base which will maintain all the internal metal surfaces above 300°F.

The heat lost from the first section (Q) is given by:

$$Q = U.\ p.\left[\left(\frac{T_i + T_o}{2}\right) - T_{amb}\right]$$

and also by

$$Q = W.C_p.\ (T_i - T_o)$$

$$U\ \left[\left(\frac{T_i + T_o}{2}\right) - T_{amb}\right] = W.C_p.\ (T_i - T_o)$$

$$T_o = T_i.\left[\frac{2\ W.C_p - U}{2\ W.C_p + U}\right] + \left[\frac{2\ T_{amb}\ U}{2\ W.C_p + U}\right]$$

The internal surface metal temperature at the outlet from the first section is given by:

$$T_{mi} = T_o - \frac{U\ (T_o - T_{amb})}{1.9}$$

The external surface metal temperature at the outlet from the first section is given by:

$$T_{mo} = \frac{U}{1.05} \cdot (T_o - T_{amb}) + 70$$

The procedure is now repeated for the second element using the calculated value of T_o as the new input condition.