ENERGY CONSERVATION

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# TECHNOLOGY FOR THE DEVELOPMENT OF HIGH-EFFICIENCY OIL-FIRED RESIDENTIAL HEATING EQUIPMENT



FINAL REPORT

June 1980

Prepared by
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of

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505 KING AVENUE
COLUMBUS, OHIO 43201

for

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973
UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE

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## ABSTRACT

With the increasing need for fuel conservation, the incentive for developing efficient residential oil-fired heating equipment is greater than ever before. Numerous concepts pursued in the past for improved residential oil burners have not reached the marketable stage for a variety of reasons, ranging from technical limitations to competitive conditions and ecomonics at the time of the development.

Most of the past R&D effort was directed to burners having good reliability and low cost. Fuel economy was a general goal, but not focused to the extent that it is now. Efforts over the past 20 years that were directed toward developing low-capacity burners had not been rewarded with a substantial market. However, the marketplace now is ready for low-capacity burners to minimize the detrimental effects on seasonal efficiency that burner oversizing can bring about and to meet the needs of new energy-efficient homes.

This report presents a review and assessment of technology that should be considered in the development of efficient residential oil-burning equipment having capability for reliable, low-capacity operation. The focus in this review is on promising technical approaches having potential application to unconventional types of oil burners and to efficient heat exchangers, including those that operate partially in the mode of condensing moisture from the flue gases to regain the latent heat of vaporization.

The following concepts are recommended for further investigation in the development of efficient oil-fired heating equipment:

- Modified high-pressure atomizing systems
  (anti-clogging nozzles, preheaters, return-flow nozzles)
- Alternative methods of atomization
  (air, ultrasonic, thermal aerosol generators)
- Blue-flame burners
- Pulse-combustion systems
- Condensing-type heat exchangers.

Special R&D focus is recommended on aspects of burner performance sensitivity to fuel quality, of pollutant emissions, and of long-term reliability.

The report is intended to serve as a reference to pertinent published information generated in various R&D programs, including those oil-industry programs supported by the American Petroleum Institute and the National Oil Fuel Institute, plus more recent R&D supported mainly by the U.S. Department of Energy.

## ACKNOWLEDGMENTS

The authors acknowledge with thanks the numerous contributions to this study from representatives of organizations within the oil-heating industry, particularly equipment manufacturers and developers. Special thanks are due to various former committee members and contractors that participated in the past oil-burner development programs of the American Petroleum Institute, the National Oil Fuel Institute, and Operation Oil Heat Associates. Key assistance and suggestions during the course of the study were received from personnel at Brookhaven National Laboratory's Conservation Program Management Group, especially Gerald Dennehy, Group Head, and Lawrence M. Woodworth, Project Officer.

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# TECHNOLOGY FOR THE DEVELOPMENT OF HIGH-EFFICIENCY OIL-FIRED RESIDENTIAL HEATING EQUIPMENT

## SECTION I

## SUMMARY

Oil shortages and rising costs have intensified public interest in fuel conservation for residential space heating. This has had two effects that have stimulated development of more efficient oil-heating equipment. The first is a recognition of the need for efficient burners capable of low firing rates. The second is the incentive provided to manufacturers for the introduction of more efficient equipment, now that higher first costs can be justified by fuel savings.

With the trend to more home insulation and better general weatherproofing, heat losses are lower, and there is a need for lower capacity burners. Moreover, there is a growing recognition that oversizing a conventional heating system results in higher standby losses and, thus, higher fuel consumption. The current focus is on seasonal or part-load efficiency of intermittently operating equipment, rather than only steady-state efficiency that was traditionally the measure of performance.

Manufacturers of residential oil-fired equipment are responding to the market opportunity and are undertaking new R&D on a more active basis than at any time in the past 25 years. One impetus is the added focus on seasonal efficiency that is stimulated by the labeling program for furnace and boiler efficiency that is being implemented by the U.S. Department of Energy and the Federal Trade Commission.

### PRESENT STUDY

As part of the U.S. Department of Energy program to stimulate the development of more efficient heating equipment, Brookhaven National Laboratory (BNL) sponsored this study at Battelle-Columbus to examine equipment R&D options for residential oil-fired equipment. The scope of this study included an examination of pertinent R&D on oil-fired equipment, past and present.

This report of the study presents a review of the technology based on the state of the art and results of R&D efforts directed to oil-fired residential heating equipment. It is structured in such a way that it can be used as a reference, with keyed reference lists, to facilitate its use by investigators in a particular area of the technology.

## OBJECTIVES OF STUDY

The specific objectives of this study were:

1. To review the status of new and unconventional developments in residential oil burners
2. To identify and assess promising design approaches as options for improved oil-fired residential heating equipment that is capable of higher seasonal efficiency at acceptable costs
3. To identify and assess potential improvements in heat exchangers for boilers and furnaces of higher seasonal efficiency, including condensing-type heat exchangers
4. To recommend promising areas of research, development, and demonstration.

## PERTINENT TECHNOLOGY AND INFORMATION RESOURCES

Past R&D efforts on oil burners have made significant contributions in terms of concepts and basic design data. Much of this information can be applied in current R&D efforts directed to more efficient equipment, even though the main goals in past efforts were lower cost and higher reliability of equipment, rather than operating efficiency.

Oil-industry groups had been particularly active in organizing and supporting R&D to improve oil-burning equipment. For example, the American Petroleum Institute (API) sponsored R&D over a period of 7 years as part of the API Oil Burner Research Program; many of the results of that program are applicable to present needs, are well documented, and are available to equipment developers today. In addition, the National Oil Fuel Institute (NOFI) extended the oil-industry R&D effort through the NOFI Equipment Development Program. Many concepts from these programs were reported at industry conferences, and some have reached the market.

More recently, the U.S. Department of Energy has initiated programs, through both Brookhaven and the National Bureau of Standards, that have included tests on efficiency of residential oil-burning equipment. In addition, the Canadian Combustion Research Laboratory and the U.S. Environmental Protection Agency have conducted or sponsored programs that add to the technology of residential oil-burning equipment.

## CRITERIA FOR TECHNOLOGY ASSESSMENT

In the study, two types of criteria were involved in assessing technical approaches to more efficient equipment design: (1) those oriented to performance, especially seasonal efficiency, and (2) those oriented to aspects of marketability and acceptability. Special consideration was devoted to areas of reliability and long-term durability and, also, fuel-quality sensitivity.

Reliability and Long-Term Durability. There has been much attention in the home-heating trade press and energy press as to the potential for improving seasonal efficiency and the potential for low-capacity operation. However, the other criteria are equally significant to suitability and acceptance in the marketplace. This is especially true of reliability and durability; many otherwise promising developments in the past have suffered with respect to these criteria. To identify critical elements, long-term performance and durability tests are essential before full-scale market introduction. Often, it is a subtle design change that improves performance and reliability.

Fuel Sensitivity. Another point that should be emphasized is the fact that fuel quality can strongly affect burner performance and reliability. The quality of No. 2 fuel oil is likely to suffer in times of tight supply as other demands grow for middle distillates (e.g., the fuel demand for automotive diesels). Petroleum-based fuels for home heating have already suffered some quality deterioration, and more deterioration can be expected.

In the 1950s and early 1960s, most of the major oil companies in the U.S. maintained substantial oil-burner laboratories and skilled staff for purposes of fuel-quality surveillance and tests of fuel-quality sensitivity of typical oil burners in service or being introduced. However, in recent years, these activities have been severely reduced and burner laboratories have been abandoned, to the point where only a few refiners have maintained significant facilities and staff capabilities. Thus, the oil industry no longer has the former level of continuous monitoring of fuel quality and problems that are encountered in the field. This could become critical to homeowners if there is a decline in fuel quality during fuel supply emergencies.

With the advent of synthetic fuels from coal or shale, the fuel sensitivity problem can be accentuated, because these fuels may have higher proportions of aromatic hydrocarbons and poorer thermal stability than petroleum fuels; these factors can lead to problems with smoke formation, carbon deposition, and plugging of small passages in fuel nozzles. Low-capacity and prevaporizing type burners can be particularly sensitive to these problems. Thus, it is important to evaluate new developmental equipment for sensitivity to changes in fuel properties.

## TECHNOLOGY REVIEW

In this study, concepts potentially applicable to more efficient oil-heating systems were assessed in these broad categories: (1) oil-burner fuel-preparation; (2) combustion systems; and (3) heat exchangers. Candidate concepts are classified as follows:

## 1. OIL-BURNER FUEL PREPARATION

The method of fuel preparation is a key characterization for oil burners -- whether atomizing, prevaporizing, or a combination of the two.

### A. Atomizing Burners

Burners where fuel is prepared by atomization, without special provision for vaporization, except droplet vaporization in the flame.

- High-pressure atomization using low-rate nozzles having anti-clogging tendency
- High-pressure atomization with return-flow nozzles
- High-pressure atomization with nozzle preheaters
- Air atomization
- Ultrasonic atomization

### B. Prevaporizing Burners

Thermal vaporizing burners rely on external heat input or heat from the flame, as in typical pot-type burners. The oil is vaporized, or partially vaporized, and mixed with air before it reaches the flame.

- Unconventional thermal vaporizing burners
- Thermal aerosol generators and burners

  (Where external heat is applied to the oil for partial vaporization; then vapor and small oil droplets are mixed with air and burned as an aerosol.)

### C. Combination Atomizing/Vaporizing Burners

Fuel is initially atomized or thrown into a vaporizing zone where it is vaporized and burned, or vaporization and mixing can occur in a zone separated from the flame. Various approaches to catalytic burners can fall in this class.

## 2. COMBUSTION SYSTEMS

The method of fuel/air mixing and the combustion regime are important in this characterization of oil-burning systems.

D. Blue-Flame Burners

Special means of fuel/air mixing, usually with recirculation of combustion products, can provide blue-flame burning.

E. Pulse-Combustion Systems

Intermittent combustion, where the frequency of combustion-driven oscillations is determined by the acoustic properties of the system.

## 3. HEAT EXCHANGERS

No matter how high the combustion performance of the burner, the heat exchanger of the furnace or boiler is critical to the utilization of the heat available, and thus to the seasonal efficiency.

F. Condensing-Type Heat Exchangers

Heat exchangers designed to cool combustion products below their dewpoint to regain part of the the latent heat of condensation of water vapor generated in the combustion process.

It should be recognized that these approaches are not mutually exclusive. For example, any of the forms of atomization could be used in blue-flame burners or pulse-combustion systems, or any burner concept could be used to fire a unit having a condensing-type heat exchanger.

## ASSESSMENT OF TECHNOLOGY

### ASSESSMENT CRITERIA

The following criteria were used in the overall subjective assessment of burner technology for the development of high-efficiency oil-fired residential heating equipment.

#### Performance-Oriented Criteria

- Burner performance potential (ability to operate cleanly at low excess air).
- Low-rate potential (ability to operate at low-firing rates without atomizer clogging or fuel-preparation problems).
- Reliability potential (ability to operate reliably with durable components).

- Fuel insensitivity (expected freedom from performance deterioration resulting from variations in fuel quality).
- Expected freedom from problems on starting or shutdown.
- Low CO and HC emissions.
- Low $NO_x$ emissions.
- Low noise.

Other Marketability Criteria

- Low manufacturing cost potential.
- Retrofit potential.
- Service training required.
- Likely market acceptance.
- Free of standards problems.
- Relative time to introduce.
- Relative cost and risk to introduce.

## PROMISING TECHNOLOGY

Each of the more promising concepts is discussed briefly below and general recommendations are noted.

### Pressure Atomization

Special anti-clogging nozzles have just been introduced by Delavan for improved atomization and anti-clogging characteristics at firing rates down to 0.3 gph. The low clogging tendency is achieved by the design of internal passages. Considerable versatility in retrofit is possible with standard fuel-system components. Further investigation is warranted, especially regarding atomization and clogging characteristics at low rates with different fuels.

Return-flow nozzles permit good atomization at low firing rates and with large nozzle ports. Rotational momentum of a high fuel flow imparts atomizing energy to the fuel in the nozzle swirl chamber, but the excess fuel is directed back to a return line. Good atomization can be maintained with larger nozzle passages than for conventional nozzles. Fuel systems for gas turbines and naval boilers have utilized this concept. It has not been fully exploited in residential oil burners, although it was used in a low-capacity burner that was introduced 25 years ago, ahead of the market's readiness for such a burner. That experience should be reexamined in detail, with a view to potential application today.

Nozzle preheaters with high-pressure atomization are being introduced to enable lower-capacity operation while still maintaining atomization. At normal atomizing pressures, the increased fuel temperature results in lower mass firing rate and improved atomization; this allows pressure to be reduced, such that the capacity is reduced still further. By a combination of nozzle-line heating and pressure reduction, European practice is to reduce firing rate to about 75 percent of the rate expected for the same nozzle at conventional atomizing pressures and temperatures. The concept should be evaluated, especially with regard to reliability and any side effects encountered with U.S. fuels, before it can be recommended for full application.

## Air Atomization

Air atomization is established as an effective approach for low-capacity burners and can be used for variable firing rates. The key to commercialization is the availability of a suitable air compressor that is reliable and low in cost. Promising new types of air atomization that give fine atomization include those that use the stretched film principle, as in the Babington atomizer and the Vapex atomizer, where an air blast through an orifice atomizes the oil from an oil film at the edge of the orifice. The Babington concept uses a flooded spherical atomizer surface with recycle of surplus oil. The Vapex nozzle flows the oil over a nozzle front surface by a controlled channel and can be applied in much the same way as a conventional atomizing nozzle. The potential of these approaches should be further explored.

## Ultrasonic Atomization

Although ultrasonic atomization has been applied to developmental oil burner prototypes, it has not been commercialized for residential applications. However, it is an established concept for liquid-fuel-fired military thermoelectric generators. Recent improvements in Battelle's military atomizer concept have been developed by Sono-Tek, and a residential burner using this atomizer is under development by Wayne Home Equipment.

A key to the application of ultrasonic atomizers for oil burners has long been the availability of a suitable metering device and oil-delivery pump. A new fuel-metering pump, recently announced by Sundstrand Hydraulics, appears to serve this need and may speed the commercialization of the concept. Long-term durability of all components should be examined.

Thermal Aerosol Generators

A unique thermal aerosol generator is under development for Brookhaven by the University of Virginia, using the Schladitz fuel injector. Oil flows through a porous network of iron fibers that is electrically heated; vapor and fine droplets are produced that can be burned with a blue flame. The long-term durability and deposit characteristics should be explored with different fuel-oil samples.

Blue-Flame Burners

The main advantage of blue-flame combustion, exemplified in a number of burner developments including the Blueray and Breda units, is to assure that smoke and particulate emission levels will be low and soot fouling tendency will be minimized. This is especially important for compact, high-resistance heat exchangers or condensing-type heat exchangers. The fact that the flame is nonluminous, with low radiation emissivity, is not a serious disadvantage in the heat-transfer design, except that the combustion space may have to be larger for blue flames of low fuel/air mixing intensity. Generally, low-intensity blue flames operate with very low combustion noise.

A problem with some blue-flame burners is flame instability during the starting transient period. Also, flame failure detection is more of a problem than with luminous flames that can be detected with a cadmium-sulfide-cell sensor. If oil flow is interrupted for a period shorter than the safety shutdown response of the flame-detection system, explosive conditions can result when the oil flow is reestablished and there is some hot spot available for reignition. These modes should be carefully checked.

A further question with blue-flame burners is sensitivity to fuel variations, which is likely to be more of a problem with low-intensity burners. For high-intensity burners, noise may present problems. These aspects warrant further exploration.

Pulse-Combustion Systems

Pulse combustion offers a unique approach to an efficient boiler or furnace, mainly because of pressure boost capability of pulse combustors that can overcome the pressure drop of high-resistance, compact heat exchangers, including those designed for condensing operation. Low $NO_x$ emission levels appear feasible with this approach. For oil firing, the concept may encounter limitations and problems in fuel preparation of the same sort as for continuous burners of low-firing rates. Because of potential problems with combustion noise, special provision for muffling is required.

Gas-fired pulse-combustion boilers are on the market in the U.S. in residential sizes, and furnaces are in field test. A Swiss-developed oil-fired pulse-combustion boiler of residential size has been exhibited in the

U.S.; however, oil-fired units are not yet available on the U.S. market. The concept should be more fully developed and evaluated as the basis for low-capacity, high-efficiency, oil-fired equipment.

### Condensing-Type Heat Exchangers

The design of residential furnaces and boilers to utilize condensing heat exchangers offers a new plateau of seasonal efficiency beyond the limitations of conventional design practice. A number of design options are open as trade-offs; these include the temperature of the return heating medium, the degree of latent heat recovery desired, heat-exchanger configuration and materials, and overall economics.

A key issue is the choice of corrosion-resistant materials that will give reasonable heat-exchanger life and result in acceptable manufacturing cost. Because the sulfur content of No. 2 heating oil is far greater than that of gaseous fuels, the potential for corrosion from acidic condensate is greater. Additional issues include problems of condensate disposal and venting of combustion gases, plus limitations imposed by present codes and standards. A project involving materials evaluation in a generic sense (not design specific) is under way as part of the Brookhaven program. This should be continued to include the interrelation of design alternatives and overall economics.

Condensing-type systems have other attributes that contribute to high seasonal efficiency but need further exploration. One is that the burner/heat-exchanger resistance to off-period air flow can drastically reduce off-period losses. Another is the possibility that low-excess-air operation is relatively less important to overall efficiency than in conventional systems, so that additional burner-design alternatives become more feasible.

## SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

As a result of the overall assessment, the following concepts were judged as having the most promise in meeting the needs for high-efficiency and low-firing-rate, oil-fired residential heating equipment. Three levels of R&D priority are based on nearness to implementation and to anticipated technical risk. Further R&D is recommended in these areas.

### 1. BURNER FUEL PREPARATION

#### Near Term and Relatively Low Technical Risk

- Special anti-clogging nozzles -- retrofit and new burners

- Nozzle-line preheaters -- retrofit and new burner application
- Return-flow nozzles -- new burner application.

Intermediate Term and Technical Risk

- Air-atomization approaches -- new burner application
- Ultrasonic atomization -- new burner application.

Longer Term and Higher Risk

- Thermal aerosol generators -- new burner application (long-term performance).

2. COMBUSTION SYSTEMS

Near Term and Relatively Low Technical Risk

- Blue-flame burners -- both retrofit and new burner application, performance and application limits.

Longer Term and Higher Risk

- Pulse-combustion systems for condensing heat exchangers -- new unit application, long-term performance and materials durability.

3. HEAT EXCHANGERS

Near Term and Relatively Low Technical Risk

- Generic consideration of condensing heat exchangers (approaches, materials, and related issues).

Intermediate Term and Technical Risk

- Application of condensing heat exchangers to specific burner-unit combinations.

4. SUPPORTING TECHNOLOGY

General

Various efforts are needed to support the RD&D in a broad sense.

- Engineering analysis of overall systems from standpoint of seasonal efficiency

- Investigation of sensitivity of burner concepts to fuel-quality variations.

Each concept above warrants additional R&D, to the point where a full evaluation of performance and durability is accomplished. For each of the concepts in categories 1, 2, and 3, special emphasis is recommended on aspects of sensitivity to adjustment, sensitivity to fuel quality, pollutant emissions, and long-term reliability. Parallel approaches are justified at early stages of development for a broad R&D program. But, it could be expected that the priority would shift in time as the relative potential of alternative approaches becomes clearer.

Overall findings from the total activity would be expected to guide future design of oil-fired heating equipment.

## STRUCTURE OF THIS REPORT

Additional details are contained in the main body of this report, organized in the following main sections:



The text and tables of this report contain extensive citations of pertinent literature, such that the report can be used as a reference source.

*Part of the API planning report is reproduced in this Appendix, because many of the topics discussed are pertinent to present R&D needs and because that report is now out of print.

# SECTION II

# INTRODUCTION

## BACKGROUND

### THE NEED FOR ENERGY CONSERVATION

Fuel oil is the major source of energy for residential space heating in a significant portion of the U.S., with a high concentration along the east coast. Nationwide, about 20 percent of the homes rely on an oil for space heating. The present situation of high prices for fuel oil and threats of tight supply have resulted in some shift to gas for space heating where gas is available and price is favorable. However, many areas will remain heavily dependent on oil for some time to come.

Another trend threatening the availability of heating oil is the increasing competition for supply from growing numbers of automotive diesels and jet aircraft. The commercial availability of suitable synthetic liquid fuels from coal or shale oil will be slow in developing, and the new synthetic fuels will be expensive at best; such fuels are not likely to gain real significance for at least a decade.

The pressure for fuel conservation in residential heating is obvious from the standpoints of both cost and threatened shortages in supply. A large aftermarket is developing in retrofitting existing oil-fired installations with upgraded equipment for improved overall efficiency. With 12 million oil-fired central heating systems in operation nationwide, the potential market and potential fuel savings are significant.

### The Need For Low-Capacity Equipment -- a Consequence of Conservation

As conservation and new building practices of insulation and weather proofing become more effective, the desired firing rate for new or retrofit equipment becomes lower. Moreover, field studies on energy use in conventional equipment have shown that oversizing (in terms of firing rate) is detrimental to seasonal efficiency. Thus, there is a need for oil burners capable of reliable operation at lower firing rates, while maintaining high steady-state efficiency.

To set the perspective of needed development and the potentials of new concepts, the following paragraphs outline the evolution and status of different types of oil burners that have achieved substantial use.

## HISTORICAL VIEW OF ESTABLISHED TYPES OF OIL BURNERS

A wide variety of oil-burner types have been introduced in the U.S. at one time or another; these have met with varying degrees of market success and service longevity. As a guide to a historical perspective, Table II-1 identifies references that provide excellent descriptions of oil burner types introduced on the market in the U.S. over the past 50 years. (API Publication 1537, cited in Table II-1, contains many abstracts of references prior to 1960 that are pertinent to residential oil burning.)

### Evolution of Burner Types and Recent Trends

Oil-burner types are frequently classified by their method of fuel preparation. Major classifications are as follows, with some typical examples of commercially significant burners:

#### Atomizing Type

- Low Pressure Burners
  - GE, Williams, Winkler, etc.
- High-Pressure Burners
  - Older types with open mixing head
  - Flame-retention heads with higher pressure drop (recent burners by ABC/Sunray, Beckett, Carlin, Wayne, etc.)

#### Vaporizing Type

- Vaporizing Pot-Type Burners
  - Breeze, Duotherm, etc.

#### Combination Atomizing/Vaporizing Type

- Rotary Wall-Flame Burners
  - Timken, Fluid-Heet, Torridheat, etc.
- Atomizing Rotary Burners
  - ABC, Hayward, etc.

TABLE II-1. HISTORICAL PERSPECTIVE ON OIL BURNER TYPES

General References Describing Residential Oil-Burner Types on the Market During the Past 50 Years

| AUTHOR(S) | DATE | TITLE AND PUBLISHER |
|---|---|---|
| Olmstead, F. | 1926 | "Handbook of Domestic Oil Burning", American Oil Burner Association, 224 pgs |
| Tapp, H. F. | 1928 | "Handbook of Domestic Oil Heating", American Oil Burner Association, 386 pgs |
| Tapp, H. F. | 1931 | "Handbook of Oil Burning", American Oil Burner Association, 625 pgs |
| Romp, H. A. | 1937 | "Oil Burning", Martinus Nijhoff, The Hague, 336 pgs |
| Faust, F. H. and G. T. Kaufman | 1951 | "Handbook of Oil Burning", Oil Heat Institute of America, Inc., 978 pgs |
| Schulz, J. W. | 1952 | "Remember the Early Burners?" Fueloil & Oil Heat, 11, 7, p 58 |
| Speich, C. F. and D. W. Locklin | 1960 | "Literature Pertaining to the Art and Science of Oil Burning for Residential Applications", by Battelle Memorial Institute. API Publ 1537, 112 pgs* |
| Burkhardt, C. H. | 1969 | "Domestic and Commercial Oil Burners—Installation and Servicing", 3rd Edition, McGraw-Hill Book Company, New York |

*Update supplements were issued as API Publ. 1537 A through D covering the period to 1974.

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

Vaporizing pot-type burners gained popularity for firing natural-draft space heaters, but they are limited to the use of kerosene or No. 1 heating oil, because of their tendency to form carbon deposits in the vaporizing chamber with No. 2 oil. They were also used in central furnaces, but this application has diminished markedly since World War II.

Rotary wall-flame and rotary-atomizing burners were common types before and immediately following World War II. The rotary-atomizing burner produced a sunflower-like flame. The wall-flame burner concept provided very efficient, quiet, and clean combustion. It could also be adapted to low firing rates, down to 0.3 gph. In view of their high performance, these burners were widely sold directly to homeowners for retrofit conversion of coal furnaces or boilers. With the trend to package burner/boiler and burner/furnace units, decisions on burner choice shifted away from the fuel-economy-conscience homeowner to furnace and boiler manufacturers that competed on a first-cost basis for the builder market. Because initial costs of wall-flame burners were several times greater than the cost of competitive gun-type burners, and they required specially trained service personnel, they did not compete effectively in the builder market after the early 1950s. However, many of these units are still in operation, both in conversion installations and in matched units. Many of those are operating on kerosene or No. 1 oil to minimize service problems.

<u>The high-pressure gun-type burner</u>, with 100 psi fuel pressure, has emerged as the most common burner in the U.S. The principal attributes of the high-pressure burner are its low cost and relatively modest requirement for service. Its combustion performance depends mainly on the matching of the air pattern to the oil spray in the fuel/air mixing process. Before the advent of flame-retention heads in the late 1950s, high-pressure burners usually did not achieve the high levels of performance typical of low-pressure or wall-flame burners; the introduction of flame-retention heads has markedly improved the performance of high-pressure gun-type burners.

The high-pressure burner is relatively forgiving of misadjustment, as it will operate fairly reliably for long periods of time with usually adequate combustion performance, even though it is misadjusted or needs maintenance. This attribute of reliability is a disadvantage when considering air-pollutant emissions, because there is little warning to the homeowner that a burner is operating with marginal performance, perhaps near the onset of particulate and hydrocarbon emissions that result from incomplete combustion.

High-pressure gun-type burners are usually designed to be adaptable to a range of firing rates with minimum design changes except combustion head and nozzle size, but mixing turbulence is sacrificed at lower firing rates if a single combustion head is used over a range of firing rates.

## Typical Combustion Performance of Various Burner Types

Figure II-1 illustrates how oil burner performance is usually visualized and evaluated in the residential heating industry.* This shows the relation of smoke number to $CO_2$ for burner designs having different characteristics. (Excess air is an inverse relationship to $CO_2$ and indicates the percentage excess of combustion air over the theoretical requirement for complete burning of a given fuel) Here smoke is measured by the Bacharach scale, which is the industry standard for smoke level as determined by the ASTM smoke method**.

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* ASTM D2157, "Standard Method of Test for Effective Air Supply on Smoke density in burning distillate fuels."

** ASTM D2156-65(70), "Standard Method of Test for Smoke Density in the Flue Gases from Distillate Fuels."

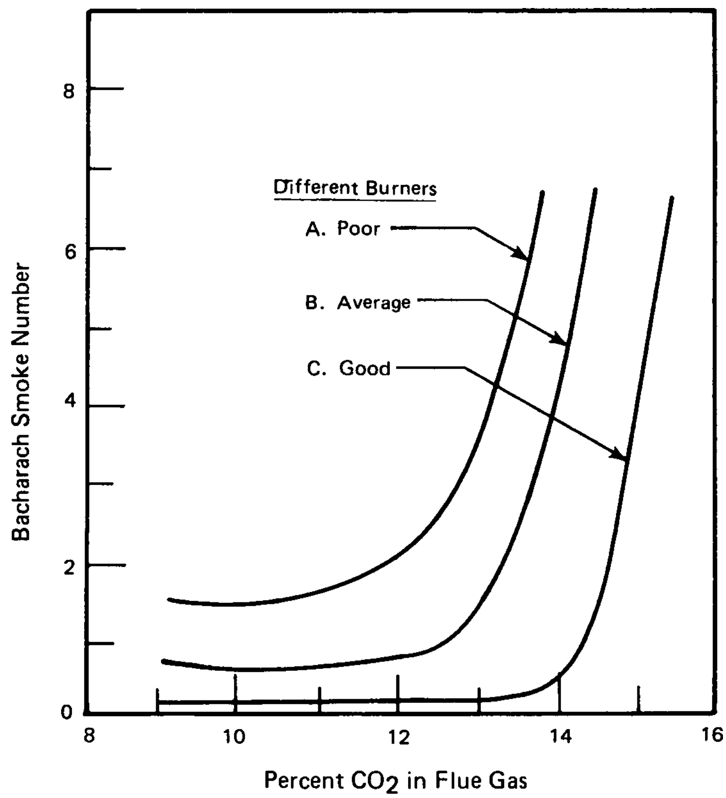



FIGURE II-1. METHOD OF CHARACTERIZING OIL BURNERS – Different Burners Have Different Smoke-$CO_2$ Curves

Table II-2 illustrates typical performance of individual types of burners in a comparative way. These data are taken from the document published for service technicians by the U.S. Environmental Protection Agency: "Guidelines for Residential Oil Burners Adjustments". (Locklin and Barrett, 1975)* The data represent the lower limit of $CO_2$ content in the flue gases when a typical burner is tuned to operate at a smoke level of number 1 or less on the Bacharach scale. It should be recognized that these are lower limits; burners operate frequently with a $CO_2$ level 1/2 to 1 percent higher than shown.

*References are cited in this report by author and date. For full information on sources cited, see author-alphabetical list in Section VIII of this report, REFERENCES.

TABLE II-2. TYPICAL AIR ADJUSTMENTS FOR DIFFERENT TYPES OF RESIDENTIAL BURNERS
(Locklin & Barrett, 1975)

| OIL-BURNER TYPE | TYPICAL $CO_2$ IN FLUE GAS WHEN TUNED* |
|---|---|
| HIGH-PRESSURE GUN-TYPE BURNERS | |
| • Old-Style Gun Burners | 8% |
| - No internal air-handling parts other then an end cone and stabilizer | |
| • Newer-Style Gun Burners | 9% |
| - Special internal air-handling parts | |
| • Flame-Retention Gun Burners | 10% |
| - Flame-retention heads | |
| OTHER TYPES OF BURNERS | |
| • Atomizing Rotary Burners | 8% |
| - ABC, Hayward, etc. | |
| • Rotary Wall-Flame Burners | 12% |
| - Timken, Fluid-Heat, Torridheet, etc. | |
| • Miscellaneous Low-Pressure Burners | ** |

*Based on acceptable Bacharach smoke — generally No 1 or trace, but not exceeding No 2.

Caution should be used in setting burners with $CO_2$ level higher than 13%.

**Variable, depending on design. See manufacturers instructions.

## TRENDS IN HIGH-PRESSURE GUN-TYPE BURNERS

Because high-pressure burners have dominated the residential oil-heating market since World War II, some comments on trends in their development are in order. Marked advances have been made over the past two decades even though basic principals and component functions for high-pressure gun-type burners have generally remained the same. The improvements have resulted in more compact burners having improved efficiency, flame stability, and serviceability. Some are operable at lower firing rates than previously. Major factors in these developments are:

- Flame-retention heads having higher pressure drops for better mixing
- Higher speed fan motors for high-pressure capability
- Lower nozzle temperatures, for reduced clogging
- Improved nozzles, pumps, and controls
- More compact components.

Improved methods of fuel/air mixing in gun burner operation have received considerable attention. (Lang, 1961; Beach & Seigmund, 1962) In retrofit programs even before the oil crisis, oil marketers were urging the upgrading of existing burners by installing improved mixing devices. (Fuel oil and Oil Heat, 1963; Luther et al, 1964)

The introduction of flame-retention heads in the 1960s was an extension of general concepts of improved fuel/air mixing that were sought in various developments including the Shell Head that was introduced in the 1940s. Flame-retention heads give compact, stable flames that are often quieter than those in conventional burners where the flame front is allowed to "float". Excellent mixing is provided in the vortex induced by the swirl vanes. Flame retention heads are a key part of current retrofit programs for more efficient furnaces.

The use of two-pole, high-speed electric motors for blower drive has permitted high-pressure drops across the burner head, enabling improved fuel/air mixing. The trend towards two-pole motors, initially prevalent in Europe (Howe, 1964) has spread to the U.S. (Lord, 1968) Smaller fans and pumps have led to more compact burners which have advantages in some package units.

There has been a strong trend toward lower firing rates for residential heating in the U.S. over the past four decades. (Olson, 1965; Fueloil & Oil Heat, 1979) The ability to operate high-pressure burners reliably at lower firing rates is enhanced by the trend toward completely engineered or matched burner/boiler or burner/furnace units. Designers have incorporated features to improve fuel/air mixing and to minimize nozzle temperatures. In addition, light-weight, ceramic-fiber refractory materials are being used for combustion chambers, reducing the heat radiated to the nozzle after shut-down and therefore reducing nozzle clogging. Fuel pumps for high-pressure burners have been improved to give rapid fuel cut-off. (Nelson, 1968) Along with these equipment improvements, an upgrading of fuel quality in the early 1950s contributed to the success of low-firing-rate operation; (Olson, 1965) however, fuel quality can be expected to vary in periods of tight supply.

Another trend in residential oil burners is the use of photo-electric burner-mounted combustion safety controls, particularly of the cadmium-sulfide-cell type, which give quicker response in the case of flame failure than former stack-mounted thermal-sensing types. With the flame-sensing cell mounted in the air tube of the burner, there is less chance of improper installation than with a stack-mounted control. In addition, solid-state electronic circuits are being introduced in combustion safety controls. (Evans, 1968; Bauer, 1968) New ignition transformers, some of the pulse-discharge type, are now more compact than previous transformers. (Stutz & Hazard, 1962)

New controls combine the functions of ignition transformer and combustion safety control, making possible further compactness in design. (Rheaume, 1968)

## Major Limitations of High-Pressure Burners

High-pressure burners have been shown to be capable of excellent combustion performance, even operating near stoichiometric air settings with some systems (particularly blue-flame burners). However, the atomizing nozzle represents the main limitation. Plugging of the tiny passages of high-pressure atomizing nozzles by sediment or fuel-varnish deposits sometimes occurs, especially when operating at low firing rates. Thus, reliability suffers at firing rates below about 0.5 or 0.6 gph. This is the principal limitation of the high-pressure burner in meeting requirements for today's needs for low-firing rate burners.

# SECTION III

## SEASONAL HEATING-SYSTEM PERFORMANCE AND EFFICIENCY

Although the main emphasis in this report is on technology for efficient oil burners, it is necessary to recognize a perspective of how the oil burner interacts with other system components and modes of operation in affecting seasonal efficiency of the entire space-heating system.

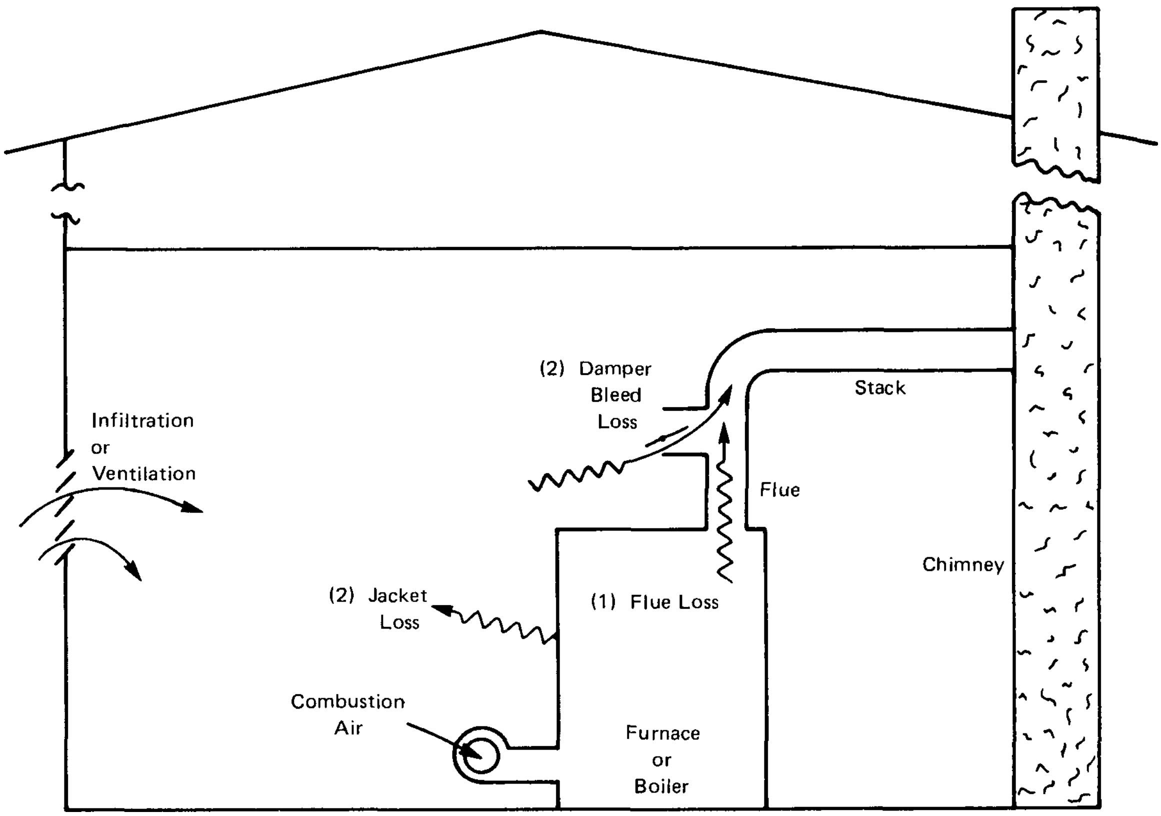
### SEASONAL EFFICIENCY

Figure III-1 illustrates major losses from a typical oil-fired space-heating system. Steady-state and off-period losses are characterized separately. Seasonal efficiency of the heating system is usually less than steady-state efficiency because of losses that occur during the off-period of cyclic operation. (Neglected in Figure III-1 are losses and gains from the chimney, ducting or piping, and the flue pipe.)

1. Flue Loss. The heat in combustion products lost up the flue is the largest heat loss. It is governed by (a) performance capabilities of the burner that determine excess-air level and (b) the heat-exchanger design for the burner/furnace or burner/boiler unit that determines the flue-gas temperature exiting the unit. This loss occurs regardless of installation location.

Air circulation through the unit during the off-period, resulting from chimney draft or stack effect from heat within the unit, removes stored heat from the combustion chamber and heat exchanger. The stored heat is then lost out the flue. This loss can be reduced significantly by automatic flue dampers, stack dampers, or burner-inlet dampers that close (or nearly close) the duct during off periods. Burners and heat exchangers with high flow resistance also serve to minimize the amount of air circulation through the unit during off periods.

2. Jacket Loss. For installations where the unit is within a heated space, jacket losses (and losses from external surfaces of the flue and stack) are not actually losses, but contribute to heating the space. If the jacket




| | Steady-State Losses | Off-Period Losses |
|---|---|---|
| 1. Flue Loss | Depends on excess combustion air and flue-gas temperature. | Depends on air-flow resistance through burner and heat capacity of unit. |
| 2. Jacket Loss (including base) | Depends on insulation and design (usually 1-3 percent). | Usually small (except for boilers with water coils). |
| 3. Damper Bleed Loss | Depends on chimney draft and characteristics of draft control damper. | |

FIGURE III-1. MAJOR HEAT LOSSES FROM A TYPICAL OIL-HEATING SYSTEM loss is excessive, it may result in overheating of the equipment jacket, so it is desirable to reduce this loss by design. In the DOE efficiency rating procedure by the flue loss method, jacket loss is credited as useful heat delivered to the heated space for indoor units (DOE, 1978). This procedure determines what is defined as the Annual Fuel Utilization Efficiency (AFUE). The BNL input/ output test procedure for seasonal efficiency does not credit jacket loss as part of the output.

3. Draft-Control Damper Bleed Air Loss. For installations in heated heated spaces, bleed air entering the draft-control damper is replaced by cold infiltration or ventilation air that must be heated, and therefore represents a loss. Damper bleed loss during off-periods, although less in rate than during on-periods, can be a substantial portion of seasonal losses because there is potential for air flow during essentially all of the heating season. This loss is not actually chargeable to the heating unit, but is a loss from the heated structure that results from the pumping action of the draft system and from the way draft is controlled. Sealed combustion systems that duct outside air to the burner for combustion and for draft control can eliminate this loss.

It should be noted that the damper-bleed-air loss is not measured or charged against the unit in the seasonal efficiency rating by the input/output test procedure used at Brookhaven. An estimate of this loss is included in the DOE prediction of annual fuel use.

## STEADY-STATE EFFICIENCY

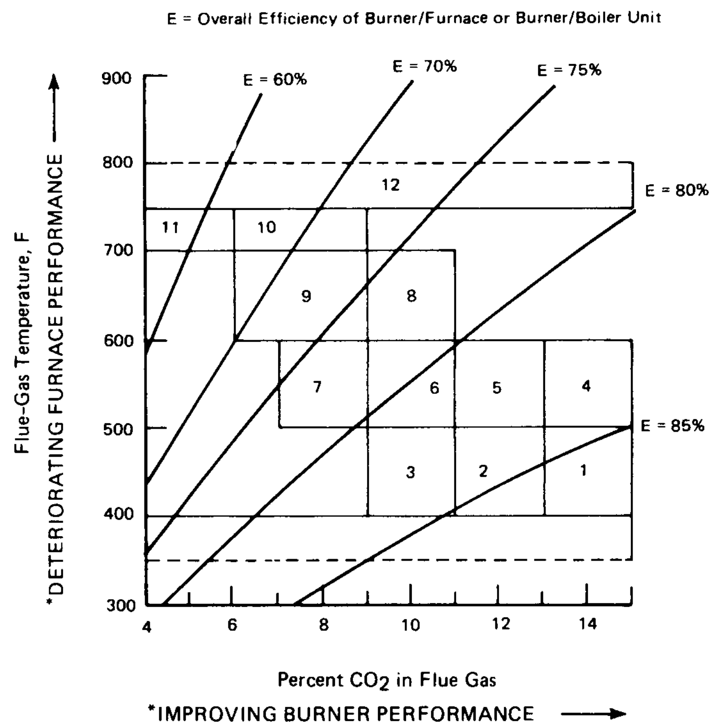
Figure III-2 illustrates the effect of burner performance and flue-gas temperature on steady-state efficiency of the heating units. The numbered zones are defined by the $CO_2$ level and flue-gas temperature.

## SEASONAL EFFICIENCY

While steady-state efficiency is the traditional measure of thermal performance of residential furnaces and boilers, the determining factor in seasonal fuel consumption is the efficiency over an entire heating season of intermittent operation in response to different heating loads.

### Overall Efficiency at Part Load Determines Seasonal Efficiency

Figure III-3 illustrates the part-load efficiency of several burner/boiler systems tested at Brookhaven by the direct input/output method (Batey, et al., 1977; McDonald, et al., 1979). Overall efficiency is plotted against burner fractional "on" time.




| Zone Number | Quality of Performance: Furnace | Quality of Performance: Burner | Steady State Efficiency Range (percent) | Commentary |
|---|---|---|---|---|
| 1 | Excellent | Excellent | 90–83 | Rarely, if ever achieved |
| 2 | Excellent | Good | 87–82 | Uncommon; only achieved by the best of new (less than 5-year-old) equipment |
| 3 | Excellent | Typical | 85–80 | Common to new (less than 5-year-old) equipment, retention head burners |
| 4 | Typical | Excellent | 85–82 | Rare |
| 5 | Typical | Good | 84–80 | Uncommon, except in good retention head burners |
| 6 | Typical | Typical | 82–76 | Common to new (less than 5-year-old) equipment, retention head burners |
| 7 | Typical | Poor | 80–72 | Unfortunately common in new equipment where it is evidence of a poor burner; in old equipment (more than 5 years old with standard head burners) this is a good performance |
| 8 | Poor | Typical | 80–74 | Common; in new equipment it is evidence of poor heat-exchanger design or overfiring |
| 9 | Poor | Poor | 76–65 | Common in old systems where again it may be evidence of overfiring or inadequate heat-exchanger design |
| 10 | Bad | Poor | 74–61 | Both categories are uncommon except in the oldest of systems. This performance is very poor |
| 11 | Bad | Bad | Below 61 | |
| 12 | Completely unacceptable. Flue-gas temperatures above 750 F constitute a materials problem and a fire hazard | | | Unsafe operation from the point of view of fire hazard |
| 13 | Completely unacceptable. Flue-gas temperatures below 400 F can constitute a corrosion hazard | | | Unsafe operation from the point of view of the structural stability of the chimney |

FIGURE III-2. STEADY-STATE EFFICIENCY OF VARIOUS OIL-FIRED HEATING SYSTEMS (Source: Department of Energy, Mines and Resources, Canada)

The efficiency at 100 percent "on" time is the steady-state efficiency that is measured in traditional boiler output rating tests, where jacket loss is not credited to the useful heat output. Thus, this steady-state efficiency is lower than the value determined by the flue-loss method that is based on traditional field determinations using flue-gas analysis and flue-gas temperature. The difference is the jacket loss, generally in the range from 0.5 to 3 percent for better conventional equipment. (With some dry-base boilers, the jacket loss may be as high as 5 to 10 percent.)

Seasonal efficiency is estimated from the data on these curves by a BNL calculation procedure that accounts for the number of operating hours annually at each load for an assumed combination of geographic location, weather, and system conditions. Values for seasonal efficiency are listed with the symbols for each curve in Figure 1.

The curves of Figure III-3 illustrate the following effects:

- The gain in efficiency due to more effective boiler heat-exchanger surface (Compare the two conventional burner curves for boilers A and C).

- The gain in efficiency due to a higher-performance burner that is capable of operating cleanly at lower excess air and capable of reducing off-period losses (Compare the conventional burner with the flame-retention-head burner for both boilers A and C).

The higher performance burner yields relatively higher efficiencies at low loads, shifting the knee in the curve. This is due, in part, to the lower off-period losses for the high-pressure drop, flame-retention heads that are used in the high-performance burners and that restrict off-period air flow. The improved efficiency at low loads is important to the seasonal efficiency, since most of the running time is at low loads.

The principal factors that affect seasonal efficiency are summarized as follows, classified by their influence during on-periods and off-periods.

- <u>On-Period Losses</u>

  Factors that influence <u>steady-state</u> losses and efficiency:

  - burner excess-air level
  - flue-gas temperature
  - jacket losses
  - source and temperature of air

  Other factors involved during the on-period during <u>intermittent</u> operation:

  - system load
  - cycle length
  - thermal mass of the furnace/boiler and heating medium

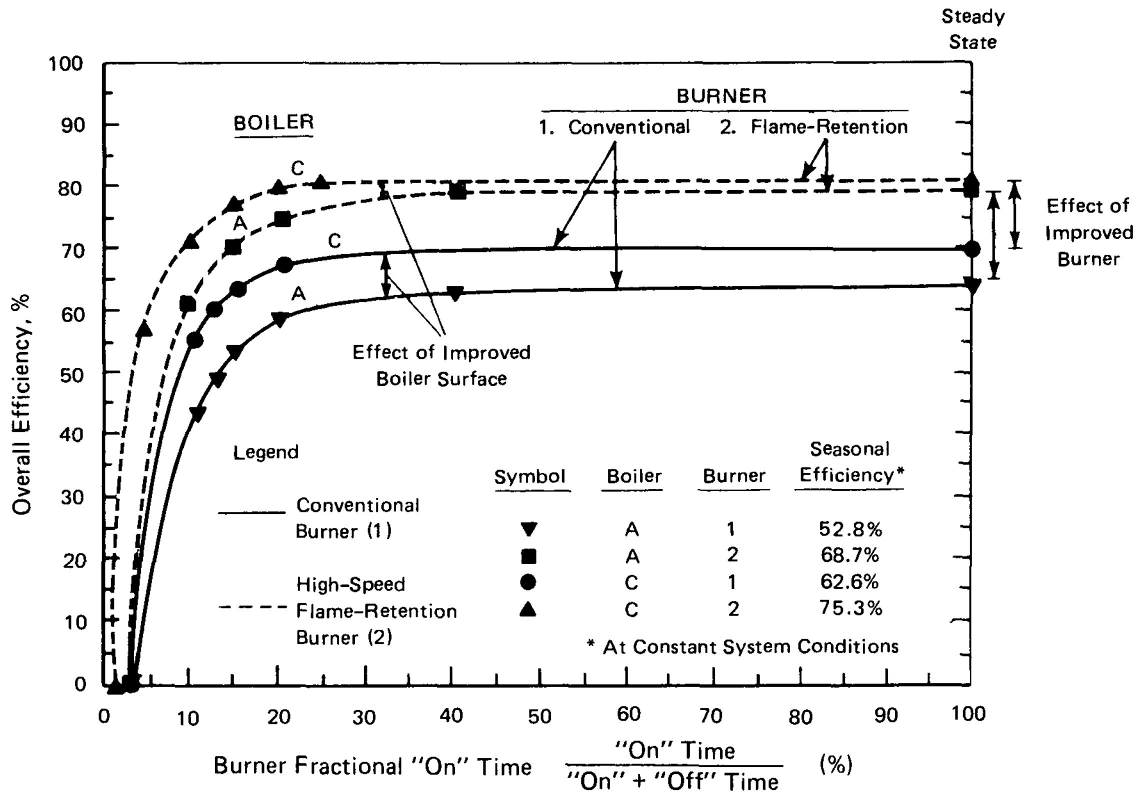



FIGURE III-3. PART-LOAD EFFICIENCY IN BNL DIRECT INPUT/OUTPUT TESTS (McDonald et al, 1979)

– Showing effect of boiler design and burner performance

– Boiler maintained at temperature for water-heating coil.

- Off-Period Losses
  - air-flow through the burner and heat exchanger
  - system load
  - cycle length
  - thermal mass of furnace/boiler and heating medium.

These factors then suggest approaches to the design of more efficient heating systems, discussed below.

## DESIGN ROUTES TO HIGH SEASONAL EFFICIENCY

The following design routes will contribute to higher seasonal efficiency, either separately or in combination.

1. Low-excess air operation
2. Efficient heat exchanger

3. Reduction of burner oversizing
4. Reduction of off-period losses
5. Reduction of jacket losses
6. Reduction of furnace/boiler-induced air infiltration.

## 1. LOW-EXCESS-AIR OPERATION

Reducing excess air reduces the mass and temperature of heated air lost up the flue during on-periods. In addition, tighter burner air ports for lower excess air settings result in lower off-period losses.

As oil burners have been developed and improved, designers have sought clean operation at low excess air*, such that low-smoke operation in the range of 13 to 15 percent $CO_2$ is achievable with some burners. A practical limitation in field operation arises due to shifts that may occur in firing rate or air supply. Thus, while 15 (plus) percent $CO_2$ is theoretically possible**, a more practical setting is 13 to 13.5 percent, even for the best performing burners. As more efficient and compact heat exchangers are used, the advantage of high $CO_2$ is decreased somewhat, but the problem of fouling with soot deposits can become more acute.

## 2. EFFICIENT HEAT EXCHANGERS

The design of heat exchangers for fuel-fired heating equipment has been limited, traditionally, by (1) the objectives of maintaining exit flue-gas temperatures high enough to avoid condensation of moisture that would result in corrosion of conventional materials and (2) by the cost-benefits of furnace or boiler design for the competitive builder market, where first cost is all important. In the days of relatively low fuel costs, the oil-fired furnace and boiler industry reached an economic compromise of overall steady-state efficiency. For example, to achieve a steady-state efficiency in the range of 78 to 80 percent for a $CO_2$ level of 10 percent and jacket loss of 2 percent, requires a gross flue-gas temperature of about 500 F.

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* $CO_2$ content in the flue gas is a measure of excess air level and is widely used in the residential oil-heating industry, mainly because of the early availability of inexpensive field instruments. $O_2$ content is commonly used in industrial combustion measurements, and its use is growing in residential measurements. Figure III-4 shows the relationship between $CO_2$, $O_2$ and percent excess air for a typical No. 2 fuel oil fired with complete combustion.

**The ultimate $CO_2$ for a given fuel oil depends on its hydrogen/carbon ratio. For typical No. 2 fuel oils having an API gravity of 35 degrees at 60 F, the hydrogen/carbon ratio is about 6.5, and the ultimate $CO_2$ is about 15.5 percent.

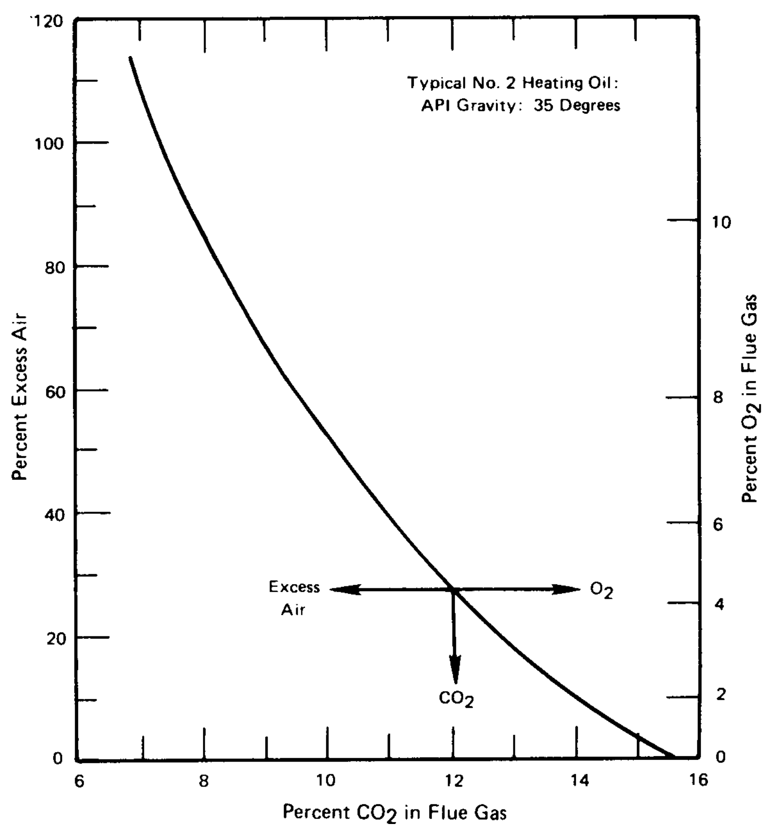


FIGURE III-4. RELATIONSHIP BETWEEN $CO_2$ AND $O_2$ IN FLUE GAS AND PERCENT EXCESS AIR — Typical No. 2 Heating Oil

As heat exchangers are designed to remove more heat from the flue gases, two practical limitations arise for conventional practice:

1. Condensation of water vapor causes corrosion of steel surfaces and deterioration of masonry chimneys.
2. Exhaust gases lose buoyancy for escape up the chimney.

These problems can be overcome with proper design and materials selection for new units and installations, but they may limit retrofit opportunities in existing installations.

## Condensing Heat Exchangers

A significant increase in overall steady-state efficiency can be gained by the use of corrosion-resistant materials in the heat exchanger, such that condensing operation is practical. This enables the regain of a portion of the latent heat of condensation of combustion-generated water vapor. The following example illustrates this effect as flue-gas temperature is reduced.

| Flue-Gas Temperature, F | Maximum Steady-State Efficiency,%* |
|---|---|
| 500 | 83 |
| 300 | 88 |
| 200 | 91 |
| 124 dew point | 92 |
| 100 | 95 |
| 80 | 98 |

*Assumes that jacket heat loss contributes to heating the space.

The gain in efficiency is linear with flue-gas temperature reduction until the dew point is reached where moisture condenses, and then efficiency increases rapidly. Condensation will occur on cool surfaces well before the bulk flue temperature is reduced to the dew point-temperature, which happens in fact for a portion of a heat exchanger each time the unit is started from cold. The degree of condensing operation is a design compromise that the designer must make, considering tradeoffs between overall performance and manufacturing cost.

Because of the sulfur content of fuel oil, the acid dew point is higher than the water dew point and sulfuric acid will condense on surfaces as warm as 260 F for oil having a sulfur content of 0.3 percent. Thus, corrosion can be expected to be more severe with oil firing than for gas firing, and corrosion-resistant materials or coatings are a necessity.

Battelle is currently evaluating materials for oil-fired condensing-type heat exchangers under contract with Brookhaven; the project includes an assessment of other problems, such as condensate disposal, and issues raised by codes and standards. A companion program for gas-fired systems at the Canadian Gas Research Institute is being supported by the Gas Research Institute.

Additional discussion of condensing-type systems and associated problems is presented in Section VII.

## 3. REDUCTION OF BURNER OVERSIZING

Off-period losses are minimized if the firing rate of the burner is matched to the overall heat loss of the space. This has been demonstrated in recent field studies. (Katzman and Weitzman, 1976)

## Variable Firing Rate to Match Load

The ideal situation would be a continuously variable firing rate to match the heating load, were it not for limitations of corrosion caused by flue condensation and the lack of burner reliability at low input rates. These practical problems, plus the complexity of controls needed to modulate fuel input and combustion air (and circulating air for furnace installations), make this approach a formidable challenge for burner designers and would likely result in higher first cost and poorer reliability.

A simpler approach, and perhaps nearly as effective for efficient operation, would be a stepped firing rate, with fuel and air controlled in two or more fixed stages. For example, the low firing rate in a two-stage-input burner could be selected such that the cold-end heat exchanger, constructed of special material, would operate in the condensing mode; the high firing rate could be chosen to achieve a reasonable efficiency with the same heat exchanger, still limiting the materials hot-spot temperatures as appropriate for the materials chosen. An alternative would be the use of an auxiliary heat exchanger for full firing rate. A major improvement in seasonal efficiency is to be gained from the use of the condensing mode at low firing rates, where most of the running time is accumulated.

## Fixed Firing Rate at Low Capacities

For best seasonal efficiency with conventional systems using a fixed firing rate, the input should not exceed the design load on the furnace/boiler, allowing a modest over-capacity to handle pickup if there is night setback. Usually, 20 to 60 percent overfiring is an optimum reserve, considering pickup from night setback and other factors. (MacArthur and Nelson, 1978) With modern, well-insulated and weatherproofed homes, this desired firing rate may still be below that for long-term reliability of conventional high-pressure oil burners. Accordingly, there is incentive for the development of low-capacity burners that will operate reliably and with good efficiency at low firing rates (between 0.3 and 0.75 gph).

## 4. REDUCTION OF OFF-PERIOD LOSSES

Several approaches are possible for reducing off-period losses. The principal approaches are:

1. Reduce air flow through the unit, and/or
2. Reduce stored heat in the system.

For the first approach, the addition of automatic dampers at burner inlet, flue, or stack will reduce off-period air flow. Or alternatively, high-resistance burner air passages or heat exchangers will provide a substantial reduction in off-period air flow.

An example of the second approach is a low-thermal-mass unit which is controlled to minimize stored heat during the off cycle. The circulator for a boiler having low water volume could be controlled to cool the boiler quickly at the end of an on period; the warm-air equivalent would be constant blower operation, or at least long blower afterrun. In either case, additional costs for auxiliary electrical energy would become a factor.

## 5. REDUCTION OF JACKET LOSSES

Reduction of furnace/boiler jacket temperatures, as by more effective insulation, will reduce external losses if the unit is located in an unheated or partially heated space. This loss can occur both during on-periods and off-periods.

## 6. REDUCTION OF FURNACE/BOILER-INDUCED AIR INFILTRATION

Use of direct vents or sealed combustion systems, without a barometric draft control, will reduce bleed air losses that must be made up by infiltration air. This loss also can occur during both on-periods and off-periods. For practical use of direct vents, the burner performance must be relatively insensitive to changes in draft. While the bleed air loss is not a factor in seasonal efficiency of the furnace/boiler unit per se, it does increase seasonal fuel consumption.

## INTERACTION OF DESIGN APPROACHES

There are elements of interdependence in the effects of the different approaches cited. For example, if there is condensing operation, a low-excess-air burner is somewhat less important for steady-state efficiency. Or, if there is little air flow during off periods, there will be minor advantage (except for jacket loss) in reducing stored heat by reduced thermal mass. High thermal mass can actually be beneficial in intermittent operation by its effect in delaying flue-temperature rise during on-periods. The complex interrelationships between the design variables make it difficult to assess the overall performance in different modes of operation.

## SUMMARY OF APPROACHES TO IMPROVED EFFICIENCY

Table III-1 illustrates some example approaches to retrofit and new equipment design and offers some subjective estimates of resulting seasonal efficiency. It should be noted that jacket heat loss is credited as useful heat input, as would be the case for an installation in a heated first-flow utility room.

The information in the first three columns states the assumptions used in estimating the steady-state efficiency, and the three, at the right identify the assumptions that relate to off-period losses as used in estimating the seasonal efficiency.

Among the retrofit opportunities, the installation of a new high-performance burner can yield substantial fuel savings, but only if the present system is low in efficiency. Stack dampers are useful only when the equipment is installed in heated spaces. Considering the options for new equipment, condensing-type heat exchangers offer the principal increment of efficiency gain.

Although Table III-1 is based on hydronic systems, the same trends would be expected to apply to warm-air systems.

TABLE III-1. EXPECTED SEASONAL EFFICIENCY BY VARIOUS RETROFIT STEPS AND INSTALLATION OF NEW-HIGH EFFICIENCY EQUIPMENT *

| | ASSUMPTIONS RELATING TO STEADY-STATE EFFICIENCY | | | | ASSUMPTIONS RELATING TO OFF-PERIOD LOSSES | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Burner Excess Air Level, % $CO_2$ | Heat Exchanger | Flue Gas Temp. (gross) F | Steady-State Eff., % | Firing Rate/ Load | Off-Period Air Flow | Damper Bleed Loss | Stored Heat Loss | Estim. Seasonal Efficiency; Range, % |
| A. Baseline: Typical of Conventional Burner/Boilers | 8 | Conventional | 600 | 73 | 2.0 | Avg | Avg | Avg | 63-67 |
| B. Upgrading Installations by Retrofit | | | | | | | | | |
| 1. Tune existing burner | 9 | Conventional | 600 | 76 | 1.8 | Avg | Avg | Avg | 66-70 |
| 2. Stack damper | | Conventional | 600 | 76 | 1.8 | Very Low | Very Low | Very Low | 70-73 |
| 3. New conventional burner | 11 | Conventional | 550 | 78 | 1.5 | Low | Avg | Low | 70-74 |
| 4. New high-performance burner and constant circulator operation | 13 | Conventional | 500 | 82 | 1.3 | Very Low | Avg | Reduced | 72-79 |
| C. New Burner/Boiler Unit | | | | | | | | | |
| 1. High-performance burner, conventional heat exchanger | 12 | Conventional | 450 | 82 | 1.3 | Very Low | Avg | Avg | 72-76 |
| 2. High-performance burner, high efficiency heat exchanger | 13 | Multipass | 400 | 86 | 1.3 | Very Low | Avg | Low | 76-80 |
| 3. Conventional burner, condensing heat exchanger with direct vent | 11 | Partially Condensing | 200 | 91 | 1.3 | Low | None | Low | 81-85 |
| 4. High-performance burner, condensing heat exchanger with direct vent | 13 | Partially Condensing | 100 | 95 | 1.3 | Very Low | None | Nil | 87-92 |

* Seasonal efficiency ranges estimated by Battelle and BNL staff based on available data, overall experience, and judgement. For a typical home requiring 40,000 Btu/hr output at design conditions, hot-water boiler without domestic coil, no night setback. Jacket loss is credited as useful heat output. Efficiency is "fuel efficiency"; electrical input is not considered.

# SECTION IV

## HISTORICAL REVIEW OF OIL-INDUSTRY R&D PROGRAMS

During the 1950s and 1960s, considerable R&D effort toward improving residential oil burners was organized and supported by oil refiners and oil marketers. These efforts were generally geared toward lower cost, lower capacity, and more reliable residential oil burners that could compete more effectively with gas heating. Major programs were as folows:

1. American Petroleum Institute (API)

   API Oil-Burner Research Program

2. National Oil Fuel Institute (NOFI)

   NOFI Equipment Development Program

3. Operation Oil Heat Associates (OOHA)

   OOHA Oil Burner Development Program.

The API and NOFI programs were funded by a group of major oil refiners and were planned and monitored by technical representatives of those refiners. The OOHA Program was a marketer-sponsored program directed to the development of a low-cost oil burner that would strengthen oil heating in competition with gas heating; funding was mainly from a group of fuel-oil distributors formed for this purpose, but some funding was from oil refiners through NOFI.

These programs are discussed in more detail in the sections that follow. Independent R&D by the refiners or equipment manufacturers is identified with the programs under which it was reported and/or published. Technical details of the R&D within these programs are not presented in this section. However, certain of the more pertinent results are described in Section VI on TECHNICAL APPROACHES TO BURNER DESIGN -- EXAMPLES AND ASSESSMENTS.

## API OIL-BURNER RESEARCH PROGRAM

The API Oil-Burner Research Program was initiated in 1959 under the Fuel Oil Committee of the API marketing division. Ten major R&D projects were supported within the period 1960 to 1967. A distinguishing feature of this program was that all results were presented to the industry and published for public use, and patents were dedicated to the public domain.

The evolution of the API program was described by J. L. Minner (1959) Chairman of the Research Subcommittee of the API Fuel Oil Committee and by C. J. Livingstone (1961), chairman of the API Technical Advisory Group.

Funding of R&D contracts was through refiner contributions to API. In addition, a substantial contribution of technical effort was made by refiners through R&D conducted independently in their own laboratories.

## OBJECTIVES

The objectives of the API program were as follows (Livingstone, 1961):

- Search for new principles in fuel oil combustion.
- Search for greater understanding of combustion principles, both new and old.
- Search for ways of exploiting these principles.
- Demonstrate principles in bench scale or prototype equipment.
- Interpret research results in terms of their practical application to combustion equipment.
- Solve problems which present major obstacles to development of new equipment.
- Communicate needed information to developers and manufacturers to stimulate final development and commercialization of equipment.

It will be noted that the scope did not include final development, production design, and commercialization of specific oil burner equipment.

## PLANNING STUDY AND R&D RECOMMENDATIONS

A comprehensive study of R&D needs was conducted for the API Fuel Oil Committee in 1959 and 1960 by Battelle-Columbus. Phases in this study were:

1. Survey of current research activities in the industry pertaining to fuel-oil combustion, and particularly to oil-burner development for residential heating
2. A study of unconventional concepts for oil burners with a view to their potential application for residential heating,
3. Appraisal of research needs and the recommendation of a program of research
4. Assistance to the Research Subcommittee in stimulating the activation of research needed to realize commercial development and manufacture of improved oil-fired equipment.

### R&D Recommendations

The findings of the planning study were reported in API publication 1700. (Locklin, 1960) The report identified various research needs and recommended specific R&D projects

Table IV-1 summarizes the areas in which R&D was recommended. The Appendix to this report contains a summary of the specific R&D recommended in the various areas, listed by priority; also shown are the results of the qualitative appraisal that was used in establishing the priorities. Detailed descriptions and appraisals of the identified R&D needs are included in the Appendix for the categories of principal interest to the current study for BNL. A number of R&D needs are flagged for which new R&D would contribute to the overall BNL program.

## MAJOR R&D PROJECTS IN THE API PROGRAM

In the selection of R&D that was initiated under the API Oil Burner Research Program, limitations in oil-industry funds allocated for the program required some further prioritizing of R&D needs. Through evaluation and discussions by the API Technical Advisory Group, the final program of API contract R&D was evolved. R&D projects were initiated at the beginning of the API program in the following areas:

- Atomization concepts and spray droplet effects
- Fuel vaporization from surfaces
- Air-fuel mixing and recirculation
- Burner concepts

TABLE IV-1. AREAS OF R&D ORIGINALLY RECOMMENDED FOR API BURNER PROGRAM (Locklin, 1960)

| GENERAL CATEGORIES | SPECIFIC AREAS IN WHICH R&D WERE RECOMMENDED |
|---|---|
| A. Combustion Fundamentals and Burner Concepts | 1. Atomization<br>2. Vaporization and Preflame Deposits<br>3. Ignition<br>4. Mixing and Recirculation<br>5. Combustion Processes and Smoke Formation<br>6. Surface and Catalytic Combustion<br>7. Experimental Techniques |
| B. Product Development and Application | 8. Burner Design and Development<br>9. Heat Exchanger Equipment, Including Water Heaters |
| C. Residential Installations | 10. The Systems Approach and the Oil Tank<br>11. Combustion Air Supply and Venting, Including Prefabricated Flues |
| D. Industry Codes and Standards | 12. Research for Codes and Standards |
| E. New Uses for Fuel Oil | 13. Oil-Fired Refrigeration and Air Conditioning<br>14. Household Appliances<br>15. Agriculture, Industry, and Transportation |

Battelle was retained under contract from API to coordinate technical aspects of the program relative to the contract program and to the refiner's in-house programs. In addition, supporting activity was conducted by Battelle (1) to coordinate the oil-industry panels that supervised the projects and (2) to provide communications for technology transfer to the oil-heating industry -- including abstracting and publication of pertinent information, organizing R&D Conferences on an annual basis, and publishing reports and proceedings.

## Summary Reports of R&D Projects

Table IV-2 lists the major R&D projects, contractors, and summary reports of the API Burner Research Program. Initially, these reports were

TABLE IV-2. R&D PROJECTS CONDUCTED AND SUMMARY REPORTS ISSUED UNDER THE API OIL-BURNER RESEARCH PROGRAM

| R&D PROJECTS | CONTRACTOR | SUMMARY REPORT[a] Author(s) | Date | API Publ. No. |
|---|---|---|---|---|
| ATOMIZATION CONCEPTS AND SPRAY DROPLET EFFECTS | | | | |
| A Study of Ignition and Combustion of Fuel Droplets* | SRI ** | Wood, Rosser, & Wise | 1963 | 1722 |
| Analytical Studies on Mechanisms of Fuel Oil Atomization* | Rutgers University | Peskin & Raco | 1967 | 1727 |
| A Study of New Means for Atomization of Distillate Fuel Oil* | A. D. Little ** | Doyle, Perron, & Shanley | 1967 | 1725 |
| The Development of Ultrasonic Atomizers for Domestic Oil Burners | A. D. Little ** | Perron, McCullough, & Shanley | 1967 | 1725-A |
| Electrostatic Atomizer and Burner Research | SRI ** | Newgard & Noon | 1964 | 1724 |
| FUEL VAPORIZATION FROM SURFACES | | | | |
| Surface Vaporization Studies with No. 2 Fuel Oil (paper in '62 Proceedings)* | Atlantic Res. Corp. ** | Morgenthaler | 1962 | 1701 |
| Vaporization and Combustion of No. 2 Heating Oil (Dev. of a vaporizing burner prototype) | Battelle ** | Hein, Weller, & Locklin | 1967 | 1726 |
| AIR-FUEL MIXING AND RECIRCULATION | | | | |
| Recirculation and Fuel-Air Mixing as Related to Oil-Burner Design* | IITRI ** | Cooper, Kamo, Marek, & Solbrig | 1964 | 1723 |
| Design of Blue-Flame Oil Burners Utilizing Vortex Flow or Attached Jet Entrainment | IITRI ** | Cooper & Marek | 1965 | 1723-A |
| BURNER COMPONENTS | | | | |
| A Survey of Components for Use with Air-Atomizing Oil Burner Nozzles* | Battelle | Yeager & Coffin ** | 1961 | 1720 |
| A Survey of Ignition Technology for Residential Burners | Battelle | Stutz & Hazard | 1962 | 1721 |
| SUPPORTING ACTIVITY AND PUBLICATIONS | | | | |
| Planning Study | | | | |
| Recommendations for an Industry-Wide Oil Burner Research Program | Battelle | Locklin | 1960 | 1700 |
| Technology Review and Abstracts | | | | |
| Literature Pertaining to the Art and Science of Oil Burning for Residential Applications | Battelle | Speich & Locklin | 1960 | 1537 |
| Abstract Supplements | Battelle | Locklin, et. al. | 1961<br>1962<br>1963<br>1964 | 1537-A<br>1537-B<br>1537-C<br>1537-D |

(a) Photocopies can be obtained from: Library, American Petroleum Institute, 2101 L Street, Washington, DC 20037, phone (202) 457-7000.
* Indicates the project was initiated at the beginning of the API R&D Program.
** Indicates that some cooperative efforts by oil refiners also contributed to this area of R&D.

available for purchase from the API Publication Section. Stocks of these reports are now essentially exhausted, but photocopies can be obtained at 25 cents per page from the API Library, American Petroleum Institute, 2101 "L" Street, NW, Washington, D.C. 20037. Phone 202-457-7000.*

Table IV-3 provides abstracts of these API reports.

## Proceedings of Annual Research Conferences

Open research conferences were held annually during the API Oil Burner Research Program to report results from the contract R&D projects, from the cooperative R&D effort by oil refiners, and from pertinent independent R&D by other investigators. Proceedings containing all papers were published for each of the conferences from 1961 to 1966 and made available as API publications.

Tables IV-4 contains a list of papers contained in each of the proceedings. The technical aspects of many of these papers and reports are discussed in Section VI, TECHNICAL APPROACHES TO BURNER DESIGN -- EXAMPLES AND ASSESSMENTS.

The API Oil Burner Research Program, was discontinued in 1966, when the oil-industry R&D mission was transferred to the National Oil Fuel Institute (NOFI), which was just being formed with the help of API to pursue oil-heating industry activities. The NOFI Equipment Development Program is discussed in a subsequent subsection.

## API INVESTIGATION OF OIL-BURNER POLLUTANT EMISSIONS

In 1970, API initiated a 2-year field investigation of emissions from residential and commercial oil-fired heating equipment that was conducted by Battelle. (Levy et al, 1971; Barrett et al, 1973) In the second year, the U.S. Environmental Protection Agency shared support with API. This study, covering emission measurements on 33 residential heating units and 13 commercial boilers, is described in more detail in Section V of this report under "Government Programs Oriented Mainly to Air-Pollutant Emissions".

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* As a result of renewed interest in these reports expected to be generated by the publication of this BNL report, API is considering entering the reports in the National Technical Information Service system, where they would be included in computer search systems and would be available through NTIS.

## TABLE IV-3. ABSTRACTS OF SUMMARY REPORTS FROM THE API OIL BURNER RESEARCH PROGRAM

### A SURVEY OF COMPONENTS FOR USE WITH AIR-ATOMIZING OIL-BURNER NOZZLES.

Summarized in this report are the results of an investigation as to the availability of air compressors, fuel pumps, and metering devices which would fulfill the needs of small air-atomizing burners. General requirements of air-atomizing burner systems are discussed. Approximately 650 component manufacturers were surveyed, and components within the general range of interest are listed. Also listed are manufacturers who report new developments in progress and those who indicate an interest in cooperating with burner manufacturers in the development of new components.

**M. L. Yeager** and **C. L. Coffin**, Battelle Memorial Institute. *API Publication 1720*, October 1961. (34 Pages.)

### A SURVEY OF IGNITION TECHNOLOGY FOR RESIDENTIAL OIL BURNERS

Recent advances in ignition technology are reviewed with respect to their suitability for residential burners. Energy requirements and spark characteristics are discussed. Among the specific systems considered are: conventional transformers, oscillating capacitor-discharge systems, shock-excited systems, electronic automotive ignition systems, piezoelectric devices, magnetos, vibratory sparking units, and hot wire igniters.

**D. E. Stutz** and **H. R. Hazard**, Battelle Memorial Institute. *API Publication 1721*, January 1962. (60 pages.)

### A STUDY OF IGNITION AND COMBUSTION OF FUEL DROPLETS.

Studied experimentally were the phenomena of the ignition and steady-state combustion of fuel droplets in the size range commonly encountered in No. 2 oil burners. Measurements were obtained on ignition lag, droplet burning rates, and flame propagation velocities through aerosols under a variety of imposed conditions of droplet size, oxidizer composition, and ambient temperature. For spray combustion in oil burners, the role of droplet size distribution is discussed in terms of flame propagation velocity, flame dimensions, and luminosity. Numerical results are presented in a nomograph which permits determination of the required preheat zone temperature and the spray residence time in the perheat zone necessary for blue-flame combustion.

**B. J. Wood, W. A. Rosser, Jr.,** and **H. Wise**, Stanford Research Institute. *API Publication 1722*, August 1963. (44 pages.)

### RECIRCULATION AND FUEL-AIR MIXING AS RELATED TO OIL-BURNER DESIGN

In this experimental investigation, the effects of excess air, turbulance level, and combustion-products recirculation were evaluated quantitatively for a pressure-atomizing burner. Under conditions of turbulance and excess air which normally yield smoke, the recirculation of sufficient combustion products back to the burner inlet was found to produce a sharp transition to smoke-free combustion. A second transition was also found which produced nonluminous, quiet and still smoke-free combustion at even higher levels of recirculation. These results show how the incorporation of combustion-products recirculation into burner design can permit smoke-free operation at lower levels of excess air than is possible for a similar design without recirculation.

**P. W. Cooper, R. Kamo, C. J. Marek** and **C. W. Solbrig**, IIT Research Institute. *API Publication 1723*, May 1964. (75 pages.)

### DESIGN OF BLUE-FLAME OIL BURNERS UTILIZING VORTEX FLOW OR ATTACHED JET ENTRAINMENT

Two burner prototypes were developed to illustrate the use of internal recirculation of combustion products in an oil-burning system. In one prototype, combustion air is introduced tangentially into a chamber, setting up a vortex flow pattern in which combustion products recirculate back into the core. In the second prototype, entrainment of combustion products is induced by the inlet air jet. This jet is directly along the surface of a curved solid body, enhancing the ability of the jet to entrain recirculated combustion products. In tests from 0.65 to 1.1 gph, clean blue-flame burning was obtained with excess air levels from stoichiometric to 30 per cent and with inlet air pressures as low as 2 inches of water.

**P. W. Cooper** and **C. J. Marek**, IIT Research Institute. *API Publication 1723-A*, January 1965. (48 pages.)

### ELECTROSTATIC ATOMIZER AND BURNER RESEARCH

The phenomenon of electrostatic atomization of fuel oil was investigated with the objective being its application in residential oil burners. Electrostatic fields produced by different arrangements of conducting atomizer electrodes were studied to define limiting dimensions of conductive atomizer electrodes and to formulate design criteria. Atomization to small droplets (less than 100-micron size) was demonstrated at relatively low flow rates, not high enough for residential burners. Experiments performed on a highly resistive tubular emitter achieved flow rates up to 0.2 gph per emitter but with droplets of 1000-micron diameters. A burner which could accept this size droplets, although not suitable as a final burner design, proved the technical feasibility of separating the atomizer and combustion chamber.

**P. M. Newgard** and **A. W. Noon**, Stanford Research Institute. *API Publication 1724*, November 1964. (56 pages.)

### A STUDY OF NEW MEANS FOR ATOMIZATION OF DISTILLATE FUEL OIL

New means of atomization were evaluated with respect to their applicability to domestic oil burners capable of reliable operation at firing rates below 1.0 gph. A number of atomizing devices were studied, including impact atomizers, jet-impingement devices, return-flow pressure nozzles, pneumatic atomizers, spinning disks, and vibrational devices. The most encouraging results were obtained with electrostatic and ultrasonic atomizers; efforts were thus concentrated on the development and application of these devices. However, the flow capability of electrostatic atomizers was found to be inadequate for practical burners. Successful ultrasonic atomizers were developed with a flow-rate capability from zero up to about 0.7 gph and with a mass-median droplet size of somewhat over 100 microns at the higher rate. Satisfactory combustion was demonstrated in conventional gun burners, but optimum performance may require different air-fuel mixing or further improvements in atomization.

A. W. Doyle, R. R. Perron, and E. S. Shanley. Arthur D. Little, Inc. *API Publication 1725*, 1967. (50 pages,)

### THE DEVELOPMENT OF ULTRASONIC ATOMIZERS FOR DOMESTIC OIL BURNERS

Prototype ultrasonic atomizers developed under API sponsorship have operated continuously for periods as long as two years without failure or deterioration of atomizer performance. The API development is based on atomization from a fuel wetted vibrating surface which is piezoelectrically driven at a frequency of 56 kilocycles per second. Ultrasonic atomizers of this design are believed to be capable of long, maintenance-free service in low-capacity domestic oil burners. Mechanisms of ultrasonic atomization have been studied in considerable detail, and means for reducing droplet size have been explored. Combustion systems have been developed which accommodate the spray produced by the 56-kHz prototype atomizer; a swirl-stabilized burner system has performed well in cycling tests at .28 and .4 gph, simulating several years domestic use.

R. R. Perron, J. E. McCullough, and E. S. Shanley. Arthur D. Little, Inc. *API Publication 1725-A*, 1967.

### VAPORIZATION AND COMBUSTION OF No. 2 HEATING OIL

Analytical and experimental studies were conducted on deposit formation rates during vaporization of No. 2 heating oil. Results established that excessive accumulation of deposits could be avoided by providing two key operating conditions: (1) a hot vaporizing surface above 800°F for rapid vaporization to minimize formation of deposits, and (2) a periodic oxidizing environment to remove trace deposits. These operating conditions were incorporated into a series of demonstration prototype burners capable of operating at low firing rates (0.25 to 0.6 gph). The latest prototype consists of a small vaporizing chamber (insulated and kept hot continuously), a swirl-type vapor-air burner, a refractory combustion chamber with means for regeneratively heating the vaporizing chamber, and controls to provide automatic on-off operation. Successful performance was demonstrated for periods equivalent to a heating season.
G. M. Hein, A. E. Weller, and D. W. Locklin, Battelle Memorial Institute. *API Publication 1726*, 1967. (58 pages)

### ANALYTICAL STUDIES ON MECHANISMS OF FUEL OIL ATOMIZATION

The basic mechanisms in atomization are analyzed in terms of stability theory of liquid surfaces. Droplet formation occurs when the atomization driving mechanism causes small perturbations on the surface of a bulk liquid which become unstable and grow; eventually these perturbations break off from the bulk liquid and form droplets. This theory is applied to spinning-disc atomization and air atomization, and a complete theory of ultrasonic atomization is presented for frequencies less than 100 kHz. Parameters governing electrostatic atomization for both direct current and alternating current are treated in detail. Finally, fuel droplet ignition and combustion is discussed in terms of droplet size as a major parameter. If droplet size is a limiting factor in combustion performance, modifications in recirculation, temperature, and fuel-air ratio can often be used to compensate for this limitation.
R. L. Peskin and R. J. Raco, Rutgers University. *API Publication 1727*, 1967.

## OTHER PUBLICATIONS

### RECOMMENDATIONS FOR AN INDUSTRY-WIDE OIL-BURNER RESEARCH PROGRAM

This report on research and development needs for oil-burning equipment formed the basis for the present API program for distillate utilization. The study was conducted under the sponsorship of the API Fuel Oil Committee. Included are sections on the competitive situation in home heating, technical and economic aspects of heating equipment, the need for new design concepts, status of research and development activity, research needs in specific areas, the stimulation of research and development.
D. W. Locklin, Battelle Memorial Institute. *API Publication 1700*, March 1960. (155 Pages.)

### RECENT RESEARCH IN DISTILLATE-FUEL COMBUSTION.

This paper, reprinted from the April 1963 issue of the ASHRAE JOURNAL, summarizes the most sginificant findings reported at API Research Conferences in 1961 and 1962.
D. W. Locklin and C. F. Speich, Battelle Memorial Institute, February 1963. (9 pages.)

### LITERATURE PERTAINING TO THE ART AND SCIENCE OF OIL BURNING FOR RESIDENTIAL APPLICATIONS

This publication provides a guide to technical literature, relating particularly to distillate-fuel combustion for residential heating equipment and similar low-capacity oil-fired applications. A review of the literature is provided in 16 broad subject classifications which range from fundamental aspects, including physics and chemistry of combustion, to recent equipment developments.
*API Publication 1537*, January 1960. (111 Pages.)

### ABSTRACT SUPPLEMENTS TO PUBLICATION 1537

These abstract supplements cover technical literature published the previous year, plus pertinent references not already covered in the 1537 publication series.

1st, *API Publication 1537-A* December 1961 (58 pages)
2nd, *API Publication 1537-B* May 1962 (55 pages)
3rd, *API Publication 1537-C* May 1963 (44 pages)
4th, *API Publication 1537-D* December 1964 (45 pages)

## TABLE IV-4. PAPERS IN API CONFERENCE PROCEEDINGS

### 1961

**PROCEEDINGS: 1st API RESEARCH CONFERENCE ON DISTILLATE FUEL COMBUSTION.**

1. *Objectives and Scope of the New API Research Program*, C. J. Livingstone.
2. *The API Research Program for Distillate Fuel Combustion—Plans for 1961*, D. W. Locklin.
3. *Vaporization of Distillate Fuels in an Idealized System*, J. R. Tuttle.
4. *Burning of Oil Droplets Premixed With Air*, R. E. Paterson and D. F. Fairbanks.
5. *Short-Cut Method of Determining Drop Size From an Atomizer*, J. R. English.
6. *A Gravimetric Correlation of Smoke Measurements*, R. A. Hunt, Jr.
7. *Air-Oil Pattern Matching in Gun Burners*, R. J. Lang.
8. *Improved Oil-Burner Performance With Recirculation of Combustion Gases*, F. R. Dunn, Jr.
9. *Potential Uses of Distillate Fuels in Agriculture*, G. W. Flint.
10. *The Ventres Blue-Flame Burner*, D. J. Saxton and E. R. Lane.
11. *Air-Aspirated Oil Burners*, B. R. Walsh.

***API Publication 1541***, March 14-15, 1961. (162 Pages.)

### 1962

**PROCEEDINGS: 2nd API RESEARCH CONFERENCE ON DISTILLATE FUEL COMBUSTION.**

1. *New Means of Fuel Atomization*, A. W. Doyle, B. V. Mokler, and R. R. Perron.
2. *Results from Analytical Studies of Droplet Formation*, R. L. Peskin and J. P. Lawler.
3. *Electrostatic Atomization of No. 2 Heating Oil*, F. E. Luther.
4. *Breakup of Small Liquid Volumes by Electrical Charging*, P. E. Graf.
5. *The Measurement and Significance of Fuel-Spray Momentum*, W. Tipler.
6. *A Survey of Air-Atomizing Systems for Small Oil Burners*, C. L. Coffin and W. A. Spraker.
7. *An Ultrasonic Oil Burner*, R. J. Lang, J. C. O'C Young, and J. A. Wilson.
8. *Surface Vaporization Studies With No. 2 Fuel Oil*, J. H. Morgenthaler.
9. *The Influence of Surface on Vaporization of No. 2 Heating Oil*, F. W. Rakowsky.
10. *A Survey of Ignition Systems for Oil Burners*, D. E. Stutz and H. R. Hazard.
11. *Combustion of Fuel-Oil Droplets*, B. J. Wood, W. A. Rosser, G. N. Spokes, and H. Wise.
12. *The Effect of Ail-Fuel Mixing and Recirculation on Combustion*, R. Kamo, P. W. Cooper, and S. Radner.
13. *Burner Research Related to the API Program*, B. R. Walsh.
14. *Flame Studies Leading to Improved Combustion in Domestic Burners*, W. A. Beach and C. W. Siegmund.

***API Publication 1701***, June 19-20, 1962. (290 Pages.)

### 1963

**PROCEEDINGS: 3rd RESEARCH CONFERENCE ON DISTILLATE FUEL COMBUSTION.**

1. *A Practical Ultrasonic Oil Burner*, R. R. Perron, J. R. Swanton, and E. S. Shanley.
2. *Optimization Studies on the Ultrasonic Burner*, R. J. Lang.
3. *Some Results from the Study of Ultrasonic and Electrostatic Atomization*, R. L. Peskin and R. Raco.
4. *A Photographic Method of Measuring the Drop Size Distribution of a Spray*, S. M. DeCorso.
5. *Feasibility of a Vaporizing Burner for No. 2 Heating Oil*, G. M. Hein and A. E. Weller.
6. *Precombustion Deposits*, F. W. Rakowsky and G. H. Meguerian.
7. *The Ignition and Combustion of Drops in Sprays of No. 2 Heating Oil*, B. J. Wood, W. A. Rosser, Jr., and H. Wise.
8. *Turbulence and Recirculatin as Combustion Parameters*, R. Kamo, P. W. Cooper, and C. W. Solbrig.
9. *The Application of Available Research Results to the Design of Practical Oil Burners*, W. A. Don and W. Tipler.

***API Publication 1702***, June 18-19, 1963. (197 Pages.)

### 1964

**PROCEEDINGS: 4th API RESEARCH CONFERENCE ON DISTILLATE FUEL COMBUSTION.**

1. *Further Improvements of an Ultrasonic Oil Burner*, E. S. Shanley, T. E. Hoffman, J. E. McCullough and R. R. Perron.
2. *Some Aspects of Electrostatic Atomization*, R. Raco.
3. *Development of an Electrostatic Atomizer and Burner*, P. M. Newgard and A. W. Noon.
4. *Progress in the Development of a Vaporizing Burner for No. 2 Heating Oil*, G. M. Hein, A. E. Weller and G. R. Whitacre.
5. *Understanding Pressure-Jet Flames—A Stepwise Research Procedure*, A. M. Brown and M. W. Thring.
6. *Aspiration in Fuel-Oil Combustion*, B. R. Walsh.
7. *Burning Rate and Ignition of Liquid-Fuel Drops*, R. L. Peskin, H. Wise and W. A. Rosser.
8. *Nonluminous Combustion of Heating Oil Through Recirculation*, R. Kamo, P. W. Cooper, B. N. Glicksberg and J. A. Fitzgerald.
9. *On the Stability and Combustion Intensity of Pressure-Jet Oil Flames*, J. M. Beer.

***API Publication 1703***, June 2-4, 1964. (202 Pages.)

TABLE IV-4. (Continued)

## 1965

**PROCEEDINGS: 5th API RESEARCH CONFERENCE ON DISTILLATE FUEL COMBUSTION.**

1. *Recirculation in a Vortex-Stabilized Oil Flame*, R. E. Schindler and W. E. Ranz.
2. *Design of Blue-Flame Oil Burners Utilizing Vortex Flow or Attached Jet Entrainment*, P. W. Cooper and C. J. Marek.
3. *Flame Radiation in Domestic Oil Burners*, R. H. Torborg and J. E. Janssen.
4. *Development and Evaluation of a Vaporizing Burner for No. 2 Heating Oil*, G. M. Hein, A. E. Weller, and J. D. Hummell.
5. *The API Ultrasonic Atomizer and Oil Burner Program*, J. E. McCullough, R. R. Perron, and E. S. Shanley.
6. *A Study of the Parameters Governing Electrostatic Atomization of Fuel Oil*, R. L. Peskin, R. Raco, and J. Morehouse.
7. *The Vibrative Atomizer*, B. J. Eisenkraft.

***API Publication 1704***, June 1-3, 1965 (175 Pages.)

## 1966

**PROCEEDINGS: 6th API RESEARCH CONFERENCE ON DISTILLATE FUEL COMBUSTION.**

1. *A Progress Report on the API Ultrasonic Atomizer and Burner Development*, E. S. Shanley, R. R. Perron, and J. E. McCullough.
2. *Application of the API Ultrasonic Atomizer to a Vortex Combustion System*, W. D. Dysart.
3. *A Miniature Ultrasonic Burner for a Multifueled Thermoelectric Generator*, H. R. Hazard and H. H. Hunter.
4. *The Ultrasonic Atomization of Liquid Fuels — Some British Developments*, C. H. Bradbury.
5. *An Ultrasonic Atomizer Capable of High Rates*, J. G. Martner.
6. *A Progress Report on API Analytical Studies of Electrostatic Atomization*, R. J. Raco and R. L. Peskin.
7. *A Progress Report on the API Vaporizing Burner Program*, G. M. Hein, A. E. Weller, and J. D. Hummell.
8. *The Influence of Recirculation in Combustion Processes*, A. B. Hedley and E. W. Jackson.
9. *Performance and Radiation Studies with the API Prototype Blue-Flame Burner*, R. H. Torborg and J. E. Janssen.
10. *Analytical Studies of Fuel-Droplet Combustion — A Status Summary*, R. L. Peskin.
11. *Studies of Heat Transfer in Oil-Fired Water Heaters*, B. R. Walsh.
12. *Type-L Venting Systems for Oil-Fired Appliances Having Low Flue-Gas Temperature*, H. Witte.
13. *Performance Standards for Oil-Fired Equipment — A Progress Report on ASA Committee Work*, C. E. Blome.
14. *$CO_2$ Enrichment of Commercial Greenhouse Environments Using an Oil-Fired $CO_2$ Source*, E. C. Briggs and K. J. Hood.
15. *A New Domestic Oil Burner — Low in Capacity, Pressure, Noise, and Cost*, R. H. Mueller and G. F. Schrader.
16. *Field Tests of a Rotary-Vaporizing Burner*, R. W. Carl, R. A. Hunt, and R. A. Martz.
17. *Noise Reduction in a Low-Capacity Air-Atomizing Oil Burner*, R. D. Wilson.
18. *Possibilities for Oil-Burner Simplification*, W. H. DeLancey.

***API Publication 1705***, June 13-15, 1966

## NATIONAL OIL FUEL INSTITUTE

The National Oil Fuel Institute (NOFI) was formed in 1966, succeeding the Oil Heat Institute of America, Inc. (OHI). The purpose of the organizational change was to bring under "one roof" the three main segments of the oil-heating industry, namely (1) oil refiners, (2) oil marketers, including independent distributors and dealers, and (3) equipment manufacturers. Participation of refining companies in oil-heating industry affairs had previously been through the Fuel Oil Committee of the API Division of Marketing, which had been the sponsoring group for the API Oil Burner Research Program. These activities of refiners were brought into NOFI with the reorganization.

### NOFI EQUIPMENT DEVELOPMENT PROGRAM

The NOFI Equipment Development Program was started in 1966 and operated until 1973 under the NOFI staff, with inputs by oil refiners and oil marketer representatives on the NOFI Equipment Development Committee. Funding was from the NOFI refiner membership.

The NOFI program was geared to allow for direct participation in contracts by equipment manufacturers, with the goal directed to the early commercialization of new and improved burning equipment. The API program had, by intent, included studies that examined unconventional concepts that were considered too high a technological risk or too long term from R&D to product introduction for individual manufacturers to undertake with their own resources; in short, it was designed to explore areas that manufacturers were unlikely to or unable to investigate on their own. In contrast, the NOFI Program provided for funding by contracts or subsidies to developers that had already established proprietary concepts but needed additional development to reach the market.

This difference in approach brought about differences in availability of reports and information in the public domain. In order to protect the incentives and proprietary interest developed through private investment, NOFI contracts with manufacturers or developers included mutual disclosure restrictions which provided that both NOFI and the contractor would have to clear any disclosure of reports or results of the R&D. Except for general descriptions of the R&D progress reports made at several NOFI Workshops that were open to the industry, the contractor reports resulting from the NOFI program have not been made publicly available. Thus, the documentation of the NOFI program is limited.

#### NOFI R&D Contracts

Projects funded by the NOFI Equipment Development Program included the following. Those projects identified by an asterisk were reported in published papers at NOFI Equipment Workshops.

| | | |
|---|---|---|
| • Solid-state oil primary controls | Simicon | * |
| • Una Spray, air-atomizing burner system including integrated furnace compact heat exchanger | Rocketdyne | * |
| • Una Burner, (commercialized version of Una Spray) | Una, Inc.<br>Rocket Research Corp. | |
| • Vaporizing rod-type burner as a replacement for gas burners in sectional gas fired furnaces | Rocketdyne | |
| • Combination oil pump and air compressor development | Studebaker-Worthington | |
| • Air-atomizing burner using Sonicore nozzle and Compump air/oil pump | ABC,<br>Sonic & Dev.<br>Compump. | * |
| • Oil-fired version of Raytheon Heat Transfer Module (HTM) | Raytheon | |
| • Safety requirements for metal vents with oil-fired equipment and the effect of soot fires | Canadian Standards Association | |
| • Blue-flame recirculation burner | OOHA/Carlin | * |
| • A system study of oil-fired appliances and markets | Thermo Electron | |
| • Recirculation concept for low emission oil burners | Marquardt | * |
| • Total comfort system incorporating water heater | OOHA<br>Am. Air Filter | * |

NOFI Workshops

New and Improved Oil Burner Equipment Workshops were held each year from 1968 through 1972 under NOFI auspices. These included both presentation of prepared papers and demonstrations of operating equipment. Proceedings containing the prepared papers were published for the first three workshops. (NOFI, 1968; 1969; & 1970) Tables IV-5 and IV-6 identify the individual papers presented at these three workshops.

While no proceedings were available for the workshops and equipment demonstrations in 1971 and 1972, Fueloil and Oil Heat carried brief accounts of these workshops (Beals, 1971 and 1972) as listed below.

In conjunction with the 1971 NOFI Workshop, held at Philadelphia, equipment demonstrations were:

| | |
|---|---|
| • Blue-flame burning by internal recirculation | OOHA/Carlin |
| • Prevaporizing blue-flame burner/boiler unit, the burner being adapted from an industrial process burner | Burnham |
| • Heat-transfer module fired by an air-atomizing burner | Raytheon/ Koehring |
| • Air-atomizing burners field-test prototype, an extension of the Rocketdyne Una Spray burner | Una, Inc. |
| • Infra-red oil-fired heater for commercial/industrial spot heating | Inray |
| • Water-in-fuel oil emulsion burner that operates with low particulate emission | Elf Union (France) |
| • All solid-state primary control and ignition system | Webster |

For the 1972 NOFI Workshop, held at Newton Mass, demonstrations included the following:

| | |
|---|---|
| • Heat pipe application, both heat recovery type and direct fired | Isothermics Inc. |
| • Mini boiler using oil-fired version using HTM, with domestic water heating | Raytheon |
| • Oil burner combining an ABC gun-type burner and a sonic atomizing nozzle, using a Compump for air compression and fuel lift | ABC/Sonic Dev. Co. |
| • Air-curtain door system, oil fired | Disco Engineering |
| • Compact blue-flame burner using conventional gun-burner components | OOHA Carlin |

A number of the NOFI developments reached commercialization, including some equipment demonstrated at the Workshops.

NOFI MERGER WITH NOJC

The NOFI Equipment Development Program was terminated in 1974 when refiner support was discontinued and NOFI was merged with the National Oil Jobbers Council.

TABLE IV-5. NOFI's NEW AND IMPROVED OIL BURNER EQUIPMENT WORKSHOP – 1968

Papers Presented in NOFI Workshop and Published in Proceedings; NOFI Technical Publication 106ED

| AUTHOR(S) | ORGANIZATION | TITLE OF PAPER | PAPER NO. |
|---|---|---|---|
| 1968 PROCEEDINGS: NOFI 106ED, September 17-18, 1968 | | | |
| Lord | ABC | Design Modifications of High Pressure Oil Burner | 101 |
| Florio | Prestolite Co. | Solid State Electronic Ignition and Control System for Domestic and Small Commercial Oil Burners | 102 |
| Nelson | Sundstrand | The New Sundstrand Model A Fuel Unit | 103 |
| Bauer | Simicon Co. | Solid State Oil Primary Controls | 104 |
| Rheaume | Webster Products | Pulse Ignition and Control System for Oil Burning Equipment | 105 |
| Bailey | OOHA | OOHA Blue Flame Burner Systems | 106 |
| Kramer | Gulf | Report on the Husqvarna Blue Flame Burner | Not Released |
| Hooper | HEW/NAPCA | Effects of Combustion Improving Devices on Air Pollution Emissions from Residential Oil-Fired Furnaces | 108 |
| Evans | Honeywell | Honeywell's Approach to Solid State on Oil-Fired Equipment | 109 |
| Wasser, et al | NAPCA | Effects of Combustion Gas Residence Time on Air Pollutant Emissions from an Oil-Fired Test Furnace | 110 |
| Paterson | Chevron Res. Co. | Some Design Consideration for Heat Exchangers | 111 |
| DeLancey | Consultant | Low Cost Centrifugal Clutches for Oil Burners | 112 |
| Bell & Korn | Sonic Dev. Corp. of America | Developments in Sonic Atomization for Domestic Oil Burner Applications | 113 |
| Merritt | Vapo Products Co. | Vapo Products' Approach to Sonic Atomization of Fuel Oil | 114 |
| Briggs | Koehring Co. | Application of an Air Atomizing Oil Burner to the Gas-Fired Whirlpool Chiller Unit | 115 |
| Velie | Rocketdyne | New Concept for Domestic Oil Burners – Una* Spray Oil Burner Development | 116 |

*Indicates development was funded, in part, by NOFI.

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

TABLE IV-6. NOFI's NEW AND IMPROVED OIL BURNER EQUIPMENT WORKSHOPS – 1969 & 1970

Papers Presented in NOFI Workshops and Published in Proceedings; NOFI Technical Publications 107ED and 108ED

| AUTHOR(S) | ORGANIZATION | TITLE OF PAPER | PAGE |
|---|---|---|---|
| **1969 PROCEEDINGS: NOFI 107ED, September 24-25, 1969** | | | |
| Bauer | Simicon Co. | Solid State Oil Primary Controls – Type SJ-4 | 7 |
| Walker | Amoco | New Oil-Fired Grain Dryer Burner | 11 |
| Deutsch | New York Testing Lab. | Total Energy for Homes, New Market for the Oil Fuel Industry | 17 |
| Esmay & Boyd | Mich. State Univ. | Drying and Incineration as Means of Animal Waste Management | 27 |
| Howekamp & Hooper | HEW/NAPCA | Effects of Combustion Improving Devices on Air Pollutant Emissions from Residential Oil-Fired Furnaces | 35 |
| Wylie & Tyne | Gilbarco & GSA (Canada) | Soot Accumulation and Soot Fires in Type "B" Vents | 59 |
| Panel Discussion | – | British Oil Burners Limited Blue Flame Burner | 69 |
| Coker | Shell Oil Co. | Oil Powered Air-Conditioning – Friend or Foe? | 77 |
| Panel Discussion | – | Whirlpool/NOFI Air Conditioning Test Program | 97 |
| Norton | Am. Air Filter | An Assessment of the Rankine Cycle Heater | 105 |
| Bailey | OOHA | New Product Developments from the OOHA Laboratory Utilizing Blue Flame Burner Systems | 115 |
| Velie | Rocketdyne | Una*Spray Integrated Furnace | 125 |
| **1970 PROCEEDINGS: NOFI 108ED, September 23-24, 1970** | | | |
| Tyne | Canadian Stds. Assn. | Soot Accumulation and Soot Fires in Type "B" Vents | 7 |
| Barrett, Hazard & Locklin | Battelle | Design and Preliminary Combustion Trials of a Burner for Firing No. 6 Fuel Oil at Low Rates | 13 |
| Bailey | OOHA | Blue Flame Burner Development at the OOHA Laboratory | 41 |
| Norton & Kirk | Am. Air Filter | Development of Prototype Atmospheric Oil Burning System of Combustion | 57 |
| Brema & Lee | Marquardt Corp. | Use of Staged Air Admission to Reduce Emissions in Combustion of Hydrocarbon Fuels | 63 |
| Martz & Paterson | Stewart Warner & Chevron | Manufactured Housing Heating System | 73 |
| Hall & Wasser | HEW/NAPCA | NAPCA Combustion Research Programs to Control Pollutant Emissions from Domestic and Commercial Heating Systems | 83 |
| Hapgood & Freedman | Raytheon Co. | The Heat Transfer Module as a Novel Compact Boiler | 95 |
| Martin | HEW/NAPCA | Use of Fuel Additives and Combustion Improving Devices to Reduce Air Pollution Emissions from Domestic Oil Furnaces | 111 |
| Hagel | Rocketdyne | Una*Spray Integrated Furnace | 127 |

*Indicates development was funded, in part, by NOFI.

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

## OPERATION OIL HEAT ASSOCIATES

Another oil-industry R&D program was supported by Operation Oil Heat Associates (OOHA) during the period from 1956 to 1972. This group consisted of approximately sixty independent American and Canadian fuel oil distributors and dealers who were interested in extending the market for residential fuel oil through applied research and product development. OOHA funded the R&D activities of a two-man team, headed by Frank W. Bailey.

This R&D program started with a comprehensive study ("Morphological Survey") of oil-burner design opportunities and moved to the development of many operating prototypes of residential oil burners and associated equipment in a laboratory in Newark, New Jersey.

### OOHA Oil-Burner Development Program

From an engineering standpoint, the OOHA program reflected three phases of product needs in the marketplace.

Phase 1. During the first phase, a primary objective was to develop low-firing rate and low-cost burner components which would be competitive with gas and electrical heating systems, particularly for water heating. Novel techniques for burning fuel oil at low-gallonage (0.2 gph, or less) were investigated. Air atomization and mechanical "smash" atomization systems were studied, along with low-cost liquid-ring air pumps and resonant water-heater systems. Positive-displacement fuel-oil metering systems were also developed and demonstrated. Several of these systems were capable of firing rate modulation with "blue-flame" burner units with staged combustion and self-sustained operation without combustion-products recirculation.

Phase 2. During the second phase, the primary objective involved the development of relatively high firing rate burners with market appeal based on pollution control and maximum utilization of conventional burner production components. The earlier developments relating to staged blue-flame combustion systems were displaced by a development involving generation of a blue flame with a conventional pressure-jet burner and matched heat exchanger.
A licensing program was then set up with the Carlin Company and a field test program was arranged under the surveillance of the Buckley & Scott Company.

Phase 3. During the third and final phase of the OOHA program, it became apparent that the technical objectives should involve heating system equipment with greater energy conservation. Projects were initiated involving blue-flame burner adaptation to higher-pressure-drop heat exchangers, and novel high-convection heat-exchanger systems were investigated. Relatively little development work was done with these systems, since commercialization of the blue-flame-retention gun-burner system was a primary objective with the Carlin Company.

Table IV-7 identifies papers and patents resulting from the OOHA R&D program.

## Basis and Unique Aspects of OOHA Support

Although the OOHA program was supported by numerous marketers from large and small companies in the fuel oil industry, two individuals provided leadership and continuity: OOHA President, W. F. Kenny, Jr. of Mennan Oil Company, and OOHA Secretary-Treasurer, T. J. Scott of Buckley & Scott Company.

The OOHA program was unique in several respects. It is probably the only example in which a group of independent marketing companies supported product development in the heating industry for an extended period of time. Initiation of the OOHA program was catalysed (as was the API program) by a speech by C. D. MacCracken before a convention of fuel oil marketers in 1956. Some of these marketers, who recognized a critical need for oil-burner product development in the face of competition with other residential heating systems, felt that their effort through OOHA could initiate and accelerate a greater effort in product development by the major oil companies and the American Petroleum Institute. When the API responsibilities for burner research were transferred to NOFI, the OOHA members felt that their program and accomplishments could also provide some orientation for the NOFI research.

## Cooperation Among Oil Industry Programs

During the course of the API, NOFI, and OOHA programs, there was a cooperative technical exchange between engineers in these programs, as well as manufacturers of heating equipment. Many of the concepts which developed during the course of the OOHA program were based in part on the API research. (Bailey 1968, 1969, & 1970) The continued development of these concepts, with the participation of the Carlin Company and some funding by NOFI, led to the evolution and commercialization of the blue-flame burner equipment now being marketed by Blueray Systems, Inc.

TABLE IV-7. PUBLICATIONS ON THE OOHA R&D PROGRAM

— all by F. W. Bailey

| DATE | PUBL. | TITLE |
|---|---|---|
| 1962 | API | Oil-Burner Adaptation of a Low-Cost Air-Oil Pump with Differential Displacement Metering |
| 1964 | API | Status of the OOHA Burner Development Program |
| 1967 | Patent | Liquid Fuel, Smash Atomizing and Burner Apparatus |
| 1967 | Patent | Liquid Ring Pumps and Systems |
| 1968 | NOFI | OOHA Blue Flame Burner Systems |
| 1968 | Patent | Annular Burner Apparatus Providing Blue Flame Combustion of Domestic Fuel Oil |
| 1969 | NOFI | New Product Developments from the OOHA Laboratory Utilizing Blue Flame Burner Systems |
| 1970 | NOFI | Blue Flame Burner Development at the OOHA Laboratory |
| 1970 | Patent | Liquid Fuel Burner Process and Apparatus |
| 1971 | Patent | Liquid Fuel Burning Process and Apparatus |
| 1972 | Patent | Blue-Flame Liquid Fuel Burner Process and Apparatus with Utilization System |
| 1973 | Patent | Blue-Flame Retention Gun Burners, and Heat Exchanger Systems |

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

# SECTION V

## RECENT AND CURRENT GOVERNMENT R&D PROGRAMS

A number of government agencies have sponsored programs directed to some aspect of residential oil heating -- including field investigations, field retrofit programs, R&D efforts, and investigations of air-pollutant emissions. The principal agencies supporting these programs are:

Programs Oriented to Energy Conservation

- Brookhaven National Laboratory/Department of Energy
- National Bureau of Standards/Federal Energy Administration/ Department of Energy
- Canadian Combustion Research Laboratory

Programs Oriented Mainly to Air-Pollution Control

- Environmental Protection Agency

The following section provides a brief overview of their programs that are related to residential oil heating.

### PROGRAMS ORIENTED TO ENERGY CONSERVATION

#### BROOKHAVEN NATIONAL LABORATORY/ U.S. DEPARTMENT OF ENERGY

As part of DOE's residential energy conservation program, Brookhaven National Laboratory (BNL) operates a laboratory for performance testing of residential heating equipment and has sponsored RD&D programs to stimulate the development of high-efficiency equipment. This activity is managed by the Conservation Program Management Group at BNL.

Figure V-1 shows the efficiency targets in the BNL programs for oil-fired residential heating equipment. Areas on the chart illustrate seasonal efficiency levels measured for conventional equipment and expected of new and unconventional types of equipment. The seasonal efficiencies are as measured by BNL's input/output testing method and calculational procedures, in which jacket losses are not counted as useful heat.

Table V-1 lists key reports and papers resulting from BNL's residential energy-conservation programs.

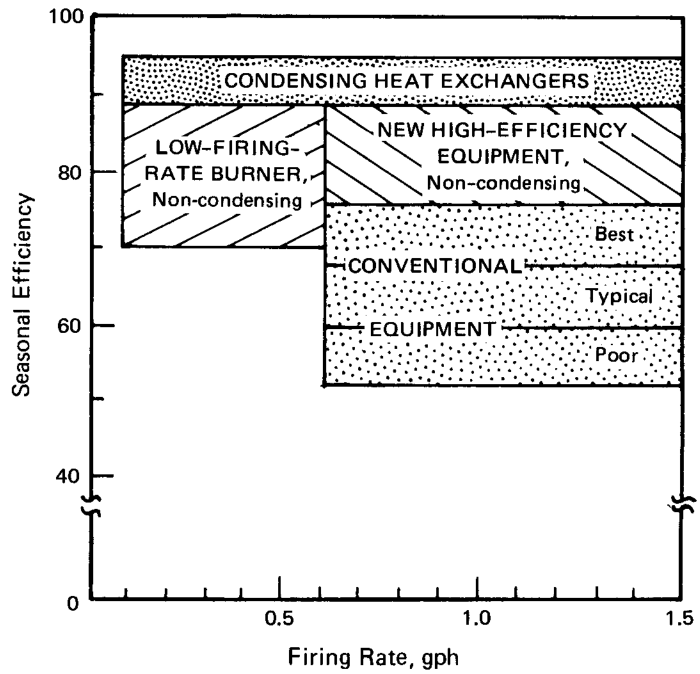


FIGURE V-1. BROOKHAVEN TARGETS FOR SEASONAL EFFICIENCY OF NEW OIL-HEATING EQUIPMENT (Dennehy, 1980)

BNL Heating Equipment Laboratory

BNL began a program of testing residential oil-fired heating equipment in 1976 and, to date, over 100 items of equipment have been tested -- including burners, burner/boiler units, and various efficiency improving devices. (Batey et al, 1977; McDonald et al, 1979; Krajewski, 1980) The BNL laboratory was initially set up to provide a specially instrumented facility for efficiency tests on residential boilers, under both steady-state and cyclic operating conditions by the direct input-output method. Recently, a test facility has been added for measuring cyclic efficiency of residential furnaces, but the facility has just been placed in operation and no reports of test results have been issued.

Testing is performed on developmental and commercial heating equipment to assess thermal performance. The test results are disseminated selectively to accomplish a broad range of objectives, which include assisting an inventor in licensing his design, introducing foreign technology to the U.S., and providing consumers with technical information to assist in decision making relative to the purchase of high-efficiency heating equipment or the upgrading of existing systems.

TABLE V-1. KEY PUBLICATIONS FROM THE BROOKHAVEN PROGRAM FOR RESIDENTIAL OIL HEATING

| AUTHOR(S) | DATE | BNL NO. | TITLE |
|---|---|---|---|
| Batey, Gazerro, Salzano & Berlad | 1976 | 50576 | Energy Management in Residential and Small Commercial Buildings |
| Berlad, Batey, Hoppe & Salzano | 1976 | 50572 | Seasonal Performance and Cost Factors of Oil or Gas-Fired Boilers and Furnaces |
| Berlad, Lin, Batey, Salzano, Yu, Hoppe & Allen | 1977 | 50647 | Seasonal Performance and Energy Costs of Oil or Gas Fired Boiler and Furnaces |
| Batey, Hoppe, Salzano & Berlad | 1977 | 50644 | Hydronic Equipment Findings Report Reference Manual |
| Batey, Hoppe, Berlad, Allen & McDonald | 1977 | 50816 | Annual Fuel Use and Efficiency Reference Manual: Hydronic Equipment |
| Batey, Allen, McDonald, Hoppe, Salzano & Berlad | 1978 | 50853 | Direct Measurement of the Overall Efficiency and Annual Fuel Consumption of Residential Oil-Fired Boilers |
| Berlad, Yeh, Salzano, Hoppe & Batey | 1978 | 50903 | Annual Fuel Usage Charts for Oil-Fired Boilers |
| Batey, McDonald & Hoppe | 1979 | 26467 | Reduction of Residential Fuel Oil Consumption by Vent Dampers |
| McDonald, Batey, Allen & Hoppe | 1979 | 51171 | Direct Efficiency Measurement and Analysis of Residential Oil-Fired Boiler Systems |
| Krajewski | 1980 | — | Efficiency Test Results for Retrofit Modifications |

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

## BNL Program of Equipment RD&D

BNL plans and manages the DOE program for RD&D of high efficiency heating equipment for residential and light commercial application. The program includes both oil- and gas-fired equipment -- but not heat pumps, the responsibility for which has been assigned by DOE to Oak Ridge National Laboratory (ORNL). (The ORNL heat-pump program includes consideration of fossil-fueled heat pumps, including hybrid systems where an oil-burner provides supplementary heating at low outdoor temperatures.) The BNL projects are performed largely through contracts with outside organizations such as industrial firms, research organizations, universities, and, in some instances, contracts with individuals.

TABLE V-2. BROOKHAVEN PROGRAM FOR RESIDENTIAL OIL HEATING – EQUIPMENT R&D

| PROJECT | CONTRACTOR | START DATE | TYPE* |
|---|---|---|---|
| HIGH EFFICIENCY EQUIPMENT | | | |
| Blue-Flame Oil Burner and Boiler | Blueray Systems | 11/77 | R&D |
| LOW-FIRING RATE BURNERS | | | |
| Prevaporization Oil Burner Using a Vaporizing Aerosol Generator | Univ. of Virginia | 8/78 | R&D |
| Variable Low-Firing-Rate Oil Burner | Foster-Miller Assoc. | 4/78 | R&D |
| Ultrasonic Atomization Oil Burner | Sono-Tek Corp. | 7/77 | PO |
| High Efficiency Air-Atomization Oil Burner | Robert Babington | 11/77 | PO |
| HIGH-EFFICIENCY HEAT TRANSFER | | | |
| Survey of Materials for Condensing Systems | Battelle-Columbus | 9/79 | R&D |
| Condensing Furnace | Timberline Industries | 2/80 | R&D |
| Low-Mass Boiler | J. D. Marran | 2/80 | PO |
| PLANNING AND SUPPORT | | | |
| Survey of Oil-Fired Heating Equipment Technology | Battelle-Columbus | 3/79 | R&D |
| Heating-Equipment Combustion-Efficiency Meter | Honeywell | 7/77 | R&D |
| Oil-Burner Test-Stand Optimization Study | Dayton T. Brown | 4/79 | R&D |
| Support Contractor for Field Testing of Advanced Oil-Fired Heating Equipment | New York State ERDA Subcontractor, Dayton T. Brown | 2/80 | R&D |

*Type of Procurement:
R&D: CPFF or FP Development Contract
PO: FP Purchase Order for prototype.

Table V-2 provides a summary of the portion of the BNL program of equipment RD&D that is concerned with oil-fired systems. The RD&D projects cover the following categories:

- High efficiency equipment
- Low-firing rate burners
- High-efficiency heat transfer
- Planning and support

A brief description of each of the projects follows.

Blue-Flame Oil Burner and Boiler. This project provides for development of a line of blue-flame oil burners and matching boilers under a cost-sharing contract with Blueray Systems, Inc. The purpose of the contract is to accelerate commercialization by about three years. The equipment offers high efficiency, both steady-state and seasonal, with low soot formation. Two sizes (0.6 and 0.75 gph firing rate) have been placed on the market and three more sizes are under development (0.5, 0.9, and 1.0 gph). In addition, feasibility is being investigated of developing a version of the burner that would be retrofittable into existing boilers and furnaces.

Vaporizing Aerosol Generator.* This project, one of four approaches being investigated for low and variable firing rate burners, is based on prevaporization of No. 2 oil in a heated iron-whisker matrix. It is being conducted at the University of Virginia.

Variable Low-Firing-Rate Oil Burner.* This is a second approach to low and variable firing rates, based on combined atomization and vaporization. The contractor is Foster-Miller Associates.

Ultrasonic Atomization Oil Burner.* The BNL program provided support to Sono-Tek Corp. for further development of its ultrasonic atomization oil burner. This is a third way of achieving low and variable firing rates.

High Efficiency Air-Atomization Oil Burner.* The fourth approach to low firing rates supported in the BNL program is based on low-pressure, air atomization. Support has been provided to Robert Babington for further development of an oil burner with an atomization principal that is in use in commercial medical nebulizers.

Survey of Materials for Condensing Systems. One of the longer term goals of the BNL program is the commercialization of residential oil-heating systems that can operate reliably with heat exchangers in a condensing mode. The first step in this effort is to identify and evaluate low-cost corrosion-resistant materials suitable for use in the heat exchangers of such systems. The materials investigation for oil-fired equipment is being performed by Battelle-Columbus. (This project is discussed in Section VII of this report.)

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*One of the four variable-rate burner projects; it is described in detail in Section VI of the report.

Condensing Furnace. This project involves modification of a standard residential oil furnace to permit operating with condensation of flue products. Condensation occurs in a Teflon-lined secondary heat exchanger.

Low-Mass Boiler. In this project, support is being provided to an inventor for preliminary design and development of a compact, low-mass boiler with excellent heat transfer properties. The boiler is expected to have a very high seasonal efficiency associated with low off-cycle losses.

Survey of Oil-Fired Heating Equipment Technology. The scope and results of this project are the subject of the present report.

Heating-Equipment Combustion-Efficiency Meter. This project provides for design and development of a prototype portable instrumentation package for use in adjusting oil-and gas-fired heating systems for maximum efficiency. The equipment measures oxygen content and temperature in the flue, calculates efficiency, and displays all three values on digital displays. Included is a subsystem for continuous readout of the smoke level in the flue on a Bacharach-equivalent scale.

Oil-Burner Test-Stand Optimization Study. Under this project, conducted by Dayton T. Brown, Inc., a study was made of BNL's hydronic test stand, its controller, and data-acquisition system. Areas were identified where design changes could provide simplification and cost reduction. A specification was prepared for a test stand incorporating these changes.

Support Contractor for Field Testing of Advanced Oil-Fired Heating Equipment. As equipment moves ahead in the development process, it is often desirable to test the product under field conditions. BNL receives assistance from the New York State Energy Research and Development Authority (and its subcontractor, Dayton T. Brown, Inc.) in conducting such field tests.

## Field Bulletins

BNL has prepared a series of bulletins for the oil-heating industry and for homeowners. Those published to date are noted below:

| BNL Number | Title | Date |
|---|---|---|
| 120-1 | Upgrading Oil Home-Heating Units | revised 12/79 |
| 120-2 | Converting to a Flame-Retention Burner for More Efficient Heating | 9/79 |
| 120-3 | Adding a Flue Damper to a Home-Heating System | 9/79 |
| 120-4 | Adding a Flue Economizer to a Home-Heating System | 9/79 |
| 120-5 | High-Efficiency Residential Boilers | 9/79 |
| 120-8 | Rating Your Oil-Heating System | 3/80 |

Copies may be obtained at no charge by writing the Department of Energy and Environment, Building 120, Brookhaven National Laboratory, Upton, New York, 11973.

## NATIONAL BUREAU OF STANDARDS/FEA/DOE

Starting in 1974, significant field investigations were funded by the Federal Energy Administration (FEA), with project management by the National Bureau of Standards (NBS) through the NBS Center for Building Technology. These studies were subsequently funded by DOE.

A series of field investigations under this program was conducted in the Boston area by Walden Research Division of Abcor to examine the steady-state efficiency of oil-heating equipment and the effect of various conservation steps. (Katzman & D'Agostino, 1975) These results were then analyzed by Honeywell Research using their H-FLAME Model to assess seasonal efficiency. (Bonne, 1975)

Table V-3 lists reports & papers relevant to the field investigations on seasonal efficiency, plus those developed as a result of the NBS/FEA/DOE program on heating equipment efficiency.

## Boston Field Study

A field investigation was conducted in 1974 and 1975 by Walden with funding by FEA (and, later, by DOE) to evaluate potential energy savings resulting from the implementation of various procedures on existing oil-fired residential heating plants in the New England area. The procedures evaluated

TABLE V-3. PUBLICATIONS RESULTING FROM THE NBS/FEA/DOE PROGRAM OF FIELD INVESTIGATIONS AND ANALYSES OF SEASONAL EFFICIENCY OF RESIDENTIAL OIL-HEATING EQUIPMENT

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Bonne | 1975 | Purdue | Effect of Reducing Excess Firing Rate on the Seasonal Efficiency of 26 Boston Oil-Fired Heating Systems |
| Bonne, Johnson, Glatzel & Torberg | 1975 | NBS | Analysis of New England Oil Burner Data. Effect of Reduced Excess Firing Rate on Seasonal Efficiency |
| Katzman & D'Agostino | 1975 | NBS | A Study to Evaluate the Effect of Performing Various Energy Saving Procedures on Residential Oil Burner Installations in the New England Area to Gather Information on the Steady-State and Dynamic Performance of These Installations |
| Katzman & Weitzman | 1976 | NBS | A Study to Evaluate the Effect of Reducing Firing Rates on Residential Oil Burner Installations |
| Chi | 1976 | Purdue | Computer Simulation of Fossil-Fuel-Fired Boilers |
| Chi | 1977 | ASME | DEPAF — A Computer Model for Design and Performance Analysis of Furnaces |
| Chi, Kelly & Didion | 1978 | IHTC | Use of a Computer Model to Evaluate Energy Saving Potentials for Gas Fired Furnaces |
| Katzman, Kelly & Kuklewicz | 1978 | Purdue | An Assessment of Retrofitting Automatic Vent Dampers on Oil-Fired Residential Heating Systems in the New England Area |
| Chi & Kelly | 1978 | ASHRAE | A Method for Estimating the Seasonal Performance of Residential Gas and Oil-Fired Heating Systems |
| Kelly, Chi & Kuklewicz | 1978 | NBS | Recommended Testing and Calculation Procedures for Determining the Seasonal Performance of Residential Central Furnaces and Boilers |
| — | 1978 | Fed. Register | Final Energy Conservation Test Procedures |
| Katzman & Monat | 1978 | NBS | Study to Evaluate the Energy Efficiency Improvement of Residential Heating Equipment Modifications |
| Katzman & Monat | 1978 | APCA | Field Study of Energy Efficiency Improvements on Residential Oil Heating Installations |

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

were (1) performance of a yearly tune-up and servicing by trained servicemen, (2) the reduction of nozzle sizes on selected installations found to be overfired with respect to their maximum heating load and (3) the effect of various retrofit devices. Three series of tests were conducted:

1. Initial Study or Effect of Tune-up. (Katzman & D'Agostino, 1975) Walden reported that the effect of a yearly tune-up was to increase the average steady-rate efficiency from 74.2 to 76.1 percent (1.9 percentage points).

2. Effect of Firing-Rate Reduction. (Katzman & Weitzman, 1976; Bonne et al, 1975) Walden investigated 26 forced warm air and hot-water heating systems that underwent nozzle reduction to reduce overfiring. The analysis of data was extended by Honeywell by the use of a digital system model. By this analysis, it was generalized for the New England area that the average seasonal efficiency increased from 65.3 to 67.1 percent, for an average reduction in firing rate of 29 percent. The calculated annual fuel savings was 5.2 percent and a cost savings of 3.7 percent.

3. Effect of Retrofit Measures and other Aspects. (Katzman & Monat, 1978) Walden conducted an investigation of three devices for residential oil-fired heating systems, off-cycle stack flows, and blue-flame burner systems. The retrofit devices included motorized stack dampers, sealed combustion systems, and flue-gas heat reclaimers. The results of tests on motorized stack dampers were projected to an average U.S. climate, with an estimated average fuel savings of 8.2 percent and annual cost savings of $44. Similarly, savings for flue-gas heat reclaimers was 6.6 percent and an average cost savings of $39. Tests on blue-flame burner/furnace units indicated that the manufacturers specifications for adjustment can be maintained in the field. Tracer-gas measurements of off-cycle flow provided verification for the factors used in the NBS system model. (Chi, 1977)

## NBS Development of Efficiency Rating Procedures

As part of the Federal Trade Commission's efficiency labeling program for residential appliances, NBS developed a testing and calculation procedure (Kelly et al, 1978) which was the basis for DOE's test procedure promulgated in the Federal Register (DOE, 1978). The purpose of this procedure is to provide a simplified method by which manufacturers can estimate the seasonal performance of their equipment for the Federal Trade Commission efficiency labeling program. The test requires operation of the equipment over pre-scheduled cycles to obtain information on transients in flue-gas-temperature for use in the calculation procedure. By assuming factors to account for variables, the procedure does not require a direct input/output test.

Manufacturers have recently submitted test information on existing units, and a summary is available from DOE (U.S. DOE, June 1980). Proposed minimum standards for seasonal efficiency were promulgated by DOE for implementation by the Federal Trade Commission. (U.S. DOE, June 30, 1980)

## CANADIAN COMBUSTION RESEARCH LABORATORY

The Canadian Department of Energy, Mines and Resources, operates a center of Energy Research Laboratories near Ottawa, Ontario. One of these laboratories, the Canadian Combustion Research Laboratory, has conducted a number of relevant programs in residential oil heating. Projects have included burner concept development and evaluation, efficiency and fuel-conservation practices, and air-pollution control. A retrofit program for residential oil-heating systems is being planned for broad-scale implementation by the Canadian government.

Table V-4 lists some of the recent publications of that Laboratory pertinent to residential oil heating. The technical quality of the R&D from this laboratory is excellent. Moreover, the field guidelines documents and consumer bulletins, prepared with the R&D as a basis, are especially effective. Attention is called to the reports and papers listed in Table V-4, with the suggestion that manufacturers and investigators in the U.S. can benefit from these publications and from following the work of this laboratory.

TABLE V-4. REPORTS AND PAPERS ON RESIDENTIAL OIL HEATING RESULTING FROM PROGRAMS OF THE CANADIAN COMBUSTION RESEARCH LABORATORY (CCRL)

| AUTHOR(S) | YEAR | PUBLICATION* | TITLE |
|---|---|---|---|
| Brown | 1972 | 72/8 CCRL *** | Some Performance Characteristics of Flame Retention-Head Domestic Burners |
| Brown | 1973 | IR 73-32 (73/28) *** | The Oil Heating Association of Canada Clean Air Program: Phase I: Facilities, Techniques and Procedures |
| Brown | 1973 | IR 73-33 (73/34) *** | The Oil Heating Association of Canada Clean Air Program: Phase II: Evaluation of Burners with High-Speed Motors in Warm Air Furnaces |
| Brown | 1973 | 73/28 CCRL (IR 73-32) *** | The Oil Heating Association of Canada Clean Air Program: First Investigation Report |
| Brown | 1973 | 73/34 CCRL (IR 73-33) *** | The Oil Heating Association of Canada Clean Air Program Second Investigation Report |
| Brown | 1973 | 73/69 CCRL (IR 73-70) *** | The Oil Heating Association of Canada Clean Air Program: Phase III: Evaluation of Burners with Low-Speed Motors in Warm-Air Furnaces |
| Brown | 1974 | 74/91 CCRL *** | An Assessment of Burner Performance in the Oil Heating Association of Canada Clean Air Program |
| Brown | 1974 | 74/52 CCRL (IR 74-43) *** | The Oil Heating Association of Canada Clean Air Program: Phase IV: Evaluation of Burners with High and Low Speed Motors in a Domestic Hot Water Heater |
| Brown | 1974 | 74/69 CCRL (IR 74-45) *** | The Oil Heating Association of Canada Clean Air Program: Phase V: Evaluation of Burners with High and Low Speed Motors in a Domestic Hot Water Heater |
| Brown, Hayden & Braaten | 1975 | CFTR 75-134 (CF) ** | A Laboratory Evaluation of the Marois Blue-Flame Burner System |
| Brown | 1975 | 75-72 (CF) ** | Evaluation of the Blueray BFH 0.75 and BFH 0.60 Domestic Warm-Air Heating Systems |
| Brown | 1975 | EMR M-27-10/1975 ***** | Billpayer's Guide to Furnace Servicing |
| Brown | 1975 | 75-1 (CF) *** | The Oil Heating Association of Canada Clean Air Program Phase VI: Assessment of Burner Performance |
| Brown | 1975 | 75-4 (CF) *** | Noise Levels From Residential Oil Burners |
| Brown & Dunfield | 1976 | 76-39 (CF) (IR) ** | Evaluation of a Laboratory Hybrid Warm-Air Heating System |

TABLE V-4. (Continued)

| AUTHOR(S) | YEAR | PUBLICATION* | TITLE |
|---|---|---|---|
| Lee, Brown & Braster | 1976 | 76-44 (CF) IR) ** | Combustion Evaluation of a Commercial Soot Remover |
| Brown & Dunfield | 1976 | 76-9 (IR) ** | A Comparative Evaluation of Two-Oil Fired Warm-Air Furnaces |
| Hayden, et. al. | 1976 | ASME | Oil Conservation in Home Heating |
| Brown & Braaten | 1977 | 77-69 (CF) ** | Performance of the Carswell 300-C Warm-Air Furnace During a 6000 Cycle Test |
| Brown & Braaten | 1977 | 77-131 (IR) ** | Cyclic Performance Tests on the Blue-Ray BFM 0.75 Warm-Air Heating System |
| Dewees | 1977 | U. of Toronto | The Economics of Home Furnace Efficiency |
| Hayden | 1977 | 77-115 (J) ** | Utilization of Methanol in Stationary Source Combustion |
| Brown & Hayden | 1978 | 78-02 (CF) ** | The Effect of Fuel Aromatic Content on Soot Formation in a No 2 Oil Combustion System |
| Hayden, Braaten & Brown | 1978 | APCA | Emissions and Energy Conservation in Residential Oil Heating |
| Whaley & Braaten | 1978 | 78-100 (TR) ** | An Evaluation of Water-In-Oil Emulsions in an Oil-Fired Residential Hot-Water Furnace |
| Whaley | 1978 | 78-41 (OP) ** | The Effect of Water-in-Oil Emulsions on Energy Conservation and Emissions Reduction in Practical Oil-Fired Combustion Systems |
| Braaten, Brown & Hayden | 1979 | ERP/ERL 72-29 (TR) ** | Evaluation of a Modified Carswell 300-C Warm Air Furnace |
| Hayden & Braaten | 1979 | ERP/ERL 79-63 (TR) ** | Performance of Retrofit Flame Retention Heads in Domestic Oil Furnaces |
| CSA | 1979 | CSA **** | Replacement Combustion Heads for Residential Oil Burners |
| CSA | 1979 | CSA **** | Automatic Flue Pipe Dampers for Use with Oil-Fired Appliances |
| Hayden & Braaten | 1980 | Report E1 79-8 ***** | Efficient Residential Oil Heating—A Manual For Servicemen, Designers and Builders |

* Numbers refer to CCRL report numbers.

** Available from Canadian Combustion Research Laboratory; Energy, Mines and Resources Canada, 555 Booth Street, Ottawa, Canada K1A 0G1.

*** Contained in Compendium: "Comparative Performance of Typical Oil-Fired Domestic Space and Water Heating Appliances", available from the Ontario Petroleum Association, 2300 Yonge Street, Toronto, Canada M4P 1E4.

**** Available from the Canadian Standards Association, 178 Rexdale Boulevard, Rexdale, Ontario, Canada M9W 1R3.

***** Available from the Conservation and Renewable Energy Branch; Energy, Mines and Resources Canada, 580 Booth Street, Ottawa, Canada K1A 0E4.

## PROGRAMS ORIENTED MAINLY TO AIR-POLLUTANT EMISSIONS

A number of field investigations and R&D projects on oil burning equipment have been funded by the U.S. Environmental Protection Agency (EPA). Although some of these efforts have included specific concerns relative to operating efficiency, they are mentioned in this section only if the intent of the original project was control of air-pollutant emissions.

### U.S. ENVIRONMENTAL PROTECTION AGENCY

Early EPA investigations were directed mainly to smoke emissions and the criteria pollutants, those pollutants featured in EPA Criteria Documents (i.e. particulate, CO, gaseous hydrocarbons, $SO_2$ and nitrogen oxides). For residential equipment, the focus has mainly been on nitrogen oxides ($NO_x$), with some limited work on polycylic organic material (POM), because of the potential for carcinogenic hazard of some of these compounds. EPA comprehensive environmental assessments of stationary sources have included a few measurements on residential oil-fired equipment.

Table V-5 lists a number of reports and papers relevant to emissions from residential oil burning that resulted from work sponsored by EPA or its predecessor agencies.

#### EPA In-House Investigations

A program involving characterization of emissions from residential oil-burning equipment was initiated in 1968 at the NAPCA* laboratory at Cincinnati. After the formation of EPA, this program was continued at Research Triangle Park, North Carolina. Equipment investigated in this program included:

- Conventional high-pressure burners
- Combustion-improving measures
  - Flame-retention-type combustion heads
  - Water-oil emulsions

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*National Air Pollution Control Administration, one of the predessor agencies of the present EPA.

TABLE V-5. EPA REPORTS AND PAPERS RELATING TO AIR-POLLUTANT EMISSIONS FROM RESIDENTIAL OIL-FIRED EQUIPMENT

Reporting R&D funded by the U.S. Environmental Protection Agency or its predecessor agencies

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Copeland<br>EPA | 1967 | NCAPC | Preliminary Report on Smoke Emissions From Small Oil-Fired Combustion Units |
| Bunyard & Copeland<br>EPA | 1968 | NCAPC | Soiling Characteristics and Performance of Domestic and Commercial Oil-Burning Units |
| Wasser, Hangebrauck & Schwartz<br>EPA | 1968 | APCA | Effects of Air-Fuel Stoichiometry on Air Pollutant Emissions From an Oil-Fired Test Furnace |
| Hooper<br>EPA | 1968 | NOFI | Effects of Combustion Improving Devices on Air Pollution Emissions From Residential Oil-Fired Furnaces |
| Wasser, Martin & Hangebrauck<br>EPA | 1968 | NOFI | Effects of Combustion Gas Residence Time on Air Pollutant Emissions From an Oil-Fired Test Furnace |
| Barrett & Moody<br>Battelle | 1968 | NAPCA | Preparation and Firing of Emulsions of No. 2 Fuel Oil and Water |
| Trayser, Creswick, Gieske, Hazard & Weller<br>Battelle | 1969 | EPA | A Study of the Influence of Fuel Atomization, Vaporization, and Mixing Processes on Pollutant Emissions From Motor-Vehicle Powerplants |
| Howekamp<br>EPA | 1970 | NOFI | Flame Retention-Effects on Air Pollution |
| Howekamp & Hooper<br>EPA | 1970 | APCA | Effects of Combustion Improving Devices on Air Pollutant Emissions From Residential Oil-Fired Furnaces |
| Hall & Wasser<br>EPA | 1970 | NOFI | NAPCA Combustion Research Programs to Control Pollutant Emissions From Domestic and Commercial Heating Systems |
| Locklin, Weller & Barrett<br>Battelle | 1971 | EPA | The Federal R&D Plan for Air-Pollution Control by Combustion Process Modification |
| Martin, Pershing & Berkau<br>EPA | 1971 | EPA | Effects of Fuel Additives on Air Pollutant Emissions From Distillate-Oil-Fired Furnaces |
| Hazard, Fischer & McComis<br>Battelle | 1973 | EPA | Low-Emission Burners for Automotive Rankine Cycle Engines |
| Barrett, Miller & Locklin<br>Battelle | 1973 | EPA | Field Investigation of Combustion Emissions From Space Heating Equipment |
| Hall, Wasser & Berkau<br>EPA | 1974 | EPA | A Study of Air Pollutant Emissions From Residential Heating Systems |
| Barrett, Locklin & Miller<br>Battelle | 1974 | EPA | Investigation of Particulate Emissions From Oil-Fired Residential Heating Units |

TABLE V-5. (Continued)

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Dickerson & Okuda<br>Rockwell | 1974 | EPA | Design of an Optimum Distillate Oil Burner for Control of Pollutant Emissions |
| Hazard<br>Battelle | 1974 | ASME | Conversion of Fuel Nitrogen to $NO_x$ in a Compact Combustor |
| Martin<br>EPA | 1974 | EPA | Environmental Considerations in the Use of Alternate Clean Fuels in Stationary Combustion Processes |
| Martin<br>EPA | 1975 | C.I. | Evaluation of $NO_x$ Emission Characteristics or Alcohol Fuels in Stationary Combustion Systems |
| Hall<br>EPA | 1975 | APCA | The Effect of Water/Distillate Oil Emulsions on Pollutants and Efficiency of Residential and Commercial Heating Systems |
| Locklin & Barrett<br>Battelle | 1975 | EPA | Guidelines for Residential Oil Burners Adjustments |
| Combs & Okuda<br>Rockwell | 1976 | EPA | Residential Oil Furnace System Optimization — Phase I |
| Offen, et al<br>Acurex | 1976 | EPA | Control of Particulate Matter From Oil Burners and Boilers |
| Combs & Okuda<br>Rockwell | 1976 | EPA | Commercial Feasibility of an Optimum Residential Oil Burner Head |
| Hall<br>EPA | 1976 | ASME | Status of EPA's Residential Space Heating Research Program — 1976 |
| Combs & Okuda<br>Rockwell | 1976 | ASME | Design Criteria for Reducing Pollutant Emissions and Fuel Consumption by Residential Oil-Fired Combustors |
| Krause, Hillenbrand, Weller & Locklin<br>Battelle | 1977 | EPA | Combustion Additives for Pollution Control — A State-of-the-Art Review |
| Combs & Okuda<br>Rockwell | 1977 | EPA | Residential Oil Furnace System Optimization — Phase II |
| Combs & Okuda<br>Rockwell | 1977 | EPA | Design Optimization and Field Verification of an Integrated Residential Furnace |
| Janssen, Clatzel, Wabasha & Bonne<br>Honeywell | 1977 | EPA | Study of a Thermal Aerosol Oil Burner |
| TRW, Inc. | 1978 | EPA | Emissions Assessment of Conventional Combustion Systems. Volume I: Gas-Fired and Oil-Fired Residential Heating Systems Source Categories |
| Matthews & Surpranant<br>TRW | 1978 | EPA | Emission Assessment of Conventional Combustion Systems: Gas-Fired and Oil-Fired Residential Heating System Source Categories |

TABLE V-5. (Continued)

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Mason, Higginbotham, Evans, Salvesen & Waterland<br>Acurex | 1979 | EPA | Environmental Assessment of Stationary Source $NO_x$ Control Technologies |
| EPA<br>EPA | 1979 | EPA | Proceedings: Third Workshop on Catalytic Combustion |
| Kesselring, Krill, Chu & Kendall<br>Acurex | 1979 | EPA | Catalytic Combustion System Development for Stationary Source Applications |
| Okuda & Combs<br>Rockwell | 1979 | EPA | Design Optimization and Field Verification of an Integrated Residential Furnace — Phase I |
| Okuda & Combs<br>Rockwell | 1979 | EPA | Field Verification of Low-Emission Integrated Residential Furnaces |
| Ackerman, Hamersma & Matthews<br>TRW | 1979 | EPA | Emissions Assessment of Conventional Combustion Systems |
| Surprenant, et al.<br>GCA | 1979 | EPA | Emission Assessment of Conventional Stationary Combustion Systems, Volume 1. Gas- and Oil-Fired Residential Heating Sources |
| Okuda & Combs<br>Rockwell | 1979 | APCA | Development and Field Verification of an Integrated Residential Oil Furnace |
| Higginbotham<br>EPA | 1979 | EPA | Field Testing of a Low Emission Oil-Fired Residential Heating Unit |
| Waterland, et al.<br>Acurex | 1979 | EPA | Environmental Assessment of Stationary Source $NO_x$ Control Technologies — Final Report |
| EPA | 1980 | EPA | Fourth Workshop on Catalytic Combustion |
| Okuda & Martin<br>Rockwell | 1980 | APCA | Field Verification of Low-Emission/High Efficiency Oil-Fired Residential Furnaces |
| Okuda & Martin<br>Rockwell | 1980 | APCA | Thermal Efficiency Evaluation of Installed Warm-Air Furnaces in the Field |

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

- Unconventional burners
  - Air atomizing burners
  - Rotary wall-flame burner
  - Baily/OOHA blue-flame burner
  - Various other blue-flame burners
  - Ultrasonic atomizing burner.

The results of these tests have been published, some in summary form only, in various EPA publications listed in Table V-5. An overview of this program is contained in a report, EPA-650/2-74-003 (Hall, Wasser, & Berkau, 1974) and a more recent ASME paper. (Hall, 1976)

In general, it was found (1) that certain flame-rentention-head burners were significantly lower in smoke and particulate emissions and (2) that flue-gas recirculation in some blue-flame burners was effective in reducing $NO_x$ emissions. Special attention is called to Appendix C of the EPA 1974 report for tabulation of emissions and performance of a number of the commercial and developmental oil burners listed above.

## EPA/API Field Investigation of Residential Burner Emissions

In a jointly funded program, EPA and the American Petroleum Institute sponsored a 2-year field investigation conducted by Battelle to measure air-pollution emissions from residential and commercial oil-fired heating equipment. (Barrett, Miller & Locklin, 1973) The study covered emissions from 33 residential heating units and 13 commercial boilers, including the effects of tuning, of various combustion parameters, and of fuel-oil composition.

Table V-6 summarizes the significant results pertaining to residential equipment. All pollutant measurements were taken with the burner cycling on an imposed cycle of 10 minutes on and 20 minutes off. $CO_2$ and smoke readings were recorded at the 10th minute of the on-period.

Figure V-2 shows the distribution of $CO_2$, smoke, and $NO_x$ measurements for the 33 residential units in the as-found and tuned condition. Three units were found in poor condition and in need of complete replacement. Excluding these units, mean levels of $CO_2$ were increased from 7.9 percent to 8.2 in tuning; mean smoke levels were decreased by tuning from 3.1 to 1.6 on the Bacharach scale. $NO_x$ levels were essentially unchanged (from about 19 lbs of $NO_x$/1000 gallons of fuel). Although tuning of the residential units that were performing normally resulted in lower smoke levels, only slight reduction in CO, CH, and particulate emissions were observed on a gravimetric basis. Burners equipped with flame-retention-type combustion heads produced lower emissions than those with conventional heads, and newer burners generally performed with lower emission than did older burners. A brief follow-on investigation was conducted in Battelle's laboratory to examine the effects of different cycles of operation for residential equipment. (Barrett et al, 1974)

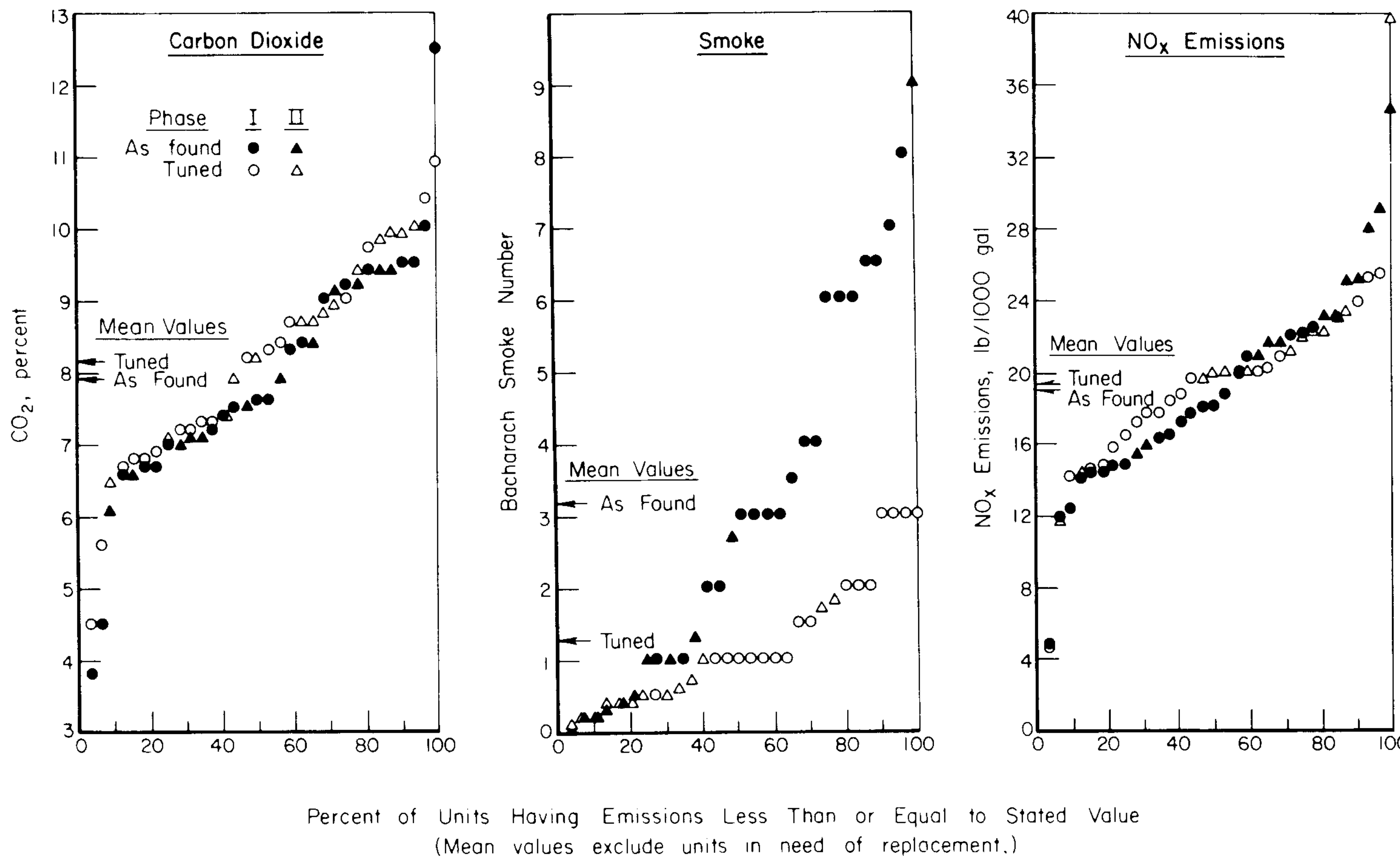


**FIGURE V-2. DISTRIBUTION OF $CO_2$, SMOKE, AND $NO_x$, FOR RESIDENTIAL UNITS FROM BATTELLE FIELD STUDY FOR API/EPA (Barrett, Miller & Locklin, 1973)**

TABLE V-6. COMPARISON OF MEAN EMISSIONS FOR CYCLIC RUNS ON RESIDENTIAL OIL-FIRED UNITS

| Units | Condition | Units in Sample[a] | Mean Smoke No.[b] | Mean Emission Factors, lb/1000 gal CO | HC | $NO_x$ | Filterable Particulate |
|---|---|---|---|---|---|---|---|
| Mean Values From Phase I and II Battelle/API/EPA Investigation (Barrett et al., 1973) | | | | | | | |
| All units | As-Found | 32 | (c) | >22.1 | 5.7 | 19.4 | 2.9 |
| | Tuned | 33 | (c) | >16.4 | 3.0 | 19.5 | 2.3 |
| All units, except those in need of replacement | As-Found | 29 | 3.2 | 7.8 | 0.72 | 19.6 | 2.4 |
| | Tuned | 30 | 1.3 | 4.3 | 0.57 | 19.5 | 2.2 |
| Suggested Emission Factors: For residential units in areas having regular service and inspection | | | | | | | |
| | | | – | 10.0 | 1.5 | 20.0 | 2.5 |

[a] One unit was a furnace installed in the laboratory and was not included in deriving the mean emissions values for the as-found condition.
[b] Smoke data at 5-minute point of on-cycle.
[c] Oily smoke spots prevented valid mean values.

The investigation of commercial boiler emissions included effects of adjustment parameters and load. Fuel effects were investigated by firing several fuel samples in a given boiler.

## EPA Project on a Thermal Aerosol Oil Burner

A concept for a thermal aerosol oil burner was recently investigated by Honeywell, Inc. under EPA contract as a means of achieving low-emission operation. (Janssen et al, 1977) The concept involves preheating oil to a high enough temperature that flash vaporization occurs when the pressure is lowered as oil passes through a conventional high-pressure atomizing nozzle. This program is discussed in more detail in Section VI of this report, "Technical Approaches to Burner Design -- Examples and Assessments".

## EPA Investigation of Fuel Additives

Over 200 fuel additives were evaluated during an EPA in-house study to determine effects on pollutant emissions from No. 2 oil fired equipment. (Martin et al, 1971) Tests were made on a conventional pressure burner firing a simulated warm-air furnace. No additives were effective in reducing $NO_x$ or $SO_x$ emissions, and only 17 reduced particulate emissions. None reduced unburned hydrocarbons or CO. Toxicity, corrosion, and fuel stability were not investigated. It was concluded that additives should not be used as a means of controlling air pollutant emissions from distillate oil burning, unless the metalic emissions that they may produce can be shown to be completely harmless. Corrosion, fuel and additive stability, and long-term effects, in addition to toxicity, are areas of additive research that need detailed investigation before any general use could be recommended.

## EPA Low-Emission Burner Mixing Head and Furnace

Over the past several years, EPA has sponsored a contract at Rocketdyne (now Rockwell International) that has been directed to

1. Development of a fuel/air mixing head for residential oil burners that will provide low $NO_x$ emissions
2. Integration of this burner concept into a warm-air furnace having high seasonal efficiency
3. Field tests to investigate seasonal efficiency
4. Investigation of the cyclic efficiency as determined by the DOE/NBS rating method.

The overall purpose of this continuing program is to demonstrate that low emissions and high efficiencies can be achieved at the same time. A series of reports and technical papers have reported this development, as listed in Table V-5. The most recent papers are those prepared for presentation to the Air Pollution Control Association's 1980 session on residential emissions. (Okuda & Martin, 1980a&b)

Features incorporated in this development are as follows:

- Conventional high-pressure atomization
- A special combustion head that provides controlled mixing of fuel and air (termed by EPA as an "optimum burner head")
- Air-cooled combustion chamber (finned cast-iron construction)
- Sealed system for combustion air and direct venting
- Positive shutoff of combustion air during off cycles.

Control of $NO_x$. The special mixing head and the cooled combustion chamber were developed to minimize $NO_x$ emissions; (Dickerson and Okuda, 1974) 60 percent reduction in $NO_x$ emission is reported over conventional oil-fired furnaces. The mixing head results in less-intense turbulence and a longer flame than modern flame-retention heads, in order to spread the flame over a larger volume and reduce peak temperatures. The relatively large, finned and air-cooled, cast-iron firebox further limits temperatures by extracting about 20-25 percent of the heat. In this sense, the system is like European practice where no refractory lining of combustion chambers is employed.

Control of Off-Period Losses. The sealed combustion-air system and damper shutoff was designed to minimize off-period thermal losses. The positive shut-off on the burner-inlet side retains heat stored in the firebox to provide favorable conditions for restart on the next on cycle. The sealed-air system eliminates the bleed loss through the barometric damper, as defined in Section III of this report. Although this does not improve the efficiency of the furnace itself, this feature reduces the infiltration heat loss from the structure and results in a fuel saving.

Field Test for Seasonal Efficiency -- Procedure and Results. Good thermal performance has been achieved with six field test units operating for two heating seasons in the northeast. (Okuda & Martin, 1980b) Excess air was set at approximately 20 percent, equivalent to about 13 percent $CO_2$ in the flue gas. Average seasonal efficiency was reported to be 73.5 percent.

Details of the test procedure, described by Okuda & Martin (1980b), are significant because they represent the first attempt to use a direct input/output measurement for warm-air furnaces during cyclic operation in field service. Laminar-flow elements were placed in the furnace circulating air stream. Cycle-averaged output was determined using pressure sensors to detect pressure across the element; a continuously operating data logger system recorded the flow and corresponding air temperature rise through the furnace during the cycle and recorded the total heat delivered. By this method, average seasonal efficiency is reported to be 73.5 percent.

Because this procedure does not account for any savings in the bleed loss resulting from the sealed-combustion system, actual fuel-use records were used to assess the savings over the previous conventional units installed. Overall, the new furnace system yielded an average fuel savings of 16 percent, with the contribution from the savings in bleed loss estimated to be on the order of 5 percent. This saving was judged to be highest for the units with taller chimneys.

A comparison was made between the seasonal efficiency determined in the field test with that of the DOE/NBS test procedure (DOE, 1978). The DOE/NBS tests were performed in the field on two units, except that the existing chimney was used instead of the 5-foot stack specified in the procedures. When compared at the utilization level of 22.5 percent as specified in the DOE/NBS method, this method yielded seasonal performance about 10 percentage points higher than the direct measurement method. Part of this is due to the difference between the two methods in crediting jacket loss. EPA plans to repeat the rating procedure in the laboratory to investigate whether there is any effect of the site on the procedures.

EPA Environmental Assessments of Residential Combustion Systems

EPA has recently initiated environmental assessments of significant stationary sources by a comprehensive protocol. Field tests under this program include examination of organic emissions, including POM, polycyclic organic matter suspected of carciniogenic activity, and also bioassays to evaluate mutagenicity and carcinogenicity of emissions. A limited amount of information has been reported to date on residential oil-burning installations. (Ackerman et al, 1979; Acurex, 1979) EPA has conducted comprehensive analyses as part of in-house exploratory studies on a residential oil furnace, using a dilution tunnel similar to that for diesel engine emission measurements. An additional field investigation is being planned to examine organic emissions during cyclic operation of residential oil-burning equipment.

# SECTION VI

# TECHNICAL APPROACHES TO BURNER DESIGN — EXAMPLES AND ASSESSMENTS

This section of the report discusses a number of technical approaches to meet today's needs for efficient and reliable, low-capacity oil-burning equipment. Examples of developments, both past and present, are cited. Subjective assessments are made for each of the candidate classifications of technical approaches.

## CLASSIFICATION OF TECHNICAL APPROACHES

For purposes of this discussion, the technical approaches classified in three major areas: (1) oil-burner fuel preparation concepts, (2) combustion systems, and (3) heat exchangers. The third category is treated separately in Section VII. A further breakdown and explanation of the classifications follow.

### 1. OIL-BURNER FUEL-PREPARATION CONCEPTS

The method of fuel preparation is a key characterization.

A. Atomizing Burners

Burners where fuel is prepared by atomization, without special provision for vaporization, except droplet vaporization in the flame.

- High-pressure atomization *
  - Special low-rate nozzles having anti-clogging tendency

*The asterisks identify the main subsections for the discussion in this section.

- Return-flow nozzles
- Nozzle preheaters
- Air atomization *
- Ultrasonic atomization *
- Electrostatic atomization *

B. Prevaporizing Burners *

Thermal vaporizing burners that rely on external heat input or heat from the flame, as in typical pot-type burners. The oil is vaporized, or partially vaporized, and mixed with air before it reaches the flame.

- Unconventional thermal vaporizing burners

- Thermal aerosol generators and burners

  (Where external heat is applied to the oil for partial vaporization; then vapor and small oil droplets are mixed with air and burner as an aerosol.)

C. Combination Atomizing/Vaporizing Burners *

Fuel is initially atomized or thrown into a vaporizing zone where it is vaporized and burned, or vaporization and mixing can occur in a zone separated from the flame. Various approaches to catalytic burners can fall in this class.

2. COMBUSTION SYSTEMS

The method of fuel/air mixing and the combustion regime are important in this characterization of oil-burning systems.

D. Blue-Flame Burners *

Special means of fuel/air mixing, usually with recirculation of combustion products, can provide blue-flame burning.

E. Pulse-Combustors *

Intermittent combustion, where the frequency of combustion-driven oscillations is determined by the acoustic properties of the system.

Discussion of these approaches is organized by subsections as noted by the asterisks above.

## HIGH-PRESSURE ATOMIZATION

High-pressure atomization* is simple and is used effectively in conventional gun-type oil burners down to firing rates of about 0.5 to 0.6 gph. For lower-firing rates, the orifice and nozzle passages of conventional high-pressure nozzles become excessively small and encounter problems of clogging with fuel deposits and sediment. Approaches to overcome the orifice-size limitation are low-clog nozzles, return-flow nozzles, and nozzle preheaters.

### SPECIAL ANTI-CLOGGING NOZZLES

A special low-rate nozzle that is intended to have a low-clogging tendency is being introduced by Delavan in sizes from 0.3 to 0.6 gph.** (Tate, 1980) This is generally of the conventional high-pressure-type (Simplex atomizer) with a slotted distributor, but the internal passages have been redesigned to minimize clogging and to maximize atomization quality at low rates. Although the nozzle concept has undergone limited long-term tests thus far, there is need to investigate clogging tendency of different fuels. Early investigations by a burner manufacturer suggest superior clogging resistance and atomization quality at low rates, compared to conventional high-pressure nozzles of the same capacity; with the new nozzle, $CO_2$ levels 0.5 to 1.5 percent higher are reported to be achievable with equivalent smoke readings. (Cooperrider, 1980)

This nozzle can be used with conventional components for the entire system, assuming the combustion head is designed and sized to accommodate the low-firing rate. Thus, it is adaptable to easy field retrofit. Moreover, it has the added attribute that the fuel system is familiar to present-day service technicians.

Further investigation is needed on clogging tendency and atomizing performance for various combinations of fuels and temperatures. The gum and sediment producing characteristics of fuels vary widely, and it can be expected that fuel quality may deteriorate in periods of short fuel supply and as other applications demand the most stable fuel stocks.

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* Also called 'pressure-jet atomization' in the literature, especially the British literature.

** The Del-O-Flow nozzle is a trademark of Delavan, Inc.

RETURN-FLOW NOZZLES

In the return-flow nozzle, rotational momentum of a relatively high delivery rate at 100 psi pressure is used to impart atomizing energy to the fuel in a swirl chamber. Part of the fuel leaves the swirl chamber through the exit orifice to be atomized and a portion of the fuel is diverted back to the return line. Good atomization is thus maintained, and larger passages can be used for low firing rates than would be required in conventional nozzles. Figure VI-1 shows the schematic arrangement of return-flow nozzle, sometimes called a bypass nozzle. (Olson, 1957)

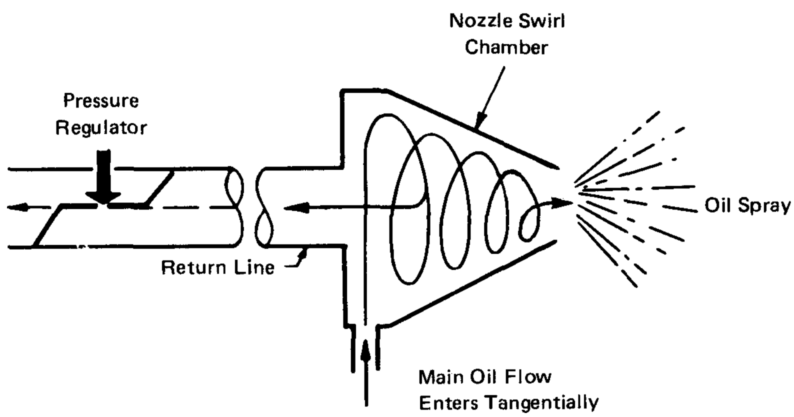


FIGURE VI-1. RETURN-FLOW NOZZLE – Schematic Diagram (Olson, 1957)

This approach offers an opportunity for variable-flow-rate control by varying the amount of return flow. However, atomization quality suffers to some extent at low turndowns. Also, additional fuel-system components to accommodate the return flow and pressure regulation are an added complication and a limitation to commercial acceptance.

The development of a low-firing rate burner was pursued by Gilbarco in the early 1950s. (Fueloil & Oil Heat, 1963) A burner that would operate between 0.4 and 0.65 gph was introduced, but it never reached full commercialization -- probably for reasons that include the lack of market demand then for low-capacity burners, higher cost, and requirements for greater understanding by service technicians. With respect to the last point, it was not uncommon in the early field introduction for a service technician to plug the return-flow system and replace the nozzle with a conventional high-pressure nozzle. Such occurrences should serve as a caution to designers in introducing new burners without adequate service training.

## NOZZLE PREHEATERS

A fairly recent approach, rapidly growing in Europe, is the electric nozzle-line heater of low wattage input that is used with conventional high-pressure nozzles to preheat the oil before atomization. (Schwarz, 1980) In European practice for residential burners, these heaters are typically 40 to 60 watts, and are controlled in temperature by a positive-temperature-coefficient element (PTC element) that limits temperature. A separate thermal switch delays the burner in starting from cold until the desired temperature is achieved, usually 160-180 F. The delay is usually only 8 to 15 seconds.

### Advantages

The objectives or advantages of nozzle preheating are as follows:

1. To operate conventional nozzles reliably at lower firing rates
2. To compensate for variations in fuel viscosity that affect atomization and firing rates
3. To minimize the tendency for firing rates to droop from cold starting to steady state when the nozzle warms up
4. To reduce peaks of air-pollutant emissions on starting.

In meeting the first objective, raising the temperature of No. 2 oil delivered to a conventional high-pressure nozzle will reduce the mass firing rate, because of the characteristics of the swirl chamber and the film thickness in the nozzle. (Janssen et al, 1977) At the same time, the higher oil temperature will lower the viscosity and improve atomization. This then allows the nozzle pressure to be reduced, thus lowering the flow rate for a given atomizer.

Nozzle preheating assists in meeting the second objective, that of compensating for fuel characteristics, because at higher temperature, there is more tolerance to fuel-quality variations that are more prevalent as oil supplies become scarce. To provide some margin of safeguard against such fuel quality changes, some manufacturers of commercial burners supply a preheater as standard equipment for all burners, even if they are to be fired by No. 2 oil only.

Regarding the third objective, some burner installations have a tendency to start from cold with a higher firing rate than the steady-state firing rate; this is sometimes called firing-rate droop. If the air supply is fairly constant, this means starting with a richer mixture, possibly producing high smoke and particulate emissions. This is a common phenomenon that is usually traceable to the nozzle design and/or the change in nozzle temperatures from starting to steady-state operation. The nozzle preheater should minimize this effect. Gulf R&D developed nozzle designs, known as "constant flow nozzles," that were less sensitive to this effect (Walsh, 1959), and several manufacturers offer special nozzles having this characteristic.

Toward the fourth objective, improved starting should result from t nozzle preheating and the reduced tendency for firing-rate droop. This woul be expected to decrease emissions of smoke, CO, and HC on starting.

## Potential Disadvantages

Limitations or disadvantages of the nozzle-line heater are as follows:

1. The cost of electric power required for operation of the heater might be be considered a detriment.
2. There is the possibility of varnish formation or deposits on nozzle parts that will degrade atomization or firing rate over time. Any transient overshoot of temperature on shut down may tend to cause nozzle clogging. European fuels generally do not contain as much cracked stock as U.S. fuels so thermal stability of some U.S. fuels may result in clogging.
3. Burner performance will deteriorate if the heater element should fail, so some fail-safe control may be needed.

Further investigation of these factors is needed. It is likely that trade-offs must be considered between the advantages sought and the potential disadvantages that may be encountered.

## APPRAISAL OF PRESSURE-ATOMIZATION FOR LOW-FIRING RATE BURNERS

Of the candidate concepts for low-firing application of high-pressure atomization, the simplist and lowest cost appears to be the anti-clogging nozzle, if a fixed firing rate is acceptable. It can be retrofitted into any conventional high-pressure burner as long as the combustion head is suitable for low rate operation. The concept is so new that information is limited on clogging tendency under varying conditions; considerable information is needed in this area.

Return-flow nozzles require more complication in the fuel system and, operated at very low turndown, may suffer atomization quality. The concept does offer a possibility for variable firing rates.

Nozzle preheaters are gaining popularity in Europe as means of reducing firing rates of conventional nozzles, but have not seen significant commercial use on residential burners in the U.S. Their potential for reliability is unknown when operating with U.S. fuels of varying quality. The concept merits further investigation of these factors, plus transients in operation and durability of electrical components. Although there is variable-firing-rate potential with control of both oil pressure and fuel temperature, this concept seems better suited to fixed-rate applications.

## AIR ATOMIZATION

In air atomization*, energy for fuel atomization is supplied by pressurized air, with fuel flowing at low pressure in relatively large passages. It is of particular interest for residential burners sized for fuel flow rates below 0.5 gph.

The technology of air atomization is well developed and widely used in industrial burners. It permits good atomization over a wide turndown range, in that atomization energy provided by the air is maintained as fuel flow is varied. It also permits use of high energy levels for atomization, as needed for very viscous fuels or for ultrafine atomization.

### ADVANTAGES

The advantages of air atomization for residential burners include

1. Suitability for low firing rates,
2. Suitability for variable-rate operation, and
3. Capability of superior atomizing performance, leading to clean combustion with low excess air.

The principle disadvantage is the need for an air compressor.

Air atomization was the basis for low-pressure oil burners that were popular 30 years ago. (Fueloil & Oil Heat, 1948) In most of these burners, the oil and atomizing air were mixed in the pump; however, more recent developments have separated the oil and air, except for compressor lubrication. However, the concept is seldom used in new residential oil burners, partly because of the somewhat higher cost of a burner incorporating an air compressor and because of the success of high-pressure burners. Nevertheless, air atomization has remained a promising candidate for development of very-low-capacity oil burners and has received widespread investigation.

Table VI-1 identifies references pertinent to air atomization and its application to residential burners.

### COMPRESSED AIR REQUIREMENTS

The quantity of air used for atomization varies with the atomizer design, and it is possible to trade off air quantity and pressure for similar

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* Also called "two-fluid atomization" or "low-pressure atomization" in the literature.

TABLE VI-1. REFERENCES ON AIR ATOMIZATION AND ITS APPLICATION TO OIL BURNERS

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Fuel Oil and Oil Heat | 1948 | FO & OH | Low-pressure Oil Burners—Operating Principles and Construction (Compilation of articles, reprinted 1971) |
| Putnam, et. al. Battelle | 1957 | WPAFB | Injection and Combustion of Liquid Fuels |
| Pilcher & Mitchell Battelle | 1960 | API | Atomization: in Literature Pertaining to the Art & Sciences of Oil Burning for Residential Applications |
| Walsh Gulf R&D | 1961 | API | Air-Aspirated Oil Burners |
| Yeager | 1961 | API | A Survey of Components for Use with Air-Atomizing Oil Burner Nozzles |
| Bailey OOHA | 1962 | API | Oil-Burner Adaptation of a Low-Cost Air-Oil Pump with Differential Displacement Metering |
| Coffin & Spraker Battelle | 1962 | API | A Survey of Air-Atomizing Systems for Small Oil Burners |
| Hadvig Tech. U. of Denmark | 1962 | API | Design Criteria for Combustion-Air Handling in a Small Domestic Oil Burner |
| Henwood FO & OH | 1962 | API | Future Markets and Marketing Channels for Oil-Fired Equipment |
| Krouse Nat. Union Elec. | 1962 | API | New Air-Oil Pump for Air-Atomizing Oil Burners |
| McCullough & Zinn A. D. Little | 1962 | API | A Rotary-Screen Vaporizing Burner |
| Scott Buckley & Scott | 1962 | API | Direct Powered Water Heaters—Improvement Opportunities and Markets |
| Walsh Gulf R&D | 1962 | API | Burner Research Related to the API Program |
| Bailey OOHA | 1964 | API | Status of the OOHA Burner Development Program |
| Walsh Gulf R&D | 1964 | API | Aspiration in Fuel-Oil Combustion |
| Briggs, Farkas & Wilson Master Consol. | 1965 | API | Air-Atomizing Oil Burner for Low-Firing-Rate Applications |
| Hughes, Schurig & Hommel Sonic Dev. Corp. | 1965 | API | Application of Air-Powered Sonic Energy in Atomization for Domestic Oil Burners |
| Doyle, Perron, & Shanley | 1967 | API | A Study of New Means for Atomization of Distillate Fuel |
| Bailey OOHA | 1968 | NOFI | OOHA Blue Flame Burner Systems |
| Bell & Korn Sonic Dev. Corp. | 1968 | NOFI | Developments in Sonic Atomization for Domestic Oil Burner Applications |

TABLE VI-1. (Continued)

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Briggs<br>Koehring Co. | 1968 | NOFI | Application of an Air Atomizing Oil Burner to the Gas Fired Whirlpool Chiller Unit |
| Velie<br>Rocketdyne | 1968 | NOFI | New Concept for Domestic Oil Burners—Una*Spray Oil Burner Development Progress |
| Babington, Slivka, & Yetman | 1969 | Patents | 1. Method of Atomizing Liquids in a Mono-dispersed Spray, and<br>2. Apparatus for spraying Liquids in a Mono-dispersed Form |
| Bailey<br>OOHA | 1969 | NOFI | New Product Developments from the OOHA laboratory Utilizing Blue Flame Burner Systems |
| Velie<br>Rocketdyne | 1969 | NOFI | Una*Spray Integrated Furnace |
| Bailey<br>OOHA | 1970 | NOFI | Blue Flame Burner Development at the OOHA Laboratory |
| Hagel<br>Rocketdyne | 1970 | NOFI | Una*Spray Integrated Furnace |
| Editor | 1972 | ARRD | The Babington Nebulizer: A New Principle for Generation of Therapeutic Aerosols |
| Hazard<br>Battelle | 1972 | ASME | $NO_x$ Emission from Experimental Compact Combustors |
| Hazard<br>Battelle | 1973 | EPA | Low Emission Burners for Automotive Rankine Cycle Engines |
| Hazard<br>Battelle | 1974 | ASME | Reduction of $NO_x$ by EGR in a Compact Combustor |
| Metzger<br>Popular Science | 1976 | Pop. Sci. | Clog-Proof Superspray Oil Burner Saves Fuel Costs Two Ways |
| Erb & Resch<br>Vapex | 1979 | Patent | Pneumatic Nebulizer and Method |
| Aronson<br>Compump Systems | 1979 | BNL | Compump Model 3D-2 Compressor/Pump |

NOTE: For full information on sources is included in author-alphabetical listing in REFERENCES section of this report.

available energy. For example, small syphon-type atomizers operate with a pressure of 3 to 5 psi and air flow rates of 0.3 to 3 cfm, for mass ratios of air to oil ranging from 0.13 to 0.66 lb air/lb oil. Acoustic-type nozzles for superfine atomization (discussed subsequently) operate with air pressure of 13 to 15 psi and mass ratios of air to oil of 0.18 to 0.31 lb air/lb oil. These air quantities are small in terms of combustion air, ranging from 0.9 to 2.1 percent of stoichiometric air.

Conventional air-atomizing nozzles for residential heating operate th air pressures and oil pressures below 5 psi. In syphon-type nozzles (Olson, 1965) air flow within the the swirl chamber of the nozzle produces a low-pressure region into which oil is drawn from a constant-level reservoir. In most of these designs, the oil passages are large enough that they do not plug at flow rates above about 0.1 gph.

Figure VI-2 shows the relation of atomizing-air flow to oil flow rates for a number of air-atomizing nozzles. These include complete low-pressure burners, and nozzles available as separate components. These nozzles require small positive-displacement compressors, generally providing less than 1 cfm air at adequate atomizing pressure. (Yaeger and Coffin, 1961)

## Spray Droplet Size

Figure VI-3 summarizes data relating mass median diameter of atomized liquids to the mass ratio of atomizing air to liquid, using air at about 15 psi. These data include a variety of liquids, as labeled. (Doyle, Perron, and Shanley, 1966) In the figure, Curve B, for molten wax, shows a range of 30 to 70 micrometers as the mass median diameters for air/liquid ratios of 0.1 to 0.7, the same range as used in typical residential burners. The slopes of these curves are indicative of the effect of air/liquid ratio on atomizer performance; the actual performance of a particular atomizer, however, depends greatly upon details of its design.

## UNCONVENTIONAL AIR-ATOMIZING SYSTEMS

Several unconventional air atomizing systems have been introduced in recent years:

- The Sonicore acoustic atomizer
- The Babington atomizer and burner
- The Vapex pneumatic atomizer.

These are described below.

## The Sonicore Acoustic Atomizer

The Sonicore* atomizing nozzle, shown in Figure VI-4 utilizes sound energy to augment fuel atomization and produce an ultrafine spray. (Hughes et al, 1965; Bell & Korn, 1968) In the Sonicore atomizer, air flows at near-sonic velocity through a venturi on the axis, and fuel flows into the venturi

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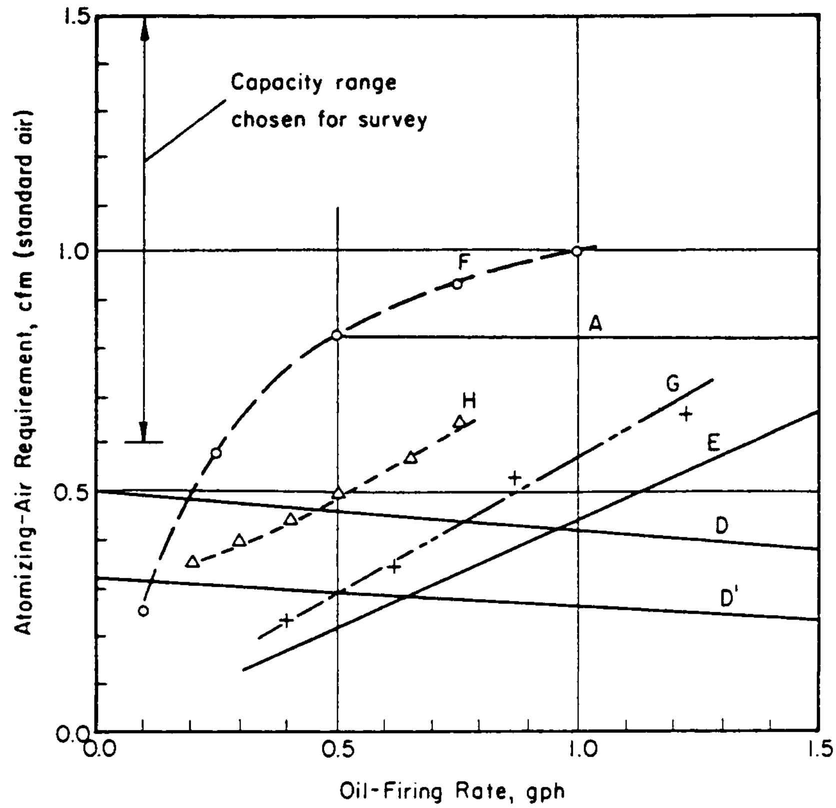
* Registered trademark of Sonic Development Corp. of America.




| | | Lift | Air Pressure, psig | Oil-Firing Rate, gph | Air Requirement, cfm |
|---|---|---|---|---|---|
| Complete LP burners: | A | | 3-1/4 – 3-1/4 | Shown | Shown |
| | B | | 15 | 0.5 – 1.5 | 3 – 5 |
| | C | | 1 – 1-1/2 | 0.4 – 1.5 | 3 |
| LP systems: | D + D' | | 4 – 4-1/2 | 2 makes of nozzles shown | |
| | E | | 4 | One nozzle shown | |
| Siphon-type nozzles: | F | 1" | 3 | Separate nozzles shown | |
| | G | 1" | 3 | Separate nozzles shown | |
| | H | 4" | 4 | Separate nozzles shown | |

FIGURE VI-2. AIR CAPACITIES REQUIRED FOR VARIOUS AIR-ATOMIZING NOZZLES (Yeager, 1961)

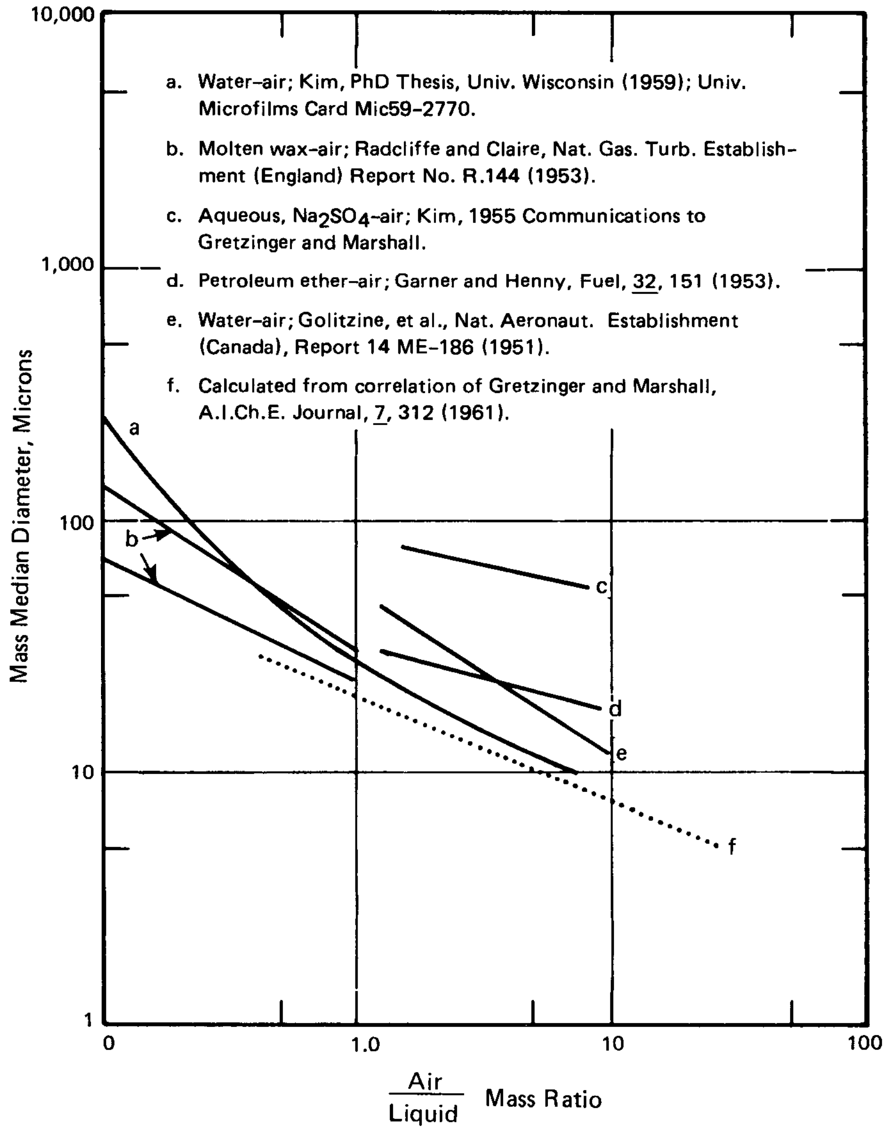



FIGURE VI-3. RELATION OF DROP SIZE TO AIR/LIQUID MASS RATIO FOR TYPICAL PNEUMATIC ATOMIZERS (Doyle et al, 1967)

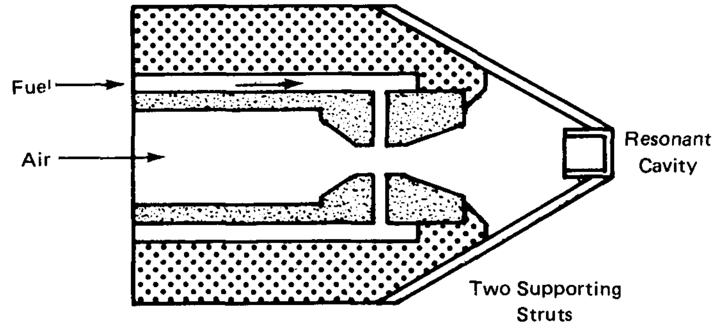



FIGURE VI-4. SONICORE ACOUSTIC-TYPE AIR-ATOMIZING NOZZLE

throat through radial holes. Primary atomization takes place by the shearing action of the high-velocity air passing over the fuel ports. The atomized fuel-and-air mixture leaving the venturi then impacts on a cup spaced a short distance away, which acts as a whistle to produce intense sound waves at ultrasonic frequency, through which the fuel-and-air mixture passes. These sound waves cause further atomization of the fuel to produce an extremely fine spray, which permits very clean combustion in a small space with low excess air, and with a turn-down ratio of 10:1 or more. The Sonicore Model 028 atomizer, is rated at 0.1 to 1 gph, and requires 0.4 scfm air (1.79 lb/hr) at 15 psi, which is equivalent to 0.31 lb air/lb oil.

Larger capacity versions of the Sonicore atomizer have been used for higher capacity oil burners firing residual oil in industrial and marine boilers. The small sizes of Sonicore atomizer are available commercially, but are not used in current production of residential burners.

The Sonicore atomizer proved particularly suitable for a high-intensity oil burner, requiring a 100:1 turndown ratio, that was developed to demonstrate burner technology for low-emission, Rankine-cycle automobiles. (Hazard, 1972) Clean combustion was obtained at rates of 1.5 to 110 lb fuel/hr in a space of 8-inch diamater and 16-inch length.

This atomizer was applied to an ABC burner, using a Compump oil/air pump as part of the NOFI Equipment Development Program.

## The Babington Atomizer and Burner

Mr. Robert Babington has developed a principle of air atomization that is used in commercial medical nebulizers, and he has applied the principle in a residential oil burner that is now under development. This burner is of interest because it is suitable for variable-rate operation at low firing rates, ranging from 0.2 to 0.8 gal/hr, and shows promise of high combustion efficiency and high reliability. (Metzger, 1976) A demonstration model will be tested as part of the BNL program of RD&D on variable-rate oil burners.

Figure VI-5 shows the principle of the Babington atomizer. Fuel is supplied to the outside of a hollow convex surface containing an aperture or slit. The liquid fuel spreads out across the atomizing surface in a thin film, where it is ruptured by low-pressure air expanding through the aperture. This creates a dispersion of fine liquid droplets. Excess fuel which is not atomized is drained from the base of the atomizer and recirculated via a simple pump. The use of a freely-flowing film of liquid on the surface of the atomizing sphere results in good atomization of fluids having a wide range of viscosity; fluids containing particulates as contaminants pass freely over the sphere without degrading atomization or blocking fuel flow.

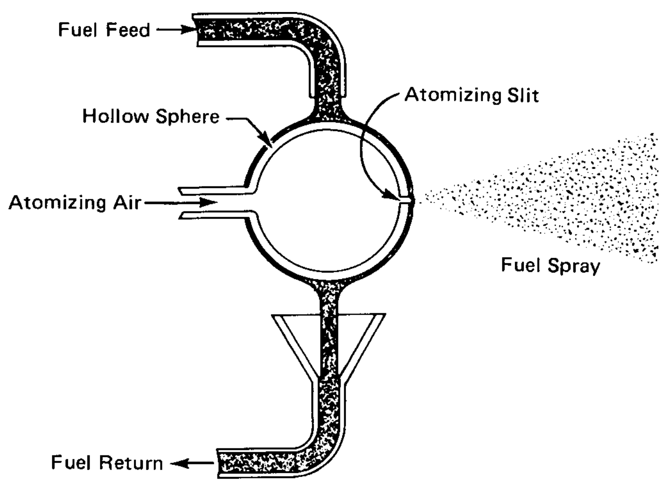



FIGURE VI-5. PRINCIPLE OF BABINGTON AIR ATOMIZER
(Courtesy: R. S. Babington)

This principle of atomization is the subject of more than 100 U.S. and foreign patents by Mr. Babington. Several medical products utilizing the principle have been on the market for about five years. (ARRD, 1972)

Because of the nature of the fuel-spray and oil fuel, application of this atomizing principle to residential oil burners requires some departures from conventional oil-burners, especially in fuel/air mixing and the oil supply system. This was investigated by Rocketdyne under contract with NOFI as part of the NOFI Equipment Development Program. (Velie 1968 & 1969) A number of prototypes were developed by Rocketdyne which they termed the Una Spray Burner. Later the concept was licensed to Una, Inc. Although the basic atomization concept showed promise, the prototype burners encountered a number of problems that limited reliability and durability. These problems involved burn back in the atomizing chamber, combustion chamber hot spots, poor ignition, sooting of the ignitors, an undersized compressor, and an unorthodox fuel supply system. Some units were field tested, but the concept did not reach commercialization.

Present Babington Burner Development. Subsequently, Robert Babington spent about six years of independent research, culminating in the design and development of an entirely new burner. Although this new burner utilizes the same principle of atomization, it bears no further resemblance to Rocketdyne's Una Spray Burner. (Babington, 1979)

The new Babington burner overcomes the problems encountered with the Rocketdyne design as cited above. The new burner features dual atomizers which provide aerodynamic flame holding at the point where the two sprays intersect. The atomized fuel is mixed with air in a flame tube where complete combustion takes place. This feature, along with a fuel/air mixing technique adapted to the spray characteristics, allows the Babington burner to perform cleanly at very low excess air, essentially independent of the combustion chamber in which the burner is installed. Thus, it is adaptable to retrofit application in a variety of existing furnaces and boilers having different combustion-chamber size and configuration.

The burner is supplied with 0.13 scfm of atomizing air at 13 to 16 psi pressure, using a small piston-type pump. This is equivalent to a mass ratio of atomizing air to fuel of 0.22 lb air/lb fuel. Thus, atomizing-air quantity is relatively low, compared with conventional atomizing nozzles. The firing rate is controlled by varying the film thickness over the spray heads. Variable firing rates from 1.0 gph down to 0.2 gph can be achieved by simply turning the fuel-control adjustment screw.

A prototype of an early version of a Babington burner was tested at BNL over its full operating range in a conventional boiler. Good combustion was obtained with 13.0 percent $CO_2$ at 0.3 gph and 14.5 percent at 0.6 gph. (Dennehy, 1979)

Since the conduct of preliminary tests at Brookhaven, the inventor has continued to make progress. The most recent burner design can operate at 15 percent $CO_2$ even in cold boilers. A new and simple fuel supply system has been developed. The new simplified fuel supply and recirculation system involves modification of a high-pressure pump with a one-line fuel system. It is self priming and has a lift capability in excess of 20 feet, with tolerance to suction-line leakage. The burner makes use of commercially available materials and components for good reliability and ease of field servicing.

Although longer-term durability tests are needed, the burner shows promise as a variable-rate oil burner suitable for retrofit applictions.

## The Vapex Pneumatic Atomizer

The Vapex* pneumatic atomizer utilizes another approach to forming a thin film of fluid around an air orifice, with atomization of the fluid by flow of air through the orifice. With a very thin oil film, and high air velocity, the spray produced can be very fine; for example, one atomizer geometry produced a mass median diameter of 7 micrometers. This principle has been used by Vapex Pneumatic Atomizers for medical nebulizers and appears promising for use in oil burners.

Figure VI-6 illustrates the atomizing principle of the Vapex "stretched-film" nebulizer. A film of fluid is formed on a filming surface, liquid being supplied at a controlled-rate from between two disc surface at the periphery of the filming surface. Air flowing through a central orifice entrains liquid, breaking it into small drops. The removal of liquid at the air jet draws liquid from the edge of the filming surface, stretching and thinning the liquid film. The size of liquid drops formed is a function of film thickness, so that this stretched-film principle reduces droplet size. The typical droplet size range for a medical nebulizer of this design is 3 to 7 micrometers, which is much smaller than usual in oil burners.

Figure VI-7 shows a Vapex air-atomizing nozzle, based on the "stretched-film" principle. The nozzle includes a filming plate and distributing disc, with fuel and air supply passages, all retained by screw threads. The nozzle design appears suitable for use in a conventional gun-type burner if it is adapted to air atomization. The size, shape, and number of air holes in the filming disc can be varied, as can the size and number of liquid-supply slots.

In a series of atomizing tests (Erb, 1979), it was shown that liquid droplets having a mass median diameter of 7 micrometers were produced with atomizing air at 5 psi and with a mass ratio of air to liquid of 0.5. This small droplet size is far below that for conventional atomizers, as shown in Figure VI-3. This air/liquid ratio is within range for conventional syphon-type nozzles producing 50-micrometer mass median droplet size.

An oil burner was assembled using a nozzle similar to that of Figure VI-7, supplied by atomizing air at 25 psi, using the atomizing air and fuel mixture in a venturi to supply combustion air (as in an aspirating gas burner). When firing at 0.125 gal. of No. 2 fuel oil/hr, fuel droplet size was below 8 micrometers. The fuel burned with a blue flame, resembling a gas flame, at between 1.2 and 6.2 percent excess air. This was a simple exploratory test, and no effort was made to vary combustion conditions. However, the Bacharach smoke number was zero, the flame was steady, and it was possible to modulate the flow rate. (Erb, 1979)

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*Vapex is a registered trademark of Vapex Pneumatic Atomizers.

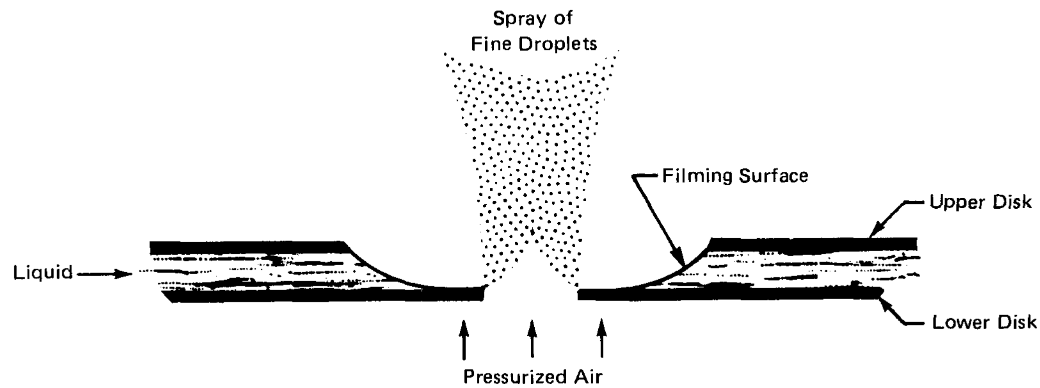



FIGURE VI-6. ATOMIZING PRINCIPLE OF VAPEX "STRETCHED-FILM" ATOMIZER

Air flowing through orifice entrains liquid, breaking it into small drops. Liquid is drawn toward orifice by surface tension, thinning liquid film for finer atomization. (Courtesy, Vapex Pneumatic Atomizers)

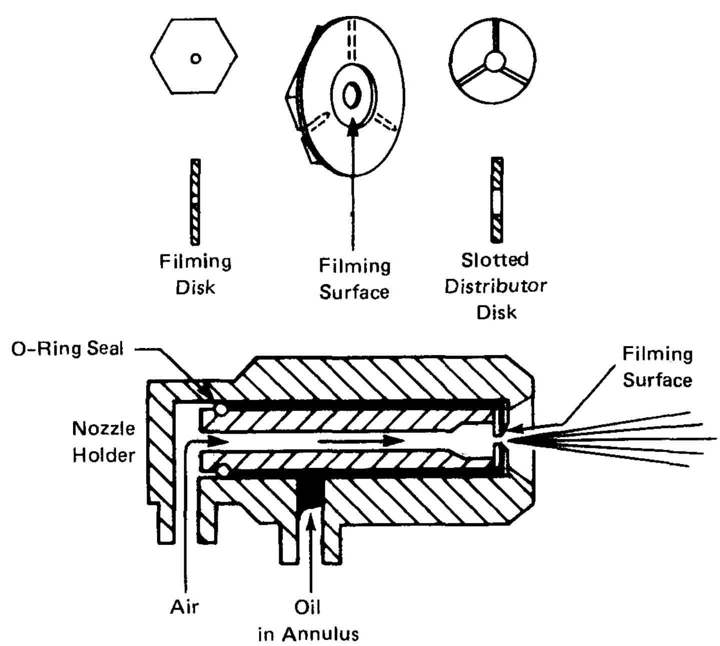



FIGURE VI-7. VAPEX AIR-ATOMIZING NOZZLE BASED ON "STRETCHED-FILM" ATOMIZER PRINCIPLE (Courtesy, Vapex Pneumatic Atomizers)

In another series of tests a Vapex nozzle mounted in a standard gun-type oil burner was fired in a cast-iron bioler; zero smoke was obtained over a full range from 0.10 to 0.60 gph, and $CO_2$ levels ranged from 14.3 to 15.1. Air pressure was 5 psig and atomizing air supply was 0.65 CFM over the full range. (Demler, 1978)

The atomizer is not yet used on commercially available burners, but there is recent development activity by a foreign burner manufacturer and by the U.S. Army for military applications.

## APPLICATION OF AIR ATOMIZATION TO OIL BURNER SYSTEMS

The versatility of air atomization has intrigued oil-burner designers for many years. (Fueloil & Oil Heat, 1948) In addition to performing the function of fuel atomization, the momentum of the atomizing air stream can be used to aspirate air or combustion products into the system. Thus, an atmospheric-type burner, similar to a gas burner is feasible with oil firing. Air momentum can also be used to provide fuel lift, as in the case of the siphon-type nozzle.

### Example Burner Developments

Gulf Research and Development Company demonstrated a number of burner approaches using air atomization; some were atmospheric-type burners that did not require a separate blower. (Walsh, 1961, 1962 & 1964) Figure VI-8 shows an example of a burner that relies on the momentum of the atomizing air and fuel spray to aspirate much of the secondary air. (Walsh, 1962)

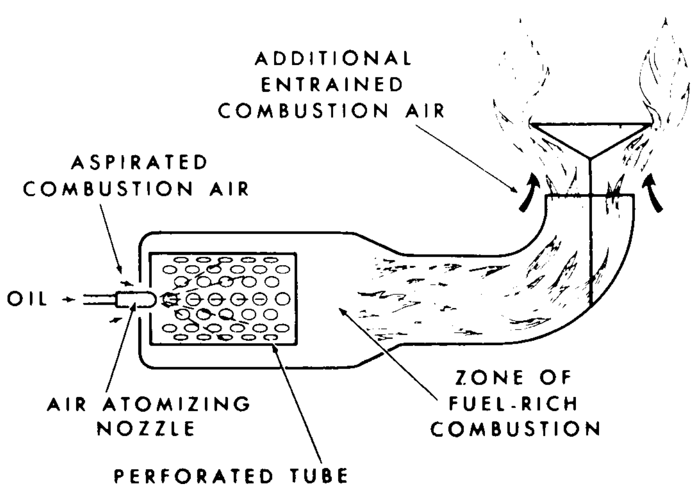
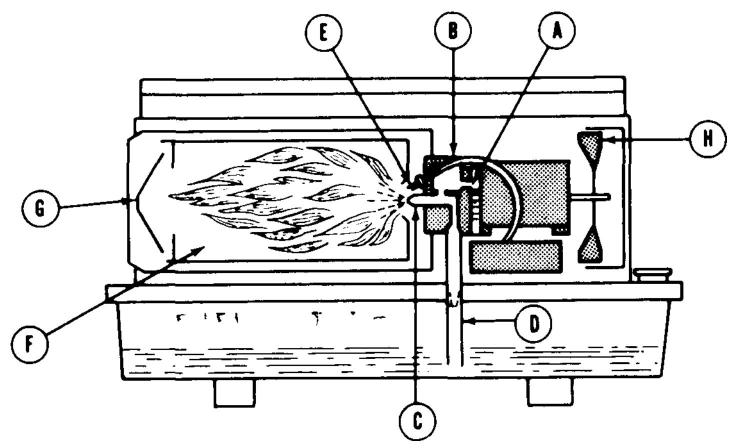



FIGURE VI-8. CONCEPT OF AN AIR-ASPIRATED, NATURAL-DRAFT BURNER (Walsh, 1962)

The rod-type atomizing/vaporizing burner development, listed under the NOFI projects in Section IV of this report, was somewhat similar in concept, but not configuration. That burner, suggested and originally constructed by Babington as a conversion burner for sectional gas furnaces was investigated by Rocketdyne with funding from Chevron Research Company and from NOFI. (Babington and Velie, 1971)

Figure VI-9 shows a unique application to a portable space heater that uses a siphon-type nozzle to lift fuel from the storage tank by the nozzle suction capability. (Briggs, Farkas & Wilson, 1965)

Carlin has participated in the BNL oil burner RD&D program conducted by Foster-Miller and has investigated application of the Vapo film-atomizing concept to residential oil burners. (Fischer, 1979)




A. AIR COMPRESSOR
B. AIR FILTER
C. NOZZLE (AIR-ATOMIZING, SIPHON-TYPE)
D. FUEL LINE
E. IGNITER
F. COMBUSTION CHAMBER
G. BAFFLE
H. FAN

FIGURE VI-9. PORTABLE HEATER USING SIPHON-TYPE AIR ATOMIZER (Briggs et al, 1965)

## Air Compressors for Air Atomization

The development of air atomizing oil burners has been limited by the requirement for a low-cost and reliable air compressor. Unfortunately, no market has existed for a small air compressor meeting these needs. Suitable pumps and metering devices are also required in a complete burner assembly. As part of the API Oil-Burner Research Program, Battelle conducted a survey of approximately 650 manufacturers of air compressors, fuel pumps and metering devices. (Yaeger and Coffin, 1961) In this study, general requirements of these components were examined. A listing was compiled of manufacturers that indicated an interest in cooperating with burner manufacturers in the development of new components.

Papers were presented in API and NOFI meetings that described new air compressor developments. (Bailey, 1965 & 1969; Krouse, 1965; Briggs et al, 1965 & 1968) More recently, Compump Systems, Inc. has developed a combination air compressor and metering type oil pump intended for air-atomizing-oil burners (Aronson, 1979); a similar Compump was used in the NOFI development by ABC and Sonicore.

If air compressors become available that successfully meet the needs, new air-atomizing systems will be feasible. In R&D at Webster Electric, a combination air compressor and oil pump has been investigated, the system used a demand-actuated oil metering value for use in conjunction with siphon-type nozzles. (Dalziel, 1980) Piston-type air compressors have also been used or have been under under development over the past few years for use with air atomization in both U.S. and foreign oil-burner developments.

The Atomaster Division of Koehring has successfully marketed an air-atomizing oil-burner system in portable heaters. The type of heater shown in Figure 9 has been on the market for approximately 20 years. Similar versions of this low-firing rate burner have been developed for water heaters (Briggs et al, 1965) and more recently for low-capacity window-type heaters using sealed-combustion systems. (Briggs, 1980) Atomaster is offering to supply this compressor to oil-burner manufacturers. The vane-type air compressors used in these heaters have logged many hours of operation, although the type of service for most portable heater applications is not as demanding as residential heating in terms of expected operating hours per year or during the lifetime of the oil burner. None-the-less, this compressor has a longer record of field use than other compressors being considered for oil burers at the present time.

## APPRAISAL OF AIR ATOMIZATION

Air atomization approaches to oil-burner design have a long history. The success of high-pressure-atomizing burners over the past 2 decades has resulted in virtual disappearance of the earlier low-pressure air atomizing burners. However, the need for lower firing rates, and the interest in variable rate burners, makes air atomization a promising candidate. An air compressor that has the necessary long-term durability is needed for the success of new burners using air atomization. It appears that the competitive systems described under high-pressure atomization also show promise, possibly at a lower manufacturing cost.

Air-atomizing systems warrant further R&D, especially as related to the long-term durability of the air compressor and other system components.

## ULTRASONIC ATOMIZATION

Ultrasonic atomizers are of current interest because they are suitable for fuel flow rates below 0.5 gph, and for modulated flow rates. In the ultrasonic atomizer, a thin film of fuel flows over a surface that vibrates perpendicular to the surface at high frequency. The vibration causes a wave pattern over the fuel surface. With sufficient wave amplitude, fuel droplets are thrown from wave crests. Droplet size is a function of wave size, and depends upon atomizer frequency and fuel density, viscosity, and surface tension. The piezoelectric ultrasonic atomizer utilizes piezoelectric material to drive the atomizer vibrations, resulting in a compact, efficient system. Magnetostrictive drives have also been used to produce the vibrations.

Figure VI-10 illustrates the concept used in a piezoelectric ultrasonic atomizer; this is a miniature atomizer developed by Battelle in 1965 for use in a multifuel burner for a 100-watt thermoelectric generator. This atomizer was driven at 85 kHz by a transistorized power oscillator requiring 4 watts input at 12 volts; although designed for operation at a fuel rate of 1 lb/hr, it could operate at somewhat above 2 lb/hr with No. 2 fuel oil (about 0.3 gph). The fuel spray was very fine, estimated at about 20 micrometers mean diameter, and the fuel rate could be modulated to any desired value below the maximum flow rate. (Hazard & Hunter, 1966)

Other piezoelectric ultrasonic atomizers varying in size, shape, frequency, and capacity have been developed for different purposes, but they combine the basic principles illustrated in Figure VI-10. Applications range from experimental automobile carburetor atomizers, sized for about 20 gph flow rate, to medical nebulizers having a capacity of a few grams/hr and submicron droplet size.

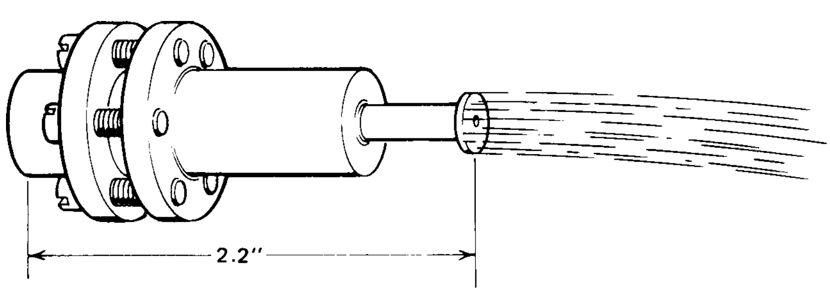



FIGURE VI-10. BATTELLE'S MINIATURE ULTRASONIC ATOMIZER FOR LOW FIRING RATES – 85-k Hz (Hazard and Hunter, 1965)

## ADVANTAGES

Features that make the ultrasonic atomizer a candidate for low-firing rate application are:

- Electric power consumption for atomization is extremely low -- typically below 5 watts. It is probably lower than for any other type of atomizer now available.
- Variable-flow-rate atomization is excellent over a range from the maximum design rate to zero flow.
- Fuel passages should not plug, as they are large, and are ultrasonically cleaned.
- Fuel pressure drop is very low, so that a low-pressure metering system, requiring little power, can be used.
- Fuel rate can be controlled by a metering pump (possibly controlled electronically by variation of the speed) or by an orifice with controlled head.
- The atomizer is suitable for operation at fuel rates well below 0.5 gph, a range where conventional pressure-atomizing nozzles are not suitable.

## CHARACTERISTICS OF ULTRASONIC ATOMIZERS

Piezoelectric ultrasonic atomizers have characteristics rather different from conventional pressure-atomizing fuel nozzles, some of which are advantageous and some of which are so different as to require significant changes in burner design if they are to be applied to residential oil burners.

Some of the operating characteristics that affect burner design and cost are:

- Fuel metering is a problem, as it must be done externally to the atomizer by means such as a positive-displacement metering pump (used in military thermoelectric generators), or a metering valve, orifice, or capillary tube taking a predictable pressure drop. Until recently, a metering pump suitable for residential oil burners has not been available.
- The atomizer produces a fine spray with little momentum or penetration. In the atomizer of Figure VI-10, this spray was a narrow, axial column unsuitable for use in a gun-type burner. The spray pattern can be modified by modifications of the shape of the atomizer tip, but it is necessary to develop a special burner air-flow pattern to accommodate the spray characteristic.

- The atomizer must be mounted in such a way that it is not overheated and does not touch any other component.

The durability of a properly-designed ultrasonic atomizer appears to be excellent; the atomizer shown in Figures VI-10 was operated for 33,000 hours continuously in a 4-year life test. However, stress levels can be high if a nominal amplitude is exceeded as a means of increasing atomizing capacity. This relation between atomizer life and power input requires careful consideration in atomizer design.

## HISTORICAL BACKGROUND

Table VI-2 identifies references pertaining to ultrasonic atomization, listed chronologically. One of the early accounts of experiments with ultrasonic atomization was a Battelle investigation for the purpose of paint spraying; it also contains a discussion of the theory. Antonovich at Battelle (1957) and Lang at Esso Research and Engineering (1962) also discussed the theory of ultrasonic atomization.

Ultrasonic atomization for residential oil burners has been an R&D focus for nearly 20 years. The major developments regarding oil burners, that are known to the authors, are traced in the following discussion.

### Exxon / API / A.D. Little

Early work was carried by the Esso Research and Engineering Company. (Young et al, 1962; Lang et al, 1961, 1962; Lang, 1963) In 1960, API initiated a major research program on new oil-burner technology. Under this program, A. D. Little developed the piezoelectric atomizer shown in Figure VI-11 and a matching gun-type oil burner. This atomizer operated at 57 kHz, was 13.4 cm long, and had a power requirement of 17 watts to the tube-type power supply.

The API project drew from the results of the earlier Esso development, which were contributed to the API program, and resulted in the demonstration of the workable model shown in Figure VI-11. The API atomizer development is summarized in papers by (McCullough et al, 1965 & 1966) and in two API summary reports. (Doyle et al, 1967; Perron et al, 1967) The API program produced three patents on ultrasonic atomizer design that were dedicated to the public domain. (Doyle et al, 1964; Perron, 1965; McCullough, 1966) McCullough's patent was directed to the application of the atomizer to a burner system.

As part of the API program, a quantity of piezoelectric ultrasonic atomizers was constructed and sold to burner manufacturers and other R&D groups that were interested in evaluating them in burner configurations. This

TABLE VI-2. REFERENCES ON ULTRASONIC ATOMIZATION

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Joeck | 1950 | Patent | Method for Atomizing by Supersonic Sound Vibrations |
| Antonevich<br>Battelle | 1957 | Nat. Elec. | Ultrasonic Atomization of Liquids |
| Lang<br>Esso R&E | 1962 | ASOA | Ultrasonic Atomization of Liquids |
| Doyle, Mokler & Perron<br>A. D. Little | 1962 | API | New Means of Fuel Atomization |
| Lang, Young & Wilson<br>Esso R&E | 1962 | API | An Ultrasonic Oil Burner |
| Peskin & Lawler<br>Rutgers Univ. | 1962 | API | Results from Analytical Studies of Droplet Formation |
| Lang<br>Esso R&E | 1963 | API | Optimization Studies on the Ultrasonic Burner |
| Perron, Swanton & Shanley<br>A. D. Little | 1963 | API | A Practical Ultrasonic Oil Burner |
| Peskin & Raco<br>Rutgers Univ. | 1963 | API | Some Results from the Study of Ultrasonic and Electrostatic Atomization |
| Doyle, Perron & Swanton<br>A. D. Little | 1964 | Patent | Apparatus for Atomizing and Burning Liquid Fuel |
| Eisenkraft<br>Spray Designs | 1965 | API | The Vibrative Atomizer |
| McCullough, Perron & Shanley<br>A. D. Little | 1965 | API | The API Ultrasonic Atomizer and Oil Burner Program |
| Hazard & Hunter<br>Battelle | 1965 | USAECOM | Multifueled Thermal-Energy-Conversion Systems |
| Perron<br>A. D. Little | 1965 | Patent | Apparatus for Atomizing a Liquid |
| Hazard<br>Battelle | 1966 | Pow. Sources | An Ultrasonic Burner for Liquid Hydrocarbon Fuels |
| Herchakowski<br>U.S. Army | 1966 | Pow. Sources | 100-Watt Thermoelectric Generator Development |
| Bradbury<br>Simms, Ltd. | 1966 | API | The Ultrasonic Atomization of Liquid Fuels — Some British Developments |
| Doyle, Perron & Shanley<br>A. D. Little | 1966 | API | A Study of New Means for Atomization of Distillate Fuel Oil |
| Dysart<br>Pure Oil Co. | 1966 | API | Application of the API Ultrasonic Atomizer to a Vortex Combustion System |

TABLE VI-2. (Continued)

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Hazard & Hunter<br>Battelle | 1966 | API | A Miniature Ultrasonic Burner for a Multi-Fueled Thermoelectric Generator |
| Shanley, Perron & McCullough<br>A. D. Little | 1966 | API | A Progress Report on the API Ultrasonic Atomizer and Oil Burner Development |
| Martner<br>Stanford Res. | 1966 | API | An Ultrasonic Atomizer Capable of High Rates |
| Perron, McCullough & Shanley<br>A. D. Little | 1967 | API | The Development of Ultrasonic Atomizers for Domestic Oil Burners |
| Peskin & Raco<br>Rutgers Univ. | 1966 | API | Analytical Studies on Mechanisms of Fuel Oil Atomization |
| McCullough<br>A. D. Little | 1966 | Patent | Nozzle System and Fuel Oil Burner Incorporating It |
| Ensminger<br>Battelle | 1968 | Patent | Resonant Vibratory Apparatus |
| Angelo<br>U.S. Army | 1969 | Pow. Sources | Static, Silent, Thermoelectric Power Sources |
| Brookhaven | 1977 | BNL | Findings Report, Burner-Boiler/Furnace Test Project, on Sono-Tek Ultrasonic Atomizing Oil Burner |
| Berger<br>Sono-Tek Corp. | 1977 | APCA | Emission and Operation Characteristics of a Modulating Ultrasonic Distillate Oil Burner |
| Berger & Brandow<br>Sono-Tek Corp. | 1979 | Patent | Transducer Assembly, Ultrasonic Atomizer and Fuel Burner |

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

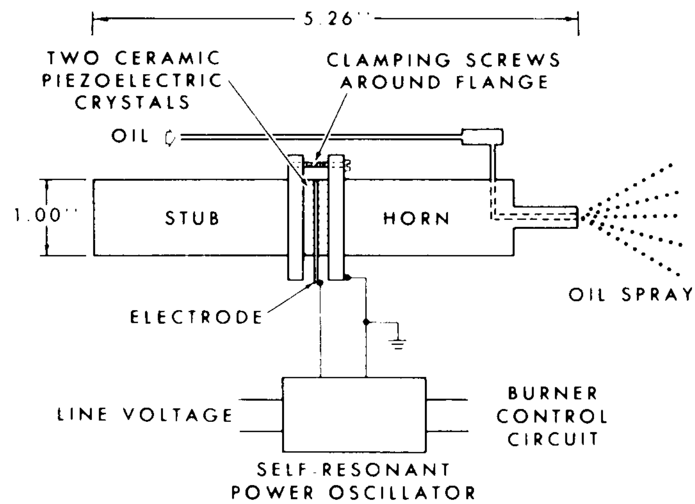



FIGURE VI-11. SCHEMATIC REPRESENTATION OF THE API ULTRASONIC ATOMIZER – 56-k Hz frequency (Perron et al, 1966)

provided hardware through which the ultrasonic atomizer could be evaluated for a number of applications. Although none of these applications were commercialized, some of the experiments provided useful information on matching of burner air supply with such atomizers.

The spray-droplet velocity from an ultrasonic atomizer is low compared with that of a conventional high-pressure spray, so the droplet penetration into the airstream is less. Thus, for good combustion, air must be introduced in such a way as to provide proper droplet transport and fuel-air mixing.

Applications of the API Ultrasonic Atomizers to Oil Burners. Swirl- or vortex-type burners have been employed successfully to burn sprays from ultrasonic atomizers. Figure VI-12 shows an axially fired, swirl-type burner developed at A. D. Little to match the 56-kHz API ultrasoniz atomizer at 0.4 gph firing rate. Combustion performance was excellent in long-term tests with these prototypes. (McCullough et al, 1966) An ultrasonic atomizer has also been successfully demonstrated with an axially fired burner that gave a conventional "sunflower" flame pattern. (Lang, 1963)

Another approach is to fire the ultrasonic atomizer with the fuel spray perpendicular to the axis of a vortex burner, as shown in Figure VI-13 for one of the atomizers investigated by Pure Oil Co. (Dysart, 1966; MacCracken and McLendon, 1964); this arrangement is similar to that of the burner developed at Battelle for the miniature military atomizer. (Hazard and Hunter, 1966)

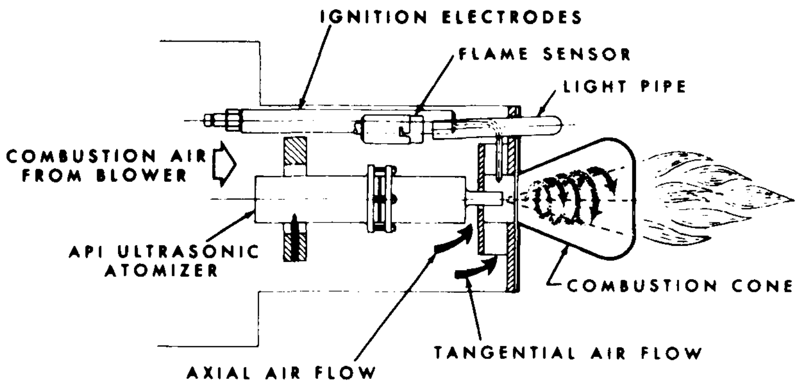



FIGURE VI-12. SWIRL-TYPE BURNER DEVELOPED TO DEMONSTRATE THE API ULTRASONIC ATOMIZER (Perron et al, 1966)

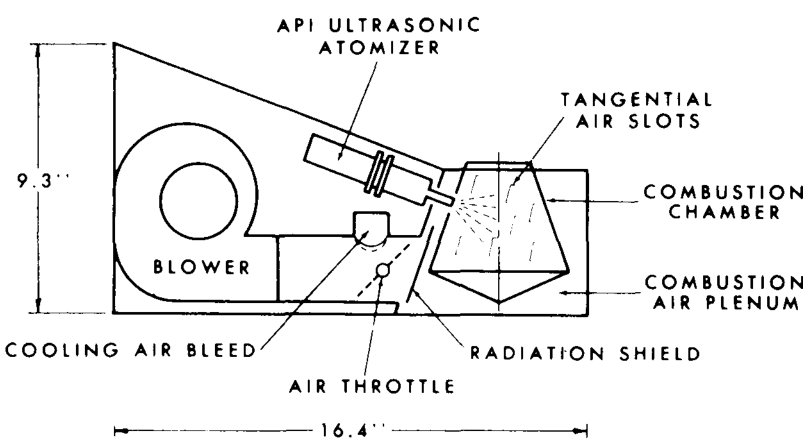



FIGURE VI-13. SCHEMATIC OF DOUBLE-VORTEX TYPE COMBUSTION CHAMBER FIRED BY API ULTRASONIC ATOMIZER (Dysart, 1966)

U. S. Army Electronics Command / Battelle

For many years the U. S. Army Electronics Laboratory had a requirement for small multifuel burners, compatible with a range of fuels from gasoline through No. 2 diesel fuel, for use in thermoelectric generators. For this application, quick starting, silent operation, low weight, and extremely low power consumption are required. To meet this requirement, Battelle suggested a burner utilizing a miniature piezoelectric ultrasonic atomizer with solid-state electronics and, in January, 1964, began development of a demonstration model to fit a 100-watt RCA thermoelectric generator. (Hazard and Hunter, 1965 & 1966; Hazard, 1966) The resulting burner was successful and was used in an RCA 100-watt thermoelectric generator. (Herchakowski, 1966)

In developing the Army atomizer, shown in Figure VI-14, Battelle drew freely from API-developed technology. The resulting design, quite different from the API-developed design, was miniaturized and optimized for the Army application. This atomizer, operated at kHz, was 2.2 inches long, weighed 50 grams, and required power input of 4 watts to the solid-state power oscillator. The details of the atomizer are described in a patent by Ensmiger (1968) who developed the atomizer horn.

The success of this design led the Electronics Command to require modification of thermoelectric generators under development by Minnesota Mining and Manufacturing Co. (3M), in 1965, to replace vaporizing gasoline burners with ultrasonic-atomizing burners. A recent military application uses a power supply with a printed circuit board and fixed electronic components; higher firing rates have been achieved with the higher power levels of this system. (Angelo, 1969)

An ultrasonic atomizer based on the Battelle design, for the 3M generators was developed and manufactured by the Sono-Tek Corporation for the Electronics Command. (Berger & Levine, 1979)

Sono-Tek / Wayne

Sono-Tek has carried out extensive development of ultrasonic atomizer technology for residential oil burners to increase fuel capacity and improve life and reliability over that of the Battelle design, using their own funds and a model construction contract with BNL. Figure VI-15 is a view of an early Sono-Tek atomizer, taken from a patent drawing. (Berger & Brandow, 1979) They have carried out considerable development toward a residential oil burner application. This development was reported in an APCA paper. (Berger, 1977)

For the residential application, they have modified the spray characteristics and the mounting arrangement of the atomizer, have modified the electrical circuit to permit grounding of the atomizer in mounting, and have

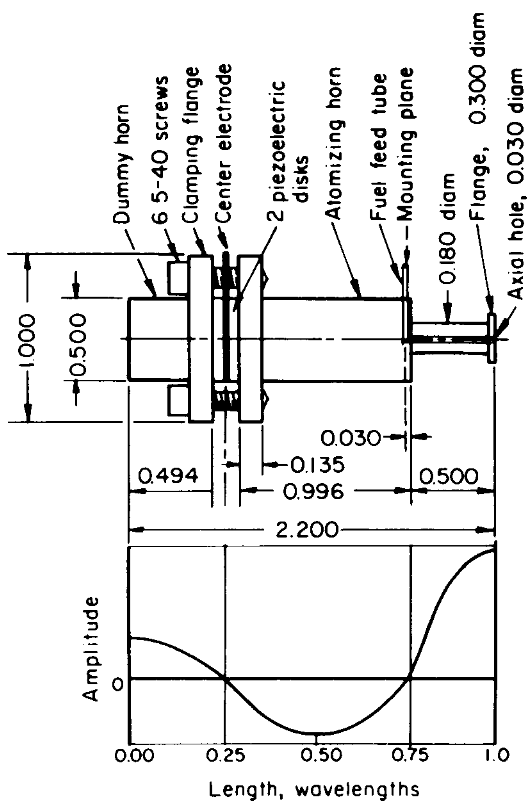



FIGURE VI-14. DESIGN DETAILS AND AMPLITUDE OF AXIAL VIBRATION FOR ARMY/BATTELLE ULTRASONIC ATOMIZER
(Hazard and Hunter, 1966)
— Dimensions are in inches.

developed a burner head suitable for use in a gun burner. In this design, the ultrasonic atomizer mounts at the end of an oil pipe much like a standard pressure atomizing fuel nozzle and its holder, and the assembled burner appears much like a standard gun burner. (This is shown in Figure VI-16)

An earlier burner version with a Sono-Tek atomizer has been evaluated at BNL, with good combustion demonstrated at firing rates of 0.3 and 0.5 gph and $CO_2$ levels between 12 and 13.5 percent $CO_2$. (Brookhaven, 1979)

Sono-Tek believes that the atomizer is developed sufficiently for commercialization, and has negotiated a licensing agreement with the Wayne Home Equipment Division of the Scott & Fetzer Company. (Berger & Levine, 1979) Field tests of 20 Wayne burners are planned for 1980, with commercial introduction to follow if justified by field test experience. Sono-Tek is also discussing licensing agreements with European burner manufacturers. At this time, it appears closer to commercialization than any other ultrasonic-atomizing burner has in the past.

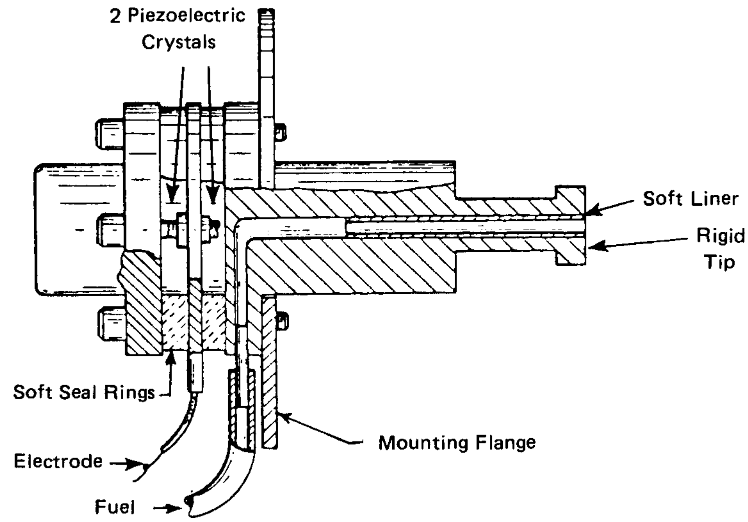



FIGURE VI-15. SONO-TEK ULTRASONIC ATOMIZER (Berger & Brandow, 1979)

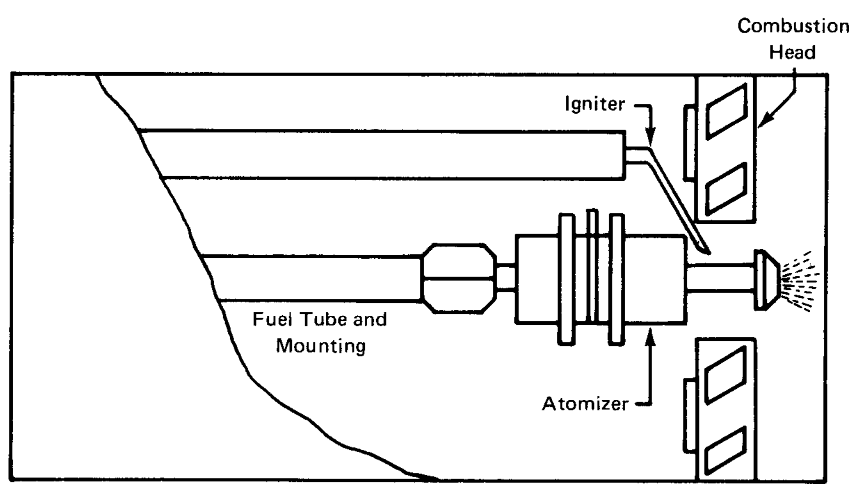



FIGURE VI-16. SONO-TEK ULTRASONIC ATOMIZER APPLIED TO A BURNER
(Courtesy: Sono-Tek Corp.)

Global Thermoelectric Power Systems Ltd., Canada

Global thermoelectric Power Systems Ltd., Canada, was formed in 1975 by 3M employees when 3M dropped the thermoelectric generator business. They produce, in small quantities, thermoelectric power units used in microwave communications and other applications where long-life, reliable power sources are needed. They make their own ultrasonic burners, based on the Battelle atomizer design, with some modifications. (Nystrom, 1979) Their burner utilizes a small positive-displacement pump manufactured by Micropump for fuel metering, as did the API atomizer/burner combination. Normal fuels are kerosene or No. 2 fuel oil.

Global has submitted a small modulating ultrasonic burner for use in home heating to the Canadian Department of Energy, Mines, and Resources. It is being evaluated in an existing warm-air furnace. It follows load by modulation, without on-off cycling. (No information on design details of the burner were available for this report.)

Other Developments

An ultrasonic atomizer was developed by Simms Ltd. in the United Kingdom for use in diesel-engine air-intake fuel addition. (Bradbury, 1966) Figure VI-17 shows the atomizer and its method of clamping the piezoelectric crystal.

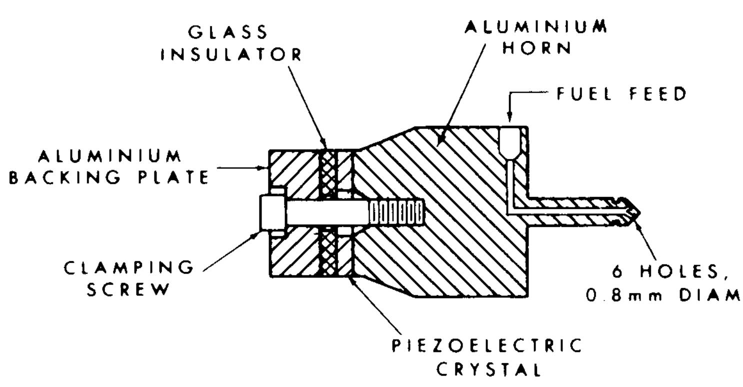



FIGURE VI-17. BRITISH ULTRASONIC ATOMIZER – 40-kHz Frequency (Bradbury, 1966)

The Tymponic Corporation constructed and tested a 20 kHz piezo-electric ultrasonic atomizer aimed at use in a residential oil burner. This device appears to be in an early stage of development and no development is now in progress. The inventor indicates that the atomizer performed its function, but there are no present plans to continue the development. (Cottell, 1979)

## APPRAISAL OF ULTRASONIC ATOMIZATION

Ultrasonic atomization is a promising candidate for low-capacity oil burners due to large fuel passages and good atomization at low rates. Recent advances in flow stabilization and mounting of the atomizer are significant in making the atomizer more compatible with conventional gun burners.

A key to the applicability of ultrasonic atomization is a practical and low-cost fuel metering and transfer pump with primary capabilities. It appears that a metering pump recently introduced by Sundstrand Hydraulics may fill this void; this pump allows adjustment of the metered rate by variation of the internal pressure in the pump. It uses mainly commercially proven components that are used in standard oil-burner fuel units and are familiar to service technicians.

Continued development of ultrasonic atomization is warranted for application to residential oil burners. One important need is for long-term operating information to determine the performance over time and the durability of components in actual application.

## ELECTROSTATIC ATOMIZATION

The principle of electrostatic atomization was investigated during the API Oil Burner Research Program, stimulated by early results demonstrated by California Research Corporation. (Graf, 1962; Luther et al, 1962) In electrostatic atomization, an electrostatic charge is imposed on the fuel as it flows from an emitter; the liquid surface is stretched by its attraction in an electrostatic field to a target electrode of opposed charge.

Table VI-3 identifies pertinent references in the area of electrostatic atomization. In the API study by A. D. Little, in which new means of atomization were sought, electrostatic atomization was selected for experimental trials of the concept. (Doyle et al, 1967) Supporting analytical studies were carried out at Rutgers University to search for new ways to overcome limitations in the experimental program. (Peskin & Raco, 1967)

TABLE VI-3. API PUBLICATIONS ON ELECTROSTATIC ATOMIZATION

| AUTHOR(S) | DATE | TITLE |
|---|---|---|
| Doyle, Mokler & Perron<br>A. D. Little | 1962 | New Means of Fuel Atomization |
| Graf<br>California Res. | 1962 | Breakup of Small Liquid Volumes by Electrical Charging |
| Peskin & Raco<br>Rutgers Univ. | 1963 | Some Results from the Study of Ultrasonic and Electrostatic Atomization |
| Luther, Cheney & Paterson<br>California Res. | 1964 | Devices for Improving Domestic Burner Performance |
| Newgard & Noon<br>Stanford Res. | 1964 | Development of an Electrostatic Atomizer and Burner |
| Raco<br>Rutgers Univ. | 1964 | Some Aspects of Electrostatic Atomization |
| Doyle, Perron & Shanley<br>A. D. Little | 1966 | A Study of New Means for Atomization of Distillate Fuel Oil — Summary Report |
| Raco & Peskin<br>Rutgers Univ. | 1966 | A Progress Report on API Analytical Studies of Electrostatic Atomization |
| Peskin & Raco<br>Rutgers Univ. | 1967 | Analytical Studies on Mechanisms of Fuel Oil Atomization — Summary Report |

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

In addition, an API project was conducted at Stanford Research Institute to develop means for application to a burner configuration. (Newgard & Noon, 1964a&b) The flow capacity and atomization quality of the electrostatic atomizer were found to be inadequate for residential oil burners of reasonable physical size; also, the need for separation of the atomizer emitter and the combustion zone produced practical problems of design. The work was terminated for these reasons, and the concept does not appear to warrant further R&D for residential oil burners.

## PREVAPORIZING BURNERS

Another approach to burner design is to prevaporize the fuel prior to its introduction into the flame zone. "Thermal vaporizing burners" rely on external heat input or heat from the flame; the oil is completely vaporized and mixed with air before it reaches the flame. The term "thermal aerosol generators" is used herein to clarify systems where oil is heated for partial vaporization and then mixed with air, for burning as an aerosol.

### THERMAL-VAPORIZING CONCEPTS

One of the oldest and simplest ways to prepare distillate fuel oils for combustion is to vaporize the fuel directly from the bulk liquid. Vaporizing or "pot-type" burners have been used with kerosene and No. 1 heating oil for many years, and mechanical-draft versions have gained popularity in the United Kingdom and in Europe. However, with No. 2 oil, vaporization deposits are formed -- sometimes as much as 750 grams of deposits per thousand gallons of oil (Rakowsky, 1962). Nevertheless, a vaporizing burner for No. 2 oil has been of interest because of its potential advantages of simplicity and quiet, low-capacity operation. It was one of the areas of focus in the API oil-burner research program. (Locklin, 1961)

#### Fundamental Information Developed in API Program

A combination of API-sponsored and in-house oil-company research established conditions for reducing deposits to an acceptable level. (Morgenthaler, 1962; Hein & Weller, 1963; Tuttle, 1961; Rakowsky and Meguerian, 1963; Hein et al, 1966) The requirements are rapid vaporization from a hot surface and periodic removal of trace deposits from the hot surface by air oxidation.

Figure VI-18 summarizes results of the API study at Battelle on deposit formation from No. 2 oil as a function of heat flux to the oil vaporizing surface and of oil-film thickness, both of which determine oil residence time (Hein and Weller, 1963). To minimize deposits, residence time must be limited, continuous fractionation must be prevented, and oxidative fuel degradation must be limited. These conditions were incorporated in several demonstration prototype burners developed as part of the API program. (Hein et al, 1966)

#### API Prototype Vaporizing Burner

Figure VI-19 shows one of these prototype vaporizing burners which is unlike conventional pot-type burners, in that the vaporizing chamber is separate from the combustion chamber and operates at a high temperature (above 800 F). Oil is introduced into the hot cast-steel vaporizing chamber where it

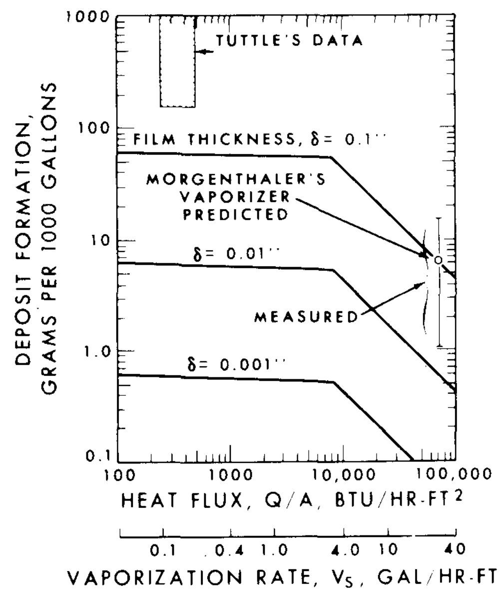



FIGURE VI-18. CONDITIONS AFFECTING DEPOSITS DURING VAPORIZATION OF NO. 2 HEATING OIL

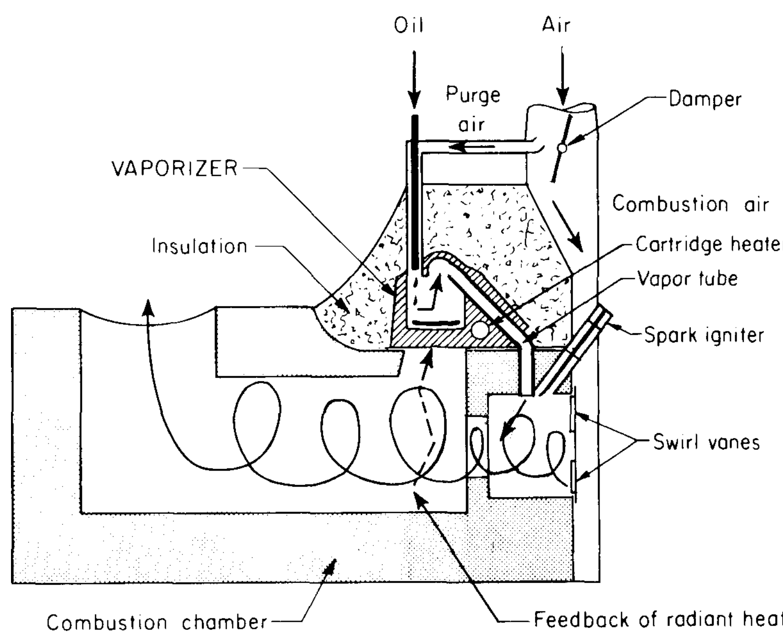



FIGURE VI-19. CUTAWAY VIEW SHOWING API DEMONSTRATION PROTOTYPE VAPORIZING BURNER vaporizes quickly. The vapor is conducted to a combustion chamber, where it is mixed with air in a swirl-type burner. Heat is radiated from the refractory to the vaporizer through a small opening in the combustion chamber. The heavy vaporizer casting is extensively insulated, except for the radiation-receiving surface, and retains heat between firing cycles. However, when needed, the vaporizer is heated with an electric cartridge element, thermostatically controlled to maintain it in a ready condition during off periods. Purge air, about 1 percent of the combustion air, is introduced through the vaporizer to prevent condensation of vapor in the oil inlet and to limit oil temperature. During off periods, the flow of purge air is maintained to oxidize deposits.

API prototype burners of this design have performed satisfactorily on typical No. 2 oil for periods equivalent to a heating season, firing 0.5 gph on an intermittent basis. One of these units logged over more than 1000 hours firing time installed in a storage-type water heater. (Hein et al, 1966)

In order to satisfactorily handle No. 2 oil, the requirements for maintaining temperature and providing purge air served to complicate the control and auxiliary equipment; this would result in manufacturing cost too high to compete with conventional high-pressure burners. At that time, no U.S. manufacturers were interested in pursuing the concept. However, some additional investigation was conducted in Europe.

## THERMAL AEROSOL GENERATORS AND BURNERS

Two developments use preheating of the oil, plus flash vaporization into an air stream:

1 The Honeywell thermal aerosol burner

2 The Schladitz fuel injector

Descriptions of these concepts follow.

### The Honeywell Thermal Aerosol Burner

In a recent project for EPA, Honeywell investigated the potential of a thermal aerosol generator as the fuel preparation means for a low-capacity residential oil-burner. (Janssen et al, 1977) The generator was based on a concept (Tenney, 1977) in which oil under pressure was heated up to 400 F and flashed into a vapor as the pressure was lowered as the oil left a conventional high-pressure nozzle.* Upon cooling downstream of the nozzle,

* This is similar to the nozzle-preheater concept described earlier in high-pressure atomization, but the fuel is heated to a higher temperature.

but upstream of the flame, the vapor condensed into very fine droplets (less than 1 micrometer) which produced an aerosol that was a dense white smoke. This aerosol was then mixed with additional air and burned in a combustion chamber. The objective of the project was to explore whether the concept could result in satisfactory combustion and low emission levels at firing rates below those of conventional high-pressure burners.

With No. 1 oil, and 40 psi oil pressure, a firing rate reduction of 40 percent of the conventional nozzle rating was achieved with nozzle temperatures of 400 F. When combined with a high degree of air swirl in a burner, a clean, nonluminous flame was achieved. Smoke, CO, and HC were not detectable when operating at 13.5 percent $CO_2$ in the flue gas. $NO_x$ emissions were generally lower than conventional burners, and emissions during start-up were reduced.

The development was not pursued to commercialization, partly because the $NO_x$ reduction was only slight and additional control complication could be required. Also, there were concerns that thermal degradation of the fuel would result in varnish or other deposits in the nozzle that would ultimately interfere with operation.

## The Schladitz Fuel Injector

An unusual approach to thermal vaporization of distillate fuel has been developed by Prof. H. J. Schladitz, formerly of Munich, Germany, and now at the University of Virginia. The concept is based on heating the oil electrically, using a matrix of fine conducting fibers to provide a large heat-transfer area. BNL is sponsoring a development program at the University of Virginia to adapt this vaporizer/aerosol-generator concept to low-input, variable-firing-rate oil burners.

Figure IV-20 shows the concept of a "fuel injector". (Schladitz, 1973 & 1977) A porous network of steel "Schladitz Whiskers"*, similar to steel wool, but finer and shorter fibers, is contained in a fuel passage that is milled in an iron bar. An electric heating element outside the bar heats the network and the fuel to a temperature well below the boiling point to reduce its viscosity and atomize the fuel by forcing it through the extremely small pores of the whisker network. An aerosol of vapor and droplets is produced, with fuel droplets said to be mostly less than 10 micrometers in diamater.

The small droplet size is believed to be caused by the flashing of a small fraction of the fuel which vaporizes at the outlet of the whisker network and is aided by the lower viscosity and surface tension produced by heating. The choice of oil temperature is a design compromise between the

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*Prof. Schladitz also developed the technique for producing the polycrystalline whiskers.

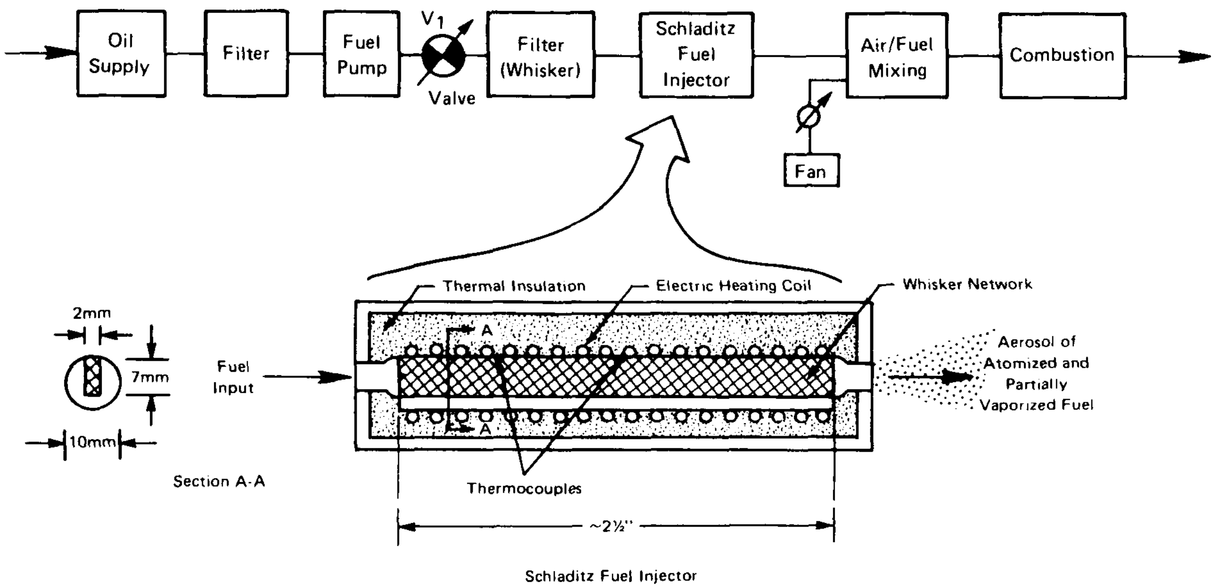


FIGURE VI-20. THE SCHLADITZ FUEL INJECTOR AND BURNER CONCEPT (Courtesy, Univ. of Virginia)

high temperatures needed for complete vaporization of the fuel and lower temperatures necessary to avoid possible degradation of the fuel injector resulting from varnish formation and fuel cracking. Since vaporization of only a small fraction of the fuel (1-2 percent) is theoretically sufficient to produce flashing, only a small amount of energy is consumed by the heating element.

The large surface areas characteristic of the whisker network enhances the flash vaporization process by providing a very large number of vapor nucleation sites. This large surface area also allows the fuel injector to be very compact.

The design has the following attributes:

- Small fuel droplet size resulting from flash vaporization.
- Electrical power required may be as low as 70 watts/kg/hr.
- Will operate effectively at flow rates up to 5 liters/hr (has been tested from 0.04 to 5 liters/hr).
- Atomization is sufficient to insure good mixing with air and prevent condensing on cooler surfaces.
- Because of small mass and electrical heating, heatup delay is expected to be less than 30 seconds.

Atomization Mechanism of the Schladitz Fuel Injector. The following description was supplied by the University of Virginia. (McAlpine, 1979)

In normal pressure atomizing nozzles, the small droplets are created by the pressure drop, $\Delta P$, across the nozzle. A number of analyses and tests on these nozzles have been made showing that the surface mean diameter (SMD) is proportional to

$$\text{SMD} \propto \frac{\dot{m}^a \sigma^b \mu^c}{\Delta P^d}$$

where $\dot{m}$ is the fuel flow rate, $\sigma$ is the fuel surface tension, and $\mu$ is the fuel viscosity. Various investigators report values of the exponents between 0.1 and 0.5.

A common method of decreasing SMD is to increase $\Delta P$; however, due to the exponent d, there is a practical limit, i.e. repeated doubling of $\Delta P$ does not repeatedly halve SMD.

Another technique is to heat the fuel in order to decrease $\sigma$ and $\mu$. With moderate heating, $\sigma$ and $\mu$ may be decreased by 50 percent, but, since b and c are typically 0.25, the resulting decrease in SMD is only $1/\sqrt{2}$.

In the Schladitz fuel injector, neither of these techniques is used as the primary atomizing scheme. The energy input to the injector is instead used to generate a small amount of vapor* from the more volatile fuel components. This vapor forms rapidly when the hot fuel is injected into the ambient pressure and the rapid vapor bubble growth shatters the remaining liquid into small droplets.

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* The amount of vapor depends on several design parameters of the oil burner in which the Schladitz fuel injector is being used.

Studies of this "flash vaporization" process have demonstrated its effectiveness in creating small droplet sizes without the need for high pressures; in fact, ordinary aerosol spray cans employ this method. (Brown & York, 1962; Leinhard & Day, 1970; Sher & Elata, 1977) The work of Brown & York has shown that "flashing" is more efficient when rough surfaces are present. The high surface area unique to the injector thus enhances the spray process by providing a large amount of bubble nucleation area.

For No. 2 fuel oil with a specific heat of 0.43 Btu/lb-F and a latent heat of 105 Btu/lb, the vaporization of 1 to 2 percent requires only 1 to 2 Btu/lb. This may be achieved by heating to 200-250 F, a process requiring about 60-80 Btu/lb of fuel.

This energy requirement is met by the electric heater. With good insulation, 70 to 80 percent of the electrical energy of the heater goes into the fuel. The total heater energy requirements are thus on the order of 100 Btu per lb of fuel (70 Watt-hr/kg). At a low firing rate of 0.5 gph of fuel oil, this represents about 100 watts of required heater power.

The actual energy consumed depends on heater efficiency, how hot the liquid must become before the necessary fraction becomes superheated, and how large this necessary fraction is. All these items are closely related to the design of the unit. The amount of energy required by designs previously tested has been steadily decreasing as the investigators learn more about the phenomena involved.

Development of Prototype Burners. Under the Brookhaven contract, the Schladitz fuel injector is being applied to two variable flow rate oil burners: (1) a retrofit system to be applied to a conventional high-pressure gun burner in the field, and (2) a new burner assembly as a replacement of a complete oil burner. The target was to be variable flow rate between 0.1 and 0.6 gph, which has been achieved with the new design; the present approach is for two fixed firing rates according to a manual selection. The new system uses a Japanese solenoid-type fuel pump with 80-100 psi delivery pressure, requiring 30 watts input, and a specially designed pressure-atomizing nozzle. The retrofit burner uses a positive displacement gear pump and conventional 2.5 gph nozzle. The burner operates with a blue flame because of the prevaporization and very fine oil mist.

The residence time of the oil at high temperatures in the injector, about 1 second at 600 F, is said to be too low for cracking of the oil. However, it is recognized that the active heat transfer and flow area of the whisker network eventually can become reduced by fuel deposits. The whisker material is low in cost, and the cost of replacing an entire injector is said to be less than $1.00.

The heater element in the present fuel injector is 500 watts maximum input. (No attempt has yet been made to preheat the oil using combustion-derived heat.) The warmup time from cold is about 30-60 seconds, requiring a controlled delay.

The developers have constructed larger burners, one at 8 gph under a contract with the Dahlgren Laboratory of the U.S. Naval Surface Weapons Center, and they presently have a DOE contract in partnership with Dunham-Bush for the development of a commercial burner.

## APPRAISAL OF CONCEPTS

Although there are advantages of excellent fuel preparation and clean burning at very low rates, limitations of the example systems appear to be: (1) the input heat to the nozzle injector, (2) the warmup time and necessary controls to achieve the delay, yet provide a temperature limit, (3) transients in cyclic operation, and (4) the problem of deposits in the system network and a gradual deterioration in performance that necessitates replacement of components, especially the fuel injector in the case of the Schladitz approach. These problems appear solvable technically, but it is not yet clear whether the solutions will result in a commercially acceptable approach for the residential market.

## COMBINATION ATOMIZING-VAPORIZING BURNERS

Another concept for domestic burners is the combination atomizing-vaporizing burner. In this concept, fuel is atomized or distributed in relatively large droplets which then are vaporized either while in flight in hot gases or after impinging upon a hot surface.

### ROTARY BURNERS

#### Wall-Flame Type

One example of this principle is in the vertical rotary wall-flame burner shown in Figure VI-21, formerly popular in the U.S. and recently introduced in Europe. A rotating distributor on a vertical shaft throws oil against a wall rim where the oil is vaporized. After mixing with air, the vapor burns with a bluish flame. These burners normally operated at $CO_2$ levels of 12 to 14 percent, even at firing rates down to 0.5 gph, so they could be applied to achieve efficient heating systems. Sales of wall-flame burners declined in the U.S. over the last two decades, because of higher manufacturing costs than pressure burners and a requirement for specialized know-how by service technicians.

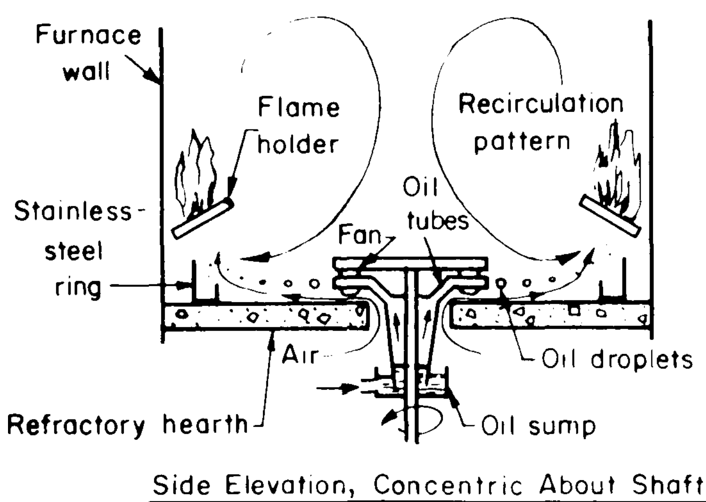


FIGURE VI-21. VERTICAL ROTARY WALL-FLAME BURNER

The quiet, efficient operation at low rates made the wall-flame burner a favorite to fire domestic boilers for central heating in the United Kingdom. (Howe, 1964) Two significant improvements were introduced in European wall-flame burners (Bullock, 1964) to reduce aldehyde odors on startup and shutdown: (a) the flame rim was electrically preheated on startup for rapid vaporization, and (b) an electric "brake" was used to stop rotation of the distributor to ensure quick oil cutoff on shutdown. These improvements in European wall-flame burners occurred after wall-flame burner development declined in the U.S., and were not incorporated in U.S. versions.

Wick Type

Figure VI-22 shows an example of an experimental low-capacity atomizing-vaporizing burner developed by E.S. Downs. (Will et al, 1964; Carl et al, 1966) Fuel burns with a bright luminous flame in a much smaller volume than in the wall-flame burner. The distributor throws oil droplets against a ceramic-fiber wick to promote vaporization. Primary air is introduced around the distributor shaft and secondary air through the ceramic-fiber wick. Some recirculation of combustion gas occurs, but less than in wall-flame burners. This burner was not commercialized, mainly because of cost considerations and the lack of market for low-capacity oil burners.

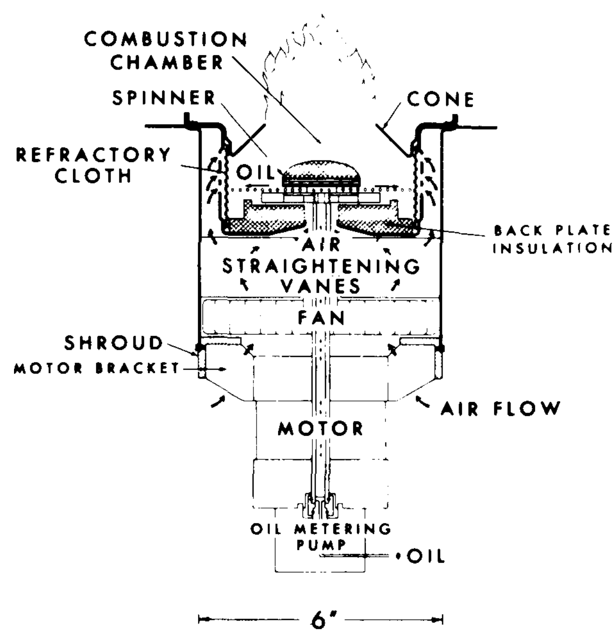


FIGURE VI-22. CROSS-SECTION OF VERTICAL ROTARY-VAPORIZING BURNER (Carl et al, 1966)

## HIGH-PRESSURE ATOMIZING TYPE

One atomizing-vaporizing burner prototype developed in the 1960's used a conventional pressure-atomizing nozzle but operate at reduced pressure to take advantage of larger nozzle orifices for low firing rates. An experimental burner operated at 0.5 gph using 35-psi atomizing pressure with a conventional 0.8 gph high-pressure nozzle (Mueller and Schrader, 1966). On start-up, oil droplets impinged on a steel target until vaporizing temperatures are achieved. Combustion air introduced to the primary chamber was staged much the same as in conventional pot-type burners. The flame was predominantly yellow, and the operation was extremely quiet. This too did not reach the market.

## LOW-PRESSURE ATOMIZING TYPE

### Foster-Miller Burner Development

A variable firing rate oil burner developed at Foster-Miller under contract with BNL is of the combination atomizing/vaporizing type, but it also has the feature of internal recirculation of combustion products, so it has attributes of blue-flame burners discussed later in this section. The fundamental burner principle is to premix and prevaporize fuel in hot air and then burn this homogeneous mixture from a multi-port flameholder. (Demler, 1980)

Figure VI-23 shows a schematic representation of the concept. Air is drawn in from the motor end and passes into the fuel spray through four radial cross ports. Air flow is controlled by a central air valve that progressively blocks the cross ports when moved by the air valve actuator linkage. The blower suction also draws combustion gases back to the fuel spray to heat the air mixture to 500 F for fuel vaporization. The central air valve is also scheduled to regulate the combustion gas recirculation flow in proportion to the fresh air flow. The burner runs at a constant mixture temperature at all firing rates. An air-atomizing nozzle sprays fuel into the heated air stream. Fuel flow is matched to the air flow with a fuel metering valve linked to the air-valve linkage. The heated fuel/air mixture is drawn through the blower and delivered to the flame holder. Blower turbulence and the vapor residence time between the fuel nozzle and flameholder assure vaporization and a uniform mixture for combustion. A 500-watt heater is used for 20 seconds at startup for clean ignition.

The key attributes of this concept are high efficiency with clean burning at about 13 percent $CO_2$, and stored heat is low, so off-period losses will be low. Relative to fixed-firing rate high-pressure burners, the only additional components are the atomizing-air compressor, the electric preheater, delay control logic, and the solenoid linkage of fuel metering and air valve.

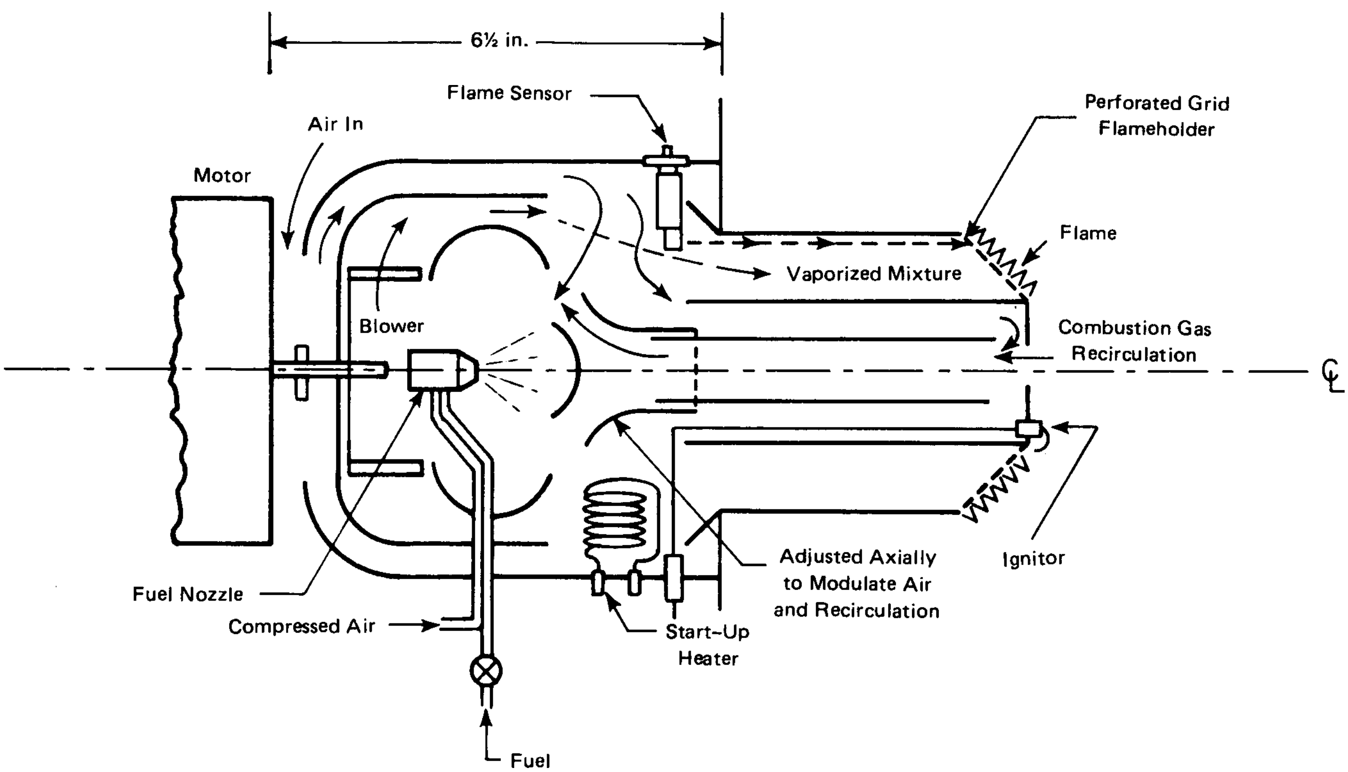


FIGURE VI-23. VARIABLE FIRING RATE OIL BURNER DEVELOPED AS PART OF BNL PROGRAM
(Courtesy: Foster-Miller Associates)

CATALYTIC BURNERS

The possibilities of catalytic combustion were examined early in the API Burner Research Program. (Weller, 1960; Locklin, March 1960) At that time, the incentives and chances of successful development were not judged sufficient for the concept to be included in the experimental R&D finally selected for the API Oil Burner Research Program. (Locklin, 1961)

However, recent concern regarding pollutant emissions, particularly $NO_x$, has resulted in considerable work on catalytic combustors, mainly for gas-turbine applications. EPA has recently sponsored its fourth Workshop on Catalytic Combustion. (EPA, 1980)

A catalyst permits stable and "complete" combustion at lower-than-normal combustion temperatures, typically near 2000 F, where very little thermal $NO_x$ is formed. Most of the combustors now being studied are only "partially" catalytic. The catalyst serves to initiate the combustion reaction and release sufficient heat to bring the temperature up to a point, roughly 1800 F, where homogeneous reactions complete the combustion of the fuel. Such burners require less catalyst and operate at higher throughputs and lower pressure drops than "fully" catalytic combustors. (Heck & Roberts, 1975)

When applied to liquid fuels, these catalytic burners typically incorporate the atomizing/vaporizing mode of fuel preparation. Liquid fuel is sprayed into a stream of preheated air, vaporized, and passed through the catalyst bed. Other vaporization methods would also appear to be applicable, but the need to preheat the combustion air at least to the dew point of the final mixture (to prevent condensation of the fuel on mixing with the air) cannot be avoided easily. The catalyst beds do appear to have some tolerance for limited quantities of unvaporized fuel.

The low combustion temperature is typically obtained by high excess air. The required excess air does not detract from overall efficiency for gas-turbine applications. For residential heating applications, the high excess air would reduce the thermal efficiency compared to that obtainable at normal excess air levels. (As noted elsewhere in this report, as the effectiveness of the heat exchanger is increased, the efficiency penalty for high excess air is reduced. Hence, possible advantages of high excess-air levels could be traded off against more costly heat exchangers.) Recirculated, cooled, flue gases could replace the excess air needed for combustion temperature control, but this does not appear to have been demonstrated. Other approaches to controlling combustion include (comparatively) large radiating catalyst surfaces, and staged combustion with intermediate heat extraction. (Krill and Kesselring, 1978)

Catalytic combustors have not shown any advantage in controlling the component of $NO_x$ from fuel-bound nitrogen; the conversion of fuel nitrogen to $NO_x$ can approach 100 percent for fuel-lean catalytic combustors. Staged combustion, just as in noncatalytic combustion, provides relatively good control of $NO_x$ from fuel-bound nitrogen.

## Design Problems for Catalytic Burners

As currently developed, catalytic combustors operating with vaporized liquid fuels have the following features and problems:

1. Preheat is required, both to vaporize the fuel and bring the mixture/catalyst to the catalyst "ignition" temperature. Preheat temperatures of 500 to 1000 F are typically required.
2. Flash-back or preignition can occur in the vaporization zone.
3. The combustion temperature is confined to a narrow range, bounded on the low side by the temperature required to achieve the homogeneous reaction and on the high side by the maximum temperature that can be tolerated by the catalyst system.
4. Uniform mixing of fuel and air is required. Very lean zones result in cold spots and incomplete reactions, and near-stoichiometric zones cause hot spots that can deactivate or destroy the catalyst.
5. Demonstrated catalyst life is not yet adequate for residential heating applications.

## APPRAISAL OF COMBINATION ATOMIZING/VAPORIZING BURNER APPROACHES

A limitation of this general approach to burner design, where oil impingement and vaporization from surfaces is involved, has been sensitivity to fuel properties and resulting deposits, although there is much less fuel sensitivity than in vaporizing pot-type burners where fuel deposits are a major problem. Fuel-quality variation can be expected to become more severe and prevalent as supply and demand relationships of fuel oil shift to tighter supply. The need for a starting delay during the warmup period complicates the control system and reduces the response to load demands, as in a boiler equipped with an instantaneous domestic hot water coil. In general, problems from transients can be expected to be greater than in conventional burners.

For catalytic burners, the apparent necessity of preheating to achieve fuel vaporization and catalyst ignition makes application to residential heating equipment difficult. Catalytic burner concepts appear better adapted to steady or continuous loads than on-off cycling or wide load swings as encountered in residential heating.

It appears that concepts discussed under atomizing/vaporizing burner approaches are at a disadvantage when considering criteria of manufacturing cost, fuel sensitivity, and overall long-term durability.

## BLUE-FLAME BURNERS

Oil burners that operate with a blue flame have been a goal of burner designers for many years. An important feature sought in blue-flame combustion is that soot is not present in the flue gas to foul heat-transfer surfaces.

### Principles and Advantages of Blue-Flame Burning

Three basic approaches can be used to achieve a blue flame:

1. One approach is to mix combustion air with recirculated combustion products before mixing with the fuel. A varient is to introduce the recirculated products into the fuel or a fuel/air mixture.
2. A second approach is to prevaporize by carrying out fuel vaporization and mixing with combustion air in a space separate from the combustion space.
3. A third approach, a variation of the second, is to start with extra-fine fuel atomization to promote prevaporization within the flame.

These approaches have been used in a number of burners that are discussed in this section.

The advantage of blue-flame burning are summarized below.

- The excess air needed for smokeless operation approaches zero, with normal operation at 5 to 10 percent excess air to accommodate variations in air and/or fuel delivery. The low excess air enhances boiler or furnace efficiency by minimizing stack loss.
- The fouling of heat-exchanger surface by soot is eliminated, so that heat-exchange efficiency of boilers and furnaces does not deteriorate over a period of time if combustion conditions are maintained. (This is not true of all yellow-flame burners.)
- The soot-free combustion products are suitable for use in compact heat-exchangers of high efficiency, which would suffer excessive deterioration in efficiency if fouled with soot.

In blue-flame burners designed to use flue gas recirculation, two other advantages can be gained, if combustion intensity is kept low:

- Quiet combustion
- Low emission of $NO_x$.

Interest in limiting $NO_x$ emissions is a fairly recent outgrowth of environmental concerns relating to fuel combustion. This consideration has given impetus for considerable R&D on combustion-products recirculation in larger-scale combustion systems for control of $NO_x$ emissions.

## HISTORICAL DEVELOPMENT OF BLUE-FLAME TECHNOLOGY

Table VI-4 lists significant references pertinent to blue-flame combustion.

Experiments during the 1890s revealed that the addition of small amounts of $CO_2$, water vapor, or nitrogen to illuminating gas would decrease the luminosity and smoking tendency of those gas flames. (Lewes, 1892) Because the principal fuel use was for illumination, no practical application of this finding was made at the time for oil burning.

Early in the development of steam-atomizing oil burners, it was recognized that the atomizing steam contributed to smokeless combustion. (Romp, 1937) Also, it was found that steam introduced into the firebox of a coal furnace would reduce soot and smoke. In the development of oil burning, it was discovered that flue gases (containing nitrogen, $CO_2$, and water vapor) had the same effect on combustion as steam.

Over the years, many oil-burner concepts have been developed that resulted in blue-flame combustion. Early blue-flame burners were non-atomizing types that involved prevaporization of the fuel in a zone adjacent to, but not actually in, the flame. Pot-type and sleeve-type vaporizing burners are examples, and many such burners were in service operating on kerosene or No. 1 heating oil. Rotary wall-flame burners (described in this report under combination atomizing/vaporizing burners) were designed to recirculate combustion products back into the fresh air, upstream of the flame; many of these rotary wall-flame burners are still in service.

In the development of an orchard heater having low smoke emissions, Leonard observed that diluting the vaporized fuel oil with an inert gas prior to combustion greatly reduced smoke emissions. (Leonard, 1939 & 1951) The return stack orchard heater, which recirculates combustion products to the fuel reservior/vaporizer, was the outcome of this development. A laboratory study (Leonard & Boelter, 1942) compared the effectiveness of premixed air, nitrogen, $CO_2$, and water vapor in inducing blue-flame combustion of gaseous and vaporized light hydrocarbon fuels (including benzene and acetylene); $CO_2$ was found to be more than twice as effective as water vapor, while water vapor was less than 1.25 times as effective as nitrogen in achieving carbon-free combustion.

TABLE VI-4. REFERENCES PERTINENT TO BLUE-FLAME COMBUSTION

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Lewes<br>UK | 1892 | Chem. Soc. | The Luminosity of Coal-Gas Flames |
| Tapp<br>AOBA | 1928 | AOBA | Handbook of Domestic-Oil Heating |
| Tapp<br>AOBA | 1931 | AOBA | Handbook of Oil Burning |
| Romp<br>Netherlands | 1937 | Nijhoff | Oil Burning |
| Leonard<br>U. Calif. | 1939 | Mech. Eng. | A New-Type Orchard Heater |
| Leonard & Boelter<br>U. Calif. | 1942 | PCGA | Some Effects of Inert Diluents on the Combustion of Hydrocarbon Fuels |
| Leonard<br>U. Calif. | 1951 | Ag. Eng. | The Return-Stack Orchard Heater |
| Putnam<br>Battelle | 1957 | WADC | Injection and Combustion of Liquid Fuels |
| Weller<br>Battelle | 1958 | U.S. Army | Investigation of Gravity-Fed Vaporizing Puddling-Type Burners |
| Locklin<br>Battelle | 1960 | API | Laboratory and Field Performance Studies |
| Locklin<br>Battelle | 1960 | API | Fuel-Oil Applications and Equipment Developments |
| Putnam<br>Battelle | 1960 | API | Fuel-Air Mixing and Recirculation |
| Dunn<br>Atlantic Ref. | 1961 | API | Improved Oil-Burner Performance With Recirculation of Combustion Gases |
| Saxton & Lane<br>Shell | 1961 | API | The Ventres Blue-Flame Burner |
| Walsh<br>Gulf R&D | 1961 | API | Air-Aspirated Oil Burners |
| Kamo, Cooper & Radner<br>IITRI | 1962 | API | The Effect of Air-Fuel Mixing and Recirculation on Combustion |
| Walsh<br>Gulf R&D | 1962 | API | Burner Research Related to the API Program |
| Gilson | 1962 | FON | Meet the New Oil Powered Appliances |

TABLE VI-4. (Continued)

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Kamo, Cooper & Solbrig<br>IITRI | 1963 | API | Turbulence and Recirculation as Combustion Parameters |
| Cooper, Kamo, Marek & Solbrig<br>IITRI | 1964 | API | Recirculation and Fuel-Air Mixing as Related to Oil-Burner Design |
| Walsh<br>Gulf R&D | 1964 | API | Aspiration in Fuel-Oil Combustion |
| Beer<br>Penn. State Univ. | 1964 | API | On the Stability and Combustion Intensity of Pressure-Jet Oil Flames |
| Brown & Thring<br>U. Sheffield | 1964 | API | Understanding Pressure-Jet Flames – A Stepwise Research Procedure |
| Kamo, Cooper, Glicksberg & Fitzgerald<br>IITRI | 1964 | API | Nonluminous Combustion of Heating Oil Through Recirculation |
| Bailey<br>OOHA | 1964 | API | Status of the OOHA Burner Development Program |
| Bullock<br>Landon (UK) | 1964 | P&JH | Developments in Wallflame Burners |
| Cooper & Marek<br>IITRI | 1965 | API | Design of Blue-Flame Oil Burners Utilizing Vortex Flow or Attached-Jet Entrainment |
| Schindler & Ranz<br>U. Minn. | 1965 | API | Recirculation in a Vortex-Stabilized Oil Flame |
| Torborg & Janssen<br>Honeywell | 1965 | API | Flame Radiation in Domestic Oil Burners |
| Torborg & Janssen<br>Honeywell | 1966 | API | Performance and Radiation Studies With the API Prototype Blue-Flame Burner |
| Hedley & Jackson<br>U. Sheffield | 1966 | API | The Influence of Recirculation in Combustion Processes |
| Putnam<br>Battelle | 1967 | AFRC | Swirl Burning |
| Bolt & Locklin<br>Am. Oil | 1967 | WPC | Recent Developments in Oil Burners for Space Heating and Industrial Applications |
| Andrews, Siegmund & Levine<br>Esso | 1968 | APCA | Effect of Flue Gas Recirculation on Emissions From Heating Oil Combustion |
| Bailey<br>OOHA | 1968 | NOFI | OOHA Blue Flame Burner Systems |
| Locklin<br>Battelle | 1969 | ASME | Small Oil Burners – A Review of Some Recent Developments |

TABLE VI-4. (Continued)

| AUTHOR(S) | YEAR | PUBL. | TITLE |
|---|---|---|---|
| Bailey<br>OOHA | 1969 | NOFI | New Product Developments From the OOHA Laboratory Utilizing Blue Flame Burner Systems |
| Paterson<br>Chevron Res. | 1970 | NOFI | Review of Oil Burner Developments in the United States |
| Bailey<br>OOHA | 1970 | NOFI | Blue Flame Burner Development at the OOHA Laboratory |
| Locklin<br>Battelle | 1974 | Academic | Recent Research and Development in Residential Oil Burners |
| Syred & Beer<br>U. Sheffield | 1974 | C&F | Combustion in Swirling Flows: A Review |
| Meier & Vollerin<br>Battelle-Geneva | 1976 | Comb. Symp. | The Design of an Integrated Burner-Boiler System Using Flue-Gas Recirculation |
| Blueray<br>FO&OH | 1977 | FO&OH | The Blueray System |
| Buschulte<br>W. Germany | 1978 | VDI-GDI | Blueflame Combustion System |
| Brookhaven | 1979 | BNL | Efficiency Test Results for Blueray Blue-Flame Boiler |

NOTE: For full information on sources cited, see author-alphabetical list in REFERENCES Section of this report (Section VIII).

Blue-flame combustion was investigated at Battelle as part of research on pot-type, tent-heater stoves for the U.S. Army. (Weller, 1958) The importance was demonstrated of recirculated combustion products or initial reaction in a well-mixed, very-rich combustion zone in controlling soot emissions and in establishing the boundaries of blue-flame combustion.

Trials with atomizing-type burners using recirculated combustion products were made at Atlantic Refining Company (Dunn, 1961), at Shell Oil Company (Saxton & Lane, 1961) and at the University of Sheffield. (Hedley & Jackson, 1966) Their trials demonstrated that quiet and clean combustion could be obtained with pressure-atomization by using flue-gas recirculation.

## API Research on Combustion Products Recirculation

As part of the API burner research program carried out in the early 1960's, development of blue-flame burner technology based on combustion products recirculation was carried out at IIT Research Institute (IITRI). Quantitative data on the effects of flue-gas recirculation on combustion were developed (Cooper et al, 1964), a prototype burner demonstrating the principles of flue-gas recirculation was developed, and a design procedure for determining dimensions of burner components was published. (Cooper and Marek, 1965)

Figure VI-24 shows representative results with the API experimental apparatus. (Cooper et al, 1964) This variation of smoke with excess air is typical of pressure burners having no special provision for recirculation; the tests with recirculation at stoichiometric conditions show a marked transition from high smoke levels to smokeless operation when the quantity of combustion products recirculated back to the burner inlet amounts to about 45 percent of the stoichiometric air requirements. At still higher levels of recirculation, a transition is observed from a yellow flame to a blue flame with very quiet combustion.

Figure VI-25 shows the combined effects of excess air and recirculation on the location of these transitions in the API experimental apparatus. They form boundaries between three regions: one of smoky yellow-flame combustion, another of clean yellow-flame combustion, and a third of clean blue-flame quiet combustion. Additional operating limits may exist in the blue-flame region at low excess air: flame instability and CO formation.

API Demonstration Prototype. Figure VI-26 shows a burner concept that applied the above findings to achieve blue-flame combustion. (Cooper and Marek, 1965) With recirculation rates above 50 percent, this burner provided blue-flame operation with smoke-free operation at zero excess air. Combustion products were entrained by the inlet air jet, which followed the surface of a curved solid body by the attached-jet effect. The combustion air and flue gas were mixed in the entrainment section and following mixing chamber, and burned downstream in a combustion space separated from the mixing chamber by an orifice.

In tests at rates from 0.65 to 1.1 gph, clean blue-flame burning was obtained with air pressures as low as 2 inches of water. A design procedure for selecting burner dimensions was developed. Although this burner was not developed for commercialization, later blue-flame burner developments drew upon this technology in development of different designs accomplishing similar mixing and combustion conditions.

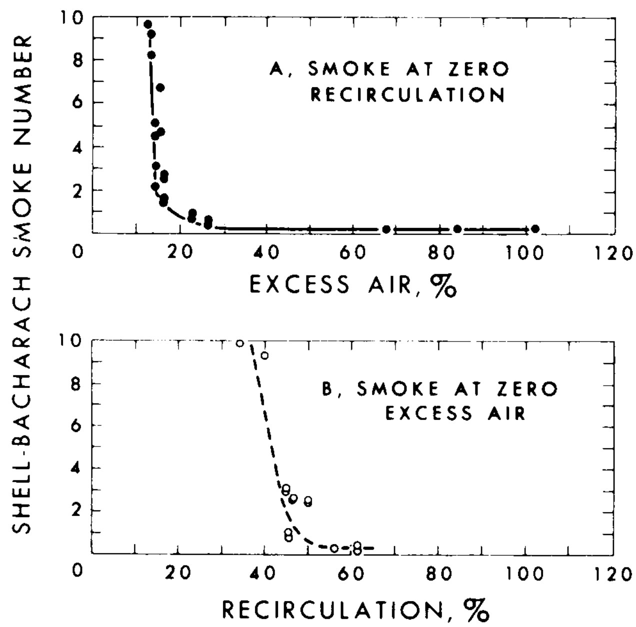


FIGURE VI-24. EFFECT OF EXCESS AIR AND COMBUSTION-PRODUCTS RECIRCULATION ON SMOKE DENSITY (Cooper et al, 1964)

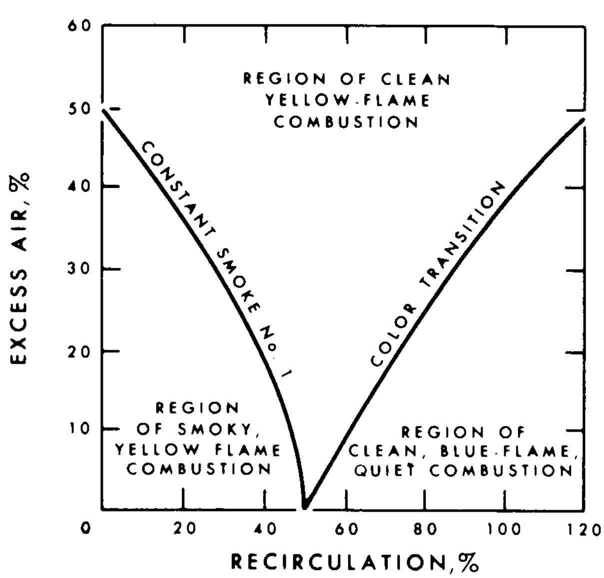


FIGURE VI-25. TRANSITION FROM YELLOW TO BLUE-FLAME BURNING — Combined Effects of Excess Air and Recirculation (Cooper et al, 1964)

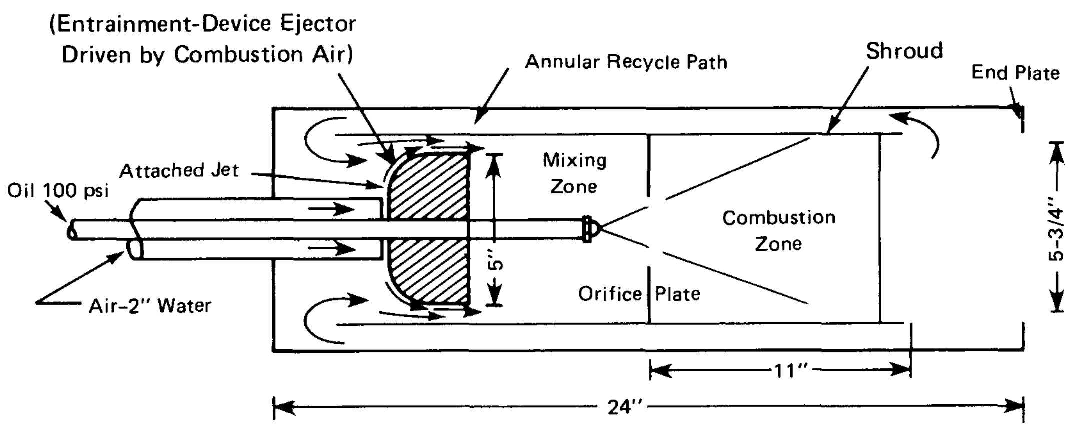


FIGURE VI-26. IITRI LABORATORY MODEL BLUE-FLAME BURNER USING ATTACHED JET ENTRAINMENT TO INDUCE RECIRCULATION (Cooper and Marek, 1965)

## Other Blue-Flame R&D During the 1960s and 1970s

Measurements of flame-radiation spectra (Torborg & Janssen, 1965 & 1966) indicate that the API prototype provided flame characteristics similar to those achieved in the Ventres blue-flame burner concept shown in Figure VI-27, originally developed by Shell Oil Co. (Saxton & Lane, 1961) Another version was developed (Gilson, 1962) but never reached full commercialization. These burners depend on recirculation of gases entrained into a central vaporizing tube where some fuel droplets impinge and vaporize in a fuel-rich zone. The final combustion air is added through ports in the outer double-walled chamber where small blue-flame jets appear.

Figure VI-28 shows another blue-flame burner concept developed for use with air-atomizing nozzles; this shows a natural-draft application to a domestic water heater developed in the OOHA program. (Bailey, 1964 & 1968) About 10 percent of the combustion air is supplied as atomizing air which induces secondary air (about 70 percent) into the primary mixing zone; the remaining air to complete combustion reaches the secondary mixing zone through the base.

Studies of recirculation in swirl-type burners have shown that enough reverse flow of combustion products can be induced by vortex action to provide blue-flame burning in a high-pressure burner by internal recirculation in the combustion chamber without special mixing passages (Schindler & Ranz, 1965); a number of versions were under development in Europe and several have been introduced on the market. Two reviews of swirl burning are pertinent to the overall subjects of internal recirculation and blue-flame combustion. (Putnam, 1967) (Syred & Beer, 1974)

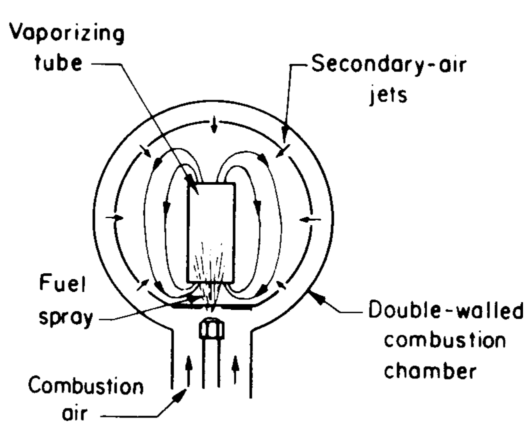


FIGURE VI-27. RECIRCULATION PATTERN IN THE VENTRES BLUE-FLAME OIL BURNER (Saxton & Lane, 1961)

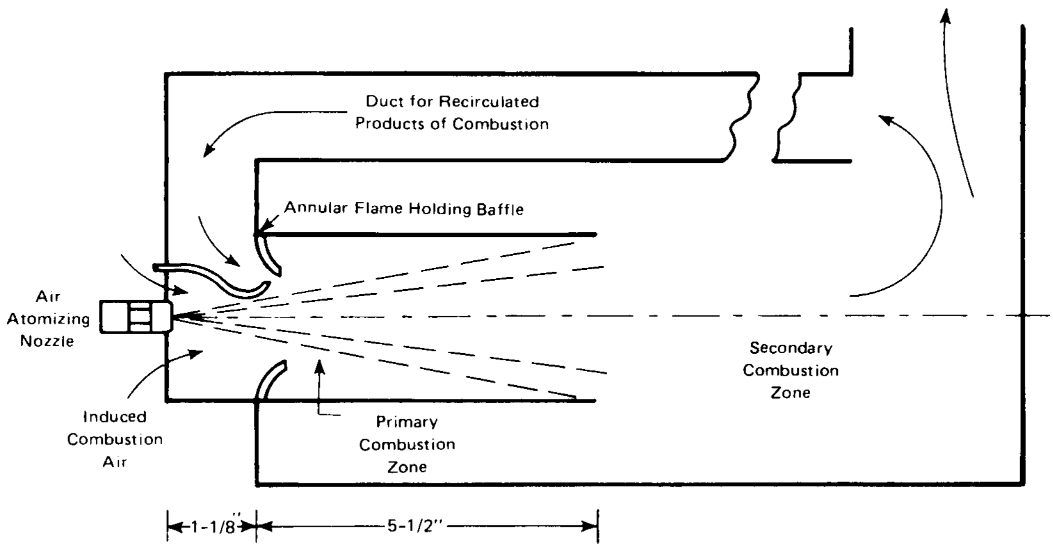


FIGURE VI-28. BLUE-J BURNER USING AIR ATOMIZATION TO INDUCE COMBUSTION AIR – Developed During OOHA Program (Bailey, 1970)

COMMERCIAL STATUS OF BLUE-FLAME BURNERS

At the present time, two manufacturers are offering integrated furnace or boiler units including blue-flame burners, and two companies offer blue-flame burners suitable for installation with existing equipment. Blueray Systems, Inc., offers both boilers and furnaces in which flue gas is recirculated in the burner through ejector action. Breda offers a line of boilers, manufactured in Italy, in which flue gas is recirculated through the burner fan for blue-flame operation. Blue-flame burners are also offered by M.A.N. of Germany and the Miyahara Burner Company of Japan.*

## The Blueray Blue-Flame Burner

The Blueray burner development was an evolution of the API blue-flame development through funding by the group of fuel oil and oil-burner distributors that formed OOHA. In 1976, the Meenan Oil Company purchased the Blueray development and, in 1977, began marketing two blue-flame furnaces rated at 70,000 and 88,000 Btu/hr. In 1977, 1000 field-trial units were in service (Cutter, 1977) Blueray Systems, Inc., is now under contract with BNL to further develop the concept.

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*The Miyahara Burner could also be considered to be an atomizing/vaporizing type burner.

The objectives of this project are (1) to develop and demonstrate six hot-water boilers for hydronic heating systems, with firing rates from 0.5 to 1.0 gal oil/hr, (2) to develop a larger furnace firing 0.9 gal/hr oil, and (3) to develop a blue-flame replacement burner for existing boilers and furnaces. A total of 25 field-trial units is to be tested under this program.

Figure VI-29 is a schematic drawing showing the principles of the Blueray burner. The combustion air aspirates gaseous products of combustion into a mixing throat, where air and gas mix. The fuel nozzle extends downstream from the air nozzle, so that atomized fuel burns with the mixture of air and gas to form a blue flame. The amount of gas recirculated is determined by the geometry of the burner parts and by the adjustment of a flow-restricting band. Recirculating gas flows around an annular baffle, passing radially inward to the ejector inlet around the fuel nozzle. The exact temperature and composition of the recirculated gas depend upon the combustion chamber shape and combustion conditions; this complicates the application of the concept as a replacement burner that must be adaptable to a variety of combustion chamber designs.

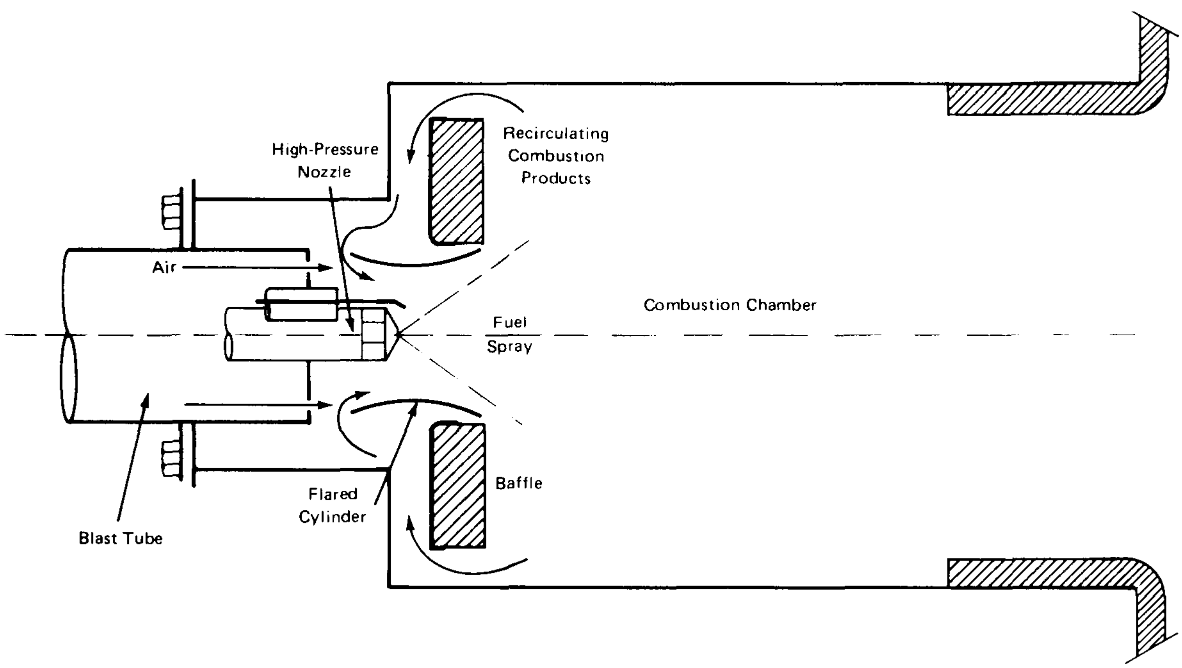



FIGURE VI-29. THE BLUERAY BLUE-FLAME OIL BURNER – Flow Pattern of Recirculating Combustion Products (Courtesy, Blueray Systems)

In BNL input/output tests a Blueray boiler equipped with this burner operated at 14 percent $CO_2$. The steady-state efficiency was 84.5 percent and the seasonal efficiency was 76.2 percent. Some flame instability and pulsation were observed. (Brookhaven, 1979)

The burner ignites readily and the flame changes from yellow to blue almost immediately, as soon as combustion products reach the mixing throat. An advantage claimed for the Blueray burner is that heat-exchange efficiency does not decline through a heating season, because soot is not deposited in the heat exchanger.

## The Breda Blue-Flame Burner/Boiler Unit

The Breda System 91 boilers are manufactured in Bari, Italy. The boiler line consists of 16 sizes of sectional cast-iron boilers designed for very high efficiency; the boilers use blue-flame burners that minimize soot deposition in the small flue-gas passages. The concept was originally developed by the Battelle-Geneva Research Center in Switzerland. (Meier & Vollerin, 1976) The boilers range from 80,000 to 450,000 Btu/hr, and a larger series for commercial application is also marketed. Several hundred field-trial units were in service during 1979, and production of several thousand units is planned for 1980.

In contrast to the blue-flame burners described previously that use internal recirculation, the Breda burner uses external recirculation. Figure VI-30 shows the recirculation concept schematically, and Figure VI-31 shows the actual configuration of the unusual wet-base boiler. Boiler stack gas, (drawn by a fan from the boiler exit) passes through a mixing box, where it is metered and mixed with combustion air, and then through the burner fan and burner. Thus, the combustion air and recirculated flue gas are relatively cool and well mixed before they enter the burner. The original design utilized intense swirl for flame stabilization; the most recent design operates with moderate swirl while completing most of the combustion within a small, hot, metal burner can. To ignite the burner under cold conditions, it is necessary to reduce the air flow and close off the flue-gas flow; this is done by dampers in the mixing box that are opened a few seconds after ignition.

Figure VI-32 shows the combustion regimes, compared to those in Figure VI-25. (Cooper et al, 1964) $NO_x$ levels were reduced about two-thirds with 60 percent recircirculation.

The burner operates with zero smoke and less than 1 percent oxygen, with gas recirculation of 30 to 50 percent of combustion air. This permits high boiler efficiency, in the range of 86 percent. One model was tested by BNL firing at 1.3 gph. At 14.1 percent $CO_2$, the steady-state efficiency was 83.7 percent by the input/output method; with no domestic hot water coil, the seasonal efficiency was determined to be 77.8 percent for an oversizing factor of 2, comparable to the conditions for the curves in Section III.

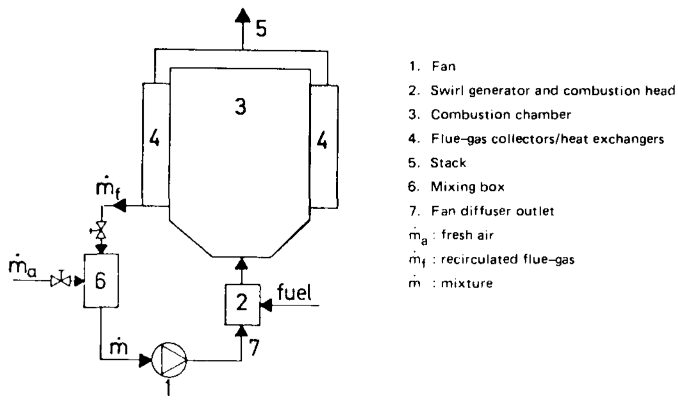



FIGURE VI-30. SCHEMATIC OF FLOW SYSTEM FOR THE BREDA BLUE-FLAME BURNER/BOILER UNIT – Illustrating External Recirculation of Cooled Flue-Gas (Meier & Vollerin, 1976)

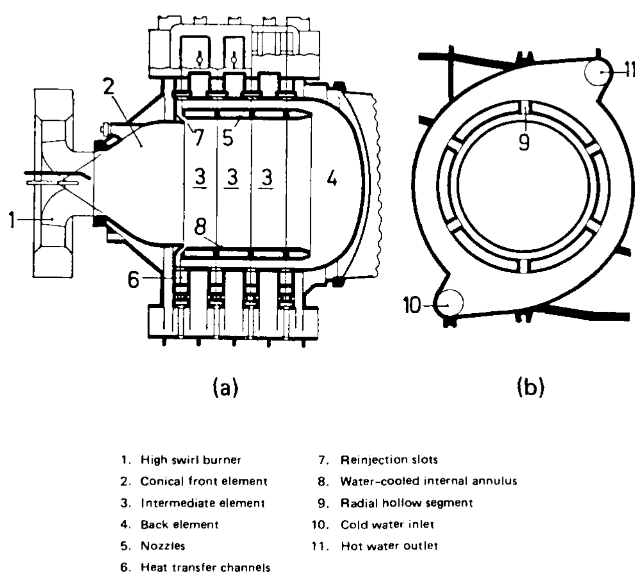



FIGURE VI-31. CROSS-SECTIONAL VIEWS OF THE BREDA BOILER. (a) Longitudinal cross-sectional view showing the combustion chamber shape; (b) transversal cross-sectional view showing the water passages in the intermediate elements. (Meier & Vollerin, 1976)

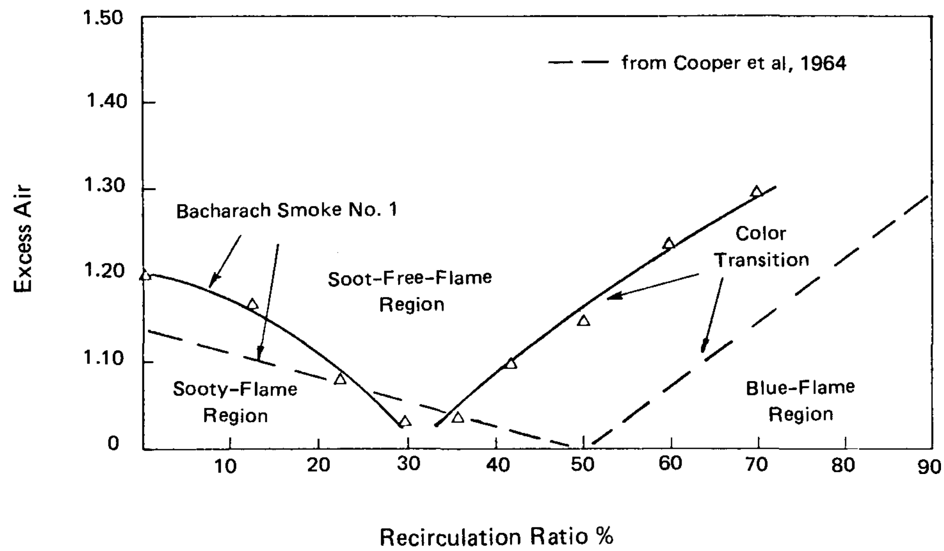



FIGURE VI-32. VARIOUS COMBUSTION REGIMES OBSERVED FOR THE BREDA BOILER — No. 2 Fuel-Oil at Burner (Meier & Vollerin, 1976)

At this time, the Breda System 91 boiler is marketed in Italy. Broader marketing, both in Europe and in the U.S., is under consideration.

## The M.A.N. Rocketburner

The RE-1 "Rocketburner" is a blue-flame burner manufactured by M.A.N. Brennerbau, Hamburg, Germany. In this burner, combustion products from a small, integral combustion space are recirculated into a smaller vaporizing space upstream of the combustion space, as shown in Figure VI-33.

A paper describing the development of the burner (Buschulte, 1978), states that soot formation is avoided by carrying out fuel evaporation at moderate temperature within a mixing tube, in which flow velocity is higher than flame speed. If droplet evaporation is completed within the mixing tube, droplet burning is avoided and, with it, cracking of liquid fuel to form soot. Combustion is confined within a flame tube having a defined volume, which assures optimum recirculation conditions for stable combustion. Because most of the combustion takes place within the burner tube, geometry of the boiler space into which it is fired is not critical. Buschulte describes the design criteria for each dimension of the burner parts, and also discusses requirements for atomization to the required droplet size for complete vaporization.

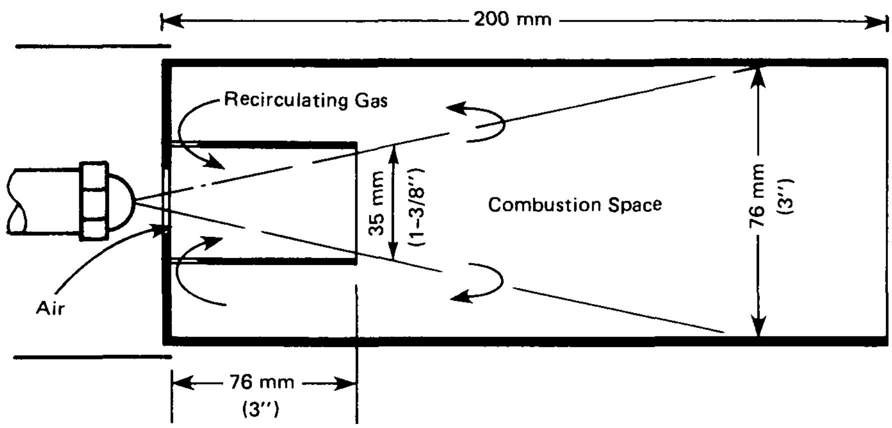



FIGURE VI-33. SCHEMATIC ARRANGEMENT OF M.A.N. REI ROCKETBURNER

The burner is started by closing a damper to reduce air flow, so that burning takes place within the mixing tube for about two seconds. This damper is then gradually opened over several seconds, by which time recirculation of hot gas through the mixing tube has been established. Field trial burners for residential heating showed no deterioration with heat inputs from 72,000 to 112,000 Btu/hr.

The M.A.N. burner burns with a blue flame, with $CO_2$ near 15 percent, and without soot. CO emission is high during the startup period of two seconds, but is otherwise below 20 ppm; $NO_x$ is about 40 ppm. This burner is of particular interest because it appears suitable for use as a replacement burner for many existing boilers and furnaces.

## Other Blue-Flame Developments in Europe

A number of blue-flame burners have been developed in Europe. The following information on European development was assembled for this study by the Battelle Geneva Research Center. (Noir, 1979; Houlman, 1980) A number of European manufacturers have introduced blue-flame burners, as noted below, but only three still offer blue flame burners: M.A.N. (described above), Ceunod DER (under the M.A.N. license), and Rheinstahl RU 100.

The Rheinstahl RU 100 burner obtains a blue flame by partially vaporizing the fuel in the burner head. The range of capacity is from 0.8 to 2.0 gph, obtained with different nozzles. It is claimed to be clean, quiet, and efficient.

The Weishaupt blue-flame WL2VB burner was commercialized in 1971, but was discontinued. Its main feature was a perforated, hollow half sphere operating as a bluff-body flame stabilizer. This low-capacity burner was considered to be particularly quiet, and economical. However, carbon deposits formed on the hemispherical stabilizer from impaction of fuel drops during cold starts.

The Riello DVB 5 burner operated on the principle of intense swirl generation, resulting in a clean, blue, quiet flame. The Riello blue-flame versions were sold under the name Mainflamme in Germany, but they are no longer marketed.

The Smit Ultramizing combustion system of 1 to 4 gph capacity was developed for inert-gas generators. This burner had unusually fine fuel dispersion and mixing with combustion air, obtained by using a conventional atomizing nozzle followed by mixing in air at high tangential velocity before entering the combustion space. Typical analysis of combustion products was reported to be 0.5 percent $O_2$, 10 ppm CO, 50 to 100 ppm $NO_x$, and zero Bacharach smoke.

The Oertli EO-1 burner, vaporized fuel in a hot ceramic pre-chamber. The ceramic nozzle is added to the standard OE-1 burner having ratings between 0.25 and 0.70 gph.

Staged Combustion. A Swedish engineer, A. Inovius, has developed a two-stage combustion system for retrofit on conventional burners. It used two ceramic combustion chambers; the first chamber operated fuel-rich at a temperature of about 2100 F and additional air is supplied to the second stage where the temperature is about 1400 F and the $CO_2$ is 11.6 percent. The developer claims no soot, smoke, or unburned hydrocarbons. $NO_x$ is reported to be 20 ppm, extremely low for an oil burner.

## Japanese Blue-Flame Burner

The Miyahara Burner Co., Ltd., of Osaka, Japan, produces a kerosene-fired blue-flame burner for firing rates up to 180,000 Btu/hr. (Miyahara, 1979)

Figure VI-34 shows the Miyahara burner. In this burner, kerosene is atomized with a spinning-cup atomizer, then vaporized in a vaporizing chamber. The combustion air is admitted around the spinning cup and mixes with vaporizing kerosene in the vaporizing chamber. The air-vapor mixture then passes through a dome-shaped burner having many fine, radial slots, and burns as a blue flame out of these slots, much like a premixing gas burner. When starting from a cold condition, a 600-watt electric heating element is used to preheat the vaporizing chamber. Although no detailed description was available to describe the means of heating the vaporizing chamber during normal operation, it appears that the structure is heavy enough to provide heat conduction from the burner head to the vaporizing chamber after startup.

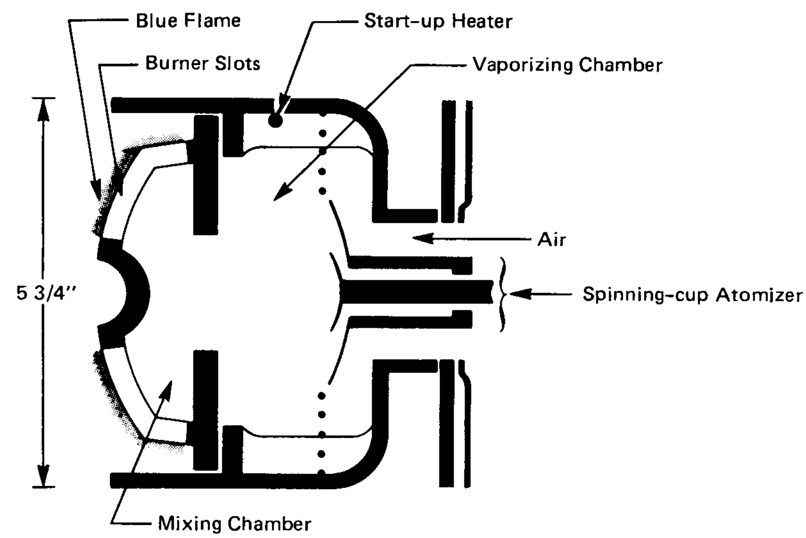



FIGURE VI-34. MIYAHARA RG-5000 VAPORIZING BLUE-FLAME BURNER (Courtesy: Miyahara Burner Co., 1979)

Unlike other blue-flame burners being developed, this burner does not utilize flue-gas recirculation. Instead it relies on forming a vapor/air mixture isolated from the combustion region, then burning this gaseous mixture in a burner with small ports to limit flashback of flame to the mixing chamber.

This burner could also be categorized as an atomizing/vaporizing burner. It is similar in some respects to the rotary atomizing Downs burner (Carl et al, 1966) shown earlier in this Section, but the Downs burner is a luminous-flame burner and is oriented with a vertical distributor shaft.

## APPRAISAL OF BLUE-FLAME BURNERS

Blue-flame burners offer several significant advantages -- namely, soot-free combustion at low-excess air, quiet combustion for low-intensity types, and low $NO_x$ emissions for some versions. Several potential problems appear to be more prevalent with blue-flame burners than conventional burners and should receive special attention; these problems include transients on starting from cold, CO emissions and flame instability at very low excess air, flame detection for safety controls to avoid hazard during brief interruptions in oil supply, and possible sensivity to variations in a fuel quality. Materials durability is especially important to examine in burners of the recirculating-type, because higher temperatures can be reached in the burner mixing components. Their potential for application to condensing-type heat exchangers makes blue-flame burners a promising candidate for high-efficiency heating units.

## PULSE COMBUSTION

Pulse-combustion systems have been explored over a period of many years. However, recent introduction and exhibition of residential boilers fired by pulse combustion systems, coupled with a recent symposium at Argonne National Laboratory (Clinch, 1979), has stimulated renewed interest in the U.S. for application of pulse combustion to high-efficiency heating boilers and furnaces.

Pulse combustion differs from conventional steady-flow combustion, in that the air enters the combustion chamber in a pulsed flow that is induced by the pressure oscillations. The fuel may enter mixed with the air, or separately either in a pulsed or steady-state manner. The pressure oscillations are set up and maintained by the unsteady energy release; these oscillations are associated with the acoustics of the entire combustion and heat-transfer system between the decoupling chambers.

### Principle of Operation

Figure VI-35 shows the principle of operation of a typical pulse combustor. Figure VI-36 illustrates the basic design differences in the inlet valving approach between mechanically-valved pulse combustors and aerodynamically valved pulse combustors. The latter have no moving parts and rely on the inlet design to provide higher resistance to net flow in the forward direction; they are sometimes referred to as "valveless".

Briefly, pulse combustors perform in the following manner. (Putnam, 1971 & 1979) After a combustible mixture is ignited in the combustion chamber, the products expand and flow out the exiting resonance tube. In mechanically valved types, the flapper valve blocks flow out the inlet. In aerodynamically valved types, there is some backflow out the inlet but the inlet is designed to provide the net flow in the forward direction by virtue of the higher resistance for backflow. The momentum of the exiting gases reduces pressure in the combustion chamber. This results in an inflow of fresh air through the inlet. A gaseous, liquid, or solid fuel may be fed either continuously or periodically in phase with the combustion-air inflow. Each new charge of mixture is ignited by hot products and/or hot walls, and/or pressure effect, to continue the cycle.

In starting a pulse combustor, a small jet or flow of air is normally necessary. This purges the system, starts a flow of air through the system, and opens the valve in the case of a mechanically valved unit. The ignition system is then activated and the fuel injection started. After the first explosion, the system will continue to operate without either starting fan or further outside ignition source.

For oil-fired units, several methods of supplying the fuel have been used in various designs, including a steady-state supply from a pressure jet atomizer, a periodic supply with a low-pressure two-fluid atomizer and a

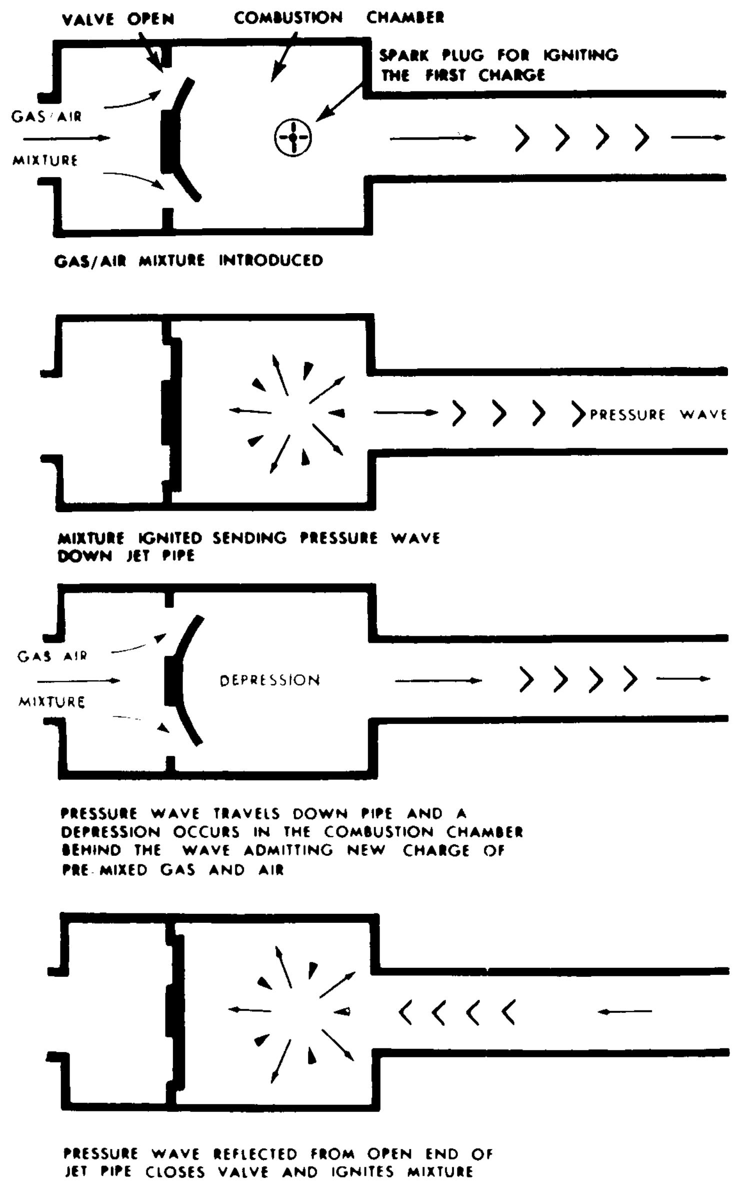
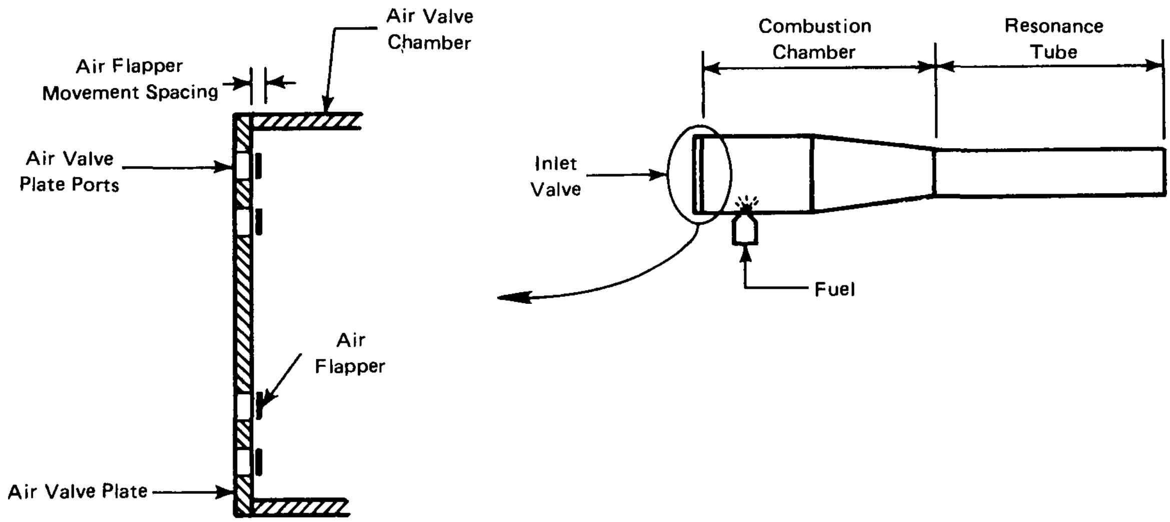
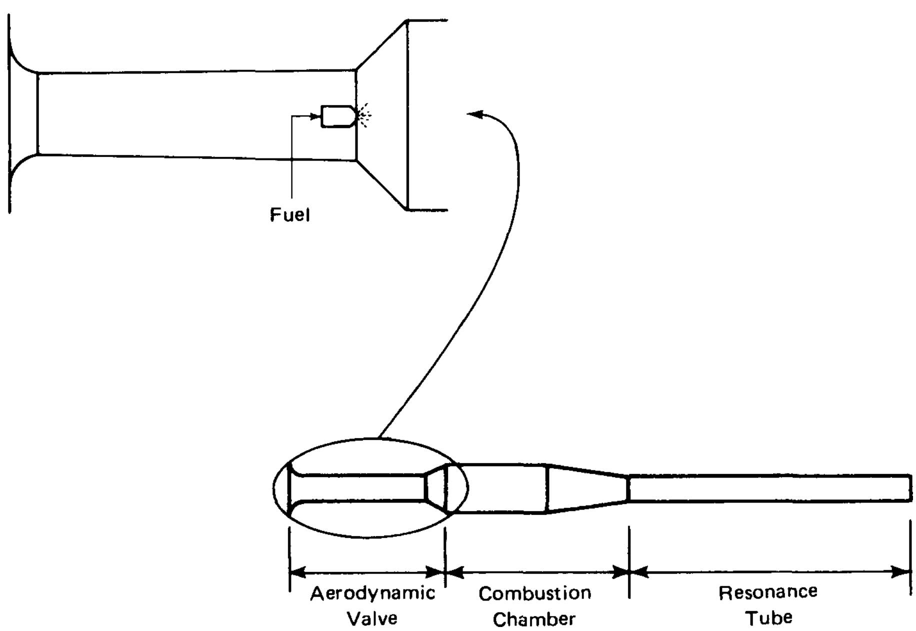



FIGURE VI-35. OPERATING CYCLE OF A PULSE COMBUSTOR (Pulsomatic)




A. Mechanically Valved Pulse Combustor – Flapper-Type Valve




B. Aerodynamically Valved Pulse Combustor

FIGURE VI-36. SCHEMATICS OF TWO BASIC DESIGNS FOR PULSE COMBUSTORS (Putnam, 1979) pulsed supply with either a carburetor or entrainment of fuel from a fuel-wet surface with the inflowing air. (Putnam, 1979)

## Advantages of Pulse Combustion

Key characteristics of the pulse combustor are (1) the intense combustion and high rates of heat transfer resulting from the periodic operation, and (2) the pressure boost available from the one-way action of the valves. Advantages of the concept are as follows:

- A compact combustor and high-resistance heat exchanger can be used; the oscillations in the resonance tube also increase the rate of heat transfer and allow compactness.

- Because of the pressure boost capability, there is no need for a large combustion air fan; at the most, only a small starting fan is needed. The pressure boost makes it practical to use high-resistance heat exchangers, including those designed for operation in the condensing mode.

The combination can result in a compact overall unit with a small duct for venting.

With the use of small flue passages, the off-cycle losses through the system will be low and the overall efficiency high, even with aerodynamic valves. Although aerodynamically valved pulse combustors are not normally capable of as high a pressure boost as mechanically valved units, the added simplicity of the design and a possibility of removing the need for even a starting fan make their development attractive. The backflow of cooled product gases into the combustion chamber insures a high degree of turbulence, and may also result in a reduction of $NO_x$.

## COMMERCIAL STATUS FOR RESIDENTIAL APPLICATIONS

Although pulse combustors were first investigated in the early 1900s, they came to prominence through the World War II German V-1 Buzz-bomb. (Putnam, 1971 & 1979) For residential heating, they first were introduced on the market in Canada about 1960 in the form of the Lucas/Rotax Pulsomatic, a gas-fired hydronic unit. (Kitchen, 1979) Many of these units are still in operation. Although the unit was a technical success, the higher first cost for the increased efficiency was not justified in the marketplace by the fuel savings. The current rapidly increasing price of fuel has caused a resurgence of interest in the device.

The Hydro-Pulse gas-fired boiler, an updated version of the Pulsomatic, is being manufactured by Hydrotherm, has recently been introduced in the U.S. in residential sizes. (May, 1979) GRI is supporting development of a gas-fired warm-air furnace by Lennox and the A.G.A. Laboratories using a highly modified

Pulsomatic design. (Belles, 1979) The BNL program of equipment R&D includes contracts with Yankee Engineering and Shock Hydrodynamics for RD&D on gas-fired pulse-combustion equipment. (Woodworth, 1979)

A European development, the Turbopuls boiler has been exhibited in the U. S. in both gas-fired and oil-fired versions by Turbopuls S.A.R.D. An oil-fired Turbopuls boiler has been tested at Brookhaven, with a steady-state efficiency of 88.1 percent. (Brookhaven, 1979)

## State of the Art for Other Applications

Table VI-5 lists a variety of pulse-combustion applications, both potential and established. (Putnam, 1971) Evidence in the literature indicate that all but a few applications in the "other uses" category have been at least tried. Areas of active development and substantial use are indicated in the table by the asterisks.

TABLE VI-5. APPLICATIONS OF PULSE COMBUSTION

| General Category of Purpose | Specific Applications | Activity |
| --- | --- | --- |
| Thrust Producing | Propulsion | ** |
| | Vertical lift devices | |
| | Gas-turbine starter | |
| Pressure Gain and Fluid Pumping | Gas-turbine compressor augmentor | * |
| | Fan/blower replacement | |
| | Flue-gas recirculation | |
| Liquid Heating | Steam raising | * |
| | Water heating | * |
| Air Heating | Drying | ** |
| | Comfort heating in vehicles | ** |
| | Comfort heating in home | * |
| | Engine and machinery heating | * |
| Other Uses | Fogging | * |
| | Insecticide spraying | * |
| | Ice melting | |
| | After burning | |
| | Refuse incineration | |
| | MFD power generation | |
| | Gasification | |

*Active development under way.
**Substantial use.

In general, the developments may be divided into two application reas depending on pressure requirements, high-pressure-amplitude devices and low-pressure-amplitude devices.

Higher-pressure-amplitude devices include those for thrust generation or propulsion, vertical lift devices, driers, ice melting, pressure-gain combustors, gas-turbine starters, magneto-fluid-dynamic power generators, and fan/blower replacements. In these instances, the noise problem is secondary in the sense that extensive noise suppression measures are not needed for the pulse combustor itself. Indeed, for drying operations, the high noise level is inherent with the desirable features, and suppression takes place only within the confines of the entire system. High pressure levels are more easily reached with mechanical valves, but they are not absolutely necessary for high pressure amplitudes.

Low-pressure-amplitude pulse combustors are used where high pressure rise is not needed. They minimize silencing problems, and have been used in steam raising, water heating, and most of the air-heating applications. Thus, it is the various low-pressure amplitude applications that are most likely to provide experience that can be utilized in the design of systems for residential heating.

## DEVELOPMENT PROBLEMS

The main development problem for pulse combustion is that of noise. This was emphasized in a recent survey of investigators in the field, worldwide. (Severyanin & Dereshcuk, 1977) Yet there appears to be no doubt that the noise problem can be overcome for many applications. Recent developments of a natural-gas-fired, pulse-combustor system for warm-air heating have been made acceptably quiet by proper design and use of mufflers and resonance chambers; the experimental units have achieved the goal of being as quiet as a conventional furnace with an oil-burner or a power gas burner. (Belles, 1979) The European Turbopuls boiler, displayed in operation at exhibitions in the U.S., is relatively quiet.

In the case of oil-fired units, the development of acceptable fuel supply systems is an important problem; they must be reasonable in cost and of long life. In addition, valve deposits in mechanically valved units can be a problem. In aerodynamically valved units, some designs have a small mechanical valve associated with the carburetion systems, imposing a component-durability problem that needs to be explored. A continuous fuel-supply system is preferable from the standpoint of simplicity.

Several aerodynamically valved oil-fired fog generators have been developed, including a unit that fires diesel fuel with a pressure atomizing burner. (Persechino, 1959) It is not certain that the same type of fuel nozzle would be optimum for both valved and valveless pulse combustors, but the development of satisfactory systems would be expected to be along similar lines for both types.

## APPRAISAL OF PULSE COMBUSTION

Pulse combustion warrants further development for oil-fired heating equipment. Two main directions are indicated for R&D; they deal with the two basic valving concepts:

1. Since a variety of pulse combustors using mechanical valves has been developed for residential heating, these could be used as a starting point for investigating the relative performance of oil-fired pulse-combustion systems using different designs of fuel-injection.
2. The development of oil-fired aerodynamically valved pulse systems also appears warranted to extend the durability of the system.

The criteria for acceptable performance should consider deposit problems in the combustor and the inlet valve, the smoke characteristics at low excess air, the effects on pressure boost, $NO_x$ emission levels, and long-term durability of components.

## OVERALL ASSESSMENT OF TECHNICAL APPROACHES TO BURNER DESIGN

Table VI-6 summarizes a subjective assessment of the more promising of the technical approaches described previously. This assessment is based on principal criteria identified in Part I, with a comparison of the technical approaches judged on a relative basis against each of the evaluation criteria.

The evaluation for a conventional high-pressure atomizing, flame-retention-head burner is defined as the baseline. A given concept can be more favorable, equivalent, or less favorable when compared to the baseline for a given criterion. The maximum rating in VI-6 for a given criterion is three bullets. Question marks are shown were the concept is at an early state of development such that information is inadequate to judge a particular criterion.

It should be recognized that these approaches are not mutually exclusive. For example, any of the forms of fuel preparation could be used in blue-flame burners or pulse combustion systems.

### EVALUATION CRITERIA

The following explanation of the criteria will assist in the understanding of Table VI-6.

#### Performance-Oriented Criteria

1. Burner Performance Potential. Ability to operate cleanly at low excess air.
2. Low-Rate Potential. Ability to operate at low-firing rates without atomizer clogging or fuel preparation problems.
3. Reliability Potential. Ability to operate reliably with durable components. (For example, question marks have been shown for air atomization because of lack of an air-compressor of proven long-term reliability.)
4. Fuel Insensitivity. Expected freedom from performance deterioration resulting from variations in fuel quality.
5. Free from Transients. Expected freedom from problems on starting or shutdown.

| | |
|---|---|
| ●●● | Most favorable |
| ●● | Intermediate |
| ● | Less favorable |
| ? | Uncertain** |

## TABLE VI-6. ASSESSMENT OF THE MORE PROMISING TECHNICAL APPROACHES TO BURNER DESIGN*

| | PERFORMANCE-ORIENTED CRITERIA | | | | | | | | OTHER MARKETABILITY CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CONCEPTS | 1. Burner Performance Potential | 2. Low-Rate Potential | 3. Reliability Potential | 4. Fuel Insensitivity | 5. Free From Transients | 6. Low CO and HC Emissions | 7. Low $NO_x$ Emissions | 8. Low Noise | 9. Low Mfg-Cost Potential | 10. Retrofit Potential | 11. Service Training Req. | 12. Likely Market Acceptance | 13. Free of Stds. Problems | 14. Rel. Time to Introduce | 15. Rel. Cost & Risk to Intro. |
| **HIGH-PRESSURE ATOMIZATION** | | | | | | | | | | | | | | | |
| Conventional (Baseline) | ●● | ● | ●●● | ●● | ●● | ●●● | ● | ●● | ●●● | ●●● | ●●● | ●●● | ●●● | ●●● | ●●● |
| Special Anti-Clogging Nozzles | ●●● | ●● | ? | ? | ●● | ●●● | ● | ●● | ●●● | ●●● | ●●● | ●●● | ●●● | ●●● | ●●● |
| Return-Flow Nozzles | ●●● | ●●● | ●●● | ●●● | ●●● | ●●● | ● | ●● | ●● | ●● | ● | ● | ●●● | ● | ●● |
| Nozzle-Line Heaters | ●● | ●● | ? | ? | ● | ●●● | ● | ●● | ●● | ●●● | ●● | ●● | ●●● | ●● | ●● |
| **AIR ATOMIZATION** | | | | | | | | | | | | | | | |
| Acoustic Atomizer | ●●● | ●●● | ●●● | ●●● | ●●● | ●●● | ● | ● | ●● | ●●● | ●● | ●● | ●●● | ●● | ●● |
| Stretched-film, | ●●● | ●●● | ●●● | ? | ●●● | ●●● | ● | ●● | ●● | ●●● | ●● | ●● | ●●● | ● | ● |
| **ULTRASONIC ATOMIZATION** | | | | | | | | | | | | | | | |
| Piezoelectric | ●●● | ●●● | ? | ●●● | ●●● | ●●● | ● | ●●● | ? | ●● | ● | ●● | ●●● | ●● | ●● |
| **PREVAPORIZING BURNERS** | | | | | | | | | | | | | | | |
| Thermal Aerosol Generators | ●●● | ●●● | ? | ? | ? | ? | ● | ●●● | ● | ●● | ● | ● | ? | ● | ● |
| **COMBINATION ATOMIZING/ VAPORIZING** | | | | | | | | | | | | | | | |
| Variable flow rate | ●●● | ●● | ? | ? | ? | ? | ●● | ●●● | ● | ? | ● | ? | ? | ● | ● |
| **BLUE-FLAME (Hi-Press. Atom.)** | | ** | | | | | | | | | | | | | |
| Low-intensity | ●●● | ● | ●●● | ●● | ● | ● | ●● | ●●● | ●● | ● | ●● | ●●● | ●●● | ●●● | ●●● |
| High-intensity | ●●● | ● | ? | ●● | ? | ●● | ●● | ● | ●● | ●●● | ●● | ●● | ●●● | ●● | ●● |
| **PULSE COMBUSTION** | | | | | | | | | | | | | | | |
| Mechanically-valved or aerodynamically valved | ●●● | ? | ? | ? | ? | ●● | ●●● | ? | ? | ●● | ● | ? | ? | ● | ● |

* Subjective assessment of each concept, compared to baseline of conventional high-pressure burner. Combinations of concepts can result in different assessments.
** "Uncertain" (?) includes circumstances where experience or information is limited.
*** Low-rate potential would be expected to follow that for the fuel preparation means.

6. Low CO and HC Emissions. Expected low levels of CO and HC emissions during cyclic operation.

7. Low $NO_x$ Emissions. Expected low levels of $NO_x$ emissions at steady state, compared to conventional equipment.

8. Low Noise. Expected low overall noise levels during operation; includes both combustion roar and equipment noise.

Other Marketability Criteria

9. Low Manufacturing Cost Potential. Relative to other concepts performing the same function.

10. Retrofit Potential. Ability to be field applied in existing equipment, perhaps as part of a complete burner assembly.

11. Service Training Required. Degree of additional service training required over conventional equipment.

12. Likely Market Acceptance. Estimated overall acceptance of concept to consumers and oil-heating dealers, assuming continued successful technical development.

13. Free of Standards Problems. Estimated freedom from problems imposed by codes and standards.

14. Relative Time to Introduce. Estimated time necessary to introduce on the market in full-scale production.

15. Relative Cost and Risk to Introduce. Estimated technical and economic risk (relative) in pursuing development to full-scale introduction, considering present state of development and unknowns.

## RECOMMENDATIONS FOR RD&D ON BURNER APPROACHES

Continued RD&D is recommended in two major categories of technical approaches to burner design: (1) burner fuel preparation concepts; and (2) combustion system. The assessment leads to recommendations for RD&D on the following technical approaches to burner design:

## 1. BURNER FUEL PREPARATION

### A. Near Term and Relatively Low Technical Risk.

- Special anti-clogging nozzles -- retrofit and new burners
- Nozzle preheaters -- retrofit and new burner application
- Return-flow nozzles -- new burner application.

### B. Intermediate Term and Technical Risk.

- Air-Atomization approaches -- new burner application
- Ultrasonic atomization -- new burner application.

### C. Longer Term and Higher Risk.

- Thermal aerosol generators, new burner application (long-term performance).

## 2. COMBUSTION SYSTEMS

### A. Near Term and Relatively Low Technical Risk.

- Blue-flame burners -- both retrofit and new unit application, performance and application limits.

### B. Longer Term and Higher Risk.

- Pulse-combustion systems for condensing heat exchangers -- new unit application, long-term performance and materials durability.

The performance potential and other issues involving condensing-type heat exchangers are discussed in the following section.

# SECTION VII

# CONDENSING-TYPE HEAT EXCHANGERS

This section will expand on the introduction to condensing-type systems for residential oil-heating systems contained in Section III of this report.

## THE INCENTIVES AND PROBLEMS OF CONDENSING HEAT EXCHANGERS

### EFFICIENCY POTENTIAL

Figure VII-1 illustrates the potential benefits of condensing operation on steady-state efficiency. It shows the amount of heat lost in flue products for various flue-gas temperatures. This heat is made up of two components: (1) sensible heat resulting from the heat content of the dry gas, which varies with flue-gas temperature, and (2) latent heat needed to vaporize the water vapor formed in the combustion process, which remains constant with flue-gas temperature. With oil firing, this latent heat represents 6.5 percent by weight of the flue gas (with gas, more water vapor is formed because of the high hydrogen content of the gas, representing 8.8 percent of the flue gas).

For typical No. 2 oil, the dewpoint is 124 F, the temperature at which surfaces will begin to condense moisture and, thus, regain the latent heat by transfer to the circulating heating medium. When the bulk temperature of the flue gas drops below the dewpoint, the regain of latent heat proceeds rapidly, so the flue loss drops markedly. Assuming other losses are negligible, the thermal efficiency increases an equivalent amount. If the flue gas temperature is reduced to 100 F, then the thermal efficiency will be about 95 percent, neglecting jacket losses.

The acid dewpoint, the temperature where sulfuric acid condenses, increases with sulfur content in the fuel. In Figure VII-1, the acid dewpoint is shown to be 260 F, corresponding to a fuel sulfur level of 0.3 percent. The sulfur content of No. 2 fuel ranges from 0.01 to about 0.5 percent, with the national average being 0.22 percent (Shelton, 1979). There is some indication that the sulfur content of No. 2 oil is increasing in some market areas.

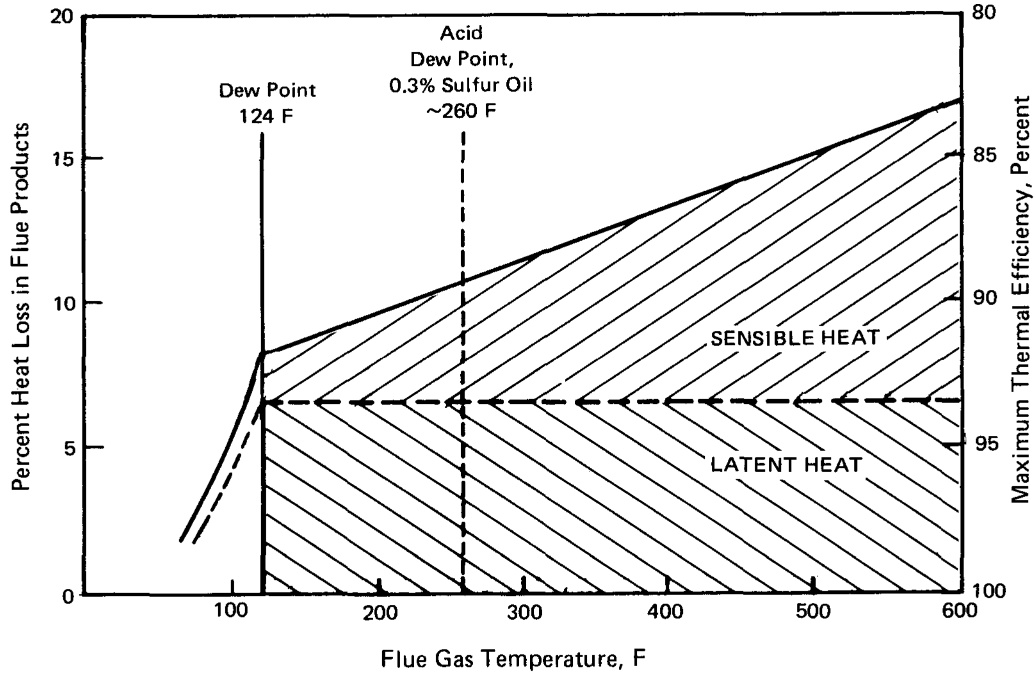



FIGURE VII-1. STEADY-STATE EFFICIENCY OF CONDENSING HEAT EXCHANGER SYSTEM — Heat Loss in Flue Products as a Function of Flue-Gas Temperature

## CORROSION POTENTIAL AND THE MATERIALS PROBLEM

The cost-effectiveness of condensing-type heat-exchanger systems will depend strongly on the materials requirements for adequate life and the designer's compromise between tradeoffs between efficiency and manufacturing costs.

The corrosion potential for oil-fired combustion systems is greater than with gas-fired systems, because of the higher sulfur content. In the presence of condensed moisture, $SO_3$ and $NO_2$ result in the formation of the strong acids, sulfuric and nitric acid, and even small quantities of $SO_3$ cause appreciable elevations of the dew point. $SO_2$ and $CO_2$ cause the formation of the weaker sulfurous and carbonic acids. All of these acids are corrosive to metals in greater or lesser degree.

The pH of condensate from firing No. 2 fuel oil was analyzed in experiments at Battelle to be about 3.0, compared to about 4.0 for gas firing (Heffelfinger, 1980).

These conditions make it necessary that special materials or coatings will have to be used to achieve reasonable life of the portions of a heat-exchanger system that are exposed to continuously condensing conditions during operation.

## Candidate Materials for Heat Exchangers

Corrosion resistance may be sought by use of stainless steel or other metal alloys, by ceramic materials, or even plastic materials in the low-temperature parts of the heat exchanger. Protective metal films, vitreous-enamel coatings or organic coatings on cold-rolled steel are also candidates.

Two recent reports describe results of materials testing for low-temperature corrosion, simulating condensing operation of heat exchangers. The Canadian Gas Research Institute tested a number of metals and coatings for corrosion resistance when exposed to cyclic condensing operation in a gas-fired system intended to simulate the heat exchanger of a warm-air furnace. (Beck & Khoo 1978) Results from the condensation test facility gave low weight losses for both aluminum and stainless steel alloys. Aluminum was susceptible to severe pitting even when anodized. Stainless steel (304 and 316) tended to undergo crevice attack, but this was not considered to be a serious drawback since this problem can be reduced to a great extent by careful heat-exchanger design. Coatings of Teflon-on-copper and lead-on-copper were recommended for further evaluation.

In a recent study on industrial waste-heat recovery for the Gas Research Institute, Solar Turbines International conducted some materials evaluation tests in flue gas from both No. 2 and natural-gas firing. During 100 hr tests in a condensing mode with oil firing, corrosion was visible with carbon steel; no corrosion was observed on Incoloy 800, Incoloy 825, and Hastalloy G, Teflon-coated carbon steel, and polyphenylene-sulfide-coated carbon steel.

Teflon sheet is being used in a condensing heat-exchanger development, supported in part by BNL. Timberline Industries has developed a tube-bundle assembly technique of joining Teflon-covered tubes to a tube sheet, as shown in Figure VII-2. The Teflon lining of the tube sheet is upset into the hole so that it contacts the Teflon sleeve covering the steel tubes; the seal is then Teflon to Teflon.

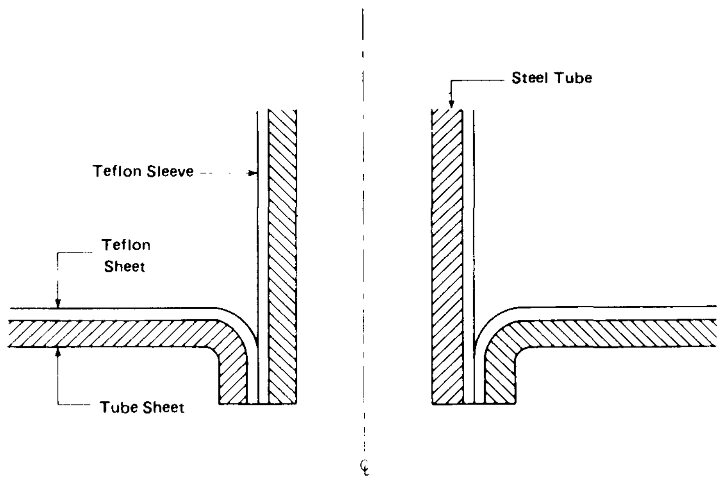



FIGURE VII-2. TECHNIQUE OF CLADDING METAL HEAT EXCHANGERS WITH PLASTIC (Timberline Industries, 1980)

Factors in addition to corrosion resistance must also be considered in the materials selection. These include:

- Formability
- Ability to weld or join
- Fatigue resistance
- High-temperature suitability (if used for the complete heat exchanger.)
- Availability of material in desired form
- Cost.

The materials choices will depend on the overall design approach.

## CONDENSATE CHARACTERIZATION AND DISPOSAL

Table VII-2 shows the chemical analyses of condensate from oil and gas firing obtained as part of the Brookhaven/GRI program. The Battelle samples were obtained with a furnace firing No. 2 oil operating at 11 percent $CO_2$ at an intermittent cycle of four minutes on and eleven minutes off. The AGAL samples for gas firing, shown for comparison, were obtained under steady-state firing of natural gas in a laboratory apparatus.

TABLE VII-2. CHARACTERIZATION OF CONDENSATE
(- Samples obtained from condensing flue gas on cooled glassware)

| | | COMPOSITION OF CONDENSATE | | | | |
|---|---|---|---|---|---|---|
| FUEL | EXCESS AIR, % | $NO_3^-$ PPM | $NO_2^-$ PPM | $SO_4^=$ PPM | $CO_2$ PPM | pH |
| Natural Gas* (A.G.A. Laboratories) | 40 | < 1 | 10.7 | 2.5 | 82 | 3.63 |
| No. 2 Fuel Oil** (Battelle) | 35 | 8.8 | – | 131 | – | 2.92 |

* Condensing Temperature 64 F (DeWerth, 1980), Cleveland Natural Gas

** (Heffelfinger 1980), No. 2 heating oil having sulfur content of 0.17 percent; intermittent firing of furnace, 5 minutes on and 11 minutes off; 11 percent $CO_2$ and zero smoke in flue gas; condensing temperature ~ 50 F.

All these samples were condensed on glassware and are "virgin" samples that were not exposed to metal or organic surfaces where additional reactions with the surface could occur. Condensate from metal surfaces may show evidence of reactions with these metals. With the pH levels shown in Table VII-2, condensate disposal to sanitary sewer lines may pose problems to house plumbing drains or municipal systems with mortared joints, unless dilution water flow can be assured. Some plumbing codes prohibit discharges of liquids having pH below 5.0. However, this range would prohibit the discharge of many common household liquids, including carbonated soft drinks. These issues are to be further explored as part of the DOE/BNL/GRI program.

## DESIGN AND APPLICATION CONSIDERATIONS

### Heat-Exchanger Design

In the design of condensing heat-exchanger systems, it should be recognized that all parts of a heat exchanger may be subjected to condensing operation at least for a brief period on startup from cold. Figure VII-3 illustrates this effect for two portions of a conventional furnace heat exchanger (Curves A&B) and for a portion of a condensing heat exchanger (Curve C). In the latter case, the surfaces would remain wet for a period after shutdown, possibly through the next cycle. The potential for corrosive attack would be expected to be particularly severe in this case. A design alternative is to allow the temperature to rise above condensing conditions just at the end of the firing cycle to dry off the surface; this could be accomplished by briefly reducing the cooling medium flow or by briefly increasing firing rate.

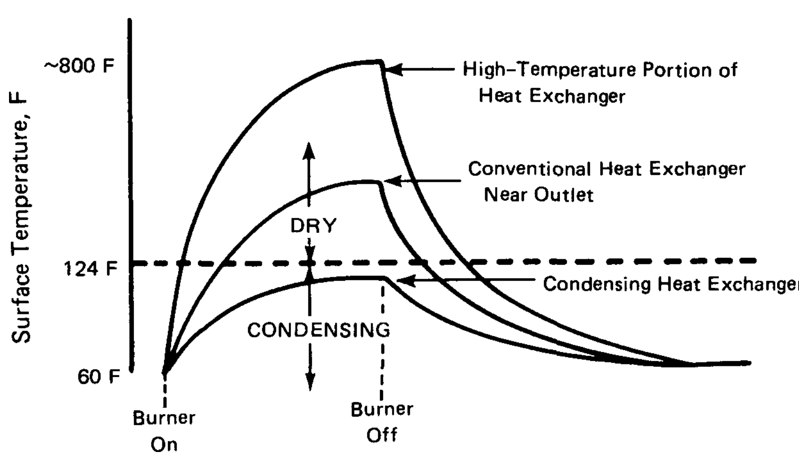



FIGURE VII-3. ILLUSTRATION OF CONDENSING MODE DURING CYCLIC OPERATION — All Surfaces of Heat Exchanger May Be Condensing On Start

The orientation of the heat exchanger surface and its relation to the flue gas flow are also important in design considerations. Figure VII-4 illustrates this effect. Sketch A shows how the wetted surface can shift and how reevaporation can increase the acid concentration of the condensate runoff. Sketch B shows a vertical surface with downward flue gas flow such that wetting occurs only on the lower portion below the dew point. Sketch C shows a vertical surface with upward flue-gas flow such that the upper part is below the dew point; here the condensate will flow and wet the entire surface, a condition desirable for increasing the condensing action and heat transfer.

The characteristics of the surface may also be significant, with heat transfer improved by surfaces that promote dropwise condensation, as opposed to film condensation.

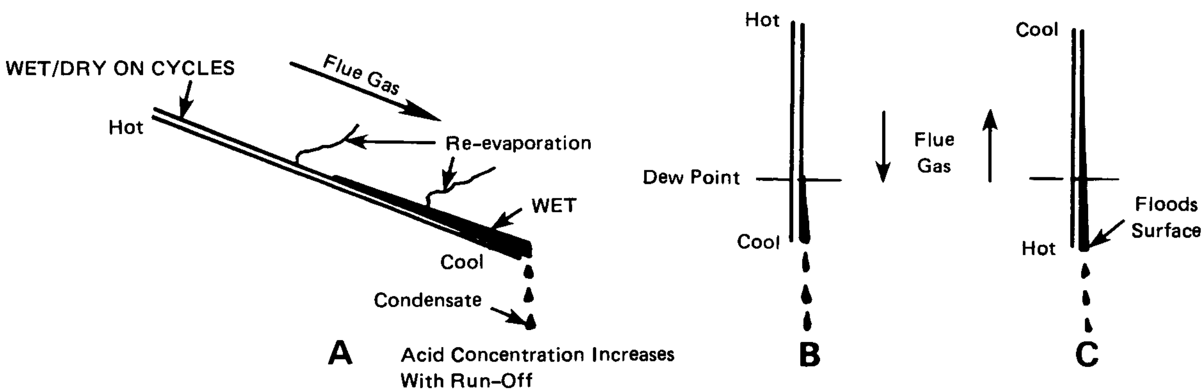



FIGURE VII-4. EFFECT OF SURFACE ORIENTATION IN CONDENSING HEAT EXCHANGERS

## Venting the Flue Gases

Low-temperature exhaust gases create some problems in venting. The main problems are (1) lack of buoyancy of the flue gas and (2) continued condensation in the venting system.

The bouyancy of the cooled gas is not adequate to create the degree of stack effect as in a conventional chimney or vent, so that a powered or pressurized vent may be necessary. A preferred venting method is directly to the outside through a corrosion-resistant pipe, often PVC plastic pipe. Runs must be pitched to drain to the inside and/or outside without dips that would collect condensate. Hundreds of gas-fired, pulse-combustion water-heater units have operated for more than 20 years in Canada, using small diameter plastic tubing for exhaust. A similar arrangement is being used in recent installations of pulse-combustion boilers in the U.S.

Problems with Retrofit Installations. Condensation in the venting system can cause deterioration unless the system is designed for the condensate. In retrofit installations, direct use of masonry chimneys should be avoided because of moisture and acid attack of masonry and mortar. Freezing at the top may also be a problem, both from materials deterioration and actual plugging by ice formation. A preferable approach is to install plastic pipe inside the chimney flue.

Factory-built vents or chimneys are not designed for pressurized or condensing operation, and the material may corrode severely. Moreover, for insulated metal vents, condensate leakage through joints may damage the insulation value such that fire safety is compromised, because the insulation is needed to limit temperature of combustible materials of the structure.

## PERSPECTIVE ON CONDENSING HEAT EXCHANGERS

Although the foregoing problems must be recognized, it appears that none are insolvable. The incentive to gain a new plateau of seasonal efficiency is certain to stimulate R&D on units with condensing heat exchangers. Their success in the marketplace will depend on the cost of materials and construction for adequate durability, plus constraints posed by codes and standards. It is not yet clear whether condensing-type heat exchangers will be cost-effective for oil-firing, but serious consideration is warranted, in view of the potential for high seasonal efficiency.

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# APPENDIX

## EXCERPTS FROM API PUBLICATION 1700

## "RECOMMENDATIONS FOR AN INDUSTRY-WIDE OIL-BURNER RESEARCH PROGRAM"*

**March 1960**



* Locklin, D. W., Battelle report to the American Petroleum Institute as part of the API Oil Burner Research Program, API Publication 1700 (March 1960).

** R&D areas most applicable to the present BNL/DOE program are flagged by asterisks on tables in this section.

# APPENDIX

## RESEARCH AND DEVELOPMENT NEEDS

As a result of this study, research needs are evident in many different areas. The most critical needs are considered as those which would contribute to the development of new systems for oil burning, and hence that would offer ways of overcoming existing limitations. These needs have widely differing characteristics. For example, not all the needs are of similar urgency nor have similar chances of success.

### Classification

Research needs can be classified or appraised in different ways according to objectives or points of view. Several such classifications are as follows:

- Importance or potential benefits
- Chances of success
- Application time
- Type of activity required
- Effort or expense required
- Problem area or function

The six classifications for appraising research needs are discussed in succeeding sections.

Importance or Potential Industry Benefits. The potential benefits of research efforts are of paramount significance in planning research programs. For oil-burner equipment, the research of greatest potential benefits would be those which lead to an entirely new and improved concept in oil burning, rather than to a small refinement of one or more conventional components. A research endeavor that successfully meets the objectives of a given program can be of little value if it fails to lead to beneficial application of the results, or to otherwise contribute significantly to the state of knowledge so that a later investigator may build on the nucleus of the work. For purposes of this discussion, potential benefits refer to the over-all goals of the API Fuel Oil Committee as outlined previously in this report.

Chances of Success. Research and development efforts are not always successful in the light of broad objectives formulated at the start of the work. Some exceed expectations by opening new areas, some must be written off as valueless, but more often, there are intermediate degrees of success. What is success to one point of view can be a failure to another. Frequently, the results of one phase of a program must depend for their application upon the success of another program. Thus, the estimation of the chances of success is a difficult but necessary task in planning research and development or in forecasting progress.

Application Time. Consideration must be given to the length of time for application of research results to reach the market or the field. Estimates of the time needed for application also require the forecasting of the duration of various phases of research. Many research programs yield significant and useful results throughout the duration of the work. Others may not reach useful conclusions until near the end of the program; this is particularly true of product development and of research requiring the construction and perfection of complicated experimental equipment. For purposes of this report, estimated application time will be considered in three categories:

(1) immediate – those results which can be expected to be put to immediate use in design or in field renovation for the market retention aspects of the program;

(2) intermediate – those results which must depend on other results or require extension for integration into a given application, probably to reach the market within five years;

(3) long range – those results which would not be likely to significantly influence or products on the market field practices within five years.

Activity. The type of activity required for a given program will be classified broadly in this report as follows. Research is intended to describe both fundamental and applied research without a specific and detailed equipment configuration as a development objective. This would include the investigation and explanation of physical and chemical phenomena and also investigations of feasibility of given principles within the sciences of physics, chemistry, fluid mechanics, and heat transfer. Development will be used in the context of invention and design which, through technology, integrates the sciences with practical art. Operations will refer to business functions such as production, marketing, delivery, service, and billing. Categorizing programs of research needs under these various activities is difficult, because many efforts oriented to consumer equipment will embrace one or more of these activities.

Effort required. In planning research and development, it is necessary to appraise the manpower effort and monetary expenditure necessary to achieve a given objective. Such appraisal must, of course, be considered only an estimate based on certain assumptions of progress and results since it includes estimating the rate of success within various phases. Depending on considerations of urgency and economy, different programs will have different relationships between program duration and the concentration of manpower. In some cases, a one-man effort for five years may be more fruitful than a three-man effort for a two-year period. Estimates for man-effort used in this report are considered as a professional man plus his supporting supervision, technicians, and services.

Problem areas. Research and development needs of the oil-heating industry can be classified according to broad problem areas or applications, although some overlapping is to be expected. Such classifications would include:

> Combustion Fundamentals and Burner Concepts. Atomization, vaporization, ignition, mixing and recirculation, combustion processes and smoke formation, surface and catalytic combustion, and experimental techniques.
>
> Product Development and Application. Burner design and development, and heat exchanger equipment.
>
> Residential Installations. The systems approach, combustion air supply and venting.
>
> Industry Codes and Standards. Chimneys, nozzles, filters, air pollution, and reference fuels.
>
> New Uses for Fuel Oil. Oil-fired air conditioning, household appliances, agriculture, industry and transportation, and direct generation of electricity.

For convenience, specific research needs will be discussed in detail according to these broad problem areas.

The following section covers numerous specific programs in the field of combustion fundamentals and burner concepts. It is especially important that refiners provide the lead in undertaking such work, because this area is least likely to be effectively explored by equipment manufacturers in their efforts to develop equipment by the quickest and most proven routes.

## Combustion Fundamentals and Burner Concepts

Many possible approaches can be identified that will lead to effective combustion. For example, the "brute force" approach of the pressure-atomizing burner involves mechanical atomization, high air velocity, controlled recirculation of combustion products, short residence time, and considerable combustion noise. The can-type combustor used on aircraft jet engines exemplifies extreme examples of each of these aspects, but achieves a high volumetric combustion rate at the expense of high pressure loss for mixing and combustion noise. In contrast is the natural-draft vaporizing burner which has no mechanical atomization but depends on regenerative heat for thermal vaporization; it is characterized by low air momentum, high degree of recirculation of combustion products, long residence time, and low combustion noise. When viewed in this manner, the rotary wall-flame burner is intermediate between the pressure-atomizing burner and the vaporizing burner; mechanical atomization is largely for fluid distribution and does not result in small droplet size. Large-scale controlled recirculation of combustion products aids vaporization, residence time is long, and combustion noise is moderate. Each of these systems has inherent practical limitations.

Factors other than purely combustion aspects also contribute to the limitations in reliability. Deposit formation and operational sensitivity to fuel characteristics are key factors in the success of practical application. Performance during cold starting and during normal intermittent operation is also of practical significance. Present oil burners have been largely developed as an art and, like all combustion systems, involved design compromises.

The art of oil burning has generally led the theory, as most theoretical and experimental studies have been based on systems already in use and have been directed to the measurement or explanation of phenomena already observed. Thus, there is need for information to permit the combination of principles which can exploit desirable performance characteristics, while minimizing practical limitations. To place oil-burner design on a rational basis, rather than a cut-and-try basis, a greater understanding is needed: (1) of the physical and chemical phenomena involved, (2) of the conditions that prevail in various zones of burner systems, and (3) the behavior of No. 2 fuels under different conditions. Unfortunately, a major portion of fundamental combustion research has been devoted to gaseous fuels and to simpler liquid fuels rather than to No. 2 fuels, which contain many components of varying characteristics. There are, thus, broad gaps in information of interest in the development of new combustion systems for oil-fired equipment.

In the sections which follow, specific research needs will be pointed out in each of seven areas:

(1) Atomization

(2) Vaporization and Preflame Deposits

(3) Ignition

(4) Mixing and Recirculation

(5) Combustion Processes and Smoke Formation

(6) Surface and Catalytic Combustion

(7) Experimental Techniques

Subsections describing research tasks recommended for consideration in planning a coordinated program are identified by decimal numbers within those sections. A brief appraisal follows each subsection. The research tasks will then be summarized and arranged according to importance under the main section on "Recommended Research and Development Priorities".

## 1. Atomization

As a preliminary step in the combustion of fuel oil, the liquid fuel must first be vaporized to permit mixing with air to form a combustible mixture. This vaporization can be provided thermally from the bulk liquid or from a hot surface, as in the case of the simple natural-draft vaporizing or pot-type burner, or can be facilitated by breaking the oil up into droplets from which the vaporization can occur as the spray approaches the combustion zone. The discussion which follows will apply to the atomization of fuel oil and utilization of the fuel spray with respect to droplet evaporation and combustion. The succeeding section will treat the thermal vaporization or gasification of liquid fuel directly for introduction to the combustion zone.

If the fuel oil can be atomized to a droplet size sufficiently small, the fuel spray can be considered to behave essentially as a gas for all practical aspects of mixing and combustion.[50] This critical droplet size would likely vary according to the system conditions, but it is generally considered to be between 1 and 20 microns, being probably in the neighborhood of 10 microns for conventional systems. Insufficient information is available as to the droplet-size distribution for conventional pressure atomizing nozzles, but it is doubtful that droplet sizes this small are obtained in significant mass percentages. In the over-all problem of combustion cleanliness, a relatively few large droplets can be the factor which makes the bulk-average smoke level unacceptable.

Various means of atomizing fuel are classified and discussed in API Publication No. 1537.[28] The principal limitation of the conventional high-pressure atomizing nozzle used in most residential oil-heating equipment is its sensitivity to fuel-oil deposits or particulate matter. The tendency toward clogging by deposits can be relieved to some extent by careful application techniques[33] but the inherent limitation of small and critical nozzle passages still remains. This is particularly true of burners having very low capacities. At low capacities, fuel properties have an appreciable effect on spray characteristics. With conventional air-atomizing or low-pressure atomizing nozzles, the clogging tendency is relieved to some extent, but droplet-size control at low capacities deteriorates to some extent. Low-pressure burners have not been successful in gaining dominance in the residential field, chiefly because of the higher initial cost and additional mechanical complication.

Figure 13 shows a return-flow nozzle, in which the rotational momentum of a relatively high delivery rate is used to impart atomizing energy to the fuel spray, bı

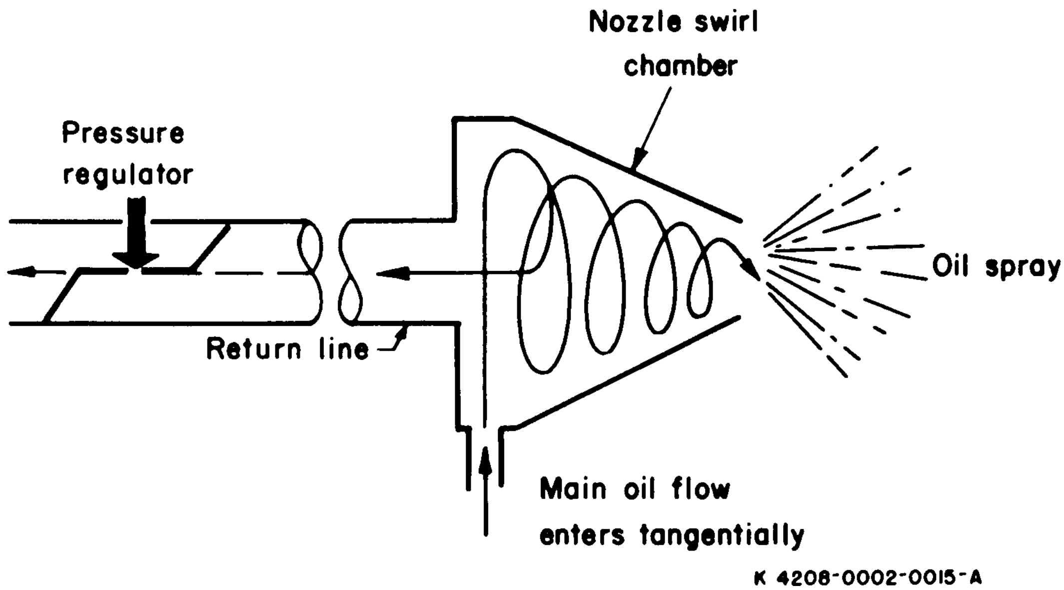



FIGURE 13. SCHEMATIC DIAGRAM OF A RETURN-FLOW NOZZLE[51]

portion of the main oil flow is diverted back to the source so a relatively low firing rate is achieved in the spray orifice. For a given delivery rate, a larger orifice is used than for conventional high-pressure nozzles. Of the commercially available atomizing systems employed on residential burners, the return-flow or bypass nozzle operating as a single-fluid atomizer is one relatively new approach to a satisfactory system.[51] The additional parts, particularly the pressure regulator and the additional mechanical complication, have severely hampered its commercial acceptance.

Other atomizing systems show promise and should be further explored for use in low capacity oil burners.

Recommended Research. Numbers applied to the following research tasks are intended to aid in identification for discussion of the recommended research priorities, outlined in a subsequent section of this report.

1.1 Determination of Quantitative Effects of Spray Droplet-Size Distribution on Combustion in Various Systems. Relatively little quantitative information is available on the droplet-size distribution of conventional oil-burner nozzles and of the effects of such distribution on the combustion process. This lack of information is due, in part, to the difficulty in making quantitative measurements.[52,53,54] Various techniques are discussed in API Publication No. 1537.[28] Experience suggests that there is a limiting mean droplet size which begins to have an important effect on combustion and also that a range of droplet sizes may be desirable within limits. Studies on evaporation from droplets indicate that the residence time and transport distance required to vaporize large droplets can exceed that of the combustion system. Thus, for the development of improved combustion systems it becomes desirable to have more information on the relation between droplet-size distribution and combustion characteristics. Such a research program should include the determination of spray characteristics of conventional or proposed atomizers and their performance in several representative burner configurations. This would form the basis for evaluating new atomization devices.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair

Application time – intermediate to long range

Estimated effort needed – 4 to 6 man-years

Estimated duration – 3 to 5 years.

1.2 Theoretical and Experimental Investigation of Fundamental Principles in Air Atomization of Fuel Oil. Air-atomizing nozzles have shown promise for application to low firing rates. However, the theoretical principles which govern their performance are not sufficiently well known to permit rational design of nozzles.[55,56,57] A thorough analytical and experimental study of these principles might provide important guides in the development of atomizing devices, such that atomization of sufficiently small droplets could be achieved with a minimum requirement for pressurized atomizing air.

Appraisal. Potential industry benefits – great

Chances of success – fair

Application time – long range

Estimated effort needed – 2 to 4 man-years

Estimated duration – 2 to 4 years.

1.3 Development and Evaluation of Syphon-Type Air-Atomizing Systems. An air-atomizing system can be designed in such a way that oil is lifted to the nozzle and airflow rate is controllable by air pressure. "Flit-gun-type" atomizers[58] are considered to be in this category of syphon-type air-atomizing systems. Recent developments in special nozzles(59) suggest that this system offers considerable promise as a means for burner design simplification by eliminating the need for a fuel pump in some installations. Substantial progress has already been made. This work should be extended to provide quantitative data on the relationship between physical configuration, air pressure and flow rates, oil-lift capability, noise, and oil-spray characteristics.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair to good

Application time – intermediate

Estimated effort needed – 2 to 4 man-years

Estimated duration – 1 to 3 years.

1.4 Conception and Evaluation of New or Unusual Means for Atomization. Present methods of high-pressure atomization are extremely inefficient in energy utilization, being less than one per cent efficient in terms of the theoretical energy requirements as a percentage of the actual energy supplied. Although not economically significant in itself, this fact suggests that there should be other methods yet unknown or undeveloped which would provide simpler, less costly, and more reliable equipment for atomization. Generation of droplets of smaller size, that would behave like a gas, could also permit the simplification of the remainder of the combustion system.

New means should be sought for supplying energy to the fuel required for atomization. Ultrasonic energy, although relatively inefficient, can be used to produce atomization by focusing a sound field near a surface of a liquid or by vibrating a surface on which, or through which, a fluid is flowing.(60,61) Vibratory energy generated by such means as fluid dynamic, electrodynamic, magnetostrictive, or piezoelectric transducers may find utility in atomizing oil as the cost of associated equipment is reduced by advancing technology. Atomization can also be accomplished by impact or by shearing action of a multibladed rotor moving relative to a fuel jet or sheet; contra-rotating blade systems have been used to accomplish this action. Impingement of two high-velocity liquid jets has been used to achieve atomization in rocket combusters but has not been employed in residential oil burners.(42) Generation of foams for fuel dispersal may have possibilities at low firing rates.(62) Electrostatically induced atomization is also possible; although the energy requirements and the necessary system arrangements have not been established for electrostatic atomization, this principle has been demonstrated.(63) These and other systems are discussed in the API Publication No. 1537 and should receive consideration as a part of the search for new concepts in atomization.

Appraisal. Potential industry benefits – great

Chances of success – fair

Application time – intermediate to long range

Estimated effort needed – 3 to 6 man-years

Estimated duration – 2 to 4 years.

<u>1.5 Feasibility Investigation of Spinning-Disk Atomizers for Low Firing Rates for Use in Premixed Burners</u>. Spinning-disk-type atomizers of various types are capable of producing a spray of extremely uniform droplet size, provided the loading ratio of oil flow rate to disk surface area is low. The size distribution becomes broader with heavier loading. The general theory and operating techniques are reasonably well established for spinning-disk atomizers.[42,64] However, investigation should be made of the relationship between fuel-feeding method, disk diameter, and rpm required to produce droplet sizes in the desirable range for premixed burners using No. 2 oil.

Figure 14 shows a spinning-disk used in atomizing fuel oil. This principle has been used in various oil burners, but past residential applications have been higher in firing rate and have involved a flame front in close proximity to the disk[65]; the accompanying problems of fuel deposit and materials life at elevated temperatures could be relieved by so designing the system that the combustion zone is not immediately adjacent to the disk. The spinning-disk-type atomizer shows promise in application at low firing rates.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair

Application time – intermediate

Estimated effort needed – 1 man-year

Estimated duration – 1 year.

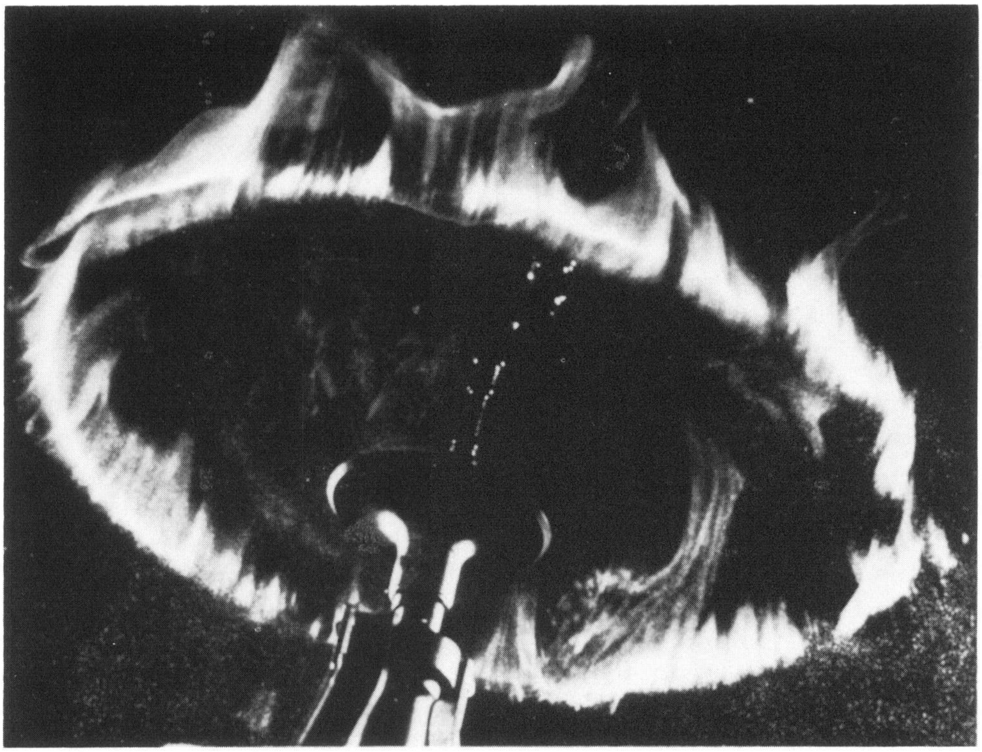


FIGURE 14. COMBUSTION OF FUEL-OIL DROPLETS GENERATED BY A SPINNING-DISK-TYPE ATOMIZER[42]

1.6 Feasibility Investigation of Aerodynamic Devices Like the Hartmann Whistle for Atomization at Low Firing Rates. Aerodynamically generated shock waves can be utilized to atomize fuel but it would be necessary to design such devices to operate outside the range of audible sound frequencies. Devices like the Hartmann whistle, as shown in Figure 15, have been used in atomization of other liquids[61,66] by adding energy to the system in the form of pressurized air; however, it is not known whether desirable droplet sizes of fuel oil can be generated within practical limits of pressure and quantity of air. The relationship of droplet distribution, air pressure and volume requirements, and fuel rate should be investigated experimentally for various device configurations to evaluate the economic and practical feasibility of application to small residential burners.

Appraisal. Potential industry benefits – moderate to great

Chances of success – poor

Application time – intermediate

Estimated effort needed – 1 man-year

Estimated duration – 1 year

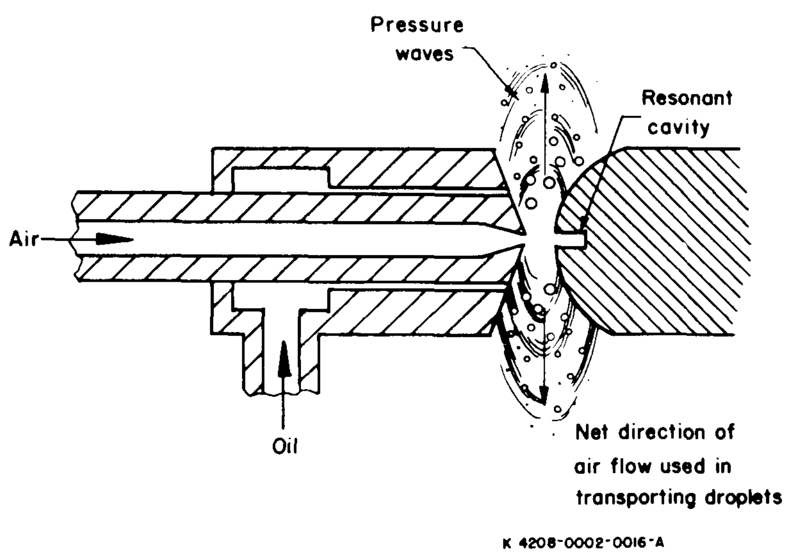



FIGURE 15. SCHEMATIC VIEW OF THE HARTMANN WHISTLE USED AS A LIQUID-ATOMIZING DEVICE(61,66)

2. Vaporization and Preflame Deposits

A broad scope of new burner design possibilities would be opened by the development of an effective, reliable, and low-cost vaporizer or gasifier for No. 2 fuel oil. The fuel-air mixing process would be greatly simplified and the burner could be similar in characteristics to that of a conventional gas burner. Complete vaporization appears to be necessary for the application of porous-type burners(67,68), whether catalytic action is involved or not.

Figure 16 illustrates schematically the vaporization process in several conventional types of oil burners and two concepts in preflame vaporizers. The chief problem in burner development lies in determining and providing the conditions required for vaporization without fuel deposits in locations or in quantities that interfere with a reliable, automatic operation of the equipment. One requirement for a successful burner is the ability to transfer the fuel from the relatively cool handling system to the hot-combustion zone without such deposits. Vaporization and combustion are generally controlled by physical rather than chemical processes; however, deposit formation may be controlled to some degree by chemical processes. Preflame reactions are possible under some conditions to the extent that appreciable energy could be released in a preflame zone. The complexity of the factors involved has not been conducive to a systematized and rational understanding of the limiting conditions where deposit is to be expected.

In view of the advantages to be gained from a No. 2 fuel-oil vaporizer, this represents an important area for research.

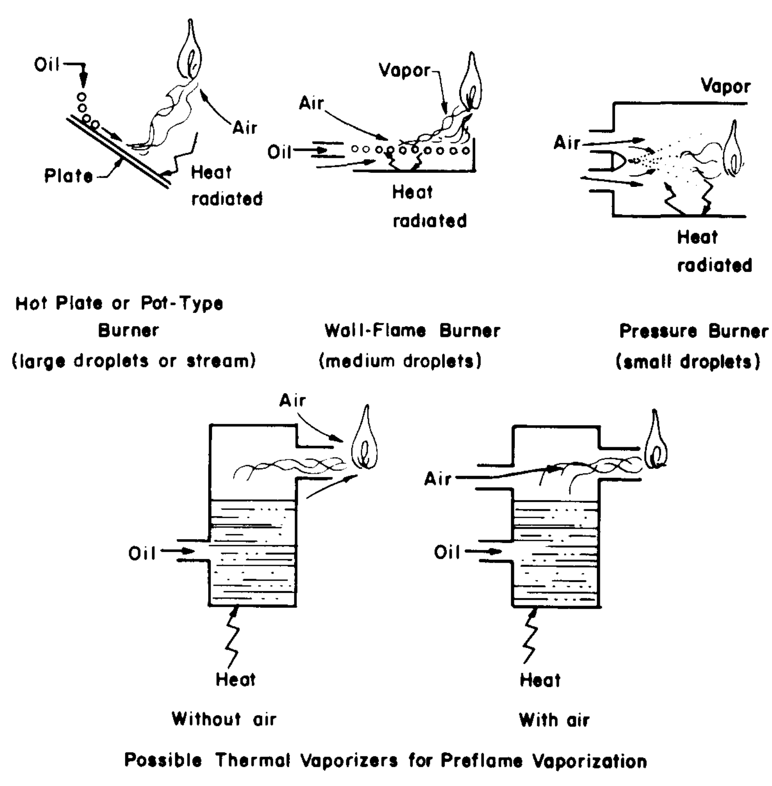



FIGURE 16. SCHEMATIC REPRESENTATION OF FUEL VAPORIZATION IN OIL BURNERS

2.1 Determination of Conditions for Vaporization of No. 2 Fuel Without Surface Deposits. It is not known whether conditions exist which would allow practical operation of a vaporizer for No. 2 oil; however, a serious attempt should be made to ascertain and delineate such areas. Not only are equilibrium conditions important, but a knowledge is needed of regions through which successful cyclic burner operation can be expected. Factors of importance include residence time, vapor or liquid temperature, surface temperatures, and mixture compositions. The addition of air or other diluent, such as recirculated combustion products, to a flash-vaporization process can reduce the temperature required for vaporization by depressing the partial pressure. For example, substantially complete vaporization of the typical No. 2 fuel oil can be achieved at 290 F in the presence of 150 per cent of stoichiometric air, whereas 558 F is required for complete vaporization without air. Essentially complete vaporization occurs in fuel-rich zones of some burners, particularly pot-type burners.[69] A quantitative knowledge of conditions in various burner types is, therefore, of importance.

Research in connection with military aircraft fuels is now being reported on vaporization, deposits, and combustion processes of multicomponent fuels.[70,71,72,73] A systematic review of this type of information is in order, although it is likely that there are broad gaps in the knowledge applicable to deposits of No. 2 heating fuels which would have to be filled in by additional experimental investigation. Differences in fuel characteristics are unquestionably a critical factor; however, this should not deter an attempt at mapping ranges of deposit-free conditions which may be used in a rational approach to vaporizer development for representative No. 2 fuels.

Appraisal. Potential industry benefits – great

Chances of success – fair to good

Application time – intermediate to long range

Estimated effort needed – 6 to 10 man-years

Estimated duration – 2 to 5 years.

2.2 Conception and Evaluation of Schemes for Precombustion-Zone Vaporization. Vaporization can be achieved either by an external energy source such as an electric-resistance heater or by utilization of heat from the combustion process itself, as by recirculated products of combustion. Possibilities for precombustion-zone vaporization include evaporation from the liquid phase, from a liquid on a hot surface, or by heating suspended liquid droplets. Consideration should be given to various novel systems which can be evaluated in the light of the results of the program previously described in 2.1.

Experience with existing burner types suggests that it is possible to operate a burner successfully through conditions which are conducive to deposit, provided the deposit can be consumed during conditions occurring at another time in the normal cycle. For example, an electric heater for a vaporizer could conceivably be operated with an air purge at the end of a cycle to provide temperatures sufficiently high to consume the deposit. Another design possibility, if deposit location and amount can be controlled, is an expendable element which would contain the deposit and be replaced or cleaned at intervals; in order to be practical, the frequency of attention required should not be oftener than once every several seasons nor oftener than the fuel line filter needs replacement with fuels of the quality expected in the future.

Appraisal. Potential industry benefits – great

Chances of success – fair

Application time – intermediate

Estimated effort needed – 2 to 3 man-years

Estimated duration – 1 to 2 years.

2.3 Investigation of Factors Involved in Deposit Formation in Conventional Nozzles and Determination of Permissible Operating Limits. Important to the reliability of an atomizing device is its ability to operate without fuel deposits. This problem of deposits in nozzles is generally considered to be a fuel-handling problem, but the mechanism of deposit may be partially a vapor-phase deposit during off-periods, making it somewhat similar to that which would be encountered in thermal vaporizers.

Deposits in nozzles comprise the most serious single service problem to the residential oil-heating industry and account for the greatest number of interruptions in automatic operation of oil burners, aside from problems associated with controls.[74] Yet, there is little conclusive information which can be used as a guide to the design or application engineer as to the critical temperatures for nozzles. Knowing the maximum permissible nozzle temperature for a given set of conditions, the application engineer could use this as an experimental criterion for selecting combinations of air-pattern and combustion-chamber designs. The temperature environment of the nozzle, both during the firing cycle and immediately following shutdown, is believed to play a significant part in the deposit problem.[33] Fuel characteristics are also important; however, more information is needed concerning application and material factors which can be controlled in equipment design. Planned field-performance investigations would aid in judging the applicability of results obtained from experimental laboratory studies. A greater knowledge of these factors influencing deposits could lead to improvement or replacement of components for existing equipment in the field.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair

Application time – immediate to intermediate

Estimated effort needed – 1 to 3 man-years

Estimated duration – 2 to 3 years.

### 3. Ignition

Initial ignition of a combustible mixture is generally brought about by the addition of energy to the mixture and, in most residential oil burners, this is accomplished by an electric spark. Other means of adding energy include hot-wire resistance heaters and pilot burners. Because a flame can propagate and expand into a flammable mixture, it is only necessary to cause ignition to occur in a small localized region of the mixture; consequently, only small quantities of energy are required to cause ignition if the energy is concentrated.

In considering the reliability of spark ignition in oil burners, two basic phases are involved: (1) the establishment and maintenance of the initial cascade or discharge of electrons to form the spark across the electrodes and (2) the ignition of the combustible mixture by the energy supplied by the spark. Both of these phenomena are statistical in nature and are affected by surrounding conditions. The first phase is favored by narrow electrode spacings and the second phase is favored by wider spacings. High velocities of air or mixture have an adverse effect on both phases. The shape of electrode tips is significant in ignition delay of the first phase, in that pointed electrodes improve chances of establishing the spark[75]; however, in service a marginal condition can be reached when electrode tips become burned off. Wider electrode spacings place a heavier load on the transformer.[76] Fuel deposits on the electrodes will obviously affect spark establishment. Radioactive materials near the electrode have been used to improve the threshold of sparking by providing spark-gap ionization.[77] In addition, the second phase of ignition is governed largely by the electrode geometry[78], composition, and velocity of the fuel-air mixture in proximity to the spark; thus, the location of the electrode is important.

Hot wires, glowing conductive ceramic bars, friction-generated sparks, catalytic devices, and pilot flames have been used for ignition in practical systems. Hot gas jets have also been studied.[79] In contrast to electric sparks, these devices are generally characterized by: (1) a relatively slow addition of energy to the combustible mixture, (2) a relatively large physical area or volume influenced by their operation, and (3) a large energy release during the ignition period. These devices appear to operate by a temperature mechanism rather than an energy mechanism as in electric sparks; that is ignition occurs when a local region of the combustible mixture is heated above its ignition temperature. Pilot flames offer interesting prospects in application to oil burners since the primary safety-control circuit might be simplified to that used for gas burners, by "proving" the existence of the pilot flame and with the assurance that the main burner would always ignite if the pilot were burning. In an oil-fired pilot, the chief problem lies in the control of low oil-flow rates and in the development of a small burner capable of clean and reliable operation.

Of the ignition systems other than spark type, the hot wire appears to offer the greatest chance of successful application.

3.1 Investigation of the Fundamental Requirements for Ignition of Fuel-Oil Sprays and Vapor-Air Mixtures. Energy supplied in the electric spark in ignition systems of present burners is many times that needed for ignition of a combustible mixture at rest. Before ignition can occur in sprays of fuel oil, the ignition system must first vaporize a portion of this fuel. With few exceptions(80,81,82), fundamental studies on ignition of combustible mixtures have been concerned with the ignition of homogeneous, quiescent gases by single electric sparks of short duration. A review(42) of these studies has shows that ignition will occur if more than a certain minimum energy is released by the spark. This minimum energy is influenced by the type of fuel, the temperature and pressure of the mixture, and the geometry of the spark electrodes. Although none of these investigations have provided data which would apply to the design of fuel-oil ignition systems, they add to the knowledge of the important factors involved. Thus, knowledge is needed concerning fundamental energy requirements for ignition of No. 2 fuel by electric sparks, hot wires, hot gas jets, and pilot burners. Experimental investigation of the minimum energy requirements for these types of ignition should include effects of mixture velocity and temperature, spray droplet-size distribution, and mixture composition. This information might not be directly and quantitatively applicable to the design of burner ignition systems, but would lead to an improved understanding of ignition, particularly as regards the location and the most desirable mixture conditions for the ignition system.

Appraisal. Potential industry benefits – small

Chances of success – fair to good

Application time – long range

Estimated effort needed – 3 man-years

Estimated duration – 2 years

3.2 Evaluation of Performance and Life of Alternate Ignition Means. Less conventional ignition means should be examined, in the light of new materials and technology for their applicability to oil-fired combustion systems. Capacitor-discharge spark devices should be considered. Other ignition devices, such as a resistance-type hot wires of high-temperature alloys and glowing ceramic bars, may have application for ignition in oil-fired combustion systems if properly located. Some degree of localized catalytic action could conceivably be obtained, for example, by coating the hot wire with a catalyst if the material were sufficiently stable at the temperature required. Compared to equipment for spark ignition, smaller and lower cost transformers may be possible with hot-wire ignition systems; also insulation requirements may be reduced. Advances in high-temperature metallurgy may provide materials suitable for igniters. Determination of factors governing their ignition performance and service life should prove of assistance in judging their applicability in burner design.

Appraisal. Potential industry benefits – moderate

Chances of success – fair

Application time – immediate to intermediate

Estimated effort needed – 2 to 3 man-years

Estimated duration – 1 to 2 years.

3.3 Feasibility and Conceptual Investigation of Low-Capacity Oil Burners for Pilot Operation. A reliable and clean-burning small pilot flame would offer advantages (1) as an ignition device and means to simplify primary safety control and (2) as a means of maintaining temperatures which might be needed for cold starting of vaporizing and/or recirculating-type burners. Improved and deposit-free pilot burning has long been an objective in the field of vaporizing burners. One approach might be the use of an electric heater, maintaining a surface hot enough to ignite small quantities of oil. Another approach might be the use of a small standby pilot plus a second pilot stage for ignition. Problems in combustion, metering, and over-all burner design are generally found to increase in inverse proportion to firing rate; hence, a pilot burner for No. 2 fuel would present a difficult task, but a rewarding one if successful.

Appraisal. Potential industry benefits – moderate to great

Chances of success – poor to fair

Application time – long range

Estimated effort needed – 3 to 5 man-years

Estimated duration – 2 to 3 years.

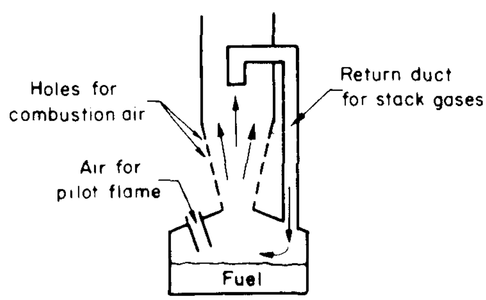
### 4. Mixing and Recirculation

Mixing of the fuel spray and/or fuel vapors to permit diffusion with combustion air is the rate-controlling mechanism in most combustion systems and is the principal distinguishing feature of combustion characteristics found in different burners. The final process of intimate mixing of the fuel and air is by molecular diffusion. However, for practical combustion systems, proper mixing and turbulence is required to provide the small-scale mixing that moves various fuel-rich and fuel-lean zones close enough together that molecular diffusion can rapidly produce an intimate mixture. The equipment designer has little control over molecular diffusion, but both turbulent mixing and recirculation can be influenced by design. Inasmuch as the design of features to provide this control is generally by empirical cut-and-try methods, information is needed which would permit a more rational approach or at least a better definition of guiding principles.

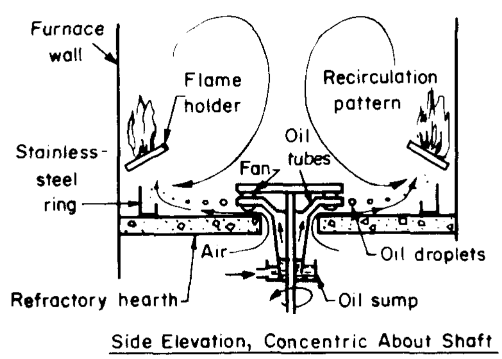
Recirculation of combustion products into the flame occurs in nearly all combustion systems, including pressure-atomizing burners. However, some burner designs control and exploit this principle to a greater extent than others. Rotary wall-flame burners and vaporizing burners are common examples, and other more recent burner developments have special features to utilize combustion products recirculation to a high degree. Demonstrated benefits from such recirculation include cleaner combustion at low excess air, higher combustion rate per unit volume, and reduced combustion noise level.

Figure 17 illustrates six burners which utilize recirculation of combustion products: (a) vaporizing burner with recirculating tube(69), (b) rotary wall flame burner(65), (c) burner with recirculation "can" and secondary air jets(83,84), (d) high velocity burner with similar "can"(85), (e) louvered combustion chamber to induce recirculation for a pressure burner(86), and (f) continuous-loop-type perforated-tube burner(59).

Although the benefits from recirculation are known in a qualitative way(85,87,88,89,90), the exact mechanism by which dilution of combustion air supply affects the combustion process is not fully understood. One of the most promising areas for development of improved burner systems lies in the controlled recirculation of combustion products; however, quantitative data are lacking for use in designing these systems.



(a) Return-Stack Vaporizing-Type Orchard Heater



(b) Vertical Rotary Wall-Flame Burner

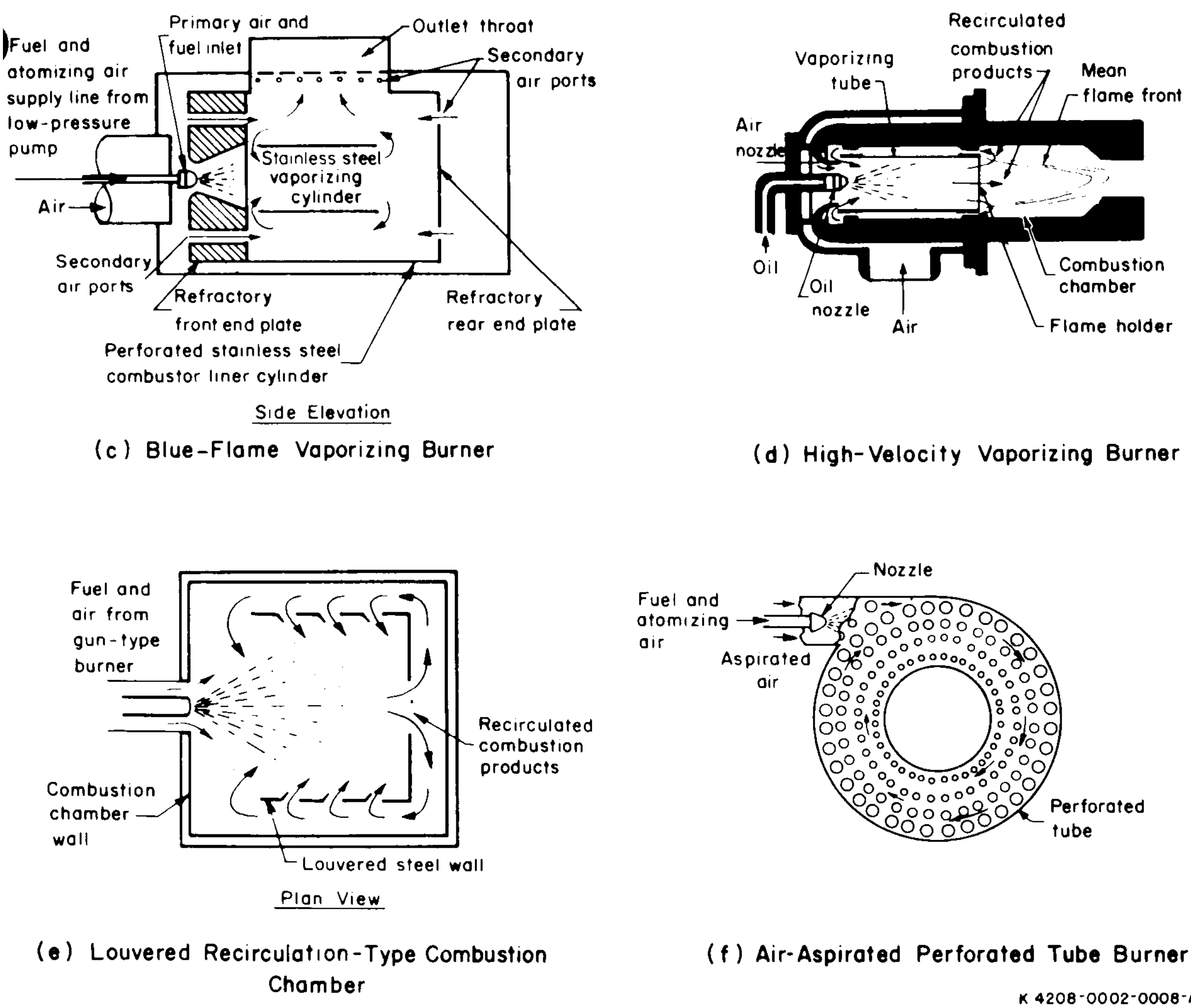



FIGURE 17. EXAMPLES OF RECIRCULATION-TYPE BURNERS

4.1 Study of the Combustion Mechanism as Affected by Air-Supply Dilution – Including Controlled Recirculation of Combustion Products. Benefits resulting from the introduction of recirculated combustion products are greater than can be explained by thermal effects alone, which would certainly aid in droplet vaporization and kinetic diffusion in mixing. Limited experiments have demonstrated that inert diluents added to the combustion air supply will aid in combustion[69,91]; thus, the benefit is not entirely chemical. This lends support to the theory that partial pressure relationships between the fuel droplets and the mixture are important or that separation of fuel molecules is effective in reducing smoke formation during combustion. Burners with marked recirculation features have characteristically nonluminous flames, indicating little free carbon in the flame.

Research is needed on the mechanism involved and the quantitative effects of recirculation to determine (1) optimum recirculation ratios, (2) the stage of the combustion process where dilution is most effectively introduced, (3) the influence of diluent composition and temperature, and (4) the effect of diluent on flame-speed and stability. A more thorough understanding of the interrelationships of these factors would be of great value in advancing oil-burner design.

Appraisal: Potential industry benefits – moderate to great

Chances of success – good

Application time – intermediate to long range

Estimated effort needed – 5 to 6 man-years

Estimated duration – 3 to 4 years.

4.2 Determination of Gas Composition, Temperatures, and Smoke Within Local Zones of Various Burner Systems – Particularly Recirculating Types. Even though developers have devised equipment which is believed to make use of the beneficial effects of recirculation and intense mixing, few have attempted to measure the conditions which prevail in various local zones in the combustion system. A knowledge of these conditions should aid materially in guiding and extending development of recirculating-type burners. A survey involving experimental probing of existing systems would supplement and guide the efforts in the more fundamental approach recommended under 4.1.

Appraisal. Potential industry benefits – moderate to great

Chances of success – good

Application time – intermediate to long range

Estimated effort needed – 4 man-years

Estimated duration – 1 to 2 years.

4.3 Development of Combustion Systems to Exploit Recirculation – With Practical Means for Cold Starting. Certain practical problems are inherent in combustion systems which provide benefits of recirculation. These include problems incurred in intermittent operation, of fuel deposits, of premature failure due to high component temperatures, of mechanical complication, and of initial equipment cost.

The most significant of these problems which must be overcome is involved with the intermittent operation found in residential heating and similar applications of small burners. On cold starting, the burner must operate without the benefit of the thermal or other effects of recirculated products of combustion, unless special provisions are made. If the starting and warmup period is short and does not lead to progressive soot or deposit buildup, the situation of initially poor combustion might be tolerated. The use of light-weight materials, such as stainless steel and ceramic combustion chamber materials[92,93], might provide a sufficiently rapid approach to equilibrium combustion conditions. Other means of overcoming the starting problem should also be considered, such as the use of combustion chamber preheaters, pilot flames, and staged proportioning devices. To be successfully applied to residential heating, the system must be reasonably low in cost and must provide adequate component life and extreme reliability.

It is conceivable, in systems with high recirculation rates and long residence times, that the requirements for fine droplet size of fuel sprays may be much less critical and, therefore, open new areas to atomization techniques which are more reliable at low capacities.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair

Application time – intermediate to long range

Estimated effort needed – 4 to 8 man-years

Estimated duration – 2 to 4 years.

<u>4.4 Development of a Rational Method for Predicting or Experimentally Determining the Optimum Relationship Between Air Pattern and Oil-Spray Pattern</u>. In burners utilizing a fuel spray, the relationship between the spray pattern and the pattern of combustion air is critical in determining combustion performance. Further, these are the factors which can be controlled by the burner designer and, to some extent, by the serviceman in the field. Greater knowledge is needed of the desirable relationship between spray pattern and air pattern.

Figure 18 illustrates how fuel droplets can miss the main air pattern in a pressure burner. Simple matching of the over-all pattern angles, to assure that all the fuel droplets are air-swept[17], has been demonstrated to be helpful but is probably not adequate alone in assuring the best combinations of patterns. Spray distribution should be considered. Study should also include the extent to which recirculation is significant in pressure burners.[94] Information gained in this area of mixing would not only be of assistance in new burner development but would also contribute to improvement of existing field installations.

Appraisal: Potential industry benefits – moderate

Chances of success – good

Application time – immediate to intermediate

Estimated effort needed – 4 to 6 man-years

Estimated duration – 2 to 3 years.

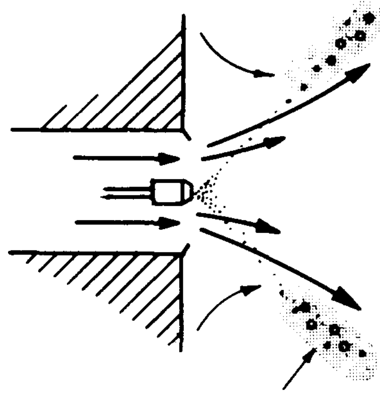



FIGURE 18. EXAMPLE OF MISMATCHED AIR PATTERN AND FUEL-SPRAY PATTERN

4.5 Investigation of Relationship Between Burner Entrance Velocity, Mixing Turbulence, Recirculation, Volumetric Heat Release, Scale Factor, and Random Flame Noise in Combustion Systems. High-volumetric combustion rates are possible when a high degree of turbulent mixing is provided, but this is accomplished at the expense of pressure drop and noise. The important factor in determining the pressure drop across the combustion zone is the entrance velocity. There may be limiting relationships among the various factors which would define design boundaries. A fundamental analysis and model study might reveal the significant variables involved, but, in addition, a thorough survey and cataloging of existing burner types should be made. Some attempts have been made within a limited field of industrial burners(90) but this should be extended to other criteria and to combustion systems including recirculating-type and porous-type premixed burners. The influence of various special design features should become more evident and provide significant data for more rational, but still empirical, design of burners.

Appraisal. Potential industry benefits – moderate

Chances of success – fair

Application time – long range

Estimated effort needed – 4 to 6 man-years

Estimated duration – 2 to 4 years.

## 5. Combustion Processes and Smoke Formation

Relatively little quantitative information is available on the fundamental process or sequence of processes by which combustion of fuel oil takes place.[42] Fundamental studies of combustion and flames have largely been carried out with simple burners using gaseous fuels having single or relatively few hydrocarbon components. Unfortunately, these results are of limited direct value in design or evaluation of fuel-oil combustion processes. The combustion of liquid fuel oil is complicated by the fact that vaporization must precede actual burning and also that the fuel is composed of many different hydrocarbons varying in density, carbon-hydrogen ratio, volatility, saturation, stoichiometric air requirements, and over-all burning characteristics.[95] An additional problem with fuel oils is the tendency of heavy components to polymerize or to form gas-borne carbon particles or smoke.

Surprisingly little fundamental combustion data have been obtained with vaporized fuel oil or with vaporized individual cuts from fuel oil. Information that does exist on combustion of liquid hydrocarbons is principally based on kerosine-type hydrocarbons which are more favorable for clean combustion than the heavier components found in No. 2 fuel oil.[95] Because of the limitations imposed by idealized or simplified conditions needed in the measurement of fundamental combustion factors and reactions, research from this area cannot be expected to provide data which can immediately be applied quantitatively to design of new combustion systems. Nevertheless, this area should be explored to permit definition of limiting conditions and significant guiding principles.

5.1 Fundamental Investigation of the Mechanism of Smoke Formation in Fuel-Oil Combustion Processes. The formation of smoke is not understood and it is likely that there are several mechanisms which can lead to particles borne in the combustion gases.[96] The character of the particles is important relative to their deposit tendencies on heat-transfer surfaces and in the flues. In present residential oil-fired equipment operating normally, smoke is not an air-pollution nuisance, nor does the quantity of combustible material represent a significant economic loss to operating economy in itself. The chief interest in smoke formation and soot deposit stems from their effects upon the operational reliability of the equipment and upon the effectiveness of the heat-transfer surfaces. Deposits referred to here are combustion and post-combustion deposits, as distinguished from the surface deposits in the pre-combustion zone discussed previously in connection with liquid-phase and vapor-phase deposits in vaporization.

Among the processes and mechanisms which are thought to be important in the formation of smoke are thermal decomposition and cracking, partial oxidation, polymerization of fuel molecules, and fragmentation and agglomeration of carbon particles. The effectiveness of so-called combustion improvers is believed to lie in their influence on one or more of these mechanisms of smoke formation.

Because of the time variation of mixture ratio in various zones of the combustion chamber, it is possible for a droplet to go entirely through the combustion chamber without being properly mixed with air to form a combustible mixture around the droplet; this can produce smoke even though the bulk of the combustion is normal and without smoke. Usually, the portion of the fuel which appears as smoke is exceedingly small. The regions where smoke occurs are thus localized and these localized regions are responsible for the apparent poor combustion of the over-all combustion process.

While knowledge of the precise mechanisms of smoke formation would be a guide to understanding and developing combustion systems, such research would be a formidable undertaking and would not necessarily provide data needed for design. An approach of more immediate value is described in 5. 2.

Appraisal. Potential industry benefits – small to moderate

Chances of success – poor to fair

Application time – long range

Estimated effort needed – 4 to 8 man-years

Estimated duration – 3 to 5 years.

5. 2 Determination and Mapping of Combustion Conditions Which do not Produce Smoke for a Typical Fuel Oil. An empirical approach to the determination of smoke-free combustion conditions would yield quantitative data for design, without necessarily leading to an understanding of the fundamental phenomena involved. What is needed are experimental investigations which would permit mapping a field of conditions with boundaries establishing where smoke begins. Parameters of interest would include droplet-size distribution, mixture composition, preflame mixture temperature, pressure, turbulence, and the character of the smoke produced as certain boundaries are crossed. This type of information would be most valuable in analyzing combustion systems.

Appraisal. Potential industry benefits – great

Chances of success – fair

Application time – long range

Estimated effort needed – 3 to 5 man-years

Estimated duration – 2 to 4 years.

5.3 Fundamental Investigation of the Combustion Process and Flame Propagation in Turbulent Flames of No. 2 Fuel-Oil Vapor-Air and Spray-Air Mixtures. Combustion in practical burner systems is nearly always involved with turbulent flames, as contrasted to laminar flames. Although fundamental data are available for turbulent flames in simple gaseous fuels, data are lacking on the fundamental properties of turbulent flames in fuel-oil combustion. Experimental studies are needed to provide such information as the burning velocity, flame thickness, and stability limits for both fuel vapor-air mixtures and for fuel spray-air mixtures. This type of information is of value in proportioning ducting within combustion systems.

Appraisal: Potential industry benefits – small to moderate

Chances of success – fair

Application time – long range

Estimated effort needed – 3 to 4 man-years

Estimated duration – 2 to 4 years.

## 6. Surface and Catalytic Combustion

Recent developments in porous-type burners for both natural gas[67,97,98] and vaporized-fuel oil[68] have renewed interest in surface combustion and in catalytic combustion[99]. The two terms are not necessarily synonymous. Surface combustion refers to combustion in close proximity to a surface which acts in a physical manner to transfer heat or to stabilize the flame or both. In catalytic combustion, the chemical reaction occurs at a properly active surface, at a lower temperature than the uncatalyzed combustion reaction would normally occur with the reactants involved. For true catalysis, the catalyst must be unchanged by the reaction and, therefore, not be consumed in the process. No precise definitions of surface and catalytic combustion processes have been universally accepted and their individual effects cannot generally be distinguished, except at low temperatures. Much confusion, therefore, occurs in the terminology applied to surface and catalytic combustion.

Figure 19-a and b show examples of porous-type burners in which a combustible mixture is forced through a porous material, usually ceramic[98], or through small

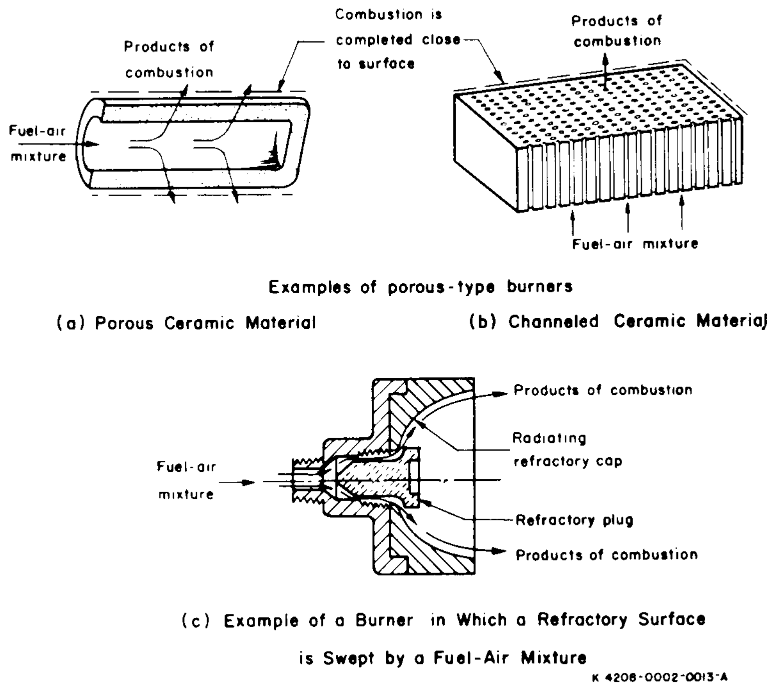


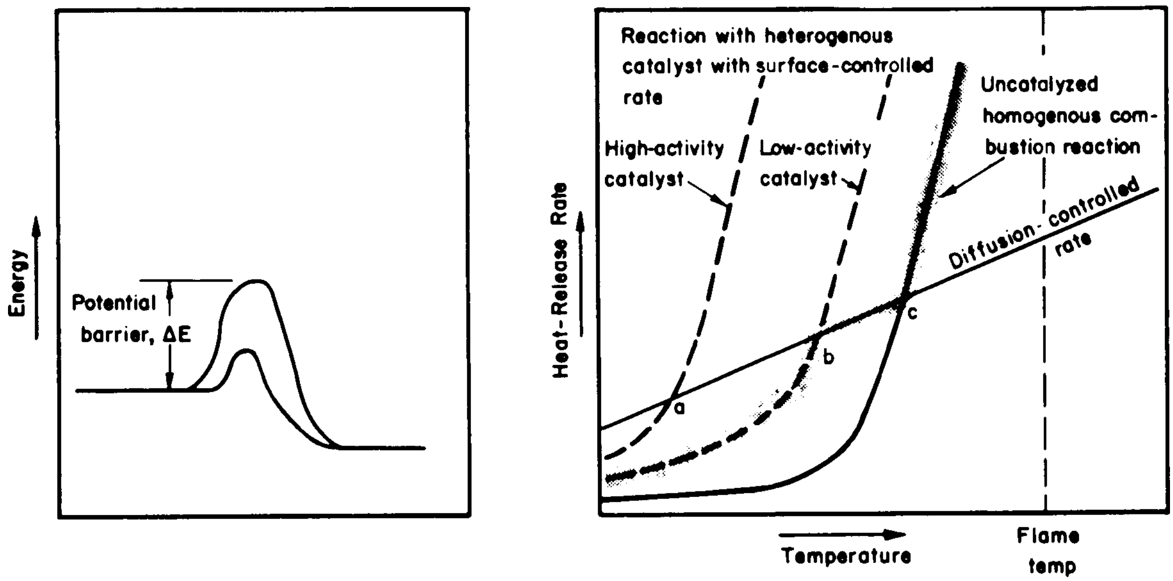

FIGURE 19. PREMIX BURNERS ILLUSTRATING SURFACE COMBUSTION[67,98,103]

channels in a block of ceramic.[67] Another example would be the Wellsbach mantle. Surface combustion can occur either within the pores or near the outside surface. The combustion process in porous burners can be considered to be a large number of micro-flames established at the pore openings either inside or at the surface.[100] In addition, there may be a third-body reaction[101] in which the surface serves to carry away some of the energy of the combustion reaction. Although the material is usually of low conductivity to maintain a large temperature gradient in the block, there is some regenerative action by heat conduction to the preflame zone. Catalytic action in the strictest sense need not be involved in a porous-type burner, although catalysis could aid in cold starting or modify the temperature gradient which would prevail without catalysis.

Heat-release rates per unit area with high-temperature types of such burners[67,98] are reported to be from 44,000 to 144,000 Btu/hr/sq ft of surface area. It is of interest to note that, within premixed hydrocarbon flames, the heat release rate is approximately 360,000 Btu/hr/sq ft of flame surface.

Porous-type burners permit a reduction in over-all equipment volume devoted to combustion as compared to conventional burners; this can become advantageous where compactness is desirable.[12] Although high outside surface temperatures are possible with surface-combustion burners, their heat-transfer characteristics follow established principles. To heat a second fluid, such as furnace air or boiler water, and achieve high over-all thermal efficiency, both radiation and a considerable degree of convective heat transfer must be utilized. Some porous-type burners have a high enough pressure drop that a blower is required to deliver the combustible mixture. Because this blower is already required, a compact and relatively high-pressure-drop heat exchanger can be utilized without a further serious cost penalty in equipment design.

Figure 20-a shows the way in which a catalyst reduces the activation energy of a reaction and therefore increases the rate at which the reaction will occur at a given temperature. Catalytic combustion has been established as a means of oxidizing trace




(a) Energy to Overcome Potential Barrier

(b) Combustion Rates

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FIGURE 20. INFLUENCE OF CATALYSTS ON COMBUSTION

amounts of fuels in air streams at relatively low temperature.[102] Such applications include the elimination of objectionable combustibles from industrial stacks and from automobile exhausts. Another example is the low-temperature oxidation of volatile hydrocarbons in handwarmers. Platinum is the most common of the catalysts, although other materials are also used.

Where heterogeneous catalytic effects are located on a surface, the activity of the catalyst is limited either by the exposed surface area or by the rate at which reactant molecules can reach the surface by diffusion. Hence, active catalysts applied in practice are generally finely divided porous materials with extremely large surface areas per unit volume. The mixture must be diffused into contact with the surface to have the catalyst be effective. The mere lining of a conventional-type combustion chamber with such material would not provide the surface required to have an appreciable influence on over-all combustion, and the surface would be too far removed from a major portion of the reactants to be effective.

Figure 20-b illustrates the reaction rates of catalyzed and uncatalyzed combustion. The two dashed curves show the trend of catalyzed reactions where surface activity is limiting. Under conditions when diffusion limits the process, the rate of the catalyzed reaction is approximately proportional to temperature, whereas, the reaction rate of an uncatalyzed reaction may be slower at low temperatures but increases more rapidly with temperature. The accented lines illustrate the dominant influence for the case shown: below point b the activity of the low activity catalyst is controlling, from b to c diffusion is controlling, and above c the heat release rate due to the uncatalyzed reaction increases so rapidly that no catalyst is sufficiently active to give substantial improvement. Thus, at high temperatures, almost any surface is "catalytic" by virtue of its ability to heat the combustible mixture. No definitive methods have been devised to distinguish between surface combustion and catalytic combustion at high temperatures.

Because of these characteristics of reaction rates, the contribution of combustion catalysis is most significant at low temperatures. It is conceivable that at lower temperatures, catalytic combustion could assist flame combustion by adding heat for vaporization or for preflame reactions. In some heating devices, such as direct-fired low-temperature radiant heaters, high flame temperature serves no necessary purpose and low-temperature catalytic combustion is ideal.

6.1 Fundamental Investigation of High-Temperature Noncatalytic Surface Combustion With Vaporized-Fuel-Air Mixtures and Fuel Sprays. Uncatalyzed high-temperature surface combustion possibilities could be divided into two broad categories: (1) burners which operate as porous burners with premixed fuel vapor and air as in Figure 19 a and b, and (2) burners[103] in which a vapor-air premixture or fuel-mist-air mixture is swept over a refractory surface, as Figure 19 c. New light-weight insulating materials suitable for direct high-temperature flame applications may extend the practical design possibilities of such concepts.

At the present time, most of the commercially available porous burners have been operated with gaseous fuels. A wetted porous-type burner using capillary action of ceramic-fiber material has been successfully applied to salamander-type portable space heaters firing No. 1 oil. Although some porous burners or flame holders with fuel-wetted surfaces have been used for more volatile liquid fuels, it appears necessary that No. 2 fuels must first be vaporized for use in porous burners which must operate reliably and without deposit under cycling conditions over extended periods of time. Thus, the practical application of porous burners is closely tied in with vaporization as discussed under subsections 2.1 and 2.2. An additional problem with porous burners would be lint or dust collection; however, means might be devised for consuming such deposits. In the spray-type applications, envisioned under the second category, fuel-deposit problems must be solved in intermittent operation of residential burners because the surface might become wetted before the inflight vaporization of droplets is completed. If the entire spray is composed of sufficiently small droplets, the droplets can be transported by the air stream without significant deposition on surfaces.

Theoretical examination and experimental investigation of the factors involved in these types of combustion are needed. It would aid the understanding and development of such parameters if rational relationships could be developed between surface roughness, pore size, capillary action in wetted burners, thermal conductivity, temperature gradients, effective emissivity, flashback characteristics, mixture velocity, and mixture composition.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair to good

Application time – intermediate to long range

Estimated effort needed – 4 to 6 man-years

Estimated duration – 2 to 4 years.

6.2 Feasibility Investigation of the Phenomena of Catalytic Combustion of Vaporized Fuel Oil. The practical success of catalytic combustion at low temperatures depends largely upon the ability of catalysts to operate over long periods of time and through many heating and cooling cycles without changing their activity. Unfortunately, many oxidation catalysts – including platinum and vanadium pentoxide – are poisoned by trace amounts of material, such as sulfur and metallic compounds which might be present in fuel oil or in the air stream from lubricated air pumps. In industrial or refining applications, catalyst replacement or regeneration is practical, but such complication in residential burners could overcome any real advantages to the use of catalytic combustion. Also, catalysts generally have limiting temperatures above which their activity deteriorates. Most high-activity oxidation catalysts deteriorate well below flame temperatures. These considerations, plus the fact that catalytic activity at high temperature offers little advantage, dictate that catalytic combustion is best applied in the low-temperature zones of combustion systems. This could be accomplished in the upstream portion of porous-type burners which may be maintained at sufficiently low temperatures.

Some indications point to the fact that catalysts could be selective with the result that some fractions might be catalytically oxidized early in the process at relatively low temperature to feed energy into the system for the combustion of other fractions. It is thus conceivable that catalysts could aid in the vaporization process. The ability of low-temperature catalytic burners to operate with extremely lean fuel-air mixtures or diluted mixtures suggests that such burners could conceivably operate with a low-temperature vaporizer in which the temperature for complete vaporization was depressed by a large excess of air or by massive recirculation of combustion products. Problems of temperature limitations and tendency toward poisoning would still have to be overcome.

A detailed and complete knowledge of the catalytic process as applied to combustion of fuel-oil vapors would be helpful; however, of more immediate interest is whether any known catalytic materials will maintain their activity over long periods of time and offer any advantage in fuel-oil combustion systems. Thus, a feasibility investigation is needed of the properties of catalytic materials in contact with various fuel-air mixtures. Of interest are changes in the effects on reaction limits, smoke formation, thermal gradients, CO formation, and air-flow resistance for various through-puts, temperatures, vapor-air mixtures, and cycling conditions.

Appraisal. Potential industry benefits – moderate

Chances of success – poor to fair

Application time – long range

Estimated effort needed – 5 to 10 man-years

Estimated duration – 2 to 5 years.

6.3 Feasibility Investigation of Liquid-Phase Catalysis of Fuel Oil. The development of a catalytic burner which could operate with fuel in the liquid phase, either to gasify the fuel or to completely consume the fuel, would be extremely valuable. At the present time, however, there are no indications in the technical literature which would suggest that this has been accomplished. Catalytic oxidation which takes place in the human body at low temperatures would suggest that low-temperature catalytic action might be possible with the proper catalyst. Assuming that a nonpoisoning-type catalyst could be found, air might be bubbled through a mixture of fuel oil and catalytic particles to yield some exothermic reaction; depending on the temperature level involved, this might be used for vaporization or for the means of space heating. This and other types of schemes warrant some study and feasibility trials. Although their feasibility seems remote, a more extensive program would be in order if early efforts look promising in terms of practical possibilities.

Appraisal. Potential industry benefits – moderate to great

Chances of success – poor

Application time – long range

Estimated effort needed – 1 to 2 man-years

Estimated duration – 1 to 2 years.

## 7. Experimental Techniques

Experimental investigations or development activities often involve much expenditure of time perfecting measurement or evaluation techniques. The assembly of such existing published information would be helpful as a guide to laboratory investigators. For example, color photography and high-speed motion-picture techniques have been developed by cut-and-try procedures in some laboratories and a summary of this type of information would aid other groups. One such compilation[104] has been made and should be extended on a basis directed to oil-burner research and development. Several areas appear to need further experimental effort and would be of common industry benefit. These include smoke measurement, gas analysis and combustibles measurement, flue-gas temperature measurement, and spray droplet-size determination.

7.1 Evaluation of Methods of Smoke Measurement. An important criterion for judging the performance of combustion systems is the smoke production at given conditions.[105] Many methods have been used to measure smoke: these include light transmission through flue products, impingement on surfaces in the gas stream, and filtration of a small sample. The standard now recently adopted by the oil-heating industry for evaluating distillate burners is the Bacharach-Shell method which uses the filter-paper technique and calibrated shade scale.[106] While the introduction and acceptance of this method has played a substantial part in the establishment and upgrading of equipment performance standards, it should be examined from the viewpoint of its adequacy in more fundamental laboratory investigations of combustion. There are indications that different methods are indicative of different smoke-deposit characteristics, all of which may be of importance to some aspects of burner operation.[107,108]

The sampling technique usually employed with the industry standard method does not guarantee sampling velocity equal to stream velocity; heavy particles with high momentum could be missed by the perpendicular-type sampling technique and some particle loss could occur in the sampling line and heat exchanger. Stickiness of the particles may also be a factor in sampling-line loss.

There is some unpublished information on the fundamental calibration of smoke-metering methods in terms of weight of particulate matter in a unit volume of flue products. These data should be collected and extended to include limits of applicability. An experimental investigation is also needed which would provide additional information on (1) smoke characteristics including particle size, weight, and stickiness, (2) sooting tendencies on given types of surfaces, and (3) concentration of particles in the sample, and effect of various sampling techniques. The significance of the standard method of smoke measurement becomes of greater concern as the smoke requirements for oil-burner equipment standards are further tightened.

Appraisal. Potential industry benefits – small to moderate

Chances of success – fair to good

Application time – long range

Estimated effort needed – 2 to 4 man-years

Estimated duration – 1 to 2 years.

7.2 Development of a Convenient Method for Evaluating Combustibles in the Flue Products. Small quantities of unburned fuel oil frequently escape the combustion zone, particularly on cold starting of the burner. These contribute to deposits or conditions in flue passages which can form a trap for particulate matter; both efficiency and ultimately reliability can be effected. Combustibles are often present in flue gases from recirculating-type burners on starting, until equilibrium warm-up is approached. The accuracy of Orsat analysis in determining fuel-air ratio is also upset by the presence of unburned fuel in the flue products; such an effect has been observed especially with mixtures near stoichiometric[109]. The development of a rapid method for detecting transient conditions of combustibles would be a helpful technique in burner development and evaluation.

Appraisal: Potential industry benefits – small to moderate

Chances of success – fair

Application time – long range

Estimated effort needed – 1 to 2 man-years

Estimated duration – 1 to 2 years.

7.3 Evaluation of Methods for Measuring Flue-Gas Temperature. Methods employed in equipment standards and rating codes for the determination of flue-gas temperature are inconsistent and can yield differences in apparent reading from 50 to 100 F for a given heating device. Stack insulation requirements and measuring location are considerably different in various rating or testing codes. These differing methods have an appreciable effect on the apparent or reported absorption efficiency of the over-all burner-furnace combination or burner-boiler combination. Moreover, in field measurements, large errors can be introduced by the techniques commonly used. An experimental study is needed to draw definitive comparisons between these various methods. Evaluation should include such means as aspirating thermocouples, thermocouple grids, shielded thermocouples, laboratory thermometers, and field-type thermometers. Comparison should be made of using the various insulation and location specified in rating codes of I=B=R, A. G. A. , Underwriters' Laboratories, and Commercial Standard CS195. Results of such a study could lead ultimately to a more standardized approach to such a basic measurement.

Appraisal. Potential industry benefits – moderate to great

Chances of success – good

Application time – immediate to intermediate

Estimated effort needed – 1 to 2 man-years

Estimated duration – 1 year.

7.4 Development of a Simplified Method for Evaluating Droplet Sizes of Fuel Sprays. Present methods of spray droplet-size determination are generally so cumbersome and laborious that few research and development efforts on residential oil burners have made use of them. Various methods for measuring droplet size are discussed in API Publication No. 1537 and have been reviewed in greater detail by Pilcher and Thomas[52].

For purposes of evaluating atomizing devices for oil burners, it may not be necessary in each case to know the droplet-size distribution in precise numerical terms. Rather, a rough approximation may often be adequate. Probably the sizes of the largest droplets are the most significant to the performance of the combustion system with reference to smoke and, hence, evaluation techniques which would provide a clue to these large sizes would be helpful. In addition, it would be desirable to know what fraction of the fuel was present as very fine droplets, probably in the range below 10 microns, since these sizes are important to stability of the initial flame front. The simplified method would not fully replace the more precise measurements but would supplement them. Once such a simplified method was established, sprays with known droplet-size distributions could be compared as a standard.

Figure 21 illustrates the droplet-size ranges of interest in a simplified method. It would be desirable that such a technique be so inexpensive to construct and so simple to use that combustion researchers and manufacturers of atomizing devices would be encouraged to routinely evaluate droplet sizes. Widespread use would have the effect of encouraging improvement in atomizing devices and might form the basis for standards defining performance.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair

Application time – long range

Estimated effort required – 2 to 4 man-years

Estimated duration – 1 to 2 years.

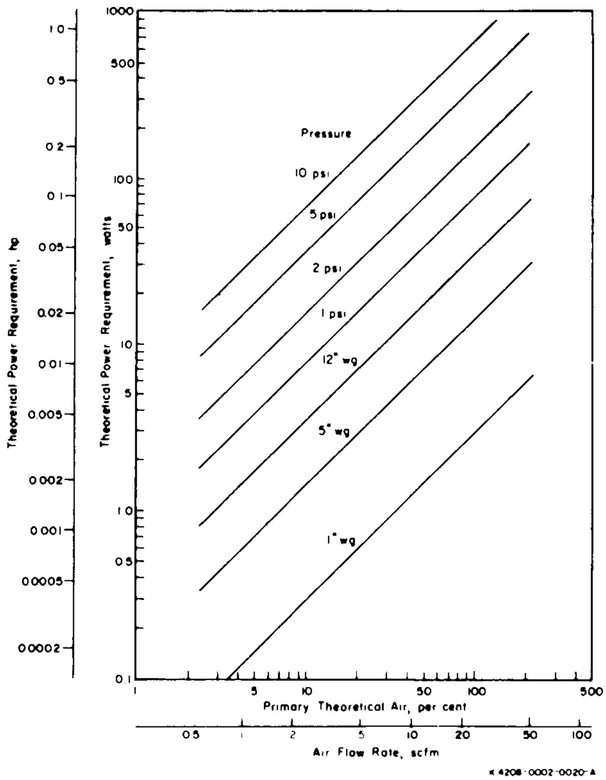


FIGURE 22. THEORETICAL POWER REQUIREMENTS TO COMPRESS ATOMIZING AIR OR COMBUSTION AIR - BASED ON 1.0 gph OIL-FIRING RATE

several fold in bearing and brush life. Where pressure requirements are not high, centrifugal blowers should be considered in combination with shaded-pole motors operating at 3400 rpm. Rotary-vane-type, positive-displacement compressors offer promise because of their reliability and design versatility. The diaphragm or bellows-type pump, similar to an automotive fuel pump or windshield-wiper vacuum pump, should also be carefully examined for possible use as an air compressor for oil burners.

This area warrants special investigation for combustion systems requiring air for atomization or substantial pressure of combustion air, because the compressor and its motor may be the most critical component in the system from the standpoint of reliability and initial cost.

Appraisal. Potential industry benefits - moderate to great

Chances of success - good

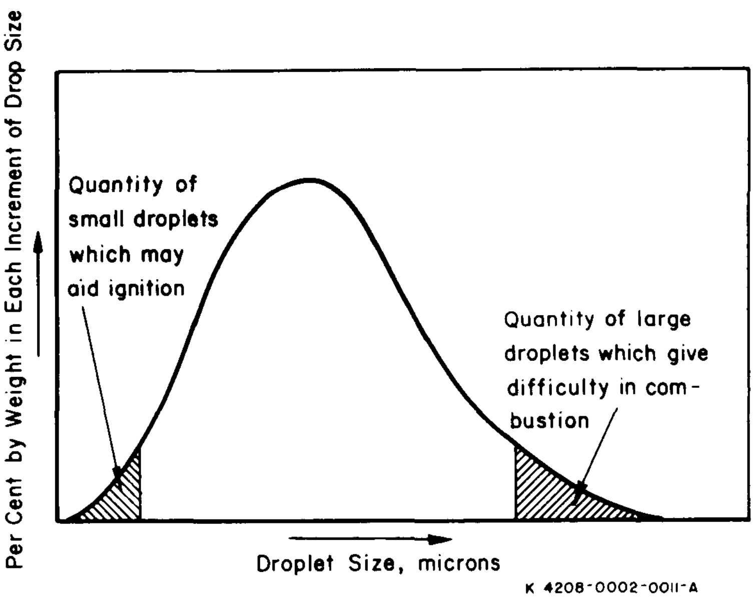


FIGURE 21. FACTORS OF INTEREST IN SIMPLIFIED DETERMINATION OF SPRAY-DROPLET SIZE

## Product Development and Application

Research on combustion fundamentals and burner concepts discussed previously should add to the science of oil burning for development of specific products and for advances in their application. The design of marketable and economically producible hardware products, such as burners and heating equipment, requires the extension of engineering principles to product design. This involves details of components and their arrangement. To be successful in its end use, the application and service of the product must also be considered. In the section which immediately follows, programs will be discussed which deal with the detailed design of the equipment, including burner and heat-exchanger equipment, application to residential installation, and the oil supply system. Equipment manufacturers and dealers have a direct interest in these areas of activity and should participate in programs directed to these areas.

### 8. Burner Design and Development

Individual components for conventional pressure-atomizing burners have been developed to a high degree in terms of performance and manufacturing cost. Moreover, these components have been highly standardized both in new burner production and in the stocking of service-replacement parts. This situation makes it difficult for a manufacturer to risk departure from the relatively few established sources and from interchangeable low-cost standard components; thus, each succeeding burner design has a tendency to be simply a new method of arranging the standard components. It follows that significant advances in design must result in a departure from one or more of these components. As the technology advances, due to the research envisioned by the coordinated research program, it is hoped that new principles will encourage new components and new combinations.

Many programs with many design approaches might be recommended within the category of burner design and development. However, few programs, outside the cut-and-try approach, are free from some heavy dependence on the more broadly applicable information which would be gained in the programs outlined under "Combustion Fundamentals and Burner Concepts". It is explicitly assumed in these recommendations that frequent reporting of results from the coordinated research program would stimulate their use in design, either by the originating research group or by others in the industry. Thus, burner development activity must be considered fluid and must stand ready to take advantage of all opportunities.

Several programs which would be only partially dependent upon other research results are outlined as follows:

8.1 Development or Selection of Low-Cost Long-Life Air Compressors for Low-Capacity Burners. Many of the burner systems under consideration require pressurized air for atomization and/or combustion. Siphon-type air-atomizing devices could utilize a gravity-type oil-feed system and, therefore, would not require a fuel pump when the oil tank is sufficiently high in relation to the burner. An air compressor could then be considered to replace the oil pump. Several of the new air-atomizing devices under development in the industry require an air supply having a pressure of several inches of water and a capacity in the range of 1 to 5 cfm.

Figure 22 shows the relationship between air-delivery capacity, pressure, and theoretical power requirements based on an oil-burner capacity of 1 gph. Because compressor and motor efficiency are also involved, the actual electrical energy demand may be about three times the theoretical value. When pressures exceed about 2 inches of water, the squirrel-cage-type centrifugal fan becomes impractical and such devices as centrifugal blowers and rotary-vane compressors are generally considered.

High-speed centrifugal blowers, like those used on vacuum cleaners, are mass produced at low cost. These operate at 17,000 rpm and are capable of pressures of approximately 40 inches of water and with a maximum capacity of 60 cfm, but the life of their series motor and bearings is only about 1000 to 2000 hours – far short of the reliability needed in oil burners which are expected to operate for many seasons. Also, bearing and commutator noise, and some aerodynamic noise, at high rpm add noise problems which must be solved. Reducing the pressure rise and capacity of such machines might allow speed to be reduced sufficiently to permit an increase of

Application time – immediate to intermediate

Estimated effort required – 2 to 4 man-years

Estimated duration – 1 to 2 years.

8.2 Development or Selection of Low-Cost Long-Life Fuel Pumps for Low-Capacity Burners. Mechanical equipment associated with high-pressure atomization represents a substantial portion of the burner initial cost. The present high-pressure nozzle requires a pump capable of delivery at pressures in excess of 100 psi. Pumps supplied on even the smallest size of burners are capable of delivery of approximately 18 gph, because pump manufacturers find that a pump with a lower maximum capacity offers little saving in size or cost and results in loss of standardization which has achieved the present low cost. Oil-burner fuel pumps incorporating a pressure regulator and protective screen have been developed and tooled to a degree where substantial improvements in reliability and initial cost are not likely. Considering the multiple functions, mechanical compexity, and ruggedness of these pumps, their cost is amazingly low. Present pumps generally use a 1/8-hp split-phase motor for purposes of providing the breakaway torque necessary on cold starting. On conventional burners the fan offers so little load on starting that the motor is sized largely according to the pump requirements. A worthwhile over-all cost reduction could be achieved by pump design for extremely low capacities, if a lower breakaway torque requirement would permit use of a lower cost shaded-pole motor.

If effective atomization systems were developed to operate on lower oil pressure, or if the atomizing system allowed the pump to act principally as a transfer device, new design possibilities might be opened. As in the field of air compressors, discussed previously, diaphragm-type and rotary-vane-type pumps should also be considered.

Appraisal. Potential industry benefits – small to moderate

Chances of success – fair

Application time – long range

Estimated effort required – 2 to 4 man-years

Estimated duration – 1 to 3 years.

8.3 Development of Oil-Metering Systems for Low-Capacity Burners and Pilot-Burner Applications. The reliable and accurate metering of oil is extremely difficult at low flow rates. Gravity-flow oil-control valves, as used on vaporizing burners, most closely approach practical operation, but these suffer from entirely unsatisfactory control if fuel properties vary between the limits permissible with No. 1 and No. 2 fuel. Therefore, there is need for a practical and low-cost oil-metering system. Siphon-type nozzles, in which oil flow is in some way proportional to air pressure, may be one answer if they can be made reasonably insensitive to changing fuel properties. However, other systems should be explored, including motor-driven devices like diaphragm pumps or rotating stopcock-type valves. In any low-capacity devices, the tendency of deposit formation and resulting deteriorating effects on operation must be considered. Reliable metering systems for extremely low rates will be a necessity if pilot burners are to become practical.

Appraisal. Potential industry benefits – moderate to great

Chances of success – fair

Application time – intermediate to long range

Estimated effort required – 3 to 5 man-years

Duration – 2 to 3 years.

8.4 Development of Devices to Utilize Unsteady-State Combustion. The energy released in combustion for residential heating is many times that needed to drive air through the combustion system, even with those systems having very high pressure drop. One of the more simple ways to utilize this energy for air handling is through unsteady or resonant combustion. Figure 23 shows a simplified pulse-jet combustor with aerodynamic valves. Rapid intermittent combustion provides a periodic increase in the volume of gases, and suitable valving controls the direction of net flow. The frequency of pulsing is established by the resonant acoustical frequency of the combustor. Most operating systems reported in the literature(110) have been applied with liquid fuels, mostly kerosine types. Initially, pulse-jet systems were applied principally to such thrust-producing devices as early air-breathing missiles. More recently, however, there is a trend toward the use of this principle for increasing the static pressure of air and, at the same time, producing a heating effect.(111) The pressure gains can be used directly to supply combustion air(112), or can be used to pump a second heat-transfer fluid, such as ventilation air in a furnace.(113) One problem associated with this latter concept is a tendency toward contamination of the air in the main driving pump by the combustion gases.

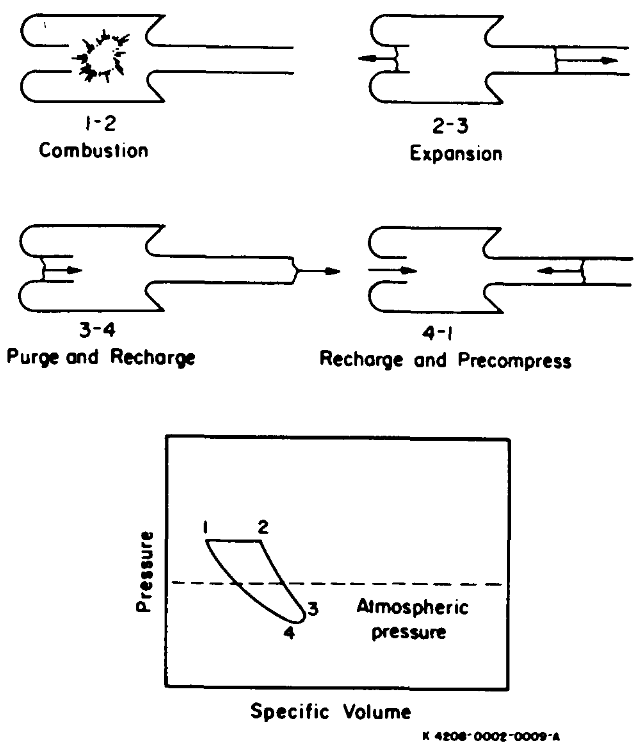


FIGURE 23. CYCLE OF EVENTS IN A PULSE-JET COMBUSTOR WITH AERODYNAMIC VALVING

Noise from the intermittent combustor is a significant problem, but can be largely offset and muffled by suitable treatment, including the use of multiple combustors properly connected and phased. In a recent Canadian development of a pulse-type gas-fired water heater and boiler(13), the noise level has been reduced considerably. The valve design in such systems is critical in terms of performance and reliability. Both mechanical and aerodynamic valves have been used. Mechanical types have included flapper-type and poppet-type valves. Aerodynamic valves, as in Figure 24, provide greater resistance to flow in one direction than in the other, so that the net flow in a pulsing system is in the direction of least resistance. Such aerodynamic valves appear to offer greater promise for reliability and long life, although higher pressure gains are possible with mechanical types.

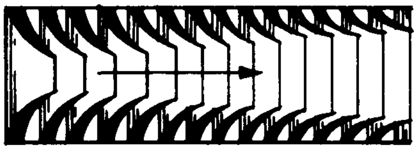

FIGURE 24. FUNNEL-TYPE AERODYNAMIC VALVING

For residential oil heating, the most practical use of the pulse pump would be in the utilization of the pressure gain to supply combustion air, and, hence, overcome the flow resistance of a compact heat exchanger. This application would favor hot-water heating because the heat-transfer coefficients on the combustion side are limiting in gas-to-water heat transfer of this type; smaller heat exchangers would be thus possible. Starting and deposit problems with No. 2 fuel oil would be expected, but the development of vaporizers would be a significant asset. Where remote or portable operation is necessary without auxiliary power, and where manual starting is permissible, unsteady-state combustion devices are likely to gain considerable application.

Appraisal. Potential industry benefits – small to moderate

Chances of success – fair

Application time – long range

Estimated effort required – 4 to 8 man-years

Estimated duration – 2 to 6 years.

Controls. New burner concepts will unquestionably require modified combustion controls. It is hoped that new concepts in burners and new applications can permit entirely different controls of integral type which will ultimately be lower in cost and have greater reliability in the hands of the trade. Some new burners may be able to use shaded-pole motors, requiring less starting current than conventional burner motors. It would seem that this would permit the use of line-voltage snap switches or some other features that would simplify and reduce the cost of controls. In light of recent advances in electronics, plus the greater familiarity of service personnel with electronic equipment, electronic circuits may become more practical for residential burners. Such advances are not likely to result in gross reduction of control costs but their possibility should be examined. New means for detecting flames for purposes of combustion safety have been studied and are still under consideration by various control manufacturers.

Leading control manufacturers have the necessary technical capabilities and [financial] resources to pursue their own developments in this area and have expressed strong interest in keeping pace with the development of new oil burners. Therefore, research and development on control aspects are not being recommended here as part of a coordinated research and development program. However, the need for integration of control function and reliability with the burner system is mentioned here as a matter of record.

## 9. Heat-Exchanger Equipment

Early automatic oil burners for residential heating were designed to be installed in existing furnaces or boilers in the conversion from coal or wood to oil firing. The design of furnaces and boilers intended for automatic oil firing has progressed somewhat from equipment designed for hand firing; however, the tradition has preserved many of the design concepts and the origin of the hand-fired equipment is still recognizable in equipment being sold today. One of the features which has been preserved in most cases is the concept of natural draft and the use of slight drafts in the combustion chamber. This stems from an attempt to replace the natural-draft, solid-fuel fire with a burner system which contains a blower just powerful enough to overcome the burner's own resistance. Recently, heating units have appeared on the market designed with pressurized combustion chambers, and other units are now equipped with induced-draft equipment to pull a substantial negative pressure in the combustion chamber.

There is advantage in considering the burner system as an integrated part of an over-all heat-producing and heat-delivery system rather than simply as a heat-generating device. Burners can utilize a substantial pressure drop to advantage in mixing for combustion and, once a volume capacity of blower or compressor is established, higher pressures may be available at relatively little increased cost. This suggests the use of more compact heat exchangers that offer more resistance to air flow. New burners with assured clean combustion would reduce the need for larger passages to allow for gas flow after sooting of flue passages. In the case of air heating, the actual requirement for heat-transfer surface would not be made substantially smaller by higher pressures available, but the flue-cross-sectional area could be reduced. In the case of water heating, for domestic purposes or for space heating, both heating surface and the cross-sectional area could be reduced. The integration of the combustion system and heat-transfer surface requires consideration of the economic factors, since physical size alone is generally not an over-riding consideration in residential heating. The industry can anticipate a greater trend toward such integrated systems.

Water Heaters. Oil-fired residential water-heater systems are potentially an important factor in the sale of No. 2 heating oil. The year-around fuel requirement for water heating is substantial and is growing. In some areas of the country, residential water heaters used in conjunction with steam or hot-water heating systems are very popular and effective.[114] The sales of direct oil-fired storage-type water heaters is increasing.

Most of the residential oil-fired water heaters on the market today are fired with gun-type burners, eventhough this application is generally not an effective and economical integration of burner and tank. The high firing rates best suited to the burner are often excessive for the tank and heat exchangers; this leads to inefficient operation and high material temperatures which contribute to premature deterioration. On the other hand, if the burner is fired at lower firing rates, the deposit problem inherent with such operation reduces the reliability of the system. Burner types which perform better at lower rates, such as low-pressure burners or vertical rotary burners, are generally not applied because of their increased cost. Vaporizing burners were once popular for use in water heaters, but the requirement of No. 1 fuel oil and frequent necessity to clean deposits makes them unsuited to the competition with electric and gas-fired hot-water heaters.

Manufacturers of boilers, tanks, and household appliances will quickly apply to hot-water heaters any new burners which show promise of low cost and reliability. Thus, no specific program is recommended, other than to point out the need for such burners and to stimulate their development.

Oil-Fired Unit Heaters. The field of unit-heater application, as used in industrial and garage heating, has not been aggressively pursued by the oil-heating industry on a broad scale. Oil would be more advantageous in some cases than other fuels, and multiple installations could utilize a common piping system. Frequently, oil-fired horizontal furnaces are used in this way but this application is not necessarily the most economical approach. The development of improved unit heaters, even with existing oil burners, would assist in this market. Burners capable of low firing rates and assured reliability would be an additional help in this type of application. No specific program is recommended in this area. However, manufacturers should be encouraged to take advantage of this market.

Submerged Combustion and Heat Transfer. Where hot water or other fluid is required in a process or non-recirculating system, direct heat transfer offers a simple opportunity for extremely high heat-transfer rates per unit volume.[115] In this type of system, combustion products are bubbled directly through the fluid to be heated, as in Figure 25. Such a system has been successfully applied to snow melting.[116] Contamination of a fluid by the combustion products precludes the use of such systems in water heating for human consumption. Also, this principle is generally not practical for recirculating-type systems because of the buildup of acid concentration, which will present a corrosion problem to piping and other containing parts. In some cases, a water makeup and blowdown system might be provided to control the concentration. However, it is not considered a sufficient advantage in residential heating applications to be recommended here.

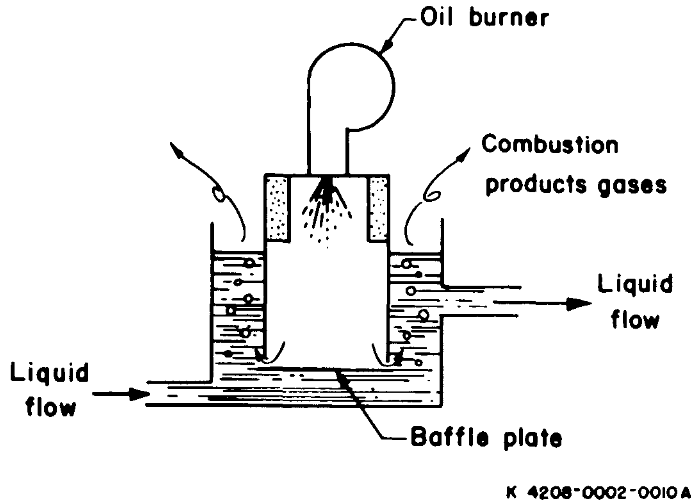


FIGURE 25. EXAMPLE OF SUBMERGED HEAT TRANSFER

<u>9.1 Feasibility and Conceptual Investigation of Oil-Fired Radiant Heaters.</u> Radiant and infrared heaters are gaining popularity for heating comfort in industry and for special applications such as drying. From a heat-utilization standpoint, these are not as efficient as unit heaters or central heating systems, but their effectiveness and convenience in special applications should increase their popularity. Electric lamps and porous-type gas heaters are being sold commercially for these applications[97]; however, oil-fired applications are also possible. If an oil flame is used to heat a ceramic insulating material to a high enough temperature, the required source for radiation can be produced.

Figure 26 suggests schematically a simple way in which existing oil burners could be inexpensively applied to direct radiant heating. Other types of oil burners, such as premixed-type porous burners, would open up other possibilities. A study of the over-all heat-transfer and combustion requirements would be extremely helpful in designing for this type of application.

Appraisal. Potential industry benefits – small to moderate

Chances of success – fair to good

Application time – immediate to intermediate

Effort required – 1 to 3 man-years

Duration – 1 to 2 years.

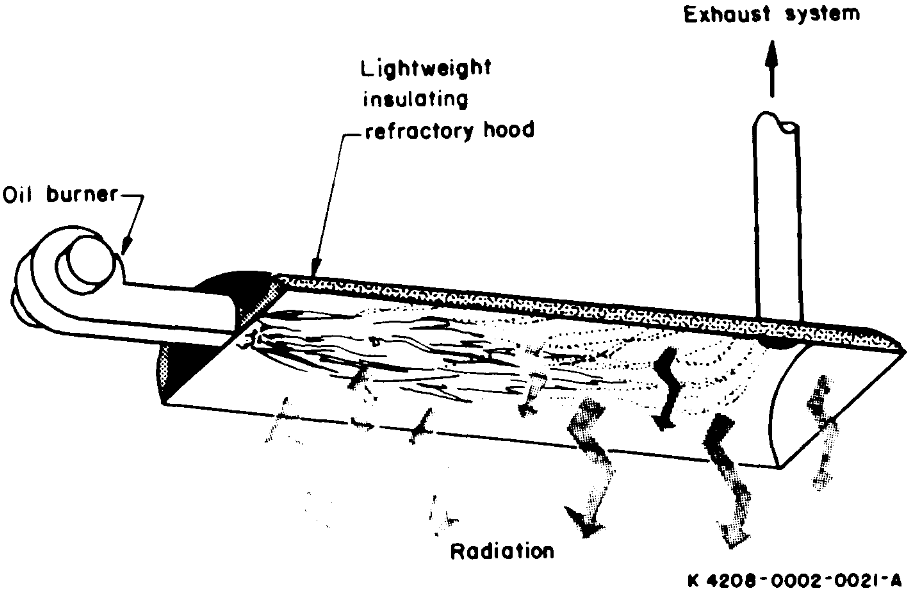


FIGURE 26. SIMPLIFIED APPLICATION OF AN OIL BURNER TO AN OVERHEAD RADIANT HEATER

## RECOMMENDED RESEARCH AND DEVELOPMENT PRIORITIES

Priorities must be established for initiating research in the various areas outlined in the previous section, inasmuch as the entire scope obviously cannot be undertaken at once and some needs are more urgent than others. It should be emphasized that research efforts in many of these areas would be somewhat interdependent and reinforcing; promising results in one area could provide information or an advance which would alter the priority of research in another area. Thus, the recommendations contained in this section are to be considered as initial priorities that must be reviewed periodically, and not less than every two years.

### Need for a Balanced Program

Fundamental and applied research in the field of combustion and equipment utilizing No. 2 fuel oil is lacking and there are indications that equipment manufacturers alone are not prepared to expend the substantial effort in these areas to provide the necessary advances.

Mechanical development and design can sometimes operate as an art on a cut-and-try basis with rapid achievement but often misses the best combination or reaches a level of saturation without a supporting technology. When the objectives of development programs are of vital importance, parallel approaches are warranted. However, a more fundamental approach to the phenomena involved offers a better chance of significant advances. There have been many years of cut-and-try mechanical inventions in oil-burner development, but the present conditions motivating the establishment of the API research program attest to the limitation of this method alone.

The magnitude of problems to be resolved in making truly effective advances is such that a broadly based research assault is necessary. Such an effort will require that every available technological resource be brought to bear on the objectives.

## Establishing Priorities

Tables II-10, II-11, and II-12 summarize, respectively, the research and development tasks recommended under these categories:

(1) To be initiated in the first year of the coordinated program

(2) To be initiated within two or three years

(3) To be considered for initiation within three to six years.

In establishing these priorities, the over-all appraisal of the research or development task was considered. The potential benefits to the industry in light of the objectives of the over-all program were judged to be of paramount importance. The chances of success of a particular research effort were given second consideration, and time to reach application in the field was ranked third. The estimated duration of the work was given only minor weight. No attempt has been made to tailor a rate of effort to an assumed availability of funds or rate of expenditure.

Research and development within some of the areas recommended are already under way by oil refiners. Where a specific case was known, the research entry in Tables II-10, II-11, and II-12 is noted by an asterisk. In selecting research assignments, it may be desirable, in some cases, to reach into a relatively low-priority area because of availability of particular skills or equipment. Also, it may not be possible to immediately locate or assign qualified personnel to some of the work having high priority.

## Effort Required

The following summarizes the total effort represented by the appraisal of tasks in the three categories of priority.

| Priority Category of Tasks | Total Effort, man-years | | |
|---|---|---|---|
| | Minimum | Average | Maximum |
| (1) Table II-10 | 46 | 60 | 74 |
| (2) Table II-11 | 35 | 45 | 56 |
| (3) Table II-12 | 39 | 55 | 70 |
| Totals | 120 | 160 | 200 |

## Schedule

Figure 28 illustrates a suggested schedule for initiation of the recommended research and development, although many different schedules are possible in undertaking the tasks outlined. In the example shown in Figure 28, it has been assumed that the start of tasks would be so phased (1) that all the tasks recommended in Table II-10 would be started the first year, (2) that approximately half the tasks described in Table II-11 would be started at the beginning of the second year and the remainder started the third year, and (3) that one-third of the work described in Table II-12 would be started successively each year for three years.

It would be possible to compress or expand the duration of the work by accelerating or slowing the rate of effort suggested; however, the rates of effort suggested are believed to be consistent with effective and efficient research management.

The overlapping of the tasks is also illustrated in Figure 28. For purposes of this example, it has been assumed that the total effort and duration required for a given research assignment is represented by the average of estimates noted in the appraisal for each task. It should be emphasized that, in research and development programs of complex nature, the effort or duration of a given task cannot be predicted with accuracy. Provided no new research is added, the rate of effort for this initial program would diminish after the second year and all the tasks would be essentially complete within a period of eight years.

## TABLE II-10. PRIORITIES FOR RESEARCH AND DEVELOPMENT

| Priority* | RESEARCH AND DEVELOPMENT RECOMMENDED<br>Description |
|---|---|
| 1 | Determination of Conditions for Vaporization of No. 2 Fuel Without Surface Deposits* |
| 2 | Experimental and Field Investigation to Evolve a Smoke Test Procedure Suitable to Qualify Units for Low-Temperature Prefabricated Flues |
| 3 | Conception and Evaluation of Schemes for Precombustion-Zone Vaporization |
| 4 | Theoretical and Experimental Investigation of Fundamental Principles in Air Atomization of Fuel Oil |
| *5 | Conception and Evaluation of New or Unusual Means for Atomization* |
| 6 | Determination and Mapping of Combustion Conditions Which Do Not Produce Smoke for a Typical Fuel Oil |
| 7 | Study of the Combustion Mechanism as Affected by Air-Supply Dilution – Including Controlled Recirculation of Combustion Products* |
| *8 | Determination of Gas Composition, Temperature, and Smoke Within Local Zones of Various Burner Systems – Particularly Recirculating Types |
| *9 | Development or Selection of Low-Cost Long-Life Air Compressors for Low-Capacity Burners* |
| 10 | Evaluation of Methods for Measuring Flue-Gas Temperature |
| 11 | Development and Evaluation of Syphon-Type Air-Atomizing Systems* |
| 12 | Fundamental Investigation of High-Temperature Noncatalytic Surface Combustion with Vaporized-Fuel-Air Mixtures and Fuel Sprays |
| *13 | Investigation of Factors Involved in Deposit Formation in Conventional Nozzles and Determination of Permissible Operating Limits* |
| 14 | Development of a Simplified Method for Evaluating Droplet Sizes of Fuel Sprays |
| *15 | Determination of Quantitative Effects of Spray Droplet-Size Distribution on Combustion in Various Systems |
| 16 | Feasibility Investigation of Spinning-Disk Atomizers for Low Firing Rates for Use in Premixed Burners |

*An asterisk in this column indicates items that are most applicable to present BNL/DOE program.

RECOMMENDED TO BE INITIATED IN THE FIRST YEAR

| Classification and Identification | | APPRAISAL | | | | |
|---|---|---|---|---|---|---|
| | | Potential Industry Benefits<br>Great<br>Moderate<br>Small | Chances of Success<br>Good<br>Fair<br>Poor | Application Time<br>Immediate<br>Intermediate<br>Long Range | Effort Required<br>Man-Years | Duration<br>Years |
| Vaporization | 2. 1 | Great | Fair - Good | Int - LR | 6 - 10 | 2 - 5 |
| Venting | 11. 1 | Great | Fair - Good | Int - LR | 4 - 6 | 2 - 4 |
| Vaporization | 2. 2 | Great | Fair | Int | 2 - 3 | 1 - 2 |
| Atomization | 1. 2 | Great | Fair | LR | 2 - 4 | 2 - 4 |
| Atomization | 1. 4 | Great | Fair | Int - LR | 3 - 6 | 2 - 4 |
| Smoke Formation | 5. 2 | Great | Fair | LR | 3 - 5 | 2 - 4 |
| Recirculation | 4. 1 | Mod - Great | Good | Int - LR | 5 - 6 | 3 - 4 |
| Recirculation | 4. 2 | Mod - Great | Good | Int - LR | 4 | 1 - 2 |
| Burner Design | 8. 1 | Mod - Great | Good | Imm - Int | 2 - 4 | 1 - 2 |
| Techniques | 7. 3 | Mod - Great | Good | Imm - Int | 1 - 2 | 1 |
| Atomization | 1. 3 | Mod - Great | Fair - Good | Int | 2 - 4 | 1 - 3 |
| Surface Combustion | 6. 1 | Mod - Great | Fair - Good | Int - LR | 4 - 6 | 2 - 4 |
| Preflame Deposits | 2. 3 | Mod - Great | Fair | Imm - Int | 1 - 3 | 2 - 3 |
| Techniques | 7. 4 | Mod - Great | Fair | LR | 2 - 4 | 1 - 2 |
| Atomization | 1. 1 | Mod - Great | Fair | Int - LR | 4 - 6 | 3 - 5 |
| Atomization | 1. 5 | Mod - Great | Fair | Int | 1 | 1 |

## TABLE II-11. PRIORITIES FOR RESEARCH AND DEVELOPMENT

| RESEARCH AND DEVELOPMENT RECOMMENDED | |
|---|---|
| Priority | Description |
| * 17 | Development of Oil-Metering Systems for Low-Capacity Burners and Pilot-Burner Applications |
| 18 | Experimental and Field Investigation of Soot Combustion Rates During Chimney Soot Burnout |
| * 19 | Development of Combustion Systems to Exploit Recirculation – With Practical Means for Cold Starting* |
| * 20 | Feasibility and Conceptual Investigation of Low-Capacity Burners for Pilot Operation |
| 21 | Feasibility Investigation of Aerodynamic Devices Like the Hartmann Whistle for Atomization at Low Firing Rates |
| 22 | Feasibility Investigation of Liquid-Phase Catalysis of Fuel Oil |
| 23 | Development of a Rational Method for Predicting or Experimentally Determining the Optimum Relationship Between Air Pattern and Oil-Spray Pattern* |
| 24 | Analysis and Investigation of Combustion Air Supply and Exhaust Systems |
| 25 | Investigation and Definition of a Proposed No. 2 Reference Fuel for Research and Testing Purposes |
| 26 | Investigation Leading to Recommendations for Standardized Terminology and Rating Methods for Pressure-Atomizing Oil-Burner Nozzles |
| 27 | Feasibility Study of Oil-Piping Systems for Common Oil Storage Tanks for Groups of Homes |
| 28 | Studies of Chimney Performance Including Transient Conditions in Actual Oil-Fired Systems to Provide Application Tables |
| 29 | Evaluation of Performance and Life of Alternate Ignition Means |
| 30 | Investigation of Factors Involved in the Application of Pressurized Flues |
| 31 | Investigation of Relationship Between Burner Entrance Velocity, Mixing Turbulence, Recirculation, Volumetric Heat Release, Scale Factor, and Random Flame Noise in Combustion Systems |

RECOMMENDED TO BE INITIATED WITHIN 2 OR 3 YEARS

| Classification and Identification | | APPRAISAL: Potential Industry Benefits (Great / Moderate / Small) | Chances of Success (Good / Fair / Poor) | Application Time (Immediate / Intermediate / Long Range) | Effort Required Man-Years | Duration Years |
|---|---|---|---|---|---|---|
| Burner Development | 8.3 | Mod - Great | Fair | Int - LR | 3 - 5 | 2 - 3 |
| Venting | 11.2 | Mod - Great | Fair | Int - LR | 4 - 6 | 2 - 3 |
| Recirculation | 4.3 | Mod - Great | Fair | Int - LR | 4 - 8 | 2 - 4 |
| Ignition | 3.3 | Mod - Great | Poor - Fair | LR | 3 - 5 | 2 - 3 |
| Atomization | 1.6 | Mod - Great | Poor | Int | 1 | 1 |
| Catalytic Combustion | 6.3 | Mod - Great | Poor | LR | 1 - 2 | 1 - 2 |
| Mixing | 4.4 | Mod | Good | Imm - Int | 4 - 6 | 2 - 3 |
| Supply and Venting | 11.4 | Mod | Good | Int | 1 - 2 | 1 - 2 |
| Standards | 12.4 | Mod | Fair - Good | Int | 1/2 | 1 |
| Standards | 12.1 | Mod | Fair - Good | Imm - Int | 1 - 2 | 1 - 2 |
| Systems | 10.1 | Mod | Fair - Good | Imm - Int | 2 - 3 | 1 - 2 |
| Venting | 11.5 | Mod | Fair - Good | Int | 3 - 5 | 2 - 3 |
| Ignition | 3.2 | Mod | Fair | Imm - Int | 2 - 3 | 1 - 2 |
| Venting | 11.3 | Mod | Fair | Int - LR | 1 - 2 | 1 - 2 |
| Mixing | 4.5 | Mod | Fair | LR | 4 - 6 | 2 - 4 |

## TABLE II-12. PRIORITIES FOR RESEARCH AND DEVELOPMENT

| Priority | RESEARCH AND DEVELOPMENT RECOMMENDED — Description |
|---|---|
| 32 | Feasibility Investigation of the Phenomena of Catalytic Combustion of Vaporized Fuel Oil |
| 33 | Engineering and Economic Appraisal of the Application of Several Existing Oil Burners to Residential Incinerators* |
| 34 | Investigation and Appraisal of Equipment Requirements for Agricultural Utilization of Fuel Oil |
| *35 | Evaluation of Methods of Smoke Measurement |
| 36 | Feasibility and Conceptual Investigations of Oil-Fired Radiant Heaters |
| 37 | Development or Selection of Low-Cost Long-Life Fuel Pumps for Low-Capacity Burners |
| *38 | Development of Devices to Utilize Unsteady-State Combustion |
| 39 | Preliminary Design Investigation of the Oil-Fired Free-Piston Refrigerant Compressor to Estimate Performance and Cost |
| 40 | Feasibility Investigation of Remotely Located Oil-Fired Snow-Melting Systems on Critical Areas of Highways |
| 41 | Development of a Convenient Method of Evaluating Combustibles in the Flue Products |
| 42 | Fundamental Investigation of the Combustion Process and Flame Propagation in Turbulent Flames of No. 2 Fuel-Oil Vapor-Air and Spray-Air Mixtures |
| *43 | Fundamental Investigation of the Mechanism of Smoke Formation in Fuel-Oil Combustion Processes |
| 44 | Engineering Study of Burner Requirements and Feasibility Study of their Integration with Various Household Appliances |
| 45 | Economic Study and Preparation of Design Recommendations for Residential Snow-Melting Systems |
| 46 | Analysis of Stack Emissions from Residential Oil-Fired Systems |
| 47 | Development of a Simple Field Test Procedure for Evaluating Chimneys |
| 48 | Investigation of the Fundamental Requirements for Ignition of Fuel-Oil Sprays and Vapor-Air Mixtures |
| 49 | Investigation Leading to Recommendations for Standardized Terminology and Rating Methods for Oil Filters |

RECOMMENDED TO BE CONSIDERED FOR INITIATION WITHIN 3 TO 5 YEARS

| Classification and Identification | | APPRAISAL: Potential Industry Benefits (Great / Moderate / Small) | Chances of Success (Good / Fair / Poor) | Application Time (Immediate / Intermediate / Long Range) | Effort Required Man-Years | Duration Years |
|---|---|---|---|---|---|---|
| Catalytic Combustion | 6.2 | Mod | Poor - Fair | LR | 5 - 10 | 2 - 5 |
| Appliances | 14.1 | Small - Mod | Good | Int - LR | 1/2 - 1 | 1/2 - 1 |
| New Uses | 15.1 | Small - Mod | Good | Int - LR | 2 - 4 | 1 - 2 |
| Techniques | 7.1 | Small - Mod | Fair - Good | LR | 2 - 4 | 1 - 2 |
| Heat Exchangers | 9.1 | Small - Mod | Fair - Good | Imm - Int | 1 - 3 | 1 - 2 |
| Burner Design | 8.2 | Small - Mod | Fair | LR | 2 - 4 | 1 - 3 |
| Burner Development | 8.4 | Small - Mod | Fair | LR | 4 - 8 | 2 - 6 |
| Air Conditioning | 13.1 | Small - Mod | Fair | LR | 2 - 3 | 1 |
| New Uses | 15.2 | Small - Mod | Fair | LR | 2 - 3 | 1 - 2 |
| Techniques | 7.2 | Small - Mod | Fair | LR | 1 - 2 | 1 - 2 |
| Combustion | 5.3 | Small - Mod | Fair | LR | 3 - 4 | 2 - 4 |
| Smoke Formation | 5.1 | Small - Mod | Poor - Fair | LR | 4 - 8 | 3 - 5 |
| Appliances | 14.2 | Small - Mod | Poor - Fair | LR | 2 - 3 | 1 - 2 |
| Appliances | 14.3 | Small | Good | Imm | 1/2 - 1 | 1 |
| Standards | 12.3 | Small | Good | LR | 3 - 5 | 2 - 3 |
| Venting | 11.6 | Small | Fair - Good | Imm | 1 - 2 | 1 - 2 |
| Ignition | 3.1 | Small | Fair - Good | LR | 3 | 2 |
| Standards | 12.2 | Small | Fair | Imm - Int | 1 - 2 | 2 - 3 |

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