PHASE II

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ADVANCED COAL-FUELED COMBUSTOR FOR RESIDENTIAL SPACE HEATING APPLICATIONS

QUARTERLY REPORT

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1.0 INTRODUCTION

The objective of this program is to develop an integrated combustor/heat exchanger which burns coal either as a slurry or as dry ultrafine coal and which is suitable for use in a range of residential space heaters. The program has been divided into two phases. To date, Phase I has been completed. In Phase I, combustor concepts were developed and evaluated by means of mathematical modeling and experimental testing. The most promising concept, an air-cooled stainless steel combustion chamber, was fabricated and tested. In Phase II, an optimized prototype combustor will be integrated with a heat exchanger to complete the prototype residential space heater.

The goal of the second phase of this program is to prove that a coal-fired residential space heater can meet the following specifications:

Primary Fuel:	Coal/liquid mixture or dry ultrafine coal
Ignition:	Automatic
Response Time:	⩽5 minutes to full load
Reliability/Safety:	Comparable to oil-fired residential heating systems
Steady-State Efficiency:	⩾80 percent
Combustion Efficiency:	⩾99 percent
Daily Maintenance:	None
Scheduled Maintenance:	⩽twice a year
Size Constraints:	Height-6 ft. Floor space-15 sq. ft.
Service Life:	⩾20 years

In order to accomplish the overall program objectives, the Phase II program will be carried out in five tasks:

Task 1. Program Plan and Management
Task 2. Combustor Optimization
Task 3. Integration of Heat Exchanger
Task 4. Testing of Space Heater
Task 5. Reporting

This quarterly report describes the work performed on Task 2 - Combustor Optimization.

2.0 COMBUSTOR OPTIMIZATION

Initially the design of the combustor was optimized and included modifications of the burner and the combustion chamber. Combustion performance of the optimized combustor was conducted as well as the response time.

2.2 Combustion Chamber Design

The combustion chamber for the prototype combustor consists of a double-walled design using a jacket of cooling air surrounding the combustion chamber. The combustion chamber, cylinder made of 316 stainless steel, has an internal diameter of 12 inches and a length of 26 inches. The corresponding chamber volume is about 1.3 ft^3, including the transition section of the furnace. The outer shell has an overall length of 40 inches and is made of thin gauge carbon steel. The chamber is configured in such a way that the burner is mounted at the top end, and the flue gases exit at the bottom. To maintain the wall of the combustion chamber below the maximum tolerable level (~1500°F), cooling air circulates upward through the annulus from the bottom of the chamber toward the burner. In Phase II, the inner shell is cooled using the combustion air. This "recuperative" concept has the advantage of transferring heat from the inner shell to the combustion air, which has been shown to be beneficial to carbon burnout and flame stabilization as well. A number of longitudinal fins are included in the design of this inner shell to ensure enough surface area for heat transfer. Furthermore, to minimize heat loss from the outer shell to the surroundings, the inner wall of the outer shell is lined with insulating materials.

2.2 Burner Design

The primary function of a burner is to produce a stable flame. Flame stabilization is achieved by a combination of reduced fuel and air velocities and recirculation or back mixing of combustion products and heat to the inflowing fuel and air. There are several techniques for stabilizing a flame, among them, the use of a swirl generator to create a recirculation flow pattern near the burner zone, or the use of a hot refractory quarl to stabilize a flame by re-radiating to the inflowing fuel and air. Both flame stabilization methods were evaluated extensively through testing in Phase I.

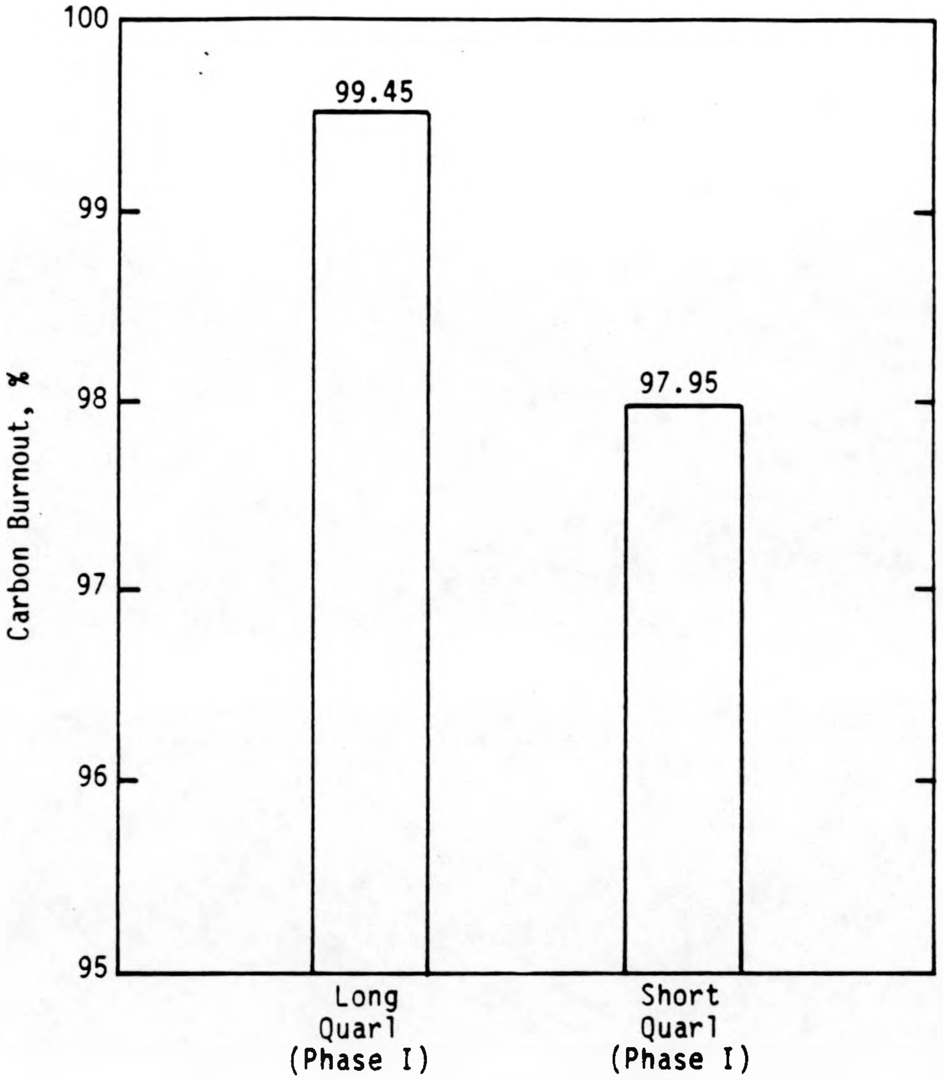

Figure 2-1. Impact of burner design on carbon burnout for dry ultrafine coal - Phase I Results.

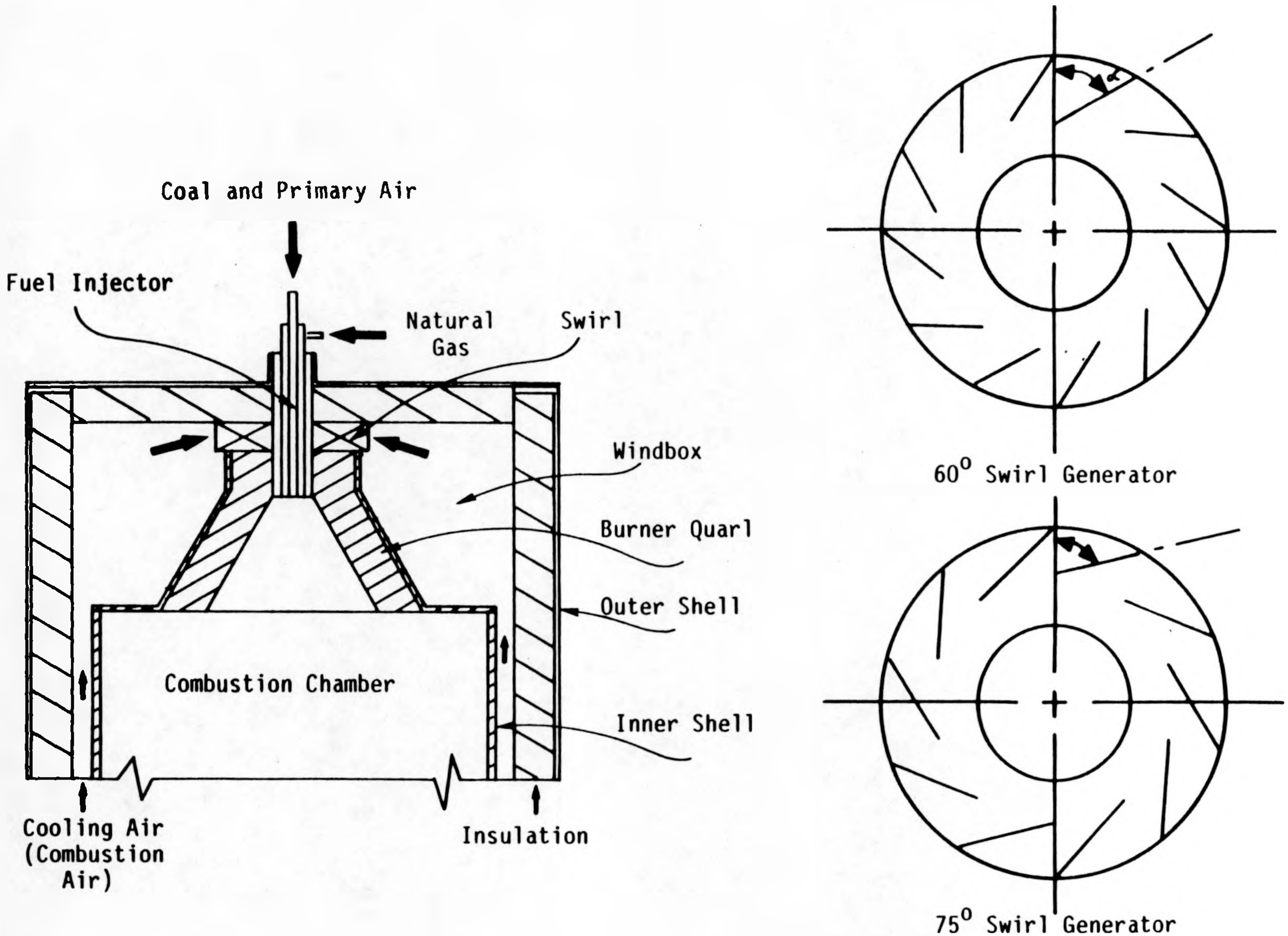

Figure 2-2. Cross-sectional view of optimized burner.

TABLE 2-1. PROTOTYPE BURNER SPECIFICATIONS

Parameters	Short Quarl
Firing Rate (Btu/hr)	100,000
Primary Design	
Stoichiometry (% TA)	35
Coal Nozzle Diameter (in)	0.495
Velocity @ 70^oF (ft/s)	70
Coal Nozzle	
Open Area (in^2)	0.15
Velocity @ 70^oF (ft/s)	93
Nozzle Position	Adjustable
Secondary Design	
Velocity (ft/s)	100
(SR_T = 1.4, 1000^oF)	
ΔP (Inch WC)	5
Swirl Generator (Removable)	Fixed Radial Vanes
Vane Angle (Degree)	60,75
Swirl Number (Estimate)	0.91, 1.54
Burner Exit	Refractory-Lined
Exit Diameter (in)	5.25
Half Angle (Degree)	40
L/D	0.66
Configuration	Air-Cooled

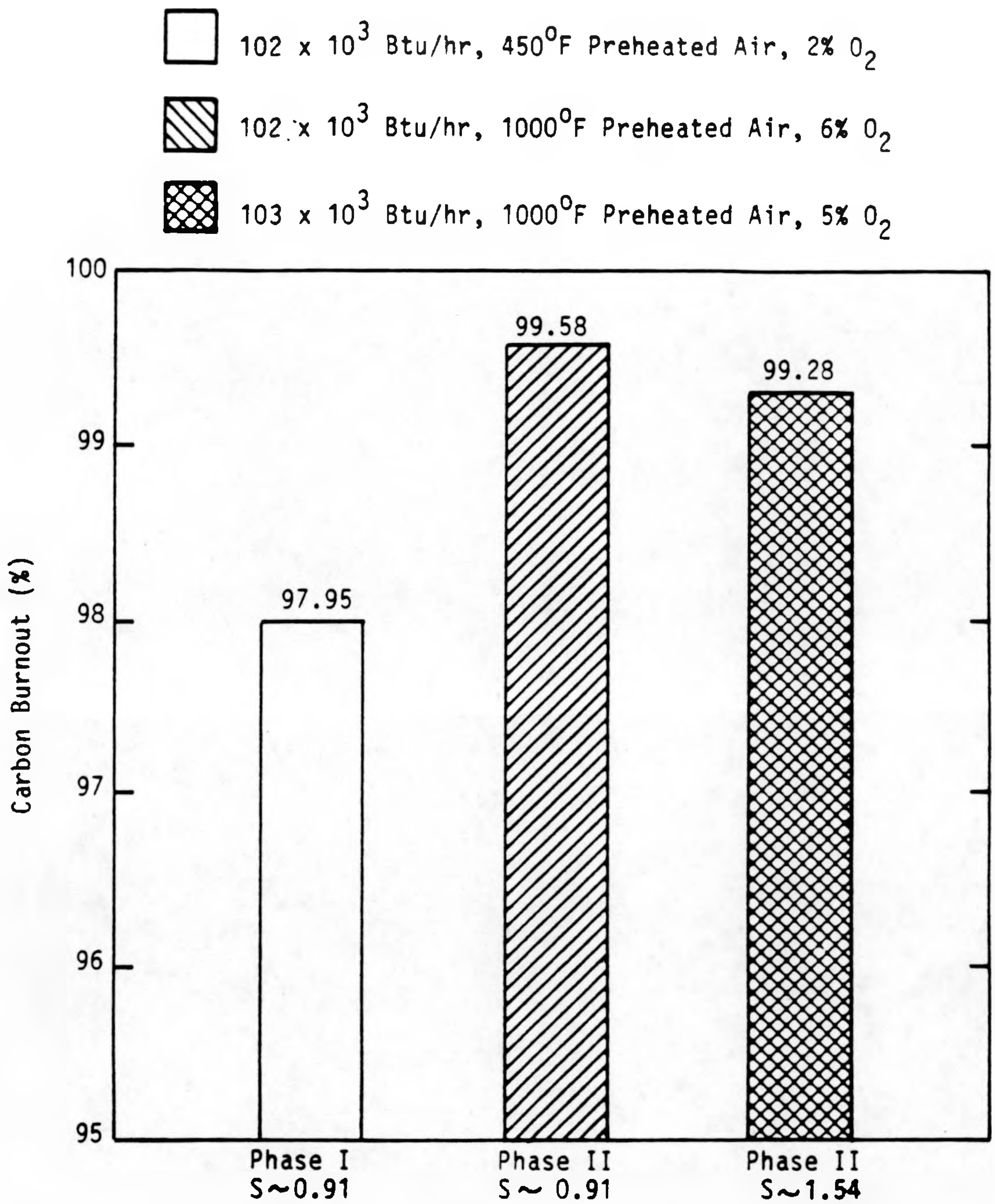

Figure 2-3. Carbon burnout for different burner designs and operating conditions - Phase II Burner Optimization.

that the low swirl intensity design seems to be more desirable. However, in evaluating both burner configurations, the higher swirl design showed better performance as far as flame stabilization is concerned, which is the subject of discussion in the next section.

2.3 Response Time

As mentioned earlier, the primary function of a burner is to produce a "stable flame". The question of how effective a burner is in stabilizing a flame was addressed in Phase II. The question is addressed as response time. Two modes of response time are defined as part of the burner development:

- Cold start-up response time, τ_{cs}
- Hot cycle restart response time, τ_{rs}

The cold start-up response time is defined as the elapsed time from the moment a cold combustor is energized to the moment when no support fuel is needed to sustain a full load coal flame. Figure 2-4 compares the cold start-up characteristics of the two burner designs as well as the amounts of auxiliary fuel (natural gas) consumed during the start-up period. With the low swirl burner ($S \sim 0.9$), full load flame stability was achieved in about an hour. The corresponding auxiliary fuel consumption during the start-up was about 48 cu. ft. As for the high swirl burner, cold start-up time was reduced to half, and about 20 percent of natural gas was saved. Tests were also conducted to see whether higher firing rates could reduce response time. Results from this series of tests are also given in Figure 2-4. By using the low swirl burner, cold start-up response time was reduced from an hour to about 43 minutes when firing rate was raised from 103×10^3 to 122×10^3 Btu/hr. Auxiliary fuel consumption was also reduced by 16 percent approximately.

The second type of response time is for cycling operation. A forced-air furnace or space heater commonly operates in a cycling mode, depending on heat demand, which in turn, depends on many factors. Among them, for example, are outdoor weather, type of insulation of a house, thermostat setpoint, etc. The cycling response time is defined as the elapsed time for the combustor to achieve a stable, full load flame from the time the combustor is re-energized to the point where no auxiliary fuel is needed.

Cycling response time for the low-swirl burner was briefly characterized. Because a variety of conditions can affect the cycling response time, a set of fixed conditions was established to conduct this series of tests, namely:

- Combustor fired on full load (100 x 10^3 Btu/hr)
- Combustor provided stable coal flame (no pilot)
- Combustor reached a thermal equilibrium condition (i.e., steady-state surface temperature at a given location of the combustor) before shutdown
- Pilot size was about 10 x 10^3 Btu/hr
- Coal feed energized upon confirmation of a pilot flame

Test results for this series of experiments are presented in Figure 2-5. Cases (a) and (b) represent the combustor shutdown for 10 and 15 minutes, respectively. In both cases, the burner produced a stable coal flame after 5 minutes of pilot-assisted ignition. For Case (c) where the shutdown time was 20 minutes, the burner required about 7 minutes of pilot flame to restore stability of coal flame. As the time of shutdown was increased to 25 minutes (Case d), about 22 minutes of continuous pilot support was needed to restore flame stability. It is interesting to see that this response time (Case d) can be cut to half by increasing the nominal firing rate from 100 x 10^3 Btu/hr to 120 btu/hr (Case e). This improvement of pilot-assist time is probably attributed to higher firing density which offsets the huge heat losses due to extended cool-down period during shutdown. Again, it is expected that the cycling response time will be a function of shutdown time. If the typical cycling mode (down time) of a space heater is between 10 and 15 minutes, 5 minutes response time will be easily achievable with this low swirl burner. Based on the performance of the cold start-up response time, the high swirl burner appears to perform much better. Full evaluation of this response time characteristics for both cold and cycling modes will be carried out for the integrated prototype combustor.

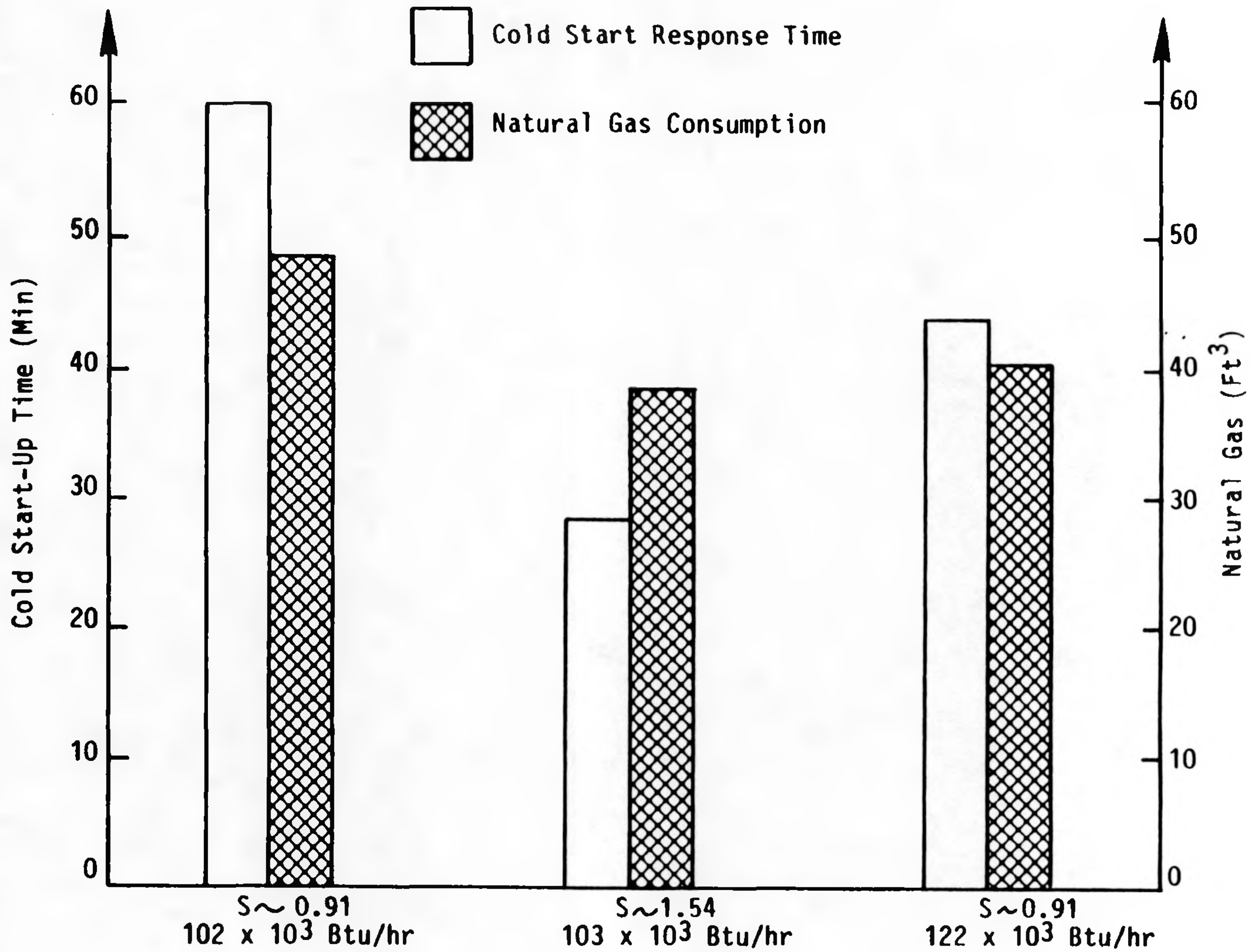

Figure 2-4. Cold start-up response for different burner designs and operating conditions.

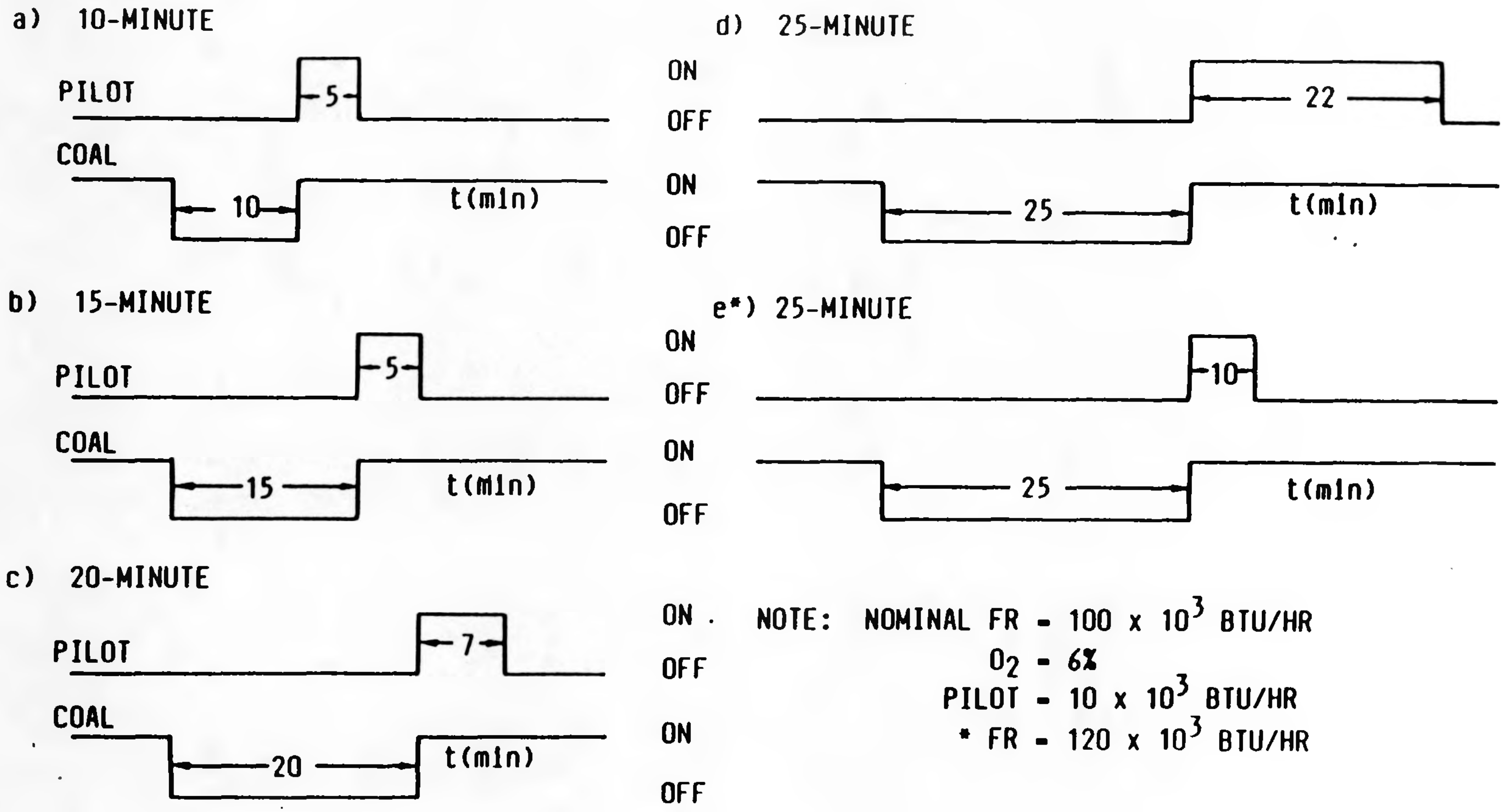

Figure 2-5. Characteristics of cycling response time for several operating conditions.