United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/7-79-037a
February 1979

EPA

Design Optimization and Field Verification of an Integrated Residential Furnace - Phase 1

Interagency Energy/Environment R&D Program Report

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U S Environmental Protection Agency, have been grouped into nine series These nine broad categories were established to facilitate further development and application of environmental technology Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are.

1 Environmental Health Effects Research

2 Environmental Protection Technology

3. Ecological Research

4 Environmental Monitoring

5 Socioeconomic Environmental Studies

6. Scientific and Technical Assessment Reports (STAR)

7. Interagency Energy-Environment Research and Development

8. "Special" Reports

9. Miscellaneous Reports

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects, assessments of, and development of, control technologies for energy systems, and integrated assessments of a wide range of energy-related environmental issues.

EPA REVIEW NOTICE

EPA-600/7-79-037a

February 1979

Design Optimization and Field Verification of an Integrated Residential Furnace - Phase 1

by

A.S. Okuda and L.P. Combs

Rockwell International
Rocketdyne Division
6633 Canoga Avenue
Canoga Park, California 91304

Contract No. 68-02-2174
Program Element No. EHE624A

EPA Project Officer: G. Blair Martin

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ABSTRACT

The report describes the first phase of an investigation to further optimize the design of a prototype low-emission residential furnace, that was derived from earlier EPA-funded studies, and to obtain field verification of its emission and performance characteristics. Details are given concerning three major subdivisions of work in Phase I, namely: (1) analytical and experimental studies to optimize the furnace design and its nominal operating ranges, and to ensure conformance with appropriate safety standards; (2) planning all aspects of the subsequent (Phase II) field test investigation, including selection of test locales and host homes, provision of local installation and service support, and all logistic and scheduling considerations; and (3) studies of the integrated furnace's capabilities to function properly with alternate fuels, such as natural gas and methanol.

CONTENTS

FIGURES

TABLES

SECTION 1

INTRODUCTION

Under a previous EPA contract (Ref. 1), design criteria were determined whereby gun-type pressure-atomizing distillate oil burners, such as are commonly used in residential and commercial space-heating systems, may be modified so that they produce substantially lower emissions of oxides of nitrogen (NO_x) and burn smoke-free at more efficient operating conditions. Those design criteria were used to modify existing burners of two sizes--a 1.05 ml/s (1.0 gph) residential burner and a 9.47 ml/s (9.0 gph) commercial burner--and were demonstrated to be valid in laboratory testing.

Further laboratory research, under another EPA contract and with the smaller of those two low-emission oil burners, provided additional design criteria for fireboxes matched to the burner to achieve even lower NO_x emissions (Ref. 2). Thereafter, proof-of-concept experiments were carried out in the laboratory using a prototype residential warm-air furnace embodying the several design criteria (Ref. 3 and 4). The resultant NO_x emissions were reduced to about 35% of the estimated average from comparable, existing, installed units. Further, the laboratory performance data showed that the prototype furnace's cycle-averaged thermal efficiency should be 10 or more percentage points higher than the estimated average of the existing residential oil furnace population.

The present investigation is a logical continuation from those encouraging laboratory results. Potential benefits of commercializing the derived technology are to be demonstrated by conducting field tests of several low-emission furnaces in actual residences. First, however, it was appropriate to effect further refinements of the burner and furnace designs, partially to further optimize emissions and efficiency performance and partially to improve commercial producibility. Thus, the two objectives of this investigation have been: (1) beginning with the prototype furnace tested earlier, to further optimize the design of an integrated, low-emission, high-performance, oil-fueled, residential warm-air furnace; and (2) to verify its pollutant emissions and thermal efficiency performance by operating units over an entire winter heating season in actual residential installations.

The investigation is being performed in two phases. In Phase I, further design optimization has been approached by making modifications to the prototype low-emission furnace described in Ref. 3, and retesting the unit in a Rocketdyne laboratory. Eventually, this led to the construction and verification testing of a second, all-new, integrated furnace unit prior to assembly of six units of the final design to be installed in the field.

Simultaneously pursued was the definition of field test requirements, comprised of selecting test locales, arranging for local support, selecting host residences, considering the logistics of shipping, installing, activating, and servicing, measuring performance and, finally, removing the experimental furnaces and restoring the host homes' heating systems to their former conditions. Phase II, which is currently being performed and will continue through the summer of 1978, is concerned with construction, shipment, and installation of the field test units, as well as with monitoring their performance and emissions and, finally, interpreting and reporting the results.

SECTION 2

CONCLUSIONS

Based on the experimental investigation to optimize further the prototype low-emission residential furnace (derived from Contract 68-02-1819) into an integrated furnace design amenable for field verification testing, it was concluded that:

1. Cast-forming of gray iron is the preferred method for fabricating the integrated furnace's finned, air-cooled combustor.

2. A satisfactory, leak-proof joint between the cast-iron firebox and steel heat exchanger may be formed by casting a cylindrical steel band into the exhaust port of the firebox and welding the heat exchanger to that band.

3. The effectiveness of heat extraction from the flue gases is influenced only slightly by variations in: (a) the air flow patterns over the outside of the air-cooled firebox and air-cooled primary heat exchanger, and (b) the flue gas distribution pattern within the heat exchanger. Proportionately greater heat extraction would require either a larger heat exchanger or a lower furnace firing rate.

4. To satisfy the target firing-cycle-averaged smoke emission requirement of < No. 1 smoke on the Bacharach scale, it was necessary to change the integrated furnaces's nominal operating set point from 1.05 ml/s (1.0 gph) and 15% excess air to 0.79 ml/s (0.75 gph) firing rate and 20% excess air. (This was attributed to the smoke measurements having been erroneously low during much of the previous prototype furnace investigation.)

5. Installation of a flanged ring on the outer perimeter of the simulated, stamped sheet metal burner head also aided in minimizing smoke emissions by preventing uncontrolled leakage of combustion air away from the main flame zone.

6. Combustion with low-temperature outdoor ambient air, admitted through the furnace's sealed air system, is accompanied by a modest increase in excess air level as the temperature falls. The emissions of air pollutants remain essentially invariant, even to subzero temperatures.

7. The integrated furnace conforms sufficiently closely to the Underwriters Laboratories (UL) safety requirements that it will not constitute a safety hazard for either host homes or service personnel in a field testing investigation. (This assessment is based on: (1) a limited, nontesting preliminary investigation by UL, (2) Rocketdyne's design modifications in response to UL's observations, and (3) Rocketdyne testing of integrated furnace behavior under limit variation conditions.)

Based on the preparations for field testing, it was concluded that:

1. Conducting the field tests in the vicinities of Boston, Mass., and Albany, N.Y., will provide adequate test furnace exposure to two distinctly different winter climates in communities having a large porportion of homes heated by fuel oil and an adequate proportion of basement installations of warm-air furnaces.

2. In Massachusetts, approval of the burner design is required before field test furnaces can be installed in homes. Otherwise, no formal government sanctions or independent laboratory certifications are required in the selected field test locales.

3. Installation of test furnaces by qualified local residential heating contractors will ensure conformance to local building codes and maintenance of good practices. Contractors have been selected and arrangements made for them to provide periodic routine inspections and emergency service as required.

4. Periodic measurements of furnace performance and air pollutant emissions can best be made during monthly visits of a Rocketdyne engineer to each field test installation. He will use a mobile laboratory and recording data loggers in this monitoring effort.

From investigation of the capability of the integrated furnace to function properly with fuels other than No. 2 fuel oil, it was concluded that:

1. Alternate gaseous and liquid fuels for residential heating most likely to be of interest in the near future are natural gas and methanol, respectively.

2. Substitution of natural gas for No. 2 fuel oil in the integrated furnace requires more than a simple replacement of the power burner's oil tube/spray nozzle with a gas/air mixing tube. Therefore, a commercially available inshot conversion gas burner was used for a limited experimental investigation.

3. At heating rates with natural gas equivalent to the design range for No. 2 fuel oil, the integrated furnace produces higher emissions of CO and UHC and lower smoke than it does with distillate oil. This was interpreted as being due to extraction of excessive heat from the flame zone and/or to the firing rate being too high for the combustion chamber volume.

4. NO_x emissions were lower with natural gas than with oil in the tests performed, but it is anticipated that they would become essentially the same if the firebox design were altered to lower the carbonaceous emissions from natural gas.

5. Substitution of methanol for No. 2 fuel oil in the integrated furnace is simple and straightforward. In the laboratory tests, only the burner spray nozzles were changed.

6. At methanol heating rates equivalent to the design range for No. 2 fuel oil, the integrated furnace produces very low emissions of smoke, UHC, and NO_x but, similar to the experience with natural gas, produces inordinately high CO emissions. The CO emissions were reduced by increasing firing rate, so their level is attributed to extraction of somewhat too much heat from the primary flame zone.

7. If the air cooling of the firebox were reoptimized for methanol, the emissions of all measured air pollutants from the integrated furnace would be substantially lower than with No. 2 fuel oil.

8. For equal operating stoichiometric conditions and noncondensing flue exhaust temperatures, the maximum achievable thermal efficiencies with natural gas and methanol are approximately 2 and 6% lower, respectively, than with No. 2 fuel oil.

SECTION 3

RECOMMENDATIONS

In view of the results and conclusions of the Phase I studies, it is recommended that:

1. The Phase II field test investigation should be undertaken immediately using the plan developed during Phase I with some slight modifications.

2. A total of six integrated furnaces should be constructed for the field test investigation. They should be built in the Rocketdyne laboratory using the same techniques for custom modifying commercially procured furnaces as were used in constructing the first two integrated furnaces in Phase I. To the extent possible, the units should be identical.

3. Rocketdyne's laboratory instrumentation for measuring emissions should be employed in a mobile laboratory configuration for monitoring the emission characteristics of the field test furnaces.

4. Depending upon the outcome of the field testing, Phase II analyses should include (a) suggested means to solve outstanding technical questions, e.g., by modifying component designs, operating conditions, control circuits, safety features, etc.; (b) consideration of alternate construction practices, particularly with respect to the firebox; and (c) engineering estimates of the unit costs of integrated furnaces, produced both in limited (R&D) quantities and in commercial volumes. Also, Phase II documentation should address service and maintainence requirements experienced and anticipated.

SECTION 4

SUMMARY OF THE PROTOTYPE FURNACE INVESTIGATION

The experimental furnace unit tested previously (Ref. 3 and 4) has been called a "prototype optimum furnace." For clarity in this report, that earlier test unit will be designated the "prototype furnace" and the further optimized unit derived from it will be referred to as the "integrated furnace." In this section are given brief descriptions of the prototype furnace and the laboratory facility in which it was tested, followed by a summarization of its emissions and efficiency performance.

PROTOTYPE FURNACE DESCRIPTION

The prototype test unit was based on modifying or replacing several specific components in a comercially available warm-air oil furnace of contemparary design*. The prototype furnace and the advanced technology modifications made to achieve it are illustrated in Fig. 1. The central line drawing is an interior side view of the furnace; the front is on the left-hand side. Each of the photographs surrounding the drawing illustrates a modification made and an arrow denotes its location in the furnace assembly.

The optimum burner head is illustrated alone although, in actuality, the furnace's entire burner was replaced with the optimum burner that had been tested extensively before, rather than replacing only the head. The combustion air fan in the replacement burner was also fitted with a quiet stator plate to prevent coupling of combustion air flow pulsations to combustion in the chamber.

The unit's original firebox, a rather typical 0.249 m (9.75 inch) inside-diameter refractory-fiber-lined design, was replaced by a larger 0.303 m (12 inch) inside-diameter, uninsulated, air-cooled firebox. Its outside surface was heavily finned to ensure adequate heat extraction from the flame zone, a key contributor to the reduction of NO_x emissions. The machined and welded mild steel prototype firebox was more massive by about 50 kg (110 lbm), than its predecessor, and thus constituted a substantial heat sink. Built as an experimental tool, the firebox was intentionally overdesigned in the interests of maintaining wall temperatures as nearly uniform as possible and retaining high wall temperatures during standby.

*A Lennox Model 011-140 furnace, supplied by Lennox Industries, Inc., was utilized.

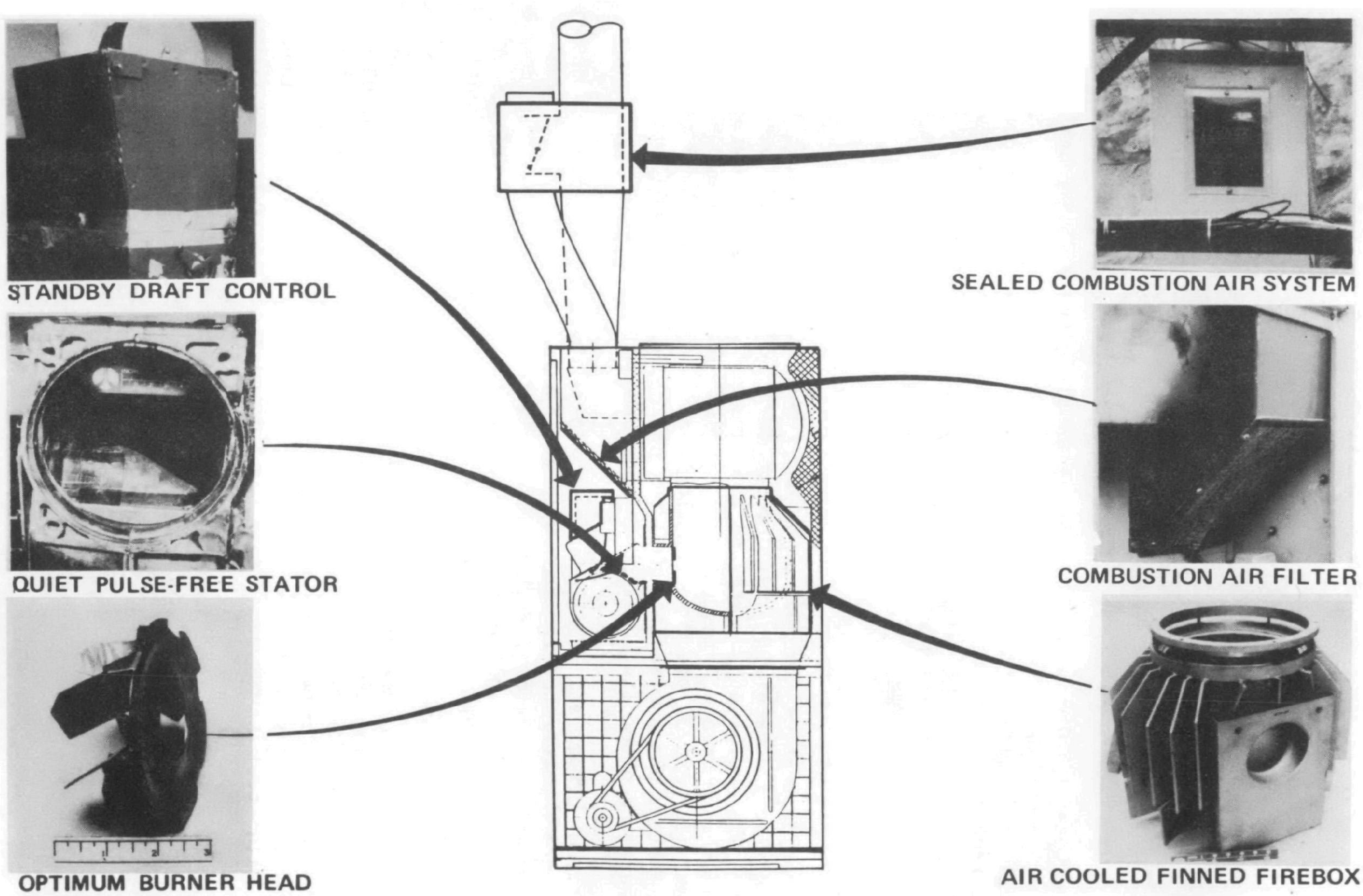


Figure 1. Prototype furnace modified components

Two related modifications were concerned with the combustion air supply. First, combustion air was admitted to the furnace through a "sealed air" supply system, adapted from Ref. 5. Simply stated, this means that combustion air, together with air drawn into the flue through a barometric pressure control damper, is brought in from outdoors rather than consuming heated (and perhaps humidified) air from within the residence. Pollutant emissions usually are not influenced by this change, but fuel consumption may be reduced by 5 to 10% or more (Ref. 5). Second, a separate filter was provided for the combustion air so that the burner could be tuned to operate with close to minimum (~15%) excess air without accumulating lint, hair, etc., on the burner air passages, fan flades, or head, which could force the burner into a smoky and/or high CO condition.

The combustion air inlet to the burner was fitted with a weighted damper which closed automatically when the burner was turned off. It was designed to eliminate the loss of heat up the flue caused by draft air flowing through the furnace during standby. Fuel savings effected by this device will probably average between 2 and 3%. This device also included a separate butterfly damper whose position controlled the flow of combustion air.

Minor modifications also were made to a few other furnace components. Louvers in the burner vestible closure panels were covered to seal the vestibule and make it part of the sealed air system. Inside the cabinet, some minor structural reinforcement was added to support the heavier firebox, and flat, vertical-panel baffles were added in the warm-air passages to force the warm air to flow over the finned firebox. Otherwise, the warm-air blower and filter, the compact heat exchanger, the furnace cabinet, and all electrical circuits and controls were left unchanged from the original stock furnace.

LABORATORY FACILITY

Performance of the prototype furnace was evaluated in an outdoor laboratory facility having provisions for measurement of pollutant emissions, operational characteristics, and thermal efficiency. Figure 2 is a schematic of the furnace evaluation system; it shows the installation of gas- and air-flow ducting and a variety of instrumentation. Basic thermal performance measurement techniques conformed with requirements of ANSI Z91.1-1972 (Ref. 6). Other instrumentation was added to provide (1) enlarged understanding of furnace behavior and (2) data for calculating cycle-averaged thermal efficiency.

Constituents in the flue gases were measured by continuously withdrawing a gas sample from the center of the flue, at the location denoted in Fig. 2, and passing it through an analysis train. The analytical system provided for manual spot samples for smoke and for continuous analyses for O_2, CO_2, CO, NO_x and unburned hydrocarbons (UHC) species remaining in the dry gases after their passage through condensible traps, filters, and driers. Detailed information of the setup and operation of the train, instruments used and their ranges, data processing, etc., has been given previously in Ref. 1 through 3.

The furnace flue thermal losses were determined by making measurements to support flue gas heat balances. The specific heat properties can be determined from the composition of the flue gas. This in combination with the net

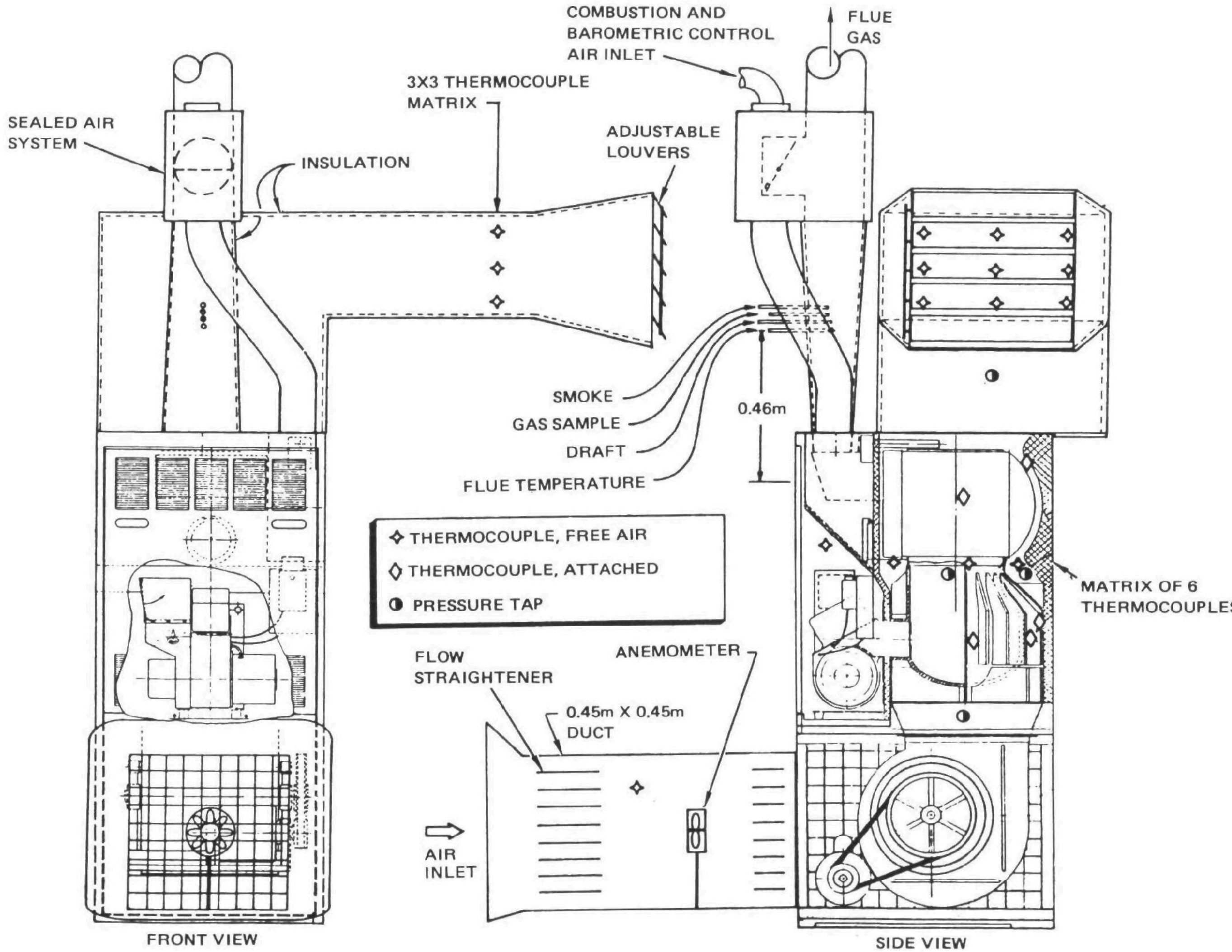


Figure 2. Schematic of the furnace performance evaluation system

flue gas temperature allows the calculation of the heat content of the flue gases relative to the heat input resulting in a thermal efficiency value. The realtionship of flue gas composition and net temperature to thermal efficiency has been tabulated in Ref. 6. The flue gas exhaust temperature was measured in an insulated flue pipe with a thermocouple located 0.46 m (18 inches) above the centerline of the heat exchanger exit. Flue draft, gas composition, and smoke measurements were taken at successive 0.0317 m (1.25 inch) increments downstream of the thermocouple, respectively.

Steady-stage thermal efficiencies were derived from the steady-state flue gas temperatures and CO_2 concentrations (Ref. 6). During cyclical operation in which steady state was not reached, values for those parameters just prior to burner cutoff were used in the same manner to get approximations of steady-state efficiencies. Burner firing times of 10 minutes gave such pseudo-steady-state efficiencies that were indistinguishable from those derived from steady-state measurements; those calculated from 4-minute burner firing time data were approximately 1% higher than the steady-state efficiencies due to heat being absorbed by the cool furnace components resulting in a lower flue gas temperature.

Data were also measured to support calculation of cycle-averaged efficiencies. However, the variable ambient-air temperature in the outdoor facility introduced considerable scatter in the data (Ref. 3). Indicated differences between the mean steady-state and mean cycle-averaged efficiencies were smaller than that scatter, so steady-state was used as the main basis for comparison.

PROTOTYPE FURNACE RESULTS

Pollutant Emissions

Prototype furnace flue gas concentrations of nitric oxide are plotted versus stoichiometric ratio in Fig. 3. A shaded region near the middle of the graph indicates that a large majority of existing residential oil furnaces release between 1.3 and 2.2 g NO/kg fuel burned. An estimated existing furnace average of 1.8 g NO/kg fuel may be used for evaluating the potential impact of applying candidate NO_x reduction techniques.

Measured NO emissions from the stock furnace, before it was converted to the low-emission prototype furnace, fell on the high side and above that typical range; at a nominal 50% excess air operating point, it produced 2.2 g NO/kg fuel burned. Measured NO emissions from the prototype furnace were much lower, falling between 0.5 and 0.75 g NO/kg fuel over the stoichiometric ratio range of interest. Tuned to the intended normal operating condition with only 15% excess air, the unit produced 0.63 g NO/kg. That corresponds to reductions of about 72 and 65%, respectively, from NO_x emissions produced by the stock furnace (at its nominal operating point) and by the average estimated for all existing installed units.

Carbonaceous emissions from the prototype furnace unit also were acceptably low at those conditions, as indicated by the lower than No. 1 smoke. A comparison of values in Table 1 shows that CO and hydrocarbon emission levels

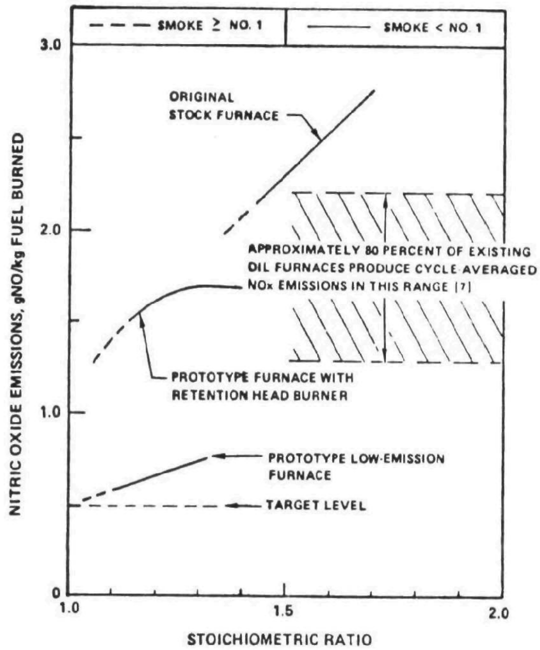


Figure 3. Cycle-Averaged NO Emissions

from the prototype furnace were somewhat higher than those measured for the stock furnace, but were quite comparable with the average tuned values measured in the field survey of Ref. 7.

TABLE 1. COMPARISON OF POLLUTANT EMISSIONS FROM VARIOUS RESIDENTIAL FURNACES

	Tuned averages from Ref. 7	Original stock furnace	Prototype furnace
Stoichiometric ratio	1.85	1.50	1.15
Carbon monoxide, g/kg fuel	0.6	0.27	0.55
Unburned hydrocarbons, g/kg fuel	0.07	0.015	0.055
Smoke, Bacharach number	1.3	0	<1
Nitric oxide, g/kg fuel	1.8	2.2	0.63

Efficiencies

Pseudo-steady-state efficiencies for the prototype furnace are compared with those for its stock predecessor in Fig. 4 by superimposing values calculated from fourth-minute data in cyclical runs on an efficiency decrement plot. The performance curve for the original stock furnace fell well below (i.e., higher efficiencies) the shaded band representative of a large majority of existing installed residential heating units. The stock unit could be tuned to a moderately low 50% excess air nominal operating condition where its net flue gas temperature averaged only 180 C (325 F). The resultant steady-state gross thermal efficiency was 82.5% (i.e., the stock furnace was among the higher-performing units in the existing population).

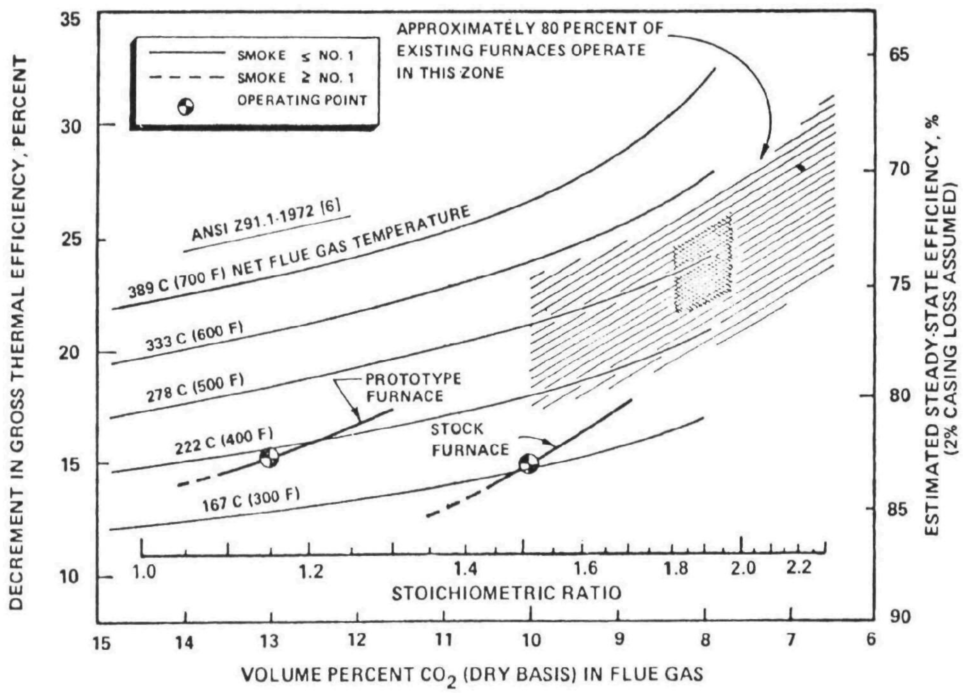


Figure 4. Pseudo-steady-state thermal efficiencies

Thermal efficiency levels achieved by the prototype furnace were qualitatively the same as those of the stock furnace. However, as is evident in Fig. 4, flue gases leaving the prototype unit were 40 to 55 C (75 to 100 F) hotter than those from the stock furnace, and the efficiency decrement due to the higher net flue gas temperature was offset by operating the prototype unit at substantially lower stoichiometric ratio. This apparently anomalous behavior was believed to be caused by warm-air jets outside of the firebox bypassing some of the main heat exchanger, a condition which was thought to be relatively easy to correct.

The 82 to 83% pseudo-steady-state thermal efficiency exhibited by the prototype furnace was close to the maximum achievable in noncondensing flue gas residential systems. Taken alone, this is not unique, since comparable efficiencies are attained by some current commercially available units (as exemplified by the stock furnace that was converted into the prototype). What is unique and important about it is the demonstration that near-maximum steady-state efficiency and near-minimum NO_x emissions can be obtained simultaneously.

SECTION 5

INTEGRATED FURNACE DESIGN OPTIMIZATION

The prototype furnace test results confirmed the feasibility of applying the several newly developed, low-emission oil burner and firebox design criteria to residential space heating equipment. When tested in the laboratory, the experimental prototype unit came very close to satisfying all of the pollutant emission and efficiency objectives for which it was designed. Operationally, its behavior was quite comparable with current commercially available furnaces. A 500-hour duration test, equivalent to about one-tenth of an average heating season, indicated that the unit might serve through an entire winter heating season without requiring substantial maintenance and without exhibiting appreciable shifts in operating conditions or pollutant emission levels. Before undertaking such a next logical step in the proof-of-concept demonstration of the furnace design criteria, however, it was appropriate to further improve some features of the prototype unit.

MODIFICATIONS FOR THE INTEGRATED FURNACE

Optimum Burner

The standby draft control device for the combustion air inlet to the burner was redesigned, as illustrated in Fig. 5. The butterfly valve was removed and air-flow control was accomplished by providing a mechanical stop to limit the opening of the weighted flap damper. A microswitch was incorporated in the stop to provide a positive electrical indication that the draft flap opens when the burner is turned on; the burner control circuitry was redesigned to take advantage of this safety feature (Fig. 6).

A commercially available (Pioneer Products Model RT-3450) centrifugal clutch was inserted in the burner's drive shaft for the fuel pump. The reason was to give a quicker cutoff of fuel flow through the oil nozzle, to better eliminate post-firing dribble.

The burner's blast tube was shortened from 0.191 m (7-1/2 inches) to 0.152 m (6 inches) to prevent the back of the burner from extending beyond the plane of the burner vestibule door.

Finned, Air-Cooled Firebox

The fabricated steel firebox, with its large external steel fins welded to a 0.64 cm (0.25 inch) thick steel shell was inordinately expensive to make, heavier than desirable, and extracted more than the designed-for quantity of heat from the flame zone. Therefore, it was replaced with a lighter-weight,

NOTE: DIMENSIONS IN METERS

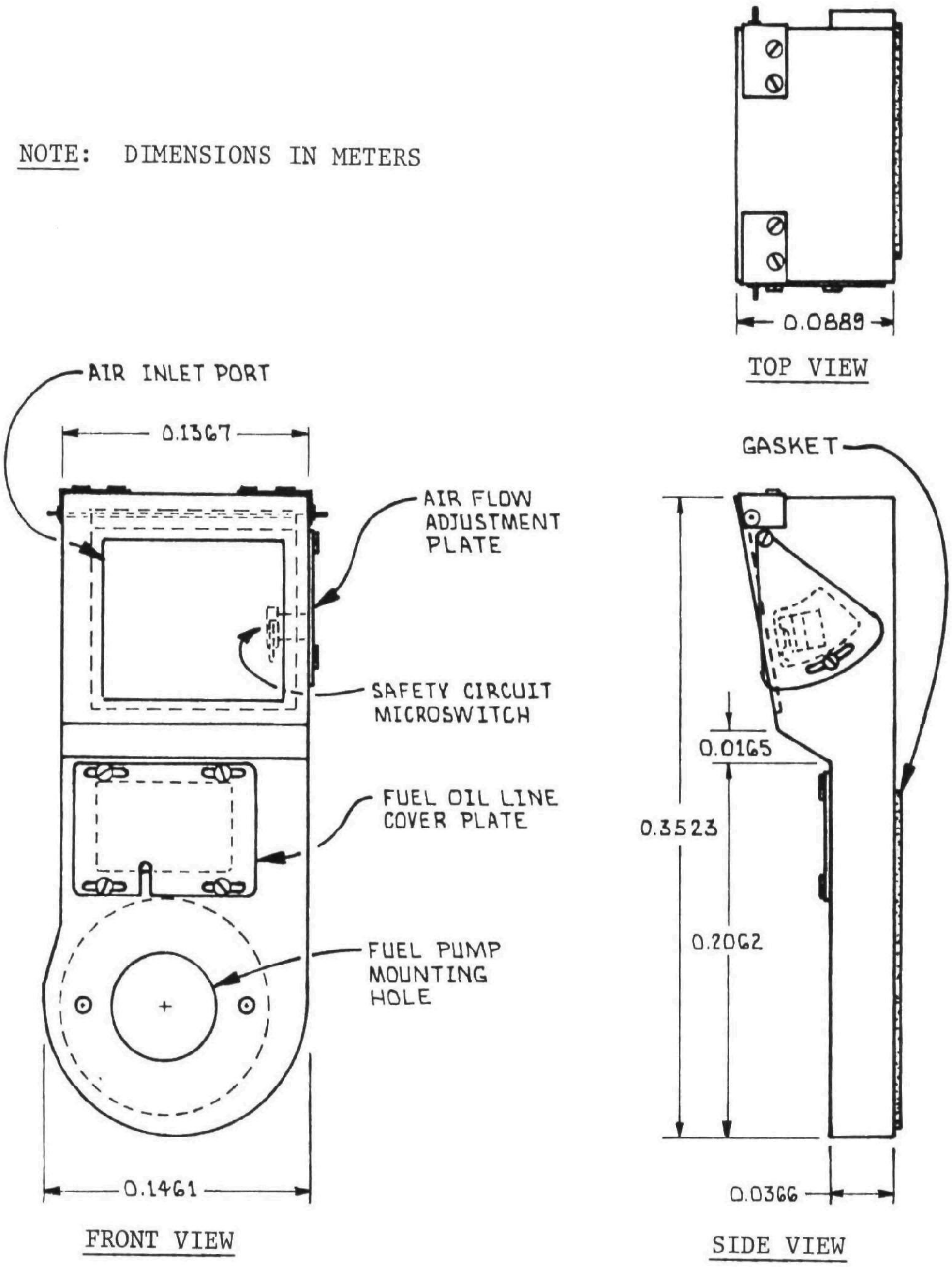


Figure 5. Combustion air inlet, draft-flap assembly for the optimum low-emission burner

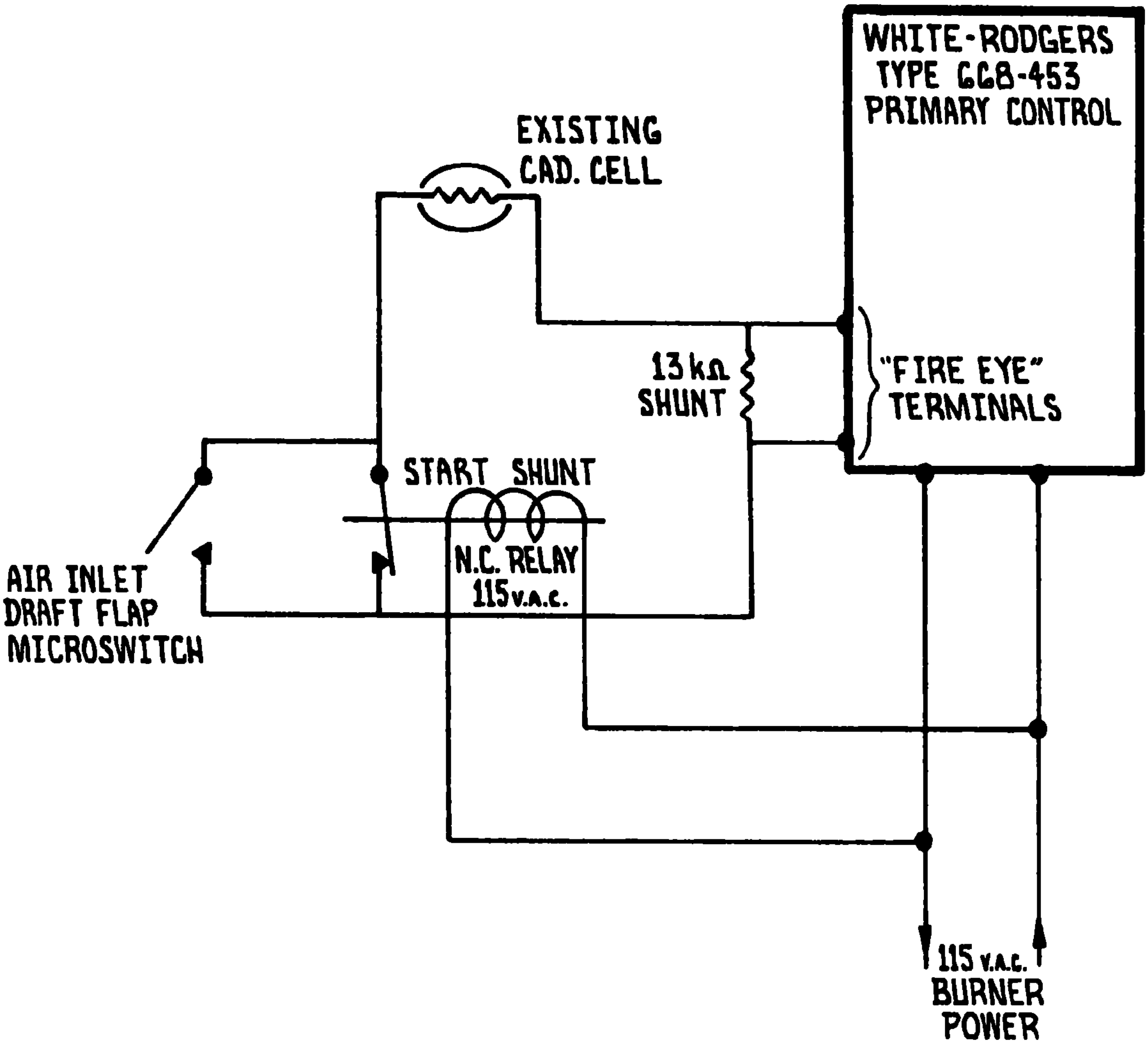


Figure 6. Electrical circuit schematic showing the inlet draft flap microswitch supplement to the flame detector circuit

cast-formed combustion chamber. Serious consideration was given to making a cast aluminum firebox (refer to Appendix A). Because aluminum has a high coefficient of thermal expansion and there is a substantial temperature gradient over the length of the cooling fins, tensile stresses approaching yield strength limit were calculated at the roots of the fins and at the firebox heat-exchanger joint, which would result in relatively short cyclical fatigue life. In principle, yield conditions could be avoided by maintaining low-wall temperatures but, even then, cycle-fatigue failure was predicted to lead to an unacceptably short firebox lifetime of 3 to 5 years. Therefore, cast iron was selected as the firebox construction material.

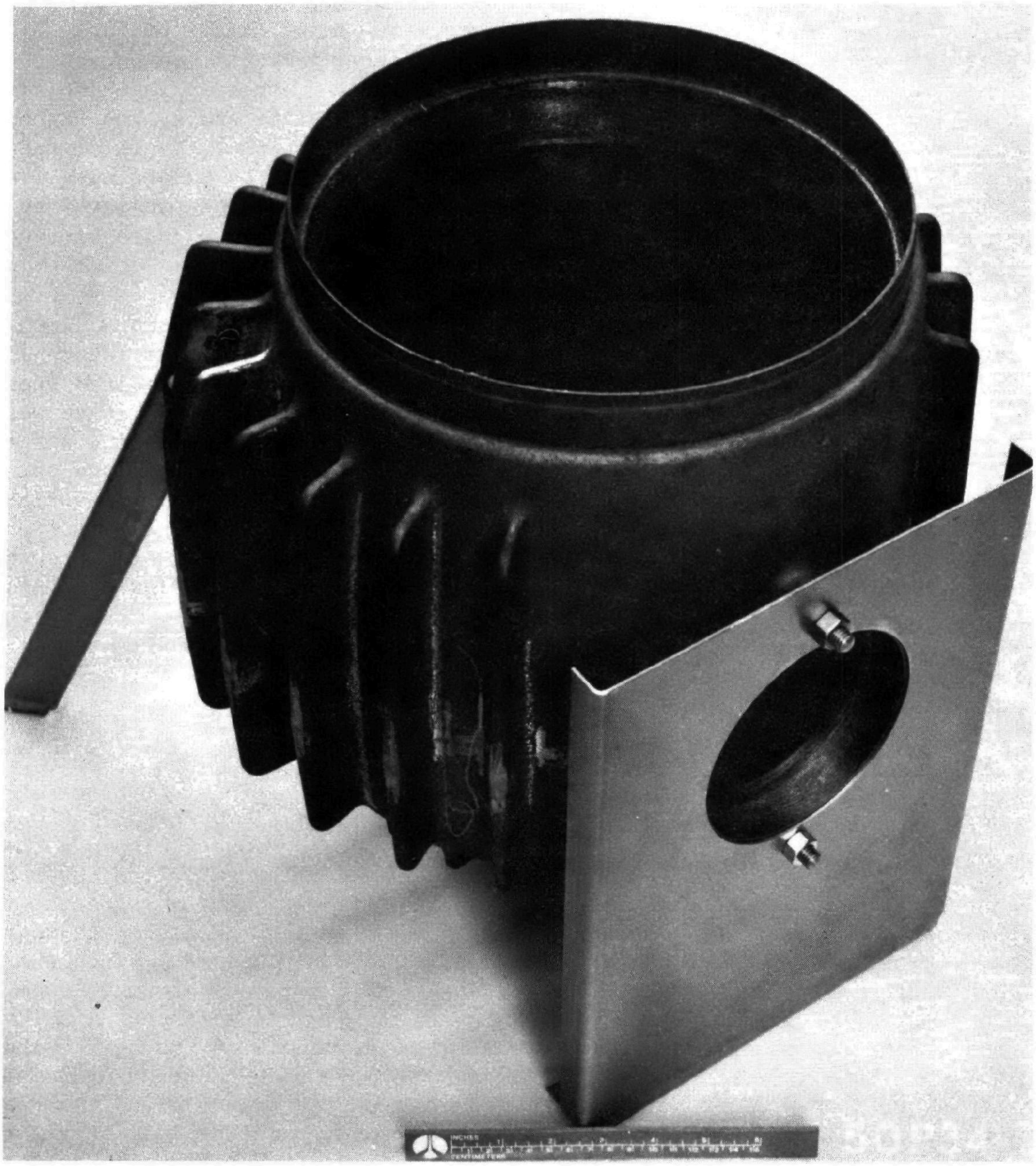
A photograph of the cast-iron firebox is shown in Fig. 7, and more dimensional detail can be seen in the two-view line drawing in Fig. 8. The internal dimensions and burner insertion port duplicate those of the fabricated steel combustor; otherwise, the designs are quite different. To facilitate welding the stock fabricated steel heat exchanger to the cast-iron firebox, a rolled steel ring is cast integrally into the wall of the firebox discharge opening. This provides a positively-sealed joint as well as a much smoother surface for the external air to flow over. All of the cast external fins are shorter than were the fabricated ones, and both their heights and spacings are graduated to promote more-nearly uniform wall temperatures. The shorter fins were designed to extract a smaller fraction of the overall heat transfer from the firebox; the cast wall temperatures were expected to average 56 C (100 F) higher than those of the former fabricated steel firebox. The cast firebox, together with its support legs and burner mounting plate, has a mass of 34 kg (75 lbm).

Warm-Air Coolant Distribution

The vertical, sheet metal baffle panels positioned close to the fin tips on each side of the prototype furnace's firebox were reshaped to improve the airflow distribution to the outside of the main heat exchanger. The baffles were bent slightly at about the midsection of the firebox to begin a gradual flaring from the constricted cross section to the full heat exchanger cross section. The location of each baffle remained the same; however, since the fins were shortened, this placed them about 0.064 m (2.5 inches) from the nearest fin tip, as opposed to nearly touching in the prototype furnace. Also, new baffle panels were added adjacent to the outside panels of the heat exchanger section. This was done to reduce the flow gaps between the heat exchanger and the wall by 0.025 m (1.0 inch), thereby reducing bypass (i.e., no heat transfer) air flow. These changes were made to restore the coolant air to the outer sections of the heat exchanger and, thus, to improve the overall heat transfer of the furnace.

LABORATORY TESTS OF THE PROTOTYPE AND FIRST INTEGRATED FURNACES

The first specimen of the integrated furnace was built by converting the prototype furnace via the foregoing modifications. It was tested in the same laboratory facility and with the same procedures as was the prototype unit. A basic test matrix provided for measurement of pollutant emissions and performance as functions of burner firing rate, overall stoichiometric ratio, combustion air supply temperature, firebox draft, and warm-air flowrate. The



50P34-1/28/77-S1F

Figure 7. Cast-formed air-cooled combustion chamber

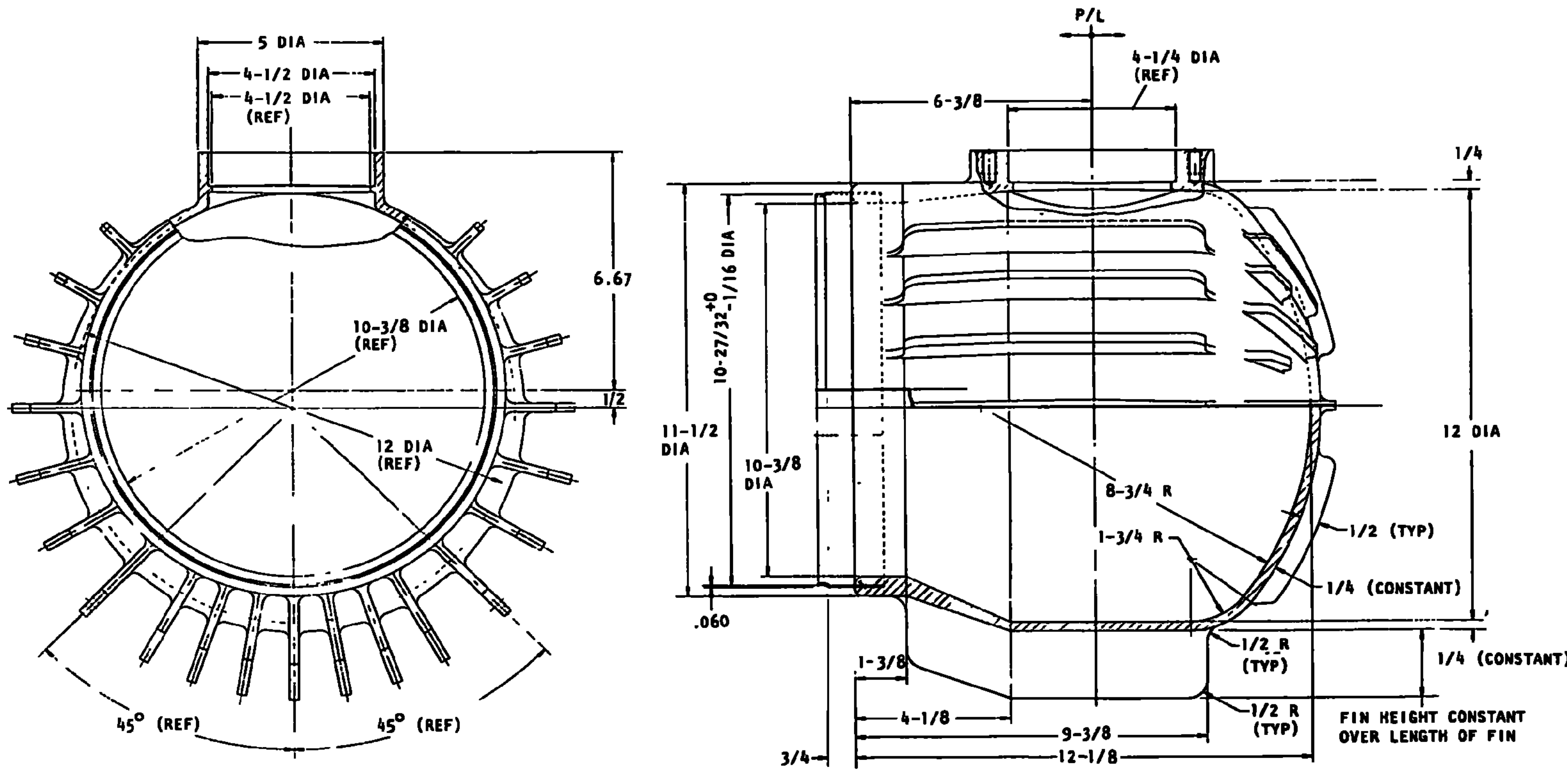


Figure 8. Drawing of the cast iron finned combustor for the integrated furnace system

test plan also allowed for retesting in the event that one or more components needed further refinements. Discussion of the extent to which this option was needed is included with the description of test results, below.

Hot-firings of the first integrated furnace were preceded by some exploratory tests of the prototype furnace, to obtain data to support firebox design, and some cold-flow tests of the burner, to measure the effects on the combustion air fan characteristics of the several complications added to the stock* burner's combustion air circuit.

Laboratory Test Results

Burner Blower Characteristics. The combustion air blower's characteristics were measured to establish the operational limits of the combustion air system. Tests were made with the air flow throttled either at the air inlet or at the exit. This was done by mounting the burner inside or outside, respectively, of a large sealed compartment and measuring the compartment pressure and air flow into or out of it. A calibrated laminar-flow element was used for accurate measurement of air flows.

Throttled outlet characteristics are shown in Fig. 9. The uppermost curves show that the presence of the quiet stator has very little effect on the blower's basic throughput characteristic. Successively lower curves show how the achievable air flow is impacted by adding, in sequence, the inlet draft flap assembly, a static disc within the blast tube, and the optimum head to complete the burner assembly. Dashed lines indicating pressure drops of the head, static disc, and draft flap were obtained by subtraction of appropriate characteristic curves. The nominal design operating point, with a firing rate of 1.05 ml/s (1.00 gph) and a stoichiometric ratio of 1.15, is indicated by an arrow at 0.0125 m^3/s (26.5 scfm). To achieve that flowrate without throttling the exit, the firebox would have to be pressurized to about 60 N/m^2 (1/4-inch water column). The usual residential furnace practice, however, is to throttle the inlet to the blower, rather than pressurizing the firebox or throttling the exit.

Effects of throttling the blower inlet (i.e., limiting the draft flap opening) are shown in Fig. 10, along with the effects of imposing a negative (suction) pressure condition on the air supplied to the inlet. The latter condition is encountered sometimes in conventional furnace practice by operating a furnace in a fairly leak-tight room or house, so that the burner blower reduces the pressure in the furnace enclosure. In the integrated furnace, pressure in the sealed burner vestibule also will be below ambient outdoor pressure by the pressure drop of the air supply system.

The throttled inlet characteristic curves show that, if the burner inlet is at sea level pressure, the nominal design conditions can be achieved with the draft flap only one-eighth open; opening it further should allow tuning for stoichiometric ratios (SR) from 1.15 to about 1.35. Reducing the inlet pressure exerts a linear reduction effect on the achievable flowrate; again, the

*The R. W. Beckett Co.'s Model AF burner was the stock unit underlying the optimum burner.

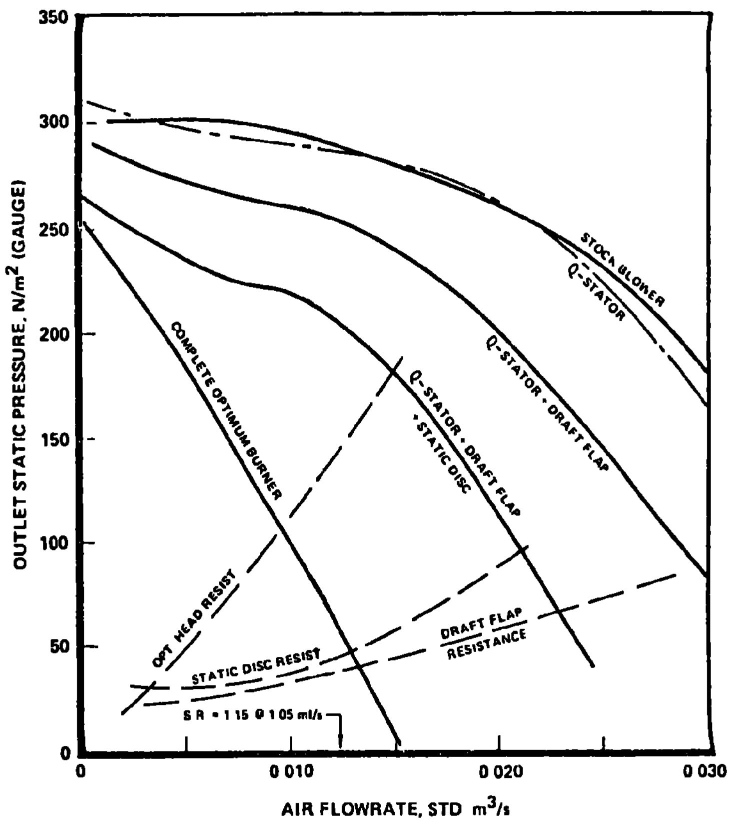


Figure 9. Throttled exit air-flow characteristics

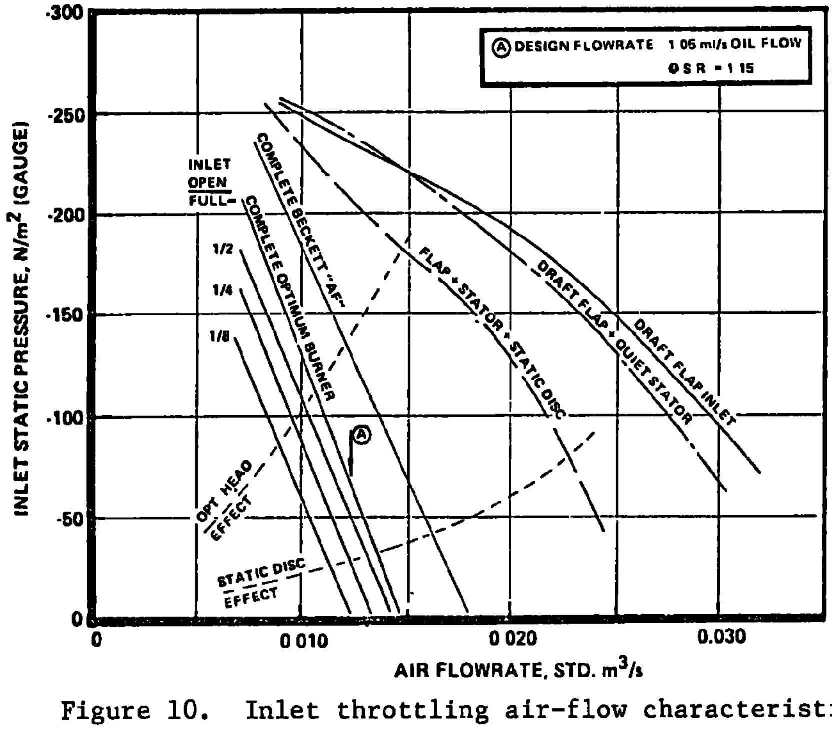


Figure 10. Inlet throttling air-flow characteristics

margin of adjustability from the design point would be eliminated by about 60 N/m^2 (1/4-inch water column) suction at the blower inlet. This condition is not likely to occur unless the combustion air filter is allowed to become very dirty.

What the burner requires is a given *weight* flowrate of air for a given firing rate and stoichiometric ratio. What the blower supplies is a given *volumetric* flowrate of air at its local (nominally inlet) conditions. If the furnace is installed at a high altitude, a greater volume must be delivered to obtain the required weight of air. The optimum burner, fired at 1.05 ml/s (1.0 gph) and a 1.15 SR, would have a fully open inlet and no margin of adjustability at about 1500 meters (4900 feet) elevation. In practice, the furnace would have to be downrated to a lower firing rate or supplied with a higher-capacity blower to allow servicemen at those altitudes some margin of tuning control.

Prototype Furnace Tests. Before the prototype furnace was converted to the first integrated furnace configuration, it was tested to provide some additional data to support the design of certain components for the conversion.

Tests to Support Firebox Design. The first test series was directed toward studying the effects of a hotter combustor wall (~340 C on the rear side) upon pollutant emissions. The higher wall temperatures were attained by simply throttling back on the warm-air, furnace coolant flow. Compared with data from earlier tests of the prototype furnace (Ref. 3), operation with hotter combustor walls tended to produce a little more smoke (~No. 1 Bacharach at 20% excess air), slightly higher (approximately 10 to 15%) nitric oxide, and substantially increased emissions of carbon monoxide. While smoke and NO emissions varied only slightly with variations in the elevated wall temperature level, the carbon monoxide concentrations began to increase sharply at wall temperatues above 340 C (650 F), going from ~0.45 g/kg to as high as 1.60 g/kg at 370 C (700 F).

To gain better quantification of maximum permissible firebox wall temperaures, the prototype furnace was partially disassembled to install sheet asbestos envelopes over the outer extremities of its fins, as a simulation of the 0.025 m (1 inch) fin height than being considered for the cast iron firebox. Additionally, 10 more thermocouples were attached to the outside of the firebox, to give a more complete picture of the distribution of temperatures over the firebox walls and fins.

While the furnace was being worked on, large sheets of iron oxide scale were found in the heat exchanger panels; that scale may have contributed to the higher CO readings. The heat exchanger was cleaned.

Firebox temperature distributions measured during steady-state operation of the modified prototype furnace are illustrated in Fig. 11, both at the nominal warm-air flowrate of 0.5663 m^3/s (1200 cfm) and also at 0.7079 m^3/s (1500 cfm). The maximum temperature measured on the combustor was 427 C (800 F), which is safely below the Underwriters' Laboratories (UL) maximum temperature limitation of ~540 C (~1000 F) for cast iron. As can be seen in Fig. 11, the nearly uniform fin arrangement produced a nonuniform shell temperature distribution, with the lowest temperature on the lower front section, and temperatures monotonically increasing toward the upper rear section.

The emissions of carbonaceous pollutants with the hotter, asbestos-enveloped finned combustor were not appreciably higher than those reported in Ref. 3 for the prototype furnace*, and the nitric oxide emissions also appeared to remain approximately the same at ~0.70 g/kg steady-state (~0.65 g/kg cyclic estimate).

The asbestos covers were left on the fins of the prototype combustor as it then more closely simulated the cast iron combustor design. The remaining hot-fire experiments conducted before the installation of the cast-formed combustor, which are discussed in the next subsection, were made with this simulated "short fin" combustor configuration.

Tests to Evaluate Ignition. The fuel pump on the optimum burner was coupled to the drive motor throug a simple centrifugal clutch, which produces "cleaner" starts and stops of the oil flow, i.e., reduced oil dribbling. The clutch characteristics provide a slight fuel lag at burner startup. It is sometimes observed that a slight fuel lead instead of a fuel lag startup can give improved ignition. To investigate this possibility, the fuel lag was eliminated by removal of the clutch drive from the optimum burner. Experimental data from these tests are given in Appendix B. Audible delayed-ignition starts were noted with this configuration and, although Runs 29 to 33 (Appendix B) show little differences in the 4-minute-averaged emission concentrations, inspection of the CO and UHC strip charts showed larger start spikes. The recommendation of a fuel-lead start may be valid for burners operating at SR > 1.5; however, for the optimum burner, which operates much closer to stoichiometric conditions, a fuel lag start appears to be more suitable. The clutch drive assembly was reinstalled in the optimum burner, and no further fuel timing experiments were conducted.

Tests of the First Integrated Furnace. Following conversion of the prototype furnace to the first integrated furnace configuration, several series of experiments were made to delineate its performance and emissions characteristics. The data obtained are given in Appendix C.

Performance of the Cast-Iron Firebox. Monitoring of test conditions during the firings and close visual inspection after firing revealed no apparent metallurgical or thermal problems with the cast-formed combustor configuration. Figure 12 is a surface temperature profile on the cast-formed combustor in steady-state operation at design conditions. As can be seen from the data recorded there, the lateral temperature distribution on the combustor wall is farily uniform from front to back, which was the objective of providing circumferentially varying fin heights in the side-fired, cast-formed combustor design. Comparison with the temperatures obtained with the constant-height, short-fin simulation, using the fabricated steel combustor (Fig. 11), shows that the cast combustor has a significantly more uniform lateral distribution. There remains a substantial longitudinal temperature gradient, but this is typical of a cocurrent-flow heat exchanger system and no problems are expected to result from this gradient.

*Although a No. 1 to 1-1/2 Bacharach smoke reading was obtained, subsequent experiments showed this to be an oil spray nozzle problem.

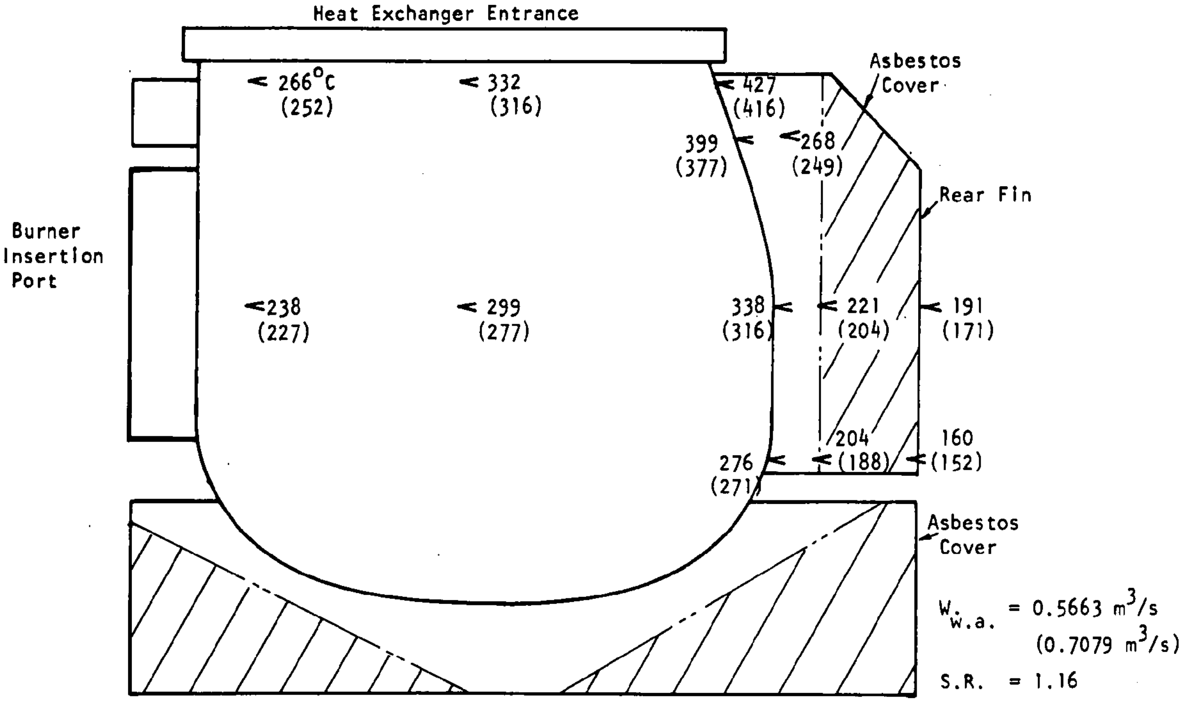


Figure 11. Steady-state temperature distribution on the finned prototype combustion with 0.025 M exposed fin length

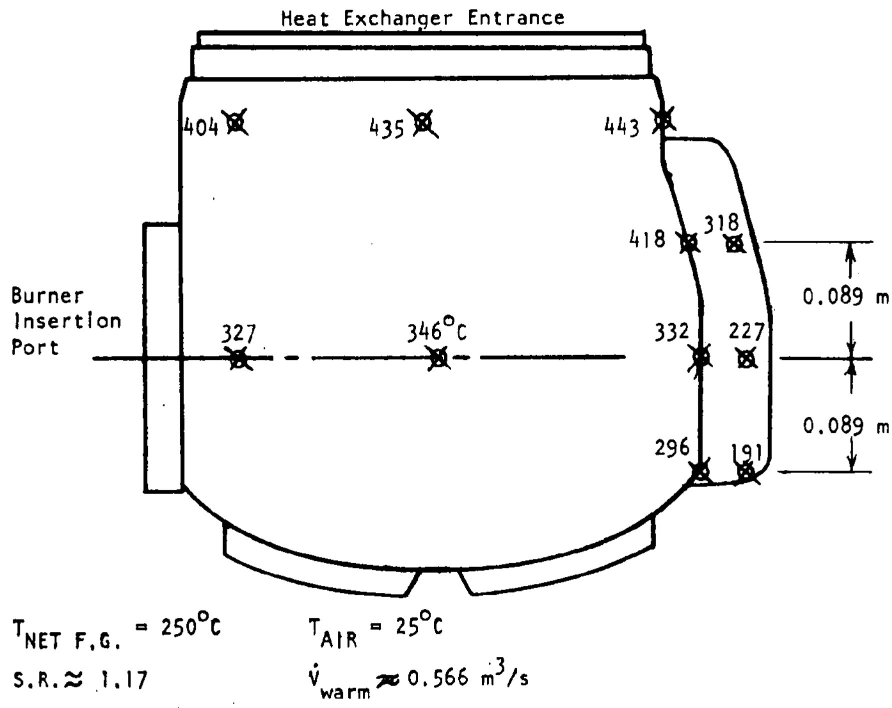


Figure 12. Steady-state surface temperature distribution on the cast-formed combustor installed in the integrated furnace system

Optimum Burner Head Modification. Some smokiness (No. 1 to No. 2 Bacharach) was noted during the initial tests at design conditions with the newly assembled integrated furnace. A switch back to the research optimum head revealed that the sheet metal optimum head, and not the new combustor design, was the source of the problem. Further investigations revealed that air leakage from the peripheral relief formed by the base folds of each vane was the specific cause. Although it had been concluded from previous testing (Ref. 8) that this air leakage was of only minor consequence, two differences were found between those earlier burner heads and the optimum burner heads made for the integrated furnace. First, careful inspection of the new sheet metal optimum heads revealed that the swirl vanes were folded on a smaller basic diameter (0.0991 m diameter specified, 0.0953 m diameter actual) than the previous heads, thereby resulting in larger peripheral openings, i.e., greater leakage. Second, the optimum burner now includes a large static disc which forces the air flow to the outer perimeter of the blast tube, possibly increasing the influence of these peripheral openings on the air/oil mixing process. A simple peripheral retainer ring was fabricated that: (1) fits over the perimeter of the optimum head choke plate, thereby covering the openings, and is welded to the choke plate, (2) folds over the edge of the choke plate, and (3) slips over the blast tube. This sheet metal optimum head/retainer ring combination eliminated the smoke emissions problem.

Thermal Efficiency. The thermal efficiency (based on flue gas measurements) of the integrated furnace system was found to be the same as that of the original prototype furance. The net flue gas temperature remained at about 225 C (460 F) steady state, 233 C (420 F) fourth minute at 12.7 - 13.0% CO_2 (SR = 1.15 to 1.18). Although the new, cast-iron combustor has less fin surface area than the fabricated steel predecessor, it was anticipated that the improved warm-air flow induced by the flangeless combustor and new baffle arrangement would result in an increase in thermal efficiency. Since the performance of the unit remained the same, a study was initiated to investigate possible improvements. The effort was first concentrated on improving the heat transfer to the warm-air flow in the combustor section. A total of eight different combustor baffle configuations was tested with no significant change in net flue gas temperatures, even though radical changes in the warm-air flow characteristics were effected. Therefore, the effort was redirected toward investigating the combustion gas-side heat transfer process.

A 3 m (10 foot) long flue pipe extension was added to the test installation to investigate the effect of firebox draft (negative static pressure) on heat transfer. The draft was increased from approximately 6.2 N/m^2 (0.025 inch of water column) to a maximum of 17.4 N/m^2 (0.07 inch) with a resultant 5 C decrease in flue gas temperature, i.e., a slight (~0.1%) increase in performance, but with a 1.5 Bacharach smoke reading. The path of the combustion gases was then altered by installing an internal baffle immediately over the combustor, oriented 45 degrees from vertical toward the front of the furnace unit. This resulted in a No. 2 Bacharach smoke reading, as did the subsequent installation of a 0.18 m (7.0 inches) diameter choke ring over the combustor; neither change affected the flue gas temperature appreciably.

To help isolate the cause of the efficiency difference between the prototype and integrated furnaces and the original Lennox unit, the configuration of the integrated test furnace was altered in the direction of the Lennox configuration. Pyroflex insulation similar in shape to the Lennox combustor section was installed inside the finned cast-iron combustor. The net steady-state flue gas temperature increased dramatically to ~292 C (~525 F), reducing steady-state thermal efficiency by almost 2%. To further the investigation toward the original configuration, the original Lennox burner was installed in this simulated Lennox combustor and a still higher, 299 C (538 F), net steady-state flue gas temperature was recorded. This nearly total reversion to the Lennox configuration with a contradictory higher flue gas temperature raised some questions as to whether degradation of the Lennox heat exchanger might be the primary cause of the thermal efficiency differences among the furnace configurations.

A long thermocouple was then inserted in the exit manifold of the heat exchanger, and gas temperatures were measured at three points very close to the exit of each of the six rectangular heat exchanger panels. Figure 13 is a schematic of the cross section of the exit manifold, with the measured combustion gas temperatures at 17 of the 18 locations. The lower temperatures measured at the lower lcoations for the inner panels implied lower combustion gas flowrate in the inner panels. However, the simple arithmetic average of the 17 temperature readings was 530 F, which is within 20 F of the measured flue gas temperature, implying nearly equal flowrates at all locations.

An attempt was made to correct the nonuniform temperature profile of the flue gases leaving the main heat exchanger and, thereby, to maximize heat transfer. Two flow control vanes, extending the full vertical length and adjustable to block nearly the full width, were installed in the inlets to the two outermost heat exchanger panels. Figure 14 shows the temperatures measured during steady state with the two vanes installed, but in their full open positions. The minimum partial obstruction caused by only the edgewise cross section of the vanes resulted in a much more nearly uniform temperature distribution. However, no significant improvement in net flue gas (FG) temperature (i.e., heat transfer) was noted (steady state $T_{FG\ net}$ = 254 C at SR $\approx$ 1.18). The vanes were then turned 30 degrees inward toward the flow, and no significant change in net flue gas temperature was observed. The vanes were then turned to 90 degrees (maximum obstruction), and a 10 C increase in net flue gas temperature resulted. Thus, it appeared that achieving a nearly uniform temperature distribution in the heat exchanger panels would have a very small effect upon thermal efficiency, so no further experiments were conducted with the internal vanes and they were removed.

A series of experiments was conducted to study the effect of internal radiant heat transfer upon the overall furnace thermal efficiency. The surfaces of the new warm-air baffles are highly reflective (galvanized zinc coated) and questions were raised as to the suppression of radiation heat transfer from both the finned combustor and the heat exchanger sections. The baffle surfaces were painted flat black with a high-temperature paint. The initial firings with the blackened baffles seemed to show a 20 C reduction in net flue gas temperature; however, subsequent firings showed no such improvement in the steady-state net flue gas temperature; it remained at about 255 C. The outer surfaces of the heat exchanger section were then painted black, and again no significant change in overall heat transfer resulted. With such drastic

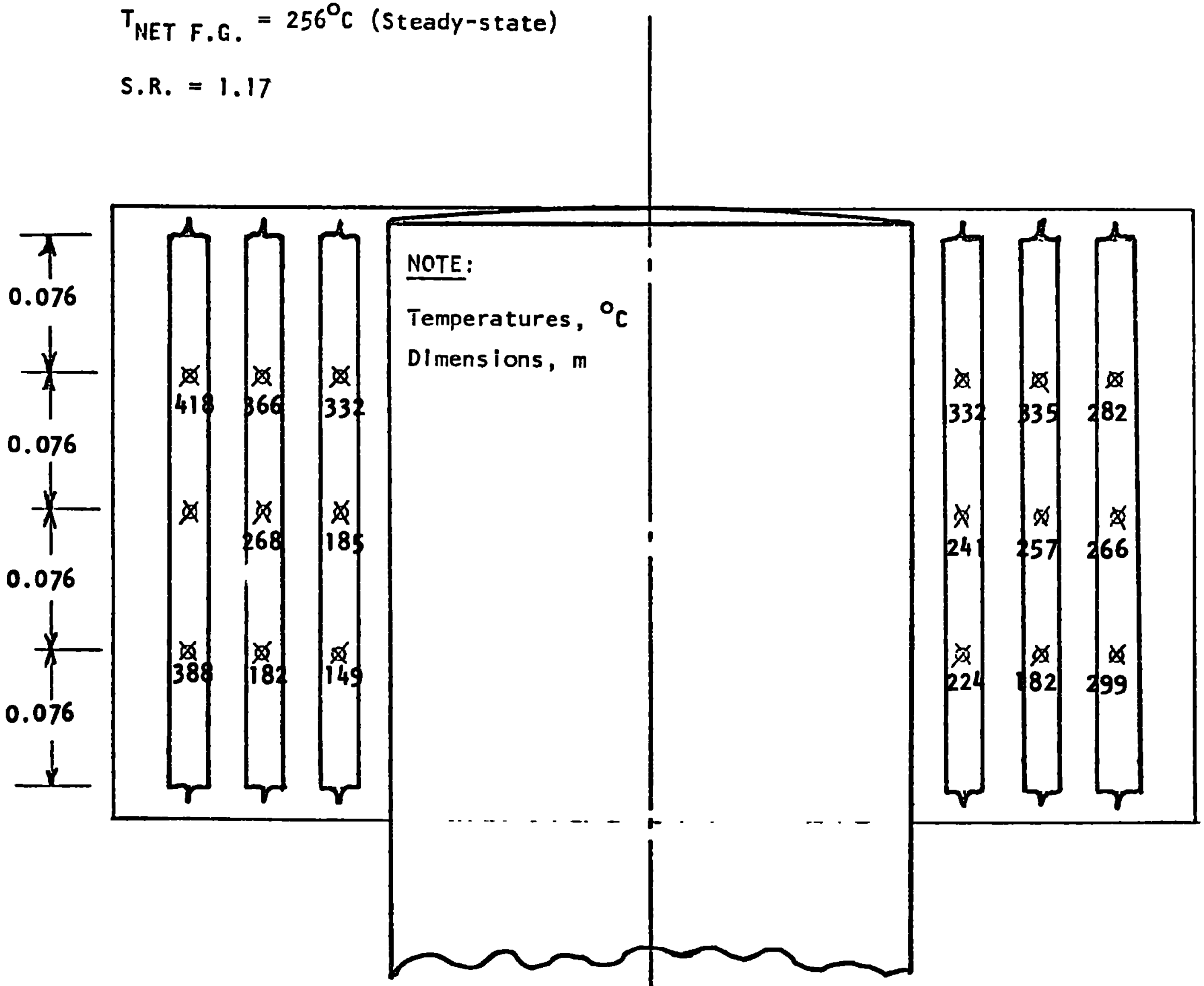


Figure 13. Combustion gas temperatures at exits of heat exchanger panels

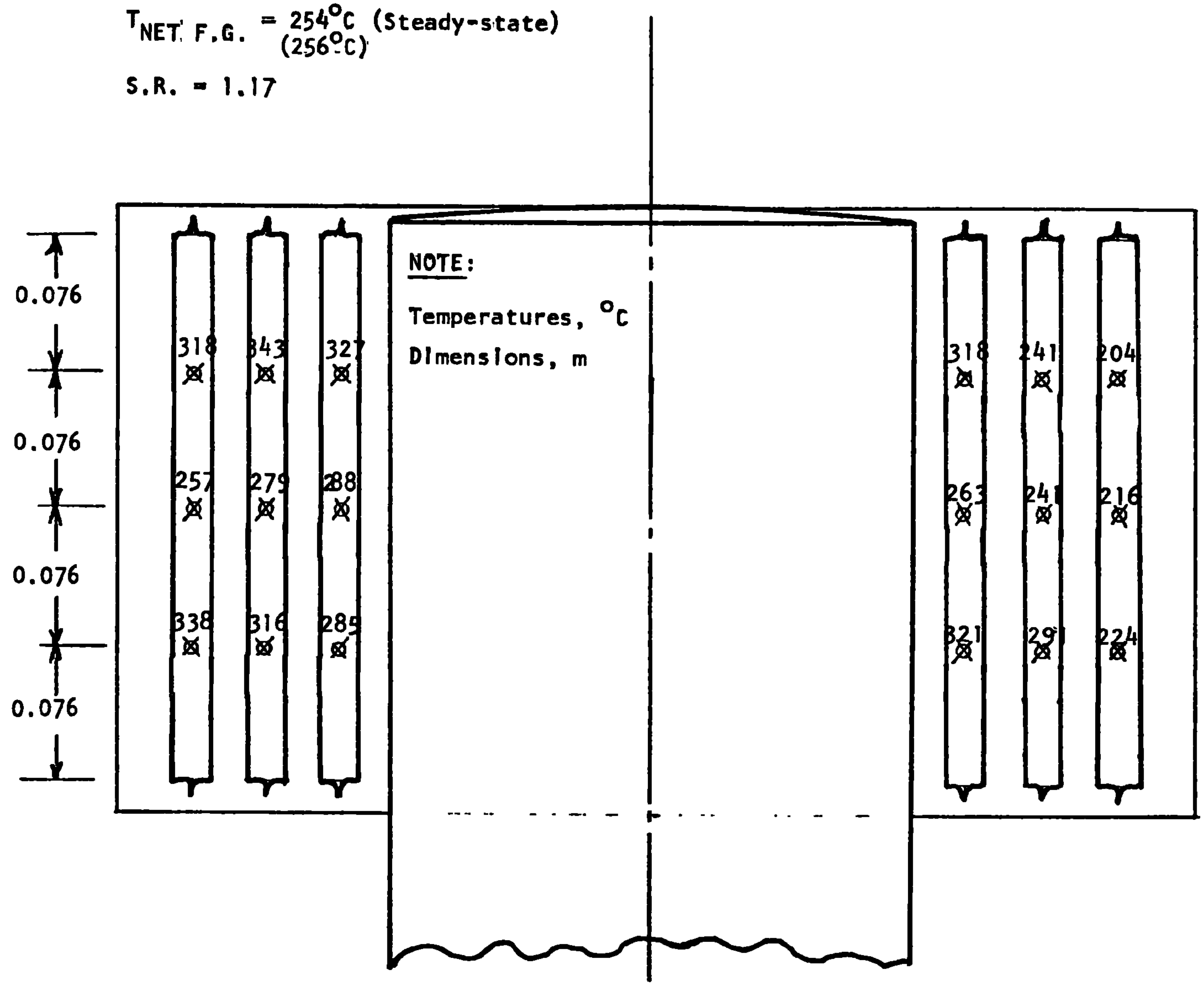


Figure 14. **Combustion gas temperatures at exits of heat exchanger panels with full-length control vanes installed in the two outer panels**

changes (reflectivity changed from $\sim$0.9 to $\sim$0.3) resulting in no measurable effect, it is apparent that the contribution of radiant heat transfer to the overall steady-state (warm-air fan on) furnace heat transfer is small.

One remaining possible explanation for the inability to approach the thermal efficiency of the former stock furnace was that the heat exchanger section had degraded since its two-step transformation into the integrated furnace. To investigate this possibility, one of two recently acquired Lennox units was set up for a long-term, hot-firing experiment. The new Lennox unit, with a new flame-cone-type retention head, operated smoke-free at a lower stoichiometric ratio (SR $\approx$ 1.25) than did the original Lennox burner (SR $\approx$ 1.45). However, this new unit's corresponding net flue gas temperatures were both higher than those of the original stock Lennox and higher than those being recorded with the first integrated furnace. The new burner head was the only notable difference between the old and the new Lennox furnace units, so the new burner was replaced with the original Lennox burner unit in an attempt to recover the low flue gas temperatuers obtained in the previous stock Lennox furnace tests.

The steady-state results showed a slight decrease in net flue gas temperature but a notable increase in nitric oxide emissions from 1.83 to 2.11 g/kg at SR $\approx$ 1.45 (Runs 38 and 43, Appendix C). (The oil flowrate was approximately 10% low, so the oil nozzle was replaced with another 1.0-70°-A nozzle for Runs 49 to 53. This new nozzle was also found to be 10% below its 1.05 ml/s rating and, therefore, this reduction of heat input has to be considered in comparisons of performance based on net flue gas temperature.) Although both the Lennox burners operated smoke-free in steady state at SR $\approx$ 1.25, cyclic firings showed a higher excess air requirement for <No. 1 Bacharach smoke reading. Runs 55 and 56 (Appendix C) provide the closest point of comparison with fourth-minute flue gas temperatures in the previous Lennox tests; the 229 to 235 C net flue gas temperatures (at SR $\approx$ 1.32) obtained are notably higher than $\sim$200 C recorded earlier. They are, in fact, closely comparable with the 220 to 225 C fourth-minute temperatures (at SR $\approx$ 1.18) observed with the integrated furance unit.

Steady-state firings with the original Lennox burner were made at minimum smoke-free air setting to investigate the effect of warm-air flowrate upon emissions and operation. These runs were made at warm-air flowrates of 0.595, 0.708, 0.479, and 0.566 m3/s (1260, 1500, 1015, and 1200 scfm), respectively. The flue gas emission concentrations showed no effect of these coolant flowrate variations, primarily due to the insulated (pyroflex) combustor design. However, the net flue gas temperature did show a maximum variation of 14 C, but this corresponds to only about 0.5% improvement in heat transfer efficiency.

The Lennox furnace was switched to the 4-minute on /8-minute off cycle mode to observe performance degradation. A check after 13 working days of cyclic operation showed an increase in the fourth-minute net flue gas temperature, from 235 C to 243 C. This mode of cyclical operation was continued for a total of 7 weeks with no further apparent change in the stock furnace's performance.

The pseudo-steady-state thermal efficiency of the integrated furnace is compared with that of the two stock Lennox furnaces in Fig. 15. No explanation has been found for the disparity between the measured efficiencies of the two stock Lennox units, although it now appears that the operating line on Fig. 15 for the No. 2 unit is probably more representative of the design's capabilities than is that of the No. 1 unit. The performance of the integrated furnace fired at 1.05 ml/s was quite comparable with the No. 2 stock furnace, with an indicated steady-state efficiency in the neighborhood of 80%. A substantial number of additional tests of the integrated furance were made, including some at reduced firing rates. During that testing, it was discovered that there was a problem with the smoke meter being used (which is discussed in a later subsection) and that the integrated furnace smoke emissions were actually higher than had been believed. One result of the investigation into that problem was a recommendation that the integrated furnace be downrated, from a 1.05 ml/s (1.0 gph) nominal firing rate to 0.79 ml/s (3/4 gph). Reducing its firing rate to 0.79 ml/s increased the achievable efficiency to approximately 85%.

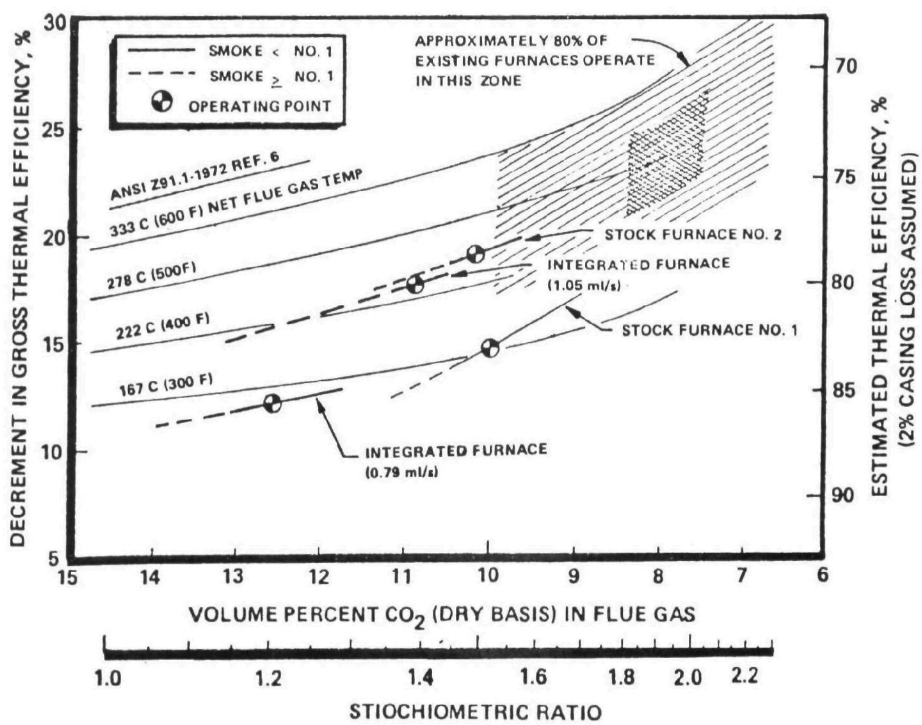


Figure 15. Thermal efficiencies of the integrated and the stock furnaces

Winter Simulation Experiments. A series of integrated furnace tests was made in which very cold air was supplied to the burner to simulate the admission of subzero combustion air through the sealed air system. A refrigerated frozen foods transport truck was rented to serve as a source of cold air. It was found that the truck enclosure could be maintained at ~-15 C (5 F) while drawing enough air to fire the furnace at 1.05 ml/s. The cold air was piped approximately 5 m (16 feet) directly to the burner's air inlet through a fiberglass-insulated 0.1 m (4 inch) diameter PVC pipe. At steady-state, temperatures as low as -10 C (14 F) were achieved at the burner inlet. The air in these experiments did not flow through the sealed vestibule, where experience shows it would have been warmed up by 10 to 15 C. Therefore, the observed data are believed to apply conservatively to outdoor ambient temperatures at least 10 C (18 F) lower than the reported burner inlet temperatures.

Scheduling of winter simulation tests was greatly influenced by meterological conditions (e.g., temperature, sunshine, wind, etc.) and this resulted in the coldest burner inlet condition (T_{air} = -10 C) being tested first (Runs 61 to 69, Appendix C). A study of the flue gas measurements data shows no notable effect of cold combustion air on the gaseous pollutant concentrations. There were, however, readable traces of smoke recorded, and these were believed at that time to be the result of the colder air. It was found in subsequent ambient combustion air condition firings (Runs 70 to 76) that the same level of smoke was still being recorded. Removal of the burner revealed that the axial alignment of the oil nozzle assembly had drifted to a slight upward bias, causing partial impingement of the oil spray on the top edge of the choke plate orifice. The nozzle alignment was corrected and Runs 77 to 79 (ambient temperature) showed a corresponding correction of the traces of smoke emission. Cold-air tests were again scheduled; however, warmer weather prevailed and -10 C combustion air temperature conditions could not be repeated. A series of firings was conducted at zero C combustion air temperature conditions (Runs 80 to 84). No smoke was measured, even to as low as SR = 1.07. The general operation of the furnace seemed even to improve at these freezing conditions, with smoother starts and quieter (i.e., more stable) combustion than with ambient air. The characteristic start spikes in CO and UHC emissions recordings were approximately 20 to 30% smaller than those seen in ambient-temperature tests. Several more attempts were made to repeat the -10 C temperature condition to check the correction of smoke emissions; however, weather conditions were not favorable and -8.5 C (Runs 88 to 91) was the lowest combustion air temperature reached. The results again show low pollutant emissions at design operating conditions (SR $\approx$ 1.15) with the smoke problem under control.

There is a ±15 C difference in net flue gas temperatures among the three (-10, 0, 15 C) sets of firings, corresponding to a ±0.5% difference in thermal efficiency. This difference is on the order of data scatter and, therefore, no firm conclusions have been based on these differences. Based on the excellent operational and consistently low emissions behavior of the prototype integrated furnace unit in these direct-plumbing cold-air tests, no cold-air related problems are anticipated in the field resulting from the use of the sealed combustion air system.

An experiment was conducted to determine the change in combustion air flow with changing air temperature. The complete burner cold-flow calibration apparatus was installed in the refrigerated enclosure and the blower was operated continuously while the enclosure's air temperature was reduced from 21 C (70 F) to -7 C (20 F). The change in air flowrate pumped by the burner blower was simply directly proportional to the change in air density (which in turn, is inversely proportional to the absolute temperature). Therefore, in very cold ambient conditions, the operating stoichiometric ratio would increase, producing a slight reduction in thermal efficiency, but without forcing the burner into adverse operating conditions.

Smoke Emissions Experiments. The Rocketdyne Environmental Systems Laboratory has had, for some time, two Bacharach Model RCC-B hand-operated smoke pumps. However, in preparation for field testing, two additional pumps were purchased. During normal experimentation with the integrated furnace unit, one of the new smoke pumps was used, and it was found that what had previously appeared to be a 0 to 1/2 Bacharach smoke reading with one of the existing pumps was now a 2-1/2 to 3 (Runs 135 and 136, Appendix C) reading with the new pumps. The suspect pump was disassembled and nothing obvious or unusual (e.g., cracking or tearing of the rubber piston) was found. The pump was well lubricated and the flexible inlet tube showed no signs of cracking. A water volume calibration device was set up in the laboratory where air drawn out from an enclosure would be replaced in volume by water drawn in from a larger water-filled container. It was calculated from the area of the smoke spot and the required 10 strokes that one stroke should equal approximately 180 ml. All four (two new, and two existing) smoke pumps were checked and the two newly acquired pumps were found to draw about 160 to 164 ml. The existing laboratory pump that was not being used drew about 150 ml. This 8 to 10% degradation was approximately what was expected for a well-used hand pump, and well within the accuracy of the human eye, reflectivity comparison method of the Bacharach smoke scale. However, the pump that had actually been in recent continuous use drew, at best, only 100 ml and showed greater sensitivity to stroke rate. Complete disassembly and cleaning revealed that the check valve was faulty and that the piston cap was cracked. Thus, the indicated smoke readings were low for the then current tests and for previous tests over some indeterminate time period.

Because of the conversion sequence from the original stock Lennox to the prototype to the integrated furnace, it was not possible to go back and retest those earlier configurations. However, the original stock Lennox burner was tested in the No. 2 stock Lennox furnace, and several exploratory modifications were made to the integrated furnace and its optimum burner to simulate the prototype configuration. It was concluded from the results that the problem with the smoke meter probably developed sometime between the stock Lennox furnace tests and the prototype furnace tests reported in Ref. 3. That is, the prototype unit's smoke emissions actually must have been appreciably higher than were reported. This put a serious question on the integrated unit's capability to be tuned to the nominal (15% excess air) design point.

The integrated furnace was retested, therefore, to determine operating conditions which produce acceptably low smoke. Some of the results are plotted in Fig. 16. At the 1.0 ml/s (1.0 gph) firing rate, smoke emissions were sensitive to excessive overfire draft conditions and in all cases exceeded No. 1. (Achievable upper values of stoichiometric ratio were restricted by combustion air-flow limitations.) At the 0.79 ml/s (0.75 gph) firing rate, there was almost no sensitivity to overfire draft variations, and less than No. 1 smoke was generally measured if excess air exceeded 20%. It was also found that, at this firing level, smoke emissions could be reduced further by insetting the burner head a small distance--0.025 m (1.0 inch)--into the combustion chamber.

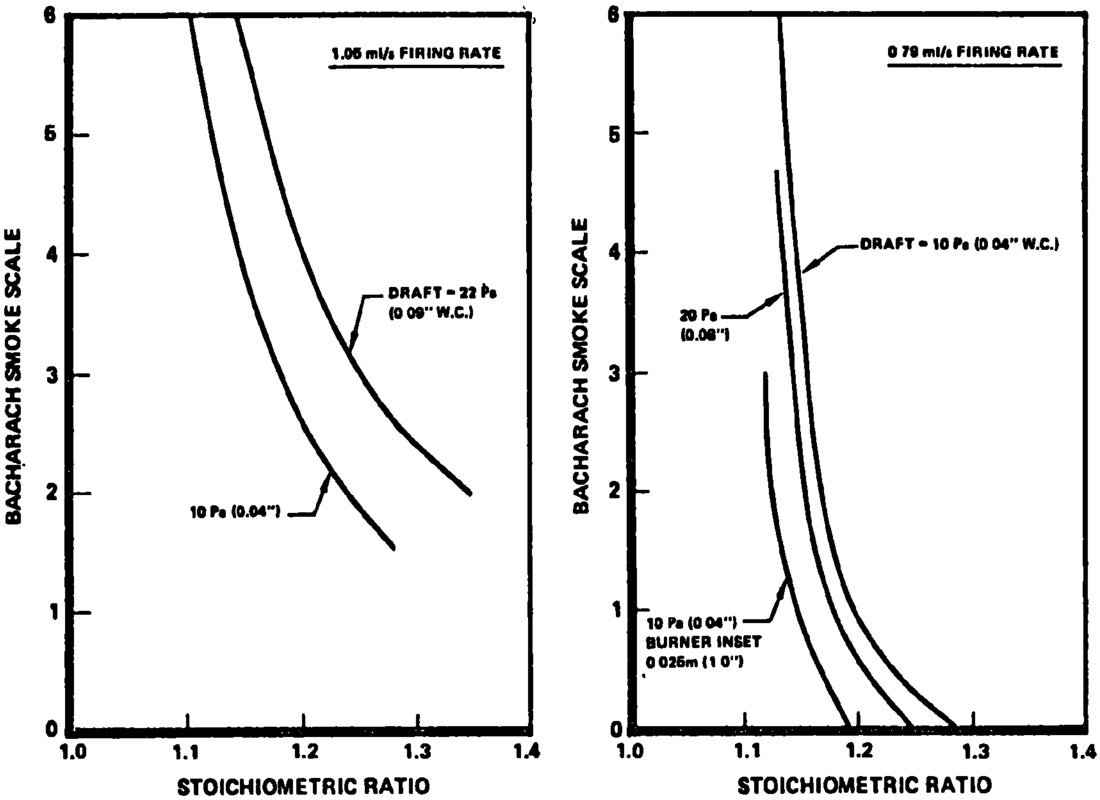


Figure 16. Cycle-averaged smoke emission characteristics of the integrated furnace tested on 4-minute-on/8-minute-off firing cycles

Ostensibly, No. 1 smoke at SR $\geq$1.15 can be achieved with the latter combination of firing level and burner/firebox configuration. However, the gradient in smoke number with decreasing stoichiometric ratio is quite steep so that attempting to tune the burner to precisely 1.15 SR involves the risk of producing excessive smoke if it is missed, or later drifts, by even a small amount. From these results, it is apparent that the integrated furnace should be rated as a nominal 0.79 ml/s (0.75 gph) unit, rather than the previously stated 1.05 ml/s (1.0 gph), and tuned to burn with about 20% excess air. At these redefined nominal design conditions, the measured steady-state and cycle-averaged emissions of CO were 0.25 and 0.60 g/kg, respectively, and of UHC were 0.02 and 0.04 g (as CH_4)/kg, respectively. Measured emissions of NO were slightly higher than at the former nominal design point, principally because of the stoichiometric ratio change.

Laboratory Measurement of Nitric Oxide. The nitric oxide concentrations in some of the tests reported on in this section appeared to be about 10 ppm higher than had been observed in the past, and some experiments on the sampling system and the sample analysis instruments were conducted to isolate the source of the difference. It was quickly established, and later confirmed by inquiries to other researchers, that the gas drying column, containing a 3Å molecular sieve topped with indicating Drierite (cobalt salt/$CaSO_4$), influences the NO concentration measurement when newly replenished. The column showed no influence with the calibration gases (NO in N_2). However, with flue gas containing hydrocarbons, oxides of carbon, and sulfur, along with water vapor, the column absorbed significant amounts of nitric oxide along with water vapor until it apparently saturated to some condition during the first day of use, so that it would thereafter absorb only the water vapor. This absorption of NO was noted on both nondispersive infrared (NDIR) and chemiluminescent (CL) analyzers. However, further experiments revealed that, while analyzing flue gas samples, some combination of molecular sieve and new indicating Drierite can cause the NDIR analyzer to read ~10 ppm higher than the CL analyzer; this apparently was the cause of the recently observed discrepancy. The CL analyzer is the intended instrument for the field test evaluation so, rather than exploring methods of optimizing the NDIR/drying column combination, the sample train was modified to utilize only the CL analyzer for oxides of nitrogen. This better conforms to the planned field test instrumentation and to that of many other researchers.

FINALIZED DESIGN OF THE INTEGRATED FURNACE

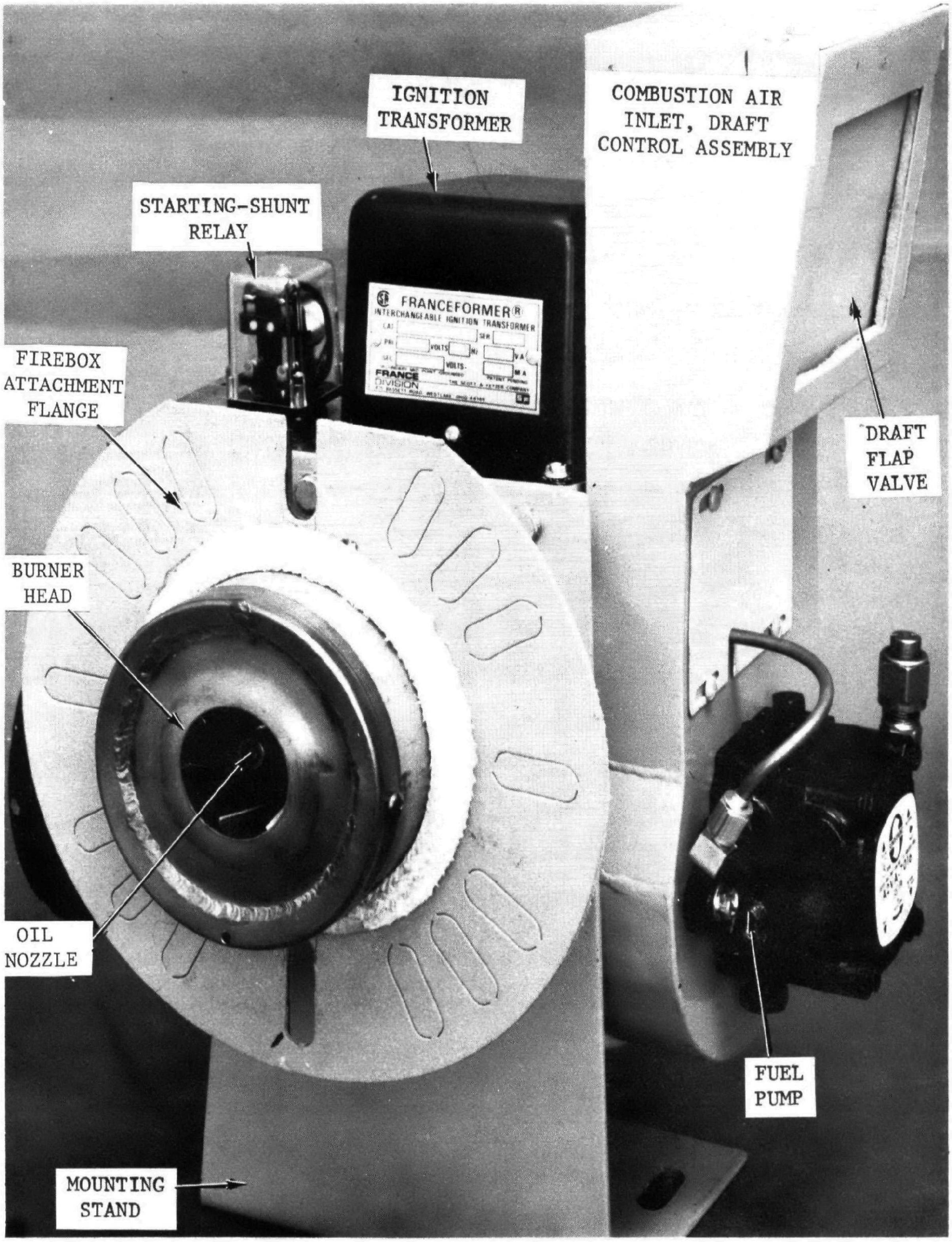
The extensive testing of the first integrated furnace unit, described above, yielded considerably greater understanding of its operation and performance, and led to adjustment of the nominal design point operating conditions. However, surprisingly few actual physical design improvements resulted from that work. None of the design changes were substantive.

As it became apparent that the initial design was not going to be changed appreciably, commitments were made to obtain stock furnaces and components needed to assemble, first, two new integrated furnace units to be used in design verification studies and, finally, four more units to bring to six the number available for installation in homes in the field.

The optimum low-emission burner assembly is shown in Fig. 17. Clearly visible in this photograph are the external modifications that distinguish this burner from the Beckett Model AF, from which it was derived. The sheet metal optimum head with its welded-on external sheet metal flange is mounted on the end of the shortened blast tube. The draft control assembly, which serves as the combustion air inlet, is nested between the fuel pump and the body of the burner. The microswitch for sensing proper opening of the draft flat is mounted inside the draft control assembly, so it is not seen in Fig. 17. The starting shunt relay (Fig. 6) is visible to the left of the ignition transformer.

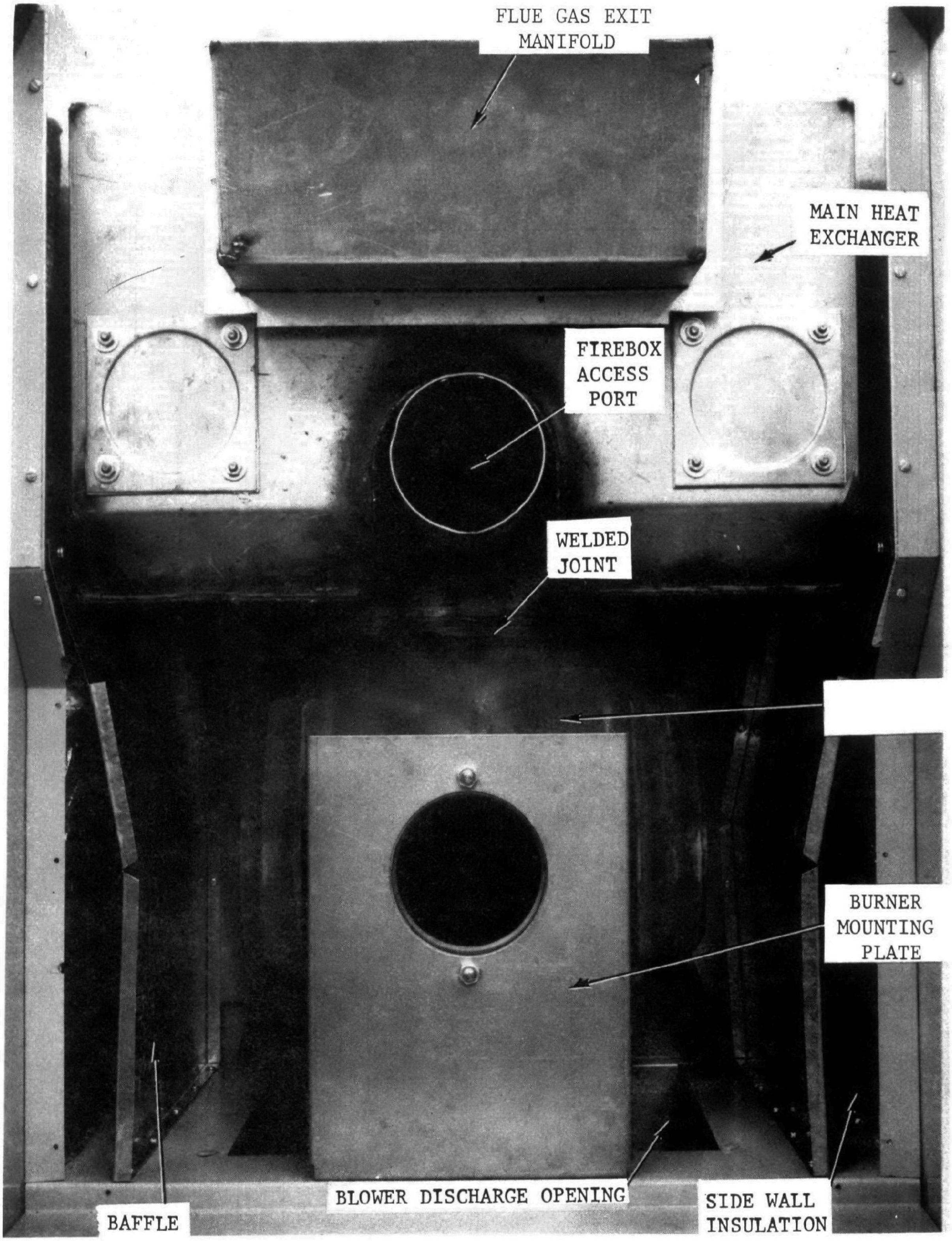
A photograph of the cast iron firebox was shown earlier in Fig. 7, and more detail may be seen in Fig. 8 which shows two views from the fabrication drawing. This design remained unchanged throughout the Phase I design optimization studies.

The firebox is shown installed in the integrated furnace in Fig. 18. The simplicity of the welded attachment of the fabricated sheet metal heat exchanger to the cast iron firebox is evident in that photograph. Also visible are the vertical, sheet metal baffles on each side of the firebox that



50P21-6/3/77-S1

Figure 17. Optimum low-emission oil burner



50P21-5/26/77-S1C

Figure 18. Internal construction of the integrated furnace

partially restrict the expansion of the warm-air stream which flows up from the blower discharge opening. The bottom edges of these baffles are approximately 2 inches inboard of the positions of their counterparts in the original stock Lennox units. The stock Lennox relied upon air gap insulation to limit heat transmission through the side walls of the cabinet. In the integrated furnace, additional insulation was installed in the side walls because the air gap had been made wider. High-temperature Johns-Manville 1/2-inch-thick Cerafelt insulation with foil on both sides was glued to the cabinet side walls and slipped into the existing air gap on the back wall. It extended on all three sides from the level of the blower discharge opening to the top of the furnace cabinet.

LABORATORY VERIFICATION STUDIES

Two units of the finalized integrated furnace design were assembled for use in laboratory verification studies. One was sent to the Underwriters Laboratories for their independent professional evaluation of potential problems in conforming to applicable residential oil furnace safety standards. The other was tested in the Rocketdyne laboratory to verify that the performance and emissions of the finalized design meet the design goals and, as well, to assess experimentally the satisfaction of safety standards.

Preliminary Examination of the Integrated Furnace by Underwriters Laboratories

Integrated Furnace Unit No. 1 of the finalized design was tested briefly in the Rocketdyne laboratory to make sure that all of its components functioned properly, then it was sent to the Underwriters Laboratories, Inc., Heating, Air Conditioning, and Refrigeration Department in Northbrook, Illinois. There, it was subjected to a preliminary examination, which is the first step UL takes in the process of *listing* a commercial applicance or component as conforming to applicable safety standards. In the preliminary examination, the furnace was inspected thoroughly, including partial disassembly, but no tests were conducted. Also, because the specimen sent was destined to be one of the units field tested, it was stipulated that UL should avoid damaging components during their disassembly and inspection.

The results of the preliminary examination were reported in a UL letter to Rocketydne dated 19 July 1977. Approximately 35 comments or questions were submitted concerning lack of conformance to particular paragraphs of oil burner and central warm-air furnace safety standards. Nearly every one of the points raised could and should be responded to by effecting appropriate design modifications before undertaking commercial manufacture of these furnaces. On the other hand, many points seem to be of little consequence with regard to field testing a limited number of custom-assembled units for the relatively brief period of one winter heating season. Therefore, the UL comments and questions were considered, one by one, specifically with respect to field testing, to determine whether and what design changes should be made immediately to ensure safety of the test furnaces.

The UL report is reproduced in Appendix D. To the right side of each of the numbered UL comments a statement is given concerning the action that Rocketdyne was later (Phase II) to implement for the six field test furnaces. In every case, it was the considered opinion that the indicated action (even if it is "no action") could be taken without compromising the safety of the host homes or service personnel.

Laboratory Testing

Integrated Furnace Unit No. 2 was tested in the Rocketdyne outdoor furnace test laboratory. The initial firings resulted in carbon monoxide concentrations approximately twice as much as anticipated, and after trying several burner mounting positions (insertion into combustor port) the burner was removed and it was found that the oil nozzle was misaligned. The problem was corrected and the burner was reinstalled; the results of the subsequent flue gas measurements are tabulated in Appendix E.

It was found during the initial checkout firings that the smoke characteristics of this furnace assembly were insensitive to the burner insertion position, so the burner was left in the flush-mounted position for those firings and most of the following UL requirements testing. The results showed no performance problems resulting from the techniques used in the assembly of the field test units.

UL Failure Mode Requirements. The safety requirements for the integrated furnace are specified in UL Standards No. 727 (ANSI Z96.1-1973) "Oil-Fired Central Furnaces" and No. 296 (ANSI Z96.2-1974) "Oil Burners." Tests were conducted using Integrated Furnace Unit No. 2 and its fully instrumented laboratory predecessor integrated furnace when extensive temperature measurements were required. The performance testing was conducted in compliance with Sections 33 through 48 in UL 727 and Sections 39 through 52 in UL 296, with only minor variances in instrumentation and procedures. Excluded were sections involving purely electrical tests of unmodified electrical components that are already UL listed (e.g., Dielectric Withstand Test), or sections involving different types of equipment (e.g., downflow furnace, vaporizing burner, etc.). Table 2 presents a listing of the headings for the above sections for both UL 727 and UL 296 standards. Most of the requirements result in pass or fail judgments, i.e., they require acceptable ignition/combustion (e.g., no backfire, less than No. 2 smoke, etc.) or a safety device lockout to prevent persistence of any unsafe condition.

A series of hot firings investigated furnace response to variations in electical supply line voltage. The line voltage to the burner unit was controlled by a "variac" transformer; the supply voltage was varied from 102 to 132 vac, the range specified in UL 296, Section 45 testing requirements. The operation of the burner revealed no adverse mechanical effects, e.g., motor overheating, sparking, etc., at either the 102 vac undervoltage or the 132 vac overvoltage settings. Ignition was smooth and combustion roughness was absent throughout the voltage variations testing. The pollutant emission concentrations remained within the nominal levels for the optimum burner. The stoichiometric ratio varied only sightly, about 2 to 3 percentage points from maximum to minimum voltage settings.

TABLE 2. LISTING OF UNDERWRITER LABORATORIES PERFORMANCE TESTING REQUIREMENTS

Requirements of UL 727, "Oil-Fired Central Furnaces"

Performance

Section 33. General

34. Test installation for standard clearances downflow and upflow furnaces (for installation in other than closets or alcoves)
    - Enclosure
    - Chimney connector
    - Air outlet and inlet-forced-air furnace
    - Horizontal furnace
        - Enclosure
        - Chimney connector
        - Air outlet and inlet
35. Test installation for alcove or closet
    - Downflow, upflow, and horizontal furnaces
        - Enclosure
        - Chimney connector
        - Air outlet and inlet
36. Instrumentation
    - Draft
    - Fuel input
    - Power measurement
    - Speed measurement
    - Static pressure
    - Temperature measurement
37. Initial test conditions
    - General
    - Furnace equipped with mechanical atomizing burner
    - Furnace equipped with vaporizing burner
    - Static pressures for tests
38. Combustion test - burner and furnace
39. Operation tests
40. Limit control cutout test
41. Continuity-of-operation test
42. Air for, downflow, or horizontal furnace test
43. Temperature tests, general
44. Continuous operation test
45. Blocked inlet test
46. Fan failure
47. Stalled fan motor test
48. Blocked outlet test

Requirements of UL 296, "Oil Burners"

Performance

Section 39. General

40. Draft
41. Fuel input
42. Power measurement
43. Speed measurement
44. Temperature measurement
45. Test voltage
46. Combustion tests
    - Mechanical atomizing burner
    - Vaporizing burner test
47. Combustion air failure test
48. Interruption of atomization test
49. Undervoltage test
50. Power interruption test
51. Temperature test
52. Ignition tests

A combustion air failure requirement, UL 296, Section 47, requires only that, upon interruption of the combustion air supply system (burner blower), the burner either terminates the firing or, if the firing continues, no unsafe condition is created. The optimum burner satisfies this requirement with its conventional direct-drive fan and fuel pump arrangement. Additionally, the optimum burner's inlet air draft flap microswitch circuit ensures that an acceptable amount of air is being supplied through the inlet system (e.g., outside air plumbing, filter, draft flap, etc.).

The maximum temperature tests (UL 727, Section 43 and UL 296, Section 51), however, require fairly elaborate temperature measurements to be recorded, and the pass or fail judgment is determined quantitatively. Unit No. 2 was used for the initial limit control cutout tests--93.3 C (171.1 F) maximum allowable warm-air temperature. During this test it was found that the approximate temperature scale on the limit control dial does not correspond closely with the actual warm-air temperature. The temperature limitation stops were re-adjusted to comply with the above UL requirement. Whether this is a typical characteristic of the integrated furnace or of the limit switch was left to be determined in Phase II when the other field test units are fired.

The testing was then shifted to the laboratory furnace unit for the component temperature measurement tests (UL 727, Sections 44, 45, 46, and 48). The primary concerns here were the sealed vestibule, which is markedly different from industry practice, and the cast iron firebox configuration. Table 3 presents the maximum temperatures measured, along with the corresponding allowable UL temperature specifications for the given conditions. As can be seen from these data, the components in contact with the combustion gases were well within the maximum allowable temperatures. However, due to the high air temperature rise [52 C (94 F) above ambient] reached in the sealed vestibule during continuous operation at 5 C (9 F) below limit control cut-out temperature, electrical components in the vestibule were close to the temperature limits for standard wiring. Standard (Type ST) appliance cord had been used to wire the draft flap microswitch circuitry, following a furnace manufacturer's suggestion that one should attempt to UL-qualify furnace wiring with standard insulation wherever possible so as to avoid the possibility of uncontrolled wire replacements in the field creating unsafe conditions. However, these tests revealed the need for higher temperature, i.e., 90 or 105 C (194 or 221 F) rated wire for this application, so plans were implemented to change all units to 105 C (221 F) wiring before field installation of any of the integrated furnaces.

Unusually high vestibule air temperatures, i.e., 78 C (172 F) maximum, were measured when the furnace was operated with unusually lowCair flowrates $\leq 0.330\ m^3/s$ (≤ 700 scfm) on a maximum-demand firing cycle. The maximum vestibule air temperature measured during a typical 4-minute-on/8-minute-off at nominal conditions was relatively low, on the order of 46 C (115 F), so no unusually rapid furnace degeneration in the vestibule area (e.g., paint peeling, rubber cracking, etc.) is anticipated during the field tests. Nonetheless, telephone inquiries were made to the manufacturers of the primary control and the draft flap relay to verify their long-term reliability under those conditions.

TABLE 3. MAXIMUM TEMPERATURE RISES MEASURED ON THE INTEGRATED FURNACE TESTED IN COMPLIANCE WITH UNDERWRITERS LABORATORIES SPECIFICATIONS

Temperature, C \ Test	Section 44 continuous operation	UL maximum	Section 45 blocked inlet	Section 46 fan failure	Section 48 blocked outlet	UL maximum
Burner head	334/351*	711	305	302	322	822
Blast tube	215/292*	517	191	227	205	683
Ignition transformer	62	65	57	47	70	90
Burner motor	72	80	65	45	72	115
Fan motor	21	75	21	--	21	115
Vestibule filter	43	50	33	17	50	97
Burner wiring	52	35/80**	46	28	56	60
Combustor	433	517	407	289	418	683
Heat exchanger	294	517	285	--	296	683
Cabinet	27	50	--	--	--	97

*Burner inserted 0.0254 m (1.0 inch) into combustor

**Allowable for 105 C (221 F) rated appliance wire

In summary, the laboratory testing of the integrated furnace according to the UL Performance Requirements for oil burners and oil-fired furnaces revealed only a need for higher temperature rated wiring on one circuitry. This correction will be made on all field test units, and the likelihood of any unsafe operation will be minimized.

SECTION 6

FIELD VERIFICATION

The basic approach to the field verification testing is to utilize a limited number of integrated furnaces as the space heating sources in as wide a variety as possible of existing oil-fueled residences. The objectives of this task were to evaluate and finalize all details of field testing up to the actual assembly and shipment of hardware for testing during the 1977-1978 winter season. This involved evaluating and selecting of test areas, arranging local test support, and determining the test measurement methods. Many of these evaluations are closely interrelated, and the overall scheme was determined in an iterative manner.

TEST LOCALE SELECTION

This effort proceeded on the basic premise from earlier evaluations of utilizing six furnace units, in two different winter climates, in high fuel oil heating areas. Oil heating is concentrated in three general regions of the U.S.: the New England states, the Great Lakes states, and the northern mid-Western states. Because these are all far from Rocketdyne's main plant in California, consideration of several logistics aspects also was involved in selecting test locales.

Three field test units are to be located in each of two test locales where oil heat is used in a substantial fraction of single-family homes and which have distinctly different winter climates. As a start toward selecting the two lcacales, winter climatic data averaged over several prior years were reviewed for approximately 35 cities, most of which are distributed throughout the three geographic regions mentioned above. Data considered were: annual and monthly degree days; monthly average temperatures and precipitations; and average diurnal temperature ranges (Ref. 9). All cities considered have normal accumulative degree days, based on 18 C (65 F), exceeding 2500 C-day (4500 F-day) for the 9-month period of September through May. Monthly average temperature data were plotted directly and on a weighted basis using U.S. census (Ref. 10) data on the number of households in each city. Mean curves were drawn through these two sets of data and were found to differ by only 1 C (2 F). Comparing the individual cities' weighted, monthly-averaged winter temperature profiles to the corresponding mean curve, 30 of the 35 cities had annual temperature profiles within ±5% of the mean. Thus, it was inferred that the weighted mean temperature profile is representative for a majority of the households in the colder regions of the 48 contiguous United States.

Based upon their closeness to the weighted mean temperature profile, seven cities were selected as being most representative; they were: Boston, MA; Cleveland and Columbus, OH; Indianapolis, IN; Providence, RI; Scranton, PA; and Springfield, IL. Comparisons of total winter precipitation and diurnal temperature ranges revealed that these cities experience two broadly distinctive winter weather patterns. The *maritime climate,* represented by Boston and Providence, encompasses the eastern seaboard. It probably extends inland for no more than a few dozen miles. Because of its proximity to Lake Erie, Cleveland's climate also falls in that climatic category. The *continental climate,* typical for the inland cities of Springfield, Indianapolis, Columbus, and Scranton, is characterized by wider diurnal temperature variations and less total precipitation than are experienced in the maritime climate. It was concluded that one test locale should be selected within each of those two general climatic categories.

Attention was then directed to nonclimatic factors, such as oil usage patterns, predominant types of residential construction, state and local code requirements, and availability of local support. Data concerning pertinent housing characteristics for 11 candidate locales are listed in Table 4. As can be seen in Table 4 all of these candidate locales well exceed the 2500 C-day (4500 F-day) degree-day heating load and there is significantly greater usage of fuel oil in the extreme northeastern/New England states. Because of the predominant use of oil for residential heating in New England, an assessment was first made of metropolitan Boston as the test locale with a maritime winter climate. From several standpoints, this area was found to be very attractive: there are very broad ranges of house ages, architectural styles, construction materials, degrees of insulation, and wind exposures; nearly all of their central heating systems are oil fueled; the only code requirements imposed on an experimental furnace is that the burner have a Massachusetts Fire Marshal approval number; there are reliable, well-established furnace equipment distributors willing to provide installation and service support for field testing; there are several environmental testing laboratories in the area; and, finally, there are regular and convenient travel and shipping connections to Los Angeles, CA. Therefore, Boston was tentatively selected as the maritime climate test locale. Emphasis then shifted to making subcontract arrangements for local installation and service support and laboratory support in Boston and, simultaneously, arriving at a tentative selection of a locale with a continental climate.

It appeared from the initial Boston contacts that laboratory support might be more difficult to arrange than either service support or host homes. It was considered that the larger metropolitan areas were most likely to have qualified, well-instrumented laboratories, so the order of examining cities with continental climates was established as from the larger to the smaller. Thus, even though oil has only a small fraction of residential heating there, Pittsburgh got first consideration. One or two apparently qualified labs were identified and an interested service contractor was found who has a substantial oil-heating background and several oil clients as potential host homeowners. Therefore, Pittsburgh was tentatively selected as the continental climate test locale.

TABLE 4. PERTINENT HOUSING CHARACTERISTICS FOR ELEVEN CANDIDATE CITIES

Candidate city	September through May degree-days (°F-days)	Thousands of housing units	With warm-air furnace, %	Heating use fuel oil, %	With basement, %	Comment
Boston	5586	891	24	66	94	Atlantic maritime climate (Boston, Providence, Hartford)
Providence	5926	263	82	66	94	
Hartford	6314	212	22	68	26	
Chicago	6093	2291	45	13	83	Great Lakes maritime climate (Chicago, Toledo, Cleveland)
Toledo	6105	186	68	12	62	
Cleveland	6088	676	71	6	84	
Indianapolis	5561	369	70	31	53	Continental climate (Indianapolis through Albany)
Scranton	6067	79	11	46	89	
Columbus	5681	296	81	8	77	
Pittsburgh	5881	789	69	6	92	
Albany	6818	98	25	43	90	

However, as the details of field testing in these specific cities were being formulated and negotiated it was found that the final competitive bid responses from analytical laboratories were much higher priced than the initial responses. Subcontracting of the flue gas analysis effort was then deemed impractical, and an option involving a mobile Rocketdyne instrumentation unit was formulated. It was apparent that with a single mobile unit to cover both test locales, many advantages could be realized with a reduction of the distance between the two locales. A review of the climatic data revealed Albany, NY as an excellent continental climate test site, separated from the Atlantic maritime climate by the Appalachian mountain range, and less than half as far from Boston, MA as Pittsburgh, PA.

The climate in Albany, NY during the heating season is somewhat colder than that in any of the other 10 cities considered in the initial evaluation. The mean temperature of Albany is 5.1 C (41 F) during the heating season as opposed to 6.5 C (44 F) for Boston. The apparent difference between these mean temperatures is actually a little smaller than the difference in the numbers of degree-days listed in Table 4. However, both criteria indicate that the thermal load is substantially greater for Albany than for Boston.

SUPPORT IN TEST LOCALES

Service Support

The selection of the local furnace service support started as a general evaluation of any furnace service contractor in the selected metropolitan areas. However, the process of evaluation quickly revealed that there are many advantages to working with distributors of the same brand name (Lennox) furnaces from which the integrated furnace was derived. These service contractors were more knowledgeable in the specifics of the construction, installation, and operation of the stock predecessor unit. The availability of spare common parts through these service contractors reduces the likelihood of unexpected delays. Moreover, many of these franchised service contractors were informed of some Lennox studies on fuel conservation devices, e.g., sealed air systems, which relate to the integrated furnace unit. The final selections of service contractors were made by standard contract bidding procedures and confirmed by visits of Rocketdyne personnel to the candidate organizations.

Selection of Host Sites

A list of potential host dwellings was supplied by each of the two service contractors from their existing customer lists. The selection of the six host sites (single-family dwellings) was based on criteria that included consideration of: (1) dwelling construction, (2) dwelling location, (3) existing dwelling furnace installation, (4) fuel usage history, and (5) host family. The dwellings with basement installations were preferred simply for the ease of accessibility and the space available for the required instrumentation packages. Other dwelling construction factors (e.g., building materials, age, number of levels, type of insulation, etc.) were considered to obtain a variety of dwellings with varying thermal characteristics. The thermal characteristics of a dwelling can also be influenced by its location where there could be significant localized differences in wind, insolation, heat retention (ground or water), etc. The integrated furnace configuration has been tested at return air flowrates from 0.425 m^3/s (900 scfm) to 0.800 m^3/s (1700 scfm) and return air temperature varying from 10 C (50 F) to 32 C (90 F) with little or no effect upon its operation. Therefore, the existing furnace installations in the candidate dwellings were evaluated primarily on the basis of geometric compatibility with the integrated furnace and the field test instrumentation requirements.

The fuel usage history considered was data for the two previous heating seasons so that correlations with degree-day data could be made to normalize all the thermal efficiency data to one baseline. This correlation may also reveal the necessity for an adjustment factor for changes in lifestyle (e.g., lowering of thermostat settings) induced by recent energy conservation campaigns. The requirement for the host family themselves is stability of the number of occupants during this and the previous two heating seasons. If, for example, there is a college student in, say, a small family of four, who will not be residing in the house this season, the thermal load upon the heating system may be affected significantly. However, if the student had also been gone in the previous two heating seasons, or if the dwelling is constantly occupied (e.g., kept heated) by another member of the house, the effect would be negligible. The ages of the children were noted as host families without children from 1 to 8 years of age were preferred. The concern here was the likelihood of inquisitive tampering with the instrumentation (e.g., pulling the power cord) by children in this age bracket. Although it is not listed as a criterion, a major influence upon the final selections was the attitudes of the host families toward the field test. Since the field test is of long duration (9 months) during adverse weather conditions and in two different cities, it is very probable that delays will arise, and these could be compounded greatly by an uncooperative host. Therefore, enthusiasm and cooperation are valued traits in the host families.

Integrated Furnace Installations

The installations of the six integrated furnaces are scheduled for the month of Sepetember 1977 and all are to be operational by the first day of October. Each installation will involve the removal and storage of the existing furnace and the mounting of the integrated furnace. The warm-air ducting will require minor modifications to allow the temporary insertion of a 0.45 x 0.45 x 1.22 m (18 x 18 x 48 inches) laminar flow element section and various thermocouple probes for cyclic thermal efficiency measurements. A full complement of instruments to evaluate thermal efficiency will be installed on one of the furnaces while the remaining five furnaces will have time event recorders to monitor furnace operations and store this information on magnetic tape (cassette). The thermal efficiency measurement apparatus will be rotated through the other five host sites during the heating season to obtain efficiency characteristics of all six units. The field test will terminate at the end of May 1978, at which time the integrated furnaces will be removed and the dwellings restored to their original conventional furnace configurations.

TEST MEASUREMENTS

The field test evaluation involves periodic measurement of flue gas emission concentrations and continuous event monitoring of cyclical operations. The primary objective of the test is to observe the long-term pollutant emissions characteristics of the integrated furnace design. A secondary objective is to establish the overall season-averaged thermal efficiency of the furnace so that the pollutant emissions results can be evaluated in light of the present concerns for energy conservation.

Air Pollutant Emissions

The long-term monitoring of flue gas pollutant emission concentrations will be conducted with measurements at monthly intervals. The pollutants to be measured are: nitric oxide (NO) and total oxides of nitrogen (NO_x) by chemiluminescence; carbon monoxide (CO) by nondispersive infrared; unburned hydrocarbons (UHC) by flame ionization; and smoke by the Bacharach method. In addition, carbon dioxide (CO_2) by NDIR and thermal conductivity and oxygen (O_2) by polarography will be measured to determine the operating conditions by stoichiometry. All of the instruments, with the exception of smoke pumps, will be installed into and operated from a 3/4-ton capacity van mobile laboratory. The van will transport the instruments to each host site, and a 0.0064 m (0.25 inch) diameter FEP Teflon line will be connected to the flue at a point near the furnace to conduct the flue gases to the analyzers. The control of the furnace will then be locked into a 4-minute-on/8-minute-off operating cycle by a repeat cycle timing device. After the calibration procedure, sample transport pumps within the van will be turned on to draw samples continuously from the flue and the gases will be analyzed throughout the 4-minute firng cycle. CO and UHC concentrations characteristically "spike" on startup and, therefore, the concentration profiles for these species will be recorded on continuous-drive paper charts. These pollutant emissions will then be averaged over the 4-minute firing and compared from month to month in terms of their cycle-averaged values. The integrated furnace has consistently operated in the laboratory at SR = 1.20, smoke <No. 1 Bacharach, CO <1.0 g/kg, UHC <0.1 g/kg, and NO <0.7 g/kg. It is expected that all six field test units will perform close to these values, and determining whether these low pollutant emission levels can be maintained throughout the heating season is a primary objective of the field test effort.

All the fuel oil consumed by the six furnaces during this field test period was originally intended to be from one known selected stock of fuel oil. However, discussions along these lines with the Sunoco Toledo Refinery revealed many problems that would detract from the objective of this additional requirement, which was, to have directly comparable data between all furnace units. The problems stem primarily from the magnitude of the petroleum industry operation where millions of gallons of crude stock are delivered by dozens of tankers from various oil sources, stored, and transferred remotely into a number of 24-hour-per-day refining operations. There is a low probability of extracting a meaningful control stock of fuel oil from this operation. Furthermore, the size of the field test order of fuel oil (~40,000 liters) excludes it from direct "over-the-counter" sales and it would have to be handled through a local oil distributor whose territory for delivery is strictly controlled, i.e., unlikely to cover test locales 325 km (~200 miles) apart. An "uncontrolled" fuel oil supply procedure would enhance the field test aspect of the task with the insertion of typical service routines, while requiring more effort in normalizing the resultant data. To gain the advantages of both the controlled and the uncontrolled oil supply procedures, the field test will be conducted with oil being supplied uncontrolled by the hosts' present oil suppliers, recording only the volume delivered. At the time of the monthly emissions measurement vist, a 500 cm^3 sample will be extracted at the burner pump and cataloged for future reference. Should any furnace emissions data appear anomolous, the associated oil sample would then be sent out for analysis.

Thermal Efficiency

Steady-state thermal efficiency of a furnace unit is normally estimated only in terms of the heat rejected out the flue during a continuous firing. This involves simply measuring the net temperature and the composition of the flue gases as described in the laboratory testing section. The flue pipe on all test installations will be insulated for approximately 0.6 m from the furnace. Measurements will be made 0.46 m from the center point of the furnace exit manifold in either a vertical or horizontal run as determined from the actual installation.

However, the accurate measurement of the cyclic operating thermal efficiency is complicated greatly by heat sinking of components, the need to measure very low pressure drop flows, relatively inconsistent furnace controls (e.g., bimetallic spring fan control), and nonuniform flow conditions. Each of these factors introduces variables that result in considerable data scatter. The measurement of season-averaged thermal efficiency is complicated further by variable cycle timing. For these reasons, substantial season-averaged thermal efficiency values have not been reported; instead, estimates have more often been reported. The influences of the many variables mandate statistical analysis techniques for evaluating season-averaged thermal efficiency. Therefore, continuously monitoring, automatic data acquistion methods were devised to record a large number of data points for a valid statistical analysis.

A Hewlett/Packard System 3051A data logging system with a programmable central controller will be used on one furnace to monitor all the timing, temperature, and flow parameters once every 4.5 seconds, and data from each firing will be stored on magnetic tape. The system utilizes eight of ten available data channels (see Fig. 19) for monitoring furnace status, warm-air flowrate, and warm-air net temperature. The cycle on and off times are determined by a counting of the number of data scans multiplied by the appropriate scan rate time constant. Upon sensing burner power on Channel 1, the burner on-time (i.e., heat input) counter is started and the logic for determining the maximum net flue gas temperature reading (T_{FG}-T_{VEST}, Channels 7 and 8) is activated until burner-off is sensed. Whenever the warm-air fan power is switched on (Channel 2), the summations of measurements of warm-air inlet temperature (Channel 3), pressure drop (Channel 6) through the laminar flow element and outlet temperature (Channel 4) are taken until fan-off. These summations are then kept until the moment of the next burner-on to include any warm-air fan

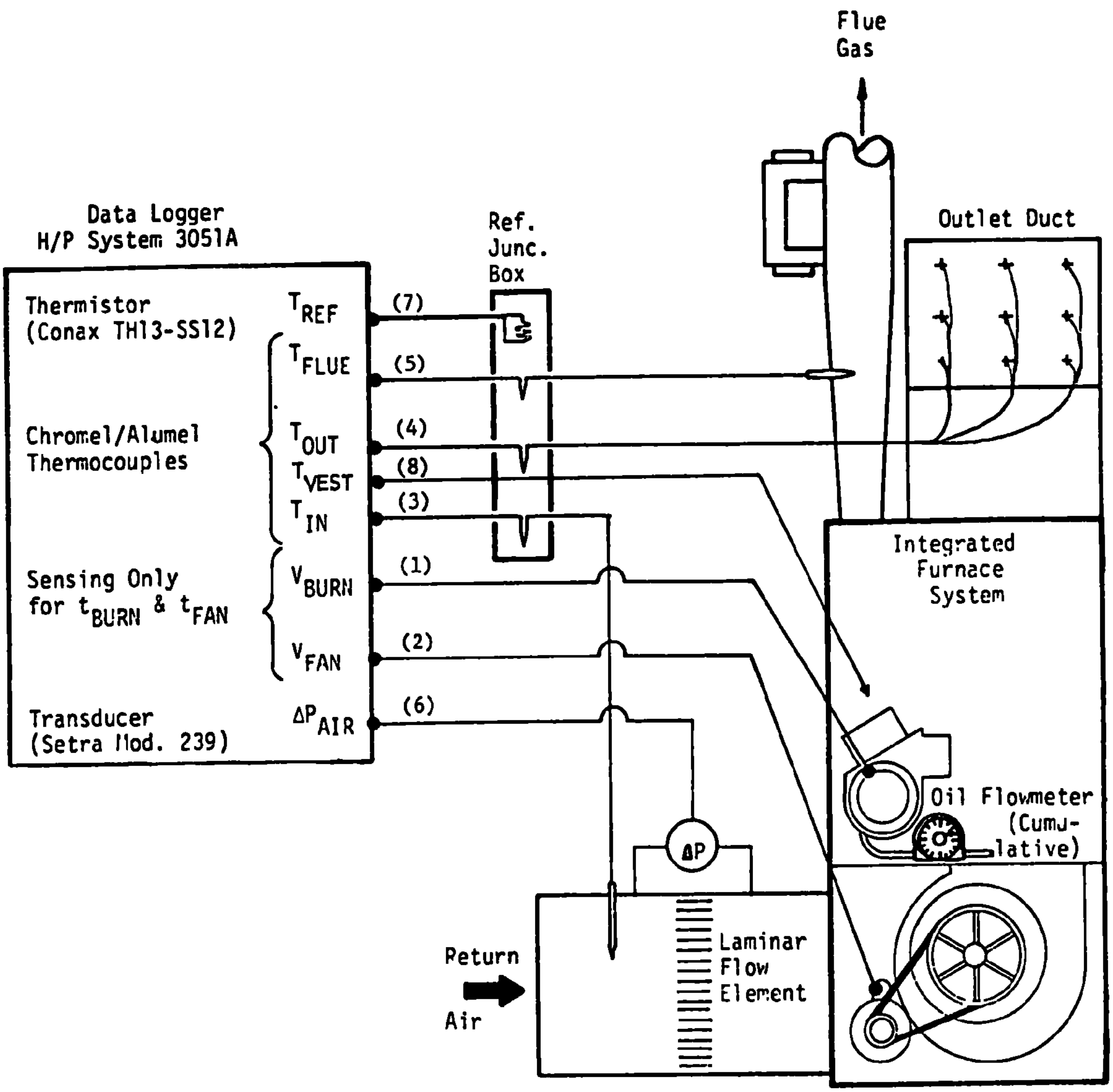


Figure 19. Schematic of automatic field test furnace efficiency data acquisition system

restarts resulting from residual heating or improper fan control unit operation. Chromel-alumel thermocouple junctions are used for all furnace temperature measurements with an insulated "floating" reference junction module, i.e., varying temperature. A thermistor probe (Channel 7) is used to monitor the referenced junction zone temperature, and this correction is applied to all thermocouple measurements. Sensing burner-on again signals not only the start of a new cycle, but also the end of the previous cycle and that the acquired data should be prepared for storage. All summations of measurements are normalized by the number of summations to establish a cycle-averaged value and then reduced. The values stored on magnetic tape are burner-on time, burner-off time, warm-air heat gain, and maximum net flue gas temperature. In addition, the controller prints a running account of the number of firings, cumulative on and off times, and the last file recorded on magnetic tape. This system will result in cycle-averaged thermal efficiency data that are correlated to cycle timing parameters and, eventually will be used to evaluate season-average performance. The data from the primary programmable data logger will be reduced on-site by the central controller on a monthly basis.

To evaluate season-average performance for all the furnaces, cycle timing will be carefully monitored on the remaining five furnaces by Instrumenation Technology Corp., Model 9676 automatic event-time data loggers storing day, hour, minutes, seconds, and on/off status information on magnetic tape. These tapes will be retrieved monthly and evaluated on a G.E. 440 time-sharing computer system. At various times during the test, each of the time data loggers will exchange positions with the thermal efficiency data logger so that each furnace can be characterized accurately.

The steady-state thermal efficiency of the integrated furnace at 0.79 ml/s (0.75 gph) firing rate is 85%, which is about the maximum achievable for non-condensing flue gas furnace systems. The cycle-average efficiency in actual homes is expected to be approximately 5% lower at about 80%. The season-average efficiency for the integrated furnace will be determined by the field test. In addition, the fuel conservation effects of the sealed air system, which does not appear in the above heat transfer evaluations, will be determined by comparison of the fuel consumption of the two previous seasons and that of the field test season, all normalized by the degree-day heating requirement index for each season. Overall reductions in fuel consumption resulting from the installation of the integrated furnace are expected to be well over 10% and might well be in the 20 to 25% range.

SECTION 7

EVALUATION OF THE USE OF OTHER FUELS

The objective of this task is to evaluate the capability of the integrated furnace to operate on other clean fuels. It is not intended to reoptimize the furnace for other fuels, but simply to assess the capability of the existing unit. Information acquired concerning pollutant emissions and efficiency performance is then used to define additional research required to establish low-emission combustion of other fuels in this and/or other types of space heating equipment.

SELECTION OF CANDIDATE FUELS

Two classes of fuels are of interest in this task: (1) those currently used for residential space heating, i.e., current competitors to No. 2 fuel oil, and (2) those which may become available in the future as competitors or replacements for currently used fuels. The first class is strongly dominated by natural gas. This is seen from the following percentages of U.S. homes heated by various fuels (1970 U.S. Census): natural gas, 58.5; fuel oils, 27.5; bottled gases, 6.4; electric 2.8; and, all others, 4.8%. Thus, if an alternate fuel is selected from this class of currently used fuels, natural gas is the only logical choice.

There are a number of both gaseous and liquid potential fuels of the future in the second class. Those include: hydrogen; substitute natural gas (SNG) derived from coal, biomass and/or waste conversion; low-Btu fuel gases from the same sources; liquid alcohol fuels, also from the same sources; and liquid oils from shale and coal liquefaction processes. Martin (Ref. 11) recently has reviewed the probable properties and combustion characteristics of many of these fuels, so that information need not be repeated here.

Low-Btu gaseous fuels have significant concentrations of inert diluents (N_2, CO_2, H_2O vapor) and/or partially oxidized fuel species (CO) which make it uneconomical to transport them very far from their sources. Thus, they are not likely to be distributed by public utilities to vast numbers of residences. The high-Btu SNG's, on the other hand, are far more likely to be distributed widely because they will be specifically tailored direct substitutes for natural gas, both in the pipeline distribution systems and in end-use consumption devices. Thus, current experience with natural gas should be equivalent to future behavior of SNG's. Hydrogen, conversely, has such different properties, composition, stoichiometry, etc., that an entirely new body of experience will be needed before wide-spread distribution to homes will be possible. Thus, residential use of H_2 is probably much further in the future than is use of SNG's. Moreover, since it is not carbonaceous, hydrogen's combustion and pollutant emissions characteristics are distinctly different from those of natural gas and distillate oils. From these considerations it is seen that natural gas is the one most logical gaseous fuel to consider as a candidate alternate fuel in this task.

Synthetic oils from coal and shale tend to have higher densities, viscosities, nitrogen contents, and carbon-to-hydrogen ratios than have No. 2 fuel oils from petroleum. It is far from certain that these tendencies will still be applicable to synthetic oils which one day might be distributed for residential space heating. If they do, they undoubtedly will force adjustments in fuel storage, pumping, atomizing, and ignition equipment as well as in excess air levels and combustion chamber volumes required to minimize smoke and other carbonaceous pollutants. In any event, fuel-bound nitrogen is likely to remain as a particularly significant problem. Therefore, the emission of NO_x from fuel nitrogen is likely to exceed NO_x from thermal fixation, and this is precisely opposite to the current situation with No. 2 distillate petroleum oil. The integrated furnace design is based substantially on reduction of thermal NO_x by techniques that have not been particularly effective in reducing fuel nitrogen-derived NO_x, so the synthetic oils may not be particularly attractive as candidate fuels for this task.

Conversely, the alcohol fuels should be essentially free of fuel-bound nitrogen. They might be produced from petroleum feedstocks, as normal liquid alternates to the cryogenic liquefied natural gas (LNG), or from a variety of conversion processes for coal, bio-mass, and wastes. The compositions of alcohol fuels will vary with the source, the conversion process, and the intended end-use, but it appears that methanol, ethanol, and/or mixtures of one or both of these with lesser quantities of higher-molecular-weight alcohols eventually may be produced and marketed as fuels. Alcohols are partially oxygenated, which may be viewed as having a water molecule imbedded in their molecular structure, and this makes them less energetic and, perhaps, slower burning than unoxygenated petroleum fuels with equivalent numbers of carbon atoms in their molecules. These properties also contribute to some desirable combustion properties, viz., alcohol fuels tend to burn cleaner (i.e., lower production of carbonaceous air pollutants) than hydrocarbon fuels with equivalent liquidity and volatility. These differences become less distinct as the alcohol molecular weight increases; i.e., they are most dominant with the lowest-molecular-weight alcohol, methanol. From these considerations, it appears that methanol is the logical candidate liquid fuel for Task 2 experiments.

NATURAL GAS

Current commercial practices in residential space heating with natural gas are reviewed, along with information on pollutant emissions and performance, to assess practical means of converting the Rocketdyne/EPA optimum oil burner to gas and its anticipated behavior in the integrated warm-air furnace.

Residential Gas Burners and Furnaces

Current state of the art was assessed by consulting a number of published sources concerning design, installation, and operation (Ref. 12 through 14), code and safety standard requirements (Ref. 15 through 17), and pollutant emissions (Ref. 18 and 19). Additionally, telephone conversations were held with several knowledgeable people in the industry, and equipment brochures were obtained from several manufacturers (Ref. 20).

New Construction. Practically all newly constructed warm-air gas furnaces use atmospheric gas burners, which are so-called because the combustion air is supplied at atmospheric pressure and is drawn into the burner and/or furnace firebox by induction and natural draft. In typical atmospheric burners, the natural gas is supplied at a regulated pressure, e.g., 3 to 11 inches water column (WC), to an injection orifice (spud) which directs a single jet of gas axially into a long mixing venturi. Atmospheric air is inspirated into the venturi, through openings near the gas spud, and is mixed with the natural gas to form a combustible mixture. That gas mixture is usually fuel-rich. From the venturi, the primary mixture flows to one or more burner heads where it is injected into a combustion space, ignited, mixed with secondary air, etc., and burned. The motive force for the primary, fuel-rich gas stream is simply the momentum of the injected gas jet. The burner, therefore, must present only a moderately small resistance to the gas flow. As a result, the final mixed-gas injection areas are relatively large, and burner designs commonly involve multiple port injection, continuous slot injection, etc., and subdivision of the total flow from the venturi among two, three, or even more burners is quite common. There are also some designs which use more than one fuel spud and venturi assembly, although these are most often seen in larger commercial and industrial installations.

The secondary air is usually not supplied through the burner, but enters the firebox through openings around the burner and is caused to flow into the flame zone by a combination of primary fuel jet induction, stack draft effect on the firebox, and natural convection associated with the flame pattern and combustion gas flow. Flow velocities are low and the pressure is essentially atmospheric throughout the burner and combustion system. To not restrict the flow of burned gases out of the firebox and to promote effective extraction of heat from them, the primary heat exchanger is typically subdivided into contoured sections keyed to the burner design.

The vast majority of warm-air gas furnaces have a standing pilot light outside of the burner head to effect ignition when the burner is turned on. Typically, the thermal input to a residential furnace pilot is about 5.28×10^6 J/hr (5000 Btu/hr).

This standby consumption is about 4 to 6% of the main burner firing rates and contributes to inefficient use of fuel. There is a developing trend toward use of interrupted pilots that are turned off during standy.

It is apparent that there are substantial design differences between atmospheric gas burners and gun-type pressure-atomizing oil burners, as well as between the furnaces in which they are fired. It is simply inappropriate to consider converting the Rocketdyne/EPA optimum oil burner and integrated furnace into that type of system.

Conversions From Oil and Coal. Several manufacturers make conversion gas burners for installation in existing oil or coal furnaces and hydronic boilers to convert them to burn natural gas or propane. Many domestic conversion burners are of the atmospheric type, with venturi mixing of the gas and primary air; nearly all of these are single-port burners of types designated "upshot" and "inshot". In the inshot-type burner, the primary mixed gas stream flows through a single horizontal mixing tube (downstream of the venturi) which directs the gas stream against the flat or contoured side of a vertical metal disc "flame spreader". A pilot flame is located near the flame-spreader and a secondary air duct typically surrounds the mixing tube to force secondary air into and around the flame zone. "Upshot" burners are very similar but have a 90-degree bend in the mixing tube so that the primary fuel stream is turned to flow vertically upward against the underneath side of a horizontal flame-spreader disc.

There is a class of domestic conversion burners known as power burners. Individual power burners may be defined broadly (Ref. 16) as: "A burner in which either gas or air, or both, are supplied at pressures exceeding, for gas, the line pressure and, for air, atmospheric pressure; this added pressure being applied at the burner," and categorized (Ref. 16) as:

"a. Forced-Draft Burner. A burner for which air for combustion is supplied by a fan ahead of the appliance.

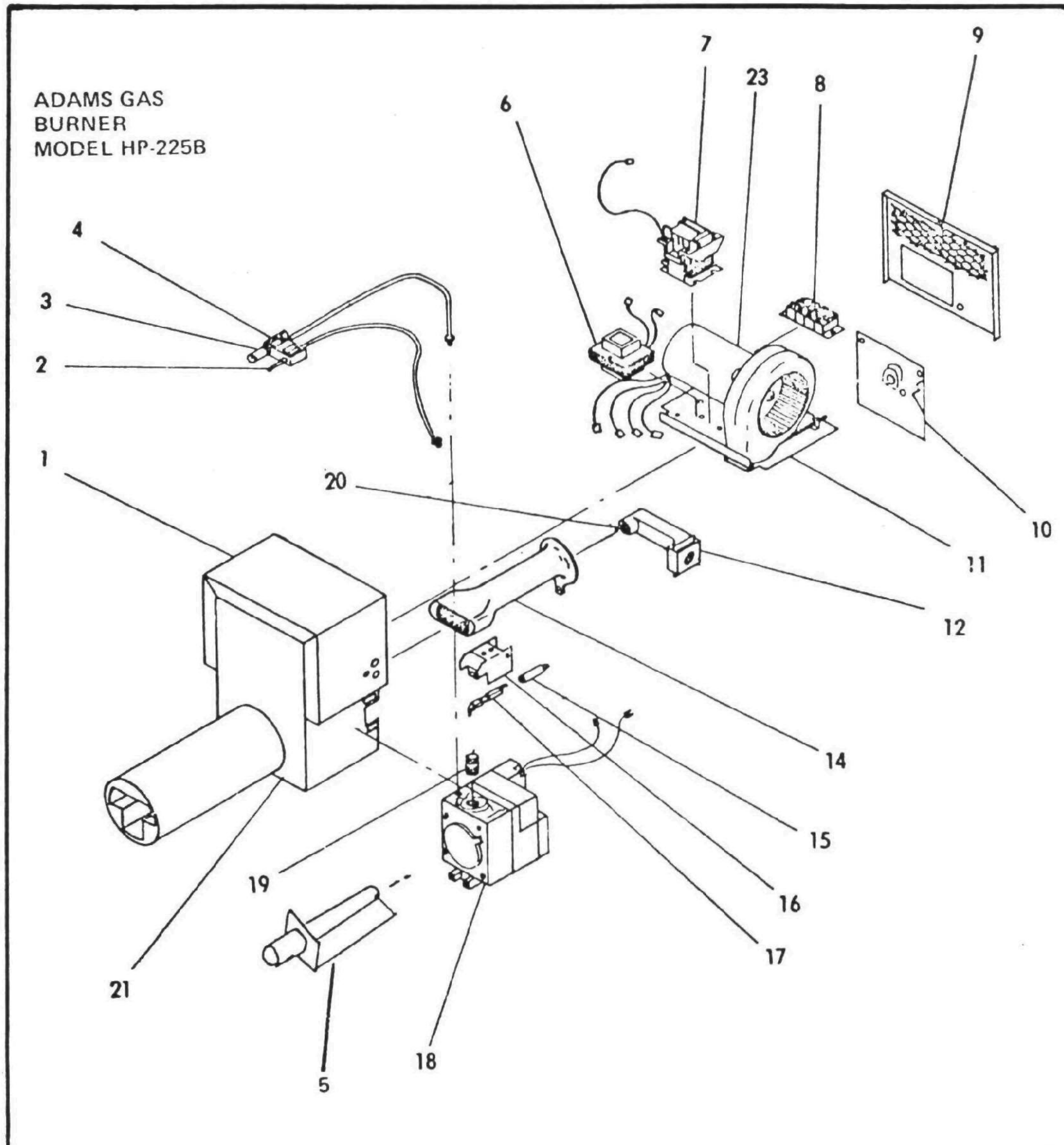
b. Induced-Draft Burner. A burner which depends on the draft induced by a fan beyond the appliance for its proper operations.

c. Premixing Burner. A power burner in which all or nearly all of the air for combustion is mixed with the gas as primary air.

d. Pressure Burner. A burner which is supplied with an air-gas mixture under pressure, usually from 0.5 to 14.0 inches of water and occasionally higher."

These are general definitions, all of which do not necessarily apply to residential-size burners. One manufacturer (Adams Manufacturing Co., Cleveland), for example, makes forced-draft power gas burners in sizes ranging from 50,000 to 1,000,000 Btu/hr thermal input. The models up to 400,000 Btu/hr input are venturi mixing designs, with forced-draft primary air fed into the venturi and forced-draft secondary air fed to the burner head. Larger models employ a patented "vacuum mixing" principle whereby the gaseous fuel and all of the combustion air are admitted separately to the upstream side of a perforated plate normal to the flow just upstream of the flame-zone. Thus, at least for that manufacturer, premixing power burners are made only in sizes larger than residential.

An exploded view of a residential-size, 237.4 x 10^6 J/hr (225,000 Btu/hr) maximum thermal input forced-draft power gas burner is shown in Fig. 20, reproduced from Ref. 21. An obvious correspondence can be seen between many of its components (and its physical arrangement) and those of a typical gun-type, pressure-atomizing oil burner. As noted above, this burner embodies venturi mixing of primary air with the fuel within burner mixing tube 14 while



REF.	DESCRIPTION
1	Top Housing
2	Thermocouple
3	Pilot
4	Pilot Orifice
5	Spark Lighter
6	Transformer
7	Relay
8	Terminal Block
9	Air Door
10	Bottom Access Door
11	Slide Tray Assembly
12	Manifold
13	Pedestal (Not Shown)
14	Burner
15	Insulating Boot
16	Pilot Shield
17	Electrode
18	Automatic Valve
19	Pipe Nipple
20	Main Burner Orifice(Spec.Size)
21	Bottom Housing Assembly
22	Mounting Flange (Not Shown, Opt.)
23	Motor Blower Assembly

Figure 20. Exploded view of a forced draft power gas burner (reproduced from Ref. 21)

secondary air flows axially along the outside of that tube, within an approximately 4-inch-diameter blast tube, to be mixed with primary gases as they are burned just outside the end of the mixing tube. This particular burner uses an intermittent pilot light which is spark-ignited at burner startup and is thermocouple-proved by a control circuit before the main valve is actuated. The automatic valve assembly (18) fulfills several functions, viz., total shutoff of fuel flow, activation of pilot fuel flow, actuation of main fuel flow, regulation of fuel output pressure, and activation of the piezoelectric spark lighter.

The pilot light on the Adams HP-225 B burner continues to burn until burner cutoff. Many conversion burners, particularly older ones, still employ the less desirable, continuously burning, standing pilot light. A somewhat different ignition system, used for example, on the Midco Economite Model DS5850 (discussed later), has no pilot light but provides direct spark ignition of the main flame, which is proved by a solid-state electronic circuit by flame-rectificaton by sensing of an imposed current between two sensor electrodes. Otherwise, this Midcontinent burner is much like the Adams burner in that it too uses power draft air, venturi primary mixing, and a multifunction main valve assembly.

Installation of Power Gas Conversion Burners. As noted before, most residential-size power gas burners are intended for conversion of older coal- or oil-fired heating systems to gaseous-fueled systems. Reference 17 delineates the requirements for effecting safe and satisfactory conversions. Some of the requirements are specific to hydronic and/or coal-fired units (e.g., water coils in the firebox are prohibited, positive-closure latches on firing doors are to be removed and/or replaced with spring-loaded safety catches, and grates and ash pits are to be strengthened, sealed, insulated, etc., in specific ways). Other requirements are specific to oil furnaces and many others are applicable to any conversion effort. Those which have some potential applicability to converting the current prototype integrated furnace may be summarized as follows:

1. Combustion air is to be supplied from outdoors if the unit is in a particularly tight or fan-vented house. (This requirement is obviously satisfied by the sealed air system.)

2. The conversion burner firing rate shall be matched to the firebox size; inshot burners are stated to require combustion chamber floor areas of 9.68×10^{4} m^2 or more per 1.055×10^{-6} J/hr (1.5 in.^{2} per 1000 Btu/hr) thermal input, unless otherwise specified by the burner manufacturer. (By this criterion, the 12-inch-ID cast firebox of the integrated furnace would be limited to a thermal input of about 92.1×10^{6} J/hr (87,300 Btu/hr) with natural gas or about 80% of its nominal 0.79 ml/s (0.75 gph) oil firing rate.)

3. With direct ignition systems, a minimum 30-second purge time is required between burner start and main flame ignition. (The present oil burner circuitry does not provide such a delay time.)

4. Top-fired oil furnaces are not to be converted to gas. (Not applicable)

5. Existing refractory firebox linings are to be removed down to the level of the burner, unless that is the only thermal protection for the steel shell. (Not applicable)

6. Movable dampers are not allowed in flue pipes.

7. A draft hood is to be installed in the flue pipe. AGA-suggested designs for vertical and horizontal runs are illustrated in Fig. 21. The pressure of the air surrounding the draft hood must be the same as the combustion air supply pressure. (Although there is no mention in Ref. 17 of barometric control dampers of the type normally used in oil furnace installations, there are allusions to them in some of the conversion burner manufacturers' installation manuals. Their retention apparently is acceptable, so the integrated furnace's sealed air system simultaneously satisfies this requirement and that listed here as item 1.)

8. The furnace shall have a 93.3 C (200 F) air overtemperature switch. (Same as integrated furnace)

9. There are a number of requirements regarding the fuel supply and its controls. There shall be provided:

   a. A manually actuated main shutoff valve

   b. A gas pressure regulator

   c. An automatic main control valve (usually combined with a transformer)

   d. A safety shutoff device, including sensors and electrical circuitry

   e. Ignition system components and controls, as appropriate (With a pilot burner, for example, this would include a pilot gas filter, a pilot shutoff valve, pilot supply tubing and, perhaps, a manually actuated or automatic spark igniter.)

   f. A pipe union between the manual shutoff valve and the pressure regulator, and a vertical drip leg to collect small quantities of moisture that might condense in the fuel line

   g. Provisions for venting bleed gases from the pressure regulator and/or diaphragm valves, as required (Gases heavier than air must be vented outdoors while those lighter than air may be vented outdoors, into the flue pipe (downstream of the draft diverter), or into the combustion chamber next to a standing pilot light.)

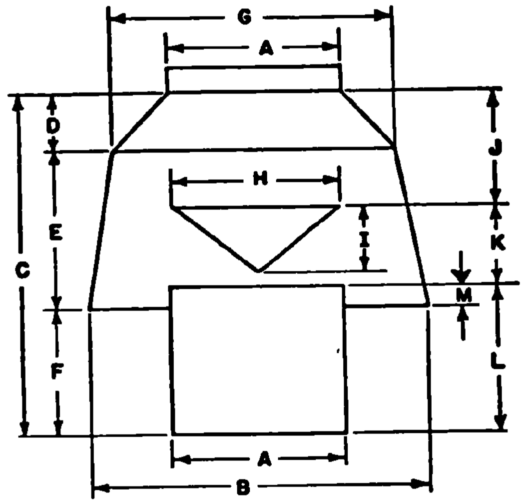


Table of Dimensions
(Inches)

A	B	C	D	E	F	G	H	I	J	K	L	M
3	55	70	07	38	2.5	4.4	30	1.5	2.3	1.5	3.2	07
4	72	9.5	10	50	35	60	40	20	30	20	4.5	10
5	94	108	15	53	40	80	50	2.3	3.5	2.4	49	09
6	11.5	120	19	56	4.5	98	60	25	40	27	5.3	08
7	135	139	23	64	53	116	70	29	46	31	6.2	09
8	155	158	27	71	60	134	80	32	5.3	35	7.0	10
9	175	175	31	77	67	152	90	35	58	4.0	7.7	10
10	197	188	36	79	73	172	100	3.8	62	4.3	8.3	10
11	222	207	4.3	84	8C	196	110	41	6.6	46	9.5	15
12	247	222	50	87	85	220	120	44	70	50	10.2	17

NOTE This is only one design of a vertical hood and should not be construed as the only design that may be used A hood of any other design which will meet the American National Standard for Draft Hoods, Z21 12-1971, should be satisfactory within the limits of performance specified

(a) Vertical Run

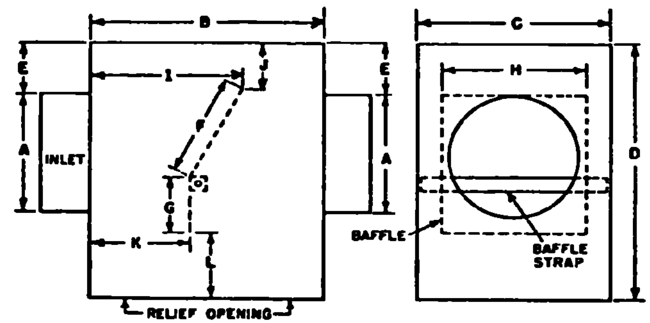


Table of Dimensions
(Inches)

A	B	C	D	E	F	G	H	I	J	K	L
3	6	5	9 7/8	1 1/2	2 1/2	1 5/16	3 1/2	3 3/4	1 3/8	2 1/2	4 3/4
4	8	6 3/4	11 5/8	2	3 3/8	2 1/8	4 5/8	5	1 7/8	3 3/8	4 3/4
5	10	8 3/8	13 1/4	2 1/2	4 5/16	2 9/16	5 7/8	6 1/4	2 3/8	4 5/16	4 3/4
6	12	10	15	3	5	3 1/8	7	7 1/2	2 7/8	5	4 3/4
7	14	11 3/4	16 3/4	3 1/2	5 7/8	3 11/16	8 1/8	8 3/4	3 3/8	5 7/8	4 3/4
8	16	13 3/8	18 1/8	4	6 11/16	4 1/8	9 3/8	10	3 7/8	6 11/16	4 3/4
9	18	15	20 1/8	4 1/2	7 1/2	4 11/16	10 1/2	11 1/4	4 3/8	7 1/2	4 3/4
10	20	16 3/4	21 3/4	5	8 3/8	5 1/8	11 5/8	12 1/2	4 7/8	8 3/8	4 3/4
11	22	18 3/8	23 1/2	5 1/2	9 5/16	5 11/16	12 3/4	13 3/4	5 3/8	9 5/16	4 3/4
12	24	20	25 1/4	6	10	6 1/4	14	15	5 7/8	10	4 3/4

NOTE This is only one design for a horizontal hood and should not be construed as the only design that may be used A hood of any either design which will meet the American National Standard for Draft Hoods, Z21 12-1971, should be satisfactory within the limits of performance specified

(b) Horizontal Run

Figure 21. Suggested general dimensions of vertical and horizontal draft hoods (Ref. 17)

Many of functions b through e are now commonly built into an integrated automatic main valve assembly (as illustrated in Fig. 20) which does not produce bleed gases, avoiding problems with requirement g.

Air Pollutant Emissions

Natural gas has a solidly established reputation as a highly convenient, very clean-burning residential, commercial, and industrial fuel. Its clean-burning reputation, for the most part, is based on two factors: (1) most natural gases contain very low concentrations of sulfur, fuel-bound nitrogen, and ash-producing inorganic solids, and (2) most natural gas flames can withstand considerable reduction in excess air levels from their normal design conditions before a visible smoke is produced. In the residential-size range, however, it appears that very few systematic and quantitative studies of pollutant emissions have, in fact, been carried out. Although admittedly far from an exhaustive search, an attempt to find pertinent reported data to consider in this task yielded results from only two recent investigations, one a laboratory study and the other a field survey.

Thrasher and DeWerth (Ref. 18) measured emissions from 38 different natural gas-fueled, forced-air furnaces (made by 29 different manufacturers) in the American Gas Association (AGA) Cleveland Laboratories. All except one of the furnaces were tested under two different steady-state operating conditions: (1) with the burner well adjusted to produce a stable, nearly nonluminous blue flame, and (2) with the burner poorly adjusted to produce a stable luminous yellow flame. Selected furnaces were tested further to determine parametric effects on emissions of variations in burner-on time, burner firing rate, circulating air temperature rise, and burner design concept (atmospheric versus powered burners). Measurements were also made on several units to determine emissions from standing pilot lights during furnace standby periods.

The main results of that study are summarized in Table 5, reproduced from Ref. 18. Average emissions are listed for 34 furnaces, 24 of which had multiport atmospheric burners and 10 of which had single port burners (four upshot and six inshot). Flue gas samples were taken downstream of the draft hoods; the low values of sample CO_2 content reflect the air dilution accomplished by those devices. Air pollutant species are reported as parts per million in stoichiometric (no excess combustion air or dilution air) combustion product gases. It is seen that single-port burners produced, on the average, slightly lower emissions of CO, NO_2, and aldehydes, and significantly lower NO emissions than did multiport burners. Generally similar differences between blue flame and yellow flame operating conditions were observed with both burner types although the latter condition, having lower excess air levels, exhibited appreciably lower NO formation in the flame zone.

Two furnaces in this study were equipped with forced-draft power burners. Emissions from one unit, whose burner was functionally similar to an atmospheric single-port inshot burner, were all within the 95% confidence bounds about the overall averages listed in Table 5. The other unit, built by AMANA, utilized tneir HTM (Heat Transfer Module) concept. The HTM has a cylindrical heat exchanger matrix surrounding a cylindrical burner screen through which

TABLE 5. AVERAGE LABORATORY-TEST EMISSIONS OF ATMOSPHERIC INJECTION FORCED AIR FURNACES (REF. 18)

Average	Flame	Sample, percent CO_2	Air-free, flue gas concentration, ppm				NO_x emission factor $lb/10^6$ Btu*
			CO	NO	NO_2	HCHO**	
Overall	Blue	5.8 ±1.0	8.1 ±2.6	88.8 ±14.0	4.7 ±2.4	0.18 ±0.14	0.098 ±0.015
	Yellow	6.0 ±1.0	208 ±4	73.6 ±16.0	9.7 ±3.9	0.60 ±0.39	0.088 ±0.014
Multiport burner	Blue	5.9 ±0.9	8.2 ±2.8	94.0 ±11.7	4.8 ±2.5	0.20 ±0.14	0.104 ±0.012
	Yellow	6.0 ±0.9	201 ±3	80.0 ±10.0	8.8 ±2.6	0.62 ±0.40	0.093 ±0.010
Single-port burner	Blue	5.5 ±1.1	7.8 ±2.1	75.0 ±9.6	4.4 ±2.2	0.14 ±0.15	0.084 ±0.010
	Yellow	5.8 ±1.1	225 ±6	56.9 ±17.6	12.1 ±5.8	0.60 ±0.40	0.073 ±0.014

Notes: *Sum of NO and NO_2 calculated as NO_2

**Total aliphatic aldehydes expressed as formaldehyde (HCHO)

The ± value is the standard deviation of the average shown.

the premixed, forced-draft, fuel-air mixture flows. The flame zone consists of a myriad of tiny flame cones and a short radial flow path followed immediately by quenching in the heat exchanger matrix. As a consequence, the measured CO levels, around 100 to 130 ppm (air-free basis), were well above those listed in Table 5 for well-adjusted burners, but also were well below the ANSI-specified (Ref. 15) maximum of 400 ppm. Another result of the HTM burner design was a substantial reduction in NO_x emission levels. Emission factors of 0.018 and 0.013 pound NO_x (as NO_2)/10^6 Btu input were reported for burner firing rates of 86.1 x 10^6 and 126.6 x 10^6 J/hr (81,600 and 120,000 Btu/hr), respectively. These were on the order of 1/7 to 1/6 those of the more conventional gas furnaces; the dramatic reduction was attributed to (1) precise control of combustion air allowing minimization of available oxygen in the flame, and (2) immediate and rapid quenching of combustion products.

Kalika, Brookman, and Yocum (Ref. 19) measured air pollutant emissions from chimneys of 100 natural gas heated homes in Connecticut. Their measurements were conducted in two discrete sampling periods, each involving a different set of 50 homes. The 1200 to 1400 ft^2 floor area homes tested in the first sampling period were built in about 1968 and were predominantly heated by gas-fueled hydronic boilers. Homes tested in the second sampling period were smaller (1000 to 1200 ft^2), older (build in the late 1950's) and were predominantly heated by gas-fueled forced air furnaces. All units were tested in their "as is" operating conditions and, since burner conditions varied widely, there were large variations in the measured emissions.

Average values of air pollutant emissions and their standard deviations for the two sampling periods are listed in Table 6. Consideration of the averages suggests that the emission levels for all pollutant species were higher in the second sampling period than in the first. However, the variations were so large that only the aldehyde, total hydrocarbons, and carbon monoxide emissions were found to be statistically different between the two groups of data.

It is tempting to conclude from the data in Table 6 that gas-fired, forced-air furnaces produce higher emissions than do hydronic boilers. There were, however, several other factors which prevent such a clear inference from being drawn from the data, e.g.: (1) approximately 14-year-old furnaces are being compared with approximately 4-year-old boilers, (2) burner firing times and cycle periods were longer and much more variable for furnaces than for boilers, and (3) flue gases from separate gas-fired water heaters were usually vented through the same chimney as those from furnaces, and carbonaceous emissions from water heaters were found to be substantially higher than from furnaces.

Air pollutant emissions data in Tables 5 and 6 are reported in different units. It is instructive to convert them to comparable units and, to promote comparison with past published data, English units of measurement are used in these three tables. This is done in Table 7, where the comparison basis is the weight (in pounds) of pollutant species emitted per million Btu thermal input. Several assumptions were made to perform the conversions, viz.: an "average" natural gas has a higher heating value of 37.3 x 10^3 J/M^3 (1055 Btu/ft^3) at STP and, when burned with stoichiometric air, produces 0.313 m^3 (11.06 ft^3) of product gases; an "average" No. 2 fuel oil has a higher heating value of 45.32 J/kg (19,480 Btu/lb) and a density of 843.4 kg/m^3 (7.04 lb/gal); and, for the

TABLE 6. SUMMARY OF RESIDENTIAL GAS HEATING SOURCE SAMPLING RESULTS FROM REF. 19

Pollutant	Results from second sampling period: No. of tests*	Results from second sampling period: Average measured emissions, $lb/10^6$ ft^3 gas	Results from second sampling period: Standard deviation	Results from first sampling period: No. of tests*	Results from first sampling period: Average measured emissions $lb/10^6$ ft^3 gas	Results from first sampling period: Standard deviation
Filterable particulate	94	0.88	0.98	96	0.63	1.16
$NO_x(NO_2)$	87	120.6	97.0	89	103.8	98.0
Aldehydes (HCHO)	81	16.3	17.6	84	11.5	9.5
Total hydrocarbons (as CH_4)	73	81.7	65.8	88	56.8**	88.0
Nonmethane hydrocarbons	25	40.3	53.9	--	--	--
Carbon monoxide (CO)	88	78.4	62.2	96	42.4	33.6

*Questionable tests and tests where furnaces were maladjusted were not included in computing averages.

**The six highest values of total hydrocarbon emissions have been deleted from the average because they are much higher than the remaining 88 samples and are considered outliers.

TABLE 7. COMPARISON OF AIR POLLUTANT EMISSIONS FROM NATURAL GAS AND OIL-FUELED RESIDENTIAL SPACE HEATING SYSTEMS (UNITS ARE $LB_M/10^6$ BTU INPUT)

	Natural gas				No. 2 fuel oil		
	Ref. 18 laboratory study		Ref. 19 field survey		Ref. 7 field survey		
Pollutant species	Tuned to blue flame	Tuned to yellow-flame	First sampling period	Second sampling period	As found	Tuned	Rocketdyne/EPA integrated furnace
NO_x (as NO_2)	0.098	0.088	0.098	0.114	0.143	0.142	0.057
CO	0.005	0.138	0.040	0.074	0.057	0.031	0.028
Aldehydes (as HCHO)	1.3×10^{-4}	4.3×10^{-4}	0.011	0.016	Not measured	Not measured	Not measured
UHC (as CH_4)	nil	nil	0.076	0.077	5.3×10^{-3}	4.2×10^{-3}	2.8×10^{-3}
Filterable particulates	Not measured	Not measured	6.0×10^{-4}	8.3×10^{-4}	0.0175	0.0160	Not measured
Smoke (Bacharach scale)	Not measured	Not measured	Not measured	Not measured	No. 3.2	No. 1.3	<No. 1

Rocketdyne/EPA integrated furnace where only NO was measured, it was assumed that NO constitutes 90% (volume) of NO_x produced. A number of very interesting comparisons can be drawn from the data in Table 7. Gas furnaces in the field can be compared with those in the laboratory as well as with oil furnaces in the field (Ref. 7).

Carbonaceous pollutant emissions (CO, UHC, and aldehydes) were all consistently higher from gas furnaces in the field than from well-tuned, gas-fueled units in the laboratory. The UHC and aldehyde levels in the field were on the order of two orders of magnitude higher than in the laboratory, while CO was on the order of one order of magnitude higher. The average CO and aldehyde production by units in the field apparently increase with age. This is probably partly caused by long-term neglect and gradual drift away from well-tuned conditions. In particular, the CO data suggest a gradual long-term migration of the average toward yellow-flame conditions. It does not appear that such a trend can account for the higher levels of UHC and aldehyde emissions observed in the field, however. It is conceivable that these latter differences were related to the compositions of the fuels used or to the mix of burner types employed, but insufficient information is given in Ref. 18 and 19 to resolve this point.

An average of the average gas furnace NO_x emissions is about 0.10 lb NO_x (as NO_2)/10^6 Btu input. The individual averages differ from that by $< \pm 14\%$ which is comparable with the scatter in the laboratory data (Table 5) and smaller than the scatter in the field test data. Thus, the individual NO_x emission averages probably are not statistically different among the gas-fired systems.

Turning now to the field survey data on oil furnaces, it is seen that: (1) average NO_x emissions were about 40% higher than the average NO_x from gas furnaces, (2) average CO emissions were roughly comparable with those from gas furnaces in the field, while (3) UHC emissions were an order of magnitude or more lower, and (4) filterable particulates were about 1-1/2 orders of magnitude higher than the averages for gas furnaces in the field. These data suggest that, from an air pollution viewpoint, residential gas and oil furnaces do not differ greatly from each other except that gas is less prone to produce smoke and filterable particulates.

The most significant air pollution difference between the Rocketdyne/EPA integrated oil furnace and the average of those oil furnaces field tested is its substantially (60%) lower NO_x emissions. The 0.057 lb $NO_x/10^6$ Btu is already 43% below the average NO_x emission level for gas furnaces. The possibility of achieving even greater percentage reductions in NO_x emission levels by converting the integrated furnace to burn natural gas does indeed appear to be worthy of experimental evaluation.

Gas-Fired Integrated Furnace System Testing

As stated earlier in this section, the objective of the testing effort of the alternate fuels evaluation is to evaluate the capability of the integrated furnace to operate on other relatively clean fuels, and not to reoptimize the furnace for these fuels. Therefore, modifications to the integrated furnace system were kept to a minimum.

Feed System Modifications. Obviously, the gaseous fuel feed system must be substantially different from the existing liquid fuel system. The approach taken was to provide a separate parallel natural gas line to the furnace. In conformity to the requirements of Ref. 17, the 1-inch steel pipe line had a manual shutoff valve and a vertical drip leg near its terminus. A section of flexible metal tubing connected the feed system to the burner's main control valve. The natural gas supply pressure was regulated to 10-inches of water column at the burner valve inlet. The fuel used was obtained directly from the local (Los Angeles) supply system. The Southerm California Gas Company stated that an average heating value of 3.93×10^6 J/m^3 (1055 Btu/ft^3) is maintained in the natural gas supplied in the Los Angeles area.

Burner Modifications. It was intended originally to utilize the optimum oil burner as the foundation for the natural gas combustion system in the integrated furnace system. This proposed modified optimum burner system is shown schematically in Fig. 22 using the gas control devices from the Midco DS5850 direct-spark power gas conversion burner. However, during the preliminary evaluation of the air/natural gas mixing process with the as-yet undetermined gas feed tube hole pattern in the optimum oil burner head, it became apparent that a relatively involved analytical or experimental optimization evaluation would be required to ensure a fair representation of the natural gas combustion. This, of course, was in conflict with the objective and the scheduling of this task. This resulted in a selection of a commercially available, state-of-the-art representative burner.

The selection of the commercially available burner was simple since most of the evaluation had already been conducted in the selection of components for the optimum burner conversion. The burner selected is a relatively advanced, gas conversion burner of the newly AGA-certified, efficient direct-spark ignition category, i.e., no pilot flame. The burner is a Mid-Continent Metal Products Co. (Midco) "Economite" Model DS5850 with capacitive discharge/direct-spark ignition and solid-state control system. Figure 23 is a reprint of the specifications page in the manufacturer's sales brochure (Ref. 22).

Gaseous fuel flow control, ignition, and flame monitoring are accomplished by the combination of a Honeywell V845A combination gas valve and a Honeywell S825C electronic control board. The combination valve serves three functions: (1) backup manual gas shutoff, (2) gas pressure regulation, and (3) automatic gas shutoff. Gas supply pressure can range from 6 to 13-1/2 inch water column, and the valve's regulator will provide a constant outlet pressure. It is preset at the factory for 3-1/2-inch water column outlet. Nominal fuel firing rates are selected by putting orifice spuds with different orifice diameter's in an orifice holder downstream of the valve. If intermediate firing rates are desired, the regulator's outlet pressure can be adjusted.

The automatic shutoff portion of the V845A valve is under control of the S825 C control board, which supplies current to the valve's electric operator. The control board supplies an intermittent 19,000 V current to the spark ignition electrodes and provides a 6-second "trial for ignition" period, after which

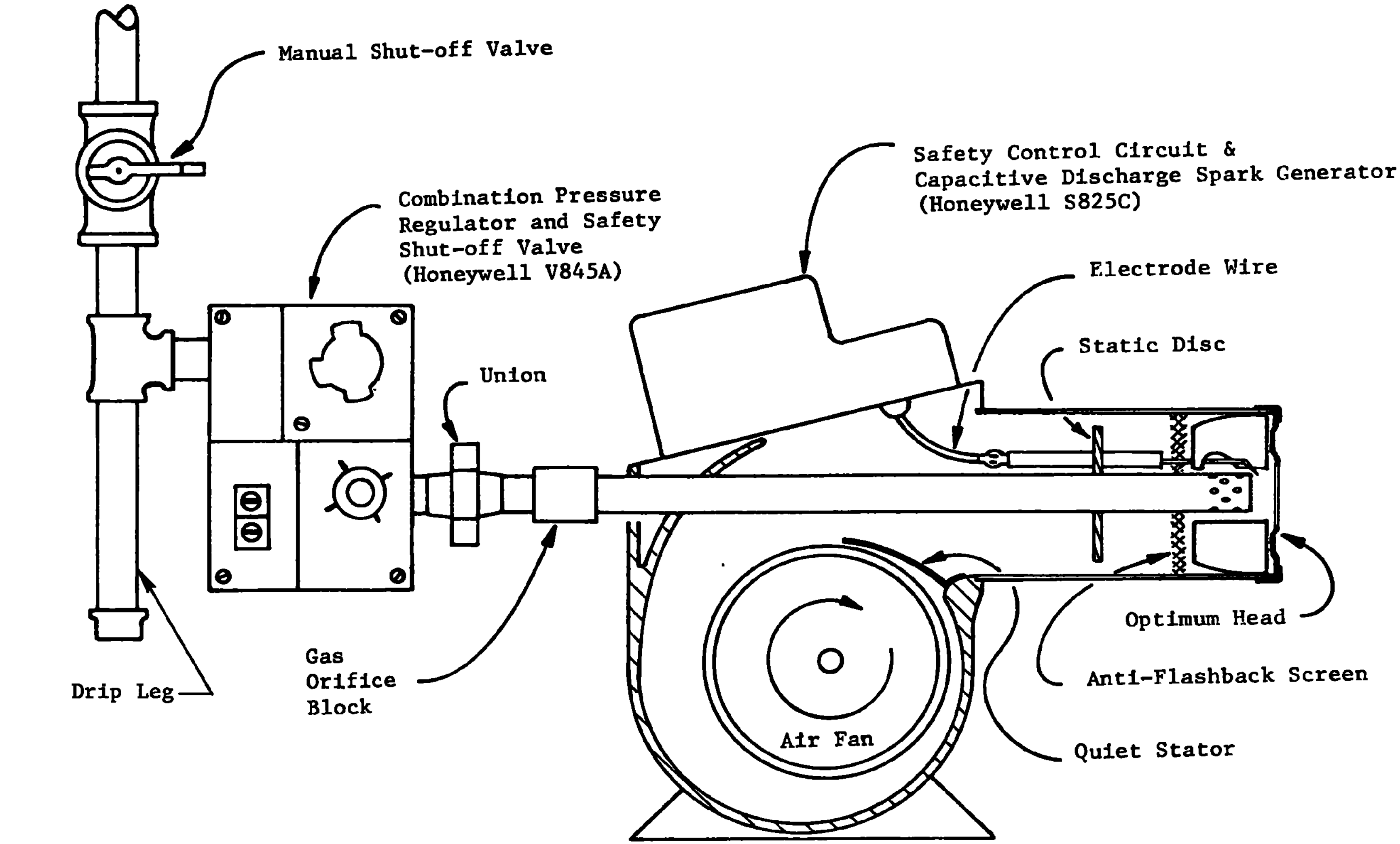
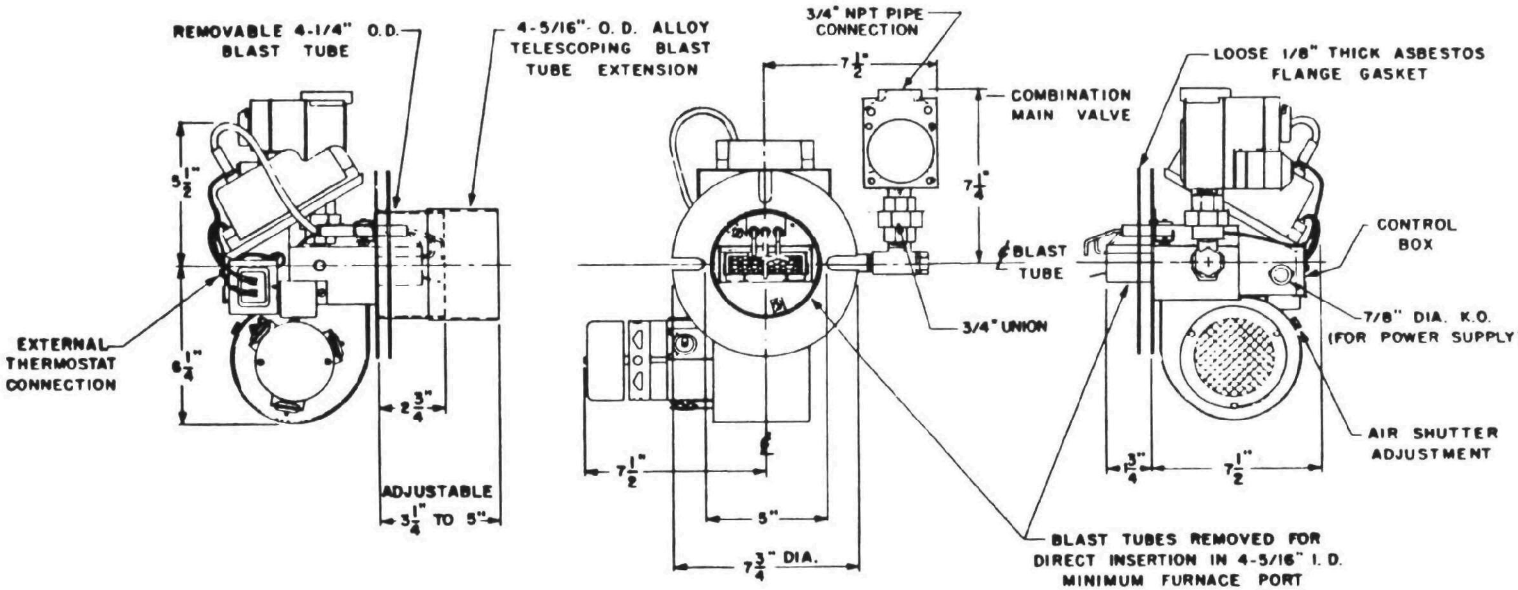


Figure 22. Conversion of the low-emission optimum burner to natural gas



SPECIFICATIONS MODEL DS5850	
Maximum input capacity BTU per hour	200,000
Minimum input capacity BTU per hour	65,000
Minimum combustion Chamber size	7″W x 11″L x 7″H or 10″ DIAMETER
Gas pressure required: Natural Gas	5″ to 13.5″ W.C.
Propane Gas	11″ W.C.

Standard voltage			120 VOLT 60 HZ
Flame Safety			ELECTRONIC
Main burner ignition			DIRECT SPARK
Nozzle Diameter	Less Blast Tube	With Blast Tube	With Blast Tube and Extension
	4 1/16″	4 1/4″	4 5/16″
Nozzle Length	2 1/2″	2 3/4″	3 1/4 to 5″

ECONOMITE DS5850 BURNERS SHIPPED WITH THE FOLLOWING STANDARD EQUIPMENT:

- Direct Spark Ignition System with Electronic Flame Safety.
- Silent Multi-Vane Blower with Resilient-Mounted Motor
- Blower Safety Interlock—Prepurge.
- Transformer for Low Voltage Thermostat 2-Wire Control System.
- Combination Main Automatic Gas Valve with Gas Pressure Regulator and Main Manual Valve.
- Flange Mount with Burner Blast Tube and Stainless Steel Blast Tube Extension.

Figure 23. Dimensions and specifications for the Midco DS5850 burner (Ref. 22)

the flame must be proved for the run to continue. If the flame is not proved, the system will lock out. If the flame is proved, the spark is terminated and the valve remains open to proceed with a normal firing. Thereafter, if flame-out occurs for any reason, the system goes through a new "trial for ignition" period; failure to prove a flame on the reignition attempt causes the system to lock out.

The S825C control board includes a solid-state electronic circuit for monitoring (i.e., proving) the flame continuously. Based on the principle of flame rectification, it requires a flame sensor electrode and a flame ground rod immersed in a stable section of the burner flame. These two sensor components are shown in Fig. 23 and appear like two crooked spark electrodes, and the electrical resistive properties between them is monitored by the control board.

Natural Gas Test Results. The Midco burner was mounted into the prototype integrated furnace system and fired at heat input rates equivalent to 0.79 ml/s and 1.05 ml/s of No. 2 fuel oil. Table 8 presents the results of the flue gas measurements of steady-state and 4-minutes-on/8-minutes-off cyclic natural gas firings. The data denoted by KG* have been normalized to the heating equivalent of 1 kg of No. 2 fuel oil, thus making them directly comparable to the prior oil-fired data obtained in this furnace system. The heating values used are 52.4×10^6 J/kg (22,500 Btu/lbm) for natural gas and 45.27×10^6 J/kg (19,460 Btu/lbm) for No. 2 fuel oil. Examination of the data in Table 8 reveals high carbon monoxide (CO) and unburned hydrocarbon (UHC) levels indicating that the finned combustor designed for the oil burner probably induces premature quenching of the natural gas/air combustion. No improvements in CO and UHC are noted in the higher (1.05 ml/s equivalent oil) firing rate tests, indicating that the overcooling of the combustion zone is substantial, with no response to a 25% change in input.

The nitric oxide (NO) concentrations are generally lower than the levels measured in the optimum oil burner experiments. However, if the combustion zone temperatures were increased to promote complete combustion, i.e., satisfy the $CO < 1.0$ g/kg and $UHC < 0.1$ g/kg criteria, the NO emissions probably would rise above the nominal levels produced by the optimum oil burner system. It is important to note that this conclusion conflicts, in most part, with the generally accepted statement that "gas is cleaner than oil". This turnaround resulted from careful utilization of simple optimization criteria that require no advancement in the state of the art of the oil industry.

However, the smoke emission results in Table 8 reveal an advantage of natural gas over fuel oil. No smoke was detected throughout the wide range of test conditions (SR = 1.16 to 1.94), even with the adversity of an overcooled combustion chamber. Although natural gas/air combustion can produce smoke, the burner used is a powered (air blower) gas burner and the added mixing energy available (compared to a naturally aspirated burner) may be partly responsible for the observed zero smoke readings even at the lower stoichiometric ratio conditions. This no-smoke characteristic again allows great flexibility in pollutant optimization development efforts.

TABLE 8. FLUE GAS EMISSIONS RESULTS USING NATURAL GAS AS FUEL IN THE INTEGRATED FURNACE SYSTEM WITH A MIDCO MODEL DS5850 BURNER

KG* = HEAT EQUIV. ØF 1 KG ØF NØ. 2 FUEL ØIL

Firing Rate	Mode	RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ G/KG*	NØ G/KG*	UHC G/KG*	BACH. SMØKE	NET TFG C
Firing Rate ≈ 0.79 ml/s #2 Fuel Oil	Steady State	616	1.63	7.3	8.8	70	33	6	1.35	0.682	0.066	0.0	275
		617	1.37	8.6	6.2	30	39	2	0.48	0.675	0.018	0.0	269
		618	1.34	8.5	5.8	45	38	4	0.71	0.642	0.036	0.0	261
		619	1.28	9.3	5.1	167	35	16	2.52	0.612	0.137	0.0	258
		620	1.20	10.1	3.9	552	33	76	7.74	0.495	0.609	0.0	244
		621	1.15	10.2	3.1	≥1600	27	700	≥21.50	0.389	5.374	0.0	234
		622	1.28	9.3	5.0	139	38	7	2.08	0.609	0.060	0.0	247
	4/8 Cyclic	623	1.27	9.5	5.0	177	16	3	2.65	0.255	0.026	0.0	164
		624	1.22	9.9	4.2	254	20	3	3.63	0.306	0.024	0.0	153
		625	1.15	10.4	3.2	≥1600	15	26	≥21.54	0.216	0.200	0.0	
		626	1.51	7.7	7.6	80	21	2	1.43	0.401	0.020	0.0	167
Firing Rate ≈ 1.05 ml/s #2 Fuel Oil	Steady State	627	1.94	6.0	11.0	266	19	100	6.18	0.473	1.327	0.0	
		628	1.63	7.5	9.1	105	31	13	2.03	0.642	0.144	0.0	264
		630	1.47	8.5	7.7	65	29	3	1.13	0.539	0.030	0.0	245
		631	1.39	8.9	6.7	55	31	1	0.90	0.543	0.009	0.0	245
		632	1.34	9.3	6.0	57	37	1	0.91	0.621	0.009	0.0	248
		633	1.16	10.4	3.4	≥1600	24	1100	≥21.73	0.349	8.537	0.0	234
		634	1.26	9.9	5.0	355	40	70	5.25	0.633	0.591	0.0	245
		635	1.29	9.7	5.4	209	42	21	3.16	0.679	0.181	0.0	245
		636	1.20	10.4	4.2	≥1600	38	650	≥22.48	0.572	5.219	0.0	242
	4/8 Cyclic	637	1.37	9.1	6.5	70	21	4	1.13	0.362	0.037	0.0	207
		638	1.24	10.0	4.6	456	18	60	6.61	0.279	0.496	0.0	206
		639	1.52	8.0	8.0	130	24	62	2.33	0.460	0.634	0.0	223
		640	1.19	10.2	3.9	1259	15	220	17.55	0.224	1.752	0.0	204
		641	1.25	9.5	4.6	177	15	30	2.60	0.235	0.251	0.0	207

METHANOL

Past and Present Applications

Methanol has long been used as a portable and clean-burning fuel. It was produced in the 19th century as a by-product from the destructive distillation of wood to charcoal and was used extensively for lighting and cooking. Methanol as a fuel was gradually displaced in the late 1800's by kerosene and other petroleum oils until it was reduced to a few specialty applications, such as shipboard cooking and laboratory burners. A resurgence occurred in Europe during the World War II era, when several countries blended both methanol and ethanol with gasoline as motor fuels (Ref. 23). From then into the 1970's, its use as a fuel was again suppressed by the ready availability of cheap natural gas and petroleum-derived liquid distillate fuels. Nonetheless, methanol was and is produced in substantial quantities for industrial uses as a solvent and as a chemical feedstock. For example, over 4.54×10^6 m^3 (1.2 billion gallons) of CH_3OH were produced in the U.S. in 1975, mostly from natural gas.

Recently, as a result of the 1973-1974 oil embargo, renewed interest has arisen in producing methanol and/or mixed alcohols for mass distribution as fuels (Ref. 24 to 26). Most attention has been given to their use as automotive fuels, either straight or in gasoline blends. Distribution systems established for automotive fuels usually are amenable to supplying fuels for stationary combustion equipment as well, so methanol as a residential heating fuel should be a natural outgrowth from any substantial automotive application.

At the present time, methanol-fueled stationary heating systems are not commercially available in the United States.

Air Pollution Emissions Studies

Residential-Sized Burning. A few experimental studies of burning methanol in modified existing oil-fueled equipment have been reported. The work of Martin (Ref. 11 and 27) is the most pertinent to residential-size equipment. Several fuels -- namely methanol, iso-propanol, a 50-50 mixture of those two alcohols, No. 2 distillate oil, oil emulsions, and propane -- were burned with a movable-block swirl burner tunnel-fired in an adiabatic research combustion chamber at a nominal 87,900 W (300,000 Btu/hr) input heat rate. The liquid fuels were injected through commercially available pressure atomizing distillate oil nozzles; nozzle sizes were varied inversely with the fuels' higher heating values to maintain the fixed heat input rate. By comparison with No. 2 fuel oil, the alcohol fuels presented no significant utilization problems. The following conclusions were drawn from the results of the study (Ref. 27):

"1. Alcohol fuels produce lower emissions of nitrogen oxides than either distillate oil or propane.

2. The NO emissions of alcohol fuels increase as the percentage of higher alcohols increases.

3. The low NO emissions for alcohol fuels appear to function from the presence and level of oxygen in the fuel molecule, which can be viewed as a diluent carried in the fuel. The operative mechanism appears to be related to thermal effects of the fuel, latent heat of vaporization, and/or decreased flame temperature; however, chemical effects cannot be totally ruled out.

4. In the experimental system, NO levels similar to those for methanol (e.g., 65 ppm) could be attained for distillate oil and propane with flue gas recirculation, and could be approached at high water levels for distillate oil emulsions.

5. Based on the calculations, the use of methanol and an equivalent water oil emulsion appears to impose a 6 to 7% increase in stack loss compared to distillate oil with flue gas recirculation; however, it is anticipated that there will be some compensating factors that can be designed into practical systems to minimize the losses.

6. The emissions of CO, UHC, and particulate from alcohol fuels were essentially the same as those for the conventional clean fuels tested.

7. From the technical standpoint, methanol appears to be a satisfactory fuel for stationary combustion systems; however, the final commercial feasibility will probably depend more on cost and availability than on the ability to burn the fuel."

Commercial Boiler Burners. Duhl (Ref. 28) reported on a two-part study of methanol as a boiler fuel. The first part was a small-scale demonstration, on a boiler test stand used to evaluate fuels and burners, that methanol could be a viable alternate fuel candidate. NO_x emissions, on an equivalent flue gas basis were about 1/4 of those from natural gas and about 1/10 of those from NO. 6 residual oil fired in this device. The second part was a larger-scale demonstration on a utility boiler rated at 193,000 kg/hr (425,000 lb/hr) steam. Only two changes were made in the fuel feed circuit: a centrifugal pump was installed in parallel with the existing fuel pumps, to provide forced recirculation from discharge to suction for startup; and, the burners' mechanical atomizing tips were replaced. (Some peripheral test tunnel experiments were used to find the best-performing, steam-atomizing spray tips.)

The results showed that methanol may be handled just as any other liquid fuel. It can be shipped and stored within the existing specifications for a number of other fuels. Flue gas CO concentrations were less with methanol than with either natural gas or residual oil. Spot analyses indicated negligible flue gas concentrations of aldehydes, organic acids and unburned hydrocarbons with methanol fuel. Smoke and particulates in the stack were nonexistent; in fact, soot deposits from oil firing were gradually burned off by methanol combustion products. NO_x emissions with methanol were about 90% as high as with natural gas, whereas, they were only 38 to 67% as high as with No. 6 oil (a smaller difference was measured as unit load was increased). No explanation was offered for the relatively smaller impact of methanol on NO_x emissions from the boiler than from the small-scale test stand.

Methanol-Fired Integrated Furnace Testing

The testing of methanol as an alternate clean fuel in the integrated furnace proceeded in the most direct and simple approach. System hardware modifications were minimized with a "try-it-and-see" approach on operational requirements and precautionary modifications made only for safety reasons.

Feed System Modifications. The higher heating value of methanol is 2.27×10^7 J/kg (9760 Btu/lbm). This is only half that of No. 2 fuel oil [$\sim 4.5 \times 10^7$ J/kg (19,400 Btu/lbm)], so the firing rate with methanol must be about twice that with No. 2 oil if the same thermal demand is to be satisfied. In a residential application, some enlargement of an existing oil storage and supply system would probably be needed to accommodate methanol. At the least, a larger fuel tank would probably be needed to avoid excessively frequent refilling, however, existing local codes for residential storage of flammable or combustible fuels may limit this preference. Also, a larger-diameter line from the tank to the burner might be needed, depending on line length, to prevent excessive line pressure losses from lowering the pump inlet suction pressure into a cavitation condition with the more volatile methanol fuel. In the Rocketdyne test laboratory, where the fuel tank is close to and elevated above the burner, line size factors are not anticipated to be of any importance, so the No. 2 fuel oil feed system was retained in its existing configuration for use with methanol. The fuel used was anhydrous, commercial grade methanol.

Burner Modifications. Conversion of the optimum oil burner to methanol is relatively simple. Unlike the liquid fuel flowrate, which we have just seen is approximately doubled, the combustion air flowrate is only slightly changed due to the stoichiometric air/fuel ratio being less than half that for No. 2 fuel oil. As a result, the most significant burner modifications in this conversion are associated with the liquid fuel circuit. Burner components which remained unchanged included the burner body, the air fan, the quiet stator, the static disc, the blast tube, the burner head, the ignition transformer, and the ignition spark electrodes. The combustion air inlet draft control assembly and the sealed vestibule door were removed as a result of recommendations from the Rocketdyne Safety Officer to eliminate potential "pockets" for accumulating methanol vapors. Additionally, a 20-second air purge, similar to a powered gas burner cycle, was included in the start sequence to clear the combustion chamber of any methanol vapors. This conservative safety procedure was used due to the lack of existing operating safety codes for methanol as a fuel for stationary sources.

The specific gravity of methanol is 6.2% lower than that of No. 2 fuel oil so that, for equal thermal inputs, the volumetric flowrate of methanol should be 2.11 times that of the No. 2 oil being replaced. The Sundstrand Model A fuel pump on the optimum burner at the normal 6.9×10^5 N/m^2 (100 psig) output pressure, has a maximum capacity that is about four times the nominal design oil firing rate [0.79 ml/s (0.75 gph)] of the integrated furnace. Therefore, the same pump was used with changes only in the ratio of pumped fluid to bypass fluid. The only potential problem was increased wear of the pump's moving parts caused by methanol not being as good a lubricant as distillate oil. From the experiences reported in the cited literature on substituting methanol for distillate fuels, it appeared that this was not a significant short-term problem.

The fuel spray nozzle was changed twice to match two oil furnace thermal inputs (0.79 and 1.05 ml/s) for which substantial data exist for No. 2 fuel oil in the integrated furnace. Rather than simply relying on the manufacturer's stated nozzle capacity, the fuel firing rate was measured while the burner was firing and adjusted to the desired value by changing the nozzle.

Originally, a Honeywell RA890G/C7027A ultraviolet (UV) spectrum-sensing safety control system was planned to be used in conjunction with a Q624 capacitive discharge ignition (CDI) system. The RA890G circuit is unique in that it does not require that the UV sensor (C7027A) be downstream of the UV-producing electrical spark. Instead, it is designed for use with CDI systems which characteristically produce a spark of extremely short duration, and the flame-generated UV light is evaluated during the relatively long no-spark period. Therefore, the UV sensor could have been installed in the conventional location in the blast tube. However, checkout firings revealed that the burner's existing CdS flame detector cell was sufficiently sensitive to the yellow-streaked blue flame produced in the cast-iron combustor of the integrated furnace with methanol to use it for proving ignition and the system was retained for this test series.

Methanol Test Results. Table 9 presents the flue gas emissions results of the methanol experiments. Both steady state and 4-minutes-on/8-minutes-off cyclical firings were made at heat input rates equivalent to 0.79 ml/s and 1.05 ml/s No. 2 fuel oil firing rates. Again, the emission concentration data have been normalized to the equivalent heating value of a kilogram of No. 2 fuel oil. The heating values used for this analysis were 45.27 x 10^6 J/kg (19,460 Btu/lbm) for No. 2 fuel oil and 22.68 x 10^6 J/kg (9750 Btu/lbm) for methanol. The ratio of heating values is approximately two, however the ratio of stoichiometric air/fuel ratios (14.45/6.50) is also about two, resulting in a normalization correction factor for methanol of approximately unity.

The CO concentrations, as in the natural gas tests, are unacceptably high. However, in this case, there appears to be an improvement with increasing firing rate. Furthermore, the UHC concentrations remain acceptably low, giving an indication of only a mild condition of overcooling of the combustion zone.

The NO results presented in Table 9 show extremely low concentrations of this pollutant. As concluded by Martin (Ref. 27), the oxygen molecule in the carbon/hydrogen structure (CH_2OH) may act as a diluent in the combustion process. This, along with the formation of a relatively large amount of water (~15 wt. % of combustion products) serve to inhibit the maximum temperature in the combustion zone, resulting in lower thermal NO. Although the combustion process in this test configuration was partially quenched by the overcooled flame zone condition, the extremely low nitric oxide concentrations indicate that the NO readings would very likely remain below 0.5 g/kg* even at the higher combustion zone temperatures required for reducing the CO concentrations (i.e., complete combustion).

The methanol results also show no smoke throughout the stiochiometric ratio range tested (SR = 1.05 to 1.78). This nonsmoking characteristic displayed in the results of this test series suggests great flexibility of low emissions

TABLE 9. FLUE GAS EMISSIONS RESULTS USING METHANOL AS FUEL IN THE INTEGRATED FURNACE SYSTEM WITH THE OPTIMUM BURNER

KG* = HEAT EQUIV. OF 1 KG OF NO. 2 FUEL OIL

Mode	RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO G/KG*	NO G/KG*	UHC G/KG*	BACH. SMOKE	NET TFG C	Firing Rate
Steady State	590	1.45	10.3	7.0	90	13	2	1.66	0.257	0.021	0.0	202	Firing Rate ≈ 0.79 ml/s #2 Oil
	591	1.32	11.3	5.4	60	14	2	1.01	0.251	0.019	0.0	194	
	592	1.21	12.3	3.8	107	15	2	1.66	0.247	0.018	0.0	191	
	593	1.16	12.7	3.1	254	14	2	3.76	0.222	0.017	0.0	188	
	594	1.12	13.1	2.4	1179	12	3	16.84	0.184	0.024	0.0	186	
	595	1.10	13.3	2.2	≥1600	11	5	≥22.59	0.166	0.040	0.0	186	
	596	1.78	8.4	10.1	≥1600	3	8	≥36.22	0.073	0.103	0.0	219	
	597	1.59	9.5	8.5	342	9	8	6.93	0.195	0.093	0.0	219	
	598	1.49	10.2	7.5	148	11	3	2.81	0.223	0.032	0.0	210	
4/8 Cyclic	599	1.46	10.4	7.2	412	8	17	7.63	0.159	0.180	0.0	172	
	600	1.23	12.3	4.3	157	5	13	2.48	0.084	0.117	0.0	164	
	601	1.16	13.0	3.2	535	10	5	7.94	0.159	0.042	0.0	166	
Steady State	602	1.10	13.3	2.1	120	13	2	1.69	0.197	0.016	0.0	241	Firing Rate ≈ 1.05 ml/s #2 Oil
	603	1.24	12.1	4.3	10	12	3	0.16	0.202	0.027	0.0	247	
	604	1.32	11.3	5.4	10	12	2	0.17	0.215	0.019	0.0	252	
	605	1.35	11.1	5.8	10	9	2	0.17	0.165	0.020	0.0	258	
	606	1.18	12.7	3.4	20	9	2	0.30	0.145	0.017	0.0	255	
	607	1.10	13.3	2.1	90	9	2	1.27	0.136	0.016	0.0	250	
	608	1.05	13.8	1.2	≥1600	9	9	≥21.62	0.130	0.069	0.0	247	
	609	1.07	13.9	1.5	1019	9	2	13.96	0.132	0.016	0.0	244	
	610	1.09	13.6	1.8	342	10	2	4.76	0.149	0.016	0.0	247	
4/8 Cyclic	611	1.09	13.3	1.8	456	10	3	6.36	0.149	0.024	0.0		
	612	1.20	12.0	3.7	157	13	4	2.42	0.214	0.035	0.0		
	613	1.31	11.1	5.2	177	10	4	2.96	0.178	0.038	0.0		
	614	1.21	12.0	3.8	130	11	3	2.00	0.182	0.026	0.0	162	
	615	1.17	12.4	3.1	254	10	3	3.78	0.159	0.025	0.0	164	

design criteria for methanol burners and combustors. Methanol, and perhaps methanol/oil mixtures, appears very promising as a low polluting fuel.

ALTERNATE FUELS EVALUATION

Current priorities mandate more than convenience and price factors for determining the applicability potential of energy-related systems. Presently, pollutant emissions and thermal efficiency are prime considerations, with the influence of price not clearly defined in these times of rapidly changing economics.

Pollutant Emissions

The pollutant emissions characteristics of natural gas, methanol, and No. 2 fuel oil have been presented in previous sections of this report. In summary, there is a slight favorable bias for the No. 2 distillate fuel oil due to the optimized state of the system for that fuel. All three fuels demonstrated the likelihood that each could be optimized to release relatively comparable carbonaceous emissions of CO $\leq$ 1.00 g/kg* and UHC $\leq$ 0.10 g/kg* presently imposed on the oil fired integrated furnace system.

Both natural gas and methanol demonstrated a lower smoke emissions advantage over No. 2 fuel oil. Quantitatively, this apparently large advantage is actually small since the smoke emission in the oil-fired integrated system has been minimized to acceptable levels at favorable operating conditions (SR = 1.20) where only negligible gains in efficiency (<1%) could be further realized. However, the advantages offered in design flexibility can result in very saleable, compact, and efficient furnace configurations; whereas, in oil-fired systems, geometric variations are limited by strict requirements defined by smoke emissions.

The NO levels from the stock natural gas burner are nominally equal to those of the optimized oil burner. However, the NO emissions from the relatively undeveloped, methanol-fired system may be approximately 40% lower than those with the other two fuels. This, combined with its no-smoke characteristic, make methanol a preferred candidate for low polluting fuel alternatives.

Efficiency

Due to the nonoptimized status of the natural gas and methanol systems, only a pseudo-quantitative efficiency analysis can be undertaken here. However, advantages and problem areas can be identified by this analysis for this fuels evaluation. All three fuels appear to be capable of operation at 10 to 20% excess air. This 10% span of operating conditions affects the thermochemical/heat transfer processes, i.e., thermal efficiency, by less than 1% and, therefore, is of only minor consequence in this evaluation. The flue gas heat loss is the limiting factor in maximizing efficiency in the noncondensing flue systems presently in operation. For example, in a No. 2 fuel oil system, the maximum achievable thermal efficiency is approximately 85%, limited by 15%

*Heating equivalent of 1 kg of No. 2 fuel oil flue gas losses. Approximately 9% of this loss is sensible heat of the flue effluents, and the remainder is attributable to the heat of vaporization of the noncondensed water vapor formed in the combustion process. Table 10 presents an evaluation of maximum obtainable steady-state efficiency based on the differences in amounts of water vapor in the products of combustion of the three fuels. This evaluation is based on prior experiences and analyses of the thermal efficiency characteristics of No. 2 fuel oil systems. Column 4 lists the weight percent of water vapor in the combustion products at 20% excess air. Column 5 relates the latent heat of vaporization to the fuel's heating values. The final column combines that latent heat loss with a sensible heat loss to arrive at an estimated maximum steady-state efficiency. It was assumed that the heat exchangers would be optimized to result in equal net flue gas temperatures of 222 C (400 F). The resulting estimates show that an oil-fueled system is capable of a slightly higher thermal efficiency than one fueled with natural gas, while significantly lower efficiency can be achieved with methanol. This notable difference in methanol thermal efficiency would require a minimum increase in energy input of approximately 8% by comparison with natural gas. Even so, the NO emissions from methanol would still be significantly lower than those from either oil or gas burned in a furnace at equivalent thermal demand.

TABLE 10. ESTIMATED MAXIMUM ACHIEVEABLE THERMAL EFFICIENCY BASED ON THE INFLUENCE OF WATER VAPOR IN THE COMBUSTION PRODUCTS OF THREE FUELS

Fuel	Relative stoichiometric mixture ratio	Relative heating value	Wt. % H_2O* in flue gas	Latent heat of Uncondensed water, % of fuel's HHV	Estimated maximum thermal efficiency, %**
No. 2 Oil	1.0	1.0	6.3	6.2	84.4
Methanol	0.45	0.5	12.9	12.0	78.4
Natural Gas	1.04	1.16	9.6	8.7	82.2

*SR = 1.20
**Assuming equal net flue gas temperatures of 222C (400 F)

Applications

As stated earlier in this section, the use of natural gas as a heating fuel in this country is predominant (~58.5%), more than twice that of fuel oil (~27.5%). The data presented in Tables 5 through 7 show that the present natural gas emissions are approximately equal to the optimum oil burner emissions, which are approximately 65% lower than the NO levels emitted by oil-fired equipment currently in service. In simplified terms, the current total NO pollutant emissions produced by oil-fired residential furnaces is ~33% more than gas. Total conversion from oil to gas would result in a ~37% reduction of total NO emissions from these stationary heating sources. However, this balance of energy sources is very strongly influenced by price and availability, and conversions would be difficult to mandate solely on the basis of emission reduction. It appears more practical to approach and obtain equal emissions reduction of oil-fired devices by equipment optimization, of which only one of the options has been investigated in this study.

Due to the already low levels of pollutant concentrations from natural gas/air devices, further emissions optimization would result in only incremental individual improvements. For example, an apparently substantial reduction in NO emission of 50% would in actuality be only ~0.3 g/kg* reduction in NO concentration for a natural-gas-fired device. However, the net overall effect of such an improvement would result in a substantial total improvement due to the sheer number, approximately 38.8 million gas-fired, residential-heating devices (Ref. 10), but it would be difficult to convince such a great number of consumers to make financial sacrifices for individually minute pollutant emissions effects with no consideration for payback. Therefore, future pollutant emissions optimization efforts on natural gas devices should proceed in a more aggressive manner and include efforts to eliminate latent heat flue gas losses, i.e., condensing flue systems. This would offer consumers an 8% savings in fuel consumption with its associated additional 8% reduction in pollutant emissions, and some further undetermined reductions in emissions resulting from the cleansing/solvent action of the liquid condensate in the flue gases, i.e., dissolving of NO_2, scrubbing of particulates, etc.

The use of methanol as fuel for stationary heat sources is essentially nil in the United States. The present method of production of methanol, using natural gas as the hydrocarbon base, is ineffective in the overall effort of conserving presently available, limited energy resources. However, other options for the production of methanol are available that utilize replenishable materials, e.g., trees, refuse, etc., that make it a suitable candidate as an alternate fuel. Further evaluation of the specifics and economics of the methanol production cycle is beyond the scope of this study, and this evaluation will proceed on the conclusion that methanol is an available alternate fuel candidate.

The above emissions evaluation revealed that the NO emissions of an optimized methanol system are significantly lower (on the order of 40%) than those of natural gas or optimized fuel oil-fired devices, with an additional advantage of lower smoke emissions than fuel oil. The laboratory hot-fire test effort demonstrated the ease of oil-to-methanol conversion on test hardware. Actual installed hardware would require a change of safety control hardware, probably very similar to the type found on powered gas burners, with air purge cycles included to reduce explosion hazards. Optimization studies could proceed in two directions: investigating retrofit conversions, and exploring all of the emission advantages of methanol in new equipment design configurations. The NO emissions data presented in Table 9 resulted from a methanol-fired furnace system in only a preliminary development stage, yet showing 80% reduction in NO from the average existing oil-fired unit (Ref. 7). Although the exact geometric dimensions were not finalized, the above methanol furnace did utilize most all of the recommended low-emissions devices, viz., cooled firebox, plug-flow burner head, and air pulsation suppressors. Most fireboxes in existing oil-fired systems are of the uncooled type (firebrick or pyroflex-insulated) to promote vaporization of the fuel oil, and are generally not amenable to direct flame impingement. Therefore, because of higher firebox temperatures, the reduction in NO from retrofit methanol conversion burners would not be as great, probably 50%, based on experience with No. 2 fuel oil emissions testing. Although the maximum achievable thermal efficiency for a methanol-fired system is 6% less than that achievable with fuel oil, a field study (Ref. 7) shows that the average operating condition of existing oil-fired equipment is more than 50% excess air. Methanol, with its essentially smoke-free characteristics, could easily improve on this less efficient condition. This, coupled with careful matching with a heat exchanger might result in competitive operating efficiencies for methanol-fired systems.

REFERENCES

1. Dickerson, R. A. and A. S. Okuda: Design of an Optimum Distillate Oil Burner for Control of Pollutant Emissions, EPA-650/2-74-047, Final Report on Contract 68-02-0017, Rockwell International/Rocketdyne Division, Canoga Park, CA, June 1974.

2. Combs, L. P. and A. S. Okuda: Residential Oil Furnace System Optimization-Phase I, EPA-600/2-76-038, Phase Report on Contract 68-02-1819, Rocketdyne, Canoga Park, CA, February 1976.

3. Combs, L. P. and A. S. Okuda: Residential Oil Furnace System Optimization-Phase II, EPA-600/2-77-028, Phase Report on Contract 68-02-1819, Rocketdyne, Canoga Park, CA, January 1977.

4. Combs, L. P. and A. S. Okuda: "Design Criteria for Reducing Pollutant Emissions and Fuel Consumption by Residential Oil-Fueled Combustors," Paper No. 76-WA/Fu-10, presented at the 97th ASME Winter Annual Meeting, New York, NY, December 1976.

5. Peoples, G.: "Sealed Oil Furnace Combustion System Reduces Fuel Consumption," Addendum to the Proceedings, Conference on Improving Efficiency in HVAC Equipment and Components for Residential and Small Commercial Buildings, Purdue University, Lafayette, Ind., October 1974, pp A66-A72.

6. American National Standard Performance Requirements for Oil-Powered Central Furnaces, ANSI Z91.1 1972, American National Standards Institute, Inc., New York, NY, June 1972.

7. Barrett, R. E., S. E. Miller, and D. W. Locklin: Field Investigation of Emissions From Combustion Equipment for Space Heating, EPA-R2-73-084a (also API Publ. 4180), Environmental Protection Agency, Research Triangle Park, NC, June 1973.

8. Combs, L. P., and A. S. Okuda: Commercial Feasibility of an Optimum Residential Oil Burner Head, EPA-650/2-76-256, Final Report on Contract 68-02-1888, Rockwell International/Rocketdyne Division, Canoga Park, CA, September 1976.

9. Climates of the States, Vol. I, NDAA, U.S. Department of Commerce, Washington, D.C., 1973.

10. Detailed Housing Characteristics, U.S. Census of Housing, Bureau of the Census, U.S. Department of Commerce, Washington, D.C., 1970.

11. Martin, G. B., "Environmental Considerations in the Use of Alternate Fuels in Stationary Combustion Processes," in symposium proceedings, Environmental Aspects of Fuel Conversion Technology, EPA-650/2-74-118, U.S. Environmental Protection Agency, Research Triangle Park, N.C., October 1974, pp 259-276.

12. Gas Engineer's Handbook, (Fuel Gas Engineering Practices), The Industrial Press, New York, N.Y., 1965.

13. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., New York, N.Y., 1972.

14. ASHRAE Guide and Data Book: Equipment 1972, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., New York, N.Y., 1972.

15. American National Standard for Gas-Fired Gravity and Forced Air Control Furnaces, ANSI Z21.47-1973, American Gas Association, Arlington, Virginia, April 1973.

16. American National Standard for Domestic Gas Conversion Burners, ANSI Z21.17-1974, American Gas Association, Arlington, Virginia, October 1974.

17. American National Standard, Installation of Domestic Gas Conversion Burners, ANSI Z21.8-1971, American Gas Association, Arlington, Virginia, December 1971.

18. Thrasher, W. H., and DeWerth, D. W., Evaluation of the Pollutant Emissions From Gas-Fired Forced Air Furnaces, Research Report No. 1503, American Gas Association, Cleveland Laboratories, Cleveland, Ohio, May 1975.

19. Kalika, P.W., Brookman, G. T., and Yocum, J. E., A Study on Measuring the Environmental Impact of Domestic Gas-Fired Heating Systems, Final Report, The Research Corporation of New England, Wethersfield, Conn., June 1974.

20. Directory of Certified Appliances and Accessories, American Gas Association Laboratories, Cleveland, Ohio, and Los Angeles, California, July 1976.

21. "Power Burner Installation and Service Manual, HP Series," Form 310B, Adams Manufacturing Company, Cleveland, Ohio, 1976.

22. "Economite Model DS5850 Gas Burner," sales brocure, Mid-Continent Metal Products Company, Chicago, Illinois, May 1976.

23. Reed, J. B., "The Use of Alcohols and Other Synthetic Fuels in Europe From 1930-1950," AIChE 80th National Meeting, Boston, Massachusetts, Sept. 1975.

24. Reed, J. B., "The Production and Use of Alcohols as Fuels," ACS Symposium on the Future of the Rubber Industry, San Francisco, CA, Oct. 1976.

25. McCloskey, J. P., "Grow Alcohol as a Replacement for Gasoline," Energy Sources, Vol. 2, No. 1, 1975.

26. Harney, B. M., "Methanol From Coal - A Step Toward Energy Self-Sufficiency," Energy Sources, Vol. 2, No. 3, 1975.

27. Martin, G. B., "Evaluation of NO_x Emission Characteristics of Alcohol Fuels in Stationary Combustion Systems," Joint Western States and Central States Sections Meeting, the Combustion Institute, San Antonio, Texas April 1975.

28. Duhl, R. W., "Methanol as Boiler Fuel," a CEP Capsule, Chemical Engineering Progress, Vol. 72, No. 7, July 1976, pp 75-76.

APPENDIX A

CAST FIREBOX MATERIAL SELECTION

The major question to be resolved in designing a cast-formed, finned firebox was selecting the material of construction. Consideration was given to two materials, cast aluminum and cast iron.

The primary advantages of aluminum over cast iron are its lighter weight and higher thermal conductivity. The weight savings of ~11 kg (24 lbm) primarily allows savings in furnace shipping costs, with only minor considerations for lower cabinet strength requirements. A transportation cost study, based on shipments of 20 furnaces from the Los Angeles area (shipping rates are approximately 15% higher west of the Rocky Mountains) revealed that even at the higher West Coast rates and a maximum distance of 2000 miles, a savings of only about $4/unit would result from using the lighter-weight, cast-aluminum combustor. Therefore, the weight savings of aluminum, while significant, was not considered to be of overriding importance.

The higher thermal conductivity of aluminum is, in this directly impinging flame and "continuous" combustion application, offset by its lower maximum temperature limitations. The establishment of maximum temperature values is a problem in itself in the Underwriters' Laboratories (UL) certification process, as no cast aluminum alloys are presently listed in UL No. 296 (residential furnace standard) for use in high-temperature combustion gases. Discussions with UL personnel revealed that establishment of their maximum temperature guidelines is more of a historical rather than a metallurgical process, based on their experience with the listed materials. This presents a major hurdle for the aluminum combustor concept as UL has had no experience with the candidate cast aluminum alloys (Al 319 and Al 356), nor did they have specific recommendations for Rocketdyne to proceed in testing and assisting in the establishment of new guidelines for these cast aluminum alloys. Thus, proceeding independently, maximum temperature guidelines were estimated by comparison of various metallurgical properties of the UL listed materials and the candidate aluminum alloys. A maximum temperature of 260 C (500 F) was set for Type 356 aluminum alloy as suitable for long life (≥10 yrs), and design calculations proceeded from this estimation.

To maintain combustor temperatures at or below this limit, very large cooling fins would be required, extending out approximately 0.064 m (2.5 inches) at the rear of the combustor. The long length of the fins introduced a problem of a large temperature difference between the base and the tip of the fins, resulting in critical internal stresses in the relatively low-ductility casting alloys. The fins would therefore have to be segmented, resulting in approximately 10% greater combustor costs. This would relieve excessive stresses in the combustor wall but would increase the likelihood of nonuniform heat transfer characteristics.

Another problem area was the differential thermal expansion between a carbon-steel adapter ring (to be attached to the steel heat exchanger) and the cast-aluminum combustor. The tensile stress in the steel ring, at maximum operating temperature, is approximately two times the level that is considered safe for 10^6 cycles. A more costly gasket-type joint would be required to absorb most of the differential in radial growth to reduce stress. A question still remaining unanswered was that of the effect of the direct flame impingement on a cast-aluminum surface. Opinions were solicited from a variety of specialists (e.g., Reynolds Aluminum representative, Rocketdyne Materials and Processes personnel, and aluminum casting foundries) concerning the durability of cast aluminum under these conditions, and a diversity of answers with no concensus was expressed.

The design effort then concentrated on a cast-iron combustor design. The maximum operating temperature allowed by UL is approximately 540 C (1000 F); compared with aluminum, this provides much more design flexibility. In contrast to the long segmented fins required on a cast-aluminum combustor, a cast-iron unit can incorporate continuous fins. A design with radially-oriented cooling fins approximately 0.025 m (1.0 inch) in height was estimated to allow parts of the combustor to approach a maximum of 340 C (650 F), still well below the 540 C (1000 F) UL limit.

Cast iron is very compatible with the concept of installing a steel heat exchanger attachment ring in the firebox casting mold so that it is integral with the casting, and no special provisions are required. In fact, some cast-iron/carbon-steel fusing is expected to occur in the casting process. Thermal stress and cycle fatigue analyses of this joint supported anticipated lifetimes exceeding 10 years without cracking.

A local iron foundry was visited to discuss the cast-iron combustor design, and it was concluded that the basic design is very amenable to cast-iron forming. Only minor detail changes were recommended and these were incorporated in the design drawings.

A summary of estimated costs of fabrication and installation of cast-aluminum and cast-iron combustors, based on production of 10,000 units/year, is given in Table A-1. The estimated aluminum unit cost of $60 each could possibly be reduced by approximately 10% by the use of permanent molds for the low-melting-temperature aluminum, or perhaps by die casting, depending on the total projected production run. Thus, the 20 to 25% higher cost of using aluminum might be approximately halved. This, coupled with the technical problems and disadvantages attending the use of aluminum reinforced the selection of cast iron as the firebox construction material.

TABLE A-1. ESTIMATED CAST COMBUSTOR COSTS

Cast aluminum (~11.3 kg)	Casting at 10,000/year		$45
	Segmenting fins	+	$5
	Machining for mount holes + burner port	+	$2
	Gasket-type joint	+	$3
	Mounting legs and face plate	+	$3
	Assembly	+	$2
			$60
Cast iron (~22.7 kg)	Casting at 10,000 year		$40
	Machining for mount holes + burner port	+	$2
	Mounting legs and face plate	+	$3
	Assembly	+	$2
	Δ Shipping cost at 1500 miles	+	$2
			$49

APPENDIX B

DATA TABULATIONS: PROTOTYPE FURNACE EXPERIMENTS

4-MINUTE-ON/8-MINUTE-OFF CYCLE-AVERAGED POLLUTANT EMISSION CONCENTRATIONS FROM THE PROTOTYPE INTEGRATED FURNACE WITH 0.025 M EXPOSED COOLING FINS AND A 0.152 M BURNER BLAST TUBE

	RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	TFG C
CENTRIFUGAL CLUTCH OIL PUMP DRIVE	25	1.19	12.8	3.6	30	35	11	0.47	0.601	0.099	0.0	221
	26	1.27	11.6	4.5	25	35	9	0.42	0.649	0.086	0.0	227
	27	1.36	11.3	5.9	20	35	8	0.36	0.698	0.083	0.0	227
	28	1.24	12.4	4.3	25	34	4	0.41	0.599	0.038	0.0	224
DIRECT OIL PUMP DRIVE	29	1.24	12.4	4.4	27	35	11	0.46	0.637	0.104	0.0	224
	30	1.24	12.4	4.4	25	35	6	0.41	0.636	0.057	0.0	224
	31	1.24	12.4	4.4	25	35	8	0.43	0.637	0.075	0.0	227
	32	1.17	13.0	3.3	71	35	7	1.12	0.600	0.064	0.0	218
	33	1.35	11.3	5.8	35	35	6	0.65	0.694	0.062	0.0	232

APPENDIX C

DATA TABULATIONS:

INTEGRATED FURNACE

OPTIMIZATION EXPERIMENTS

TABLE C-1

STEADY-STATE FLUE GAS TEMPERATURES AND POLLUTANT EMISSIONS FROM A NEW LENNOX 011-140 FURNACE

Burner	RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	NET TFG C	WARM AIR M3/S
New Lennox Burner 0.99 ml/s (0.94 gph)	34	1.24	12.2	4.3	10	104	2	0.16	1.853	0.019	0.5	256	.566
	35	1.24	12.4	4.3	10	106	2	0.16	1.880	0.019	0.5	256	
	36	1.30	11.9	5.1	11	102	2	0.21	1.888	0.020	0.0	259	
	37	1.38	11.0	6.0	10	92	1	0.18	1.816	0.010	0.0	278	
	38	1.44	10.6	6.7	10	89	1	0.19	1.831	0.011	0.0	287	
	39	1.65	9.1	8.6	10	69	2	0.22	1.642	0.025	0.0	312	
	40	1.56	9.8	8.0	10	74	2	0.21	1.679	0.024	0.0	302	
	41	1.85	8.1	10.0	10	52	2	0.25	1.408	0.029	0.0	267	
	42	1.34	11.2	5.5	10	91	2	0.18	1.739	0.020	0.0	270	
Original Lennox Burner 0.95 ml/s (0.90 gph)	43	1.43	10.7	6.7	10	103		0.19	2.109		0.0	271	
	44	1.29	11.9	5.0	15	111		0.26	2.053		0.0	254	
	45	1.21	12.7	3.9	13	118		0.22	2.040		1.5	238	
	46	1.26	12.1	4.6	10	121		0.17	2.183		0.5	242	
	47	1.57	9.9	8.1	10	106		0.21	2.399		0.0	281	
	48	1.51	10.2	7.5	10	110		0.20	2.382		0.0	278	↓

TABLE C-1 (Concluded)

Condition	RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	NET TFG C	WARM AIR M3/S
Original Lennox Burner — Replaced Nozzle 0.95 ml/s (0.90 gph)	49	1.33	11.5	5.5	10	116		0.18	2.198		0.0	253	.566
	50	1.29	11.9	4.9	10	112		0.17	2.060		0.0	242	
	51	1.19	12.6	3.5	10	110		0.16	1.869		2.0	232	
	52	1.54	10.0	7.8	10	104		0.21	2.316		0.0	286	
	53	1.24	12.2	4.3	10	107		0.16	1.898		0.5	252	
4 on/8 off Cyclic	54	1.24	12.0	4.2	20	100	3	0.33	1.764	0.028	3.0	219	
	55	1.31	11.3	5.1	20	100	3	0.35	1.868	0.030	1.0	229	
	56	1.32	11.3	5.2	21	100	3	0.39	1.878	0.030	0.5	235	
	57	1.33	11.1	5.3	15	114	2	0.26	2.160	0.020	0.0	260	.595
	58	1.34	11.1	5.4	10	114	2	0.18	2.172	0.020	0.0	255	.708
	59	1.35	11.0	5.5	10	110	1	0.18	2.117	0.010	0.0	269	.479
	60	1.34	11.1	5.4	10	110	1	0.18	2.111	0.010	0.0	263	.566

TABLE C-2

CYCLE-AVERAGED FLUE GAS EMISSIONS FROM THE INTEGRATED FURNACE TESTED IN SIMULATED WINTER CONDITIONS

	RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	NET TFG C
$T_{comb.\ air} = -10^{o}C$	61	1.21	12.8	3.9	25	39	3	0.40	0.685	0.027	1.0	253
	62	1.16	12.9	3.0	30	39	3	0.48	0.656	0.029	1.0	248
	63	1.15	13.3	2.9	37	39	2	0.57	0.650	0.022	2.0	245
	64	1.24	12.6	4.3	23	39	3	0.39	0.700	0.028	1.0	254
	65	1.24	12.5	4.4	35	39	4	0.58	0.704	0.042	1.6	254
	66	1.25	12.4	4.5	35	40	5	0.58	0.717	0.046	1.6	257
	67	1.20	12.9	3.7	35	39	6	0.56	0.678	0.054	1.4	252
	68	1.18	12.9	3.3	27	39	8	0.44	0.665	0.071	2.0	252
	69	1.18	12.9	3.4	33	39	3	0.53	0.668	0.030	1.0	255
$T_{comb.\ air}$ = Ambient	70	1.32	11.5	5.4	35	39	6	0.62	0.752	0.060	1.0	247
	71	1.31	11.7	5.2	55	39	6	0.95	0.742	0.060	1.6	244
	72	1.18	12.9	3.4	35	39	5	0.55	0.660	0.046	2.0	231
	73	1.19	12.9	3.5	45	39	4	0.71	0.671	0.034	1.0	229
	74	1.39	11.1	6.3	47	39	18	0.89	0.791	0.190	0.4	250
	75	1.26	11.9	4.5	31	39	13	0.54	0.706	0.129	1.8	241
	76	1.12	13.4	2.3	456	35	175	6.74	0.554	1.476	1.5	221
	77	1.31	11.7	5.2	50	39	25	0.89	0.742	0.248	0.0	229
	78	1.26	12.0	4.5	60	39	19	1.00	0.704	0.181	0.2	223
	79	1.17	12.7	3.2	50	38	9	0.78	0.639	0.080	0.2	215

TABLE C-2 (Concluded)

Condition	RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	NET TFG C
$T_{c.a.} = 0^oC$	80	1.19	12.7	3.5	40	35	2	0.65	0.607	0.022	0.0	217
	81	1.16	12.9	3.0	57	35	5	0.89	0.576	0.044	0.0	212
	82	1.13	13.2	2.5	77	33	3	1.17	0.537	0.026	0.0	211
	83	1.10	13.3	2.0	148	31	10	2.16	0.486	0.083	0.0	206
	84	1.07	13.8	1.5	342	30	40	4.86	0.458	0.325	0.0	206
Ambient	85	1.13	13.3	2.5	31	33	7	0.48	0.537	0.060	0.0	206
	86	1.15	13.3	2.9	31	40	7	0.49	0.666	0.061	0.1	233
	87	1.30	11.7	5.1	50	39	20	0.86	0.738	0.197	0.2	241
$T_{c.a.} = -8.5^oC$	88	1.16	13.0	3.1	30	35	1	0.46	0.594	0.009	0.0	230
	89	1.15	13.1	2.9	55	35	1	0.84	0.572	0.009	0.5	226
	90	1.08	13.9	1.7	1499	258	240	21.42	3.959	1.959	1.0	219
	91	1.19	12.7	3.6	25	35	1	0.40	0.610	0.009	0.5	228
Amb.	92	1.16	13.3	3.0	50	35	3	0.76	0.574	0.026	0.0	233
	93	1.34	11.3	5.6	55	38	22	0.98	0.734	0.224	0.5	244

TABLE C-3

CYCLE-AVERAGED FLUE GAS POLLUTANT EMISSION CONCENTRATIONS
FROM THE FIRST INTEGRATED FURNACE AT VARIOUS FIRING RATES

	RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	NET TFG C
1.0-70°-A Nozzle	94	1.17	12.8	3.1	35	36	9	0.54	0.612	0.079	0.2	221
	95	1.16	12.9	3.0	41	33	4	0.64	0.552	0.035	1.5	223
	96	1.34	11.4	5.6	55	38	16	0.98	0.742	0.163	1.0	239
	97	1.23	12.4	4.0	42	39	13	0.70	0.694	0.121	1.8	229
	98	1.19	12.7	3.6	40	38	11	0.63	0.651	0.099	0.1	217
	99	1.12	13.3	2.4	148	35	15	2.20	0.565	0.127	0.3	206
	100	1.33	11.3	5.4	65	40	24	1.15	0.773	0.242	0.0	225
1.25-70°-A	101	1.10	13.8	2.1	254	38	30	3.71	0.601	0.250	2.5	268
	102	1.26	12.0	4.5	45	40	16	0.75	0.730	0.153	3.0	284
	103	1.20	12.6	3.7	40	34	10	0.64	0.581	0.091	2.0	272
	104	1.14	13.1	2.6	65	36	8	0.98	0.588	0.069	2.5	267
0.75-70°-A	105	1.21	12.6	3.9	35	33	5	0.56	0.578	0.046	2.0	213
	106	1.15	13.3	2.9	75	34	5	1.14	0.563	0.043	1.2	212
	107	1.11	13.6	2.3	535	33	70	7.90	0.530	0.590	2.5	209
	108	1.57	9.7	8.0	55	40	22	1.16	0.919	0.264	0.0	245
	109	1.29	11.7	4.9	21	39	4	0.38	0.731	0.039	0.0	222
1.0-70°-A	110	1.21	12.6	3.9	40	40	5	0.64	0.703	0.046	0.1	214

TABLE C-3 (Concluded)

0.75-70°-A Oil Nozzle

RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	NET TFG C
111	1.47	10.6	7.2	51	45	9	1.02	0.958	0.101	0.0	198
112	1.41	11.0	6.5	31	43	5	0.60	0.870	0.056	0.0	186
113	1.17	13.0	3.3	25	40	2	0.39	0.672	0.018	0.0	176
114	1.14	13.3	2.6	35	36	2	0.53	0.595	0.017	0.0	171
115	1.07	14.0	1.5	383	33	40	5.44	0.510	0.324	0.0	174
116	1.35	11.5	5.9	35	43	4	0.63	0.834	0.041	0.0	190
117	1.20	12.9	3.7	30	40	3	0.49	0.694	0.027	0.0	179
118	1.16	13.2	3.0	27	41	1	0.43	0.686	0.013	0.0	-0
119	1.07	14.0	1.5	-1600	31	350	-22.62	0.471	2.828	1.5	167
120	1.13	13.3	2.6	40	40	3	0.60	0.656	0.026	0.2	176
121	1.14	13.3	2.7	40	39	3	0.60	0.644	0.030	0.0	181
122	1.35	11.7	6.0	35	38	4	0.63	0.751	0.041	0.0	178
123	1.21	12.7	3.9	40	40	4	0.64	0.702	0.037	0.0	179
124	1.11	13.5	2.1	148	35	8	2.17	0.564	0.067	0.0	172
125	1.17	13.0	3.2	95	35	5	1.47	0.581	0.044	0.0	174
126	1.09	13.8	1.9	-1600	27	500	-23.06	0.418	4.118	0.2	166

TABLE C-4. INTEGRATED FURNACE SYSTEM FLUE GAS POLLUTANT EMISSIONS MEASUREMENTS TAKEN WITH A CALIBRATED SMOKE METER

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION[1]
133	1.17	13.2	3.3	40	40	3	0.62	0.679	0.027	—[2]	219	1.0-70° - A Nozzle 0.14m L Blast Tube
134	1.17	13.2	3.3	40	40	4	0.62	0.679	0.035	—[2]	218	
135	1.17	13.2	3.3	40	41	5	0.62	0.695	0.044	3.0	214	
136	1.18	13.0	3.5	30	40	2	0.47	0.678	0.018	2.5	211	
137	1.43	10.8	6.7	18	39	2	0.36	0.814	0.022	2.0	227	0.85-70° - A Nozzle 0.14m B.T.
138	1.53	10.1	7.8	20	41	2	0.43	0.920	0.023	0.0	204	0.75 - 70° - A Nozzle 0.14m B.T.
139	1.42	10.8	6.5	10	43	2	0.21	0.874	0.022	0.0	200	
140	1.27	12.0	4.7	18	43	2	0.32	0.789	0.019	0.0	189	
141	1.19	12.8	3.6	20	41	2	0.32	0.708	0.018	1.0	183	
142	1.35	11.3	5.7	15	40	2	0.27	0.784	0.020	4.0	241	1.0-90° - A Nozzle 0.14m B.T.
143	1.28	12.0	4.9	20	41	4	0.34	0.761	0.039	5.0	235	
145	1.67	9.1	8.9	31	33	1	0.72	0.807	0.013	2.0	213	0.75-90° - A Nozzle 0.14m B.T.
146	1.42	10.8	6.5	17	39	1	0.34	0.806	0.011	4.0	204	
147	1.17	13.0	3.2	535	31	120	8.28	0.515	1.059	5.0	188	
148	1.42	10.7	6.5	11	50	1	0.23	1.020	0.011	0.0	189	0.75-45° - A Nozzle 0.14m B.T.
149	1.37	11.3	6.0	10	43		0.18	0.842		2.5	241	1.0-70° - A Nozzle
150	1.21	14.3	4.3	20	42		0.32	0.725		3.0	246	
151	1.12	13.3	2.5	Δ1600	23	500	Δ23.77	0.375	4.245	5.0		
152	1.19	12.6	3.5	20	38	2	0.32	0.650	0.018	3.0		1.0-70° - A, Research Opt. Head
153	1.13	13.1	2.5	383	35	30	5.73	0.561	0.256	4.0		
154	1.31	11.5	5.1	5	40	1	0.09	0.759	0.010	2.0		
155	1.18	12.7	3.4	20	39	2	0.31	0.670	0.018	4.0	247	
156	1.17	13.0	3.3	80	40	2	1.24	0.680	0.018	6.0	264	1.0-70° - A, Res. Opt. Head 0.23m x 0.25m Plate Under Combustor
157	1.18	12.7	3.4	20	44	2	0.31	0.742	0.018	4.0	257	
158	1.17	12.7	3.1	20	45	2	0.31	0.755	0.018	4.0	253	

TABLE C-4. (Cont.)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION[1]
159	1.17	13.1	3.3	90	35	4	1.40	0.599	0.035	5.0	246	1.0-70° - A, Res. Opt. Head, Static Disc .14m From Head
160	1.26	12.1	4.6	20	40	1	0.33	0.732	0.010	3.5	251	
161	1.19	12.7	3.5	40	42	2	0.63	0.713	0.018	6.0	233	1.0-70° - A, Res. Opt. Head, No Static Disc
162	1.19	12.7	3.5	30	42	2	0.47	0.713	0.018	7.0	237	
163	1.20	12.6	3.6	20	47	2	0.33	0.814	0.018	6.0	241	
164'	1.17	12.7	3.3	≥1600	36	240	≥24.82	0.615	2.127	4.0	170	0.75-70°-A, Research Optimum Burner Head
165	1.17	12.9	3.3	≥1600	37	800	≥24.77	0.621	7.077	5.5	169	
166	1.46	10.6	7.0	20	41	2	0.39	0.860	0.022	0.0	189	
167	1.22	12.6	4.0	100	40	10	1.62	0.707	0.092	2.0	167	
168	1.28	12.0	4.8	40	42	3	0.68	0.767	0.029	2.0	174	
169	1.38	11.1	6.2	25	40	2	0.46	0.806	0.021	0.0	177	
170	1.32	11.5	5.3	17	43	2	0.32	0.811	0.020	0.2	182	
171	1.19	12.7	3.5	383	35	210	6.03	0.607	1.887	3.0	166	0.75-70°-A, Res. Opt. Head, Orig. Draft Flap Assy
172	1.49	10.2	7.3	20	39	2	0.42	0.852	0.023	0.0	194	
173	1.29	11.7	4.9	25	40	2	0.43	0.749	0.020	1.0	183	
174	1.26	12.0	4.5	55	40	2	0.92	0.730	0.019	1.5	180	
175	1.36	11.3	5.9	40	39	2	0.72	0.773	0.021	2.0	196	0.75-70°-A, Res. Opt. Head, No Quiet Stator
176	1.52	10.1	7.6	30	35	2	0.61	0.785	0.023	0.0	196	
177	1.42	10.6	6.5	31	36	2	0.61	0.751	0.022	0.2	192	
178	1.20	11.9	3.6	≥1600		150	≥25.46		1.364	6.0		
179	1.19	12.6	3.5	30	45	8	0.47	0.771	0.072	4.0	231	Complete Optimum Burner for UL Inspection
180	1.21	12.6	3.9	30	15	3	0.48	0.273	0.028	4.0		
181	1.18	12.7	3.3	40	15	2	0.62	0.265	0.018	4.5	247	
182	1.13	13.3	2.5	231	15	25	3.45	0.254	0.213	5.0	239	
183	1.25	12.0	4.4	17	16	2	0.30	0.301	0.019	4.0	243	

TABLE C-4. (Cont.)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION[1]
184	1.32	11.6	5.4	10	48	5	0.18	0.911	0.050	4.0	252	0.041m Choke Dia. Burner Head, Orig. Draft Flap
185	1.24	12.2	4.3	10	32	2	0.16	0.566	0.019	5.0	245	
186	1.19	12.7	3.5	30	18		0.47	0.311		5.5	241	
187	1.24	12.3	4.3	10	31	5	0.16	0.548	0.047	2.5	248	35° Swirl Vane[4] Orig. Draft Flap
188	1.33	11.5	5.5	10	28	3	0.18	0.542	0.030	1.5	245	
189	1.10	13.6	2.0	1099	21	50	15.95	0.327	0.415	6.0	232	
190	1.24	12.4	4.3	10	50	2	0.16	0.886	0.019	3.0	256	Nozzle at 0.0095m from Exit
191	1.19	12.7	3.6	15	41	1	0.24	0.701	0.009	3.5	253	
192	1.27	12.0	4.7	10	41	1	0.17	0.754	0.010	2.0	259	
193[3]	1.16	13.1	3.1	35	40	9	0.54	0.674	0.079	2.5	211	
194	1.17	12.7	3.1	30	43	2	0.46	0.716	0.018	3.0	241	Nozzle at 0.0191m from Exit
195	1.28	11.9	4.8	20	48	2	0.34	0.890	0.019	3.0	256	
196	1.22	12.4	3.9	20	45	2	0.32	0.788	0.018	3.0	253	
197	1.26	11.9	4.5	10	46	1	0.17	0.835	0.010	1.5	259	Nozzle at 0.0238m
198	1.13	13.1	2.5	90	45	7	1.35	0.731	0.060	3.0	247	
199	1.20	12.6	3.6	20	45	1	0.32	0.775	0.009	2.0	251	
												← Tried 1.0-45°-A, No Go
200	1.29	12.0	5.0	20	54	1	0.34	1.005	0.010	2.5	240	0.23m Wide Pyroflex Liner on Front 1/4 of Combustor
201	1.33	11.6	5.6	20	52	2	0.35	1.000	0.020	2.5	242	
202	1.23	12.4	4.1	20	54	2	0.33	0.958	0.019	3.0	227	
203	1.14	13.3	2.8	30	50	1	0.45	0.816	0.009	5.0	229	
204	1.19	12.9	3.5	20	50	1	0.31	0.847	0.009	4.0	233	
205	1.19	12.8	3.5	20	50	2	0.31	0.848	0.018	4.0	227	Pyroflex Insert 0.23m Wide on Front, 0.23m Dia on Bottom
206	1.25	12.3	4.4	15	50	2	0.25	0.891	0.019	1.5	233	
207	1.27	12.0	4.7	10	50	2	0.17	0.908	0.019	1.5	238	

TABLE C-4. (Cont.)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION[1]
208	1.38	10.8	6.0	10	93	1	0.18	1.838	0.011	0.0	266	Optimum Burner in Stock Lennox 011-140 Furnace
209	1.30	11.7	5.1	5	93	1	0.09	1.726	0.010	0.0	258	
210	1.21	12.4	3.7	5	95	1	0.08	1.628	0.009	0.0	244	
211	1.16	13.0	3.0	10	96	3	0.15	1.583	0.026	0.7	236	
212	1.09	13.8	1.7	25	93	3	0.36	1.433	0.025	7.5	224	
213	1.14	13.2	2.7	10	95	3	0.15	1.539	0.026	2.5	227	
214[3]	1.13	13.4	2.5	10	93	4	0.15	1.490	0.034	4.4	203	
215[3]	1.21	12.7	3.8	20	85	4	0.32	1.458	0.036	0.1	216	
216	1.15	13.2	2.9	90	49	3	1.37	0.806	0.026	8.0	212	0.23m Wide & 0.23m Dia Pyroflex Liner, Two 0.038m Wide Fences at ±90°
217	1.20	12.8	3.8	25	49	1	0.40	0.844	0.009	6.0	221	
218	1.33	11.5	5.5	20	49	1	0.35	0.935	0.010	4.0	234	
219	1.33	11.4	5.5	10	54	1	0.18	1.043	0.010	1.5	226	0.23m dia, Pyroflex on Bottom, Burner Recessed 0.0159m
220	1.22	12.3	4.0	11	50	1	0.19	0.874	0.009	2.5	219	
221	1.19	12.9	3.5	15	49	1	0.24	0.839	0.009	3.0	216	
222	1.34	11.3	5.5	10	49	1	0.18	0.939	0.010	1.5	216	1.0-90°-A, 0.23m Dia Pyroflex, Burner Recessed 0.0159m
223	1.23	12.5	4.1	11	50	1	0.20	0.876	0.009	2.5	219	
224	1.18	12.8	3.4	10	50	1	0.16	0.844	0.009	4.0	216	
225	1.57	9.7	8.0	20	38	1	0.42	0.865	0.012	0.0	169	0.75-70°-A, Burner Recessed 0.0159m
226	1.44	10.4	6.7	15	49	1	0.29	1.019	0.011	0.0	176	
227	1.28	11.7	4.8	17	50	2	0.31	0.918	0.019	0.5	168	
228	1.22	12.4	4.0	254	40	50	4.11	0.708	0.462	3.5		
229	1.33	11.5	5.5	15	54	1	0.27	1.041	0.010	2.0	207	0.75-70°-A at 5534 N/m² Oil Supply Pressure
230	1.27	12.0	4.7	10	53	1	0.19	0.958	0.010	2.5	206	
231	1.18	12.8	3.4	120	46	7	1.88	0.781	0.063	4.0	201	
232	1.46	10.4	7.0	10	52	1	0.20	1.102	0.011	0.5	217	
233	1.40	11.0	6.3	10	54	1	0.19	1.095	0.011	1.5	212	

TABLE C-4. (Cont.)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION[1]
234	1.29	11.9	5.0	15	45	1	0.26	0.838	0.010	2.5	194	0.75-70°A at 5534 N/m² Oil Supply Pressure, 0.034m Dia Choke
235	1.35	11.3	5.7	10	47	1	0.18	0.921	0.010	1.0	202	
236	1.41	10.8	6.4	10	50	1	0.19	1.012	0.011	1.0	210	
237	1.47	10.2	7.0	10	47	1	0.20	1.010	0.011	0.5	216	
238	1.31	11.5	5.1	20	47	2	0.35	0.892	0.020	0.0	182	0.75-70°-A 0.034m Dia Choke
239	1.22	12.4	3.9	120	43	8	1.93	0.747	0.074	1.5	173	
240	1.26	11.9	4.5	30	49	3	0.50	0.885	0.029	0.0	172	
241[3]	1.23	12.0	4.0	198	40	10	3.23	0.712	0.093	0.1	144	
242[3]	1.38	10.7	5.9	70	39	5	1.29	0.785	0.052	0.0	151	
243[3]	1.29	11.7	4.9	30	41	4	0.51	0.767	0.044	0.1	150	0.75-70°-A (Cyclic)
244[3]	1.25	12.0	4.3	100	40	30	1.65	0.723	0.283	2.5	142	
245[3]	1.69	7.7	7.7	32	40	7	0.75	0.997	0.091	0.0	164	
246[3]	1.50	9.8	7.1	25	40	5	0.50	0.877	0.057	0.0		
247[3]	1.40	10.5	6.1	31	40	4	0.60	0.807	0.043	0.0	157	
248	1.51	10.4	7.7	11	33	2	0.24	0.715	0.023	0.0	196	0.75-70°-A Nozzle at 0.0238m From Exit
249	1.42	11.0	6.7	20	32	2	0.38	0.661	0.022	0.0	187	
250	1.29	11.9	5.0	30	30	5	0.51	0.562	0.049	1.0	175	
251	1.25	12.6	4.5	40	31	5	0.66	0.551	0.047	2.0	171	
252[3]	1.28	12.4	5.0	90	31	20	1.53	0.565	0.194	2.0	149	
253	1.27	12.0	4.7	30	44	1	0.51	0.806	0.010	1.0	192	Lefthand Q-Stator, 0.75-70°-A, Nozzle at 0.0238m
254	1.44	10.6	6.8	15	41	1	0.29	0.862	0.011	0.0	207	
255	1.32	11.5	5.4-	20	27	1	0.35	0.511	0.010	0.5	201	
256[3]	1.30	11.7	5.0	37	30	4	0.65	0.554	0.039	0.6	175	

TABLE C-4 (Concluded)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION[1]
257	1.53	10.0	7.7	20	38	1	0.41	0.853	0.012	0.0	179	0.75-70°-A, Nozzle at 0.0238m 45° Baffle Above Combustor
258	1.39	11.0	6.2	20	36	1	0.37	0.733	0.011	0.1	167	
259	1.28	12.0	4.9	45	31	3	0.76	0.566	0.029	2.0	162	
260[3]	1.27	12.0	4.7	80	28	11	1.35	0.516	0.106	2.1	137	
261	1.29	11.7	4.9	50	38	4	0.86	0.705	0.039	2.0	151	Same as Above, Fired With -1819 Oil Stock
262	1.48	10.4	7.2	20	39	1	0.39	0.843	0.011	0.0	166	
263	1.40	11.0	6.3	25	37	1	0.46	0.756	0.011	0.0	164	
264	1.48	10.4	7.3	11	54	1	0.24	1.147	0.011	0.0	197	0.75-70°-A, 0.23m Dia Pyroflex on Opposing Wall, Nozzle at 0.0238m
265	1.34	11.5	5.6	11	46	1	0.21	0.886	0.010	0.5	177	
266	1.29	12.0	5.0	12	35	1	0.22	0.659	0.010	1.5	172	
267	1.21	12.7	3.9	40	32	3	0.64	0.551	0.027	3.0	168	
268	1.43	10.8	6.7	10	51	1	0.19	1.046	0.011	0.0	193	0.75-70°-A 0.23m Dia Pyroflex on Opposing Wall
269	1.36	11.4	5.9	10	51	1	0.18	0.992	0.010	0.2	189	
270	1.32	11.7	5.4	17	40		0.32	0.767		2.0	174	
271[3]	1.35	11.5	5.9	10	95	1	0.18	1.836	0.010	1.8	240	Lennox #2, Seventh Week Emissions Evaluation
272[3]	1.40	11.0	6.4	10	95	2	0.19	1.905	0.021	1.0	250	
273[3]	1.48	10.3	7.2	10	93	1	0.20	1.975	0.011	0.7	252	
274[3]	1.38	11.1	6.2	10	96	2	0.18	1.902	0.021	1.6	244	

NOTES:
1. Unless otherwise specified, test configuration is: 1.0-70°-A oil nozzle recessed 0.0127m, 0.18m L blast tube, 0.0826m dia static disc at 0.0826m from exit, 0.0381m choke diameter, with quiet stator, new draft flap assembly burner fired into cast-formed, finned combustor.
2. Smoke reading taken with leaky smoke pump.
3. Cyclic firing, 4 minutes on/8 minutes off.
4. 35° swirl vanes used for Runs 187 through 270.

TABLE C-5

FLUE GAS POLLUTANT EMISSION CONCENTRATIONS FOR VARIOUS OIL NOZZLE TYPES IN THE INTEGRATED FURNACE UNIT[1]

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION
275	1.38	11.0	6.0	15	59	1	0.28	1.169	0.010	0.0	192	0.75-70°-B (Solid)
276	1.27	12.0	4.7	21	47		0.37	0.858		3.0	179	
277	1.38	11.0	6.0	11	53		0.22	1.043		0.0	191	0.75-70°-W (Semi-solid)
278	1.30	11.7	5.1	15	49		0.26	0.914		2.0	183	
SAMPLING SYSTEM AND COMBUSTOR/HEAT EXCHANGER SYSTEM LEAK CHECKED												
280	1.30	11.7	5.1	35	50		0.60	0.931		0.0	174	0.75-70°-A (Hollow)
281	1.25	12.1	4.4	27	49		0.46	0.877		2.0	169	
282	1.66	9.3	8.9	15	50	1	0.33	1.200	0.013	0.0	208	0.75-70°-A, Sealed Observation Port
283	1.37	11.3	6.0	15	60	1	0.27	1.176	0.010	0.0	189	
284	1.21	12.6	3.9	620	57	1	9.96	0.984	0.009	3.0	173	
285	1.31	11.9	5.3	15	59	1	0.26	1.108	0.010	1.0	181	

NOTE: (1) 0.23m DIAMETER PYROFLEX INSULATION ON OPPOSING WALL INSIDE CAST-FORMED COMBUSTOR

TABLE C-6. FLUE GAS POLLUTANT EMISSIONS FROM THE INTEGRATED FURNACE WITH THE FABRICATED STEEL, FINNED COMBUSTOR AND WITH THE RESEARCH OPTIMUM BURNER HEAD

RUN NO.	STOIC. RATIO	CO_2 %	O_2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION
286	1.25	12.2	4.5	10	40	1	0.17	0.728	0.010	3.0	261	1.0-70°-A Nozzle
287	1.19	12.7	3.5	11	38	1	0.19	0.643	0.009	3.5	260	
288	1.14	13.3	2.7	40	35	2	0.60	0.582	0.017	3.5	254	
289	1.32	11.7	5.4	10	40	1	0.18	0.758	0.010	2.0	266	
290	1.72	9.0	9.3	10	35	1	0.23	0.878	0.013	0.0	204	0.75-70°-A Nozzle
291	1.41	11.0	6.5	10	42	1	0.19	0.860	0.011	0.0	192	
292	1.22	12.6	4.0	20	45	2	0.32	0.790	0.018	1.5	192	
293	1.27	12.1	4.8	15	44	2	0.25	0.809	0.019	0.0	192	
294	1.16	13.1	3.0	90	39	5	1.38	0.654	0.044	3.0	193	
295[1]	1.30	11.8	5.1	20	35	3	0.34	0.647	0.030	0.0	175	
296	1.30	11.7	5.1	21	49	1	0.38	0.914	0.010	0.0	184	0.75-70°-A Nozzle Burner 0.025 m into Combustor
297	1.22	12.5	3.9	30	46	1	0.48	0.803	0.009	0.0	184	
298	1.14	13.2	2.6	37	33	30	0.57	0.540	0.258	4.5	184	
299	1.18	12.7	3.3	60	40	2	0.94	0.683	0.018	1.0	183	
300[1]	1.18	12.7	3.4	40	39	2	0.63	0.662	0.018	1.3	169	
301	1.19	12.6	3.5	20	46	2	0.32	0.787	0.018	1.0	174	0.75-70°-A Nozzle, Burner 0.050 m into Combustor
302	1.26	11.9	4.5	10	47	2	0.17	0.859	0.019	0.0	174	
303	1.22	12.4	4.0	10	48	1	0.16	0.841	0.009	0.0	174	
304	1.18	12.7	3.4	20	45	2	0.31	0.766	0.018	1.5	174	
305	1.20	13.0	3.7	20	40	2	0.32	0.693	0.018	2.5	239	1.0-70°-A Nozzle Burner 0.050 m into Combustor
306	1.22	12.6	4.1	20	40	2	0.32	0.710	0.019	2.0	244	
307	1.26	12.4	4.6	17	40	2	0.30	0.729	0.019	1.5	250	
308	1.25	12.4	4.5	17	40	2	0.30	0.726	0.019	2.5	251	1.0-70°-A Nozzle Burner 0.025 m into Combustor
309	1.23	12.6	4.1	17	40	2	0.29	0.710	0.019	2.5	249	
310	1.19	13.0	3.5	18	40	2	0.30	0.686	0.018	3.0	248	
311	1.15	13.4	2.9	20	40	3	0.30	0.665	0.026	3.5	246	
312	1.10	13.9	2.0	231	31	28	3.36	0.483	0.232	7.0	240	
313	1.13	13.7	2.5	50	37	4	0.74	0.605	0.034	5.0	242	

1. Cyclic Firing, 4-min-on/8-min-off

TABLE C-7. FLUE GAS POLLUTANT EMISSIONS FROM THE INTEGRATED FURNACE WITH THE CAST-FORMED COMBUSTOR

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION
314	1.13	13.6	2.5	40	40	2	0.60	0.652	0.017	5.5	241	
315	1.16	13.0	3.1	20	41	2	0.31	0.682	0.018	4.5	246	0.18 m Blast Tube, 1.0-70°-A Nozzle, Draft = 5 Pa
316	1.21	12.4	3.8	17	41	2	0.29	0.710	0.018	3.5	249	
317	1.29	11.8	5.0	15	41	2	0.26	0.769	0.020	3.5	255	
318	1.29	11.8	5.0	15	41	2	0.26	0.760	0.020	3.0	257	
319	1.18	12.9	3.4	20	40	2	0.31	0.685	0.018	3.5	254	0.18 m B.T. 1.0-70°-A, Draft = 10 Pa
320	1.15	13.3	2.8	30	40	3	0.45	0.663	0.026	4.0	252	
321	1.22	12.4	4.0	20	39	2	0.32	0.692	0.019	4.0	247	
322	1.29	11.9	5.0	17	40	2	0.31	0.750	0.020	3.5	259	0.18 m B.T. 1.0-70°-A, Draft = 20 Pa
323	1.38	11.1	6.1	15	40	2	0.28	0.804	0.021	2.0	266	
324	1.17	12.9	3.2	37	35	3	0.59	0.597	0.027	5.0	258	
325	1.35	11.5	5.8	10	43	2	0.18	0.840	0.020	2.0	260	
326	1.25	12.4	4.4	10	41	2	0.17	0.739	0.019	3.0	257	
327	1.11	13.4	2.3	≥1600	31	1000	≥23.54	0.490	8.406	7.5	245	
328[2]	1.33	11.5	5.5	10	44	2	0.18	0.846	0.020	2.0	266	0.14 m B.T. 1.0-70°-A Draft = 22 Pa
329[2]	1.43	10.8	6.7	5	43	2	0.10	0.883	0.022	0.0	263	
330[2]	1.37	11.3	6.0	5	42	2	0.09	0.833	0.021	1.0	266	
331[2]	1.43	10.7	6.7	5	43	2	0.10	0.885	0.022	0.0	274	
332[2]	1.56	9.9	8.0	5	42	2	0.10	0.956	0.024	0.0	284	
333	1.24	12.1	4.2	20	45	3	0.33	0.803	0.028	2.0	250	
334	1.17	12.9	3.1	30	45	3	0.46	0.754	0.026	3.0	242	
335	1.08	13.8	1.7	1019	35	60	14.58	0.552	0.490	6.0	244	0.14 m B.T., 1.0-70°-A, Draft = 10 Pa
336[2]	1.41	10.8	6.4	20	49	2	0.38	0.994	0.021	0.0	274	
337[2]	1.23	12.2	4.0	20	44	2	0.32	0.777	0.019	2.0	264	
338[2]	1.15	13.1	2.9	30	41		0.46	0.683		3.0	257	

TABLE C-7. (CONTINUED)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION
339[2]	1.15	13.1	2.8	30	41		0.46	0.672		3.0	257	0.14 m Blast Tube 1.0-70°-A Nozzle Draft = 5 Pa
340[2]	1.22	12.5	3.9	20	45	2	0.32	0.779	0.018	2.0	259	
341[2]	1.42	10.8	6.5	20	45	2	0.38	0.922	0.022	0.5	273	
342[2]	1.37	11.1	6.0	20	45	2	0.37	0.893	0.021	1.0	273	
343[2]	1.67	9.1	8.9	20	40	2	0.45	0.983	0.026	0.0	291	
344[2]	1.52	10.1	7.6	20	44	2	0.41	0.973	0.023	0.0	277	
345[2]	1.63	9.3	8.5	30	35	3	0.66	0.843	0.037	0.0	268	Original "1819" 0.14 m B.T., 1.0-70°-A, Draft = 10 Pa
346[2]	1.37	11.1	5.9	20	44	2	0.36	0.869	0.021	1.0	254	
347[2]	1.48	10.2	7.1	17	45	2	0.36	0.955	0.023	0.0	265	
348	1.28	11.9	4.8	20	42	2	0.34	0.769	0.019	1.5	257	
349	1.24	12.2	4.3	20	41	2	0.33	0.730	0.019	2.5	258	
350	1.18	12.7	3.4	20	41	2	0.31	0.694	0.018	2.5	253	
351	1.13	13.3	2.5	80	40	4	1.20	0.654	0.034	4.0	248	
352	1.09	13.6	1.9	≥1600	31	450	≥23.08	0.480	3.710	7.0	243	
353	1.21	12.4	3.7	30	41	0	0.48	0.715	-.000	3.0	254	
354[2]	1.51	10.1	7.5	17	45	2	0.36	0.989	0.023	0.0	283	0.14 m B.T. 1.0-70°-A, Draft = 10 Pa, Throttled on aux. blower
355[2]	1.44	10.6	6.7	18	45	2	0.36	0.936	0.022	0.0	278	
356[2]	1.38	11.7	6.5	28	49	3	0.53	0.975	0.032	3.0	322	
357[2]	1.28	12.0	4.8	18	43	2	0.32	0.784	0.019	2.5	264	
358[2]	1.19	12.6	3.4	25	41	2	0.39	0.695	0.018	4.0	254	
359[2]	1.13	13.3	2.5	209	38	10	3.12	0.622	0.085	6.0	250	
360	1.33	11.6	5.5	15	50	2	0.26	0.951	0.020	0.0	183	0.14 m B.T., 0.75-70°-A, Draft = 10 Pa
361	1.28	12.0	4.8	15	50	2	0.25	0.921	0.019	0.0	177	
362	1.19	12.9	3.5	20	54	3	0.33	0.909	0.027	1.0	173	
363	1.14	13.4	2.7	1019	49	150	15.30	0.794	1.287	6.0	167	
364	1.16	13.3	3.1	100	49		1.54	0.813		3.5	169	
365	1.12	13.7	2.5	1339	40	200	19.86	0.649	1.695	7.0	169	
366	1.28	12.1	4.9	20	52		0.34	0.958		0.0	177	
367	1.19	12.9	3.5	25	51		0.41	0.871		1.0	174	
368	1.23	12.6	4.1	20	52		0.32	0.915		0.5	177	
369[1]	1.21	12.7	3.8	31	48	2	0.51	0.829	0.018	1.0	154	
370[1]	1.23	12.4	4.1	25	45	3	[illegible]	0.795	0.028	0.7	154	

NOTE. 1 4-min.-on/8-min.-off cyclic firi‹y
2. Supercharged

TABLE C-7. (CONTINUED)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION
371	1.32	11.5	5.4	18	47	2	0.33	0.904	0.020	0.0	175	0.14 m Blast Tube, 0.75-70°-A Nozzle, Draft = 20 Pa
372	1.24	12.4	4.3	20	50	2	0.33	0.886	0.019	0.0	172	
373	1.16	13.2	3.0	120	45	6	1.84	0.749	0.052	2.5	169	
374	1.25	12.2	4.5	20	50	2	0.33	0.905	0.019	0.0	172	
375	1.19	12.8	3.5	25	50	2	0.39	0.856	0.018	0.0	169	
376	1.13	13.5	2.5	456	41	30	6.80	0.659	0.255	3.5	169	
377	1.11	13.1	2.2	≥1600	38	1500	≥23.49	0.612	12.583	9.0	164	
378	1.17	13.0	3.2	70	49		1.08	0.818		2.0	167	
379	1.21	12.6	3.9	30	50		0.48	0.866		0.5	168	
380[1]	1.09	13.8	1.8	456	39	25	6.57	0.615	0.206	3.0	147	
381[1]	1.21	12.5	3.8	30	44	3	0.48	0.767	0.027	0.0	150	
382	1.72	8.9	9.3	20	40	1	0.46	1.015	0.013	0.0	216	0.14 m B.T., 0.75-70°-A, Draft = 20 Pa
383	1.34	11.5	5.6	17	46	2	0.32	0.887	0.020	0.0	192	
384	1.22	12.4	4.0	20	46	2	0.32	0.808	0.019	0.0	180	
385	1.18	12.7	3.4	30	45	3	0.47	0.766	0.027	1.0	177	
386	1.13	13.3	2.6	177	40	10	2.67	0.657	0.086	3.0	174	
387	1.10	13.6	2.1	1019	38	70	14.86	0.601	0.583	6.5	172	0.14 m B.T., 0.75-70°-A, Draft = 10 Pa
388	1.25	12.4	4.4	20	50	2	0.33	0.890	0.019	0.0	176	
389	1.15	13.1	2.9	40	49	3	0.61	0.807	0.026	2.5	173	
390	1.22	12.5	4.0	20	49	2	0.32	0.864	0.018	0.0	176	
391	1.19	12.9	3.5	20	50	2	0.31	0.847	0.018	1.0	176	
392	1.31	11.6	5.3	15	50	2	0.26	0.941	0.020	0.0	182	
393	1.54	10.1	7.9	17	47	2	0.37	1.060	0.024	0.0	198	

TABLE C-7 (Concluded)

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	CONFIGURATION
394	1.52	10.2	7.6	15	46	2	0.32	1.001	0.023	0.0	191	$\dot{V}_{w.a.} \approx 0.800\ m^3/s$, 0.14 m Blast Tube, 0.75-70°-A Nozzle, Draft = 10 Pa
395	1.26	12.0	4.5	15	48	2	0.27	0.866	0.019	0.0	176	
396	1.18	12.9	3.3	21	49	2	0.34	0.824	0.018	1.0	169	
397	1.10	13.6	2.0	139	39	6	2.02	0.622	0.050	3.5	164	
398	1.15	13.2	2.8	31	43	3	0.49	0.703	0.026	2.0	164	
399	1.33	11.3	5.4	11	46	3	0.21	0.881	0.030	0.0	171	
400	1.34	11.3	5.5	17	47	2	0.32	0.912	0.020	0.0	167	$\dot{V}_{w.a.} \approx 0.800\ m^3/s$, 0.14 m B.T., 0.75-70°-A, Draft = 10 Pa, Burner 0.025 m into Combustor
401	1.12	13.4	2.4	90	45	4	1.34	0.726	0.034	3.0	162	
402	1.17	12.7	3.1	30	50	2	0.46	0.833	0.018	0.5	159	
403	1.23	12.2	4.1	20	50	2	0.33	0.880	0.019	0.0	162	
404	1.16	12.9	3.0	30	49	2	0.46	0.812	0.018	0.5	159	
405	1.19	12.6	3.5	20	49	3	0.32	0.842	0.027	0.0	159	
406	1.23	12.2	4.1	20	48	2	0.33	0.847	0.019	0.5	163	Original "1819" Oil, 0.14 m B.T., 0.75-70°-A, Draft = 10 Pa
407	1.20	12.6	3.6	30	50	2	0.48	0.855	0.018	0.5	167	
408	1.13	13.3	2.5	148	40	8	2.22	0.654	0.068	4.0	167	
409	1.17	12.8	3.2	41	46	3	0.65	0.774	0.027	2.0	168	
410	1.37	11.1	6.0	20	50	2	0.37	0.986	0.021	0.0	178	
411	1.30	11.7	5.0	20	50	2	0.34	0.927	0.020	0.0	176	
412[1]	1.16	12.7	3.0	50	40	3	0.77	0.673	0.026	1.5	148	

1. 4-min.-on/8-min.-off cyclic firing
2. Supercharged

APPENDIX D

UNDERWRITERS LABORATORIES REPORT OF PRELIMINARY INVESTIGATION AND APPROPRIATE ROCKETDYNE RESPONSE

UNDERWRITERS LABORATORIES INC.

an independent, not-for-profit organization testing for public safety

July 19, 1977

MP3279
77NK3579

Rocketdyne Division
Rockwell International Corporation
6633 Canoga Avenue
Canoga Park, California 91304

Attention: Mr. Paul Combs
Project Engineer

Subject: Preliminary Examination of Oil-Fired Central Furnace Incorporating a Sealed Combustion System

Gentlemen:

This will report the results of our preliminary examination of your oil-fired central furnace with a sealed combustion system.

The central furnace supplied to us is identified as Model Oll-140 and this unit appears to be manufactured by Lennox Industries Inc., Marshalltown, Iowa with certain modifications to the combustion chamber assembly along with addition of components to provide the sealed combustion system.

The oil burner is of the forced draft pressure atomizing type of conventional design except for the air inlet housing arrangement, burner firing head and stator plate within the burner fan housing. It appears this oil burner was manufactured by the R. W. Beckett Corporation, Clyria, Ohio and carries the Laboratories Listing Mark signifying that it was in compliance with UL requirements prior to modification by your company.

The modification of the furnace and burner is primarily to achieve a sealed combustion system. This is accomplished by delivering the combustion air supply through a 4 in. dia. flexible duct from outdoors directly into the burner compartment of the furnace. An adapter is also provided to house the barometric draft regulator within the combustion air supply so that no difference in pressure occurs between the air external to the regulator and the combustion air supply.

UNDERWRITERS LABORATORIES INC.

MP3279
Page 2
July 19, 1977

The furnace is intended for connection to a conventional chimney for venting the products of combustion to the outdoors.

The combustion air assembly installed on the burner incorporates a self closing combustion air shutter which, although adjustable, will close when the oil burner is de-energized.

The burner is intended for operation firing No. 2 Commercial Standard Grade oil fuel and is an integral part of the oil fired central furnace, special type. The appliance is an upflow type furnace intended for installation on combustible flooring and is to be equipped with a field provided and installed warm air plenum and return air duct system.

The purpose of this examination, as mentioned to Messrs. Combs and Nestlerode during their November 19, 1976 Laboratories visit, is to bring to your attention any obvious construction, design or installation features which may not conform to the applicable requirements in the Sixth Edition of the Standard For Oil Burners, UL296, and Fifth Edition of the Standard For Oil-Fired Central Furnaces, UL727. We are unable to comment on certain features relative to installation, including routing and termination of the flue pipe and combustion air duct because a copy of your operating and installation instructions was not included with the central furnace.

The following comments are based on a review of the oil burner construction and all referenced paragraphs pertain to the Standard For Oil Burners, UL296 unless otherwise specified.

1. The combustion detector mounting bracket is formed over the edge of the burner fan housing and is not mechanically fixed in position as required by Pars. 4.15 and 17.2. If a fixed position is not established tests will be necessary in both the maximum forward and rearward settings to determine conformance.

2. Removal of the burner access panel of the furnace is necessary prior to adjustment of the primary air damper door. We question how the propr air/fuel ratio is obtained following replacement of the burner access panel. We refer you to Par. 4.10 regarding this subject. We also note the air damper adjustment provides minimum and maximum stops which limits the combustion air damper travel to 2 in. and 3/16 in. maximum and minimum open travel respectively. To conform with Par. 18.1 of UL727 the adjustable damper is to include a stop at it's minimum setting which will provide sufficient air for complete combustion at the minimum burner input. We would not anticipate that complete combustion could occur at this minimum air shutter setting with a main flame hourly input of approximatley 1 gal per hour (140,000 Btu per hour).

Rocketdyne Comments and Actions
<u>Planned for Field Test Furnaces</u>

A fixed position will be established by drilling and tapping a hole in the burner housing for a cap screw.

For the field testing, the panel will be removed to adjust the combustion air, replaced to measure the flue gas composition, removed again, if further adjustment is required, etc. It is not planned to correct this minor inconvenience.

A screw stop will be added in the field to ensure that each unit operates with no less than stoichiometric air at an input of 0.75 gph. Uncertainty concerning the effects of differences among installations on this setting makes it undesirable to ship the test units with this preset.

Rocketdyne Comments and Actions Planned for Field Test Furnaces

3. Sheet metal screws are provided at the top, left and right side of the burner fan housing front section to retain the draft tube in position. To conform with Par. 4.12 sharp screw ends should not come in contact with the operators hand. As you know, access is required in this area for removal and replacement of the oil burner firing head assembly.

Neither these screws nor their protrusions into the blast tube have been altered from the stock burner. No operational problems are anticipated, so no action is planned

4. The draft fan microswitch is installed within the inlet air housing and appears to function as an air-fuel interlock control. The normally open switch contacts close when the combustion air damper door opens, completing the circuit to the combustion detector. From our examination we find that when adjusted to the minimum air shutter setting the switch contacts are open until the damper door opens at which time the switch contacts close. When the damper door closes, simulating absence of a combustion air supply the switch contacts remain closed. It appears that there is not sufficient door travel to permit the switch contact to resume the normally open position.

This condition was also observed in the Rocketdyne laboratory. It will be eliminated by provision of the microswitch position stop (Item 2, above) which will ensure no lower than stoichiometric combustion air.

5. Par. 4.16 and 17.4 include requirements covering removal and replacement of the oil burner firing head assembly. It was found that although the assembly was capable of being replaced in it's intended position, this installation was not readily accomplished. Also, during the several attempts to restore the firing head in the draft tube deformation occured of the No. 21 ga. Type 310 stainless steel vanes attached to the inner surface of the burner nose cone, resulting in a reduction of clearances between current carrying parts of the ignition electrodes and adjacent grounded metal parts. This construction does not conform with Par. 17.4.

This potential problem can be averted by exercising a minimal amount of reasonable care. The subcontractors' service personnel will be warned to be careful not to distort the vanes and to check their alignment with the electrodes before completing reassembly of a disassembled burner. No further action is planned.

6. The access cover plate of the combustion air intake assembly, through which the copper oil line passes to the burner firing head assembly, is provided with an elongated opening. This cutout in the plate is not provided with smooth well rounded edges and could cause physical damage to the tubing. This is not in compliance with Par. 13.6.

Each burner will be checked before shipment to ensure that there are not burrs or sharp edges which might penetrate the oil line.

7. The bottom section of the inlet air housing does not incorporate an open drain and will allow accumulation of oil, should leakage occur from the fitting within the housing. This construction does not conform with Par. 6.2.

A 1/8-inch-diameter hole will be drilled in the bottom of the inlet air housing.

UNDERWRITERS LABORATORIES INC.

MP3279
Page 4
July 19, 1977

8. The hinge material of the air intake shutter is 0.125 in. dia. steel rod and does not appear to be of a corrosion resistant material. We refer you to Par. 8.5 regarding material selection for this part of the assembly.

9. The furnace assembly and related parts supplied to us for examination does not include a draft regulator. Conventional oil fired central furnaces are to be connected to a draft regulator unless Listed for use without one. Shipment of a Listed draft regulator as part of Labeled appliances of conventional construction is not required, however, due to the sealed combustion system design of your heating appliance we recommend that a Labeled draft regulator be supplied with this furnace to assure that no difference in pressure occurs between the combustion air supply and air in the vicinity external to the regulator.

10. The oil supply tubing between the power operated oil burner pump and the burner firing head consists of copper tubing with aluminum fittings. To conform with Par. 13.6 the tube fittings should be Listed. Presently we believe that all Listed fittings are fabricated from brass, bronze, stainless steel or plated carbon steel and are judged suitable when used in combination with copper tubing. Copper tubing with aluminum fittings should not be used due to possible galvanic action which may cause leakage, unless we conduct a special investigation to determine that this combination of dissimilar metals are suitable for the application.

11. The thickness of the air shutter is 0.038 in. To conform with Par. 8.4 sheet metal air shutters less than 0.0508 in. thick are to be properly reinforced.

12. The electrode assembly cannot be identified as being a Recognized item. To conform with Par. 18.9 and 18.11 the ignition electrodes should be Recognized and suitable for the intended application.

13. The Recognized component White Rodgers Type 668-453 safety switch is used in conjunction with the Honeywell Type C554A combustion detector. The suitability of combination of these components has not been determined and, therefore, should not be used. We recommend the combustion detector Type 956 manufactured by White Rodgers be provided with the above safety switch. We refer you to Par. 33.1.

Rocketdyne Comments and Actions
Planned for Field Test Furnaces

The mild steel hinge rod will not be replaced for the one heating season test period unless field conditions are found to be excessively corrosive and result in sticking of the hinge.

A new UL-listed barometric draft regulator will be supplied with each test furnace.

These fittings were parts of the stock oil burner. Laboratory experience with the burner did not suggest that problems would arise during the field test period, so no action is planned.

The air shutter is small and subjected only to light pneumatic loads from the combustion air flow so it will not be disassembled for what seems to be unnecessary reinforcement.

The electrodes are the same ones supplied with the stock burner. They have been shortened by about 2 inches.

The White-Rodgers Type 956 detector has higher impedance than the Honeywell Type C554A component. Apparently as a result, it is less sensitive to flame light from this burner. In particular, spurious cut-offs were experienced with the W-R detector on short cycle interval restarts when the firebox and burner head were still warm and, presumably, the initial flame was less luminous than with a cold start. It is planned to go ahead with the Honeywell detector.

UNDERWRITERS LABORATORIES INC.

MP3279
Page 5
July 19, 1977

14. The plug provided in the burner fan housing to route the air prover switch wiring into the burner junction box could not be examined without major dismantling of the burner. Please refer to Par. 25.14 regarding material type and thickness of this plug.

15. Insulated conductors are routed from the air prover switch into the burner housing without being enclosed in conduit nor does the combustion air housing constitute a raceway or electrical enclosure. This construction does not conform with Par. 27.5 and 27.18.

16. The bushing provided in the plug through which the insulated wires of the air prover switch pass cannot be identified. We refer you to Par. 27.20 through 27.22 regarding this subject.

17. The micro switch bypass relay is installed on the cover plate of the burner junction box and receives its power from the 120 v incoming power supply. It does not appear that the required minimum spacings through air and over surface are provided as required by Table 30.1.

18. The American Zettler Co. relay, referred to in Item 17 above, and 8 pin tube socket assembly are attached to the top surface of the burner junction box cover. This cover and relay are supported only by the wiring when the cover is detached for access to the junction box. This construction does not conform with Par. 27.4.

19. The air housing of the burner as well as the burner draft tube are not bonded for grounding as required by Par. 34.1 and 34.2.

The following comments are made based on a review of the central furnace construction and all referenced paragraphs pertain to the Standard For Oil-Fired Central Furnaces, UL727 unless otherwise specified.

1. The combination fan and limit control is partially covered by the combustion air duct adaptor and filter box assembly. The control cover is difficult to remove and following removal the fan and limit adjusting mechanism is not readily visible nor does it appear that this control is accessible for replacement without the need for removal of the combustion air filter box. This construction does not conform with Par. 6.3 and 19.4.

Rocketdyne Comments and Actions Planned for Field Test Furnaces

A small rubber grommet protects the wires where they pass through a stamped, sheet steel plug. Although rubber is not listed in the cited paragraph as a suitable material, it undoubtedly will last for the field test period.

These control circuit (24V) wires will be tied down to prevent them from being abraded due to the combustion air flow blowing them about.

It's an off-the-shelf rubber grommet which, again, is not expected to deteriorate during the field test period.

The incoming power is 24V, not 120V, so the required minimum spacings are provided. The relay actuator coil is supplied 120V via two non-adjacent pins, which are also separated by more than the required minimum spacings.

Only 24V control circuits are present in the air housing and the draft tube connection has not been changed from the stock burner. No problem is anticipated, so no action is planned.

The filter box assembly will be removed to provide access to the fan and limit switch cover and control settings. This is accomplished by unscrewing three sheet metal screws; a minor inconvenience which will not be corrected in the test furnaces.

UNDERWRITERS LABORATORIES INC.

MP3279
Page 6
July 19, 1977

	Rocketdyne Comments and Actions Planned for Field Test Furnaces
2. The fiberglass insulation located within the circulating air compartment of the furnace could not be identified. To conform with Par. 11.1 the insulating material should be Classified with a fire hazard classification rating as specified in this paragraph of the Standard.	It is Johns-Manville Cerra Felt insulation, a rock wool blanket insulation with aluminum foil jackets on both sides. JM rates it as withstanding temperatures to 2300 F, which is far above the maximum of 850 F experienced by neighboring components. No action.
3. The fan and limit control is located within the combustion air filter box and the main furnace junction box is directly below the filter box. Any moisture or water within the combustion air duct will drip or run on the conduit connected to the junction box top and will enter the box to wet all electrical wiring. This construction does not conform with Par. 20.1.	Air burner moisture will be avoided either by installing a mechanical de-mister in the inlet air line or by taking the combustion air from the top of the sealed air plenum.
4. Two unused openings are provided in the left and right side casing panels in the vicinity of the burner compartment. Three nonmetallic plugs were taped to the inner surface of the furnace casing. A plate or plug as required by Par. 21.12 should be used to close unused openings.	Plugs used will be those that came with the stock furnaces which were modified to become the test units.
5. The furnace marking appears to be portions of that normally provided by Lennox Industries on their Labeled central furnace. These include the model designation, firing rate, draft, clearances and electrical rating as well as the cautionary statement relative to protection of the combustion chamber from chemical soot destroyers. When Listing is established for your product the marking should be that which is specifically indicated for your product. We refer you to Sec. 61.	Inappropriate labels will be removed from the test furnaces and, specifically, none will be allowed to remain from which it might be inferred that they are UL-listed.
6. The wiring diagram appearing on the furnace casing panel does not include all electrical components provided by your company.	A separate control circuit schematic diagram will be glued in the burner vestibule of each test furnace.
7. We question if the use of the combustion air duct will cause condensation to form on the outer surface of this pipe which, in turn, could cause wetting of live current carrying parts within the furnace junction box or other electrical enclosures within the unit casing. If this is the case, the construction does not conform with Par. 20.1.	A silicone sealer will be used to prevent external moisture from being drawn into the furnace in the vicinity of the combustion air supply connection.
8. To adjust the fan and limit control setting it is necessary to remove the control cover as indicated in Item 1 above under furnace construction comments. We note that although the control incorporates push-in terminal connectors for power supply wiring to the control, some portion of the conductors are uninsulated and could permit accidental contact with these high voltage parts. This construction does not conform with Pars. 32.1 and 32.2	This potential hazard will be corrected by shortening the bare, uninsulated stub of each wire so that its insulation is properly socketed into the terminal connectors.

MP3279
Page 7
July 19, 1977

The following comments are based on a review of the central furnace construction when equipped with the sealed combustion air system.

1. As mentioned previously, a copy of the installation manual was not provided therefore, we are not certain how the combustion air supply duct is to be routed from the sealed air plenum to the outside. This complete air intake assembly is to be provided as a component of the furnace.

2. If this appliance is to provide complete separation of the combustion system of the fuel burning appliance from the residence in which it is operating the design of the appliance should prevent operation when the burner access panel is removed or the burner access panel is to be hinged in a manner not likely to permit or invite its removal. An interlock switch if provided for this purpose should automatically open the circuit when the door or panel is opened and which will automatically close the circuit when the door or panel is closed. However, the interlock switch may be such that a serviceman can manually close the circuit for servicing but the switch will automatically return to its normal position when the door or panel is closed, i.e., be in a position to automatically open the circuit when the door or panel is reopened, provided the interlock switch is wired in the power circuit to the appliance or in the combustion-detector circuit of the primary safety control.

A burner compartment of an appliance intended to conform to the above requirements should include a warning marking which can be readily seen when the door or access panel is open. The warning is to be in contrasting colors and read as follows:

WARNING - This Compartment Must
Be Closed Except When Servicing

The word WARNING should be in 30 point (10.4 mm) and the balance of the statement in 24 point (8.4 mm) Franklin Gothic type or the equivalent.

3. The outdoor air entrance of the air intake assembly will be required as part of the appliance. Such assembly was not provided for our examination during this review. For your information we wish to advise that the air entrance is to be guarded, shielded or located to prevent rain, snow, debris and birds from entering. A screen, if used, is to have a mesh not less than 1/4 in.

Rocketdyne Comments and Actions
Planned for Field Test Furnaces

The stated approach is unreasonable in that it leaves too little latitude for field installations in existing houses.

This is a valid comment but interlocks will not be provided in the test units because of the need to remove the panel to adjust the combustion air setting.

This warning statement is appropriate and will be used.

These recommendations concerning the air inlet conform to the planned installation method.

UNDERWRITERS LABORATORIES INC.

MP3279
Page 8
July 19, 1977

UNDERWRITERS LABORATORIES INC.	Rocketdyne Comments and Actions Planned for Field Test Furnaces
4. The design of the air intake for combustion air and the path of the intake air should provide adequate combustion air to the burner and adequate dilution air to any draft regulator.	This will be provided by using a 7-inch-diameter air inlet line.
5. The flue collar ofthe appliance extends 3/4 in. above the flue collector box and is so located that screws are prevented from being used for mechanical attachment of the flue pipe to the flue collar. We suggest this flue collar height be increased to not less than 1-1/4 in. to provide a more substantial flue pipe attachment.	The flue collar is unchanged from the stock UL-listed furnaces from which the test unit was derived. No action.
From a review of the list of electrical and fuel handling components sent to us with the central furnace we have the following comments:	
1. We could not identify the Sundstrand oil burner pump Model B2VA-8216 as a Listed or Recognized power operated pump.	It came on the stock burner and carries a UL-listed label. Based on laboratory experience with this pump, no problems are anticipated, so no action is planned.
2. The Honeywell combination fan and limit control L4046A does not appear in our files as a Listed or REcognized device. Possibly, this is a typographical error in the list of components you provided and you intend to use the Type L4064A which is a Listed control.	This was a typographical error. The correct designation is Type L4064A.
3. The American Zettler Co. relay is a Recognized Component, however, it is not used in accordance with the terms of Recognition for this device. This Relay is intended for use in secondary circuits supplied by a transformer winding with a maximum available output of 200 va or with a maximum potential of less than 100 v due to spacings between opposite polarity parts. This relay does not provide the through air and over surface spacings required by Table 30.1 of UL296.	The controlled circuit is 24V, not 120V. Therefore, no action.
In addition this relay is of the open type and should be installed within a suitable electrical enclosure. The burner compartment of the furnace is not a suitable electrical enclosure for open type electrical components.	
4. The Amphenol Type 49SS8 tube socket cannot be identified as a Listed or Recognized device.	No action.

The test work anticipated on this furnace design, incorporating an unlabeled oil burner will be basically as indicated below, however, this should not be construed as a final test program as test results may indicated the need for additional tests not originally anticipated. The burner tests are based on the Standard for Oil Burners, UL296 (Sixth Edition) and Standard for Oil-Fired Central Furnaces, UL727 (Fifth Edition).

Burner Tests

1. Combustion air failure - Par. 47.1 through 47.4, UL296.

2. Undervoltage - Par. 49.1 through 49.2E of Standard UL296.

3. Power interruption - Par. 50.1 through 50.4 of Standard UL296.

4. Ignition test, electric high tension - Pars. 53.1 through 53.6 of Standard UL296.

5. Electric high tension - Pars. 18.1 through 18.4, Standard UL296.

Central Furnace

1. Combustion-Burner and Furnace - Pars. 38.1 and 38.2, UL727.

2. Operation - Par. 39.1 through 39.3, UL727.

3. Limit Control Cut-Out - Par. 40.1 through 40.7, UL727.

4. Continuity of Operation - Pars. 41.1 through 41.5 of UL727.

5. Temperature - Par. 43.1, UL727.

6. Continuous Operation - Pars. 44.1 through 44.6, UL727.

7. Blocked Inlet - Pars. 45.1 through 45.5, UL727.

8. Fan Failure - Par: 46.1 through 46.11, UL727.

9. Blocked Outlet - Par. 48.1 through 48.9, UL727.

Rocketdyne Comments and Actions
Planned for Field Test Furnaces

Except for the electric high tension and dielectric strength tests, one specimen of the test furnace was subjected to these various tests in the Rocketdyne laboratory. The only negative result was a potential overtemperature of a portion of the control circuit wiring under reduced warm-air flow conditions. As a result, higher temperature wiring will be installed in that part of the circuit.

UNDERWRITERS LABORATORIES INC.

MP3279
Page 10
July 19, 1977

10. Dielectric Strength-Par. 50.1 through 50.5, UL727.

It is anticipated that the total cost for investigation and test of the one model and style of central furnace, Special Type, with a view towards Listing will be approximately $7500.00. Provided conformance is obtained the oil burner will be described as an integral part of the heating appliance.

Applications are not enclosed at this time on the assumption that some time will be needed by your company to review the heating appliance and incorporate revised construction to obtain conformance with the items referred to above.

When you are ready to have us proceed with the test and investigation please let us know and applications will be sent to you.

At the request of Mr. Combs during the April 12, 1977 telephone conversation with the writer no destructive examination was undertaken due to the intended use of this appliance for field test. We do recommend, however, that this product be reviewed to determine that proper operation is obtained once available to you.

The furnace is being sent to your facilities in Canoga Park, California.

This completes the work undertaken based on our preliminary examination of your central furnace incorporating a sealed combustion air system under Project 77NK3579 and we have notified our Accounting Department to prepare and invoice you for the charges incurred.

For your information and guidance we are enclosing a copy of "Suggestions to Applicants" and "Information on Shipping Samples to UL - Northbrook."

Very truly yours,

J. Hughes

J. HUGHES
Senior Project Engineer
Heating, Air-Conditioning
and Refrigeration Department

Reviewed by:

Euno Toomsalu

E. TOOMSALU
Associate Managing Engineer
Heating, Air-Conditioning
and Refrigeration Department

JH:jp

P.S. In the interest of advancing consumer product safety through cooperation with the Consumer Product Safety Commission, UL is by this notice simply calling attention to the provisions of the Consumer Product Safety Act, and particularly Section 15, if your product is one covered by the Act.

APPENDIX E

FLUE GAS POLLUTANT EMISSION CONCENTRATIONS FROM INTEGRATED FURNACE FIELD TEST UNIT 2 AT 0.79 ml/s (3/4 gph) FIRING RATE

RUN NØ.	STØIC. RATIØ	CØ2 %	Ø2 %	CØ PPM	NØ PPM	UHC PPM	CØ GM/KGM	NØ GM/KGM	UHC GM/KGM	BACH. SMØKE	NET TFG C
STEADY-STATE											
476	1.16	13.2	3.0	30	37	2	0.46	0.622	0.017	1.0	179
477	1.26	12.1	4.5	10	41	2	0.17	0.746	0.019	0.0	182
478	1.38	11.1	6.1	10	42	2	0.18	0.342	0.021	0.0	185
479	1.43	10.7	6.7	10	41	2	0.19	0.355	0.022	0.0	183
480	1.55	9.9	7.9	15	35	2	0.31	0.779	0.024	0.0	196
481	1.64	9.3	8.6	100	22	10	2.19	0.518	0.125	0.0	202
482	1.45	10.6	6.9	20	35	2	0.39	0.746	0.022	0.0	187
483	1.34	11.5	5.6	20	33	2	0.36	0.741	0.020	0.0	184
484	1.25	12.3	4.4	20	42	2	0.33	0.757	0.019	0.0	182
485	1.20	12.7	3.7	25	42	2	0.40	0.728	0.018	0.0	181
486	1.19	12.9	3.5	30	43	2	0.47	0.736	0.018	0.5	181
487	1.15	13.3	2.9	90	39	5	1.37	0.650	0.043	2.0	181
Cyclical 4-min. on/8-min. off											
488	1.19	12.9	3.5	55	35	40	0.86	0.606	0.359	0.0	161

APPENDIX F

SUMMARY OF DISCUSSIONS AT THE FINAL FIELD TEST PLANNING MEETING, 7 JULY 1977

Phase II will be concerned, primarily, with field verification of six integrated furnace units whose design was finalized and where operational and performance characteristics were observed in the laboratory during Phase I. Three of the integrated furnaces will be installed in homes in each of two field test locales in the Northeastern U.S., and will be used as the homes' primary space heating sources during the 1977-1978 winter heating season. Based upon climatic, housing, and heating system comparisons among many potential candidate cities, the Boston, MA, and Albany, NY areas were selected as the field test locales. Subcontracts have been let to one furnace distributor in each area to assist Rocketdyne in the selection of host homes, installation of furnaces, provision of periodic inspection and emergency services and, at the end of the test period, removal of test units and restoration of the homes' heating systems to their former conditions.

To assist in the final stages of planning and preparing for field testing, a meeting was held at Rocketdyne's main plant in Canoga Park, CA, on 7 July 1977. In attendance were the EPA project officer, a representative of each of the subcontractors, and essentially all of the Rocketdyne employees directly associated with the project. The objectives of the meeting were to discuss the field testing thoroughly enough that all participants would understand their own and each other's roles, that all incipient and potential problems would be discerned and solutions found (or, at the very least, thought about), and to provide the subcontractors with previews of the equipment which would soon be shipped to them.

Several pages of information were arranged in outline form to serve as a discussion guide for the meeting. The discussions essentially paralleled the outline, so the approach taken in preparing this summary was simply to expand the material handed out at the meeting by inserting the results of the discussions. This process was aided by making a tape recording of most of the meeting. In the ineterests of clarity, items discussed at different times are combined herein under a single appropriate heading, peripheral and background discussions which preceded agreement on certain topics are omitted, and a few topics not in the original outline have been inserted.

Reference is made occasionally to the Statement of Work for the subcontractors, which is reproduced at the end of this Appendix.

AGENDA

FINAL FIELD TEST PLANNING MEETING

THURSDAY, 7 JULY 1977

"DESIGN OPTIMIZATION AND FIELD VERIFICATION OF
AN INTEGRATED RESIDENTIAL FURNACE"

Time	Event
8:30 (AM)	Arrival of EPA Project Officer and Subcontractor Personnel
8:35	Introductions - Dr. B. L. Tuffly's Office
8:40	EPA Objectives in Residential Emissions Program - B. Martin
8:45	Meeting and Program Overview - P. Combs
8:55	Depart for Santa Susana Field Laboratory
9:30	Tour of Furnace Assembly and Test Laboratory - A. Okuda
11:30	Return to Canoga Main Plant
12 (Noon)	Lunch - Executive Dining Room
12:50 (PM)	Detailed Discussions
4:40	Adjournment

LIST OF ATTENDEES

Name	Function	Organization
Blair Martin	Project Officer	US Environmental Protection Agency
Joseph Iorio	President	Atlantic Heating & Air Conditioning Co.
Ronald von Ronne	Representative	Main-Care Heating Service
Bart Tuffly	Program Manager	Rocketdyne Division, Rockwell International
Paul Combs	Project Engineer	↓
Allan Okuda	Research Engineer	↓
Larry Russell	Design Engineer	↓
Ronald Bartley	Purchasing Representative	↓

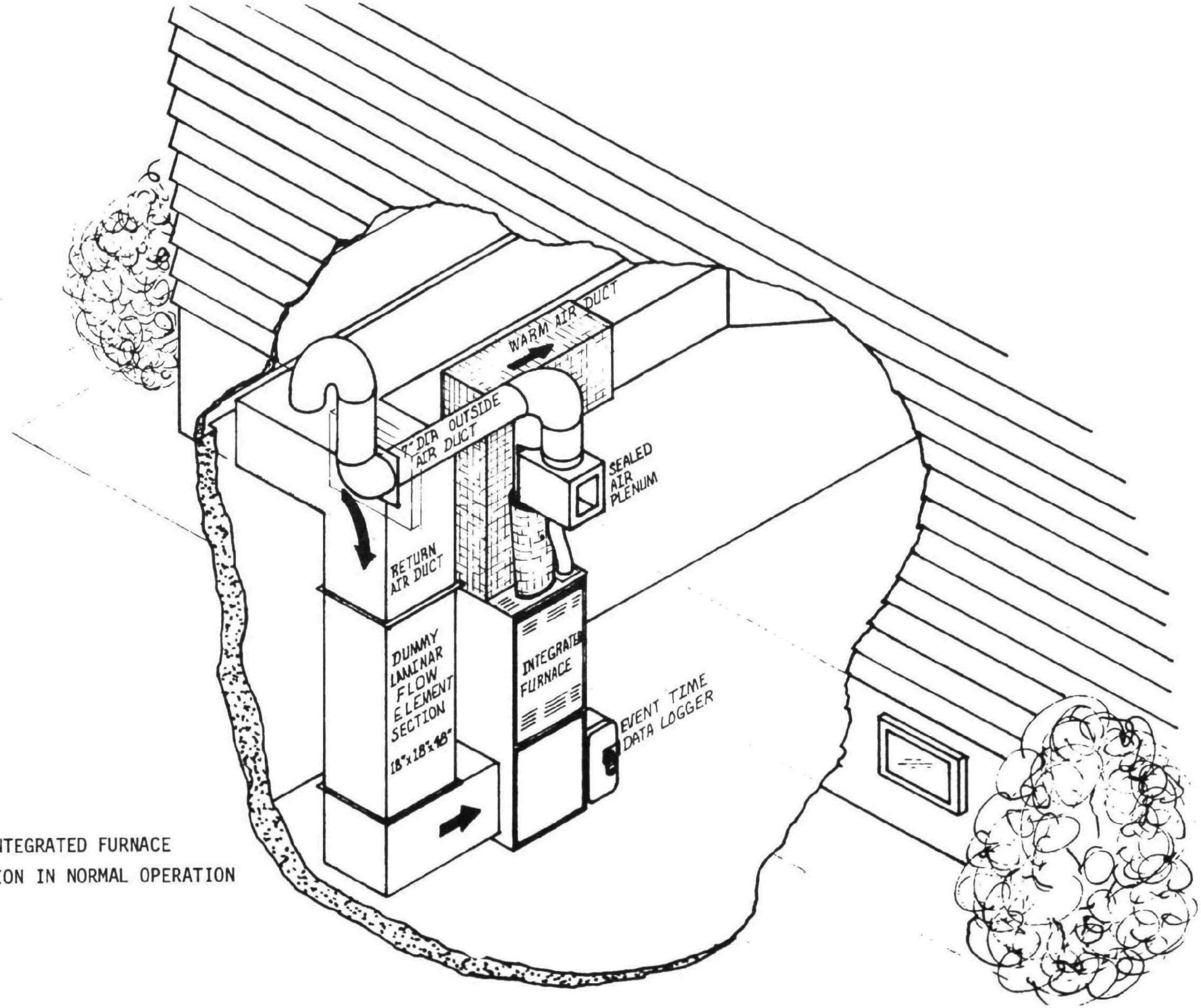
PROGRAM OVERVIEW

Objectives of field testing

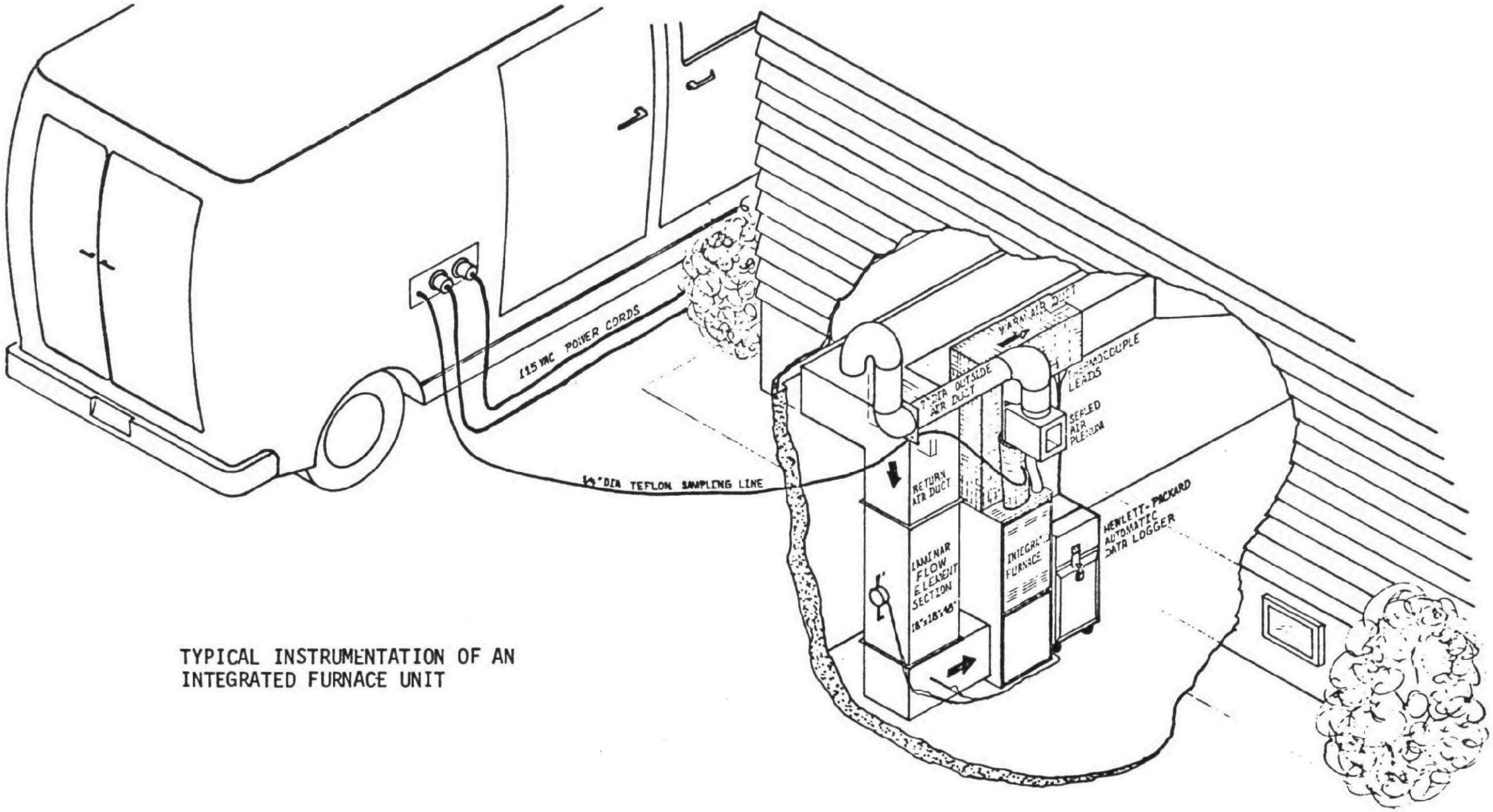
- To demonstrate proof of concept
    - Low-emission design criteria for burner and firebox
        - Are applicable to residential space heating
        - Are compatible with improved efficiency
    - Measure steady-state, cycle-averaged, and season-averaged efficiencies
- To test for a relatively long time period
    - Over one winter heating season, document:
        - Stability of emissions
        - Stability of efficiency
        - Freedom from maintenance

Approach to field testing

- Test furnaces in actual residences
  - Two distinctly different climates
    - Maritime (Boston)
    - Continental (Albany)
  - Variety among host residences
    - Construction
    - Age and insulation
    - Exposure
  - Known fuel-usage history
- Get local help from furnace service company
  - Arrangements with host homeowners
  - Installation, emergency service, maintenance, removal
  - Periodic inspections (monthly)
  - Coordinate and go along on all Rocketdyne visits to hosts
- Rocketdyne will perform specialized measurements
  - Mobile instrument laboratory for emissions
  - Recording data loggers for efficiency



TYPICAL INTEGRATED FURNACE
INSTALLATION IN NORMAL OPERATION



TYPICAL INSTRUMENTATION OF AN INTEGRATED FURNACE UNIT

Output from field testing

- Experimental results
  - Steady-state and cycle-averaged emissions
  - Steady-state and season-averaged efficiencies
  - Operational history

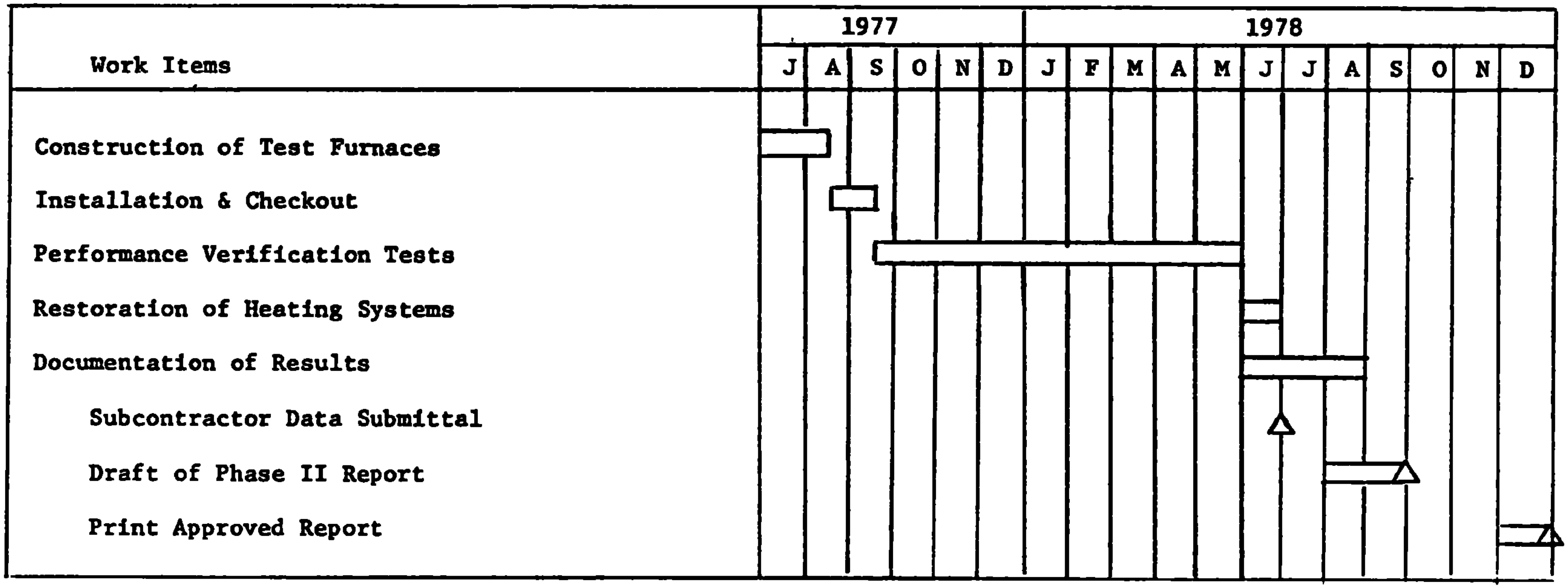
  } Based mainly on Rocketdyne data

    - Stability of performance
    - Installation versatility
    - Maintenance requirements

    } Based largely on Subcontractor data

- Documentation of results
  - Formal phase report
    - Design guide
    - Summaries in trade journals
  - Technical papers
    - EPA contractors meeting
    - Engineering societies, e.g., ASME, ASHRAE

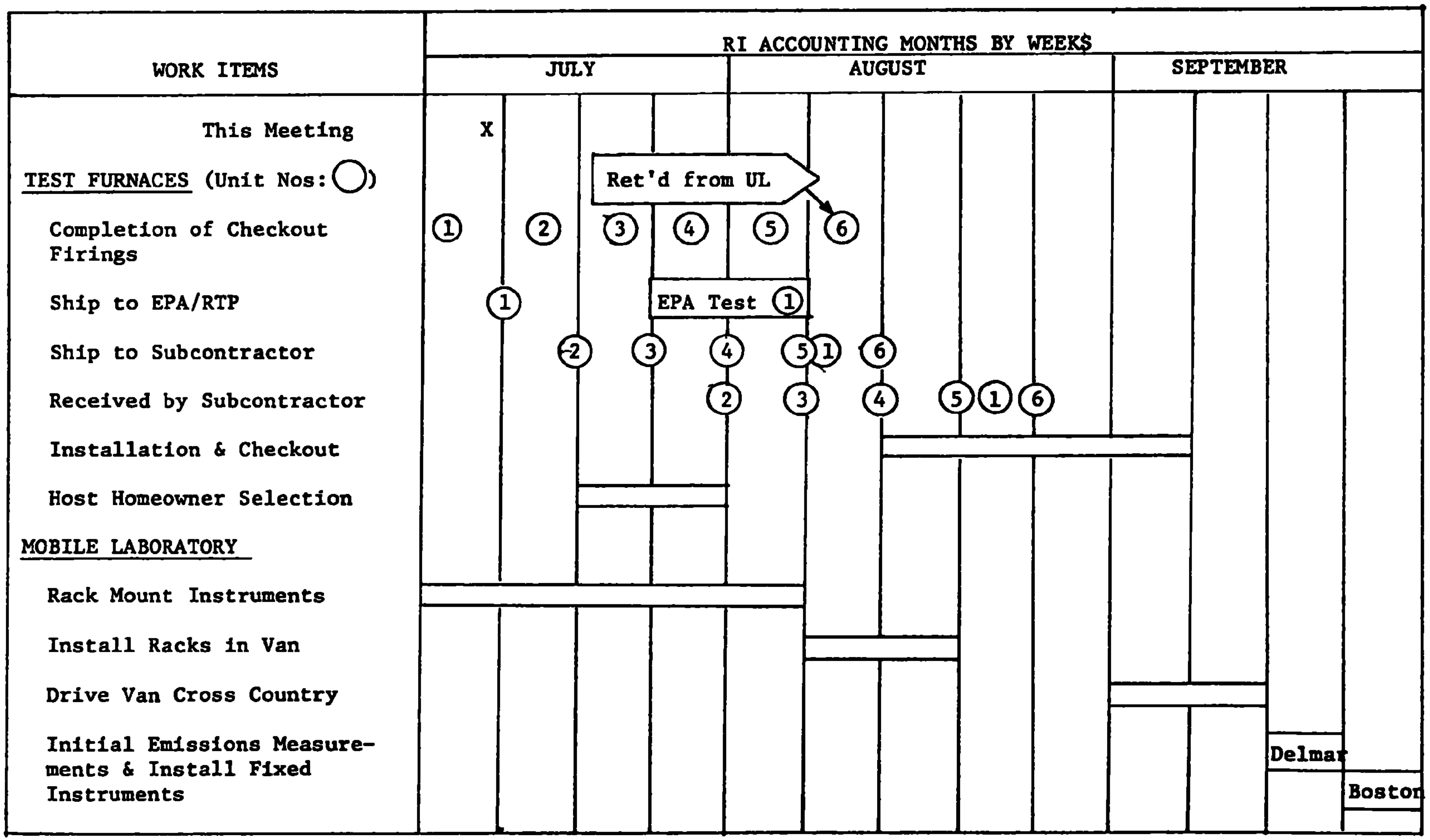
OVERALL SCHEDULE FOR FIELD TESTING



✓ This overall schedule is acceptable to all participants. Discussion centered on whether June 1st is too early for considering the heating season to be over and for removing test furnaces and restoring the former heating systems. The consensus was that that date's OK.

SCHEDULE FOR TEST FURNACE

PREPARATION - SHIPPING - INSTALLATION - ACTIVATION



DISCUSSION OF SCHEDULE

1. Projected shipment of integrated furnaces to and receipt by subcontractors appear to be timely and acceptable. Both subcontractors would like to receive all units in August so that they can have them installed before fall weather turns cold.

2. Blair Martin was uncertain as to how testing the unit tentatively scheduled to be in RTP the last week in July and the first week in August would fit into their laboratory schedule. After he has investigated, we will firm up whether that unit, a later one, or none will be shipped to RTP for test before being sent on to a subcontractor.

3. Paul Combs will visit the subcontractors soon (tentatively, July 21 and 22) to review their candidate host homes and, together, to rank them in order of preference. He will telephone on 18 July to confirm that both subcontractors are ready for this step.

4. Rocketdyne needs the mobile laboratory instruments in their Canoga Park laboratory, nominally through the end of August. The mobile van will be driven across country (probably by Al Okuda) some time in early to mid-September, so the initial detailed measurement of emissions and activation of fixed instrumentation will not be possible until late September.

5. In the meantime, the subcontractors will have installed and activated the test furnaces and each furnace may have been in use for several weeks before Rocketdyne's initial visit to begin the quantitative field test measurements.

HOST HOMES

Selection

- Procedure - Review Statement of Work for subcontractors
- Guidelines - Review Statement of Work for subcontractors
  - Selection Criteria

  √ In addition to those criteria given in the Statement of Work, it was observed that subcontractors should endeavor to select homes in "safe" areas, i.e., those having low incidences of street crime, and to select homeowners who are flexible enough not to be unduly annoyed by minor inconveniences, unscheduled loss of heat, etc. It was established that the host homes should be single-family residences, as opposed to duplexes or triplexes, where more than one family has access to the test furnace.

  - Firing Rate (0.75 ±0.1 gph)

  √ Rocketdyne has lowered the nominal firing rate to 0.75 gph to avoid greater than No. 1 smoke when the burner is tuned to 12-1/2% CO_2 or higher (19% excess air or lower). Neither subcontractor saw this as a particular problem. It was noted, however, that the design temperature in Boston (0 F) is higher than that in Albany (-10 F) and that this would allow somewhat greater freedom in selecting host homes in Boston.

  - Subcontractor personnel as hosts

  √ Subcontractors are not constrained from considering their employees as candidate host home owners. In fact, there are some distinct advantages to selecting employee hosts, such as more ready access to homes, better subcontractor control, and lower likelihood of encountering problems with home owners.

- Schedule/decision

Homeowner agreements

- Review work statement

- Complete prior to installation (i.e., by early August)

What homeowners will receive

- Remuneration

√ Both subcontractors indicated that cost-free provision of (or reimbursement for) the season's fuel should be the minimum reimbursement. An alternative that might be offered to any host whose existing furnace needs to be replaced is to install a new furnace when the test unit is removed. (Average consumption per customer was estimated at about 1400 gal/yr. At $0.50/gal, this would cost about $700 and this figure is reasonaly comparable with the installed cost of a new warm-air furnace.) Also, for those whose old units are reinstalled, the subcontractors expect more than usual maintenance will be required during the following heating season, and this service should be provided at no cost to the homeowner.

- Information

√ Rocketdyne should prepare a brief brochure for distribution to the host homeowners. It should be no more than three or four pages long and should include a summary of the program, a description of the furnace's unique features, the color cutaway perspective illustration, and a statement regarding what's expected of the home owner. (I.e., practice the same type of home temperature control as last year, leave adjustments to the subcontractor's service man, and don't meddle with special instrumentation.)

WHAT ROCKETDYNE WILL SUPPLY TO SUBCONTRACTORS

Information

- Drawings
  - Furnace assembly, draft flap assembly, burner head, sealed air plenum, cast-iron combustor, laminar flow element (warm-air flowmeter), control circuit diagram

    ✓ A complete set of available drawings was given to each of the subcontractors at the meeting. Rocketdyne will prepare sketches of two components not included in those drawings, namely the sealed air plenum and the laminar flow element, and will mail copies later.

    ✓ A copy of the control circuit diagram will be glued inside each furnace.

- Photographs

    ✓ A set of representative photographs was given to each subcontractor.

- Specifications
  - Nominal operating conditions (Firing rate, CO_2 level, smoke No., furnace draft, warm-air flow and temperature rise, fan and limit switch settings, etc.)

    ✓ Furnaces will not be preadjusted prior to shipment, so the subcontractors will adjust them to meet the nominal specifications when they are installed. Rocketdyne will supply expected values with the test furnaces. The following were discussed and should be viewed as tentative values:

      - Firing Rate: 0.75 or 0.85 gph
      - CO_2 Level: 12-1/2% or higher, consistent with smoke level
      - Smoke: Less than No. 1 at steady-state

- Furnace draft: Most Rocketdyne laboratory testing has been with 0.03 to 0.05 in. H_2O draft over the fire. Subcontractors normally adjust for about 0.01 in. H_2O overfire draft; mechanical draft-inducers would probably be needed to approach the higher draft levels. It is anticipated that the 0.01 level will be adequate, but Rocketdyne will test this in the laboratory before finalizing a nominal value.

- Warm-air flowrate: Subcontractors will use normal industry-accepted procedures to provide adequate warm-air flowrate to the various outlets of the warm-air distribution system. Resident comfort is the main criterion, rather than a particular flowrate. The warm-air flowrate usually is not measured, but is estimated by summing calculated room register flow requirements. Typically, total warm-air volumetric flows range from 750 to 900 scfm for a 0.75-gph furnace firing rate, and 85 F is a typical warm-air temperature rise. In minimum air flow tests in the laboratory, a test furnace with 80 F inlet air encountered 190 F limit cutoff (i.e., 110 F rise) when the air flow was lower than about 650 scfm. This indicates that limit cutoff normally will not be encountered in most typical installations.

- Fan and limit switch settings: Normal practice is to set the fan switch so that the fan comes on at about 100 F and cuts off at about 85 F. Both of these controls will probably need to be set approximately 5 to 10 F higher to avoid cycling the fan at either end of the burner-on period due to the massive heat sink effect of the cast-iron firebox and, also, to aid in heat retention in that component. The limit switch will be set at 200 F in the laboratory before shipment of the units.

Hardware

- Three furnace assemblies

  - Complete with burners, sealed air plenums, barometric control valves, and flexible combustion air ducts

    √ New barometric control valves supplied by Lennox with the stock furnaces will be used. The flexible combustion air ducts will be 4-inch ID by 5 feet long.

    √ Two furnaces will be shipped to each subcontractor with two-stage fuel pumps and one with a single-stage pump.

    √ An oil flowmeter will be installed in each test furnace before it is shipped from Rocketdyne.

- ✓ The fan and limit switch is positioned behind the cover plate for the combustion air filter. This constitutes an inconvenience for installing servicemen, and it was suggested that the switch be moved or that the cover plate be redesigned to allow quick removal. However, the existing cover plate is held in place by only three easily-removed sheet-metal screws, so it is unlikely that a more accessible design will be attempted in the short time preceding installation.

- ✓ A question was asked as to whether the furnace design will be changed in response to findings of the UL investigation and/or EPA testing. Probably not. The UL results are now expected to be learned too late to change anything short of a serious safety problem. Most UL standards requirements have been tested in the Rockerdyne laboratory; the only change being made as a result is use of high-temperature wiring in a portion of the control circuit. The EPA tests are intended to provide a point of reference with respect to pollutant emissions.

- Key components (list attached)

- Spare parts (list attached)

SPARE PARTS TO EACH SUBCONTRACTOR

Components	Number
Oil Burner	
Optimum head	1
Spray nozzles, 0.75-70-A	6
0.85-70-A	6
Mircroswitches	4
Relays	3
Centrifugal clutches	2
Sealed-air system	
Flexible duct	1
Plexiglas cover plates	2
Combustion air filters	12

(An extra fuel oil meter will be kept in the Hewlett-Packard automatic data logger cabinet.)

LIST OF ELECTRICAL AND FUEL-HANDLING COMPONENTS, ROCKETDYNE/EPA INTEGRATED WARM-AIR OIL FURNACE

Component	Manufacturer	Manufacturer's part or model number
Burner drive motor	Marathon Electric Co.	9PF48S34S45A (115 vac, 2.3 amp 3450 rpm, 1/7 hp)
Ignition transformer "Franceformer"	France Division, Scott & Fetzer Co. Westlake, OH	5 LAY 04 (10,000 V secondary)
Fuel pump	Sunstrand Hydraulics Division of Sunstrand Corp. Rockford, IL	A2VA-7016 (single stage) or B2VA-8216 (two stage) 3450 rpm
Spray nozzle	Delavan Mfg. Co. W. Des Moines, IA	0.75-70-A
Centrifugal clutch	Pioneer Products Co. Elyria, OH	RT-3450
Miscellaneous burner parts: ignition electrodes, fuel line and fittings, fuel tube	R. W. Beckett Co. Cleveland, OH	--
Blower drive motor	Wagner Electric Corp. St. Louis, MO	356-38485-05 (single-phase induction, 115 vac, 7.6 amp, 1725 rpm, 1/2 hp)
Primary control unit	White-Rodgers Div. Emerson Electric Co. St. Louis, MO	668-453
Flame detector	White-Rodgers or Honeywell	956 (CdS Cell) C554A
Fan and overtemperature limit switch	Honeywell, Inc Bloomington, MN	L4064A
Draft flap microswitch	Micro Switch, Div. of Honeywell Freeport, IL	311SM704-H2
Relay (microswitch bypass)	American Zettler Inc. Irvine, CA	AZ481-7-2 (115 vac, NC)
Socket (for relay)	Amphenol Connector Div. Bunker Ramo Corp. Broadview, IL	49SS8 (8-pin octal tube socket)

FURNACE INSTALLATION

Remove existing furnace

- Save all components for future reuse
- Store indoors

Insert test furnace

- Consider space requirements for
  - Immediate connections
  - Future instrumentation
- Connections
  - Oil supply
    - Pump compatibility
    - Filter
  - Warm-air outlet

  √ A warm-air plenum will extend above each furnace. There may or may not be an A-shaped refrigerant evaporator coil inside the plenum, as appropriate for the particular home. In every case, the inside of the plenum will be insulated internally, typically with a 3/4-inch thickness of high-density fiberglas composite, on five walls of a rectangular plenum. The warm air will flow out of the plenum into two or more distribution pipes which typically will not be insulated. Evantually, Rocketdyne will add thermocouple instrumentation for measuring the average outlet temperature. Usually, this will involve an array of thermocouples. The approach that will be taken is to study each furnace installation individually to determine how best to instrument the outlet. In some cases, especially those with evaporator coils, it may be possible to insert all thermcouples into the plenum. In other cases, it may be necessary to instrument individual distribution pipes; if so, additional insulation will be added to the outside of those pipes past the thermocouple insertion points.

- Return air inlet

  Temperature and flowrate measurements are integral with the 18 x 18 x 48-inch laminar flow element. A dummy section of uninsulated duct will be installed initially. Rocketdyne will build a filter into the flow element inlet. Probably 18 x 20 inches or 18 x 24 inches, the filter will be changed whenever the element is moved to another house.

- Flue

  - Install new barometric control valve

  - Barometric control location

    - Allow minimum clearance for measurement ports

      ✓ 18 inches of straight flue pipe upstream of sample point

      ✓ Either in vertical run or horizontal run

    - Insulate flue pipe up to sealed air plenum (1-inch Fiberglas with foil)

    - Consider accessibility of sealed air plenum

      - Cold air inlet from outside wall (nominal 7-inch diameter)

        ✓ Outdoor air supply will most likely be brought in through the nearest basement window by replacing a glass pane with a wood (or metal) plate. Outdoors, provision will be made to draw air vertically up into the intake pipe (i.e., a gooseneck) at a level such as to avoid ingesting rain or snow or covering the inlet with snow. A screen (1/4-inch mesh or coarser) should also be placed over the inlet to keep birds and rodents out. The intake pipe should be nominal 7-inch diameter. Inside the basement, it should be insulated (e.g., with 1-inch Fiberglas) up to the sealed air plenum. Alternatively, a self-insulated flexible plastic duct section was recommended by the subcontractors and would be suitable.

      - Flexible duct outlet to combustion air filter inlet (nominal 4-inch diameter)

- Provision for furnace draft adjustment

  ✓ Generally, no special provision will be needed if the test furnaces can operate OK with approximately 0.01-inch H_2O draft. If higher draft is really needed, a draft inducer may be required.

- Temperature control

  ✓ Replace thermostat if it is incompatible with test furnace control circuit.

INITIATION OF TESTS

Subcontractor checkout

- Fire and tune burner
    - Measure and adjust CO_2 level, smoke, and draft
        - ✓ Bacharach Fyrite instrument is OK.
    - Satisfactory appearance and stability of flame
- Warm-air circuit adjustments
    - Flowrate versus temperature rise
        - ✓ Air blower has adjustable belt drive
    - Balance distribution
- Cyclical operation
    - Limit switches
    - Thermostat control

Rocketdyne checkout

- Survey performance versus stoichiometric ratio
    - Steady-state and cyclical operation
        - Emissions
            - ✓ Emissions measurements via mobile van. Van hookup will require access to two different 110 vac household circuits. A flue gas sample will be drawn to the van through a length (up to 100 feet) of 1/4-inch OD Teflon tubing. An ice bath near the furnace will be used to condense moisture from the gas sample before it is taken outdoors. Thermostat control of the furnace will be overridden by a cycle-controller so that data are taken during consistent cycle timing conditions for all furnaces.

- Efficiency

  ✓ Rocketdyne will install a 110 vac receptacle from the furnace vestibule for powering the cycle-controller, data-loggers, etc. Provisions will be made to bolt the event-timer data logger securely to each furnace, via field fitting. Similarly, the larger Hewlett-Packard automatic data logger will be amenable to field attachment to the furnace cabinets.

- Fuel variation

  - Household fuel

    ✓ Take an initial sample of fuel being burned and measure furnace behavior with it.

  - Rocketdyne laboratory fuel

    ✓ Burn a small quantity (about 1 gallon) of reference fuel and measure initial emissions. Provides comparative data from all six furnaces.

PERIODIC CHECKS

Nominal monthly periods

- Joint visit

  ✓ Subcontractor serviceman will probably stay for entire duration of Rocketdyne visit.

- Subcontractor check (no readjustments)

  - Burner condition - CO_2, smoke, draft
  - General furnace operation
  - Filters

    ✓ Both the hammock-type warm-air filter and the small combustion air filter will be examined monthly, but they will be replaced only when needed.

- Rocketdyne check

  - Operation of data logging instrumentation

    ✓ Replace used tape recorder cassette with a fresh one.

  - Furnace performance, standardized cycle-averaged

    - Emissions

      ✓ May require overnight parking of and ~150 W power for instrumentation van at host sites for warmup.

    - Efficiency

- Determine whether any adjustment is required

  - If so, repeat measurements

- Change instrumentation as required

  - Hewlett-Packard data logger

- Fuel samples

  ✓ All sites to start season with a full tank.

  ✓ During the next periodic call after a fuel delivery has been made, a 1-pint sample will be taken of the fuel then being burned. (This procedure deviates from that stated in the Statement of Work.)

MOBILE LABORATORY

Vehicle

- 1-Ton Ford Econoline 250 (1976)
  - 130-inch wheel base
  - 4850-pound net, 2800-pound maximum payload
  - Sliding door on right side
  - Two shock-mounted racks of instrumentation
- Equipment needed for field testing
  - Alarm system
  - Locks on all tool cabinets
  - Winterization
    - √ Snow tires (buy them in the East)
      - √ Studded tires are now illegal in New York; investigate chemical radials (Goodyear, Michelin, or Continental)
    - √ Chains (may never use, but carry anyway)
    - √ Insulation (perhaps 1" thick rigid Styrofoam sheets)
    - √ Anti-freeze (60% ethylene glycol/40% water solution)
  - 110 vac space heater
  - 12 vdc to 110 v, 60 cycle a-c power inverter
    - √ Needed to supply power to two NDIR and one chemiluminescent analyzers to keep them warmed up during highway transit (approximately 250 watts)

Storage between monthly visits

√ Both subcontractors have secured storage areas which can be used. Indoors, preferably. Unheated garage OK. May want subcontractor to move van into heated garage the day before Rocketdyne engineer begins monthly checks.

EMERGENCY SERVICE

Subcontractor available 24 hours/day

- Principal concern:

  ✓ To ensure that each host home's heating system is functioning properly and safely.

    ✓ Keep the customers/hosts happy.

- Authorized to exercise judgment

  - Adjust, repair, or replace a malfunctioning test furnace, as required, to restore interrupted service in a timely manner.

    ✓ Subcontractors stated that lawsuits over disruption of service and/or damages are rare. Selection of host customers is a key element of avoiding problems.

    ✓ Replacement parts and/or labor costs beyond those included in the statement of work would be bases for subcontract changes. Contact Rocketdyne buyer: Ms. Angie Cicchese (213) 884-3200. Mail all invoices to her with copies to R. Bartley and P. Combs.

  - Promptly inform Rocketdyne engineer by telephone of action taken

    ✓ Subcontractors will be given a list of Rocketdyne business and home phone numbers.

MISCELLANEOUS TOPICS

Subcontractor recordkeeping and data submittal

- Review statement of work

Handling delays

✓ Simply reschedule visits affected, not a big problem.

Week-end work

✓ Should not normally be planned. May be worked in if necessitated by unusual circumstances.

✓ Subcontractors will probably try to have same serviceman do all periodic testing.

Mid-test period progress review

✓ Rocketdyne will probably schedule a 1-day meeting at one of the test locales sometime in early 1978.

STATEMENT OF WORK FOR
OIL FURNACE SERVICE CONTRACTOR

Seller shall provide support services, in accordance with Rocketdyne specifications provided herein, for field testing three (3) prototype integrated warm-air oil furnaces in residences in his local business area. Five different categories of services will be provided by Seller, namely: (1) selection of host residences, (2) installation of test furnaces, (3) periodic service calls, (4) removal of test furnaces upon completion of testing, and (5) record-keeping. Details of these categories are given in subsections of this flysheet.

The test furnaces are described in accompanying Flysheet B.* All three furnaces will be identical. Background information concerning their development is given in the enclosed copy of ASME paper 76-WA/Fu-10.*

Buyer will perform related and concurrent measurements, flue gas sampling and analysis on each test furnace. The extent of interaction and cooperation which will be required between the Seller and Buyer personnel is specified in this flysheet.

SELECTION OF HOST DWELLINGS

Based upon the Seller's records and knowledge of his clients who have oil furnaces, he shall identify at least five candidate homeowners whose homes, heating systems, family habits and interests would, in his opinion, support their selection as hosts for a test furnace. Among the candidate host houses, it is desirable to maximize variety, for example, in type of construction (frame versus brick), style of residence (single-level versus two-story), type of residence (single-family versus duplex or townhouse), exposure (hilltop versus valley, or open versus wooded terrain) and orientation (north versus southfacing). The installation and test procedures will probably require somewhat more than normal free space around each test furnace, so it is anticipated that basement installations will be preferred; almost certainly, closet installations should be avoided. The families' lifestyles must be amenable to providing access to the furnace during periodic (nominally monthly) service and monitoring calls, and to a certain amount of disruption and inconvenience that this entails.

The Seller shall establish willingness of the identified candidate homeowners to participate as hosts in the field test investigation, but without making definite commitments. At this point, the cognizant Rocketdyne engineer will

---

*Information not reproduced in this Appendix.

visit the contractor's office to review the list of candidates; together, he and the Seller will select three preferred hosts and rank the others in a list of alternates. Thereafter, the Seller will establish formal agreements with three host homeowners. It is anticipated that each agreement will provide for:

1. Assurance of periodic access to the dwelling's heating system by Seller and Buyer personnel. (Seller's personnel should always accompany Buyer's personnel visiting the host residences. Maximum coordination should be exercised so as to minimize the total number of visits.)

2. Each homeowner to hold Buyer (Rockwell International) harmless for injury to or death of any person(s) and for loss of or damage to any and all property arising out of the acts or omissions of the homeowner.

3. Appropriate homeowner remuneration to make attractive their acceptance of inconveniences during preparation and restoration of the heating system and during the heating season and for the requested waiver of liability.

INSTALLATION OF TEST FURNACES

The Seller shall be responsible for installing the test furnaces in conformance to applicable building codes and safety standards. Buyer will provide assistance in this regard as needed and to the extent possible, e.g., in requesting assignment of a state approval number, in explaining system modifications to a county or township fire marshall, etc.

Prior to delivery of test furnaces by Buyer and based on drawings and other pertinent information supplied by Buyer, the Seller shall ensure that all materials and equipment needed for prompt installation and activation are readied for each host residence. These preparations will include ensuring that the fuel oil tank is filled and providing Buyer with a 1-pint sample of the tank's contents. It is anticipated that the host agreement will provide for oil deliveries by the host's existing fuel oil supplier. In the event that the oil tank is refilled during the test period, Seller will take an additional 1-pint sample during the next regular service call after each refueling. Each sample will be adequately labeled to identify the date sampled and the source residence; Seller may simply hold the sample(s) until the next regular visit of the Rocketdyne engineer.

Upon receipt of test furnaces from Buyer, Seller will install a unit in each of the host residences. It is anticipated that the existing furnaces will be removed from the host heating systems and replaced with the test units. Seller will be responsible for storing the existing units during the field test period so that they may be reinstalled later. Installation of test furnaces will include, but not necessarily be limited to, fabrication of adapter sections of duct, provision of an outdoor air supply for the sealed air system (4-inch-diameter galvanized duct insulated with a minimum of 1-inch-thick foil-covered Fiberglas) and connection of all required plumbing and electrical circuits according to applicable local codes. Provisions will also be made for future insertion of a metering section in the return air duct leading into the furnace and for a number of 1/2-inch-diameter holes in the flue pipe for instrument insertion and sample extraction. The metering section (supplied by Buyer) will be a straight 48-inch-long section of 18-inch-square duct made of galvanized sheet metal. Buyer will provide appropriate drawings well ahead of the actual installation.

Checkout and startup of the unit will conform to normal heating industry practices, including measurement of flue gas temperature, CO_2 content and smoke, adjustment of burner excess air level, firebox draft, and distribution of warm-air to the residence. At the same time or soon thereafter, Seller will accompany the Rocketdyne engineer and assist with installation of two permanent recording instruments (a fuel meter and a recording clock) and will stand by while Buyer obtains more complete emissions measurements. It is anticipated that this procedure will require one full day for each residence after the completion of the mechanical installation, per se, and that all three units will be in normal service prior to 1 October 1977.

PERIODIC SERVICE CALLS

Throughout the 1977-1978 heating season, from initial installation to, say, mid-June 1978, it is intended to let the test furnaces operate normally and without adjustment, if possible. During that time, Seller will be available for 24-hour emergency service requirements and will inspect the furnace at least once a month. A Rocketdyne engineer will make emissions and performance measurements on a monthly schedule, and it is expected that Seller will accompany him, at least for the first part of his visit, to each residence, and perform the monthly inspection before emissions are measured. Furnace operation should not be adjusted unless an unsafe or excessively smoky condition exists. If an adjustment is found to be necessary, both the Seller and Buyer should make and record their measurements both before and after furnace operation is adjusted. These monthly inspection calls will probably take an average of 1 to 1-1/2 man-days per month for all three furnaces; they will normally be scheduled a month in advance by coordination among the Seller, the homeowners, and the Rocketdyne engineer.

An auxiliary package of instrumentation will be used to measure data so that thermal efficiency can be correlated to furnace cycle timing and burner firing duration. The package will be installed on one furnace and left long enough to gather sufficient data (nominally, one month), then moved to another furnace. Buyer personnel will be wholly responsible for all functions concerned with the instrument package and the resultant data, but will need assistance from Seller in installing and removing it. Installation will be timed to coincide with the regular monthly inspections as will removal a month later. It is anticipated that the service call might be lengthened by approximately one-half day to remove the package from a furnace and by approximately three-fourths of a day to install it on another furnace. Installation, removal, or both, of this package will be involved in four of the eight monthly inspection periods.

REMOVAL OF TEST FURNACES

Upon completion of the field testing, Seller shall remove the test furnaces from all three host residences. The test units will be recrated, banded and shipped to Rocketdyne in Canoga Park, California, using original shipping crates. Rocketdyne will bear shipping costs, FOB point of origin.

RECORDKEEPING/REPORTS

Seller shall obtain and supply to Buyer data covering each host residence's history of oil consumption and service requirements for the preceding two years (unless, of course, the home is not that old).

Seller also will maintain records of test furnace operating conditions observed during each inspection call, any service or adjustment required, oil consumption, degree day history for the test area throughout the test period, any unusual climatic conditions which might impact interpretation of test data obtained, and any variations in the number of people living in each host site. These data will be delivered to Buyer within 30 days after completion of the test period.

APPENDIX G

INFORMATION FOR HOMEOWNERS

You and your home have been selected to take part in a unique and meaningful field test study of a residential oil furnace that emits fewer air pollutants and operates more efficiently than conventional oil furnaces. Within a few weeks, your present furnace will be replaced temporarily with the new test furnace. Your home will be heated by this new unit during the 1977-1978 winter heating season. Identical test furnaces will be installed in five other homes in the vicinities of Boston, Massachusetts and Albany, New York.

BACKGROUND

In its continuing pursuit of ways to improve air quality in the United States, the Environmental Protection Agency has sponsored a number of research and development programs designed to promote the development of equipment producing lower levels of noxious emissions. Home heating equipment contributes substantially to lower air quality, especially in urban areas that experience relatively severe winters. Accordingly, EPA has supported R&D work on residential furnaces. Rocketdyne has contributed to this effort by performing studies of residential oil burners and oil furnaces under contract to the EPA.

The installation of a test furnace in your home is part of the last phase of those Rocketdyne studies. Until now, the investigations have been confined to laboratory investigation of oil burner and burnace design changes that could lower pollutant emissions and, simultaneously, reduce fuel consumption. Several design criteria were established as being generally applicable to both residential warm-air furnaces and hydronic boilers. These criteria were used to modify an existing commercially available, warm air oil furnace for proof-of-concept evaluation in the Rocketdyne laboratory. Laboratory results indicated that, by comparison with the estimated average performance of comparable existing furnaces installed in homes, the emission of oxides of nitrogen (NO_x) into the atmosphere could be reduced by 65% or more, and cyclical or seasonal efficiency could be increased by 10 percentage points or more without increasing the already low emissions of products of incomplete burning (namely, carbon monoxide, unburned hydrocarbons, and smoke).

PURPOSE OF THE FIELD TESTS

Field testing is a logical continuation from those encouraging laboratory results. Our objectives are to demonstrate that the underlying low emission design criteria can be applied practicably to residential space heating equipment and that they are compatible with increased fuel efficiency.

A further objective is to test for a long-enough time period to document the stability of furnace operation, emissions and efficiency, and to observe relative maintenance requirements. The basic purpose, of course, is to provide strong encouragement for furnace manufacturers to adapt the low pollution design criteria to their own products.

UNIQUE FEATURES OF THE INTEGRATED FURNACE

The new furnace being installed in your home, like the laboratory prototype after which it is patterned, was built by making several modifications to a commercially purchased, brand-name furnace. Many components, including the outside cabinet, have been altered only slightly, if at all. Components which have been modified or replaced are concerned primarily with the fuel combustion functions of the furnace and these are predominantly inside the cabinet. The major changes are illustrated in the accompanying color cut away sketch of an integrated furnace. Outwardly, therefore, the new unit may not look much different than your present furnace.

The optimum oil burner is a specially developed unit designed to operate with very little excess combustion air and to produce less NO_x than conventional burners. The combustor is made of cast iron and does not have an insulating refractory lining. It is partially cooled by the warm air circulating over cooling fins on its outside surface and this leads to further reduction of NO_x emissions. The size and degree of cooling of the combustor are matched to the burner to form an optimum combination.

Air required by the furnace is brought in from outdoors through the furnace's sealed air system. It enters a distributor box built around the draft control damper on the flue pipe. Part of the air is drawn through the damper and mixed with the flue gases, while the rest is ducted into the burner compartment. There it is filtered before being drawn into the burner and used for combustion air. This use of outdoor air to fulfill the furnace's needs will lower your home's demand for heat and humidification, and filtering it will allow the burner to be tuned more precisely to optimum firing conditions.

The combustion air inlet to the burner is fitted with a draft control assembly that closes a damper when the burner is not firing. This helps reduce heat losses up the flue during standby periods.

MONITORING FURNACE PERFORMANCE

An ideal situation would be for the test furnace, once it is installed and running in your home, to operate for the entire heating season without requiring either adjustment or serviceman maintenance. Its performance will be monitored to see how closely this ideal is approached. Normal maintenance functions, such as changing dirty filters, will be performed by service personnel who have been instructed not to retune the burner or adjust furnace operation unless an unacceptable condition is encountered.

Furnace performance will be monitored by a service representative, from the local company which will install the test unit, and a Rocketdyne engineer who will visit your home once a month to observe its operation and take measurements. Occasionally, they may be accompanied by other engineers or managers associated with the field test study. Some instruments will be installed permanently on the furnace, and others will be brought in for more or less temporary use. The permanent instruments will record data primarily concerned with fuel utilization efficiency. An assembly of several instruments for analyzing the furnace combustion products will be brought to your home each month. That assembly is installed in a van which will be parked outside your home. A long, small-diameter plastic tube will be connected between the furnace's flue and the van to draw a continuous sample of flud gases to the instrumented van. This approach avoids, as much as possible, disruptions of your normal household activities.

WHAT YOU CAN DO TO HELP

You have already make a big contribution to the field verification study by agreeing to participate in it. The EPA, Rocketdyne and the entire field test team are most appreciative of your willing cooperation. We are concerned, first and foremost, with your comfort and safety throughout the test period and we want you to be satisfied with having our test furnace in your home. It it performs as well as it has in our laboratory, you should be able to appreciate its presence without having to give it any attention at all. In that case, your most important contribution will be to continue using your heating system in the same way you did last winter. The test furnace's oil consumption will be compared with your usage in previous years and, although temperature records can be used to account for differences in winter severity, we have no way of correcting for biases in the data caused by altered heating habits. Oil price increases and shortages and emphasis on conservation have contributed to changing habits over the last few years, so the most valid comparison probably will be between the 1976-77 and the 1977-78 heating seasons. Therefore, we ask that you maintain the same thermostat control practices (including morning warmup, daytime and evening settings and night setback) that you used last year.

If you find that the way your home is heated has changed sufficiently from last year that some adjustment seems to be needed, please discuss it with your service representative.

With the exception of setting the thermostat control, all adjustable controls on the furnace and the heating system should be left as they are set by your service representative. If something about the heating system, including the instrumentation, appears to be in need of service, you should call him, rather than trying to correct or adjust it yourself. If you're interested in knowing what things are for and how they work, we will be pleased to dscuss and demonstrate them while we're in your home. Hopefully, having freed you from responsibility for routine maintenance will add to your enjoyment of participating in the study.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-79-037a	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Design Optimization and Field Verification of an Integrated Residential Furnace--Phase 1		5. REPORT DATE February 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) A.S. Okuda and L.P. Combs		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rockwell International Rocketdyne Division 6633 Canoga Avenue Canoga Park, California 91304		10. PROGRAM ELEMENT NO. EHE624A 11. CONTRACT/GRANT NO. 68-02-2174
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Phase; 8/76-12/78 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is G. Blair Martin, MD-65, 919/541-2235.

16. ABSTRACT The report describes Phase 1 of a two-phase investigation to: (1) further optimize the design of a prototype low-emission residential furnace that was derived from earlier EPA-funded studies; and (2) obtain field verification of its emission and performance characteristics. It gives details of: (1) analytical and experimental studies to optimize the furnace design and its nominal operating ranges, and to ensure conformance with appropriate safety standards; (2) planning all aspects of the Phase 2 field test investigation, including selection of test locales and host homes, provision of local installation and service support, and all logistic and scheduling considerations; and (3) studies of the integrated furnace's capabilities to function properly with such alternate fuels as natural gas and methanol. The prototype furnace, with a cast iron firebox, met all emission goals (i.e., $NOx < 0.65$ g/kg, $CO < 1.0$ g/kg, $UHC < 0.1$ g/kg, and a Bacharach smoke number < 1) at low excess air (20%). Based on climatic characteristics and available support services, Albany and Boston were selected for field verification of furnace performance.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Furnaces	Stationary Sources	13A
Residential Buildings	Residential Furnaces	13M
Design		14B
Tests		

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 161
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)