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DEVELOPMENT OF COMBUSTION DATA TO UTILIZE LOW-Btu GASES AS INDUSTRIAL PROCESS FUELS

Project 61004 Special Report No. 7

PREMIX TUNNEL BURNER

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ABSTRACT

Data were gathered to determine the performance of a premix tunnel burner when retrofit with three low-Btu fuel gases. The burner was fired on the IGT pilot-scale test furnace with a load simulating one zone of a continuous melting pot or one instant during the heat-up of a batch melter. The low-Btu fuel gases used for these combustion trials were Koppers-Totzek oxygen, Wellman-Galusha air, and Winkler air. All of the low-Btu fuel gases exhibited stable flames when directly retrofit on the burner except Winkler air, which required a pilot flame to prevent blowoff. Koppers-Totzek oxygen gave a thermal efficiency somewhat greater than that for natural gas, while both Wellman-Galusha and Winkler air fuel gases were significantly lower. All of these fuel gases had flame lengths that were longer than that for natural gas.

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OBJECTIVE

The use of low-Btu gases is a promising way for industry to meet its need for an environmentally acceptable fuel to supplement or replace natural gas and oil. Information is needed, however, to determine the extent of the problems of utilizing these fuels on existing equipment. This program is designed to develop the combustion data necessary to evaluate the feasibility of converting existing process heating equipment to the use of low-Btu gases.

Eight types of industrial burners are being tested during the program using three different low-Btu gases. The performance of each burner with these gases will be compared to its performance with natural gas in terms of flame stability and shape, furnace efficiency, heat-absorption profile, noise level, temperature profiles, radiant heat flux, post-flame emissivity, and flow direction.

INTRODUCTION

The relative availability of coal makes it desirable to utilize coal as an energy source for more industrial processes. However, for technical or environmental reasons, many processes are not able to directly fire coal. The conversion of coal to a low-sulfur, ashless, low-Btu gas for use in boilers and industrial heating processes could solve the environmental and energy supply problems. Of particular concern, however, are the potential furnace operating problems or losses in production when a facility originally designed to use natural gas is retrofit to use low-Btu gas. This program was developed to gather the combustion data necessary to evaluate the feasibility of converting existing process heating equipment to use low-Btu gases.

Combustion data will be gathered for eight types of industrial burners with three low-Btu gases in order to evaluate the magnitude of the retrofit problem. The three fuel gases are Koppers-Totzek oxygen, Wellman-Galusha air, and Winkler air. The eight types of burners are forward flow, kiln, nozzle mix, high forward momentum, flat flame, high excess air, premix tunnel and boiler burner. The firing level and load configuration on the IGT pilot-scale furnace will be adjusted to simulate a furnace on which each burner is typically found. The following data will then be collected.

- Rate of gas and air flow into the burner
- Combustion air preheat temperature
- Velocity of fuel and air at burner outlet
- Flue-gas temperature
- Volume of flue gases
- Flue-gas species concentrations
- Heat absorption profile
- Resonance noise level
- Flame length measurements and photographic documentation of the flame
- Flame-width measurements
- Furnace efficiency
- Radiant heat flux from the flame
- Radiant heat flux across the furnace
- Post flame emissivity

- Average flame temperature at six axial and ten radial positions along the furnace center line
- Flow-direction profile.

This report presents the results of combustion trials using a Maxon Series SN Sealed Nozzle burner, which is representative of the premix tunnel burner type. The burner size and firing rate were chosen to simulate the firing density (Btu/CF-hr) in a nonferrous pot melter.

While firing natural gas, the furnace load was adjusted to absorb the same fraction of the furnace heat input that occurs in one section of a continuous melter or one instant during the heat-up of a batch melter. Data were collected for natural gas firing and then for each of the three low-Btu gases. The following sections describe the furnace facility, test equipment, experimental procedures, and results.

FACILITIES

Description of Furnace Test Facility

The experimental work is being carried out in the pilot-scale furnace, shown in Figure 1. It is 14 feet long and has a cross-sectional area of 21.3 sq ft. The facility can be used for firing burners rated up to 6 million Btu/hr. Combustion air temperatures up to 1000°F can be generated with a separately fired air preheater.

The furnace is also equipped with 58 water cooling tubes, each of which can be independently inserted through the roof, along the sidewalls. Varying the number of tubes, their location, and the depth of insertion allows control over the magnitude and character of the load that can be placed on the furnace. The amount of heat absorbed by each tube can be determined by measuring the water flow through each tube and the temperature difference between the inlet and outlet. The water temperature measurements are made with a Vertronix digital thermometer. The stated accuracy is 0.25°F. These measurements were checked with a mercury-in-glass thermometer, accurate to 0.1°F, and were found to agree within 0.2°F. A temperature difference of 25°to 60°F was maintained between the water inlet and outlet. This helped minimize the effect of temperature measurement error on the heat balance. The water flow rate from each tube was determined by measuring the time to fill a bucket of known capacity The time was measured using a quartz digital stopwatch.

In addition to the combustion air preheater, a separately fired fuel preheater is available that can heat 12,000 SCF/hr of low-Btu gas to any desired temperature up to 800°F. Temperatures up to 1200°F are attainable with lower flow rates.

The overall system, shown in Figure 2, has the flexibility to independently vary—

- Fuel firing rate
- Air input
- Furnace load
- Air preheat temperature
- Fuel preheat temperature.

There are 33 panels or "sampling doors", shown in Figure 1, along one sidewall that allow insertion of probes at any axial position from the burner wall to the rear wall.

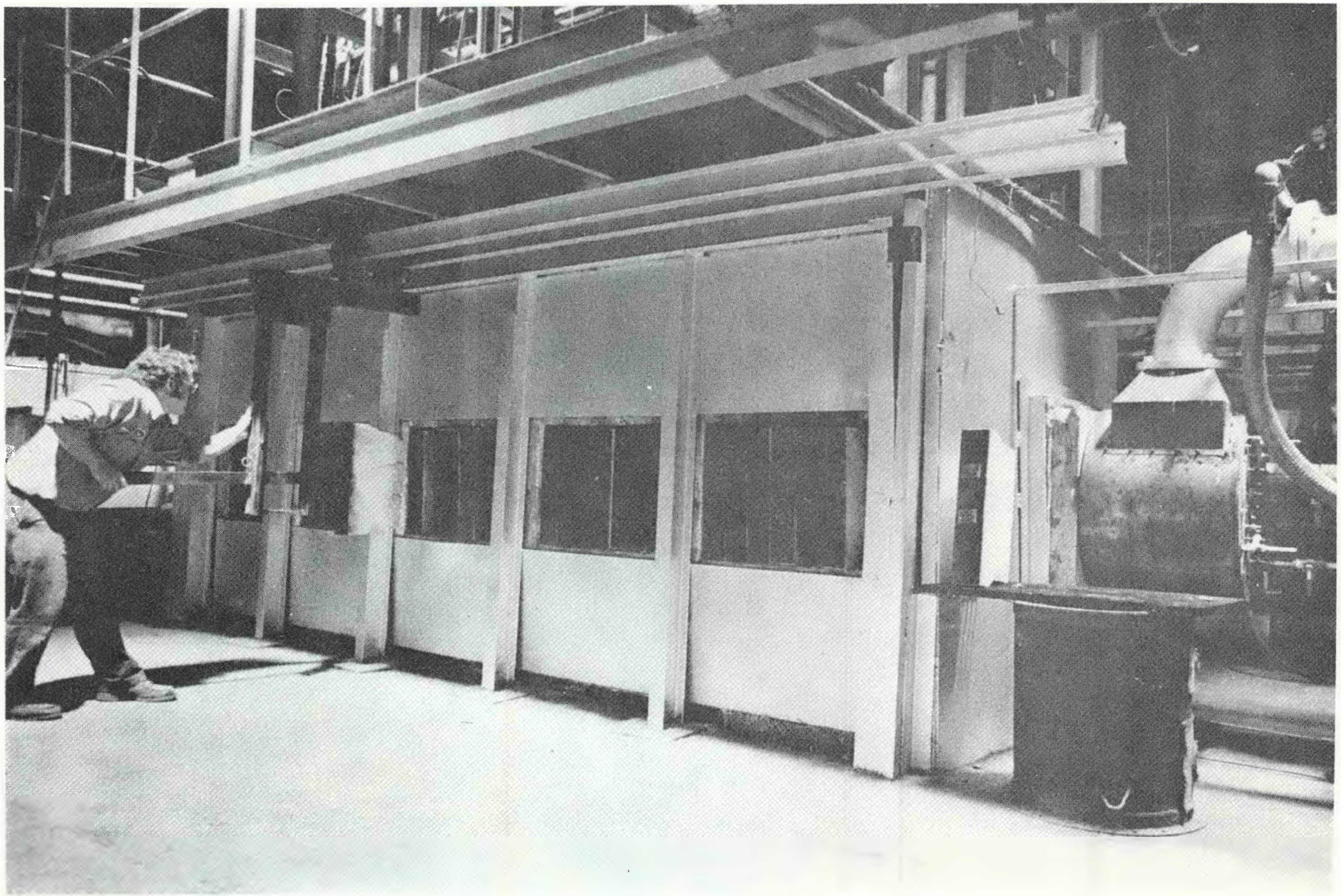

Figure 1. PILOT-SCALE TEST FURNACE

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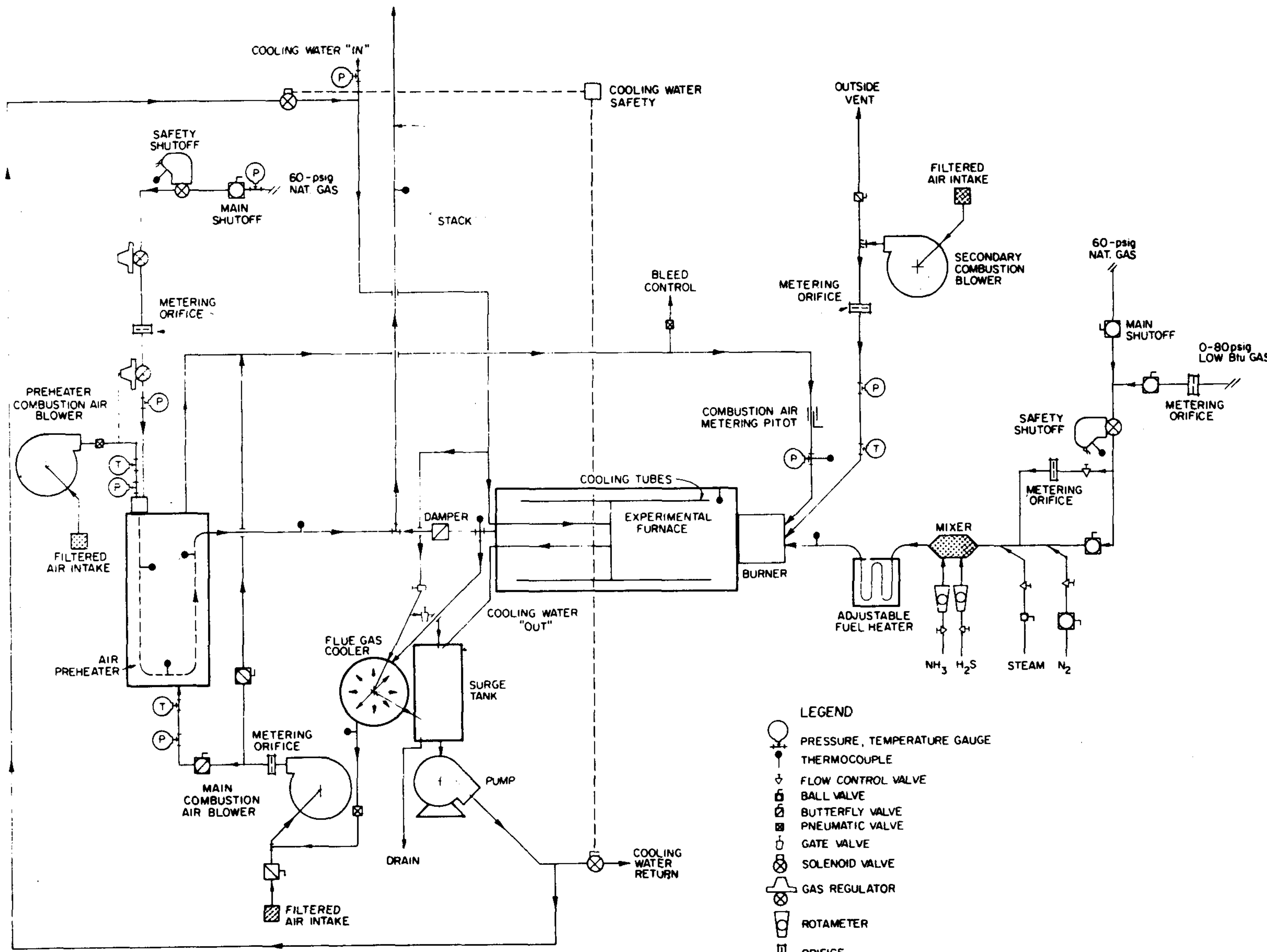

Figure 2. OVERALL FURNACE SYSTEM

Description of the Low-Btu Gas Generating System

The low-Btu gases are generated using a special gas generating and fuel preparation facility. The critical items are the special gas generators or reformers that can produce varying ratios of hydrogen and carbon monoxide. Natural gas, carbon dioxide, and steam are passed through reaction retorts contained in a vertical cylindrical furnace. The catalyst-filled retorts are heated by the furnace and the input gases undergo endothermic chemical reactions at a temperature of 2100°F. The gases are then quenched and compressed (maximum 80 psig). Facilities are available to remove excess carbon dioxide, if necessary. After compression, the product gas is blended with nitrogen, methane, carbon dioxide, and/or steam, as required, to obtain the specified composition of the fuel gas to be tested.

Up to 5.75 million Btu/hr of simulated low-Btu fuel gas can be generated. This corresponds to 50,000 SCF/hr of 115 Btu/CF low-Btu gas. Table 1 gives the composition of the Koppers-Totzek oxygen (KTO), Wellman-Galusha air (WGA), and Winkler air (WA) fuel gases, which were chosen to be simulated as test gases for the program.

Table 1. FUEL COMPOSITION FOR LOW-Btu GASES TESTED

Fuel	CO	H_2	CO_2	CH_4	N_2	H_2O	Heating Value, Btu/SCF	Adiabatic Flame Temp,* °F	Specific Gravity
Koppers-Totzek Oxygen	53.0	34.3	9.3	0.5	1.0	1.9	287	3570	0.68
Wellman-Galusha Air	26.9	14.3	7.4	2.6	46.9	1.9	160	2990	0.83
Winkler Air	21.1	13.0	6.9	0.6	56.5	1.9	116	2700	0.85

* 10% excess air at 70°F. The adiabatic flame temperature for natural gas is 3380°F for this condition.

Description of Instrumentation

A major task of this program is to measure temperature profiles, thermal radiation from the flame, flow-direction profiles, and flue-gas composition. Modified designs of the International Flame Research Foundation were used to construct probes that enabled this type of data collection.

Temperature data were collected using a suction pyrometer; the design is illustrated in Figure 3. A Pt/Pt-13% Rh thermocouple was used. The

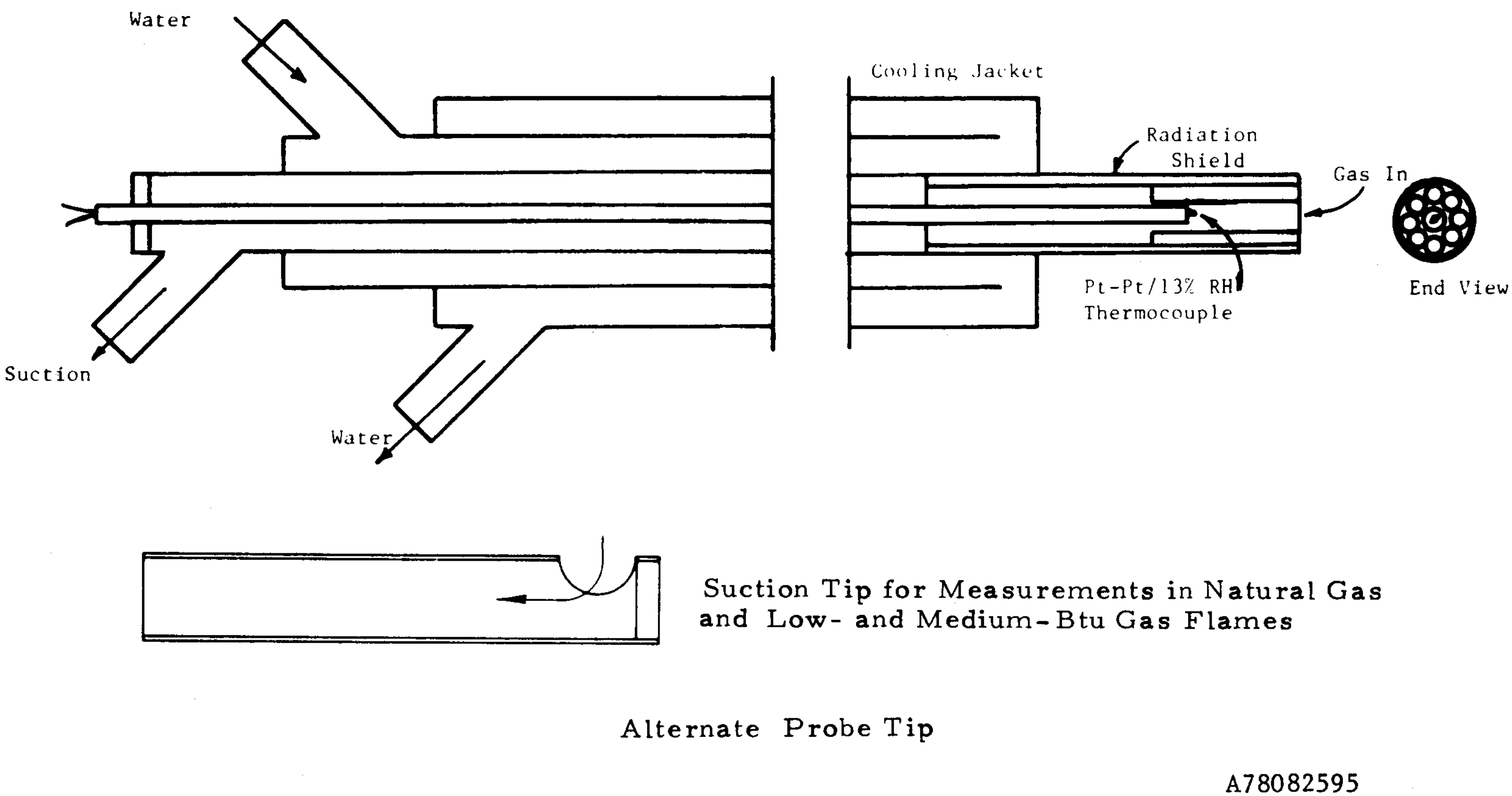

Figure 3. ASSEMBLY DRAWING OF THE SUCTION PYROMETER

efficiency of the pyrometer was monitored and was better than 95% with a 15-second response time.

The flow direction was measured using a water-cooled Hubbard probe, with the upstream and downstream pressure taps connected to a Datametrics Barocel transducer and Datametrics CGS electric manometer.

Figure 4 shows the assembly drawing of the gas-sampling probe used in the flame and the flue. To minimize NO_2 losses, the probe is water-cooled stainless steel joined to a Teflon sample line. At the end of the probe is a section of Teflon tube heated to 190°F, followed by a Millipore filter and a Permapure gas dryer. This dryer reduces the dew point to less than 32°F. In the dryer, water in the sample gas diffuses through a thin membrane into a stream of dry nitrogen. Tests have shown that only water is lost from the sample stream.

The analytic instrumentation equipment consists of the following items:

- Beckman 742 Polarographic Oxygen (O_2)
- Beckman Paramagnetic Oxygen (O_2)
- Beckman NDIR Methane (CH_4)
- Beckman NDIR Carbon Monoxide (CO)
- Beckman NDIR Carbon Dioxide (CO_2)
- Varian 1200 Flame Ionization Chromatograph (Total HC and C_2 to C_9)
- Beckman NDIR Nitric Oxide (NO)
- Beckman UV-Nitrogen Dioxide (NO_2)
- Thermo Electron Pulsed Fluorescent Sulfur Dioxide (SO_2)
- Hewlett-Packard Thermoconductivity Chromatograph, Hydrogen (H_2), Nitrogen (N_2), Argon (Ar), CO, CO_2, C_1 to C_5, Oxygen (O_2)
- Beckman Chemiluminescent NO-NO_2
- Data Integration System.

To evaluate radiation intensity, which is needed for determination of radiant flux and flame emissivity, a PR 200 Pyroelectric radiometer, manufactured by Molectron Corp. in Sunnyvale, California, was used. This radiometer uses a permanently poled lithium tantalate detector that is capable of resolving radiant power in the nanowatt range while maintaining a continuous spectral response from the vacuum UV to 500 μm. A built-in optical calibration system, in the form of a highly stable LED (light-emitting diode) that is calibrated against an NBS traceable standard of total irradiance, permits a direct correlation of experimental data from different trials.

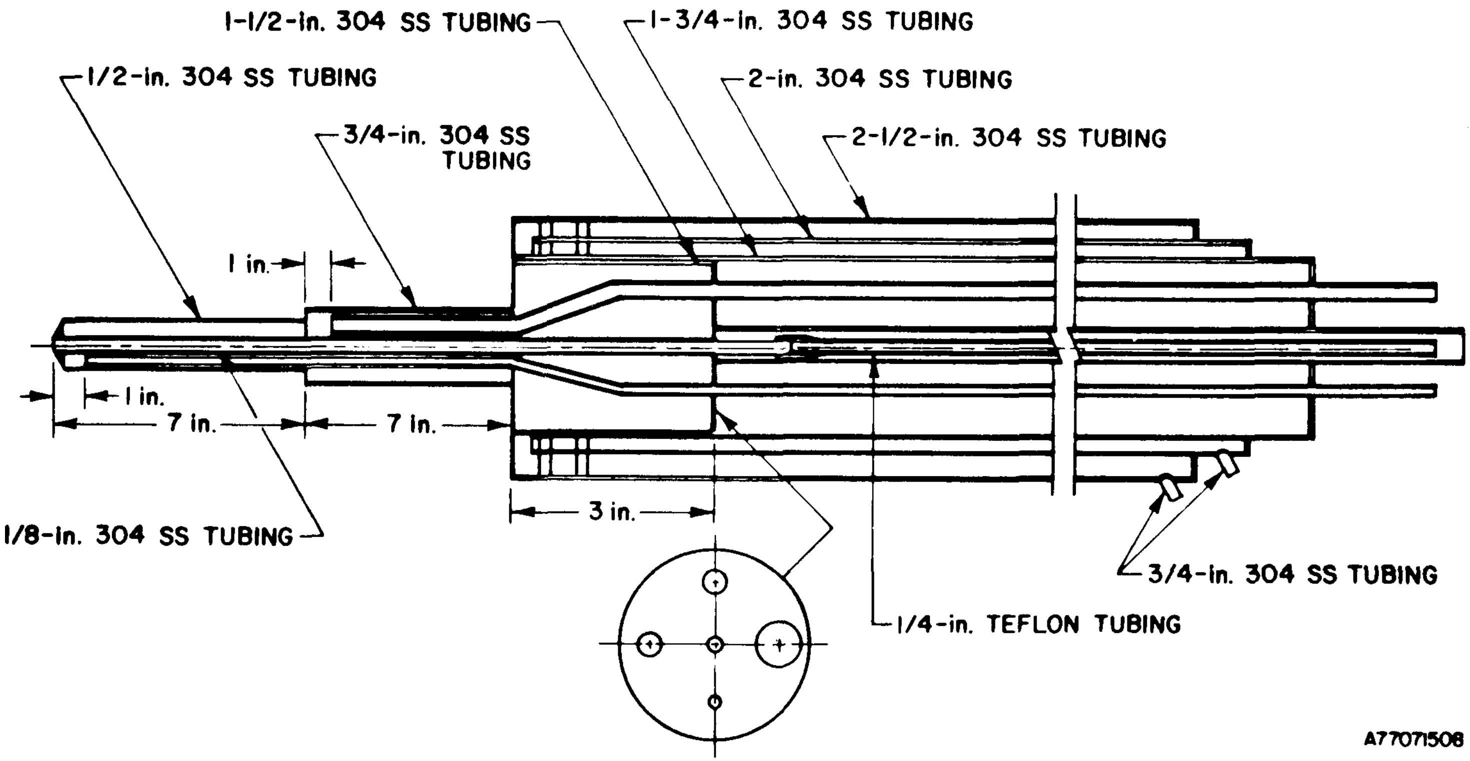

Figure 4. ASSEMBLY DRAWING OF GAS SAMPLING PROBE

BURNER TESTS

The Maxon Series SN sealed-nozzle burner was chosen as a representative premix tunnel burner. Figure 5 shows photographs of the burner (Model SN-4"-45), while Figure 6 is a schematic cross-sectional view of the burner. The fuel and air are intimately combined in a mixing tube and piped to the burner. The mixture passes through a nozzle and burner block into the furnace. The flame is stabilized in the burner block. The mixture velocity in the nozzle throat must be high enough to prevent the flame from flashing back into the supply piping.

This type of large port burner permits high heat release within a relatively small volume, giving rise to short, intense flames. Large port burners of the sealed-in type, i.e., tunnel burners, directly introduce into the furnace all the air and fuel for combustion in the primary mixture, with no secondary air requirements.

Premix tunnel burners are used in a wide variety of industrial applications, including kilns for porcelain, tile, and brick, and furnaces for heat treating, forging, and melting of nonferrous metals. In melting applications, a long oval or elliptical pot or crucible is heated from underneath usually by two to six burners. These melting pots are operated continuously or batch-wise.

Because we required long periods of stable furnace operation to collect all of the data necessary, we simulated only one instant in the transient operation of a batch-type melter or one zone of a continuous melter. In the early stages of a melting operation, large amounts of heat can be transferred to the solid material, while near the end of the melting cycle little heat is transferred. We chose to simulate an intermediate point in the load temperature cycle when about 25% of the energy input is transferred to the load.

Base-Line Natural Gas Tests

At the beginning of the natural gas base-line tests, the cooling tubes in the furnace were adjusted until 25.5% of the thermal input to the furnace was absorbed by the load. This was considered sufficiently close to the desired value of 25%. The seven cooling tubes were equally spaced along one wall of the furnace. Figure 7 shows the location of the tubes and also the

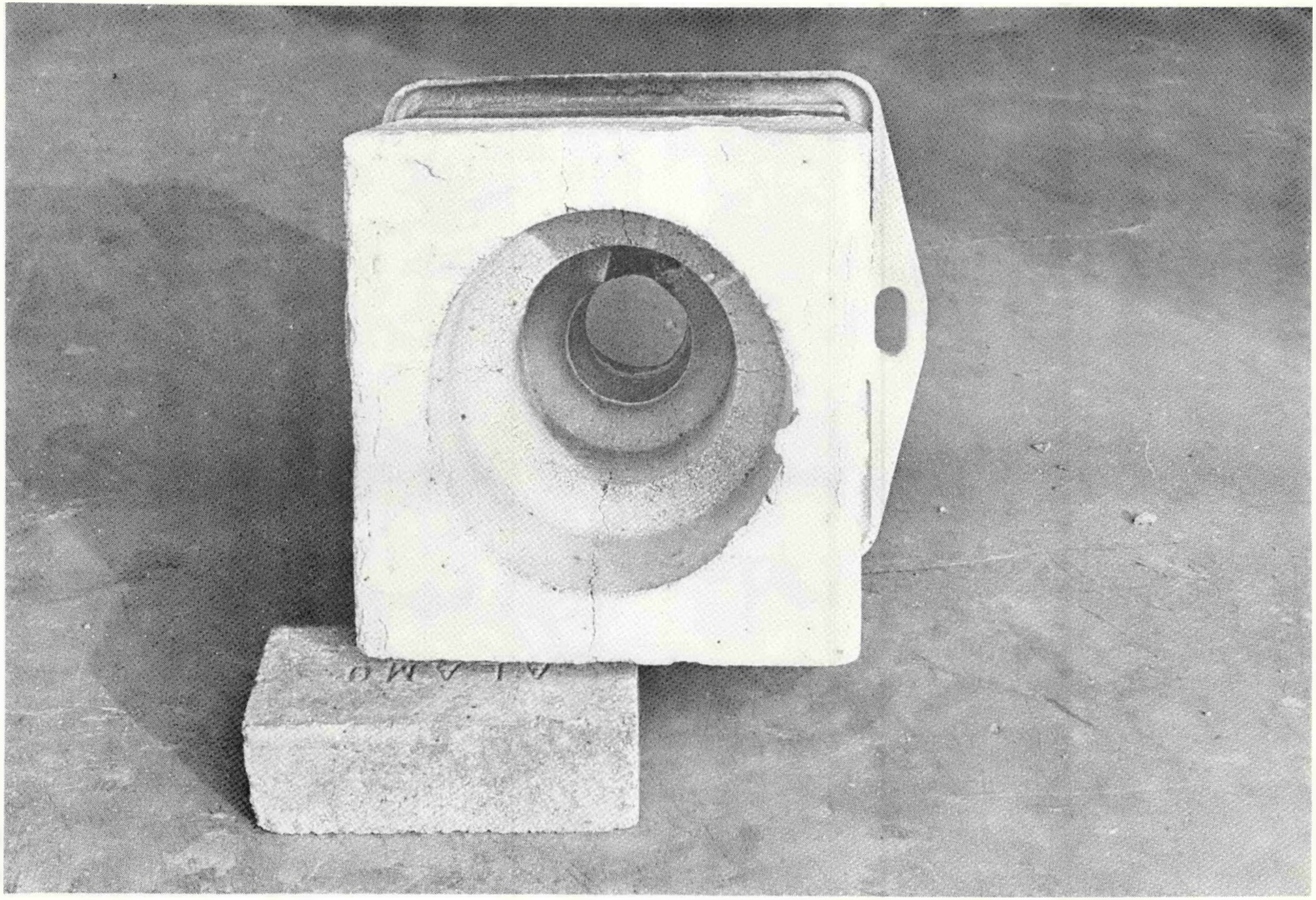

Figure 5. MAXON SERIES SN SEALED NOZZLE BURNER

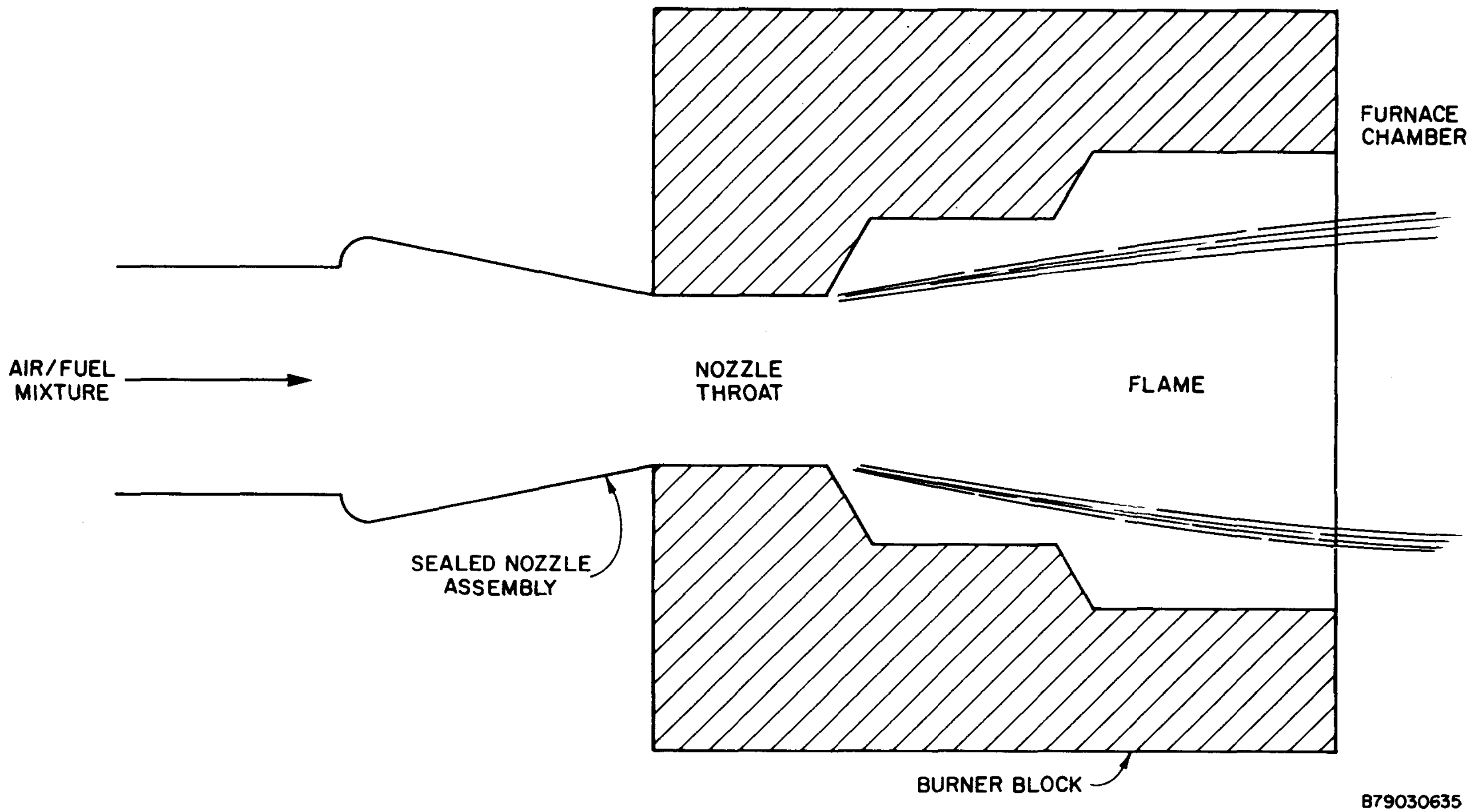

Figure 6. SCHEMATIC CROSS-SECTIONAL DRAWING OF THE PREMIX TUNNEL BURNER

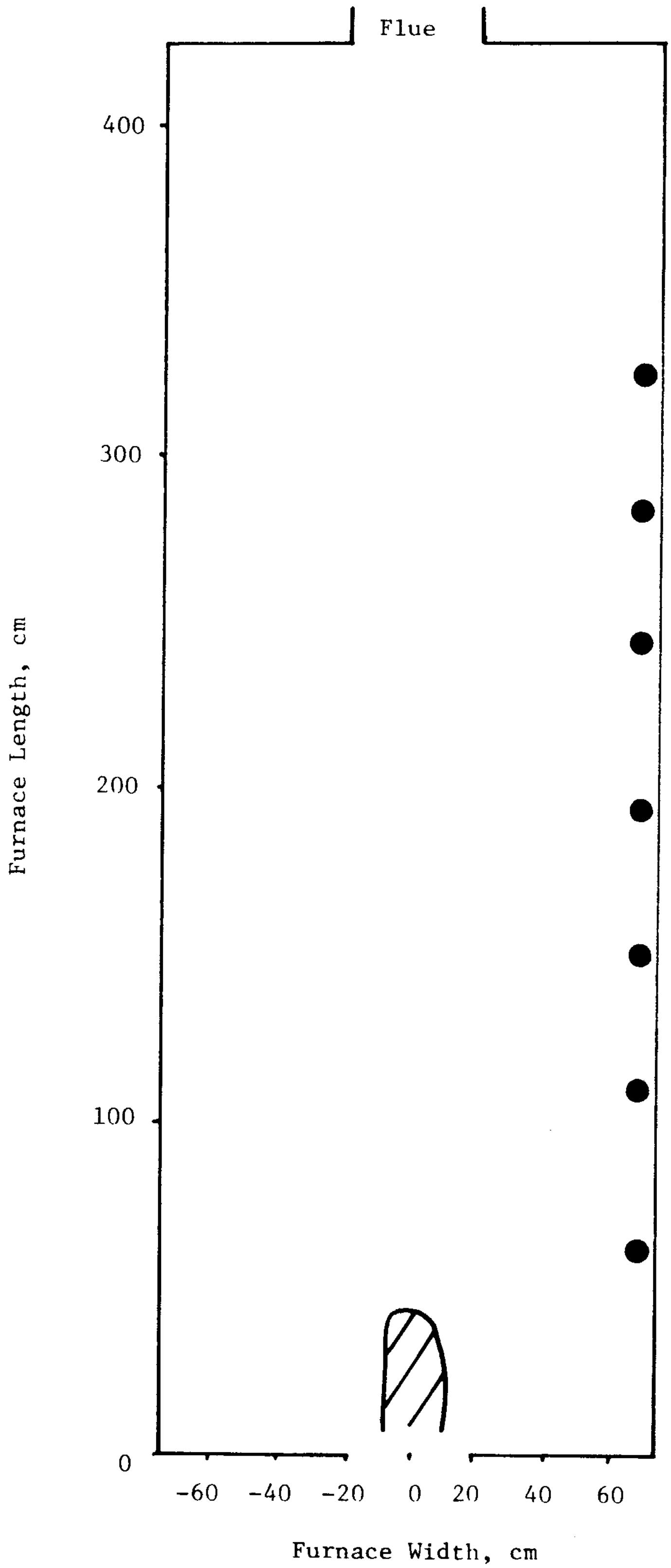

Figure 7. FLAME SHAPE FOR NATURAL GAS ON THE PREMIX TUNNEL BURNER

flame shape found for the natural gas flame. The flame shape is determined by measuring the gas composition at various points across the furnace at several locations along the furnace axis. The envelope depicted represents the zone within which 99% of the fuel is consumed. This is obtained by analysis of the carbon monoxide and oxygen levels.

Table 2 contains a summary of the natural gas base-line data. Figure 8 shows the temperature profiles found in the test furnace for the natural gas base-line conditions. The peak temperature was in excess of 1768°C (3214°F), the melting point of the thermocouple, and occurred within 36 cm from the burner wall. There is a narrow high-temperature region approximately 40 cm wide and 125 cm long with temperatures above 1500°C (2732°F); however, the bulk of the furnace is between 1250° and 1500°C.

Figure 9 shows the furnace gas flow direction profile for the natural gas flame. The open circles in this figure show the locations where the flow changes its direction from forward to reverse flow. As expected, the recirculation patterns are very large with this burner because of the high velocity of the flame jet issuing from the burner. This same flow pattern was found with all of the flames on this burner.

Sound level measurements were made during the natural gas base-line tests. At a point 1 ft from the burner, the background noise level was 89 db due to the combustion air fan. When the burner was firing, the noise level increased by 8 db. Alongside the furnace the background noise level was 86 db. When the burner was fired, this noise level increased by 6 db with the furnace closed and by 10 db with a sampling door removed.

Post flame emissivities were also measured by the Schmidt method[1] using the radiometer and water-cooled target. Three radiant flux measurements are required:

R_1 = Radiation intensity of the flame alone, obtained by viewing a cold target through the flame

R_2 = Radiation intensity of the refractory wall viewed through the flame

R_3 = Radiation intensity of the refractory wall without the flame.

The flame absorptivity is then—

$$\alpha = 1 - \frac{R_2 - R_1}{R_3} \qquad (1)$$

Table 2. FURNACE AND PREMIX TUNNEL BURNER OPERATING CONDITIONS

Fuel Type	Fuel Flow,* SCF/hr	Air Flow, SCF/hr	Fuel/Air Mixture Velocity, ft/s	Flue-Gas Temperature °F	Volume Flow Flue Gas, SCF/hr	Flame Length, cm	Thermal Efficiency, %**	Post-Flame Emissivities	Flue-Gas Analysis NO_x (ppm)	CO (ppm)	CO_2 (%, Dry Basis)	O_2 (%, Dry Basis)	N_2 (%, Dry Basis)
Natural Gas	2,900	30,700	217	2386	33,500	40	25.5	0.21	70	27	11.0	2.1	87
Koppers-Totzek Oxygen	10,900	25,400	234	2466	31,600	100	27.5	0.21	85	60	24.7	1.8	74
Wellman-Galusha Air	19,500	26,000	294	2274	41,500	60	21	0.19	16	35	18.4	1.4	80
Winkler Air	25,000	24,700	322	2205	45,400	70	19.5	0.19	10	27	18.0	1.1	81

* Fuel flow adjusted to give 3.0 ± 0.1 million Btu/hr fuel enthalpy input. (Fuel heating value varied slightly because of slight variations in fuel composition.)

**Efficiency based on load divided by product of fuel volume flow times heating value.

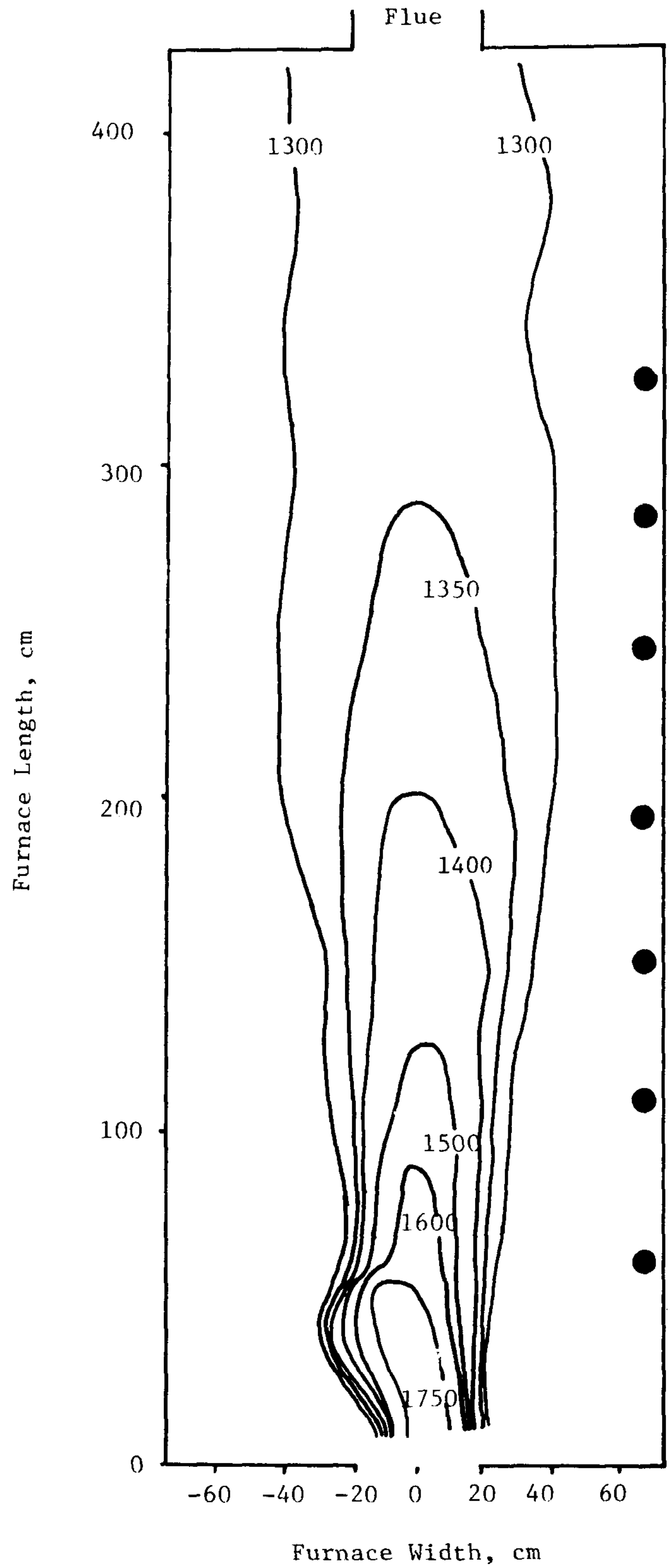

Figure 8. TEMPERATURE PROFILE (°C) FOR NATURAL GAS ON THE PREMIX TUNNEL BURNER

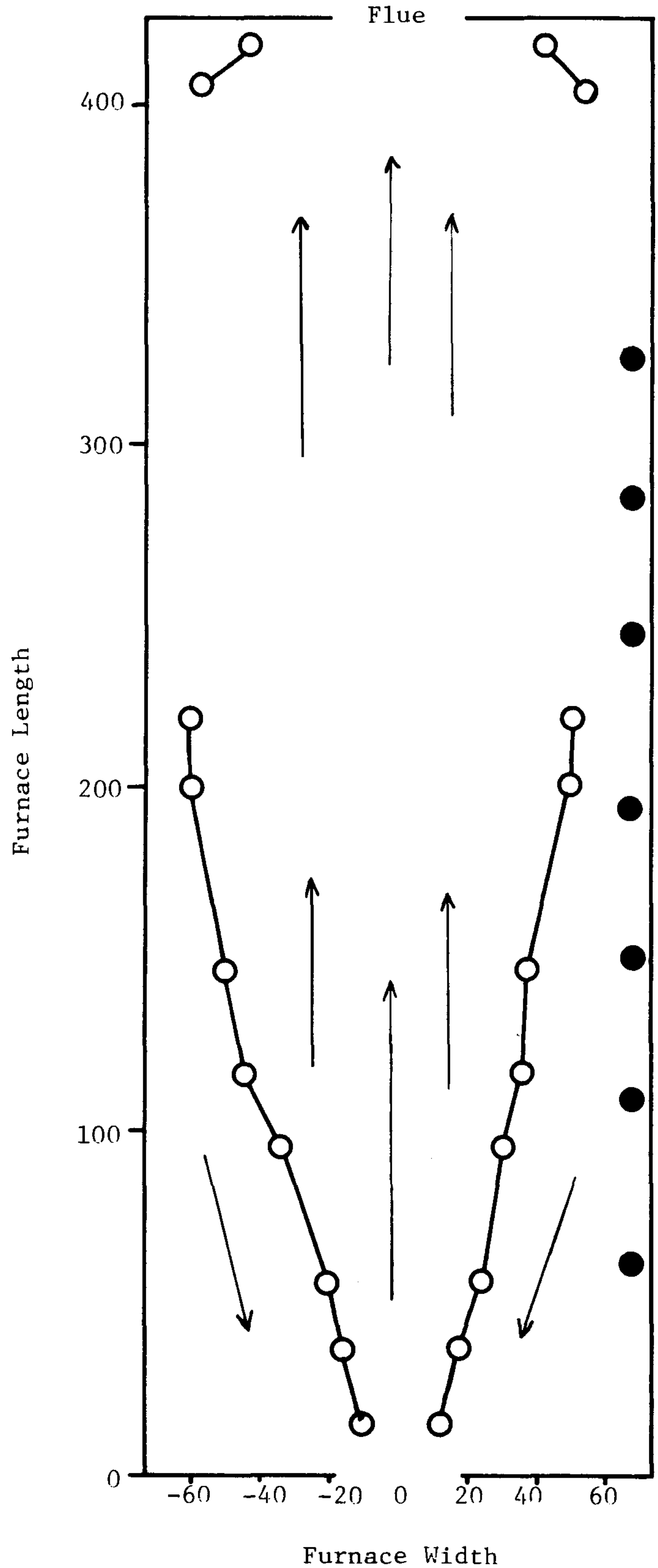

Figure 9. FLOW-DIRECTION PROFILE FOR NATURAL GAS ON THE PREMIX TUNNEL BURNER

The relationship between gas emissivity and absorptivity in a furnace, when the refractory is not a black body, can be determined from radiation theory.[2] The relation is —

$$\alpha_f = 1 - (1 - \varepsilon_f)\ \{\varepsilon_r + \rho_r\ [\frac{\varepsilon_f T_f^4}{T_r^4} + (1 - \varepsilon_f)(\frac{\varepsilon_r + \frac{\rho_r \varepsilon_f T_f^4}{T_r^4}}{1 - \rho_r (1 - \varepsilon_f)})]\} \qquad (2)$$

where ρ_r and ε_r are the reflectivity and emissivity of the refractory. T_r and T_f are the temperatures of the refractory and combustion products. The results of the gas emissivity measurements were given in Table 2. The values measured lie between the values that can be calculated by the method given in Reference 2 and the procedure proposed by Leckner.[3]

The flame radiation and heat absorption profiles measured for natural gas will be presented later in the report along with the similar measurements made for the substitute fuel gases.

Low-Btu Gas Tests

Flame Stability Tests

After completion of the natural gas baseline trials, flame stability trials began with the substitute fuel gases. The trials were initiated by attempting to stabilize a low-Btu gas flame at a fuel enthalpy input equal to the natural gas input. For KTO and WGA gases, no flame instability was encountered at the 3 million Btu/hr rate used for the natural gas baseline trials. WA, however, required a pilot flame to remain attached to the nozzle. In addition to blowoff, another potential hazard with premix burners is flashback, wherein the fuel/air mixture flow rate through the nozzle throat is not high enough to prevent the flame front from propagating into the supply piping. Since KTO has the highest hydrogen content of any of the fuels studied, it should also have the highest burning velocity and thereby be the most susceptible to flashback. At a 10% excess air level, KTO flashed back at a fuel input rate of 429,000 Btu/hr. No flashback was evident at 560,000 Btu/hr. For natural gas at fuel input rates as low as 100,000 Btu/hr no flashback occurred.

Koppers-Totzek Oxygen Fuel Gas Tests

Following the flame stability trials, the furnace was fired with KTO fuel gas and the furnace load, exit gas temperature, and wall temperature were monitored to determine when the furnace reached thermal equilibrium. When equilibrium was attained, data collection began. Table 2 contains a summary of the data collected.

With KTO the thermal efficiency (heat absorbed by the load divided by the fuel enthalpy input) was 27.5%, as compared with 25.5% for natural gas. The flame length, however, increased from 40 cm to 100 cm. Figure 10 shows the flame shape for KTO.

Figure 11 compares the heat absorption profile for KTO and natural gas. The profiles are similar because the flame is small relative to the size of the furnace and the area over which the load is distributed.

The flame temperature profiles are plotted in Figure 12. The temperatures measured for the KTO flame are similar to those found for natural gas. In most of the furnace volume the temperatures are between 1300° and 1500°C. The peak temperature for KTO exceeded the melting point of the thermocouple [1768°C (3214°F)] and occurred within 36 cm of the burner wall.

Figure 13 shows the radiation from the flame plus combustion products at points along the length of the furnace. The measurements were made by sighting a narrow-angle radiometer across the furnace toward a water-cooled target at the opposite wall. The measurements show the thermal radiation from the natural gas flame to be lower than from the KTO flame.

The solid symbols in Figure 13 show the thermal radiation from the flame alone. These were measured by placing a water-cooled target at the far-flame boundary and sighting the radiometer down a water-cooled tube placed at the near-flame boundary. Owing to the shortness of the flame, only one flame radiation measurement was possible. The flame radiation for KTO was more than that measured for natural gas.

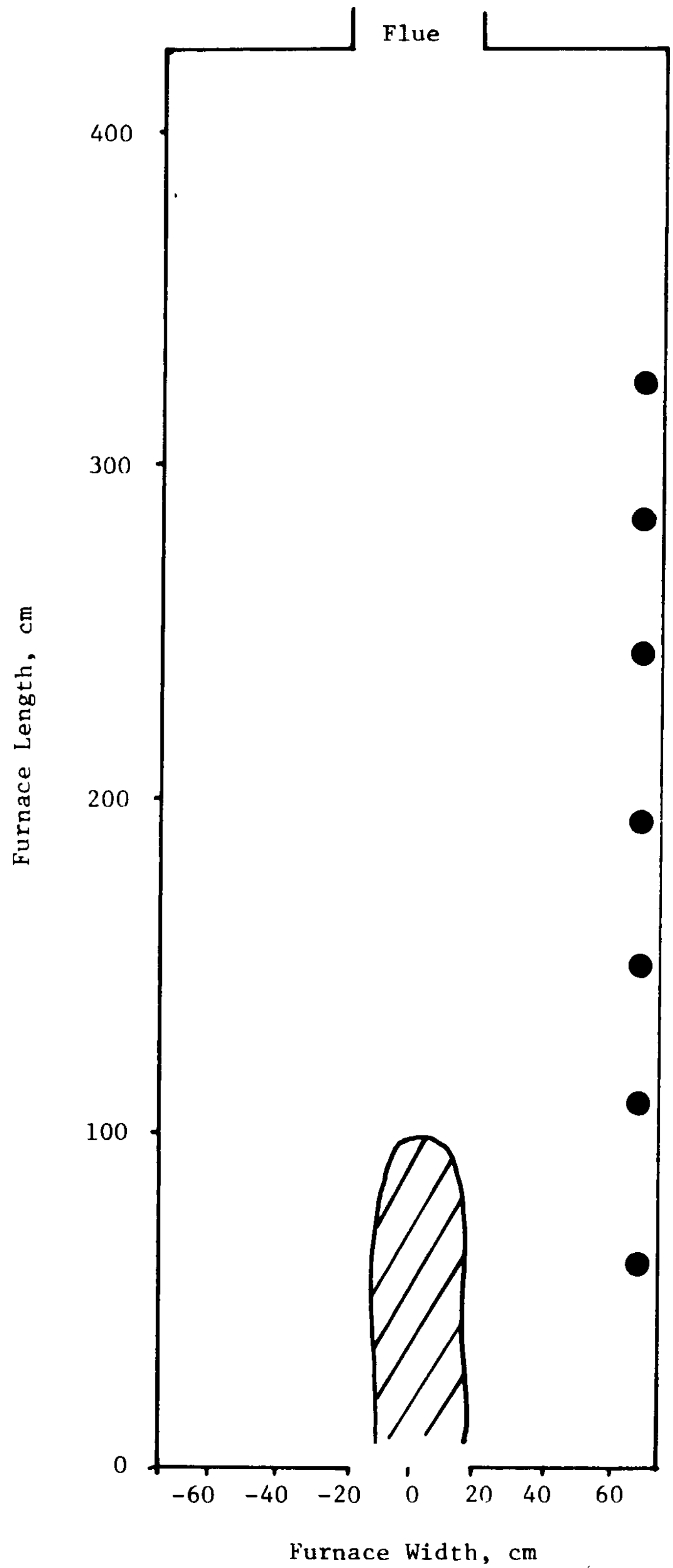

Figure 10. FLAME SHAPE FOR KOPPERS-TOTZEK OXYGEN FUEL GAS ON THE PREMIX TUNNEL BURNER

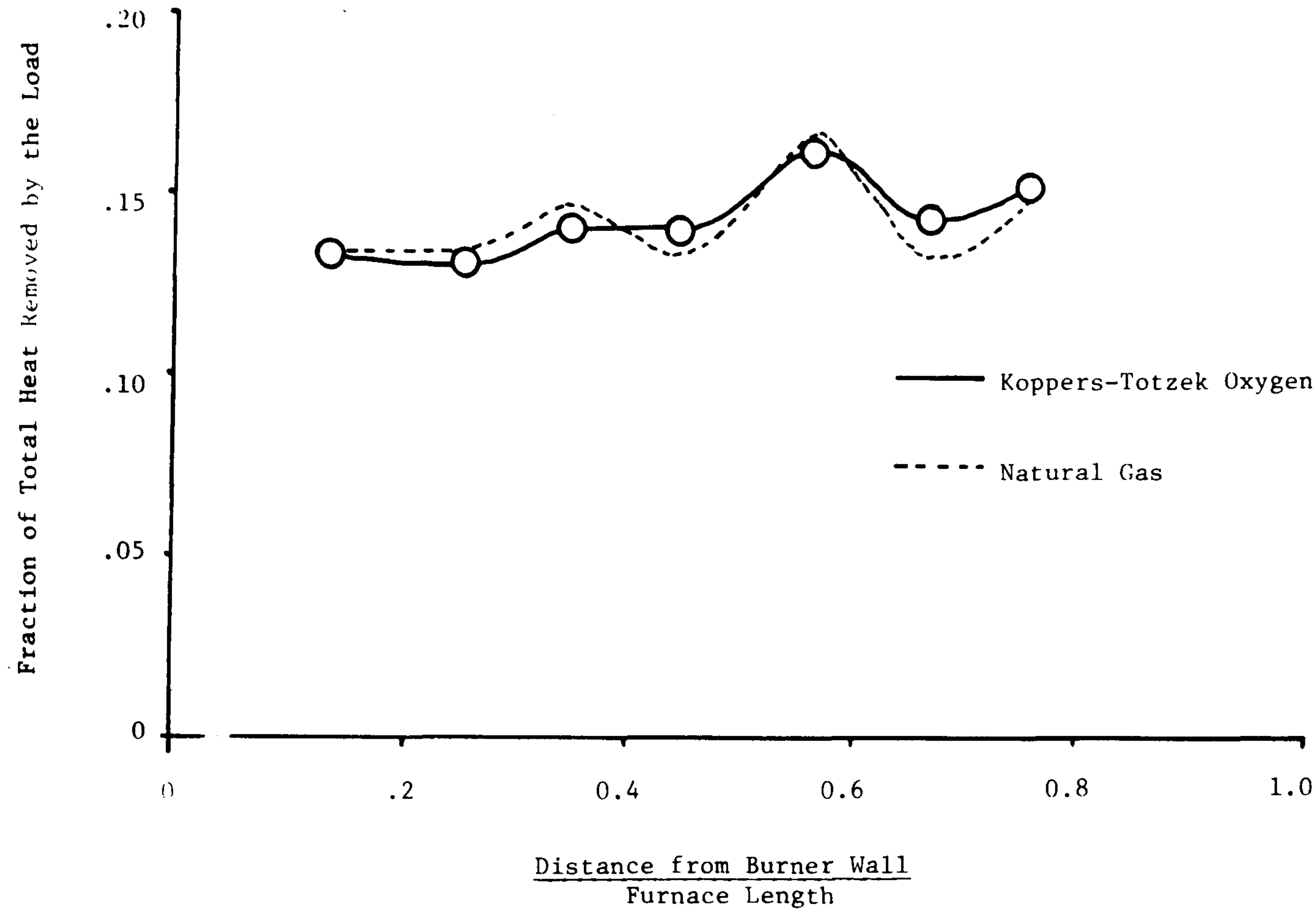

Figure 11. HEAT-ABSORPTION PROFILE FOR KOPPERS-TOTZEK OXYGEN FUEL GAS AND NATURAL GAS ON THE PREMIX TUNNEL BURNER

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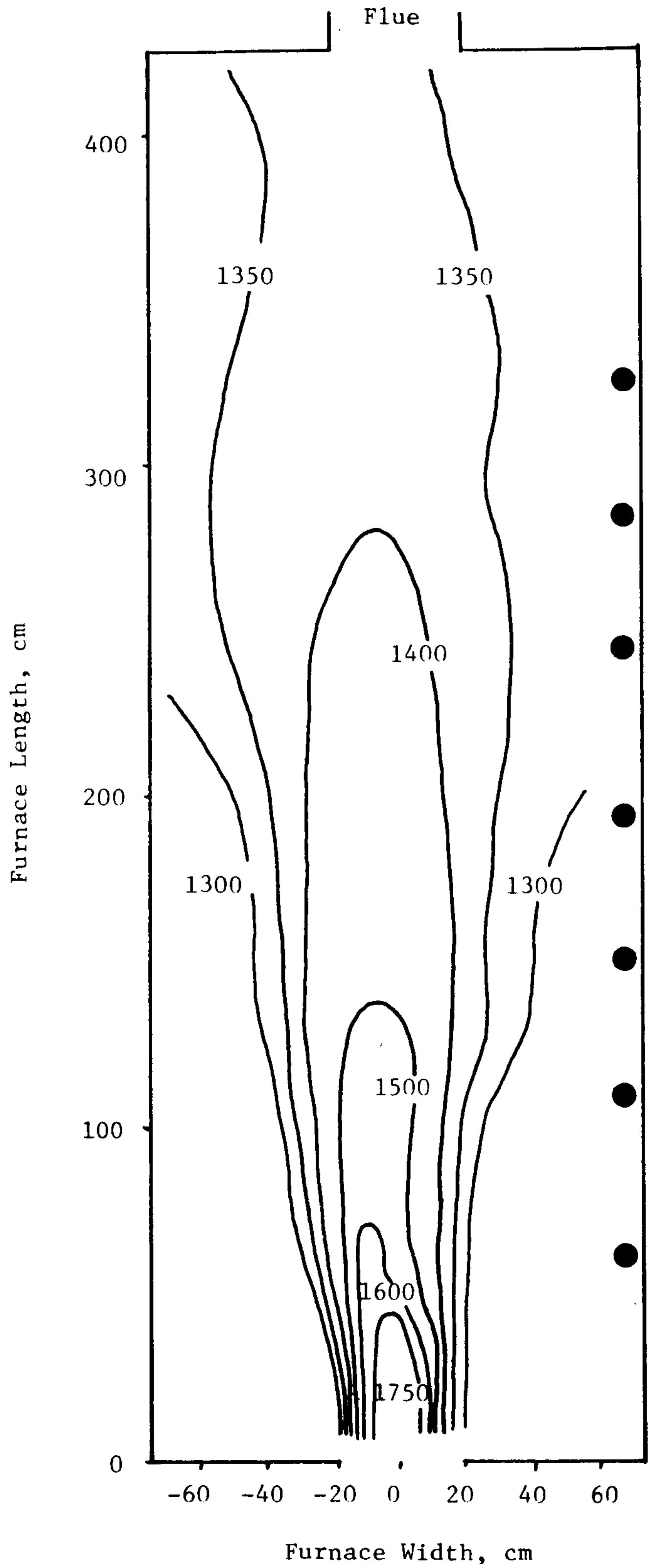

Figure 12. TEMPERATURE PROFILE (°C) FOR KOPPERS-TOTZEK OXYGEN FUEL GAS ON THE PREMIX TUNNEL BURNER

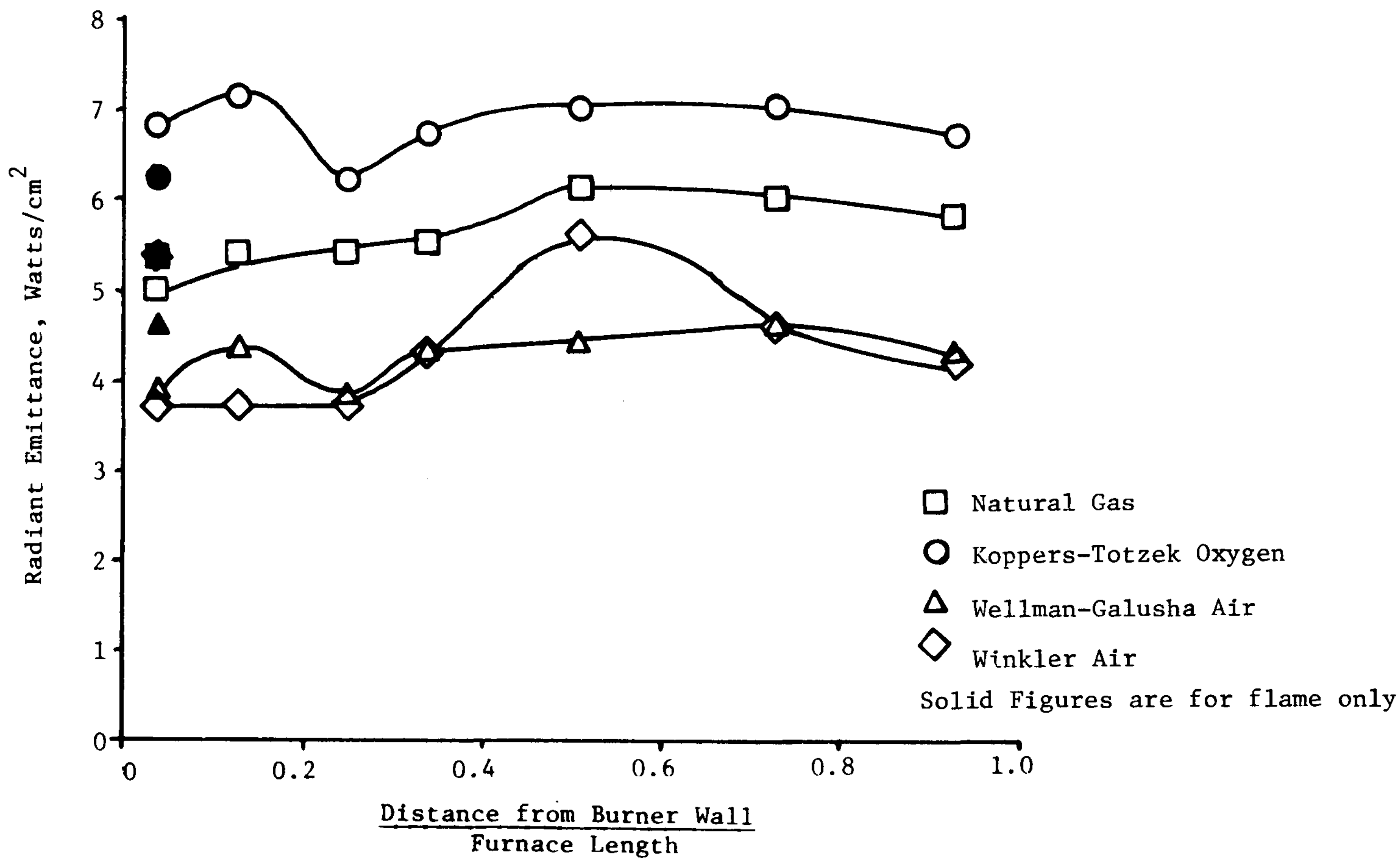

Figure 13. THERMAL RADIATION MEASUREMENTS FOR THE PREMIX TUNNEL BURNER

Sound level measurements were made during the KTO fuel gas trials. The background noise level at the burner was 89 db. This increased 8 db to 97 db when KTO was fired on the burner. At a point 2 ft from the side of the furnace, the background noise level was 86 db. When KTO was fired on the burner, the noise level increased 7 db with the furnace closed and 11 db with one sampling door removed.

As noted earlier the KTO flow direction profile was nearly identical to the profile determined for natural gas.

Koppers-Totzek Oxygen Fuel Gas Retrofit Conclusions

KTO will give few problems when retrofitted to this burner if the extended flame length (100 cm vs. 40 cm) is acceptable. This will probably be the case for many applications of this burner. The thermal efficiency, flame temperatures, and heat absorption profile are all similar to or greater than those measured for natural gas.

Wellman-Galusha Air Fuel Gas Tests

Following the Koppers-Totzek oxygen fuel gas trials, the furnace was fired with Wellman-Galusha air fuel gas and allowed to attain thermal stability. The results of this test are also summarized in Table 2.

The thermal efficiency for WGA was 21%, as compared with 25.5% for natural gas. This change in efficiency is typical of the type of decrease found with previous burners when natural gas and WGA fuel gas were compared.

The flame length with WGA fuel gas was 60 cm, compared with 40 cm for natural gas. Figure 14 shows the shape of the WGA flame. The peak flame temperature measured was 1587°C (2889°F) at 15 cm from the burner wall. Figure 15 shows the flame temperatures measured for the WGA tests. The furnace temperatures are very uniform throughout the combustion chamber, similar to the natural gas and KTO tests, although the temperatures are about 100°C lower. Figure 16 shows that the furnace load heat absorption profile during the WGA fuel gas tests was nearly identical to the baseline natural gas profile.

Figure 13 shows the radiation profiles measured during the WGA tests compared with the measurements from the tests with the other fuels. The WGA radiation emission levels are lower than those found for natural gas and KTO.

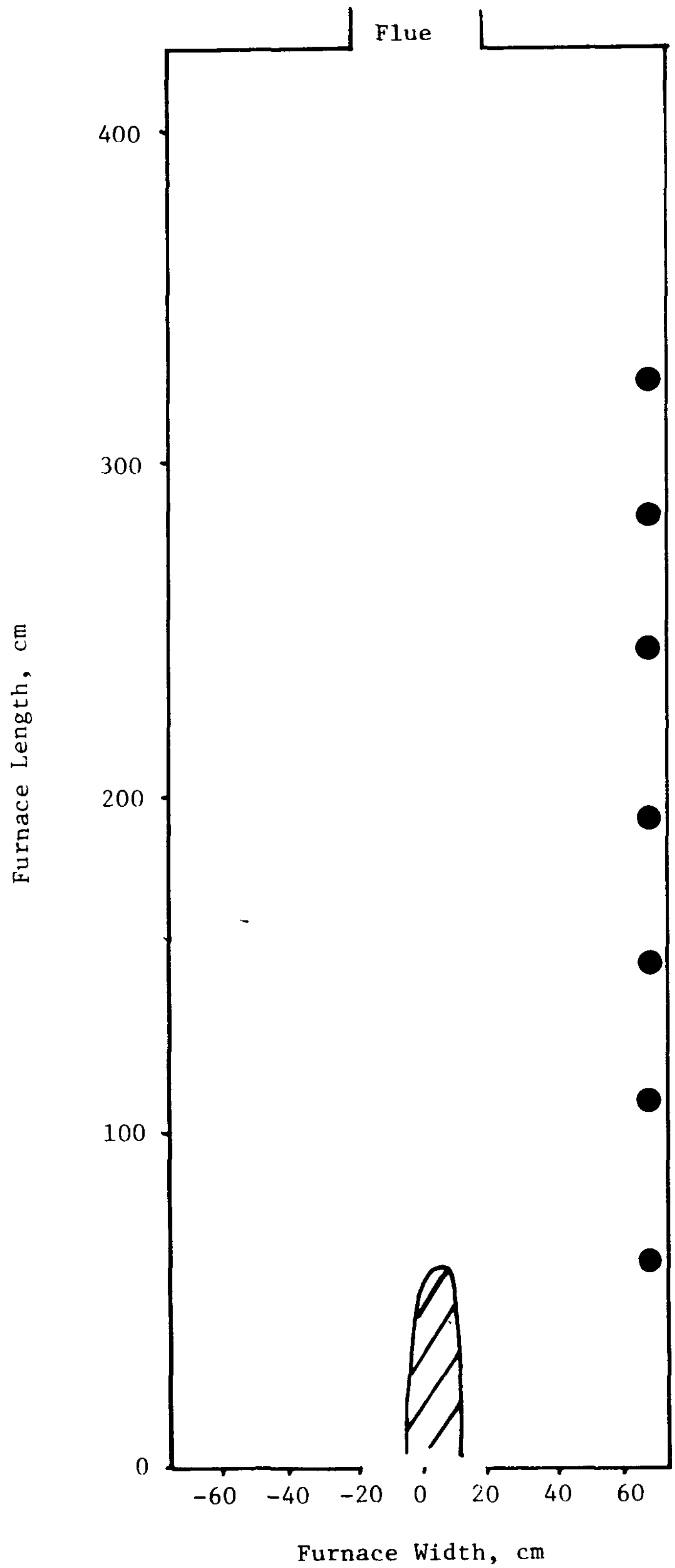

Figure 14. FLAME SHAPE FOR WELLMAN-GALUSHA AIR FUEL GAS ON THE PREMIX TUNNEL BURNER

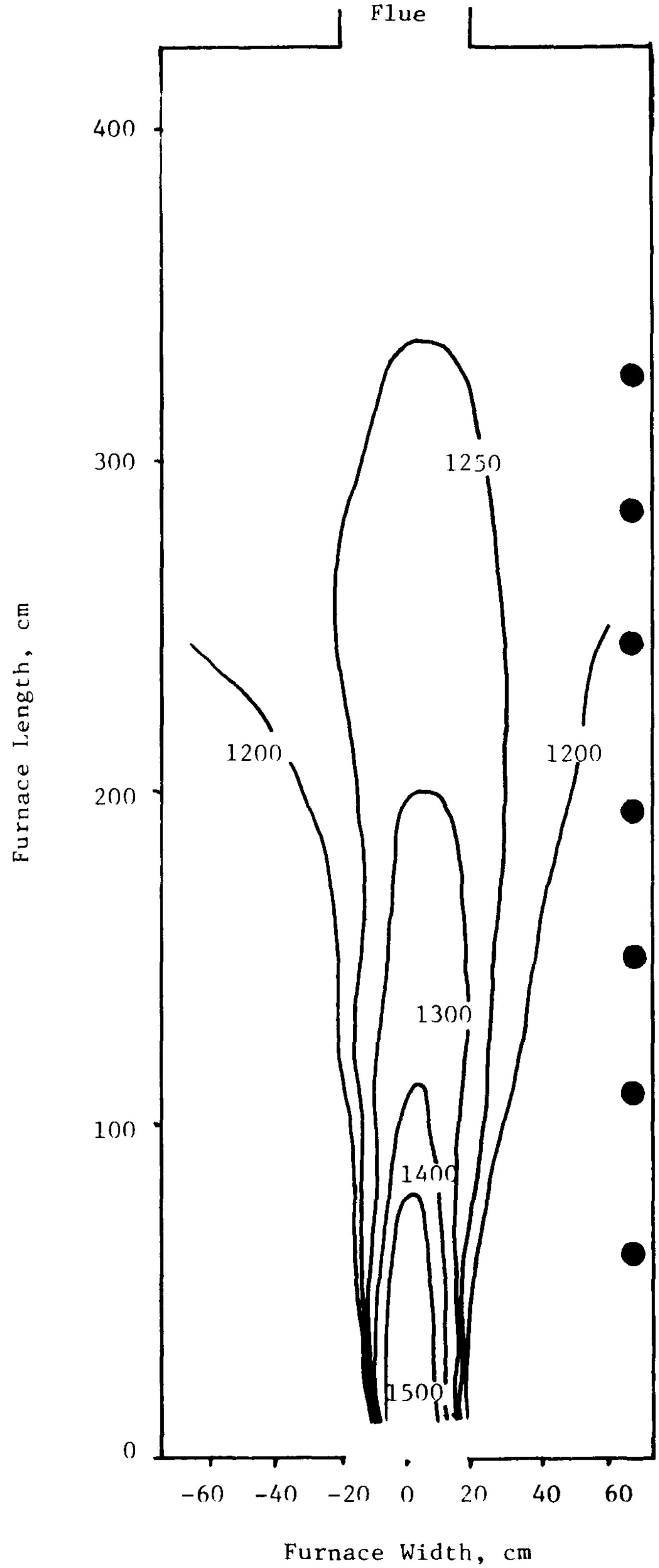

Figure 15. TEMPERATURE PROFILE (°C) FOR WELLMAN-GALUSHA AIR FUEL GAS ON THE PREMIX TUNNEL BURNER

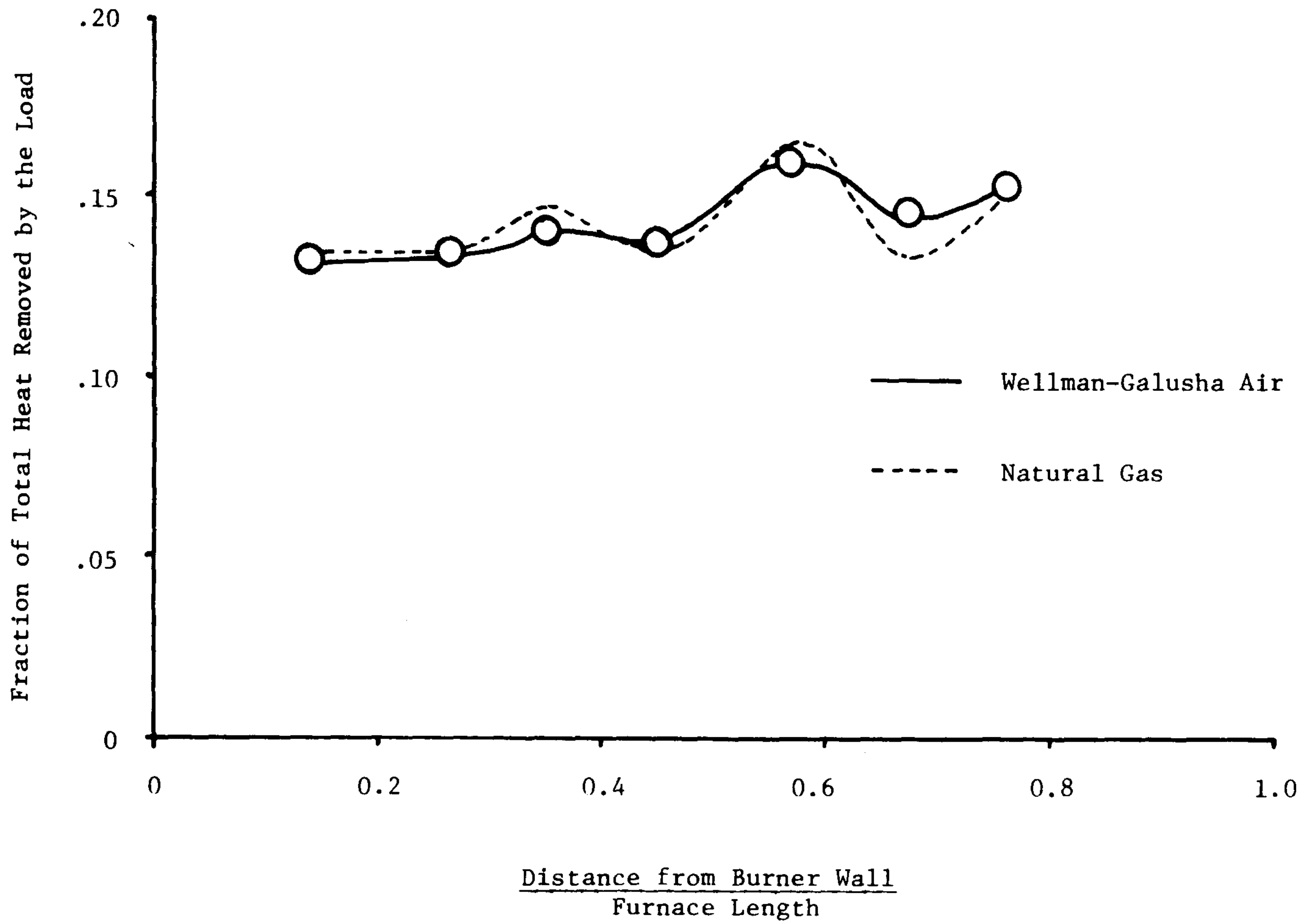

Figure 16. HEAT-ABSORPTION PROFILES FOR WELLMAN-GALUSHA AIR FUEL GAS AND NATURAL GAS ON THE PREMIX TUNNEL BURNER

These measurements are consistent with the flame temperature measurements, and they help to explain the lower thermal efficiency found for WGA.

Sound level measurements were made during the WGA tests. The background level was 89 db near the burner and 86 db at the side of the furnace. The noise level increased to 97 db at the burner when WGA was fired. It increased to 92 db at the side of the furnace with all of the sampling doors in and increased to 98 db with one sampling door removed.

The flow direction profile for WGA was the same as that shown for natural gas in Figure 9.

Wellman-Galusha Air Fuel Gas Retrofit Conclusions

Although the WGA heat absorption profile compared very well with the natural gas profile, the WGA thermal efficiency and flame temperatures are both lower than those found for natural gas. Thus, although WGA showed no flame stability or heat absorption profile problems when retrofitted to this burner, there were significant reductions in performance in terms of thermal efficiency and flame temperature.

Winkler Air Fuel Gas Tests

The results of the WA fuel gas trials are summarized in Table 2 along with those of the other fuels. The furnace thermal efficiency with WA fuel gas was only 19.5%.

The flame length for the WA fuel gas flame was 70 cm long, as compared with 40 cm for natural gas. The flame shape is shown in Figure 17. Figure 18 shows the load heat absorption profile compared with the natural gas profile. The WA profile is nearly identical to the natural gas profile. The WA flow direction profile was also the same as that shown in Figure 9.

The peak flame temperature measured for WA fuel gas was 1528°C (2782°F) at 5 cm from the burner wall. Figure 19 shows the temperature profiles in the furnace during the WA test. The figure shows the same type of temperature uniformity that was found during the tests with the other fuels. The WA and WGA flame temperatures are very similar, and this is reflected in the thermal radiation measurements shown in Figure 13.

Sound level measurements during the WA trials showed a background noise level of 89 db at the burner and 86 db at the furnace sidewall. The level

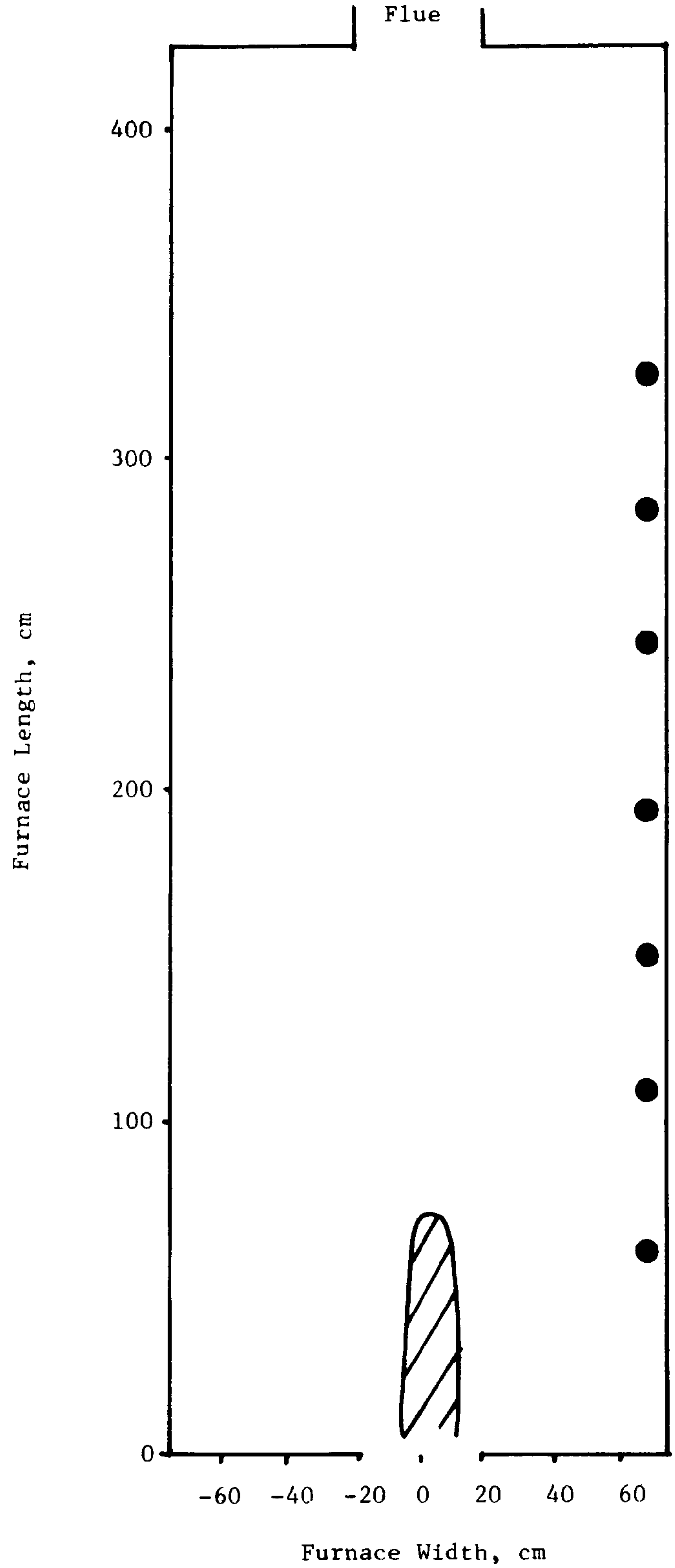

Figure 17. FLAME SHAPE FOR WINKLER AIR FUEL GAS ON THE PREMIX TUNNEL BURNER

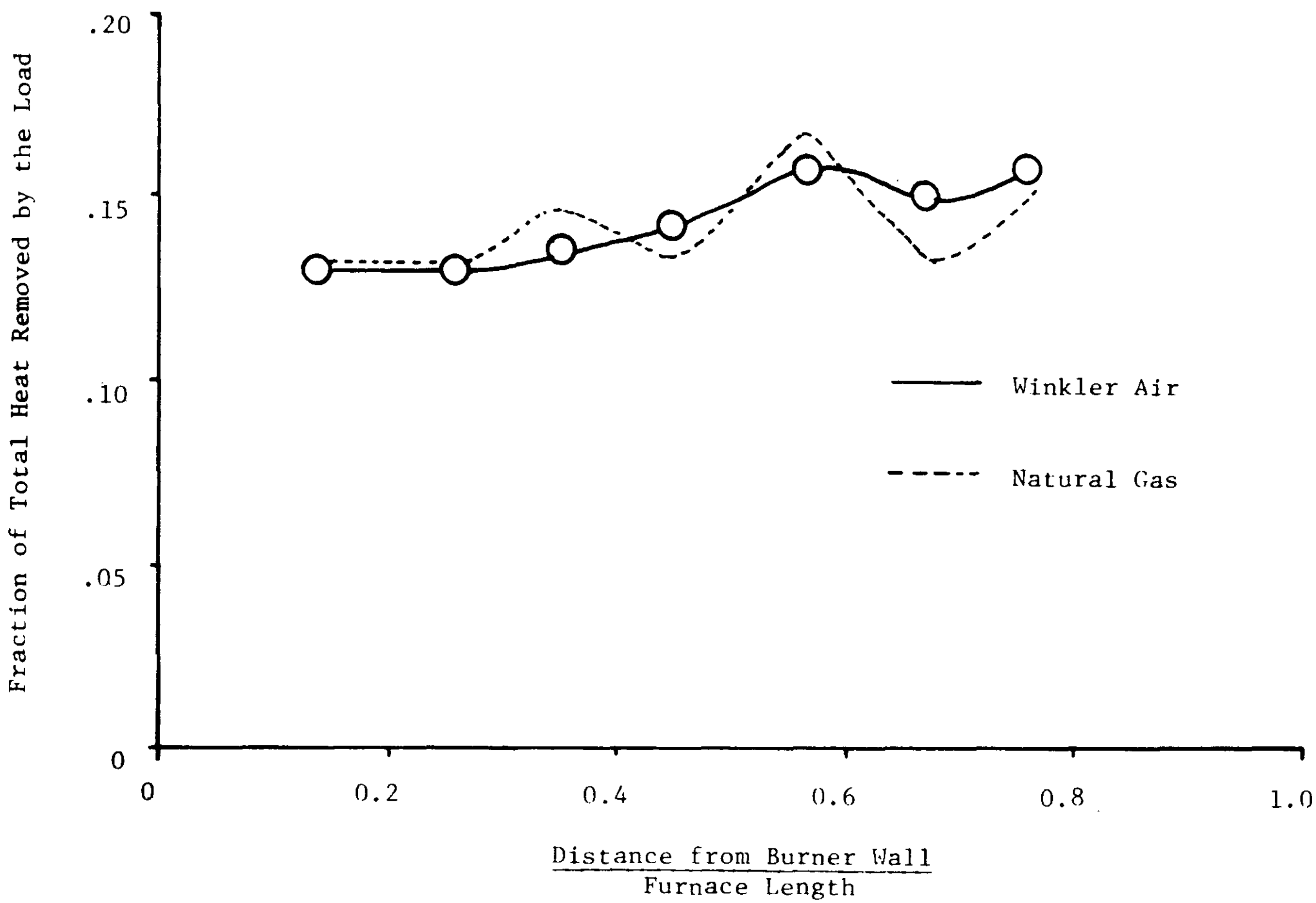

Figure 18. HEAT-ABSORPTION PROFILES FOR WINKLER AIR FUEL GAS AND NATURAL GAS ON THE PREMIX TUNNEL BURNER

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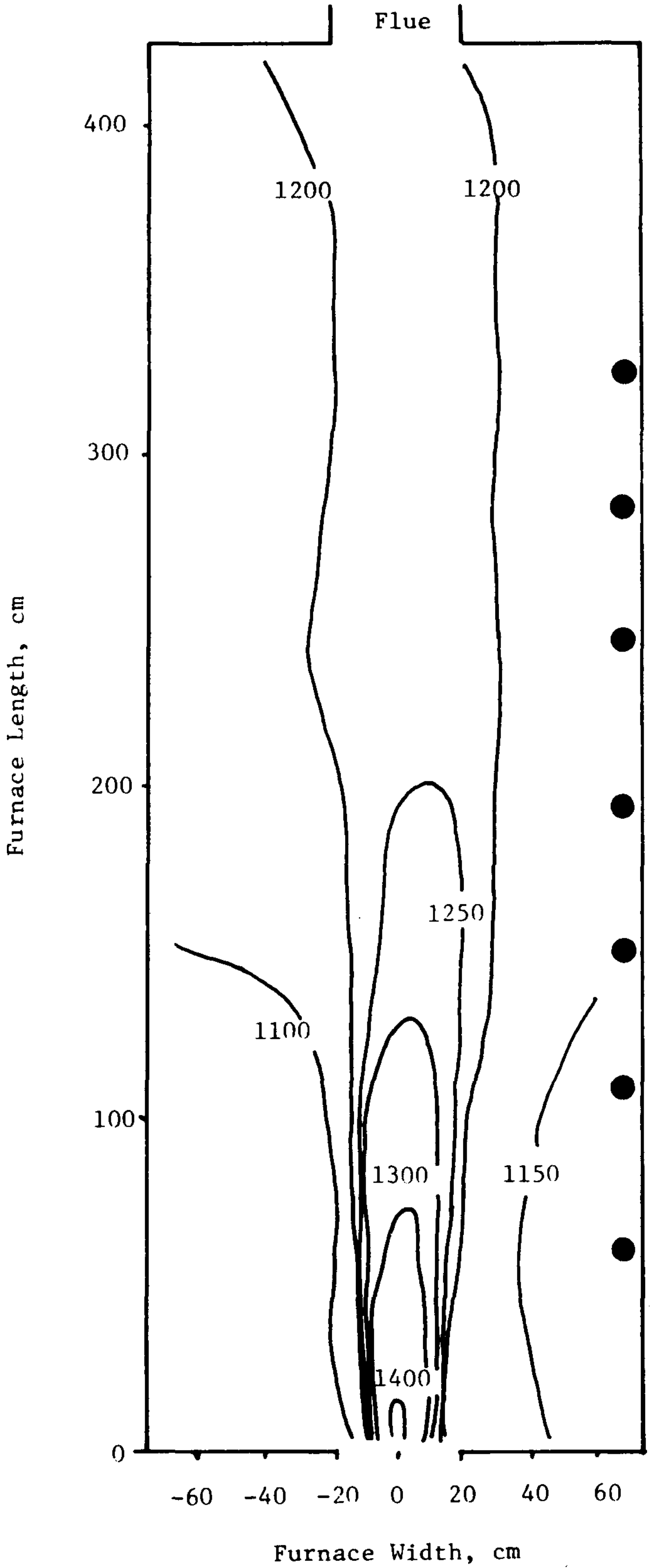

Figure 19. TEMPERATURE PROFILE (°C) FOR WINKLER AIR FUEL GAS ON THE PREMIX TUNNEL BURNER

rose 9 db at the burner when WA was fired. The level rose to 96 db at the side with the furnace closed and to 99 db when a sampling door was removed during operation of the burner.

Winkler Air Fuel Gas Retrofit Conclusions

Winkler air fuel gas gave some stability problems when fired on this burner in that a pilot flame was necessary to prevent blowoff. Although the heat-absorption profile for WA was similar to that for natural gas, the thermal efficiencies were 19.5% and 25.5%, respectively. This reduction in thermal efficiency coincides with the lower gas temperatures and radiation levels measured for WA. Thus, WA presents a significant reduction in performance compared with natural gas when retrofitted to this burner.

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