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DEVELOPMENT OF A TEST SET FOR ADJUSTMENT OF RESIDENTIAL FURNACES AND BOILERS

FINAL REPORT

MASTER

January 1980

Prepared by
HONEYWELL INC.
TECHNOLOGY STRATEGY CENTER
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for
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE

U. S. DEPARTMENT OF ENERGY

Division of Buildings and Community Systems

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Honeywell Inc.
Technology Strategy Center
2600 Ridgway Parkway
Minneapolis, Minnesota 55413

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ABSTRACT

A program was undertaken to design and develop a portable test set for simplified field adjustment of residential furnaces and boilers to achieve peak operating efficiency. Advanced technology was applied to provide continuous analysis of flue gases and the display of temperature, oxygen concentrations, smoke value and furnace efficiency. Prototype models were constructed and delivered to Brookhaven National Laboratory for further testing. A survey of furnace dealers was conducted, and a commercialization plan was developed based on survey responses and the status of the equipment developed under the program. Goals for a marketable test set and development steps to achieve a projected energy savings were determined and recommended. Recommendations for specific areas of further development are included.

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SECTION 1.0
INTRODUCTION AND SUMMARY

Residential fossil-fueled heating equipment expends approximately 11 percent of the gas and oil consumed in the United States.¹ A number of research and development programs are being conducted to find ways of reducing this consumption. These programs have the common goal of finding a more efficient way to heat homes with minimum retrofit cost. Until next-generation furnaces and burners are available, existing heating plants must operate at maximum efficiency. Early and limited tests indicate that significant savings in fuel could be possible if there was a cost-effective way to tune furnaces. This would require a portable efficiency meter that could be used in a residence by an unskilled operator spending 15 to 20 minutes at each location. At the outset of this development program, there existed a number of key questions:

- How much energy can be saved by tuning residential furnaces?
- Can a cost-effective, portable instrument be developed using current technology.
- Does a market exist for such a device with or without government regulation?
- What time estimate and government action is required to assure the commercialization of an efficiency meter for residential use?

To develop a body of information on these issues, Honeywell entered into a development contract with Brookhaven National Laboratory to explore the state of the art, develop a technical solution and examine the market.

¹"Exploring Energy Choices," Energy Policy Project of Ford Foundation, Washington, D.C., 1974.

The technologies for measuring furnace efficiency are not mature and require basic sensor development. Data on fuel savings potential is not available, and thus a market for such a device is not definable outside of government-imposed regulations. When the program was initiated, new sensor technology was promising, namely the zirconium oxide oxygen sensor. The need for an available smoke sensor was recognized early, and an effort was programmed into the project for basic research of this capability. Digital computation technology was looked upon as the solution for the portability, quick warm-up, and reliable readout and recording requirements for the instrument.

Objectives defined for the Furnace Efficiency Test Set development program were to:

- Explore the application of state-of-the-art technologies and sensors to furnace efficiency instrumentation;
- Develop six prototype devices, which might be pathfinders on the road to very low-cost, mass-produced devices;
- Perform a market analysis;
- Conceptualize a commercialization plan;
- Recommend future development.

1.1 TECHNICAL DISCUSSION

The basis for measuring efficiency of a furnace or boiler is an understanding of the combustion process. To establish a common framework for understanding the complexity of efficiency meter programs, a brief technical discussion follows.

Stoichiometric combustion is the oxidation of all the fuel's hydrogen and carbon to water and carbon dioxide, respectively, with no free oxygen left over. Practical burners cannot achieve this condition because of imperfect mixing of the fuel and oxygen atoms. Some excess oxygen is needed to ensure that all of the fuel is oxidized.

Premixed gas flames require only a small amount (1 to 2 percent) of excess oxygen. Oil, however, burns with a diffusion flame. The hydrocarbons evaporate from the surface of the oil droplets and form a boundary layer around the droplet. Oxygen atoms diffuse into this boundary layer and combine with the hydrogen and carbon atoms. The reaction is oxygen rich at the outer surface of the boundary layer and fuel rich at the surface of the liquid droplet. Many partially oxidized products are formed between these two limits. Some excess oxygen is needed to assure the complete oxidation of these intermediate products. Heat from the reactions in the boundary layer surrounding a fuel droplet is radiated into the remaining liquid fuel. This causes thermal cracking of the fuel, releasing free carbon atoms. These, in turn, agglomerate into particles of soot. The extent of soot formation depends on the size of the droplets and the amount of excess oxygen present. Thus, oil combustion presents a much more complex process than gas combustion. Too little air produces carbon monoxide and soot. Too much air lowers the combustion efficiency. The right amount of combustion air is best controlled by reducing the excess oxygen in the flue gas until soot (smoke) just begins to appear.

Gas-fired residential furnaces do not offer much opportunity for improved combustion efficiency through control of excess air. There is no provision for controlling secondary combustion air. Oil burners, on the other hand, do have means for adjusting combustion air. Further, oil strainers and burner nozzles tend to become fouled with usage. This reduces atomization effectiveness leading to larger fuel droplets and more soot. Periodic service and adjustment of oil burners is required for acceptable performance.

Fuel and air are metered and controlled in larger industrial and central station furnaces. This is true for both oil and gas. Continuous monitoring of flue oxygen and flue temperature is common. Thus, the main application for a furnace efficiency meter is for tuning residential and small commercial size oil burners. Proper maintenance of these burners can maximize efficiency while minimizing problems of pollution and excess soot accumulation on heat exchanger surfaces.

The selected approach for this program was to measure both excess flue oxygen (with a zirconium oxide sensor) and flue temperature rise. A microprocessor was then used to compute combustion efficiency from these two measurements, assuming the fuel was No. 2 oil. Smoke was measured with a light-scattering technique, which was calibrated to the Bacharach scale.

The equipment developed in the program (shown in Figure 1-1) was made portable for convenience and served as both a prototype for functional testing and as a tool to determine the most desirable feature sets. Its features included the requirements for both gas and oil furnaces, even though a final device for gas furnaces, as a stand-alone unit, would require a slightly different efficiency scale, would probably not include smoke sensing capability, and might require CO measurement.

As the basis for the program marketing study, a survey of furnace dealers and service organizations was conducted by questionnaire, telephone interviews and analysis of energy consumption data. The 237 responses received represented about 600,000 units serviced per year by about 1700 service personnel.

Finally, a model product development plan was formulated in conformance with Honeywell's standard practices and guides, and the status of development and potential for a furnace efficiency test set was evaluated against these standards.

In the balance of this report the equipment developed, while applicable to both furnaces and boilers, is referred to interchangeably as the Furnace Efficiency Test Set or the Furnace Combustion Efficiency Meter.

Figure 1-1. Prototype Furnace Efficiency Test Set

1.2 CONCLUSIONS

Measuring furnace efficiency with a low-cost device, which requires minimum time for furnace adjustment and is capable of being used by personnel with minimum skill, is technically feasible. The unit developed under this contract serves as a general prototype of such a device. However many reliability problems, which ranged from contamination to connection failures, have been encountered. We believe, at the time of this writing, that additional development of zirconium oxide sensors will have to be undertaken to provide furnace efficiency meter suppliers with a sensor that is both low in cost and reliable. We also believe that more work is needed to reduce the complexity of the smoke sensor.

We have also discovered that to tune a furnace to its maximum efficiency, (when not trying to certify specific efficiencies), a nulling display rather than an absolute numerical readout would be less costly and may be less confusing to the operator. High absolute efficiency measurement is probably not required if the instrument's primary purpose is for tuning.

Smoke measurement is of little importance for gas-fired furnaces. Residential gas furnaces do not have the means for controlling the substantial amount of excess secondary air used. When the primary air is adjusted by visual observation to eliminate any yellow flame, there is no danger of smoke. Gas-fired system adjustment does, however, require measurement of carbon monoxide levels.

Oil burners, on the other hand, require smoke measurement, because they can produce smoke even with considerable excess air. We found, however, that accurate, instantaneous measurement of smoke samples is very difficult. Obtaining a representative smoke sample and transporting it through a sample line to the measuring instrument without changing the character of the smoke is a very formidable problem. It is not at all certain that a successful instrument for continuous readout of smoke in the field can be built for a cost that would be

acceptable in the market. Carbon monoxide measurement is not needed for oil-fired systems.

The incentive for the home owner to have his furnace efficiency evaluated also differs for gas and oil users. Gas furnaces offer little flexibility for adjustment. Moreover, a gas burner will hold its efficiency indefinitely if the burner air inlets are kept free of lint and dust and the heat exchanger is kept clean. Flue temperature alone is one indicator of heat exchanger condition. Thus, in the absence of statutory requirements, there is no incentive for a home owner with gas heat to have his furnace efficiency measured with a precision instrument.

Oil burners, on the other hand, do require periodic maintenance--usually once a year. Burner nozzles are subject to fouling, oil pump pressure changes, and air passages may become restricted. The furnace efficiency meter will greatly assist servicemen in adjusting oil burners. A skilled serviceman can adjust an oil burner without measuring furnace efficiency. However, a quantitative efficiency measurement helps the home owner decide when he should buy an improved burner. Governmental regulation designed to upgrade heating equipment in the field would require such measurements on a routine basis.

Finally, we conclude that if given the required stimulus to the market, the device conceptualized in this program will in its final form be adequate to do the job quickly and efficiently at acceptable cost. Commercial organizations such as Honeywell will fill the equipment void with no further investment required by the Government.

1.3 RECOMMENDATIONS

The conclusions drawn from the Furnace Efficiency Test Set development program suggest that a successful voluntary furnace tune-up program that would yield significant savings of energy would require:

- Payback for investment on the part of the consumer;
- Verifiable, national information to indicate that a national furnace tune-up program would yield significant savings of energy.

We have further concluded that this program has demonstrated that adjustment of furnace efficiency by typically skilled servicement can be accomplished by the basic technologies and equipment developed.

Therefore, we would recommend that before equipment manufacturers are asked to invest in the mass production of furnace efficiency meters, a program be instituted to determine what the real savings in energy might be on a national scale. Given that energy savings are significant in relation to national consumption, action should be taken to stimulate the savings by such means as tax incentives, State "Red Tagging" laws or financial control through Government funding or loans, which might require periodic inspection of residential furnaces.

Given that the above recommendations are adopted, this program has proven the feasibility of actually making the measurement, and from that point on, as stated above, industry can be expected to fill the equipment void created with no further support from the Government.

The program schedule and tasks that were accomplished are described in Section 2.0.

In Sections 3.0, 4.0, and 5.0, the technical details of the furnace efficiency meter are explained, and the problems encountered in developing and testing the device are discussed in Section 6.0. Potential design improvements that might be considered in development of a next-generation efficiency meter are discussed in Section 7.0. The findings of our marketing analysis and a commercialization plan, as well as an evaluation of the status of this program against that plan, are discussed in Sections 8.0 and 9.0.

SECTION 2.0

PROGRAM SCOPE

2.1 PROGRAM TASKS

The program for development of the Furnace Efficiency Test Set consisted of the following seven major tasks and their subtasks:

- Task 1: Program Plan
- Task 2: Data Collection
 - 2.1: Smoke Detection
 - 2.2: Temperature Sensors
 - 2.3: Oxygen Sensor
 - 2.4: Carbon Monoxide Sensor
 - 2.5: Report and Sensor Recommendation
- Task 3: Preliminary Design
 - 3.1: System Design
 - 3.2: Accuracy (sensors, device)
 - 3.3: Reliability
 - 3.4: Life
 - 3.5: Physical Characteristics
 - 3.6: Feasibility Model
- Task 4: Component Test
- Task 5: Final Design
- Task 6: Prototype Manufacture and Test
- Task 7: Commercialization Plan

Reports and deliverables for the program included:

- Program Plan
- Monthly Letter Reports (including Forms 533/4/5)
- Final Report draft
- Six prototype test devices

2.2 TASK SCHEDULING AND LEVELS OF EFFORT

Figure 2-1 shows the time periods during which the program tasks were carried out and the levels of effort associated with those tasks. Major efforts were expended as follows: Preliminary Design (49 percent), Final Design (26 percent), and Fabrication/Test (14 percent). Minor efforts included: Component Test (4 percent), Data Collection (3 percent), and Reporting (3 percent).

PERCENTAGES ARE LEVELS OF EFFORT (MAN-HOURS)
PLUS 3 PERCENT FOR REPORTING

Figure 2-1. Task Scheduling and Levels of Effort, Furnace Efficiency Test Set

2.3 TASK ACTIVITY HIGHLIGHTS

This section of the report reviews program task activities and the course of events during development of prototype models of the Furnace Efficiency Test Set.

2.3.1 Task 1: Program Plan

A program plan document was developed and submitted; it was updated throughout the program as technical goals were accomplished.

2.3.2 Task 2: Data Collection

This task involved the assembly of information regarding methods and equipment for flue gas analysis applicable to the design of the Furnace Efficiency Test Set. Principal areas of investigation were: smoke density monitors; high temperature transducers and flame temperature measuring devices; high temperature metal oxide oxygen detectors. A survey was made of oil and gas service organizations seeking opinion on desired features for a furnace efficiency instrument (see Section 8.0).

Smoke detection methods receiving the most emphasis were light scattering, corona discharge, and ionization. The selected method was to provide a readout correspondence with the Bacharach Smoke Number Scale. Honeywell's smoke testing facility was used to evaluate ionization, light-scattering, and corona-discharge smoke detectors. Smoke from several combustion sources, including a residential oil burner, was characterized according to particle size and concentration. Detection techniques were evaluated as to their response correlations with the Bacharach Smoke Number scale, as well as to the effect of the sampling process on Bacharach readout. The Bacharach technique itself was evaluated regarding scale reading correspondence with smoke particle concentration distributions using No. 2 fuel oil smokes. In this connection it was noted that the Bacharach method is sensitive to the characteristics of the filter paper used.

The light-scattering method of smoke detection was ultimately selected for the Furnace Efficiency Test Set because of its sensitivity and capability for developing good signal-to-noise ratio.

Temperature sensing methods receiving most attention were: thermocouples, thermistors, and resistance temperature devices (RTDs). Selection of thermocouple temperature sensors for the Furnace Efficiency Test Set was based on review of the literature and manufacturers' information. Reasons for this selection were high temperature capability, accuracy and repeatability, response time, interchangeability, and cost.

Oxygen concentration measurement by means of a solid electrolyte oxygen sensor was virtually an a priori selection. The comparatively recent commercial appearance of this technique fills a long-standing need in oxygen measurement, where rugged instrumentation is required. At Honeywell, earlier consideration of the low-cost, industrial combustion efficiency monitoring market had led to the conclusion that the zirconium oxide oxygen cell was the best-suited technique. Sensors from UOP, Inc., and Zircoa were evaluated. The UOP sensor was selected because it operates at a lower temperature.

Carbon monoxide might become a toxicological hazard if withdrawn from flue gas too abundantly during sampling. Moreover, carbon monoxide concentration is commonly measured in analyzing combustion processes. Literature study and market survey findings led to the conclusion that carbon monoxide need not be sensed with oil firing, but should be with gas firing. With oil firing, carbon monoxide emissions are not significant if CO_2 (O_2) and smoke values are at optimum setting. Inquiries to the gas industry indicated that carbon monoxide measurement is desirable for residential gas burner monitoring. Several techniques for carbon monoxide measurement were investigated and described during this task; those considered to merit further investigation include tin oxide semiconductor, tuned infrared source (light-emitting diode), and colorimetric (chloroplatinic salts).

2.3.3 Task 3: Preliminary Design

The work involved in the formulation of a preliminary design for the Furnace Efficiency Test Set was a precedent for final design activities carried out in Task 5. Work included the development of device requirements, and design, fabrication, and performance testing of the feasibility model. Design of this feasibility model was based on a microprocessor in which sensor-derived data were inputs to the system, which then were operated on according to prescribed software regimen; finally, digital display of selected parameters was effected. The feasibility model hardware was housed in a portable carrying case, along with an associated wiring/tub-connected sampling device, or probe. The feasibility model was intended for experimental use in the laboratory and in the field; it was designed solely for function and not necessarily to withstand environmental extremes or meet ultimate size and weight constraints.

The feasibility model made use of a Motorola MC 6800 Microprocessing Unit (MCU) chip and peripheral chips for memory, clocking, and input/output. A seven-segment display group interfaced to the microprocessor gave readouts of efficiency, Bacharach number, flue gas oxygen concentration, and flue gas temperature. Sensor signals were multiplexed through an analog-to-digital converter before storage in the microprocessor. Temperature control of the zirconium oxide oxygen sensor was effected by closed-loop control from the microprocessor. Provision was made for interfacing the sampling probe to the carrying case; jacks were provided for a cassette recorder in order to enter and store software modifications developed off-line.

The computation program for the feasibility model operated in non-real time with periodic interrupt for the output and refreshing of the display digits. Software provided for:

- Programming and processing of data from the sensors, including the conversion of sensor measurement values to engineering units;

- Automatic calibration of the sensors; control of the oxygen sensor's heater;
- Computation of furnace efficiency using as parameters
 - Oxygen concentration,
 - Flue gas temperature,
 - Ambient temperature, and
 - Latent water constant for the fuel being used (i.e., natural gas, propane, No. 2 fuel oil);
- Generation of the display of four parameter values (furnace efficiency, smoke number, oxygen concentration, flue gas temperature) with seven-segment LED display digits;
- Monitoring of fault conditions including fault indication.

The feasibility model incorporated a probe to provide for withdrawal of sample gas from the furnace flue upon aspiration by a pump located in the carrying case. The probe, connected by 9-foot-long wiring and teflon tubing to the carrying case, contained the zirconium oxide oxygen sensor with its heater, the smoke sensor, and thermocouples for sensing flue gas and heater temperatures.

The feasibility model was used for obtaining engineering data at different locations and under varying furnace firing conditions. During its evaluation, development of the model design continued along the following lines:

- Initially, excessive heat emanating from the zirconium oxide oxygen sensor caused the internal temperature of the probe to exceed the

operating temperature of the electronic smoke sensor components and the permissible probe surface temperature. Several design changes were made to separate and insulate components thermally.

- Reduction of memory capacity with associated reduction of functions and hardware. The effect of this change was to reduce power requirements and thereby eliminate the need for fan cooling, as well as to eliminate electronic boards containing memory chips and associated logic.
- Correction of oxygen sensor problems, i.e., unreliable connections to the platinum electrodes; electrical isolation of platinum electrodes from ground.
- Correction of smoke sensor problems: elimination of condensation affecting sensor optics and response by resorting to higher temperature operation under closed-loop control; elimination of sample leakage from the sensing chamber; improved optical shielding to eliminate spurious response from stray ambient light.

2.3.4 Task 4: Component Test

This task involved the testing of components of the Furnace Efficiency Test Set, for the most part, the testing of the light-scattering smoke detector and zirconium oxide oxygen sensor.

Smoke detector testing was concerned with the effects of sampling tube length on detector response and the effects of sensor chamber heating. These tests led to the decision to place the smoke detector in the probe (rather than compromise quality of the sample by drawing it through a long sampling tube wherein condensation could take place) and to heat the chamber of the smoke detector. Photodiodes of different manufacture were evaluated for use in the smoke detector.

Zirconium oxide oxygen sensors of different manufacture were evaluated. The U.O.P. sensors were selected because of their lower temperature operation. These sensors were tested to determine their response to various oxygen fractions (Nernstian response), the temperature at which they should be operated, and their response time.

2.3.5 Task 5: Final Design

This task involved the final design for prototype models, a design adequate for model field testing though not necessarily representative of a production configuration. The design of these models was similar to that of the feasibility model as it evolved during its development. A principal change in the design was that the amount of electronic circuitry was minimized by limiting the software to 2K bytes of PROM and 0.5K bytes of RAM (formerly 18.5K bytes). The microprocessor and associated logic circuitry were contained on one micro-module board (Motorola 01A, replacing the Motorola D2 kit); a second board contained the analog electronics and power supply regulators.

The probe design for the feasibility model and prototype model was the same except for the outer case, which was designed to alleviate earlier high temperature problems.

The designs of the oxygen and smoke sensors, as developed under Task 3, were used for the prototype model. Later the design of the oxygen sensor was changed when ON-OFF control of the heater was replaced by "proportional" control to eliminate temperature overshoot and consequent spurious sensor output. (The zirconium oxide sensor responds to both oxygen concentration and temperature and must be closely temperature controlled.)

2.3.6 Task 6: Prototype Build/Test

Six prototype units of the Furnace Efficiency Test Set were manufactured and delivered to Brookhaven National Laboratory.

2.3.7 Task 7: Commercialization Plan

This task, development of a commercialization plan for the Furnace Efficiency Test Set, was carried out by Honeywell's Residential Marketing Department. Three market scenarios for the device were advanced assuming: 1) no change in present laws and regulations; 2) the effect of National Energy Act (NEA) provisions for informing the public as to furnace efficiency modification possibilities; 3) mandatory furnace efficiency testing by states with high heating fuel usage. As part of this task, a questionnaire was sent to heating dealers and servicemen requesting opinion on desired attributes and price of equipment for adjusting furnaces and boilers. The commercialization plan, questionnaire, and survey results summary are included in Section 9.0.

2.4 FACILITIES USE

Program activities were carried out within two of Honeywell's operating groups, Corporate Technology Center and the Energy Resources Center. The Corporate Technology Center has been advancing combustion and particle technologies for many years. Past work at this center has led to the development of an ionization type smoke detector, now extensively marketed for early detection of fires in residential and commercial applications, and an algorithm for computation of furnace efficiency based on flue gas oxygen and temperature measurements. This algorithm was used in development of the Furnace Efficiency Test Set. Extensive work done at the Center in the analysis and detection of smoke formed the basis for the light-scattering smoke sensor design used in the Furnace Efficiency Test Set. The particulate generating and measuring equipment at the Center was used in developing and evaluating the smoke sensor for the device.

The combustion test setup at the Energy Resources Center, which was used in testing the Furnace Efficiency Test Set, is shown in Figure 2-2. This setup consists of a modified trailer home oil furnace with a Wayne burner. Flue gases can be monitored in the furnace flue or in a cold box. In the latter case, smoke from the flue is withdrawn to the cold box where it is cooled, the vapor is condensed, and the sampling is done at approximately room temperature. Much of the development testing on the smoke sensor was done using this cold box.

Figure 2-2. Honeywell ERC Furnace Test Facility

2.5 PROGRAM RESULTS SUMMARY

Development of the prototype model of the Furnace Efficiency Test Set has provided solutions in parameter sensing and in automating the several functions required in its operation. In addition, insights have been gained in implementing the design of a production prototype model. Specific achievements of the program have included:

- Development of the light-scattering smoke detector with associated electronics for direct readout of Bacharach Smoke Number.
- Application of microprocessor technology for automatically and continuously carrying out numerous functions in a portable device, including:
 - Computation of furnace efficiency using analog measurements and accounting for the specific fuel being used,
 - Fault monitoring and indication,
 - Generation of digital readouts in engineering units,
 - Calibration of all sensors,
 - Device operation programming and control.
- Adaptation of a solid electrolyte oxygen sensor for oxygen concentration measurement.

Experience gained in development of the prototype design of the Furnace Efficiency Test Set can be applied in defining a version qualifying for large quantity manufacture. In succeeding paragraphs, synoptic commentary is given on present and future design features; detailed potential design improvements are discussed in Section 7.0.

2.5.1 Electronics Design

Off-the-shelf parts were used wherever possible in developing the electronics for the Furnace Efficiency Test Set to minimize program cost and risk and to enhance accuracy and reliability. In so doing, some penalty was paid in part size and power consumption; hence considerable potential exists for reducing device size and power use. Additional possibility for device size and power use reduction exists if assembly language is used for the microprocessor software. The software is presently written in FORTRAN, a language that requires considerably more memory than assembly language; i.e., the software package would require less than 2K bytes, while the present software package requires approximately 12K bytes. These possibilities are discussed further in Section 7.0.

2.5.2 Oxygen Sensor Design

As with electronic parts, an off-the-shelf design was sought for the oxygen sensor. Designs developed for the automobile industry were the best candidates because of their high-volume production and reliability. In appearance, these resemble a spark plug and are larger than necessary for our application. Size reduction and attendant heater power reduction can be achieved by sensor repackaging, essentially using only the zirconium oxide element itself with a less "massive" mounting.

The zirconium oxide oxygen sensor exhibited very good accuracy when its heater temperature was kept relatively constant. It appears that it must be heated to at least 900°F (482°C) to achieve the desired 5-second response. At this temperature, reading accuracy in response to a 10.48 percent standard oxygen reference gas was within 0.5 percent.

Bonding of leads to the sensor's platinum runners presented a problem in our application. High-temperature silver solder connections made by the vendor appear to be a satisfactory solution.

Lowering of sensor operating temperature continues to be a desirable objective in reducing heater power and promoting sensor reliability.

2.5.3 Smoke Sensor Design

The design of the smoke sensor was novel and extended the state-of-the-art. Increasing device signal-to-noise ratio is a continuing objective at this writing. Prototype devices operate at a signal-to-noise ratio of about two to one; the result is that their electronics are susceptible to noise effects giving output drift. A recommended design change, discussed in Section 7.0, increases the amount of smoke-scattered light reaching the photodiode detector, hence its output level.

Early results in the smoke sensor's development showed a susceptibility to moisture droplets present in flue gas. This difficulty was overcome by controlled heating (140°F/60°C) of its smoke chamber to prevent flue gas moisture condensation.

Testing of the smoke sensor to date has revealed no trouble with soot deposition on its optical surfaces. The sensor does, of course, have a self-monitoring feature through use of light source intensity measurement and resulting compensation of signal output. Only further experience with the device can reveal if there is a need for additional control measures (i.e., control of thermal gradients in the sample chamber, on-the-job cleaning of optical surfaces, or alternating use of optical parts).

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SECTION 3.0
SPECIFICATIONS FOR THE FURNACE EFFICIENCY TEST SET

At the outset of the program certain guidelines were given by Brookhaven National Laboratory for design of the Furnace Efficiency Test Set. These design requirements, which were not intended to be a complete listing, included the following:

- Cost--Low enough to permit widespread acceptance.
- Range and accuracy--
 - Stack gas measurements:
 - Carbon Dioxide 0 to 16 ± 0.1 percent
 - Oxygen 0 to 21 ± 0.1 percent
 - Temperature 200 to 950 ± 2 °F.
 - Smoke Density 0 - 9 Bacharach Smoke Number with direct meter readout indicating "good" (0, 1); "fair" (2, 3); "poor" (4); "unacceptable" (5 to 9).
 - Furnace Efficiency: 30 to 90 percent
- Reliability--Operable under stack conditions without frequent adjustment.

- o Life--"Useful" component life.
- o Physical characteristics--Of a size and weight to be easily transportable; sufficiently durable and shock resistant for service use; easily affixed to the boiler or furnace to provide final measurements within 10 minutes.

Using these guidelines, specifications were drawn up for the individual sensors and for the Furnace Efficiency Test Set itself. The specifications for the temperature, oxygen, and smoke sensors are given in Table 3-1. The system accuracy and environmental specifications are given in Tables 3-2 and 3-3, respectively. From Table 3-2 it is seen that furnace efficiencies are to be determined to within ± 1.5 to 4.0 percent, depending on the flue gas oxygen concentration and temperature levels. It was recognized that these overall efficiency accuracies would limit the usefulness of the test set in measuring absolute efficiencies, such as for performance certification. However, they were considered appropriate for the intended use, which was equipment adjustment for peak efficiency.

In general, design objectives for the Furnace Efficiency Test Set stressed:

- o The use of state-of-art sensors;
- o The need for minimal demand on operator for adjustment and calibration;
- o Operator safety;
- o Device portability.

Table 3-1. Sensor Specifications

SENSOR	PARAMETER	DESIGN GOAL
FLUE GAS TEMPERATURE SENSOR	DEVICE	TYPE K THERMOCOUPLE
	TEMPERATURE RANGE	93 TO 510°C (200 TO 950°F)
	ACCURACY	± 6°C (± 10°F)
	MEAN TIME BETWEEN FAILURES (MTBF)	1250 HOURS; CYCLED AT 20 USES OF 15-MINUTE DURATION PER WEEK
	PHYSICAL SIZE	BEAD TYPE: MUST FIT INTO 1/4-INCH-DIAMETER TUBE
	RESPONSE TIME	1 SECOND TO WITHIN 63 PERCENT OF NEW MEASUREMENT VALUE
	VIBRATION	OPERATING--0.5 G; ENDURANCE--1 G FOR 24 HOURS
	MECHANICAL SHOCK	NORMAL HANDLING SHOCK
	STORAGE TEMPERATURE	-46 TO +66°C (-50 TO +150°F)
	CONTAMINANTS	ABLE TO FUNCTION WITHIN SPECIFICATION IN DUST, SMOKE, DIRT, SOOT, FUEL AND MOISTURE
ZIRCONIUM OXIDE TEMPERATURE SENSOR	DEVICE	TYPE K THERMOCOUPLE
	TEMPERATURE MAXIMUM	850°C (1562°F)
	RESPONSE TIME	≈ 5 SECONDS
	ACCURACY	± 1.0 PERCENT OF SETTING
	MEAN TIME BETWEEN FAILURES (MTBF)	1250 HOURS: CYCLED AT 20 USES OF 15-MINUTE DURATION PER WEEK
	PHYSICAL SIZE	BEAD TYPE; CERAMIC INSULATED
	VIBRATION	OPERATING--0.5 G; ENDURANCE--1 G FOR 24 HOURS
	MECHANICAL SHOCK	NORMAL HANDLING SHOCK
	STORAGE TEMPERATURE	-46 TO +66°C (-50 TO +150°F)

Table 3-1. Sensor Specifications (Concluded)

SENSOR	PARAMETER	DESIGN GOAL
ZIRCONIUM OXIDE OXYGEN SENSOR	DEVICE	SOLID ELECTROLYTE TYPE; OBEYS NERNST EQUATION FROM 0.1 TO 20.9 PERCENT OXYGEN CONCENTRATION
	TEMPERATURE RANGE	600 TO 1350°F
	THERMAL SHOCK RESISTANCE	REPEATED THERMAL CYCLING FROM OPERATING TEMPERATURE TO AMBIENT AIR WILL NOT DAMAGE THE SENSOR
	ACCURACY	FOLLOWS NERNSTIAN RELATIONSHIP WITHIN ± 0.5 PERCENT OF OXYGEN VALUE
	RESPONSE TIME	WILL REACH 90 PERCENT OF FINAL VALUE WITHIN 0.5 SECOND AT 1000°F AND ABOVE, AND UNDER 10 SECONDS AT 800°F
	SENSOR LIFE	6 MONTHS MINIMUM WHEN SUBJECTED TO NORMAL ATMOSPHERES
SMOKE SENSOR	DEVICE	LIGHT-SCATTERING TYPE DETECTOR; ± 0.5 BACHARACH READING AS COMPARED TO THE FILTER PAPER METHOD
	RATE OF AIR FLOW	2 LITERS PER MINUTE
	HEATER	CHAMBER HEATED TO A MINIMUM OF +140°F TO PREVENT CONDENSATION
	SIGNAL-TO-NOISE RATIO	APPROXIMATELY 2:1
	STORAGE TEMPERATURE	-50 TO +150°F
	CONTAMINANTS	MUST BE ABLE TO FUNCTION WITHIN SPECIFICATION WHEN SUBJECTED TO MINOR DUST OR SOOT
	RESPONSE TIME	20 SECONDS TO NEW SAMPLE

Table 3-2. System Accuracy Specifications

FLUE TEMPERATURE		FLUE O ₂		EFFICIENCY	
RANGE	ACCURACY	RANGE (PERCENT)	ACCURACY (PERCENT)	RANGE (PERCENT)	ACCURACY
200 TO 500°F	±10°F	1 TO 10	±0.5	69 TO 85	±1.5
500 TO 900°F	±10°F	1 TO 10	±0.5	51 TO 78	±2.0
200 TO 500°F	±10°F	10 TO 15	±0.5	57 TO 81	±3.0
500 TO 900°F	±10°F	10 TO 15	±0.5	30 TO 69	±4.0
500 TO 900°F	±10°F	15 TO 20	±1	30 TO 57	NONE SPECIFIED
200 TO 500°F	±10°F	15 TO 20	±1	30 TO 75	NONE SPECIFIED

Table 3-3. System Environmental Specifications

PARAMETER	DESIGN GOAL
HUMIDITY	90 PERCENT RH AT 95°F FOR 30 DAYS
VIBRATION	OPERATING: 1/2 G; ENDURANCE: 1 G FOR 24 HOURS
AMBIENT TEMPERATURE EXTREMES	STORAGE: -50°F TO +150°F; OPERATING: -20°F TO +125°F
LINE VOLTAGE EXTREMES	85 PERCENT TO 110 PERCENT OF RATED
TRANSIENTS	1500-VOLT MOMENTARY TRANSIENTS OF BOTH POLARITIES
CONTAMINANTS	FREE FROM DUST, DIRT, SMOKE, SOOT, FUEL OIL, AND WATER

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SECTION 4.0

DESIGN ISSUES AND TRADE-OFFS

4.1 OXYGEN SENSOR

Several methods of oxygen sensing were considered for the Furnace Efficiency Test Set, including paramagnetic, galvanic and polarographic, thermoconductivity, molten salt electrolytes, and ceramic oxide. Oxygen concentration in atmospheres commonly is measured by taking advantage of its magnetic susceptibility, which is much greater than most other gases. It is difficult, however, to use this property of oxygen in a field-worthy instrument. The galvanic and polarographic techniques are not suitable at the high temperatures encountered with flue gas. Moreover, such sensors can be impaired in the presence of gases containing carbon and sulfur oxides through the precipitation of carbonates and sulfates within the sensing cell. The thermoconductivity method is subject to errors due to fluctuations in atmospheric pressure, humidity, cell temperature, and the presence of hydrocarbons in the flue gas. The molten salt electrolyte technique has long response time, typically several minutes. Of the several techniques considered, the zirconium oxide sensor was deemed best suited. Recently, this type of sensor increasingly has come into industrial use for monitoring reducing and oxidizing atmospheres and for flue gas analysis.

The zirconium oxide sensor was selected for use in the Furnace Efficiency Test Set because it has demonstrated performance capability in flue gas applications, has good sensitivity in the oxygen partial pressure range of interest (1 to 10 percent), operates at temperatures above 700°C (1292°F), and has a known output characteristic defined by the Nerstian equation, making for convenient calibration. Further, it is amenable to mass production techniques and consequent cost reduction possibilities.

Certain ceramic oxide materials have a crystal structure permitting the migration at high temperature of negatively charged oxygen ions, and the generation of a voltage across the ceramic, upon exposure of opposite sides of this electrolytic conductor to gases of different oxygen partial pressures. Such an oxygen sensing cell can be a closed-end tube or a separating disk of appropriate ceramic material having porous platinum coatings applied to its opposing surfaces to act as electrodes. This sensing tube is thermostatically controlled, and the two electrodes are connected to external measuring circuitry. Ambient air, at substantially constant oxygen partial pressure, is exposed to one side of the ceramic; the gas for which the oxygen content is to be measured is exposed to the other. Voltage generated across the ceramic, upon response to unequal oxygen partial pressures, bears a logarithmic relationship to the oxygen content of the gas being analyzed.

The specific zirconium oxide sensor chosen for the Furnace Efficiency Test Set was the TRUTECTM Oxygen Sensor manufactured by UOP, Inc. The specifications for this sensor are given in Figure 4-1. This sensor consists of a ceramic tube with an yttria-stabilized zirconia solid-electrolyte disk mounted in one end. Platinum electrodes on the electrolytic surface serve as electrocatalysts and electrodes between which voltages are generated in response to dissimilar oxygen concentrations on opposing sides of the electrolyte. Figure 4-2 is a schematic representation of the oxygen sensor, which shows how the reference gas (air) is contained within the sensor tubes and the sensed gas is exposed to the exterior of the sensor tube. The voltage output of the sensor follows the Nernstian equation given in the device specification (Figure 4-1). Figure 4-3 shows the voltage response of the sensor to oxygen concentration at temperatures from 300 to 1300°C (572 to 2372°F). When the oxygen concentration of the atmosphere being sensed rises to that of air (20.9 percent), there is no longer a differential oxygen pressure, and this family of curves combines into one and reaches an asymptotic value of 1 or 2 millivolts.

TYPICAL CHARACTERISTICS

TEMPERATURE RANGE: 800 TO 1350°F

THERMAL

SHOCK RESISTANCE: REPEATED THERMAL CYCLING FROM OPERATING TEMPERATURE TO AMBIENT AIR WILL NOT DAMAGE THE SENSOR.

OUTPUT: NERNSTIAN-- $emf = 0.0215 T \ln \frac{O_2 (REF)}{O_2 (UNKNOWN)}$

WHERE emf = OUTPUT VOLTAGE IN MILLIVOLTS
 T = TEMPERATURE IN °K
 $O_2 (REF)$ = OXYGEN CONCENTRATION ON REFERENCE SIDE

ACCURACY: FOLLOWS NERNSTIAN RELATIONSHIP WITHIN ± 0.5 PERCENT OF OXYGEN VALUE.

TIME RESPONSE: FUNCTION OF OPERATING TEMPERATURE. WILL REACH 90 PERCENT OF FINAL VALUE WITHIN 0.5 SECOND AT 1000°F AND ABOVE, AND UNDER 10 SECONDS AT 800°F.

ATMOSPHERES: NORMAL FLUE GAS ATMOSPHERES. SENSOR LIFE MAY BE SHORTENED BY USE IN ATMOSPHERES CONTAINING LEAD, ARSENIC OR ANTIMONY.

SENSOR LIFE: SIX MONTHS MINIMUM WHEN SUBJECTED TO NORMAL ATMOSPHERES.

Figure 4-1. TRUtecTM Oxygen Sensor Specification

Figure 4-2. Oxygen Sensor Schematic

Figure 4-3. Response of Zirconium Oxide Oxygen Sensor at 100°C Temperature Intervals

Figure 4-4 is a photograph of the oxygen sensor piece parts. The sensor with its tantalum leads is shown at the lower left. Its appearance is similar to that of an automotive spark plug; a threaded bushing provides for mounting in a cylinder heated by five piston heaters. A copper washer between the sensor and cylinder forms a seal between the sensed and reference gases. The piston heaters provide over 500 watts of heat to the cylinder, which is layer insulated (WRP-X-AQ felt, Fiberfax, foil, Fiberfax). The arrangement for inserting the oxygen sensor and heaters into the cylinder is shown at the upper right of the figure.

Figure 4-4. Oxygen Sensor Piece Parts

4.2 SMOKE SENSOR

Selection of the type of smoke sensor to be used in the Furnace Efficiency Test Set was based primarily on evaluation of light-scattering, ionization, and corona discharge techniques. Evaluation testing was done using a standard U.L. 217 smoke box, a specially built test box connected to a residential oil furnace, and several residential furnaces. Comparison of test results led to selection of the light-scattering technique because of its sensitivity, its better signal-to-noise ratio, and because it provides an output correlating with Bacharach Smoke Number. Comparative results with the light-scattering and ionization methods showed the former to have an instantaneous noise signal about 1/20 of the latter. For Bacharach Smoke Number 3, the noise signals would cause a reading uncertainty of ± 1 for the light-scattering detector and ± 2 for the ionization detector. Figure 4-5 shows comparative responses of these two types of sensors in one test and the more favorable output characteristic of the light-scattering sensor.

The corona discharge detector uses corona discharge for ion generation; the ionization sensor uses a radioactive source. Responses of these two types of sensors are shown in Figure 4-6 for smoke produced by burning cotton. When tested with the smoke of No. 2 fuel oil, the corona discharge detector gave nearly zero response in the range of 1 to 5 Bacharach.

During the investigation of smoke sensing techniques, a number of experiments were conducted using particle analyzers, not only to direct the selection of a technique, but to relate Bacharach smoke number values to particle sizes and concentrations and to direct the design of the light-scattering sensor. Some insights gained as to the nature of smoke particles and the mechanics of the Bacharach test itself are discussed in the following paragraphs.

Figure 4-5. Response of Two Smoke Detector Types to Smoke Generated by a No. 2 Fuel-Oil-Fired Residential Furnace

Figure 4-6. Comparison of Corona Discharge and Ionization Smoke Detectors

The particle concentration in furnace flue gas corresponding to a Bacharach Smoke Number of zero is non-zero. This can be seen in Figure 4-7, which shows particle concentration versus Bacharach Smoke Number for a particle diameter of $0.237 \text{ }\mu\text{m}$ ($\pm$ a factor of 1.33) in No. 2 fuel oil smoke. Particle concentration decreases as smoke number decreases, but at zero smoke number the particle concentration is still more than $3 \times 10^3 \text{ cm}^{-3}$. At a smaller particle diameter, $0.042 \text{ }\mu\text{m}$ ($\pm$ a factor of 1.33), the particle concentration at zero smoke number is apparently on the order of $3 \times 10^6 \text{ cm}^{-3}$ (Figure 4-8). For this particle size, particle concentration decreases as Bacharach Smoke Number increases. These findings with the smaller particle size ($0.042 \text{ }\mu\text{m}$) suggest the presence of fog particles having relatively high concentration at zero smoke number and the need for compositional analysis of particles in further study.

A test was made to determine the particle concentration of room air (see Figure 4-9). The particle concentration of room air at a particle size of $0.237 \text{ }\mu\text{m}$ ($\pm$ a factor of 1.33) is $4.1 \times 10^3 \text{ cm}^{-3}$ which is consistent with that found earlier for zero smoke number. However, the higher concentrations of smaller particles ($0.042 \text{ }\mu\text{m}$) found in fuel oil smoke at zero smoke number were not as high in room air.

In Figure 4-10 it can be seen that the relative number of particles retained by a Bacharach smoke filter decreases from about 100 percent for particle diameters of about $3 \text{ }\mu\text{m}$ and larger to less than 20 percent for particle diameters of $0.03 \text{ }\mu\text{m}$ and smaller. Figures 4-11 and 4-12 illustrate that the average diameter of particles retained by a Bacharach smoke filter increases with smoke number.

The length of the sampling tube may affect the results of the Bacharach test. Figure 4-13 shows a decrease in particle number by a factor of approximately three when the sample tubing length is increased from 30 cm (12 inches) to 309 cm (122 inches).

Figure 4-7. Particle Concentration Versus Bacharach Smoke Number, No. 2 Fuel Oil, $D=0.237 \mu\text{m} \pm$ Factor of 1.33

Figure 4-8. Particle Concentration Versus Bacharach Smoke Number, No. 2 Fuel Oil, $D=0.042 \mu\text{m} \pm$ Factor of 1.33

Figure 4-9. Particle Concentration in Room Air

Figure 4-10. Fraction of Particles Retained by a Bacharach Smoke Filter for Various Smoke Densities

Figure 4-11. Particles Retained by a Bacharach Smoke Filter for Various Smoke Densities

Figure 4-12. Particulate Mass Loading and Volume Fraction Versus Bacharach Smoke Number

Figure 4-13. Number of Particles Reaching the Detector With Various Lengths of Sampling Tube

To determine the effect of filter paper pore size on the determination of Bacharach Smoke Number, furnace smoke was drawn through filter papers of various porosities. Figures 4-14, 4-15 and 4-16 show the resulting number concentration/particle diameter distributions after filtering smokes of 2, 4, and 6 Bacharach. Mass concentration distributions were found for Bacharach 2, 4, and 6 smokes, with and without filtering. Figure 4-17 shows the mass concentration/particle diameter distribution of unfiltered smokes for 2, 4, and 6 Bacharach and their total particle mass. Figures 4-18, 4-19 and 4-20 show the mass concentration/particle diameter distributions after filtering Bacharach 2, 4, and 6 smokes through 5-, 2-, and 0.5-micron filters. From these figures, the following should be noted:

- Mass concentration increases with Bacharach Smoke Number.
- After being filtered, the mass concentration decreases considerably, and the fraction of particles retained by the filter increases as average filter pore size is reduced.
- The particle diameter corresponding to the peak mass concentration is about $0.065\ \mu\text{m}$ ($\pm$ a factor of 1.33) at Bacharach 2 and about $0.2\ \mu\text{m}$ ($\pm$ a factor of 1.33) at Bacharach 6.

The Bacharach Smoke Number is strongly dependent on the characteristics of the filter paper used. The recommended filter for the Bacharach test has an average pore size of over 10 microns. It was found that for a particular furnace operating condition, the Bacharach Smoke Number was up to three numbers smaller for the standard 10-micron filter than for the 0.5-micron filter. The effect of filter paper pore size on Bacharach smoke number measurements is presented in Table 4-1.

Figure 4-14. Particle Concentrations Observed After Passing Smoke Through a 5-Micron Teflon Filter, Type LS

Figure 4-15. Particle Concentrations Observed After Passing Smoke Through a 2-Micron PVC Filter, Type BS

Figure 4-16. Particle Concentrations Observed After Passing Smoke Through a 0.5-Micron PVC Filter, Type FWS-D

Figure 4-17. Mass Concentration Distributions Observed From No. 2 Fuel Oil Smoke

Figure 4-18. Mass Concentration Distributions Observed After Passing Smoke Through a 5-Micron Teflon Filter, Type LS

Figure 4-19. Mass Concentration Distributions Observed After Passing Smoke Through a 2-Micron PVC Filter, Type BS

Figure 4-20. Mass Concentration Distributions Observed After Passing Smoke Through a 0.5-Micron PVC Filter, Type FWS-D

Table 4-1. Influence of Average Filter Paper Pore Sizes on Measured Bacharach Smoke Number

FILTER AVERAGE PORE SIZE (MICRONS)	FURNACE CONDITION FOR BACHARACH SMOKE NUMBERS		
	2	4	6
~10 (STANDARD)	2	4	6
5	3	4	5
2	1.5	5	7.5
0.5	3	7	9

The fraction of particles retained by filters of different porosities after filtering smokes of different Bacharach numbers is given in Figure 4-21. It was found that the Whatman No. 41 filter, used for the standard Bacharach test, retains smaller fractions of the smoke particles than do filters having smaller average pore size. Examination of filter smoke spots under magnification substantiated these findings.

To obtain the desired correlation with Bacharach Smoke Number, a smoke sensor design was derived for the Furnace Efficiency Test Set, as shown in Figure 4-22. Features of this design include:

- Use of a light wavelength short enough to interact with smoke particles of minimum size.
- Selection of an optical path through the smoke to maximize light scattering and consequently light signal.
- Minimization of the effect of smoke-soiled surfaces on light signal.
- Matching chamber and aperture diameters so that only smoke particles (not chamber surfaces) act as light-scattering centers.

Figure 4-21. Volume Fraction of Particles Retained Versus Bacharach Smoke Number for Various Filter Porosities

- ===== BAFFLES -- ALL BAFFLE EDGES FACING DETECTOR ARE EITHER IN THE DARK SPACES OR OUTSIDE DETECTOR APERTURE
- ////// ACTIVE SMOKE SCATTERING VOLUME
- Dark Space Dark Space SHADED FROM LIGHT SOURCE
- LOW REFLECTION SURFACES
- o o o o o HEATER WIRES
- L_1 AND L_2 LIGHT SOURCE BEAMS LIMITING ACTIVE SCATTERING VOLUME
- D_1 AND D_2 DETECTOR BEAMS LIMITING EFFECTIVE SCATTERING APERTURE
- S_1 AND S_2 SUPPORT RODS ARRANGED TO MASK FRINGE SCATTERING OF S_1 BY S_2
- D MINIMUM TUBE DIAMETER DETERMINED BY INTERSECTION OF L_2 AND D_2

Figure 4-22. Schematic Drawing of Heated Light-Scattering Chamber to Measure Smoke Particle Concentration [Volumes outside aperture beams L_1 , L_2 , D_1 and D_2 can be eliminated with a filter to speed up response times. This and reference detector not shown.]

- Minimum use of optical baffles, with baffle edges facing the detector to be either in the dark spaces or outside the detector aperture.
- Use of a second detector to monitor light source output to compensate for soiling of light-transmitting surfaces.
- Use of chamber periphery heating to eliminate moisture droplets in the smoke and spurious light scattering.

The light-scattering smoke sensor built for the Furnace Efficiency Test Set is shown schematically in Figure 4-23. The sensor is essentially cylindrical, 2-1/2 inches in diameter and 5-1/2 inches long. A light-emitting diode (LED) at one end of the cylindrical cavity provides a light beam transmitting on the cylinder axis through concentric isolating windows and baffle apertures. Two photodiodes are mounted at the cylinder end opposite the light source: one on the cylinder axis directly viewing the light source (source monitor); one placed at 20 degrees to the cylinder axis viewing smoke-scattered light (signal detector). The source monitor photodiode provides a means of correcting smoke sensor output if the source light intensity is degraded by window soiling or other factors.

The light source (Fairchild FLV-104) operates in the visible region and is intended for use at relatively close range with photodiode sensors. Both the light source and the two photodiode detectors are mounted in phenolic blocks and are isolated from the smoke chamber by windows and from the heated portions of the sensor chamber by air gaps.

The periphery of the smoke sensor cylinder is maintained at a constant and elevated temperature by outer insulation and thermostatically controlled electrical heating. This is done using alternate layered wrappings of glass tape, heater tape, fiberfax insulation, and glass tape. The heater tape is

Figure 4-23. Smoke Chamber Assembly, Furnace Efficiency Test Set

rated at 96 watts, 110 VAC; however, it is energized by half-wave rectified AC to improve temperature control. A thermal switch provides protection from overheating.

Figure 4-24 is a sketch showing the location of the smoke sensor on the probe of the Furnace Efficiency Test Set. The smoke sensor is aspirated by tubing connected to a suction pump in the Furnace Efficiency Test Set proper. Figure 4-25 is a photograph of the smoke sensor piece parts. From upper left to right are: the phenolic block housing the two photodetectors; a smoke chamber end piece containing a smoke chamber window; the main cylindrical body of the smoke chamber showing the smoke inlet and outlet ports and the Klaxon temperature controller affixed to its outer diameter; another smoke chamber end piece containing a smoke chamber window; the phenolic block housing the LED light source (this block has alignment provisions for calibrating the LED). The signal preamplifier, which fits into the photodetector phenolic block, is shown at the left beneath that block. The heater tape is shown in the lower part of the figure.

Figure 4-26 is another view of the smoke sensor parts showing blackened surfaces used to minimize incidental light.

4.3 TEMPERATURE SENSOR

A preliminary survey was conducted of the major manufacturers who supply temperature sensing devices. This survey included a literature search for specifications and application notes, as well as conversations with technical experts working in the field. Table 4-2 includes a list of the manufacturers from this survey and the type of sensors they produce. Information has been limited to nonradiation sensors such as thermocouples, thermistors, and resistance temperature devices (RTDs). There are, however, several manufacturers supplying such devices as quartz crystals, infrared detectors, acoustic thermom-

Figure 4-24. Probe Assembly, Furnace Efficiency Test Set

Figure 4-25. Smoke Detector Piece Parts

Figure 4-26. Inside View of Smoke Chamber

Table 4-2. Survey of Temperature Sensor Manufacturers

COMPANY	THERMOCOUPLE	THERMISTOR	RTD	ACCESSORIES
MINCO PRODUCTS INC.	X	X	X	X
SCIENTIFIC PRODUCTS	X			
LEEDS AND NORTHRUP	X			X
GORDON	X			X
CAL-R INC.		X		X
OMEGA	X	X	X	X
HY-CAL	X		X	X
CGS/THERMODYNAMICS	X		X	X
DIGITEC		X	X	X
RDF CORP.	X		X	X
CONAX	X	X	X	X
MIDWEST COMPONENTS, INC.		X		X
YELLOW SPRINGS INSTRUMENT		X	X	X
VICTORY ENGINEERING		X		X
FENWAL		X		
HONEYWELL	X			X
COMPUTER PRODUCTS			X	X
ROCHESTER INSTRUMENT SYSTEMS			X	X
KEYSTONE		X		X
ROSEMOUNT ENGINEERING		X		X
WESTERN THERMISTOR		X		X

eters and pyroelectric thermometers for temperature monitoring. Table 4-3 shows temperature sensor parameters and values illustrative of present practice. Appendix B presents a fuller discussion of the comparative attributes and application considerations for thermocouples, thermistors, and resistance temperature sensors.

The Furnace Efficiency Test Set requires the measurement both of the zirconium oxide sensor's heater temperature and flue gas temperature. Thermocouple temperature sensors were selected for these measurements for reasons of high temperature capability, accuracy and repeatability, response, interchangeability and cost. These considerations are discussed briefly in the following paragraphs.

Table 4-4 summarizes the advantages and disadvantages of the three types of sensors surveyed. Thermocouples appear best for the high temperature requirement of the zirconium oxide sensor's heater (850°C) (1562°F). Thermistor use at a flue gas temperature of 510°C (950°F) appears marginal because of the potential instability of this device at such a temperature. Because of these temperature constraints with thermistors, thermocouples were chosen for both applications. Temperature constraints exist also for resistance temperature sensors though high-cost, special purpose versions of RTDs can be obtained for over 1000°C (1832°F) service.

Thermocouples are felt to be superior to thermistors and RTDs with regard to sensor interchangeability--important for long-life service.

Thermocouples are very repeatable in their output; when thermocouples of the same wire batch are used, interchangeability is enhanced even further. Thermocouple response over a wide temperature span is consistent, allowing replacement without point-to-point calibration as is necessary with thermistors. The slight nonlinearity of the thermocouple output can be compensated for by the digital techniques employed in the microprocessor of the Furnace Efficiency

Table 4-3. Comparison of Temperature Sensors

CHARACTERISTIC	THERMOCOUPLE (ALL TYPES)	THERMISTOR	RTD
MAXIMUM TEMPERATURE	3300°C	315°C	1100°C
STABILITY	0.5°C PER YEAR	0.1°C PER YEAR	0.1 PERCENT DRIFT IN 5 YEARS OR 0.001°C PER YEAR
FAIL-SAFE	NO	NO	YES
SENSITIVITY (25°C)	1 PERCENT PER °C	5 PERCENT PER °C	0.5 PERCENT PER °C
RANGE (TYPICALLY)	-270 TO +1800°C	-100 TO +300°C	-250 TO +900°C
OUTPUT (TYPICALLY)	10 µV PER °C	18 mV PER °C (WITH 4000 THERM)	UP TO 400 mV PER °C (WITH BRIDGE)
LINEARITY	EXCELLENT (0.03 PER- CENT OVER 200°C RANGE)	POOR (64 PERCENT OVER 200°C RANGE)	EXCELLENT (0.375 PERCENT OVER 200°C RANGE)
POWER (100 OHM LOAD)	2×10^{-7} WATTS	8×10^{-1} WATTS	4×10^{-2} WATTS
POINT SENSING (OUR APPLICATION)	EXCELLENT	EXCELLENT	POOR
AREA SENSING (NOT NEEDED FOR US)	POOR	POOR	EXCELLENT
SENSOR COST	\$1 TO \$50	\$2 TO \$10 (STANDARD) \$10 TO \$350 (SPECIAL)	\$25 TO \$1000 (STANDARD)
TEMPERATURE COEFFICIENT (25°C)	DEPENDS ON WIRE SIZE AND TYPE.	0.039 TO 0.046 Ω/Ω/°C	0.0039 Ω/Ω/°C (POINT)
DISSIPATION CONSTANT (STILL AIR)	DEPENDS ON WIRE SIZE AND TYPE.	0.1 TO 1.0 mW PER °C	0.5 TO 40 mW PER °C
TYPE OF MEASUREMENT	RELATIVE	DIRECT	DIRECT
ACCURACY (OVER MEASUREMENT RANGE)	TYPICALLY $\pm 1^\circ\text{C}$ (WITH REFERENCE)	TYPICALLY $\pm 0.1^\circ\text{C}$	0.01°C (PLATINUM)

Table 4-4. Advantages and Disadvantages of the Three Sensor Types

SENSOR TYPE	ADVANTAGES	DISADVANTAGES
THERMOCOUPLE	HIGH TEMPERATURES RELATIVELY SMALL SIZE EXCELLENT LINEARITY LOW COST POINT MEASUREMENT NEGLECTIBLE SELF-HEATING	COLD JUNCTION COMPENSATION LOW-LEVEL OUTPUT LIMITED ACCURACY (WITHOUT TABLE CORRECTION) NEEDS HIGH IMPEDANCE INSTRUMENTATION REQUIRES SPECIAL LEAD WIRE CAN INVOLVE HIGH SYSTEM COST NON-FAIL-SAFE
THERMISTOR	SMALL SIZE MODERATELY LOW COST HIGH SENSITIVITY POINT MEASUREMENT LONG-TERM STABILITY	NON-INTERCHANGEABLE NON-FAIL-SAFE POOR LINEARITY SELF-HEATING
RTD	GOOD SENSITIVITY HIGHEST STABILITY EXCELLENT LINEARITY INTERCHANGEABILITY FAIL-SAFE	HIGH COST AREA SENSING SELF-HEATING

Test Set. Temperature repeatability to within $\pm 2^{\circ}\text{C}$ is important during furnace adjustment; this requirement can be met better by thermocouples than by the thermistor or RTD.

Referring again to Table 4-4, thermocouples appear best for high temperatures, thermistors for point measurement, and RTDs for special needs of accuracy or stability where their higher cost can be justified.

Thermocouples require probe assemblies, high-gain stable amplifiers, continuous leads between junctions, and junction referencing--either temperature or electronic compensation. Thermistors and RTDs also require probe assemblies, which require precision bridge circuitry with accurate power supplies.

Taking these factors into consideration, i.e., high temperature capability, interchangeability, response, repeatability, accuracy, the thermocouple was selected for the Furnace Efficiency Test Set. Moreover, with sound design it is felt that the thermocouple configuration can be a small part of the overall system cost.

4.4 CARBON MONOXIDE SENSING

The Furnace Efficiency Test Set has no provision for carbon monoxide (CO) measurement. There is, however, reason to feel that this capability is desirable ultimately, particularly for gas-fired furnaces. The need for carbon monoxide measurement was evaluated during this program by literature search, assessment of field test data, and inquiry to the gas industry. This evaluation substantiated the desirability for carbon monoxide measurement in gas burner work, and is reported in the following paragraphs.

Figure 4-27 is a composite plot of smoke and gas emissions for a typical residential oil-fired furnace. The plot shows the Bacharach Smoke Number and carbon monoxide (CO), nitrogen oxide (NO_x) and hydrocarbon (HC) concentrations versus flue gas carbon dioxide (CO_2) concentration. Of particular interest is the curve for smoke, which shows that as CO_2 , hence furnace efficiency, increases, the smoke concentration remains flat until about 8-1/2 percent CO_2 , when it increases rapidly at higher CO_2 concentrations. The smoke increase precedes that for CO and occurs at a faster rate. Below about 7-1/2 percent CO_2 , the CO concentration increases rapidly. These data show that for a furnace adjusted to smoke incipience at about 8 percent CO_2 , there would be a minimum of CO and HC production. In effect, smoke incipience is the precursor to CO production in oil-fired furnaces and is thought to be an adequate indicator without need for a CO sensor as such.

The visual cue in setting gas burners is the balance between blue and yellow coloration of the flame. Where smoke incipience is the indicator for low CO production in oil burners, blue-to-yellow flame incipience is the corresponding indicator in gas burners. In a study by the American Gas Association², emissions from 38 forced air furnaces of 29 makes and with a wide range of adjustments were analyzed for CO, NO, NO_2 , CH_4 , and C_2H_4 . Table 4-5 shows the results. The blue flame adjustment would indicate a large percentage of primary air, indicating a relatively low efficiency, but the CO level was low enough not to be considered a health hazard. However, if the primary air were adjusted for a minimum amount of air, indicative of higher efficiency, the CO level was substantially increased. An upper limit of 200 ppm CO in the flue gas is recommended practice with gas utilities, although no standards exist for maximum CO levels after burner tune-up. (The American National Standards Institute (ANSI) standards for new furnaces require that for a blocked stack, CO in flue gas must not exceed 400 ppm.)

²American Gas Association Research Report No. 1503.

Figure 4 27. Smoke and Gaseous Emission Characteristics for a Typical Residential Oil-Fired Furnace in Tuned Condition

Table 4-5. Forced Air Furnace Emissions

FAF #	Input Rate, Btu/Hr	Blue Flame Adjustment								Yellow Flame Adjustment								Burner				Heat Exchanger									
		Sample, Percent CO ₂	Percent Primary Air	(1) ΔT °F	Flue Gas Concentration PPM, Air Free (2)				NO _x Emission Factor, (E.F.) lbs/10 ⁶ Btu	Sample, Percent CO ₂	Percent Primary Air	(1) ΔT °F	Flue Gas Concentration PPM, Air Free (2)				NO _x Emission Factor, (E.F.) lbs/10 ⁶ Btu	Multi-port	Single Port		Other	Sectional	Drum	Other							
					CO	NO	NO ₂	-CHO					CO	NO	NO ₂	-CHO			Up-shot	In-shot											
1	103,000	6.90	45	66	5.4	78.38	5.65	---	0.090	7.15	39	66	450	69.30	10.94	---	0.084														
2	102,500	5.75	69	82	30	95.52	6.26	---	0.109	5.80	48	82	715	82.76	5.48	---	0.094	X													
3	134,000	6.90	49	85	17	86.37	7.86	---	0.098	7.00	39	87	264	74.38	9.17	---	0.087	X	I												
4	82,500	6.85	62	68	75	85.86	12.89	---	0.102	7.00	42	68	236	72.05	12.81	---	0.088	X													
5	103,000	6.90	59	82	18	98.14	4.32	---	0.106	6.80	39	84	284	89.56	6.51	---	0.099	X													
6	98,000	4.95	57	90	12	102.91	2.16	---	0.108	5.05	30	86	252	89.39	10.55	---	0.103	X													
7	103,000	5.20	45	60	12	111.69	3.58	0.12	0.119	5.50	23	60	183	81.97	11.26	0.44	0.096	X													
8	99,500	6.00	46	63	16	111.18	6.94	0.33	0.122	6.10	23	61	283	88.62	9.82	---	0.101	X													
9	98,900	5.10	53	74	12	81.04	1.65	0.43	0.085	5.30	15	72	512	39.35	14.11	1.13	0.055		X									X			
10	103,000	5.45	51	67	11	64.53	4.21	0.10	0.071	5.70	33	65	467	54.46	11.14	0.53	0.068										X				
11	179,400	4.25	49	55	14	105.46	3.61	0.08	0.113	4.25	22	56	133	97.53	8.47	0.56	0.109	X									X				
12	121,500	6.20	50	89	6	89.36	1.39	0.12	0.099	6.40	31	89	469	55.93	11.44	0.83	0.072		X	I						X					
13	101,500	5.70	59	83	17	89.52	2.46	0.30	0.099	5.90	25	80	39	92.26	5.37	0.60	0.105	X								X					
14	103,000	5.90	63	74	20	76.12	2.79	0.53	0.080	5.65	20	77	255	74.78	12.36	3.07	0.091	X	I							X					
15	137,000	3.75	55	88	22	76.51	2.78	0.05	0.086	4.20	25	93	529	32.74	21.46	1.02	0.058									X					
16	126,600	5.40	39	55	1.0	58.71	2.40	0.07	0.064	6.05	18	61	20	66.39	7.00	0.17	0.079								X	I (3)		X			
17	104,600	5.45	51	63	2.8	107.63	4.34	0.13	0.118	5.45	14	67	315	82.92	9.49	1.06	0.098	X								X					
18	102,000	8.40	50	85	31.7	72.17	1.77	0.29	0.078	8.50	42	85	613	64.33	2.85	0.39	0.071	X								X					
19	96,900	5.05	62	67	5.5	96.81	3.80	0.21	0.105	5.10	29	71	379	74.75	10.64	1.40	0.091	X								X					
20	85,300	6.80	64	93	6.4	90.60	4.02	0.19	0.101	6.85	43	97	1156	68.36	8.69	0.46	0.082	X								X					
21	157,500	5.10	46	78	12.0	76.12	3.53	0.04	0.085	5.10	16	82	41.2	56.75	4.66	0.10	0.065		X	I						X					
22	116,200	6.60	76	47	8.4	97.89	7.33	0.23	0.113	6.20	23	45	248	71.86	10.05	0.94	0.087	X								X					
23	103,900	5.40	59	78	1.4	107.44	2.47	0.27	0.118	5.90	23	60	89	72.81	5.49	0.23	0.084	X								X					
24	122,000	6.05	67	96	2.8	107.05	3.00	0.01	0.118	6.35	23	99	4.4	97.76	4.06	0.16	0.110	X								X					
25	106,000	5.20	62	56	3.1	84.00	3.05	0.04	0.092	5.25	25	64	42	78.45	8.37	0.13	0.091	X								X					
26	81,600	8.80	--	54	95	9.30	7.70	0.10	0.018																X (4)				X (5)		
27	75,000	7.40	--	54	1.9	75.13	3.58	---	0.083	7.60	-	54	3.3	93.02	4.41	---	0.102									X					
28	102,100	4.70	51	74	10.7	55.86	9.11	0.07	0.068	4.85	20	76	309	62.65	10.94	0.56	0.077								X						
29	98,100	5.95	72	55	3.4	104.75	5.86	---	0.116	6.00	27	59	62	94.08	9.92	---	0.108	X								X					
30	113,500	5.60	66	87	4.7	89.74	5.47	---	0.100	6.15	42	89	1046	75.00	10.93	---	0.089	X								X					
31	98,400	5.70	74	74	3.8	84.86	5.92	---	0.095	5.80	54	77	215	73.88	10.47	---	0.088	X								X					
32	96,000	6.90	56	40	3.3	77.06	4.66	---	0.086	7.05	21	38	213	78.71	8.92	---	0.092	X								X					
33	104,200	8.70	--	79	5.1	97.39	2.59	---	0.107	11.80	--	86	75	82.29	4.16	---	0.093								X (6)		X		X (7)		
34	95,000	5.10	65	76	127	80.56	5.93	---	0.093	5.10	43	72	668	79.41	9.79	---	0.096	X								X					
35	98,500	5.10	58	50	4.5	77.95	5.46	---	0.090	5.20	34	55	12.9	48.00	20.01	---	0.073							X		X					
36	86,000	4.70	59	62	2.0	92.58	3.57	---	0.103	4.70	34	65	429	62.14	10.57	---	0.078	X							X		X				
37	100,000	3.80	45	60	12.9	79.20	7.83	---	0.090	5.00	30	59	43	69.65	10.70	---	0.089								X		X				
38	90,500	3.30	36	85	8.0	48.58	6.72	---	0.058	3.35	--	87	93	16.26	24.36	---	0.042								X (2)		X				

NOTES:

*ACTUAL INPUT RATE MEASURED AT TIME OF SAMPLING

**NO_x EMISSION FACTOR - lbs/10⁶ Btu, SUM OF NO AND NO₂ CALCULATED AS NO_x

$$NO_x \text{ (lbs/10}^6 \text{ Btu)} = \frac{NO_x \text{ (ppm air free)} \times 10^6 \text{ Btu} \times P \times d(NO_2)}{10^6 \times HV}$$

where:

HV = HEATING VALUE OF GAS IN Btu/ft³P = ft³ COMBUSTION PRODUCTS PER ft³ GAS BURNED (60 F, 30 INCH Hg)d = DENSITY OF GAS IN lbs/ft³ (60 F, 30 INCH Hg)

$$NO_2 (P \times d) - 1.061$$

***TOTAL ALIPHATIC ALDEHYDES EXPRESSED AS FORMALDEHYDE

(1) CIRCULATING AIR TEMPERATURE RISE

(2) (AIR FREE CONCENTRATION) = $\frac{\text{Ultimate CO}_2}{\text{Sample CO}_2} \times (\text{SAMPLE CONCENTRATION})$

(3) TWO RECTANGULAR RIBBON BLOCKS

(4) AND

(5) POWERED BURNER AND UNIQUE HEAT EXCHANGER

(6) AND

(7) POWERED BURNER WITH TUBES IN DRUM HEAT EXCHANGER

(8) MULTI-PORT SHAPED TO LOOK LIKE TWO LOGS

¹CAST IRON BURNER CONSTRUCTION²AMERICAN GAS ASSOCIATION RESEARCH REPORT NO. 1503.

Gas utilities generally consider the possible presence of CO to be a problem, and burner setting can involve its measurement by stain tube or wet chemistry methods. Results of inquiries to the gas industry and assessment of field test data indicate that in residential gas burners CO measurement and/or alarm is desirable.

Several techniques for sensing CO in low concentration ranges were evaluated for use in a field-service furnace efficiency test device. These included optical (IR, UV), electrochemical, dry catalytic, colorimetric, and heat-of-combustion techniques. Specificity, response, and size factors for methods capable of detecting in the parts per million range are shown in Table 4-6. Heat-of-combustion methods using heated catalytic filaments have not been included in Table 4-6 because of their inadequate sensitivity and specificity.

Table 4-6. Methods for Measurement of Carbon Monoxide in the Parts Per Million Range

METHOD	SPECIFICITY	RESPONSE	SIZE
OPTICAL			
NON DISPERSIVE INFRARED	EXCELLENT	SECONDS	LARGE
TUNED LIGHT-EMITTING DIODE	EXCELLENT	SECONDS	LARGE
ULTRAVIOLET EMISSION	GOOD	SECONDS	MEDIUM
ELECTROCHEMICAL			
SOLID POLYMER ELECTROLYTE	EXCELLENT	SECONDS	MEDIUM
STANNIC OXIDE	FAIR	SECONDS	SMALL
METAL OXIDE SILICON	FAIR	SECONDS	SMALL
DRY CATALYTIC			
ELECTROCATALYTIC ELECTRODE	EXCELLENT	SECONDS	MEDIUM
MIXED OXIDES	GOOD	SECONDS	SMALL
COLORIMETRIC			
CHLORO-PLATINIC SALTS	EXCELLENT	MINUTES	SMALL

A number of non-dispersive infrared carbon monoxide detectors are available commercially. These are based on the absorption of infrared at a wavelength of 4.7 microns--a wavelength with little interference from other atmospheric gases. Sophisticated techniques (e.g., narrow band filtering, gas correlation) make for accuracy, specificity, and reliability, but not low cost. A promising new technique in infrared uses a light-emitting diode which emits only at the desired carbon monoxide absorption frequency of 4.7 microns. This method holds promise for low cost and specificity and has been used for methane detection using the 3.3-micron wavelength. An alternate scheme for generating a "tuned" radiation frequency would use a heated sample of carbon monoxide instead of a light-emitting diode.

Ultraviolet carbon monoxide instruments have been used in automobile emissions work in the order of 0.5 percent concentration. When used with a hydrocarbon scrubber, this method is a reliable carbon monoxide indicator, but not for the less than 200 ppm range of interest for furnace work.

Electrochemical methods of interest include:

- Solid Polymer Electrolyte--Operates like a fuel cell generating electrical current due to electrochemical oxidation of carbon monoxide. The method is specific, operates at room temperature, and requires sample aspiration and a DC power supply.
- Stannic Oxide--A sintered bulk semiconductor composed mainly of tin oxide. Semiconductor material and electrodes are deposited on a ceramic tubular former with an internal coil heater. Operation is at elevated temperature, approximately 300°C (572°F), and involves electrical resistance change due to chemical adsorption/desorption of gases. Requires constant voltage excitation of heater and sensor electrodes.

- Metal Oxide Silicon--A hot metal oxide silicon wire provides a carbon monoxide signal due to the oxidation of the metal layer. Sensitive in the 10 to 50 ppm range and rechargeable by purging with carbon monoxide free air. Disadvantages include: necessity for purge (several minutes); responds also to hydrocarbons.

Dry catalytic methods of possible interest for furnace work include:

- Electrocatalytic Electrode--Sample gas is absorbed on an electrocatalytic sensing electrode (maintained at suitable potential) after passing through a diffusion medium. Chemical reaction generates a proportional electric current. Device is sensitive (0 to 100 ppm range) and specific, but costly.
- Mixed Oxides--Involves carbon monoxide oxidation using a catalyst (e.g., Hopcalite) and an electrical measuring bridge. A temperature sensor, such as a thermistor, is encapsulated in the catalyst and forms one leg of the bridge. Oxidation of carbon monoxide changes bridge balance, providing an indication of carbon monoxide concentration.

Colorimetric methods of gas detection generally are for one use only and give qualitative readout. Salts, which change color on exposure to the gas of interest, are contained in sealed glass tubes. For measurement, the seals are broken and the sample gas is passed through the tube. The degree of color change is read from a scale on the tube. Chloro-platinic salts have been developed for carbon monoxide sensing; the tubes are low cost and discarded after use.

SECTION 5.0

HARDWARE DESCRIPTION

5.1 FEASIBILITY MODEL

A feasibility model of the Furnace Efficiency Test Set was designed and built prior to construction of six prototype models. This model, shown in Figure 5-1, was used for engineering evaluation, with major emphasis on developing the smoke and oxygen sensors. Electronically, this model was built around a Motorola microprocessor kit modified to interface with sensors. The microprocessor contained 16K bytes of memory, although only 10K were used. The device was programmed in FORTRAN language, and a keyboard was provided for data monitoring and modification. Seven-segment displays provided readout of sensed values (flue gas temperature, smoke number, oxygen percent) and a calculated value of furnace efficiency. A display, located above the keyboard, gave indication of microprocessor operations. A meter was used to monitor and control the flow of sample gas through the smoke chamber (nominally 2 liters per minute). The instrument was air cooled by a fan located within the carrying case.

The feasibility model included a probe for insertion into the flue gas stream. This probe contained sensors for measuring flue gas smoke density, oxygen concentration, and temperature, and was connected to the instrument carrying case by wiring and 1/4-inch-diameter tubing for aspirating the smoke sensor. When not in use, the probe was stored in the carrying case.

Figure 5-1. Feasibility Model, Furnace Efficiency Test Set

5.2 PROTOTYPE MODEL

The prototype model, shown in Figure 5-2, represented a redesign of the feasibility model. Note that the keyboard was eliminated and the front panel was otherwise simplified. The redesigned probe also is shown in Figure 5-2.

5.2.1 Mechanical Configuration

A close-up view of the prototype model and stowed probe is shown in Figure 5-3. Four banks of three-digit LEDs are used to display percent furnace efficiency, percent flue gas oxygen concentration, flue gas temperature, and Bacharach Smoke Number. The display is tilted for easier viewing, and a fuel select switch is provided for operator selection of the appropriate setting for the fuel being used; i.e., oil, natural gas, or propane. Other switches serve to activate the instrument and to change the percent efficiency reading to a net basis.

Three LED indicators provide instrument status monitoring. READY indicates that the oxygen sensor is at operating temperature (about 5 minutes of warm-up time is required for the prototype model); HEATER ALARM indicates an overtemperature (above 704°C/1300°F) status of the oxygen sensor with resultant disconnect of its heaters; FAULT monitors several conditions arising from instrument and probe malfunctions.

Three pushbutton switches are provided on the front panel of the instrument, two for CLEAR and RESET functions, the third for computer referencing to instrument zero before making a smoke measurement.

The probe, shown in stowed position in Figure 5-3 and hand-held in Figure 5-4, consists of a handle, oxygen sensor, smoke sensor, with electronics, temperature sensor, and a ventilating fan for the smoke sensor electronics. The ventilated housing of the oxygen sensor is located opposite the probe's handle; the white

Figure 5-2. Prctctype Model, Furnace Efficiency Test Set

Figure 5-3. Prototype Model With Stowed Probe

Figure 5-4. Prototype Model Probe, Furnace Efficiency Test Set

envelope adjacent to the handle houses the smoke sensor; the slender tube-like appendage at right angles to the device contains the flue gas temperature sensor--a thermocouple placed in the appendage tip. Its beaded extension wires are routed through the hollow member to a chrome/alumel junction strip prior to transmission through the 10-foot leads to the carrying case. The tip is of stainless steel and is electrically insulated from other probe elements.

The electronics for the smoke sensor are on a printed circuit board mounted within the perforated black plastic cover, which in turn is mounted on the white envelope containing the smoke sensor. This location minimizes noise pickup between the photodiode sensor and its high gain amplifiers.

Figure 5-5 is another view of the probe showing how the temperature-measuring appendage can be disconnected when stowing the probe in the carrying case.

The smoke sensor is shown in detail in Figure 5-6. The sensor itself is cylindrical and is controlled at elevated temperature to prevent water vapor condensation in the flue gas and the consequent interference in smoke detection. The smoke chamber is wrapped with insulating layers and heating tape. The electronics card (Figure 5-6) is mounted on the probe head to keep the signal transmission line short and minimize noise pickup. (The analog signal levels from the smoke detector are so low that noise can obscure them.) An amplifier gain of about 1 million increases the smoke signal to a level adequate for conversion to digital for input to the microprocessor. The cooling fan for the smoke detector electronics (also shown in Figure 5-6) provides 30-CFM airflow continuously as long as the instrument is energized.

Figure 5-5. Prototype Model Probe Showing Temperature Sensor Disconnect Feature

Figure 5-6. Protctype Model Probe Showing Smoke Sensor Detail

The flue gas oxygen, smoke, and temperature sensors are mounted on the probe to ensure maximum isolation of their separate thermal environments.

5.2.2 Electronics Design

Figure 5-7 is a block diagram of the Furnace Efficiency Test Set electronic subsystem showing location of the various sensors and the smoke detector electronics. Two of the three Type K thermocouple sensors--a flue gas temperature sensor and an oxygen heater temperature sensor--are located in the probe head, along with the smoke detector electronics. The remaining temperature sensor, which measures the ambient, is located in the carrying case. All three sensors are multiplexed into the carrying case electronics using a differential integrated circuit chip specially designed for the thermocouple applications. As each sensor is multiplexed, a 0°C (32°F) reference junction is fed to an instrumentation amplifier that scales the thermocouple range to between 0 and 10 volts--the maximum value for the analog-to-digital (A/D) converter. Once scaled, the output representing temperature is fed to another multiplexer, which sequentially selects the oxygen and smoke signals for digital processing by an A/D converter.

The smoke sensor output is a low-level signal from a photodiode. A preamplifier is mounted next to the photodiode to minimize noise and provide amplification before coupling to the smoke detector electronics board. The first three stages of the smoke detector electronics have a gain of 1 million. The output has a signal-to-noise ratio of approximately two to one. The following stage is a synchronized rectifier that gates the smoke signal at a 1 KHz rate, thereby eliminating much of the system noise--especially the 60 cycle portion. Following the rectifier is an integrator with a 10-second time constant. This stage has a gain of approximately 100 and includes a shaping circuit that gives a full-scale output over the 0 to 9 Bacharach range. The slowly varying DC output from the integrator is fed to a buffer amplifier and then through 10 feet of cable to the analog multiplexer located in the carrying case.

Figure 5-7. Electrical Block Diagram, Furnace Efficiency Test Set

The oxygen sensor output is fed directly to an instrumentation amplifier in the carrying case, which scales the output to 10 volts. The scaled output is fed to the analog multiplexer for sequential data processing via the A/D converter.

Approximately once every second, each of the five sensor analog signals is converted into an 8-bit digital word by the A/D converter. The 8-bit resolution, one part in 256, allows a temperature increment of approximately 2.8°C (5°F), a smoke number increment of 0.2, and an oxygen increment of 0.4 percent.

As the 8-bit word is fed to the microprocessor every second, algorithms placed in the memory of the microprocessor convert this raw data into meaningful information that can be displayed to the operator. Two separate algorithms, one for oxygen and one for temperature, are combined for the calculation of furnace efficiency. The algorithm for Bacharach Smoke Number consists of two straight line segments divided at approximately 4 Bacharach. The algorithms and their constants are described in Appendix A.

Five 100-watt piston heaters maintain the oxygen sensor at approximately 566°C (1050°F). Power for these heaters is controlled by an opto-isolated triac, which in turn is controlled by the microprocessor in a closed-loop system. A thermocouple monitoring the temperature at the zirconium oxide sensor wafer is a part of this closed-loop system. The microprocessor, which monitors this thermocouple, keeps the heater between 538 and 593°C (1000 and 1100°F) by ON-OFF control of the triac heater. In case of failure in the heater control, an overtemperature circuit will de-energize the heaters. This circuit is energized directly from the heater thermocouple. When the instrument is first turned on, the heater control applies a steady voltage to the heaters until the temperature reaches approximately 350°C (1562°F). At this point, the heaters are pulsed at a 20 percent duty cycle to maintain this temperature. Pulsing prevents a large overshoot in temperature, which can damage the zirconium oxide sensor.

LED display information is fed directly from the microprocessor input/output (I/O) port via the segment and digit encoders/drivers. The displays are Monsanto MAN 74, which are updated by the microprocessor every one millisecond.

To minimize design effort, the electronics were developed using existing microprocessor boards from Motorola. Two such boards, each 9-3/4 inches by 5-3/4 inches, fit into a Motorola card rack. An additional Honeywell-designed and -built card is also contained in the rack. This card houses the analog circuitry, which interfaces the sensors to the microprocessor. Figure 5-8 shows the electronic card assembly.

DC voltages for the digital electronics were obtained using a commercial, triple-output power supply. Molex-type cables distribute power to the card rack, relays, and probe head.

Analog and logic grounds were separated to eliminate digital logic noise from interfering with the analog amplifiers. A separate DC module power supply was used to provide the necessary voltages for the analog circuitry.

5.2.3 Microprocessor Subsystem

The microprocessor consists of two subsystems--the microprocessor unit (MPU) and the memory modules. The MPU is contained on one Motorola micro-module board and is designated M68M01A. This unit provides 1K of RAM, up to 4K of AROM or 4/8K of ROM for programming, two programmable Peripheral Interface Adapters (PIAs) for parallel data transfers, and one Asynchronous Communications Interface Adapter (ACIA) for RS-232C compatible serial data transfers. The board incorporates the necessary two-phase clock generator, the reset timer for power-on initialization, address bus decoding for establishing the address for each part, and the refresh circuit for use with optional external dynamic memories such as the M68MM04. The board is also bus compatible with the M6800 EXORciser. This added versatility permits easy development and debugging of both hardware and software.

Figure 5-8. Card Rack Assembly, Furnace Efficiency Test Set

The memory board is the Motorola M68MM04, which has capacity for 16K bytes that are addressable from the MPU unit. Figure 5-9 shows a block diagram of this board. The memory elements are arranged into two blocks, each containing sockets for up to eight 1024- x 8-bit AROM devices. Each device within the two memory blocks is connected to buffered address and data buses. Modules having all 16 sockets (16K memory) are assigned memory locations A000 through DFFF. In these modules, the first memory block is assigned address locations C000 through DFFF. Bits AS0, AS1 and AS2 on the address select bus are used to assign the address to the first address of the second address block. The memory select decoder receives address bits A10 through A15 to determine which memory block is being addressed.

This decoder also receives a high-level valid memory address (VMA) signal to indicate that the address is valid. Data stored at that address location is then loaded into the data bus by the high-level R/W signal when the oxygen signal is received.

Figure 5-9. 8K/16K AROM/ROM Module Block Diagram

SECTION 6.0

DESIGN PROBLEMS

6.1 OXYGEN SENSOR

Several problems were encountered in adapting the zirconium oxide sensor to the needs of the Furnace Efficiency Test Set. These, and the solutions to them, are described briefly in the following paragraphs.

6.1.1 Lead Attachments

Initially, the oxygen sensors were supplied by the vendor with a spring-type connection that fit over the platinum runner. A photograph of this sensor is shown in the lower right hand corner of Figure 4-4. After a prolonged period of heating, this type of connection would make intermittent contact and cause erratic output. The vendor then unsuccessfully tried several methods of bonding to the platinum. Either the leads would burn off or the bond would loosen. Finally, a high-temperature bond using silver solder was employed successfully. Meanwhile, Honeywell developed a mechanical connection to the platinum using tantalum leads, which also worked well.

6.1.2 Lead Grounding

Oxygen sensors as first supplied were made with a grounded electrode for use in a single-ended amplifier configuration. Since the Furnace Efficiency Test Set operates in the differential mode to take advantage of common mode rejection, it was necessary to have both platinum electrodes separate from ground. The vendor achieved this by adding a high-temperature insulator to electrically separate the platinum electrode from ground (a mounting bolt).

6.1.3 Sensor Output Characteristic

Output of the oxygen sensor when newly made is prone to drifting without a "burn-in" at elevated temperatures. Upon return to operating temperature, the sensor output will be constant, but not necessarily the same value from sensor to sensor. This variation, from 1 to 10 millivolts, requires electrical compensation on an individual sensor basis. The sensor output is also temperature dependent, requiring either close control of its operating temperature or electrical temperature compensation. The former approach has been used on the Furnace Efficiency Test Set using a proportional temperature control with heat supplied in steps at an optimum cycle rate.

6.1.4 Sensor Interfering Gases

Honeywell tests to determine the effects of trace combustion gases on the zirconium oxide sensor have indicated the following:

- Sulfur dioxide (1 percent concentration)--The sensor impedance decreases and the sample electrode becomes more negative (as with decreasing oxygen concentration). Normal response returns upon removal of the sulfur dioxide. The effect is decreased as sensor temperature is increased and when the platinum surface area is decreased.
- Formation of sulfuric acid film on the sensor upon cooling.
- Nitrogen oxides--No effects on sensor output were noted for various oxygen concentrations at nitrogen oxide concentrations up to 0.4 percent (sensor temperatures of 700 and 800°C (1292 and 1472°F)).

6.2 SMOKE SENSOR

Problems encountered in the development of the smoke detector are summarized below.

6.2.1 Moisture Condensation

Flue gas water vapor caused erratic signals from the smoke sensor before heating of the smoke chamber was tried. Elimination of this difficulty was brought about by thermostatically controlling the envelope of the smoke chamber at 60°C (140°F) to prevent condensation of water vapor in the smoke sensor.

6.2.2 Temperature Sensitivity

Before installing windows between the smoke chamber and the LED light source and photodetectors, the analog smoke signal would drift after a few minutes of operation. The windows isolated these temperature-sensitive components from the heated flue gas in the smoke chamber.

6.2.2.1 Random Drift--With only a single LED as the light source, the signal-to-noise ratio is no better than two to one. As a consequence, the electronics are susceptible to noise, and a slight random drift occurs with time. To compensate for this drift, a potentiometer was added for operator adjustment of the electronics prior to flue sampling. This potentiometer is located on the side of the probe head.

6.2.2.2 Air Leakage--The first prototype models had a problem with air leakage around the end caps of the smoke sensor, causing the smoke pump to overload to maintain the 2-liter-per-minute sample gas flow. To alleviate this problem, rings were placed on the end caps of the smoke cylinder.

6.2.2.3 Heat Tape Effect--There was an increase in temperature at the LED mounting plate caused by temperature cycling of the heat tape with the Klixon thermal control. The temperature excursion went from +140°F to approximately +190°F and caused the closed-loop control to become ineffective. To lower temperature at the LED, an insulation barrier was placed between the cylinder and the LED mounting block. This insulation barrier included a layer of Fiberfax with alternate layers of aluminum foil.

SECTION 7.0
POTENTIAL DESIGN IMPROVEMENTS

A feasibility model and six prototype models of the Furnace Efficiency Test Set were designed and built during the program. These models used conventional temperature measuring techniques, an adaptation of a relatively new type oxygen sensor, a new development in smoke detection and transduction to Bacharach Smoke Number, and a unique method for computation of furnace efficiency. Testing to date has substantiated the basic design selection and identified areas where improvements can be made pursuant to a design suitable for field use by burner service companies. These areas include the smoke sensor (if required) with its electronics, the oxygen sensor, and certain changes in the electronics and packaging of the instrument. More specifically, the recommended improvements are:

- Smoke Sensor--Improve signal-to-noise ratio;
- Oxygen Sensor--Reduce heating power;
- Electronics--Reduce complexity, with attendant size and power reduction;
- Null indication for maximum efficiency on residential furnaces.

These design improvements are discussed more fully in the following paragraphs.

7.1 SMOKE SENSOR

With present design of the smoke sensor, the signal-to-noise ratio is marginal. The present and proposed designs of the smoke chamber optics are shown in Figures 7-1 and 7-2, respectively. The proposed design captures the smoke-scattered light through an annular portion of a lens rather than through a single window, as with the present design. The light-capturing area is increased from 0.03 to 2.40 square inches with a 1.75-inch-diameter lens; the optical gain is increased 80-fold and provides a corresponding increase in the photodiode signal sensor output. Previous analyses and tests have shown that a single LED light source is adequate for illuminating the smoke chamber. Also, the use of a light-source-monitoring photodiode, i.e., "servo sensor" (Figure 7-1), to provide a compensating signal in case of illumination deterioration will be retained in the proposed design.

The electronics for the next-generation smoke detector are shown in Figure 7-3. Light scattered from the smoke particles would be detected by the photodiode signal sensor; the current generated by the photodiode would be fed into a high-gain preamplifier, which would be located as close as possible to the photodiode to minimize noise pickup; the buffered output from the preamplifier then would be coupled to high-gain amplifiers located on the main circuit board. To further minimize noise, a synchronous rectifier would be used to gate the signal at a 1 KHz rate. This gated signal, representing smoke density, would be integrated to obtain a voltage level needed for digital processing. The integrator circuit also would contain a wave-shaping network to tailor the smoke curve to the desired function. This function would be placed in the computer for data comparisons.

Figure 7-1. Present Smoke Chamber Design

Figure 7-2. Proposed Smoke Chamber Design

Figure 7-3. Smoke Sensor Electronics Block Diagram

7.2 OXYGEN SENSOR

Figures 7-4 and 7-5 show the present and proposed zirconium oxide oxygen sensors, respectively. The proposed sensor is smaller, lighter, requires less heating power, and operates at a lower voltage. The present sensor, with its spark-plug-type mount, requires inordinate heating because of its thermal mass. The proposed design would reduce this mass, using only the zirconium oxide sensing element from the present design. It is expected that the proposed design can be heated with 50 watts from a 5-volt supply, as compared with the 500 watts from a 120-volt supply presently used.

Figure 7-4. Present Oxygen Sensor Design

Figure 7-5. Proposed Oxygen Sensor Design

7.3 ELECTRONICS

A block diagram of the electronics for the proposed design is shown in Figure 7-6. Emphasis is placed on miniaturization, low power consumption, and low cost. A single-chip microprocessor is proposed for control and arithmetic functions. Analog signals from the sensors will be converted to digital format for processing using a voltage-frequency converter (VFC). Contrasted to the present A/D converter, the VFC requires only a single voltage, needs only one line to the microprocessor, has its own reference source, and costs less. It is slower than the A/D converter, but quite adequate for this application.

A single port from the microprocessor is attached to the display. This display will be used for all parametric readouts using a DISPLAY SELECT switch. The display will be driven by a seven-segment latch/driver. The latch mode of display is preferred over the multiplexed mode to conserve memory. Memory capacity will be that of the single-chip microprocessor--2K bytes of ROM and 64K bytes of RAM.

The electronics is contained on a single circuit board small enough to fit into a single package design. DC power is distributed from "on-board" regulators supplied from a low voltage transformed AC source. It is expected that the power requirement for the electronics will be within 5 watts.

A schematic of the analog electronics is shown in Figure 7-7. The reference junction for temperature sensing by thermocouple is one developed by Honeywell that is accurate to within $\pm 1^{\circ}\text{C}$. Because the analog signals from the sensors are low level, instrumentation amplifiers are used to scale the voltages to the levels required for processing. These amplifiers are characterized by their high gain, excellent linearity, and very low offset currents.

Figure 7-6. Proposed Electronics Block Diagram

Figure 7-7. Proposed Analog Circuit Schematic

SECTION 8.0

MARKETING ANALYSIS

As part of the Furnace Efficiency Test Set development program, a survey of furnace dealers was conducted and a commercialization plan was developed. The survey was conducted by questionnaire to elicit opinion from furnace servicemen on a nationwide basis regarding desired device features. The commercialization plan was developed by Honeywell to indicate market potential, projected energy savings through device use, and development status of the device. Details regarding the survey and its results are given below, as is the commercialization plan.

8.1 SURVEY

The Honeywell Residential Division sent 1600 copies of a questionnaire to field offices and furnace service dealers throughout the United States to determine what form, function, and cost parameters were desired by potential users of the test set. The 237 responses represented some 600,000 units serviced per year by about 1700 service personnel. Figure 8-1 is a copy of the questionnaire, and its letter of transmittal is shown in Figure 8-2. The survey results are tabulated in Table 8-1.

The recommendations for parameter readouts are hardly surprising except for the desire to indicate nitrogen oxides and hydrocarbons by personnel servicing gas furnaces. Also as expected was the request for carbon monoxide measurement by gas servicemen and the indifference shown by oil servicemen. The desire for smoke number readout was more evident among oil burner service people. Expected improvement in furnace efficiency by use of the test device varied from 15 to 19 percent throughout the survey. The suggested selling price of the test device was indicated to be in the range of \$165 to \$195.

Please answer as many items as possible.

Parameter	Should be measured?			Should be displayed?			Accuracy	Range
	Yes	No	Nice-but not required	Yes	No	Nice-but not required	% or absolute	
Flue Gas								
Temperature								
CO ₂								
O ₂								
CO								
NO _x								
HC								
Smoke Number								
Efficiency								
Net								
Gross (standard)								

Max Weight _____ lbs.

Max Cable Lengths _____ ft.

Unit Purchase Price Range \$ _____

If above device available, what is the potential market at your facility? _____ devices

Expected furnace efficiency improvement _____ %

Readout _____ Digital Display _____ Meter

Printout _____ Yes _____ No

mv output for recorder _____ Yes _____ No

Alarm if used on unit permanently _____ Yes _____ No

Figure 8-1. Furnace Efficiency Equipment Questionnaire

To:

From:

Director of Marketing
Honeywell Residential Division
Honeywell, Inc.

Sir:

Conserving energy in residential and commercial buildings is a high-priority problem for the United States. Fossil fuel-fired residential and commercial heating equipment presently consumes about 25 percent of the U.S. gas and oil yearly supply. Finding a way to achieve fuel savings at the point of consumption can be achieved by increasing the efficiency of the heating equipment. Recent field tests, coupled with appropriate analysis techniques, have shown that many heating systems are not operating at an average seasonal efficiency as high as possible within the design of the equipment.

The availability of an effective means to adjust boilers and furnaces can significantly impact the critical heating fuel shortages such as experienced during the winter of 1977. Honeywell has been developing the sensor technology and has a research model of an instrument that will allow the rapid, accurate, cost-effective adjustment of oil and gas-fired boilers and furnaces.

To ensure that a test device suitable for use by furnace servicemen is brought to the market as quickly as possible, the Energy Research and Development Agency (ERDA) of the United States has funded Honeywell to design, develop and commercialize a portable device that will allow for the fast, accurate adjustment of gas and oil-fired furnaces or boilers used in residential and small commercial buildings.

To ensure that the test device has the proper form and function to permit wide spread acceptance, we are asking potential users of such a device to provide input early in the development program to aid in the device design.

To obtain this data, we are asking you to please fill out the attached questionnaire and return in the enclosed envelope. Your cooperation is appreciated and if you wish a copy of the survey, we will be glad to send it.

Thank you.

Figure 8-2. Transmittal Letter, Furnace Efficiency
Equipment Questionnaire

Table 8-1. Furnace/Boiler Efficiency Survey Results

PARAMETER	D E A L E R S		
	GAS ONLY	OIL ONLY	GAS AND OIL
NUMBER RESPONSES	13	43	181
NUMBER OF UNITS SERVICED PER YEAR	32,275	195,779	384,584
NUMBER OF SERVICE PERSONNEL	54	481	1,229
DRAFT (PERCENT YES)	89	98	99
TEMPERATURE (PERCENT YES)	100	98	99
CO ₂ (PERCENT YES)	100	98	98
O ₂ (PERCENT YES)	67	32	76
CO (PERCENT YES)	89	6	78
NO _x (PERCENT YES)	57	0	49
HC (PERCENT YES)	57	6	47
SMOKE NUMBER (PERCENT YES)	50	98	99
EFFICIENCY (PERCENT YES)	100	95	98
MAXIMUM WEIGHT (AVERAGE) - 165	10	9	12
AVERAGE MAXIMUM CABLE LENGTH	8 FEET	9 FEET	11 FEET
AVERAGE UNIT PURCHASE PRICE	\$ 163.	\$ 168.	\$ 196.
NUMBER OF UNITS DESIRED	32	250	640
EXPECTED FURNACE/BOILER EFFICIENCY IMPROVEMENT (PERCENT)	19	15	16
WANT DIGITAL READ OUT (PERCENT YES)	78	76	74
PRINTOUT DESIRED -- (PERCENT YES)	27	38	40
MV OUTPUT FOR RECORDER (PERCENT YES)	16	31	48

8.2 MARKETING ANALYSIS

8.2.1 Alternative Market Scenarios

Three residential market scenarios developed for the furnace efficiency test device can be summarized as follows:

- Baseline--No change in present laws, regulations. Decision to have furnace efficiency measured would be voluntary on the part of the consumer.
- Acceleration Due to National Energy Act (NEA)--Utilities and heating fuel dealers would offer information on obtaining furnace efficiency test in connection with the consumer information program required by NEA (National Energy Conservation Policy Act, Title II).
- State "Red Tagging"--States that are large energy consumers in residential sector heating would pass laws requiring furnaces/boilers to be checked for efficiency.

8.2.1.1 Baseline--During the fourth quarter of 1977, Honeywell conducted a market survey for the furnace efficiency test device with probable users, including utilities and heating suppliers who service residential oil- and gas-fired furnaces and boilers.

Data obtained in the survey were applied to a total potential market estimate based upon the assumptions in Table 8-2. Assuming that one serviceman equipped with a furnace efficiency test device could test 350 units per year, the potential U.S. (residential) market is on the order of 54,000 servicemen.

Survey respondents were asked to estimate an acceptable price range for the proposed test device. Applying their responses to the potential market (Table 8-2) results in the estimates shown in Table 8-3. The data in Table 8-3 suggest that while a large percentage of potential users (nearly 90 percent) would buy the device voluntarily if it sold for \$100, only a small percentage (around 5 percent) would buy it voluntarily if the selling price was \$500 or more. The number of furnace efficiency test devices sold by any one company would, of course, be a portion of the quantities shown in Table 8-3, in accordance with their market share.

Data in this scenario do not include estimates for spares or for units sold in connection with industrial or commercial applications.

8.2.1.2 Acceleration Due to National Energy Act (NEA)--The effect of the NEA on the market for furnace efficiency testing is expected to come principally via the Utility Program contained in Title II of the National Energy Conservation Policy Act, enacted November 9, 1978. That legislation requires that regulated utilities (and home heating suppliers, at the state governor's option) inform residential customers by January 1, 1980, of energy conservation measures that may be taken in the home. The NEA specifically mentions furnace efficiency modifications in connection with the Utility Program, and permits utilities and heating suppliers to arrange for such modifications.

Increased public awareness of furnace efficiency resulting from this program can be expected to increase public demand for testing. To quantify such an increase, it is necessary to use analogous "voluntary" market situations as models. The voluntary market is defined as that part of the market which is based only upon advertised advantages rather than on any mandatory, legislated, or similar circumstance. Two voluntary markets that could serve as models are:

Table 8-2. Potential U.S. Residential Market

FUEL	TOTAL UNITS	FREQUENCY OF SERVICE	UNITS SERVICED PER YEAR
GAS	35,000,000	5 YEARS	7,000,000
OIL	12,000,000	ANNUALLY	12,000,000
T O T A L:			19,000,000

Table 8-3. U.S. Residential "Voluntary" Market

SELLING PRICE (DOLLARS)	TOTAL MARKET SIZE (DOLLARS IN THOUSANDS)
100	47.0
200	27.0
300	14.0
400	4.7
500	2.6

- Night setback thermostats,
- Smoke detectors in existing construction.

Through 1978, there was little or no mandatory requirement for the installation of night setback thermostats or for the installation of smoke detectors in existing residential construction. Both devices, however, were subjects of considerable advertising activity and a resultant high level of public awareness. Market penetration for these devices is estimated as follows:

	Estimated Cumulative <u>Market Share (Percent)</u>
• Night setback thermostats	4
• Smoke detectors in existing construction	22

Since furnace efficiency modification and testing is not high in public awareness at present, the above market penetration figures represent a reasonable estimate of the voluntary penetration which could occur due to increased public awareness under the NEA Utility Program. The 4 percent market penetration associated with night setback thermostats is roughly analogous to the situation anticipated with furnace efficiency testing; both result in energy and cost savings to the consumer. The 22 percent market penetration associated with smoke detectors is based on a strong personal safety motivation and probably represents a maximum penetration.

8.2.1.3. State "Red-Tagging"--To develop a scenario in which furnace efficiency testing would be mandatory, the state "red-tagging" concept was developed. Under this concept, states with high heating fuel usage in the residential

sector would enact legislation requiring furnace/boiler efficiency testing at periodic intervals, and perhaps modifications to ensure that certain minimums are met.

Table 8-4 shows the basic data, obtained from gas and oil heating industry sources, used to develop this scenario.

High heating fuel usage might be defined in terms of total residential sector usage in a state, or alternatively, high heating fuel consumption by individual residences in a state (high fuel bills). Table 8-5 shows the rankings of the top 12 (selected arbitrarily) states in each category. It shows that "red tagging," if implemented in only 12 states having the highest total heating consumption in the residential sector, would nonetheless affect those states which account for approximately 72 percent of the national residential heating consumption. Alternatively, if "red tagging" were applied to those 12 states where individual units consume the most fuel, approximately 46 percent of the nation's residential sector would be affected.

Tables 8-6 and 8-7 further develop these 12 state scenarios to arrive at an estimated market for furnace efficiency meters. Two major assumptions are involved:

- Oil-fired furnaces/boilers are required to be checked each year; gas-fired furnaces/boilers are required to be checked every 5 years.
- One serviceman with a furnace efficiency meter can check 350 furnaces and boilers per year.

Obviously some phase-in situation would occur as states passed "red-tagging" legislation and/or allowed an extended period for the first round of efficiency testing to be completed. The estimates in Tables 8-6 and 8-7 represent a

Table 8-4. Residential Heating in States*

STATE	STATE TOTAL CONSUMPTION MMBTU PER YEAR	ANNUAL CONSUMPTION (MMBTU PER HEATING UNIT) (RANK IN TOP 12)	NUMBER OF OIL UNITS	NUMBER OF GAS UNITS
NEW YORK	552	154 (4)	1,980,862	1,640,566
CALIFORNIA	480	77	50,714	6,174,978
ILLINOIS	421	187 (1)	444,845	1,805,176
OHIO	373	139 (8)	258,213	2,416,175
MICHIGAN	331	136 (10)	459,524	1,965,243
PENNSYLVANIA	324	132	1,303,004	1,166,822
NEW JERSEY	261	133 (12)	1,109,709	834,932
MASSACHUSETTS	219	141 (7)	1,209,495	338,448
TEXAS	172	69	35,405	2,468,467
WISCONSIN	153	136 (11)	391,769	734,184
MISSOURI	143	129	103,980	1,008,252
MINNESOTA	107	122	332,304	342,492
INDIANA	92	76	271,969	931,458
CONNECTICUT	89	117	180,020	589,077
ILLINOIS	80	124	127,852	519,471
MARYLAND	77	82	417,974	522,210
KANSAS	68	129	9,605	520,739
OKLAHOMA	66	114	9,312	567,524
VIRGINIA	63	90	330,552	362,672
WASHINGTON	63	91	432,775	257,229
COLORADO	62	94	24,906	634,032
GEORGIA	61	80	50,367	719,290
N. CAROLINA	57	94	354,151	259,462
KENTUCKY	53	101	44,772	478,474
UTAH	52	158 (2)	31,489	300,242
NEBRASKA	45	143 (6)	44,556	271,139
WEST VIRGINIA	38	116	24,790	302,624
TENNESSEE	36	100	50,571	311,482
ALABAMA	35	81	15,338	413,947
LOUISIANA	31	86	18,441	343,419
NEW HAMPSHIRE	29	108 (9)	182,229	26,383
NEW MEXICO	28	115	6,699	239,697
OREGON	27	63	238,396	192,453
MAINE	23	104	217,267	4,093
MISSISSIPPI	21	74	5,160	275,576
S. CAROLINA	20	76	81,451	175,347
RHODE ISLAND	19	101	181,039	84,767
WASHINGTON, D.C.	19	102	94,439	87,183
MONTANA	18	100	21,445	158,677
IDAHO	17	100	89,674	76,554
S. DAKOTA	15	129	43,034	76,618
ARIZONA	15	40	17,022	357,899
N. DAKOTA	14	121	53,505	64,131
DELAWARE	14	110	80,476	46,496
VERMONT	12	154 (3)	69,443	7,534
NEVADA	9	58	24,110	116,347
FLORIDA	6	19	215,007	110,006
WYOMING	5	150 (5)	11,449	29,667
ARKANSAS	2	110	6,681	15,063

* SEE APPENDIX C

Table 8-5. Summary Rankings, 11-29-78

STATE TOTAL HEATING CONSUMPTION IN BTU'S PER YEAR	
<ol style="list-style-type: none"> 1. NEW YORK 2. CALIFORNIA 3. ILLINOIS 4. OHIO 5. MICHIGAN 6. PENNSYLVANIA 7. NEW JERSEY 8. MASSACHUSETTS 9. TEXAS 10. WISCONSIN 11. MISSOURI 12. MINNESOTA 	$\frac{3536 \times 10^{12}}{4917 \times 10^{12}} = 72 \text{ PERCENT OF NATIONAL HEATING CONSUMPTION}$
ANNUAL HEATING CONSUMPTION FOR AVERAGE RESIDENTIAL UNIT	
<ol style="list-style-type: none"> 1. ILLINOIS 2. UTAH 3,4. VERMONT, NEW YORK 5. WYOMING 6. NEBRASKA 7. MASSACHUSETTS 8. OHIO 9. NEW HAMPSHIRE 10. MICHIGAN 11,12. WISCONSIN, NEW JERSEY 	$\frac{2453 \times 10^{12}}{4917 \times 10^{12}} = 50 \text{ PERCENT OF NATIONAL HEATING CONSUMPTION}$

Table 8-6. Heating Fuel Consumption, State Residential Total

STATE	TOTAL CONSUMPTION (MMBTU PER YEAR)	NUMBER OF OIL	NUMBER OF GAS	NUMBER UNITS CHECKED IN ANY ONE YEAR ¹	FURNACE EFFICIENCY METERS ²
NEW YORK	552	1,980,862	1,640,566	2,308,975	6,597
CALIFORNIA	480	50,714	6,174,978	1,285,710	3,673
ILLINOIS	421	444,845	1,805,176	805,880	2,302
OHIO	373	258,213	2,416,175	741,448	2,118
MICHIGAN	331	459,524	1,975,243	854,573	2,442
PENNSYLVANIA	324	1,303,004	1,166,822	1,536,368	4,390
NEW JERSEY	261	1,109,709	834,932	1,276,695	3,648
MASSACHUSETTS	219	1,209,495	338,448	1,277,185	3,649
TEXAS	172	35,405	2,468,467	529,098	1,512
WISCONSIN	153	391,769	734,184	538,606	1,539
MISSOURI	143	103,980	1,008,252	305,630	873
MINNESOTA	107	332,504	542,492	441,002	1,260
T O T A L	3,536 (72 PERCENT OF ALL STATES)	7,680,024	21,105,735	11,899,650	34,003

¹ ASSUME ALL OIL FURNACES AND 20 PERCENT OF GAS FURNACES CHECKED IN ANY ONE YEAR FOLLOWING FEDERAL LEGISLATION REQUIRING STATES WITH HIGH HEATING OIL USAGE TO IMPLEMENT "RED TAGGING."

² ASSUME ONE FURNACE EFFICIENCY METER CAN CHECK 350 FURNACES/BOILERS PER YEAR.

Table 8-7. Heating Fuel Consumption, Average Residential

STATE	AVERAGE RESIDENTIAL UNIT ANNUAL CON- SUMPTION (MMBTU)	NUMBER OIL	NUMBER GAS	NUMBER UNITS CHECKED IN ANY ONE YEAR ¹	FURNACE EFFICIENCY METERS ²
ILLINOIS	167	444,845	1,805,176	805,880	2,302
UTAH	158	31,489	300,242	91,537	262
VERMONT	154	69,443	7,534	70,950	203
NEW YORK	154	1,980,862	1,640,566	2,308,975	6,597
WYOMING	150	11,449	29,667	17,382	50
NEBRASKA	143	44,556	271,139	98,784	282
MASSACHUSETTS	141	1,209,495	338,448	1,277,185	3,649
OHIO	139	258,213	2,416,176	741,448	2,118
NEW HAMPSHIRE	138	182,229	26,383	187,505	536
MICHIGAN	136	459,524	1,975,243	854,573	2,442
WISCONSIN	136	391,769	734,184	538,606	1,539
NEW JERSEY	133	1,109,709	834,932	1,276,695	3,648
T O T A L		6,193,583	10,379,689	8,269,520	23,628

¹ ASSUME ALL OIL FURNACES AND 20 PERCENT OF GAS FURNACES CHECKED IN ANY ONE YEAR FOLLOWING FEDERAL LEGISLATION REQUIRING STATES WITH HIGH HEATING OIL USAGE TO IMPLEMENT "RED TAGGING."

² ASSUME ONE FURNACE EFFICIENCY METER CAN CHECK 350 FURNACES/BOILERS PER YEAR.

steady-state condition, i.e., the number of furnace efficiency meters needed to make the required measurements after the phase-in period.

8.2.1.4. Summary--Figure 8-3 summarizes the data from the alternative market scenarios.

8.2.2 Required Products/Sales Volume

For a market area with known selling expenses, G&A and other cost factors, and profitability requirements, annual volume requirements can be estimated if initial investment, unit cost, and permissible selling price are known.

For the furnace efficiency meter developed under the present contract, the following assumptions have been made:

- Market--Devices are sold to wholesalers/distributors, who in turn sell to utilities and heating fuel dealers.
- Total Investment--Approximately \$700,000, assuming no further government participation.
- Factory Unit Cost--Estimated at \$450.

To meet minimum profitability requirements, while at the same time keeping selling price down by assuming minimum customary markup, the following example is representative:

<u>Selling Price</u>	<u>Minimum 5-Year Volume</u>
\$675	28,300
\$720	13,644

Figure 8-3. Furnace Efficiency Meter Residential Markets

The minimum 5-year volumes shown above are the number of units that must be sold by the organization making the original \$700,000 investment. The total market must be accordingly higher, in proportion to that company's market share. For example, a 70 percent market share would imply that a minimum market of 40,400 units would have to exist at the \$675 selling price, and a market of 19,500 units would be required at the \$720 selling price.

This analysis results in several conclusions for the residential market:

- At a projected \$675 to \$720 selling price to the distributor, the selling price for the furnace efficiency meter is significantly higher than the original market survey indicated would be appropriate to a "voluntary" market.
- The required 5-year market volumes at the probable selling price are significantly greater than would be absorbed by a "voluntary" market.
- The "red-tagging" scenarios would produce markets for furnace efficiency meters of a size that could be potentially profitable.

Figure 8-4 shows the relationship between these required volumes and the "voluntary" and "red-tagging" scenarios shown earlier in Figure 8-3.

8.2.3 Projected Energy Savings

8.2.3.1 Consumer Savings--From the consumer's point of view, furnace efficiency testing should have a reasonable payback. To evaluate this potentiality, the following scenario was postulated:

- The consumer saves twice the cost of the furnace efficiency test service call before it must be repeated.

Figure 8-4. Furnace Efficiency Meter Residential Markets
Volume Relationship

- The payback criteria should, at a minimum, be viable in the states proposed for the "red-tagging" scenario based upon high energy usage per unit.

Cost of Service Call--Based upon 1978 service rates in Minneapolis, it is estimated that a half-hour service call for furnace efficiency testing and excess air adjustment could be accomplished for a cost to the consumer of \$25. This cost is assumed to include write-off of the furnace efficiency testing instrument within 1 year. An example calculation follows:

Labor--0.5 hour at \$44 per hour	=	\$22
Equipment write-off in one year	=	<u>\$ 3</u>
Total		\$25

Savings--Based upon the above criteria, a consumer in Wisconsin (the twelfth state in the high-unit-usage "red-tagging" scenario) should be able to realize a \$50 or greater savings before the furnace efficiency test must be repeated (1 year for oil, 5 years for gas). Using current prices for fuel \$0.90 per gallon for oil and \$2 per MCF for gas) the average annual fuel bill for a residential unit in Wisconsin is \$875 for oil and \$272 for gas. For the Wisconsin consumer to realize a \$50 savings, the furnace efficiency test procedure must therefore result in a 6 percent improvement in efficiency for an oil furnace, or a 5 percent improvement for a gas furnace.

Conclusion--The above examples indicate the potential viability, from the consumer and the serviceman's points of view, of the furnace efficiency testing procedure. Preliminary data indicate that a 6 percent efficiency improvement for oil furnaces and a 5 percent improvement for gas furnaces are conservative figures. Further, this scenario would appear to allow the serviceman considerable flexibility with respect to writing off the cost of the furnace efficiency tester. For example, the serviceman could charge \$4 or \$5

per service call for equipment write-off (reflecting either a higher initial purchase price, or more rapid write-off) and still meet the consumer payback requirement described above.

8.2.3.2 Total Savings Due to "Red Tagging"--Table 8-8 shows the estimated annual energy and cost savings if "red tagging" were implemented. These annual savings data assume a 10 percent efficiency improvement for oil and 5 percent for gas, consistent with the consumer savings scenario above. Dollar savings were computed at \$0.90 per gallon for oil and \$2 per MCF for gas.

Table 8-8. Furnace Efficiency Meter Annual Savings
for "Red Tagging"

FUEL	12 HIGHEST UNIT USAGE STATES	12 HIGHEST TOTAL USAGE STATES
OIL		
ENERGY QUADS	0.0823	0.109
DOLLAR VALUE IN MILLIONS	\$ 529.	\$ 700.
GAS		
ENERGY QUADS	0.0753	0.122
DOLLAR VALUE IN MILLIONS	\$ 151.	\$ 245.
TOTAL		
ENERGY QUADS	0.158	0.232
PERCENT SECTOR ENERGY SAVED	7.0	6.6
DOLLAR VALUE IN MILLIONS	\$ 680.	\$ 945.

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SECTION 9.0

COMMERCIALIZATION PLAN AND EVALUATION

9.1 STATE OF DEVELOPMENT

9.1.1 Summary Description

Specifically, this instrument, a furnace efficiency meter, will be used for checking and adjusting oil- or gas-fired furnaces, boilers, etc., by analyzing the flue gas via smoke test, continuous oxygen, and temperature measurement. Motivation for developing such an instrument is the result of recent field test findings, which have shown that many heating systems are not operating at best efficiency. The three basic reasons for this lack of efficiency are:

- Exhaust flue gas temperature is too high,
- Firing rate is too high,
- Excess air level is too high.

Flue temperatures can be reduced by increasing the heat transfer surface area, reducing the firing rate, and minimizing excess air. The heat transfer surface area on residential furnaces is fixed; therefore, the only field adjustments available to servicemen are the firing rate and excess air level. The furnace efficiency meter can monitor related parameters and display results for optimum furnace adjustments.

The furnace efficiency meter consists of an analyzing instrument, a flue gas sampling unit, and an instrument cabinet. The analyzing instrument is contained in a metal cabinet and houses the microprocessor and sensor analog interface electronics.

The microprocessor and its memory contain an algorithm that relates flue temperature, oxygen, and smoke content to furnace efficiency. Mathematical computations of these variables are displayed on a light-emitting diode (LED) panel convenient for the serviceman.

The flue gas sampling unit contains a diaphragm pump, which draws the flue gas from the flue through an optical chamber that counts the smoke particles. This sampling unit (probe) also houses a ZrO_2 chip and heater that produces a voltage output equivalent to the amount of oxygen in the flue. Flue gas temperature is sensed using a thermocouple.

9.1.2 Questions Remaining to be Answered

9.1.2.1 Market--The principal areas of concern with respect to market feasibility are:

- How much energy can, in fact, be saved through residential furnace efficiency testing?
- In what locations would testing be most beneficial?
- What physical and performance characteristics should a residential furnace efficiency tester have? [Integrated or separate display, carbon monoxide (CO) sensing, hard copy printout *, etc.]
- Is smoke sensing really required?
- Can legislation requiring furnace efficiency testing be enacted?

*Hard copy printout is of questionable value because the meter is designed for use in adjusting for peak efficiency rather than for the precision with which the peak value is displayed.

- What selling price for the furnace efficiency test set will be acceptable in an environment where furnace efficiency testing is "required" rather than voluntary?

9.1.2.2 Technical--

- Can the smoke sensor be made to meet required sensitivity and reliability at an acceptable cost?
- Can the O₂ sensor be made at a substantially reduced cost with increased reliability?
- How can CO sensing/alarm be incorporated? Is real-time readout required?

9.3 PRODUCT DEVELOPMENT PLAN

9.3.1 Standard Development Process

A standard product development process for residential products is summarized below. Depending upon complexity of the development involved, the duration of Phases I through IV is typically 9 months to 3 years. Including the Phase 0 study, the total process could take as long as 7 years.

- Phase 0, Study -- Initiated when potential market exists or may exist in the future, but product specifics cannot be defined. This phase may include preliminary models to obtain user feedback on product feature set and/or to further refine estimates or actual market size.
- Phase I, Preparatory -- Initiated by a product development request from marketing, outlining preliminary feature set requirements,

estimated annual volumes, target factory costs/selling price and target dates. Work done in this phase may include additional model building, field studies, competitive analysis and subsystem development where technical feasibility remains an issue.

- Phase II, Producibility -- Initiated upon agreement between design and marketing on product specifications. Typically, unit cost is specified to within 15 percent and total investment within 20 percent at this point. Work done includes a detailed design of the product in conjunction with process engineering, and may include further experimental work on models or subassemblies. The result is preliminary acceptance of the design by both design engineering and process engineering and an early forecast of factory requirements for production.
- Phase III, Approval Phase -- Initiated upon agreement by design, production and marketing after successful completion of Phase II, the objectives of this phase are to obtain final design approval based upon the performance of engineering models and to provide formal records for the device. Work done in this phase includes a factory planning study (including design and ordering of necessary tools for fixtures) and submittal of models to approval bodies where necessary. The output of this phase is a final design release to production.
- Phase IV, Production Start -- Initiated upon receipt of the final design release from Phase III, the principal activities are a trial production run and the testing and evaluation of the devices resulting therefrom.
- Phase V, Factory Acceptance -- Initiated when the factory has completed a successful trial run, the objective of this phase is the acceptance by factory of the responsibility for schedule and cost of

the new device. Work completed during this period includes all permanent tooling, refinement of the production process, and establishment of firm production rates.

9.3.2 Status of Furnace Efficiency Test Device versus Standard Development Process

The furnace efficiency meter as developed under the present contract is considered to be in Phase 0, Study. Initiation of development Phases I through IV can only begin upon receipt of additional marketing information, including product feature sets, target unit costs and selling prices, and estimated annual volumes. The present device incorporates a wide range of features that would be selectively incorporated depending upon the market served. Target costs/selling prices and estimated annual volumes are also undefined, at present, and would be highly dependent on whether or not a "mandatory" market emerges.

The furnace efficiency meter developed under the present contract can serve a key test marketing function to determine the features that would be desirable for particular market segments and to determine the potential for energy savings based upon actual tests/furnace adjustments in a representative sample of residential dwellings. Such information is also seen as necessary for justifying legislation/rule-making, such as the state "red-tagging" scenarios discussed earlier.

9.3.3 Planning and Business Issues

Key factors affecting the future of furnace efficiency testing appear to be external; legislation and/or rule-making will be necessary to create a viable market in residential sector. Within the broad definition of state "red-tagging", several possibilities exist, including:

- Inclusion of a furnace efficiency test report as part of a residential energy disclosure statement at the time of sale.
- A requirement that rental property meet certain energy standards, including standards for furnace efficiency.
- A requirement that states implement furnace efficiency testing in order to receive federal energy conservation funds.

BIBLIOGRAPHY

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- [2] "Exploring Energy Choices," Energy Policy Project of Ford Foundation, Washington, D.C., 1974.
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APPENDIX A

SYSTEM SOFTWARE SPECIFICATION

This specification establishes the requirements for the design, test, qualification and performance of the computer program identified as the Furnace Efficiency Tester/Prototype Model (FET/PM). This software will be used to compute the operating efficiency of a fossil-fueled furnace or boiler from sensor inputs, compute sensor calibration constants, and generate a display of four values on seven-segment LED display digits. Other binary status indications will be displayed on discrete LEDs. The prototype model will be a portable device to be used as a test instrument for field evaluation of furnace efficiency sensing, computation, and display.

The computer program will input and process data from sensors, compute the furnace efficiency, and generate outputs for the LED digits and LED status indicators. Following restart initialization, the program will perform sensor calibration functions prior to beginning the efficiency computing and display mode.

The control program will receive data from the sensors and mode switches and generate the display and status outputs, which include a READY LED and a FAULT LED in addition to the four measured or computed values, on seven-segment LED digit displays.

INTERFACE REQUIREMENTS

The computer program FET/PM will operate within the Micromodule 01A environment. The program will be written partly in M6800 assembly language and partly in RT6800 FORTRAN, and will operate in a non-real-time environment with periodic interrupt for the output and refreshing of the display digits.

I/O and interrupt inputs for the hardware interrupt (IRQ) will be performed using the two PIAs available on the micromodule board. The Microbug monitor will be modified such that the FET/PM program will be given control at the power-up RESTART. There is no requirement for supporting an operator's terminal interface, however.

A simplified block diagram of the interfaces between components of the prototype model is shown in Figure A-1. The input/output data transfers are made by this program using the PIAs. The I/O for the M6800 is memory-mapped addresses. Consequently, a block of memory addresses is reserved for the I/O control and data transfer operations, which are then implemented with LOAD ACCUMULATOR and STORE ACCUMULATOR instructions.

Detailed Interface Definition

Hardware Interfaces--This program will input data from and output data to the Interface Unit (IFU) only, which includes the interfaces with the sensors, manual mode switches, digit displays and status indicators.

Software Interfaces--This program will reside in a memory space with the Microbug program. Interrupt vectors will be accessed through reserved locations in the Microbug RAM. The Microbug software occupies the 1K address range at the top of memory from \$FC00 to \$FFFF. Microbug will perform the functions of RESTART transfer of control to the FET/PM program and the linkage to the IRQ interrupt servicing routine in the FET/PM program. Consequently, the Microbug RESTART vector must be modified, and the FET/PM program must initialize the user IRQ vector in the Microbug RAM.

To form the linkage between Microbug and this program for the IRQ interrupt, this program will store the entry point of its IRQ servicing routine at locations \$0380 and \$0381 in the Microbug RAM.

Figure A-1. Interface Block Diagram

To be compatible with program development environments, base page allocation for this program will not start before memory address \$0020 and not exceed memory address \$037F. The program itself will start at memory location \$4000. A map of the MCU memory for EROM, RAM and I/O addresses is shown in Figure A-2. Reserved memory address ranges and the I/O addresses to be programmed are listed in Table A-1.

The Micromodule OIA board contains two PIAs identified on schematics as PIA No. 1 and PIA No. 2. Bit assignments for these PIAs are listed in Table A-2.

Input Data

Data input to the MCU consists of scaled data from the A/D input channels and discrete switch states from the manual control switches: FUEL SELECT (Net Efficiency, Oil, Propane, Natural Gas) and CALIBRATE.

This program does not input time of day from an external clock, nor use a periodic interrupt as a timing reference. The periodic IRQ interrupt is used for the refresh sequence for the LED digit displays.

Analog-to-Digital Input Data--The A/D channel selection and start of conversion are controlled by the software. The A/D channel is selected by the combination of bits in the output byte of a PIA peripheral data register. Start of conversion is performed by pulsing a PIA control bit.

End of conversion is sensed in the software by reading the input data byte twice. If the same value is read both times, the conversion is complete. A software delay of at least 80 microseconds is performed between start of conversion and data input.

The PIA bit assignments for channel selection, start of conversion, and eight-bit input data were listed in Table A-2. The format of the channel select data is listed in Table A-3.

ADDRESSES		MEMORY TYPE/BOARD
\$FFFF \$FC00	MICROBUG	PROM/01A
\$8800		
	I/O ADDRESSES	PIA NUMBER 1/01A PIA NUMBER 2/01A ACIA/01A
\$8400		
\$8000		
	PET/PM PROGRAM	PROM/04
\$4000		
\$0400		
\$0380	MICROBUG DATA	
	PET/PM DATA	RAM/01A
\$0100		
\$0000	SYSTEM DATA	

Figure A-2. Memory Map of the MCU

Table A-1. Reserved Memory Address Ranges

RESERVED MEMORY ADDRESS RANGES	
MEMORY ADDRESS (HEXADECIMAL)	DESCRIPTION
0000 - 001F	RAM FOR EXORCISOR SYSTEM ROUTINES
0020 - 00FF	RAM FOR RT6800 RTP
0100 - 037F	RAM FOR FET/PM
0380 - 03FF	MICROBUG RAM
4000 - 7FFF	EROM FOR FET/PM
8000 - 2FFF	PIA ADDRESSES
FC00 - FFFF	MICROBUG ROM

INPUT/OUTPUT ADDRESSES	
I/O ADDRESS (HEXADECIMAL)	DESCRIPTION
8400	PIA NO. 1 (A SIDE) DATA DIRECTION/PERIPHERAL DATA REGISTERS
8401	PIA NO. 1 (A SIDE) CONTROL/STATUS REGISTERS
8402	PIA NO. 1 (B SIDE) DATA DIRECTION/PERIPHERAL DATA REGISTER
8403	PIA NO. 1 (B SIDE) CONTROL/STATUS REGISTERS
8404	PIA NO. 2 (A SIDE) DATA DIRECTION/PERIPHERAL DATA REGISTER
8405	PIA NO. 2 (A SIDE) CONTROL/STATUS REGISTERS
8406	PIA NO. 2 (B SIDE) DATA DIRECTION/PERIPHERAL DATA REGISTERS
8407	PIA NO. 2 (B SIDE) CONTROL/STATUS REGISTERS
8408	ACIA U16 CONTROL/STATUS REGISTERS
8409	ACIA U16 RECEIVE/TRANSMIT DATA REGISTERS

Table A-2. PIA Bit Assignments

	BIT	DATA DIRECTION	DESCRIPTION
<u>PIA NO. 1 (A SIDE)</u>			
REGISTER ADDRESSES:			
DDR, PDR - \$8400	PA0	IN	CALIBRATE (0 = NO, 1 = YES)
CSR - \$8401	PA1	IN	CLEAR FAULT LED (0 = NO, 1 = YES)
	PA2	OUT	FAULT LED (0 = NO CHANGE, 1 = ON)
	PA3	OUT	READY LED (0 = NO CHANGE, 1 = ON)
	PA4	IN	NET EFFICIENCY, ALL FUELS (0 = YES, 1 = NO)
	PA5	IN	FUEL SELECT - OIL (0 = YES, 1 = NO)
	PA6	IN	FUEL SELECT - PROPANE (0 = YES, 1 = NO)
	PA7	IN	FUEL SELECT - NATURAL GAS (0 = YES, 1 = NO)
	CA1	(NOT USED)	
	CA2	OUT	CLEAR READY LED (PULSE)
<u>PIA NO. 1 (B SIDE)</u>			
REGISTER ADDRESSES:			
DDR, PDR - \$8402	PB0	OUT	LSB OF LED BCD DIGIT SELECT (0000 TO 1001)
CSR - \$8403	THRU		
	PB3	OUT	MSB OF LED BCD DIGIT SELECT (0000 TO 1001)
	PB4	OUT	LSB OF LED ADDRESS SELECT (0000 TO 1011)
	THRU		
	PB7	OUT	MSB OF LED ADDRESS SELECT (0000 TO 1011)
	CB1	IN	ONE MILLISECOND IRQ INTERRUPT INPUT FOR DISPLAY
	CB2	OUT	REFRESH CONTROL BIT FOR SELECTED DIGIT AT SELECTED ADDRESS (0 = NO, 1 = REFRESH)
<u>PIA NO. 2 (A SIDE)</u>			
REGISTER ADDRESSES:			
DDR, PDR - \$8404	PA0	IN	LSB OF 8 BIT A/D INPUT DATUM
CSR - \$8405	THRU		
	PA7	IN	MSB OF 8 BIT A/D INPUT DATUM
	CA1	(NOT USED)	
	CA2	OUT	START A/D CONVERSION
<u>PIA NO. 2 (B SIDE)</u>			
REGISTER ADDRESSES:			
DDR, PDR - \$8406	PB0	OUT	CLEAR CALIBRATE LATCH (0 = NO CHANGE, 1 = CLEAR)
CSR - \$8407	PB1	OUT	(A0) THERMOCOUPLE A/D CHANNEL SELECT
	PB2	OUT	(A1) THERMOCOUPLE A/D CHANNEL SELECT
	PB3	OUT	(DC 201, IN1) 0 = SELECT THERMOCOUPLE A/D CHANNELS
	PB4	OUT	(DC 201, IN2) 0 = SELECT SMOKE SENSOR A/D CHANNEL
	PB5	OUT	(DC 201, IN3) 0 = SELECT ZrO ₂ OXYGEN SENSOR A/D CHANNEL
	PB6	(UNASSIGNED)	
	PB7	(UNASSIGNED)	
	CB1	(NOT USED)	
	CB2		ZrO ₂ SENSOR HEATER CONTROL (0 = OFF, 1 = ON)

Table A-3. List of A/D Input Channels

ASSIGNMENTS	
CHANNEL NUMBER	DESCRIPTION
0	FLUE GAS TEMPERATURE THERMOCOUPLE
1	HEATER TEMPERATURE THERMOCOUPLE
2	AMBIENT TEMPERATURE THERMOCOUPLE
3	SMOKE SENSOR
4	ZrO ₂ OXYGEN SENSOR

PIA NO. 2 (B SIDE) PERIPHERAL DATA REGISTER OUTPUTS FOR A/D CHANNEL SELECTION									
CHANNEL NUMBER	PB7	PB6	PB5 (IN3)	PB4 (IN2)	PB3 (IN1)	PB2 (A1)	PB1 (A0)	PB0	HEXADECIMAL VALUE
0	0	0	1	1	0	0	0	0	30
1	0	0	1	1	0	0	1	0	32
2	0	0	1	1	0	1	0	0	34
3	0	0	1	0	1	1	1	0	2E
4	0	0	0	1	1	1	1	0	1E

Discrete Input Data--The discrete input data are the states of manual switches located on the manual control panel. The bit assignments on the PIA were listed in Table A-2. These are CALIBRATE and the four FUEL SELECT discretes (Net Efficiency, Oil, Propane, Natural Gas).

Output Data

Output data consist of bytes of data and a refresh bit for the LED display and discrete output bits for turning on the READY and FAULT indicators, clearing the READY indicator, clearing the CALIBRATE latch, and controlling the ZrO₂ sensor heater. Note that the FAULT indicator is reset entirely by hardware.

LED Display Output Data--Address select/digit select bytes are output to the LDU to display each of the 12 digits. A discrete for refreshing the selected digit is also held high except for the selection and output of the next display byte. Each of the 12 digits is refreshed individually for 1 millisecond in a

sequence of 12 milliseconds, as triggered by the IRQ interrupt on PIA No. 1 bit CB1. Bit CB2 is the refresh bit. The display byte is PB0 - PB7, as summarized in Table A-2.

Discrete Output Data--The discretes for driving the READY and FAULT LEDs are assigned to the PIA bits listed in Table A-2. The READY status is cleared from the software by pulsing the PIA control bit (listed in the same table).

Interrupts--The NMI interrupt is serviced by the Microbug software, but is not assigned for purposes of this program.

The Restart Interrupt (RES) occurs at initial power-up and transfers control via the Microbug vector to the FET/PM restart initialization program.

The IRQ interrupt is enabled by the FET/PM program following restart initialization and completion of the READY conditions. The IRQ interrupt occurs at approximately 1 millisecond intervals and signals selection of the next of 12 LED digits for output to the peripheral data register of the PIA and refresh via the control bit output.

The Software Interrupt (SWI) is used by the RT6800 FORTRAN Run Time Package and the Microbug software.

DETAILED FUNCTIONAL REQUIREMENTS

This section contains the detailed performance requirements and any special requirements for each function of the computer program. The performance requirements are categorized as executive functions, data input functions, efficiency computation and heater control functions, and data output functions.

Executive Functions

The executive functions include restart initialization, hardware interrupt servicing, scheduling, timing and other monitoring functions.

Restart Initialization--This routine shall be entered by the RESTART vector at initial power-up. There is no requirement for autorestart from power-down to continue from the execution sequence prior to power failure.

- Inputs--Constants contained in EROM as indicated herein.
- Processing--The hardware interrupt (IRQ) shall be masked with the SEI instruction. The stack pointer is initialized and the data base is cleared to zeros by the RT6800 RTP. The PIAs are initialized for inputs or outputs, as required. The display shall be blanked by loading the display bytes with the digit select \$F for all display digits and clearing the refresh control bit. The READY procedures then will be initiated.
- Outputs--The contents of the data base may be changed by this routine.

Display Refresh Interrupt Servicing Routine--This routine will be entered upon occurrence of the display refresh interrupt on the hardware interrupt request line (IRQ) via the user IRQ vector in Microbug. The LED display refresh interrupt will be the only interrupt on this line.

- Inputs--None.
- Processing--The refresh control bit will be cleared. The next address/digit select byte then will be output to the PIA PDR and the refresh control bit set.

- Outputs--The address/digit select byte is output to the PDR at the PIA, and the refresh control bit is reset and set by this routine.

Executive Scheduler--The executive scheduler routine will call the routines in the background sequence. The hardware interrupt will be enabled and inhibited by this routine, as appropriate.

- Inputs--None.
- Processing--This routine will schedule the following functions:
 - Data output,
 - Data input,
 - Monitoring,
 - Efficiency computation,
 - Heater control,
 - Output formatting,
 - Time delay.

The hardware interrupt shall be enabled except during the output formatting routine. At completion, the sequence shall be restarted.

- Outputs--The interrupt mask is set and cleared by this routine.

Timing Functions

This routine generates the appropriate time delay at the end of the background sequence.

READY Procedures--This routine performs the procedures to make the FET device ready for the run mode. It is entered from the restart initialization routine and must be completed to the READY state before the run mode cycle is initiated. The LED display digits remain blank during the READY procedures.

- Inputs--Sensor data are input to this routine.
- Processing--The ZrO_2 sensor temperature is monitored indefinitely until the temperature stays in the 1100 to 1200°F range for 5 seconds. The heater control routine is used to determine whether the heater should be ON or OFF. The discrete output routine is used to output the heater control discrete. A software delay is used such that the sensor input and control output is performed at 1-second intervals. Five consecutive cycles with the proper sensor temperature satisfy this READY condition.

When the sensor temperature condition is achieved, the READY light is turned ON and this routine is completed.

- Outputs--The READY status indicator is initiated from this routine.

Automatic Calibration Functions--This routine performs automatic calibration functions for the ZrO_2 sensor, the heater and ambient temperature sensors, and the smoke sensor during the RUN mode.

- Inputs--Sensor input data and the CALIBRATE pushbutton status are used by this routine.
- Processing--The CALIBRATE pushbutton discrete is tested for the status, which indicates that the button has been depressed. The calibration sequence is then initiated, and the calibration fault word is cleared.

The ZrO_2 sensor datum is then input and checked for the assumed ambient O_2 condition of 20.737 percent $\pm$ 1 percent.

If the O_2 is outside the ambient range, a bit is set in the fault word before the next function is performed.

The heater temperature and ambient temperature thermocouples are checked for equal temperature within $\pm 10^\circ\text{F}$. If the temperatures vary by greater than this tolerance, a bit is set in the fault word before the next function is performed.

The smoke sensor datum is used as the zero bias value for the calibration function, since the automatic calibration is performed at ambient conditions. The zero bias shall be tested to be no greater than 1500 millivolts. If the zero bias exceeds its limit, the assigned fault bit will be set in the fault status word.

After the calibration functions are performed, the fault word will contain a bit set for each fault condition. This fault word is then tested by another routine, which controls the FAULT LED.

- Outputs--The fault status word is generated by this routine and is available for inspection.

Heater Control

This routine controls the electric heater in the ZrO_2 sensor such that the temperature is maintained within the 1100 to 1200°F range. This is accomplished by turning the heater OFF at temperatures above 1200°F and ON at temperatures below 1100°F. The heater control is manually overridden to OFF by a hardware overtemperature circuit and may be assured to be OFF by executive functions.

Data Input Functions

The data input functions include the selection and control of the A/D conversion of sensor data, the input of the A/D values, and the input of discrete switch states. The A/D values are converted to sensor measurement values and engineering units for the measured parameter. These values are stored in the data base for use by other functions.

Raw Data Input--The discretes and A/D inputs are read by this routine.

- Input--The five A/D channels are input in sequence, and the bytes containing discrete switch states are input by this routine.
- Processing--Each of the five A/D channels is selected and the individual conversion is started by output in the PIA. A software time delay of at least 80 microseconds is performed, and then the A/D datum is read twice. If conversion is not complete, the two values will not agree exactly and the time delay and input are repeated. If after two attempts the two readings of the datum do not agree, a bit is set in the A/D fault word and the next channel is processed. If conversion is properly completed, the sensor input value is stored in the data base. This program will not loop on a test for end of conversion. The conversion must be completed in all cases within the two attempts.
- Outputs--The A/D conversion-control and channel-select bits will be output by this routine. The input data will be stored in the data base. The A/D values in the data base will be in FORTRAN two-byte integer format.

Data Conversion--The A/D input data are converted to sensor measurement values and then to engineering units of the measured parameter. Converted values shall be in FORTRAN real-number format.

- Input--The raw A/D sensor input data will be input to this routine.
- Processing--For each of the sensors, the scaled integer raw datum will be converted to the sensor measurement units, such as millivolts, volts or milliamps, to be available for manual verification or for use in the efficiency computation. The sensor measurement value then is processed through the appropriate calibration function to obtain the measured parameter value in engineering units of degrees Fahrenheit, percent, or smoke number. The sensor scaling functions are all of the following form:

$$SMV = A \cdot I + B$$

where

SMV = sensor measurement value,
A = constant,
B = constant,
I = scaled integer input datum.

The units and values of the constants are given in Table A-4.

The sensor measurement values are then converted to the measured parameter values by the following sensor calibration functions:

- Ambient Temperature

$$TA (^{\circ}F) = 32.118 + 44.637 \cdot SMV + 0.045242 \cdot SMV^2$$

SMV = sensor measurement value (mV)

Table A-4. Constants for the Sensor Scaling Functions

SENSOR	UNITS OF SMV	VALUE OF A (MILLIVOLTS PER COUNT)	VALUE OF B (MILLIVOLTS)
AMBIENT TEMPERATURE	MILLIVOLTS	0.12500 (32.00/256)	0
HEATER TEMPERATURE	MILLIVOLTS	0.12500 (32.00/256)	0
FLUE GAS TEMPERATURE	MILLIVOLTS	0.12500 (32.00/256)	0
SMOKE SENSOR	MILLIVOLTS	39.0625 (10000/256)	0
ZrO ₂ OXYGEN	MILLIVOLTS	0.4101563 (105/256)	0

- Heater Temperature

$$TH (^{\circ}F) = 65953 + 50.045*SMVC - 0.36656*SMVC^2 + 0.0065725*SMVC \\ - 0.000025592*SMVC^4 + 53.04/SMVC$$

SMVC = corrected sensor measurement value (mV)

$$SMVC = SMV + (32.0 - 31.055)/45.305$$

SMV = sensor measurement value (mV)

$$TH(^{\circ}C) = 5/9 (TH(^{\circ}F - 32^{\circ}))$$

- Flue Gas Temperature

$$TF (^{\circ}F) = 32.118 + 44.637*SMV - 0.045242*SMV^2$$

SMV = sensor measurement value (mV)

All three temperatures are measured using Type K thermocouples with a 32°F reference junction, and all thermocouples are calibrated in the range of 32 to 1419°F (0 to 32.0 millivolts)

- Smoke Number (Bacharach)

$$SNB = (\text{LOG (SMV 1)} - \text{LOG C1}) / \text{SLOPE 1 for SMV1} \leq A1$$

SNB = Bacharach Smoke Number

where:

$$SMV1 = \text{SMV (mV)} - \text{SSZERO (mV)}$$

SMV (mV) = Smoke Sensor Reading with LEDs ON

SSZERO = Smoke Sensor Zero

$$A1 = 4000 \text{ (mV)}$$

$$C1 = 193. \text{ (mV)}$$

$$C2 = 2340. \text{ (mV)}$$

$$\text{SLOPE 1} = 0.329 \text{ (Log mV/Bacharach)}$$

$$\text{SLOPE 2} = 0.0582 \text{ (Log mV/Bacharach)}$$

A1 = Range of applicability of first calibration curve.

The values for C1, C2, SLOPE 1, SLOPE 2 are determined from the Smoke Sensor Calibration curve, which displays SMV1 versus Bacharach Smoke Number on a semilog plot.

C_1 = y intercept of straight line in first calibration region

SLOPE 1 = Slope of first region calibration curve
(Log mV/Bacharach Number)

C_2 = y intercept of straight line in second calibration region

SLOPE 2 = Slope of second region calibration curve
(Log mV/Bacharach Number)

- ZrO₂ Oxygen Sensor

$$O_2 \text{ fraction (\%/100)} = .20737 \exp (-SMV/.021518*TH(^{\circ}K))$$

where TH(^{\circ}K) = TH (^{\circ}C) + 273.15

The data ranges for all sensors are summarized in Table A-5.

- Outputs--The computed sensor measurement values (millivolts) and the measured parameter values (engineering units) are stored in the data base.

Efficiency Computation

This routine computes the furnace efficiency in fractional form (percent/100) using the fraction of oxygen, flue gas temperature, ambient temperature and latent water constant.

- Inputs--The fractional amount of oxygen, flue gas temperature ($^{\circ}\text{F}$), ambient temperature ($^{\circ}\text{F}$), and latent water constant for the fuel type being considered are used by this routine. These values are obtained from the data base where they have been stored by previous routines.

Table A-5. Data Ranges for A/D Input Values, Sensor Measurement Values, and Measured Parameter Values*

A/D CHANNEL	SENSOR MEASUREMENT (MILLIVOLTS)	MEASURED PARAMETER
TA	0 TO 32.00	32 TO 1419 ($^{\circ}\text{F}$)
TH	0 TO 32.00	32 TO 1419 ($^{\circ}\text{F}$)
TF	0 TO 32.00	32 TO 1419 ($^{\circ}\text{F}$)
SN	0 TO 10000	0 TO 10.5 (BACHARACH)
U2	0 TO 150	20.737 TO 0. PERCENT

* ALL INPUT VALUES (EIGHT BITS): \$00 TO \$FF

- Processing--The furnace efficiency fraction is computed in the form:

$$\begin{aligned} \text{EFF} = & \text{CKO} - \text{CLW} - \text{CK1} * \text{T} - \text{CK2} * \text{T} * \text{X} / (\text{CA} - \text{X}) \\ & - \text{CK3} * \text{T} * \text{T} * \text{X} * \text{X} - \text{CK4} * \text{T} * \text{SQRT}(\text{T}) \end{aligned}$$

where

EFF = fractional efficiency

T = net temperature rise = TF - TA (°F)

X = fraction O₂ from ZRO₂ Sensor Calibration Function

CLW = latent water constant

= 0 net efficiency, all three fuel types

= 0.09631 natural gas

= 0.0800 propane

= 0.06332 No. 2 fuel oil

CKO = 0.998254

CK1 = 0.00176378 (per °F)

CK2 = 0.000193859 (per °F)

CK3 = 0.000000824422 (per °F^{3/2})

CA = 0.20737 ambient oxygen fraction

The appropriate value of CLW is set up (and stored in the data base) prior to this computation by checking the discrete inputs that specify the fuel type.

- Output--The fractional efficiency is stored in the data base.

Data Output Functions

These functions include converting the real data formatted values to the three BCD digits for display, formatting the display output bytes and the discrete

output bytes, and performing the output of the data. Note that the output of the display bytes is triggered by the IRQ interrupt. The other functions are performed in an endless loop in the background non-real-time sequence.

Conversion to BCD Display Digits--Each of the four values to be displayed on the LDU as three digits must be converted from real data format to a sequence of three four-bit BCD values in the least significant bits of successive integer variables. The binary value 1111 (\$F) is to be used for a leading blank digit.

- Input--The four display values shall be input to this routine.
- Processing--For all four display values, the decimal point is hardwired and not driven by the software. Each real value is multiplied by the appropriate decimal scale factor and converted to integer in the range 0 to 999. The three integer digits are then extracted and placed in the 4 LSB of the appropriate byte in the digit select buffer. Leading zeroes are blanked. A value out of range will be indicated by a bit in the fault word.
- Outputs--The 12 BCD digits will be stored in the data base in the least significant four bits of 12 consecutive integer variables.

Formatting--This routine will format the display bytes, which contain the address select and the digit select bits.

- Inputs--The list of the 12 BCD display digits will be used by this routine.
- Processing--Each of the 12 BCD digits will be merged with the appropriate LED address select value in the four most significant bits to form the address select/digit select bytes for output to the display. When the

12 bytes are ready in the work area of the data base, the IRQ interrupt will be masked while the 12 bytes are transferred to the buffer for the display output routine. The IRQ then will be enabled. This assures a consistent set of display digits in the display buffer.

- Outputs--The LDU display output bytes will be stored in the data base in the work space for this routine and in the buffer for the display output routine. The discrete output byte is also saved in the data base.

Discrete Outputs--This routine performs the output of the byte containing the status discrete for the FAULT LED. All other discrete output bits are handled by other routines. These other outputs include READY status, READY clear, CALIBRATE latch clear, ZrO_2 sensor heater control, and the A/D conversion control bits.

Any other discretes in the same output byte with the FAULT LED status will be placed in their no-change, unassigned, or OFF state.

Display Outputs--This routine will be entered from the hardware interrupt servicing routine to output and refresh one of 12 LED display digits.

- Input--The 12 address-select/digit-select bytes in the LDU display output buffer, the pointer to the last refreshed digit, and the end of list address will be input to this routine.
- Processing--The refresh control bit is cleared. The address of the display byte is incremented and tested for end of list. At the end of the list, the first byte is selected again. The byte is output on the PIA, and the refresh control bit is set. The routine is then completed. Each of the 12 LED digits is refreshed for approximately 1 millisecond

out of each 12-millisecond sequence. The refresh bit is set from the end of this routine until the routine is entered at the next IRQ interrupt.

- Output--The address of the current output byte is updated, and one LDU output byte is output to the PIA by this routine.

APPENDIX B

APPLICATION OF TEMPERATURE SENSING DEVICES

The rationale for selecting thermocouples for temperature measurement by the Furnace Efficiency Test Set was given in Section 4.0. That rationale is discussed in more detail here.

Characteristic values for thermocouples, thermistors, and resistance temperature detectors (RTDs) are listed in Table B-1. These values are representative of those for presently available devices, as given by manufacturers. The characteristics of these three types of temperature sensors and the factors involved in their application are discussed in the following paragraphs.

SELECTION RATIONALE

Thermocouples

A thermocouple consists of two dissimilar electrical conductors electrically insulated from one another except where joined to form a so-called measuring junction (that subjected to the temperature to be measured) and a reference, or cold junction (that subjected to a constant, known temperature). A voltage is produced in a measuring circuit when the measuring and reference junctions are at different temperatures. This voltage, which is proportional to the temperature difference between junctions, is the sum of the Peltier emf at each junction and the Thompson emf over each wire. Frequently, in lieu of maintaining the reference junction at a constant and known temperature, it is exposed to ambient temperature, and reference junction compensation is used. Compensation is achieved using an electrical bridge network containing a temperature-sensitive resistance element that is thermally integrated with the reference junction. When reference junction compensation is used, the temperature signal can be degraded through inaccuracy of compensation. Commercially

Table B-1. Comparison of Temperature Sensors

CHARACTERISTIC	(ALL TYPES) THERMOCOUPLE	THERMISTOR	RTD
MAXIMUM TEMPERATURE	3300°C	315°C	1100°C
STABILITY	0.5°C PER YEAR	0.1°C PER YEAR	0.1 PERCENT DRIFT IN 5 YEARS
FAIL-SAFE	NO	NO	YES
SENSITIVITY (25°C)	1 PERCENT PER°C	10 TO 10 ⁵	LESS THAN 0.2 OHM PER°C
RANGE (TYPICALLY)	-270 to +1300°C	-100 TO 300°C	-250 TO +900°C
OUTPUT (TYPICALLY)	40 µV/°C	18 MV PER°C (WITH 4K THERM)	UP TO 400 MV PER°C (WITH BRIDGE)
LINEARITY	EXCELLENT	POOR	EXCELLENT
POWER (100-OHM LOAD)	2 x 10 ⁻⁷ WATTS	8 x 10 ⁻¹ WATTS	4 x 10 ⁻² WATTS
POINT SENSING	EXCELLENT	EXCELLENT	POOR
AREA SENSING	POOR	POOR	EXCELLENT
SENSOR COST	\$1 TO \$50	\$2 TO \$10 STANDARD \$10 TO \$350 (SPECIAL)	\$25 TO \$1000 STANDARD
TEMPERATURE COEFFICIENT (25°C)	DEPENDS ON WIRE SIZE AND TYPE	-3.4 PERCENT PER°C	0.0039 Ω/Ω/°C POINT
DISSIPATION CONSTANT (STILL AIR)	DEPENDS ON WIRE SIZE AND TYPE	0.1 TO 1.0 MV PER°C	-
TYPE OF MEASUREMENT	RELATIVE	DIRECT	DIRECT
ACCURACY (OVER MEASUREMENT RANGE)	TYPICALLY ±1°C	TYPICALLY ±0.01°C	0.01°C (PLATINUM)
BIAS	NO	YES	YES
SELF-HEATING	NO	YES	YES
SIZE (TYPICAL)	0.50-MM BEAD	0.10-MM BEAD	3.0 TO 6.0-MM
PACKAGE	METALLIC BEAD	GLASS, EPOXY, TEFLON	GLASS, EPOXY, CERAMIC, METAL
RESISTANCE RANGE (25°C)	6 TO 80 OHMS	0.1 to 500K	8 TO 2400 OHMS
RESPONSE (STILL AIR)	0.05 TO 40 SECONDS (TYPE J-BEAD)	3 TO 100 MSEC	SEVERAL SECONDS
INTERCHANGEABILITY	GOOD	POOR	EXCELLENT (±0.25°C AT 0°C)
REPEATABILITY	EXCELLENT	POOR	0.1 PERCENT OF SPAN
FEATURES	HIGHEST RANGE AND LOWEST COST	GREATEST SENSITIVITY	GREATEST ACCURACY AND STABILITY

available compensators can provide accuracy within 0.5°C from 15 to 35°C ambient and to within 0.75°C from 10 to 50°C. Omega Corporation produces cold junction compensators that have accuracies of $\pm 0.25^\circ\text{C}$ at 25°C, 0.5°C from 15 to 35°C, and 0.75°C from 10 to 50°C.

Thermocouple systems require that the same material be used as an electrical conductor throughout the circuit between measuring and reference junctions, but copper leads are frequently used to transmit the temperature signal from the reference junction to a remote readout device.

Thermocouples are small, have relatively linear output, and are inexpensive. Commercially available thermocouples produce an output of 10 to 50 microvolts per °C--very low in comparison to the other devices. Error limits for thermocouple wire apply to specific, manufactured wire lots. For best temperature measurement accuracy in a system or instrument series, all thermocouples should be made from the same wire lot. Thermocouples of the same wire lot can be replaced with accuracy degradation of less than 0.1°C (0.06°F). Table B-2 shows a possible interchangeability tolerance over a temperature range of 200°C (392°F).

Table B-2. Thermocouple Lot Interchangeability

TEMPERATURE ($^\circ\text{C}$)	$\pm$ TOLERANCE ($^\circ\text{C}$)
0	0.02
50	0.03
100	0.05
150	0.07
200	0.10

Several companies produce thermocouples for service up to 2500°C (4532°F) using tungsten-rhenium alloy wire stock. Some caution is necessary in using thermocouples at such high temperatures because prolonged exposure tends to cause metal crystallization and a consequent change in developed emf and circuit resistance. Certain thermocouples, such as Type K, undergo solid-state transformation at temperatures above 200°C (392°F), causing deviations from specified emf values. This transformation cannot be prevented, but it can be reversed by re-annealing the thermocouple.

The slight nonlinearity of thermocouples can be corrected using analog or digital linearization techniques. In computer readout systems, polynomial equations are readily solved transforming the thermocouple voltages to degrees of temperature. For the Furnace Efficiency Test Set, portions of the emf temperature table are entered into the microprocessor and used to correct the temperature measurement.

Even though the thermocouple is a low-impedance device, good signal conditioning is necessary to minimize thermocouple heating and drift. Since the output typically shifts only tens of microvolts per degree, high-impedance measuring equipment must be used. This has an impact on the overall cost, as do the special cables and connectors needed between the thermocouple and reference junction. The overall control system using thermocouples usually will be more expensive than a comparable system using thermistors or wire sensors (RTDs). Therefore, in arriving at a comparable cost for each type of device, consideration must be given to the support circuitry necessary to make the device function.

Thermistors

A thermistor is a semiconductor device having a high negative coefficient of resistance. Within certain limits, its electrical resistance is almost entirely a function of its temperature. Specific resistance of thermistor material may

change by a factor of several thousand for a temperature change of 1.0°C . This high sensitivity is many times greater than that of thermocouples and RTDs and makes thermistors the best choice for high-resolution measurement and control applications.

The temperature resistance curve of thermistors is nonlinear, and some designers trade sensitivity for better linearity. This is done by combining the thermistor with an external resistor shunt to produce a network having a highly linear response curve. Sensitivity may be reduced about an order of magnitude to produce linearity within 0.15°C (0.08°F) over a temperature range of 0 to 100°C (32 to 212°F). Fenwal manufactures a series of thermistors that are precision matched within 0.11°C , or 0.2°F) to a standardized resistance temperature curve.

The small size of thermistors makes for fast response. Thermistor beads as small as 0.01 (Yellow Springs Instruments) and 0.014 inch in diameter (Fenwal) are marketed. Bead thermistors typically have time constants of 1 second, although some have responses in the millisecond range.

The thermistor's relatively large resistance change per degree change in temperature provides good accuracy and resolution. Resistance of a thermistor may decrease by several percent for each 1.0°C rise in temperature. A typical 2000-ohm thermistor with a temperature coefficient of 3.9 percent per $^{\circ}\text{C}$ at 25°C will exhibit a resistance change of 78 ohm per $^{\circ}\text{C}$ change in temperature. Connected in a simple bridge circuit, a thermistor can readily indicate a temperature change of as little as 0.0005°C . Fenwal Electronics has devices that range from 500 to 100,000 ohms with temperature coefficients of 3.4 percent $^{\circ}\text{C}$. Keystone Carbon has devices that range from 1000 ohms with a temperature coefficient range from 3.88 to 5.14 percent per $^{\circ}\text{C}$ at 25°C . Maximum resistance at low temperature, however, must not be too high to meet the requirements of associated circuitry. In addition, minimum resistance at

high temperature must not be too low, since error in readout may result due to contact resistance, line resistance, and line resistance variations due to temperature change.

Thermistors have better long-term stability than thermocouples, but not as good as RTD devices. Thermistor characteristics tend to become more stable with usage, while thermocouples tend to become less stable. Thermistors can vary in temperature indication by only 0.03°C a year over several years. Over a 3-month period, thermocouples have been found to shift by 0.1 to 0.3°C. When output stability is paramount, thermistors should be used.

Self-heating of a thermistor, caused by power (I^2R) dissipation, can heat it above its ambient temperature. The temperature increase is a function of the thermistor's dissipation constant (the ratio of a change in power dissipation to the resultant thermistor temperature change). Under fixed conditions of the thermistor environment, an offset allowance may be made for self-heating. The offset can change if the thermistor's thermal environment changes, such as by a velocity change in the medium being measured. It is good practice to keep the self-heat error in the thermistor smaller than the precision to which it is desired to measure. It should be noted that the dissipation constants listed in most specification sheets are obtained at 25°C ambient with the thermistor in still air. Actually, the dissipation constant will vary depending on application mounting and environmental conditions.

In general, thermistors provide relatively high absolute accuracies. Commercial-grade thermocouples normally have specified accuracies of $\pm 1^\circ\text{C}$ or less over their measurement range. Thermometrics makes devices that have accuracy and long-term stability specifications equivalent to platinum at comparable cost. Absolute accuracy of these sensors can run to 0.01°C over a 0 to 60°C range. Repeatability of thermistor measurements is such that variations and repeated readings are smaller than the overall accuracy of the measuring circuit.

Resistance Temperature Detector

The resistance temperature detector is a wire sensor made from either nickel, nickel-iron, or platinum--all having a fairly high positive temperature coefficient of resistance. The device is wire wound on any conventional form and electrically connected as one arm of a Wheatstone bridge. It is generally accepted that wire sensor bridges have a lower sensitivity (millivolts per °C) than thermistors. But this is not the case if one considers the bridge output to be dependent on the excitation of the bridge as well as on the coefficient of the sensor. The excitation that can be applied depends on the power that the sensor is capable of handling. In this respect, the wire type is clearly superior. The point is that wire sensors can provide much higher bridge outputs than thermistors do; thus, for a given temperature change, the wire type will provide greater output voltage variation despite the thermistors' higher temperature coefficient.

Self-heating is less of a problem with RTDs than with thermistors. A thermistor is a solid mass having a relatively small surface area; self-heating is high. A wire sensor, by contrast, may be extended over many square inches with ample heat-dissipating surface area. Excitation currents in a wire sensor then can be up to 40 times higher than in a thermistor.

Resistance temperature detectors are extremely stable and reliable. As an example, High-Cal Engineering specifies a mean time between failure (MTBF) of 5.2×10^6 hours, or 597 years; a failure rate of 0.00019 per 1000 hours; and a drift rate of less than 0.03°C per year. These units can be used at temperatures of 425°C (797°F) with continuous temperature cycling.

Wire sensors using platinum wire have superior, long-term stability. The better units have stabilities within 0.001°C per year and can be calibrated and certified by the National Bureau of Standards. They are nearly linear. The typical platinum sensor will have a nonlinearity less than 0.3 percent over a 200°C (392°F) temperature range.

FURTHER DISCUSSION ON SELECTION OF A THERMOCOUPLE TEMPERATURE SENSOR

The choice of thermocouples for temperature measurements with the Furnace Efficiency Test Set was made based on the results of a survey of manufacturers of thermocouples, thermistors, and RTD devices. To give some justification for this selection, several of the more important parameters are now discussed in some detail relative to the requirements for the Furnace Efficiency Test Set.

Temperature Range

In light of our requirement for heater temperature of 850°C (1562°F) and flue temperature of 510°C (950°F), the thermocouple appears to be the only device that can reliably meet these qualifications. There are several manufacturers that meet the lower temperature requirement, but only one that meets the high temperature requirement--Fenwal. Fenwal specifies their device at 1000°C (1832°F); however, several of their competitors have evaluated the device to find that instability occurs above 600°C (1112°F). In addition, the device has no hermetic seal for moisture protection--only a ceramic seal. Also, at these high temperatures the resistance rises to around 10,000 ohms. It appears that at temperatures above approximately 600°C (1112°F), most devices are still in the experimental stage. The thermistor cannot adequately meet the one high temperature requirement. Similar temperature limitations hold for the RTD devices. Here again are devices (platinum) that measure temperature over 1000°C (1832°F), but these devices are special purpose with costs that are prohibitive for our application.

Interchangeability

If we are to consider high-volume production, the ease of installation without complicated calibration is important. The thermocouple has a very good linear range over a wide temperature span; more important, it has a curve that is

very repeatable between devices, thus allowing replacement without point-to-point calibration as is required with the thermistor. Also, if the thermocouple wire is made from the same lot, interchangeability tolerance is even better. When sensor interchangeability is important and adequate provision is made for long-term usage, thermocouples offer substantial advantages over RTDs and thermistors. Since the thermocouple is a very repeatable device, compensation of the slight nonlinearity can be made by digital techniques.

Repeatability

Thermocouples are superior sensors with respect to repeatability, even though accuracy may be poor; however, a $\pm 6^{\circ}\text{C}$ accuracy for the system is adequate for most thermocouples at the temperature specified. It is important to repeat a reading to within at least $\pm 2^{\circ}\text{C}$ during furnace adjustment; the thermocouple can perform this requirement better than either the thermistor or RTD.

Cost

Thermocouples are quite inexpensive and are widely available for \$2 to \$3. Extension wire is available at only a few cents per foot. There are additional costs in the reference junction and amplifiers, however the specifications are not so stringent as to require an elaborate reference junction. Also, excellent instrumentation amplifiers can be made from low-cost integrated circuit operational amplifiers to meet the requirements. A reference voltage supply can be obtained from a low-cost, temperature-compensated Zener diode. For the same application, an RTD sensor and associated circuitry would cost anywhere from \$20 to \$50. But with all factors equal, a thermistor possibly would be less expensive in a system configuration than either of the other two devices.

In a summary, the only device that can reliably meet the temperature specifications is the thermocouple. The thermocouple also adequately meets the requirements of interchangeability, response, repeatability, and accuracy--also vital

to the application. As for cost, with good engineering design it is felt that the thermocouple configuration could be held to a low cost that would be a small part of the overall system.

SELECTION OF A THERMOCOUPLE TYPE

The Type K thermocouple was selected because it best fits the parameter requirements of the Furnace Efficiency Test Set: No. 28 AWG wire was selected for best time constant response while still meeting the temperature requirements.

Table B-3 shows typical outputs of common thermocouple types. Note that Type E provides the greatest output, while Types R and S generate relatively small outputs. Type K has moderate output with very good linearity over a wide temperature range.

Table B-4 lists the maximum temperature measurement limits as a function of the thermocouple wire size. If response is important, one should select the smallest wire size compatible to the temperature being measured. For our application, we have selected No. 28 AWG wire, which according to the table allows us to operate at a maximum temperature of 1600°F. A brief discussion of each thermocouple type is given below.

- Material: Type K, Chromel - Alumel.
- Temperature Range: Maximum at 1600°F (871°C) for No. 28 AWG wire.
- Sensitivity: $\approx 40 \mu\text{v per } ^\circ\text{C}$.
- Limits of error: ± 0.75 percent.

Table B-3. Nominal emf Outputs of Thermocouple Types (Microvolts per °C)

Temperature (°C)	E	J	K	R	S	T
-190	27.3	24.2	17.1	-	-	17.1
-100	44.8	41.4	30.6	-	-	28.4
0	58.5	50.2	39.4	-	-	38.0
200	74.5	55.8	40.0	8.8	8.5	53.0
400	80.0	55.3	42.3	10.5	9.5	-
600	81.0	58.5	42.6	11.5	10.3	-
800	78.5	64.3	41.0	12.3	11.0	-
1000	-	-	39.0	13.0	11.5	-
1200	-	-	36.5	13.8	12.0	-
1400	-	-	-	13.8	12.0	-
1600	-	-	-	-	11.8	-

Table B-4. Recommended Temperature Limits for Thermocouples

THERMOCOUPLES				EXTENSION WIRES			
THERMOCOUPLE TYPES	TEMPERATURE RANGE (°F)	LIMITS OF ERROR*		EXTENSION TYPES	TEMPERATURE RANGE (°F)	LIMITS OF ERROR*	
		STANDARD	SPECIAL			STANDARD	SPECIAL
E	32 TO 600	$\pm 3^{\circ}\text{F}$	--	EX	0 TO 400	$\pm 3^{\circ}\text{F}$	--
	600 TO 1600	$\pm 0.5\%$					
J	32 TO 530	$\pm 4^{\circ}\text{F}$	$\pm 2^{\circ}\text{F}$	JX	0 TO 400	$\pm 4^{\circ}\text{F}$	$\pm 2^{\circ}\text{F}$
	530 TO 1400	$\pm 0.75\%$	$\pm 0.375\%$				
K	32 TO 530	$\pm 4^{\circ}\text{F}$	$\pm 2^{\circ}\text{F}$	KX	0 TO 400	$\pm 4^{\circ}\text{F}$	--
	530 TO 2300	$\pm 0.75\%$	$\pm 0.375\%$				
R, S	32 TO 1000	$\pm 5^{\circ}\text{F}$	$\pm 2.5^{\circ}\text{F}$	--	--	--	--
	1000 TO 2700	$\pm 0.5\%$	$\pm 0.25\%$	--	--	--	--
T	-300 TO -75	--	$\pm 1\%$	TX	-75 TO 200	$\pm 1.5^{\circ}\text{F}$	$\pm 0.75^{\circ}\text{F}$
	-150 TO -75	$\pm 2\%$	$\pm 1\%$				
	-75 TO +200	$\pm 1.5^{\circ}\text{F}$	$\pm 0.75^{\circ}\text{F}$				
	200 TO 700	$\pm 0.75\%$	$\pm 0.375\%$				

* THE LIMITS OF ERROR OF THERMOCOUPLES AND EXTENSION WIRES ARE BASED ON A REFERENCE JUNCTION TEMPERATURE OF 32°F.

- Wire Size: 0.013 inch; No. 28 AWG.
- Output at Specified Temperature: 1562°F (850°C) = 35 millivolts;
950°F (510°C) = 21 millivolts.
- Thermocouple Resistance (+ 68°F): Alumel = 1.108 ohms per foot (No. 28 AWG); Chromel = 2.66 ohms per foot.
- Mounting--Flue Temperature: Enclosed in Honeywell-fabricated probe;
 - Heater Temperature: Embedded in ZrO_2 material.
 - Ambient Temperature: Open in base of probe.

Type T

These thermocouples are resistant to corrosion in moist atmospheres and are suitable for subzero temperature measurements. They have an upper temperature limit of 700°F (371°C) and can be used in a vacuum and in oxidizing, reducing, or inert atmospheres.

Type J

These thermocouples are suitable for use in vacuum and in oxidizing, reducing, or inert atmospheres at temperatures up to 1400°F (760°C). The rate of oxidation of the iron thermoelement is rapid above 1000°F (538°C), however, and the use of heavy-gauge wires is recommended when long life is required at the higher temperatures. Also, the bare thermocouple should not be used in sulfurous atmospheres above 1000°F (538°C).

Type K

Type K thermocouples are recommended for continuous use in oxidizing or inert atmospheres at temperatures up to 2300°F (1260°C). Because their oxidation resistance characteristics are better than those of other base metal thermocouples, they find widest use at temperatures above 1000°F (538°C).

Type E

Type E thermocouples are recommended for use over the temperature range of -420 to 1600°F (-250 to 871°C) in oxidizing or inert atmospheres. These thermocouples are not subjected to corrosion in atmospheres with high moisture content. Type E thermocouples develop the highest emf per degree of all the commonly used types and are often used primarily because of this feature.

Types R and S

Types R and S thermocouples are recommended for continuous use in oxidizing or inert atmospheres at temperatures up to 2550°F (1399°C) and intermittent use up to 2700°F (1482°C). Continued use of R and S thermocouples at high temperatures causes excessive grain growth, which can result in mechanical failure of the platinum element. This thermocouple should not be used in reducing atmospheres, nor those containing metallic or nonmetallic vapors, unless suitably protected.

All thermocouples have a standard limit of error for a specific temperature range. These accuracies are usually considered to be absolute, but in actual use, this may not necessarily be true. Table B-5 lists the limits of error for the six types of thermocouples and their extension wires. To determine the absolute accuracy, the error of the reference junction and/or the readout instrument must be added to any thermal gradients across the junction of the

thermocouple and extension wires and the gradients across the reference junction terminals. For accurate measurements, these thermal gradients must be determined or eliminated. In most applications, the complete system is calibrated at several temperature points under actual on-line conditions. This calibration provides a 2 to 5°F overall system accuracy, which is within the accepted limits of our application.

Table B-5. Limits of Error for Thermocouples

THERMOCOUPLE TYPE	WIRE SIZE (INCHES)					NOMINAL TEMPERATURE RANGE (°F)
	8 AWG (0.128)	14 AWG (0.064)	20 AWG (0.032)	24 AWG (0.020)	28 AWG (0.013)	
	UPPER TEMPERATURE LIMIT (°F)					
E	1600	1200	1000	800	800	32 TO 1600
J	1400	1100	900	700	700	-300 TO 1400
K	2300	2000	1800	1600	1600	32 TO 2300
R, S	--	--	--	2700	--	32 TO 2700
T	--	700	500	400	400	-300 TO 700

APPENDIX C
HEATING FUEL CONSUMPTION
IN RESIDENCES

- By State
- Gas, Oil
- Number of Installations
- Average Consumption/Installation

Shakil Siddiqui
Honeywell Energy Resources Center
November 1978

INTRODUCTION

The following pages tabulate the 1977 energy consumption for heating by the residential sector on a state-by-state basis. The tabulations include the number of gas and oil heating units in operation in each state, the ranking of states in total energy consumption, and total energy consumption per capita.

In this report, "residential" is defined as a single-family or multifamily unit. A state-by-state breakdown of oil consumption for heating in the residential sector was not available. The figures for oil were derived using average heating energy per unit (based upon gas) and the number of oil heating units in operation in each state.

These data were compiled as the result of research done for the Marketing Department, Honeywell Energy Resources Center.

Shakil Siddiqui

Table C-1. Total Residential Heating

STATE (RANKED)*	STATE TOTAL CONSUMPTION (BTU X 10 ¹² PER YEAR)**	ANNUAL CONSUMPTION (BTU X 10 ⁶ PER HEATING UNIT)	TOTAL NUMBER OIL UNITS	TOTAL NUMBER GAS UNITS
NEW YORK	552	154	1,980,862	1,640,566
CALIFORNIA	480	77	50,714	6,174,978
ILLINOIS	421	187	444,845	1,805,176
OHIO	373	139	258,213	2,416,175
MICHIGAN	331	136	459,524	1,975,243
PENNSYLVANIA	324	132	1,303,004	1,166,822
NEW JERSEY	261	133	1,109,709	834,932
MASSACHUSETTS	219	141	1,209,495	338,448
TEXAS	172	69	35,405	2,468,467
WISCONSIN	153	136	391,769	734,184
MISSOURI	143	129	103,980	1,008,252
MINNESOTA	107	122	332,504	542,492
INDIANA	92	76	271,979	931,458
CONNECTICUT	89	117	180,020	589,977
IOWA	80	124	127,852	519,471
MARYLAND	77	82	417,974	522,210
KANSAS	68	129	9,605	520,739
OKLAHOMA	66	114	9,312	567,524
VIRGINIA	63	90	330,552	362,672
WASHINGTON	63	91	432,775	257,229
COLORADO	62	94	24,906	634,032
GEORGIA	61	80	50,367	719,298
NORTH CAROLINA	57	94	354,151	259,462
KENTUCKY	53	101	44,772	478,474
UTAH	52	158	31,489	300,242

* A HEATING UNIT IS EITHER AN OIL UNIT (FURNACE OR BOILER) OR A GAS UNIT (FURNACE OR BOILER).

** TOTAL HEATING CONSUMPTION.

DATA SOURCE: EXCLUSIVE SPECIAL REPORT, FUEL OIL AND OIL HEAT MAGAZINE, 1977. AGA GAS HOUSE HEATING SURVEY, 1977.

Table C-1. Total Residential Heating (Concluded)

STATE * (RANKED)	STATE TOTAL CONSUMPTION (BTU X 10 ¹² PER YEAR)**	ANNUAL CONSUMPTION (BTU X 10 ⁶ PER HEATING UNIT)	TOTAL NUMBER OIL UNITS	TOTAL NUMBER GAS UNITS
NEBRASKA	45	143	44,556	271,139
WEST VIRGINIA	38	116	24,790	302,624
TENNESSEE	36	100	50,571	311,482
ALABAMA	35	81	15,338	413,947
LOUISIANA	31	86	18,441	343,419
NEW HAMPSHIRE	29	138	182,229	26,383
NEW MEXICO	28	115	6,699	239,697
OREGON	27	63	238,396	192,453
MAINE	23	104	217,267	4,093
MISSISSIPPI	21	74	5,160	275,576
SOUTH CAROLINA	20	76	81,451	175,347
RHODE ISLAND	19	101	181,039	84,767
DISTRICT OF COLUMBIA	19	102	94,459	87,185
MONTANA	18	100	21,445	158,677
IDAHO	17	100	89,674	76,554
SOUTH DAKOTA	15	129	43,034	76,618
ARIZONA	15	40	17,822	357,899
NORTH DAKOTA	14	121	53,505	64,131
DELAWARE	14	110	80,476	46,496
VERMONT	12	154	69,443	7,534
NEVADA	9	58	24,110	116,347
FLORIDA	6	19	215,007	110,006
WYOMING	5	150	11,449	29,667
ARKANSAS	2	110	6,601	15,063

* A HEATING UNIT IS EITHER AN OIL UNIT (FURNACE OR BOILER) OR A GAS UNIT (FURNACE OR BOILER).

** TOTAL HEATING CONSUMPTION.

DATA SOURCE: EXCLUSIVE SPECIAL REPORT, FUEL OIL AND OIL HEAT MAGAZINE, 1977. AGA GAS HOUSE HEATING SURVEY, 1977.

Table C-2. Heating Fuel Consumption,
State Residential Total

STATE*	TOTAL CONSUMPTION (BTU x 10 ¹² PER YEAR)	TOTAL NO. OIL UNITS	TOTAL NO. GAS UNITS
NEW YORK	552	1,980,862	1,640,566
CALIFORNIA	480	50,714	6,174,978
ILLINOIS	421	444,845	1,805,176
OHIO	373	258,213	2,416,175
MICHIGAN	331	459,524	1,975,243
PENNSYLVANIA	324	1,303,004	1,166,822
NEW JERSEY	261	1,109,709	834,932
MASSACHUSETTS	219	1,209,495	338,448
TEXAS	172	35,405	2,468,467
WISCONSIN	153	391,769	734,184
MISSOURI	143	103,980	1,008,252
MINNESOTA	<u>107</u>	<u>332,504</u>	<u>542,492</u>
TOTAL	3536	7,680,024	21,105,735
	(72 PERCENT OF U.S. TOTAL)		

* THESE STATES HAVE THE HIGHEST HEATING FUEL CONSUMPTION,
ACCOUNTING FOR 72 PERCENT OF THE NATIONAL TOTAL.

DATA SOURCE: EXCLUSIVE SPECIAL REPORT, FUEL OIL AND OIL HEAT
MAGAZINE, 1977. AGA GAS HOUSE HEATING SURVEY, 1977.

Table C-3. Heating Fuel Consumption,
Average Residential Unit

STATE*	AVERAGE ANNUAL CONSUMPTION PER UNIT (BTU $\times 10^6$)	TOTAL NO. OIL UNITS	TOTAL NO. GAS UNITS
ILLINOIS	187	444,845	1,805,176
UTAH	158	31,489	300,242
VERMONT	154	69,443	7,534
NEW YORK	154	1,980,862	1,640,566
WYOMING	150	11,449	29,667
NEBRASKA	143	44,556	271,139
MASSACHUSETTS	141	1,209,495	338,448
OHIO	139	258,213	2,416,175
NEW HAMPSHIRE	138	182,229	26,383
MICHIGAN	136	459,524	1,975,243
WISCONSIN	136	391,769	734,184

* THESE STATES HAVE THE HIGHEST HEATING FUEL CONSUMPTION PER CAPITA
(PER UNIT), ACCOUNTING FOR 46 PERCENT OF THE NATIONAL TOTAL.

DATA SOURCE: EXCLUSIVE SPECIAL REPORT, FUEL OIL AND OIL HEAT
MAGAZINE, 1977. AGA GAS HOUSE HEATING SURVEY, 1977.

Table C-4. Residential Gas Heating
(12 Top-Ranked States)

STATE (RANK)	TOTAL NO. GAS UNITS*	STATE TOTAL CONSUMPTION (BTU x 10 ¹² PER YEAR)**	ANNUAL CONSUMPTION (BTU x 10 ⁶ PER HEATING UNIT)
CALIFORNIA (1)	6,174,978	476	77
ILLINOIS (2)	1,805,176	338	187
OHIO (3)	2,416,175	337	139
MICHIGAN (4)	1,975,243	268	136
NEW YORK (5)	1,640,566	252	154
TEXAS (6)	2,468,467	170	69
PENNSYLVANIA (7)	1,166,822	154	132
MISSOURI (8)	1,008,252	130	129
NEW JERSEY (9)	834,932	111	133
WISCONSIN (10)	734,184	100	136
INDIANA (11)	931,458	71	76
KANSAS (12)	530,739	67	129

* TOTAL NO. OF GAS FURNACES AND GAS-FIRED BOILERS.

** TOTAL GAS HEATING CONSUMPTION.

DATA SOURCE: AGA GAS HOUSE HEATING SURVEY, 1977.

Table C-5. Residential Gas Heating (States
Not Ranked)

STATE	TOTAL NUMBER GAS UNITS*	STATE TOTAL CONSUMPTION (BTU X 10 ¹² PER YEAR)**	ANNUAL CONSUMPTION (BTU X 10 ⁶ PER HEATING UNIT)
MASSACHUSETTS	338,448	0.00049	141
MINNESOTA	542,492	66	122
CONNECTICUT	180,020	20.1	117
IOWA	519,471	64	124
MARYLAND	522,210	42.8	82
OKLAHOMA	567,524	64.5	114
VIRGINIA	362,672	32.6	90
WASHINGTON	257,229	23.3	91
COLORADO	634,032	59.4	94
GEORGIA	719,298	57.3	80
NORTH CAROLINA	259,462	24.4	94
KENTUCKY	478,474	48.2	101
UTAH	300,242	47.3	158
NEBRASKA	271,139	38.9	144
WEST VIRGINIA	302,624	35.2	116
TENNESSEE	311,482	31.2	100
ALABAMA	413,947	33.7	81
LOUISIANA	343,419	29.5	86
NEW HAMPSHIRE	26,383	3.7	138
NEW MEXICO	239,697	27.6	115

* TOTAL NUMBER OF GAS FURNACES AND GAS-FIRED BOILERS.

** TOTAL GAS HEATING CONSUMPTION.

DATA SOURCE: AGA GAS HOUSE HEATING SURVEY, 1977.

Table C-5. Residential Gas Heating (States
Not Ranked) (Concluded)

STATE	TOTAL NUMBER GAS UNITS*	STATE TOTAL CONSUMPTION (BTU X 10 ¹² PER YEAR)**	ANNUAL CONSUMPTION (BTU X 10 ⁶ PER HEATING UNIT)
OREGON	192,453	12.2	63
MAINE	4,093	0.4	104
MISSISSIPPI	275,576	20.4	74
SOUTH CAROLINA	175,347	13.3	76
RHODE ISLAND	84,767	8.6	101
DISTRICT OF COLUMBIA	87,185	8.9	102
MONTANA	158,677	15.9	100
IDAHO	76,554	7.7	100
SOUTH DAKOTA	76,618	9.9	129
ARIZONA	357,899	14.4	40
NORTH DAKOTA	64,131	7.8	122
DELAWARE	46,496	5.1	110
VERMONT	7,534	1.2	154
NEVADA	116,347	7.9	58
FLORIDA	110,006	2.1	19
WYOMING	29,667	4.5	150
ARKANSAS	15,063	1.7	110

* TOTAL NUMBER OF GAS FURNACES AND GAS-FIRED BOILERS.

** TOTAL GAS HEATING CONSUMPTION.

DATA SOURCE: AGA GAS HOUSE HEATING SURVEY, 1977.

Table C-6. Residential Oil Heating (12 Top-Ranked States)

STATE (RANK)	NO. OIL-FIRED FURNACES	NO. OIL-FIRED BOILERS	STATE TOTAL CONSUMPTION (BTU x 10 ¹² PER YEAR)*	ANNUAL CONSUMPTION (BTU x 10 ⁶ PER HEATING UNIT)
NEW YORK (1)	695,109	1,285,753	300	154
PENNSYLVANIA (2, TIE)	563,726	739,278	170	132
MASSACHUSETTS (2, TIE)	413,615	795,880	170	141
NEW JERSEY (3)	408,090	701,619	150	133
ILLINOIS (4)	310,509	134,336	83	187
CONNECTICUT (5)	230,941	358,136	69	117
MICHIGAN (6)	317,536	141,988	63	136
WISCONSIN (7)	276,771	114,998	53	136
MINNESOTA (8)	247,896	84,608	41	122
WASHINGTON (9)	390,379	42,396	39.2	91
OHIO (10)	188,689	69,524	36	139
MARYLAND (11)	191,610	226,364	34	82

* TOTAL OIL HEATING CONSUMPTION.

DATA SOURCE: EXCLUSIVE SPECIAL REPORT, FUEL OIL AND OIL HEAT MAGAZINE, 1977.

Table C-7. Residential Oil Heating
(States Not Ranked)

STATE	NO. OIL-FIRED FURNACES	NO. OIL-FIRED BOILERS	STATE TOTAL CONSUMPTION (BTU X 10 ¹² PER YEAR)*	ANNUAL CONSUMPTION (BTU X 10 ⁶ PER HEATING UNIT)
CALIFORNIA	45,807	4,907	3.9	77
TEXAS	26,536	8,869	2.4	69
MISSOURI	73,300	30,680	13	129
INDIANA	229,824	42,155	21	76
IOWA	89,999	37,853	16	124
KANSAS	7,731	1,874	1.2	129
OKLAHOMA	7,943	1,369	1.1	114
VIRGINIA	217,596	112,956	30	90
COLORADO	21,574	2,522	2.3	94
GEORGIA	38,575	11,792	4	80
NORTH CAROLINA	300,256	53,901	33	94
KENTUCKY	39,104	5,668	4.5	101
UTAH	28,819	2,670	5	158
NEBRASKA	33,699	10,857	6.4	144
WEST VIRGINIA	21,456	3,334	2.9	116
TENNESSEE	44,169	6,402	5.1	100
ALABAMA	11,377	3,961	1.3	81
LOUISIANA	14,760	3,681	1.6	86
NEW HAMPSHIRE	68,765	113,464	25	138

*TOTAL OIL HEATING CONSUMPTION.

DATA SOURCE: EXCLUSIVE SPECIAL REPORT, FUEL OIL AND OIL HEAT MAGAZINE, 1977.

Table C-7. Residential Oil Heating (States
Not Ranked) (Concluded)

STATE	NO. OIL-FIRED FURNACES	NO. OIL-FIRED BOILERS	STATE TOTAL CONSUMPTION (BTU X 10 ¹² PER YEAR)*	ANNUAL CONSUMPTION (BTU X 10 ⁶ PER HEATING UNIT)
NEW MEXICO	6,079	620	0.8	115
OREGON	232,769	5,627	15	63
MAINE	92,087	125,180	23	104
MISSISSIPPI	4,330	830	0.4	74
SOUTH CAROLINA	61,996	19,455	6.2	76
RHODE ISLAND	68,854	112,185	18	101
DISTRICT OF COLUMBIA	38,874	55,585	9.7	102
MONTANA	19,775	1,670	2.2	100
IDAHO	86,247	3,427	9	100
SOUTH DAKOTA	31,128	11,906	5.6	129
ARIZONA	51,121	2,701	0.7	40
NORTH DAKOTA	40,834	12,671	6.5	122
DELAWARE	42,624	37,852	8.9	110
VERMONT	33,090	36,353	11	154
NEVADA	22,027	2,083	1.4	58
FLORIDA	183,882	31,125	4.1	19
WYOMING	10,445	1,004	0.2	150
ARKANSAS	5,618	1,063	0.7	110

* TOTAL OIL HEATING CONSUMPTION.

DATA SOURCE: EXCLUSIVE SPECIAL REPORT, FUEL OIL AND OIL HEAT MAGAZINE, 1977.

Table C-8. Energy Input to the U.S. Economy, 1970 to 1975,
and Projections by Consuming Sector

IN QUADRILLIONS OF BRITISH THERMAL UNITS, EXCEPT PERCENT

ITEM	1970	1971	1972	1973	1974	1975 (Est.)	1970-75 Average	Projections	
								1980	1985
TOTAL GROSS ENERGY INPUT	67.1	68.7	71.9	74.7	72.9	71.1	71.1	87.1	103.5
TOTAL NET ENERGY USED	56.2	57.0	59.4	61.3	59.3	57.5	58.5	68.9	77.5
RESIDENTIAL AND COMMERCIAL (PERCENT OF NET)	17.0 (30.3)	17.4 (30.5)	18.1 (30.5)	18.3 (29.9)	17.6 (28.8)	17.3 (30.1)	17.6 (30.2)	21.6 (31.4)	24.6 (31.7)
INDUSTRIAL (PERCENT OF NET)	22.5 (40.0)	22.3 (39.1)	23.2 (39.1)	24.0 (39.3)	23.3 (39.3)	21.7 (37.7)	22.8 (39.1)	25.9 (37.6)	28.8 (37.2)
TRANSPORTATION (PERCENT OF NET)	16.5 (29.4)	17.1 (30.0)	18.1 (30.5)	19.0 (31.0)	18.4 (31.0)	18.5 (32.2)	17.9 (30.7)	21.4 (31.0)	24.1 (31.1)

Source: U.S. Bureau of Mines, "United States Energy Through the Year 2000;" Minerals Yearbook; and "Mineral Industry Surveys," (References 1, 2 and 3)

Figure C-1. 12 Top-Ranked Heating Fuel Consuming States, 72 Percent of National Total (Reference Table C-2).

DATA SOURCE: FEDERAL ENERGY ADMINISTRATION; "PROJECT INDEPENDENCE, RESIDENTIAL AND COMMERCIAL ENERGY USE PATTERNS 1970-1990" A.D. LITTLE INC., 1974 U.S. BUREAU OF MINES, "UNITED STATES ENERGY THROUGH THE YEAR 2000"; AND "MINERAL INDUSTRY SURVEYS," NORMAN ASSOCIATES INC. "INVENTORY AND RANKING OF THE EXISTING BUILDING MARKET 1975"; NORM SIDLEY, 1976, REFS 1, 3, 4 & 9)

Figure C-3. Commercial and Residential Energy Breakdown

Figure C-3. Heating Equipment by Region, 1970
(Percentage Housing Structures)

DATA SOURCE: U.S. DEPARTMENT OF COMMERCE, BUREAU OF CENSUS
 "STRUCTURAL CHARACTERISTICS OF THE HOUSING INVENTORY,"
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Figure C-4. Multi-Family Housing Units

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