CHAPTER 4. SCREENING ANALYSIS

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CHAPTER 4. SCREENING ANALYSIS

4.1 INTRODUCTION

The purpose of the screening analysis is to identify those design options that the Department will consider for the engineering analysis and to screen out those design options that the Department will not consider further. The Department consulted with industry, technical experts, and other interested parties to develop a list of design options for consideration. The Department then applied a set of screening criteria to determine which design options were unsuitable for further consideration in the rulemaking. These screening criteria are based on the Process Rule, 61 FR 36974 (July 15, 1996). The criteria are summarized here:

- Technological feasibility: Design options used in commercial products or in working prototypes are considered feasible.

- Practicability to manufacture, install, and service: Design options should be able to be mass-produced and be reliable to install and service on the scale necessary to serve the relevant market at the time of the effective date of the standard.

- Adverse impacts on utility or availability to consumers: Design options should not create adverse impacts on product utility, or result in the unavailability of any covered product type with performance characteristics (including reliability), features, sizes, capacities, and volumes that are substantially the same as products generally available in the U.S.

- Adverse impacts on health or safety: Design options must not adversely affect health or safety aspects of the regulated product.

Based on past analysis, and on public comments on the September 8, 1993, Advance Notice of Proposed Rulemaking (ANOPR), the Department prepared a draft screening analysis and presented it for review and comment at the Furnaces and Boilers Standards Framework Rulemaking Workshop, held in Washington, D.C. on July 17, 2001.[1] This chapter presents the screening analysis of design options that DOE carried out in response to comments received during and after the Framework Workshop. The subsequent analyses do not consider or incorporate technologies that do not pass these tests.

4.2 DISCUSSION OF DESIGN OPTIONS

This chapter presents the design options in two categories. The first category is design options that met the screening criteria and that DOE used in the subsequent analyses for at least some product classes. The second category is design options that DOE eliminated from further consideration for all product classes. The discussions under both categories respond to the screening criteria described in the Process Rule.

4.2.1 Design Options that Passed Screening

4.2.1.1 Improved Heat Exchanger Effectiveness

Heat exchanger effectiveness can be improved in many ways.[2] To accomplish this, furnace manufacturers optimize the heat exchanger size and geometry, gas input rate, combustion air delivery system, heat transfer coefficient, and heat exchanger mass, and may apply electrohydrodynamic enhancements to provide the greatest comfort, reliability, and safety. By adjusting the heat exchanger effectiveness, a gas furnace can be designed with an annual fuel utilization efficiency (AFUE) rating ranging from 75 percent to 98 percent.

Between roughly 83 percent and 89 percent AFUE, condensate problems can occur and, because of the high temperature of the flue at these efficiencies, stainless steel is needed to vent wet flue gases to the outdoors. Above 89 percent AFUE, flue-gas temperatures drop below 155°F, and polyvinyl chloride (PVC) pipe can be used for venting.[3]

Heat Exchanger Area. Heat exchanger effectiveness can be improved by increasing the heat exchanger area for a given burner input rate. This is a common way to improve the on-cycle efficiency of the furnace. Increasing the size of the heat exchanger improves the steady-state efficiency and the AFUE of the furnace. However, it also can increase the pressure drop on the flue side and/or air side of the heat exchanger, so the blower system must be rebalanced to deliver the same flows. A general rule is that doubling the heat exchanger area will increase efficiency by half the difference between the current efficiency and 100 percent AFUE.[4] For example, going from 80 percent to 90 percent AFUE requires doubling the heat exchanger area.

Derating. Derating, which usually refers to reducing the burner input of the furnace while keeping the heat exchanger area constant, is a direct way to improve furnace performance because it does not involve design changes. Decreasing the gas input rate to a furnace improves the steady-state efficiency and AFUE.

A small derate of up to10–15 percent will not impair the heat exchanger function, but a larger reduction will have a negative impact on the performance characteristics of the heat exchanger. A similar impact on efficiency may be achieved by increasing the heat exchanger area and keeping the burner input rate constant.

Combustion Air Delivery System. Reducing the excess air fraction improves efficiency because it changes the flue gas temperature and flow rates in the heat exchanger. A reduction in excess air from 50 percent to 40 percent should improve AFUE by about 1 percent. Factors to consider when reducing the excess air to the burners include size and alignment variations in the drilled gas orifices, pressure and temperature variations within the gas manifold, and pilot gas feed into only one heat exchanger tube.

Heat Transfer Coefficient. Increasing the heat transfer coefficient (on either the air side or the gas side of the heat exchanger) can improve heat exchanger efficiency. This can be achieved through special surface treatments, the addition of fins or dimples, or otherwise modifying the air- or gas-flow characteristics. Increasing the heat transfer coefficient can increase the pressure drop, which may result in increased electrical power demand.

The industry achieved a major improvement in the gas-side heat transfer coefficient when it shifted from natural-draft heat exchangers to induced-draft combustion. This allowed manufacturers to substantially reduce the size of the flue gas passageway, thus increasing the gas velocities. The heat transfer coefficient and pressure drop both increase exponentially with velocity.

The heat transfer on the internal surface of the heat exchanger offers an area for improvement. As flue gases pass through the heat exchanger of a furnace, they cool from about 2000°F to less than 400°F. With this large drop in temperature, the specific volume of the gas changes by a factor of three. Thus, the combustion gas passageway of the heat exchanger can be reduced in size by the same factor of three at the outlet, while maintaining approximately constant gas velocity.

Air-side heat exchanger coefficients also can be improved by increasing the air velocity over the heat exchanger. This can be accomplished by making the air passages smaller or by increasing the total air flow. Increasing the air flow also will reduce the change in the air temperature as it crosses over the heat exchanger.

There are several other ways to improve the heat transfer coefficient. In the case of the serpentine clamshell heat exchanger, this can be accomplished by decreasing the channel area and perimeter in the direction of the gas flow, and creating dimples in the latter passes of the channel. Each dimple consists of two half-spherical indentations that reduce the local cross-sectional area of the internal passage.[5] Gas-side performance also may be enhanced by adding external fins to the heat exchanger tubes. These are frequently used in the condensing heat-exchanger section of condensing furnaces.

Heat Exchanger Mass. Lower heat-exchanger mass allows the furnace to heat up and cool down faster during each heating cycle. This effect is due to the reduced thermal storage capacity of the heat exchanger. The overall impact is a reduction of off-cycle energy losses.

Because of the advantages of low heat-exchanger mass in terms of AFUE as well as manufacturing costs, the forced-air furnaces of today have much lighter heat exchangers than did the natural draft furnaces common 20 years ago. The blower-on time delays of today’s furnaces run about 30 seconds, whereas, with natural draft furnaces, blower-on time delays of two minutes or more were common.[4] Computer simulation studies found that the flue-gas-side heat transfer in higher-mass heat exchangers could be improved by 24 percent before reaching a steady-state efficiency where condensation problems may arise.[6]

Electrohydrodynamic Enhancement. Electrohydrodynamic enhancement is a technique for increasing heat transfer in heat exchangers for single-phase or phase-change processes. A high-voltage, low-current wire or plate electrode mixes fluid (or air, in the case of furnaces) of different temperatures by increasing turbulence and destabilizing the thermal boundary layer near the heat transfer wall. The effect, a "corona wind," is caused by accelerated ionized particles colliding with gas molecules, generating a flow that can quickly reach a speed of a few meters per second.[7] A corona wind interacting with the main gas flow intensifies mixing of the gas, increasing heat transfer rates.

Electrical power consumed by this operation is a few watts or less, additional manufacturing costs are minimal, and installation and maintenance are no more difficult than for other active heat-transfer techniques.[8] The principal cost is the high-voltage power supply. Enhancements to heat transfer can be as high as 300 percent. Safety concerns are minimal. The electrical hazard is low due to the small current and, given no moving parts, the mechanical hazard is non-existent.

Summary. All of the above technologies to increase heat exchanger effectiveness have been demonstrated and incorporated in residential or commercial products and are therefore technologically feasible. There are no known barriers to manufacturing, installing, or servicing products with these technologies. Since heat exchanger technology today is mature, there is no reason to expect adverse impacts on product utility or availability. There are, however, practical limitations to the heat exchanger technologies discussed above. For example, for a given furnace output capacity, it is mainly the heat exchanger's material properties that dictate a minimum heat exchanger size and mass. The known health and safety risks associated with heat exchangers include carbon monoxide (CO) exposure and fire danger. However, these problems are not related to a specific heat exchanger technology or attribute. Rather, they arise for several reasons, including poor design and/or fabrication, and improper furnace set-up, installation, and maintenance. In summary, improved heat exchanger effectiveness passes all of the screening criteria.

4.2.1.2 Modulating Operation

A modulating control is any control that uses either gradual or step-wise adjustment of the furnace input rate in response to changes in the heating load. Two different types of modulating controls that can be applied to furnaces and boilers—two-stage and step control—could increase AFUE and reduce electricity consumption.

Two-stage control refers to a modulating control that cycles a burner between a reduced heat-input rate and off, or between the maximum heat-input rate and off. Two-stage controls are limited to these two operations. They are not capable of operating from reduced heat input to maximum heat input, nor of operating from maximum heat input to reduced heat input.

Two-stage control can be achieved by a variety of means. Use of two-stage gas valve modulation by itself is rarely considered in practice because, if gas flow is reduced without reducing combustion air flow, the excess air increases and the steady-state operating efficiency of the furnace decreases. By reducing the firing rate for longer periods, off-cycle losses are diminished and off-period efficiency can increase.[9] A two-speed circulation fan control is also rarely considered without modulating the gas input, because increasing circulating air flow beyond a certain point reduces comfort, increases noise, and increases electrical operating cost. The heating speed of the blower should be selected to provide optimum comfort and minimum operating cost.

Another control configuration, the two-stage gas valve with two-stage combustion fan control, requires appropriate design considerations to ensure that the flue products do not condense in the primary heat exchanger. The AFUE of such a system may improve, but the furnace would run for a longer time.[4] The two-stage gas valve and two-stage circulating blower design, on the other hand, is similar to two-stage gas valve modulation, except that using an electronically commutated motor (ECM) would result in reductions in the electrical operating cost that would more than compensate for the increased cost of gas, and the AFUE rating would be lower.

The two-stage gas valve, two-speed combustion fan, and two-speed supply fan configuration is a standard way to design a modulating gas furnace. Combustion efficiency is maintained because the burners operate at high and low input rates with equal excess air rates. A considerable amount of electrical energy is saved if an ECM motor is used.

Step modulation can provide a number of performance improvements. Furnaces that operate at substantially reduced output over longer periods of time can provide more uniform space temperatures, quieter operation, greater efficiency, and reduced emissions. Achieving these objectives, however, requires that the combustion stoichiometry (the proper fuel/air mixture to assure clean combustion) be carefully controlled at all firing rates to ensure safe operation and minimum emissions.

The primary difference between two-stage and step-modulating control is that the two-stage control must operate between either the low firing rate and off, or the high firing rate and off, whereas the continuous modulating control can operate between multiple firing rates (e.g., off to low-fire to high-fire to low-fire to off). According to manufacturer literature,[10, 11] a continuously modulating furnace contains several specific components: modulated output thermostat, modulating gas valve, integrated furnace control, two-speed or variable-speed blower, two-speed induced draft blower, supply-air temperature sensor, and return-air temperature sensor.

Step modulation can be achieved by the same variety of means described for two-stage modulation. This system would have all the advantages of the modulating gas valve, modulating combustion fan, and modulating supply fan configuration, with the further advantage of slightly better efficiency and less electrical consumption.

According to manufacturers, step modulation requires a fully modulating gas valve, a variable-output induced draft fan, a variable-output circulating air fan, and a combustion controller, to maintain proper control of a modulating gas-fired appliance.[11] This is the key to a fully modulating appliance, which interfaces with all of the furnace controls, including the thermostat, the ignition and flame-proving devices, the two motors, the gas valve, and all of the safety controls.

Based on current information, modulating technologies do not pose any known safety hazards. The manufacturer installation manuals[12] state that the venting system for modulating gas furnaces (at 80 percent and 81 percent AFUE levels) should use double-wall vent connectors, which are widely used in venting heating equipment. The double-wall vent connector ensures that condensation does not occur in the vent connector, which is the most likely point in the vent system for condensation to occur.[13]

Brookhaven National Laboratory is currently testing prototypical air-atomizing oil burners (fan-atomizing burners) for potential two-stage firing rates. However, the conventional pressure-atomizing burners used in residential applications operate with firing rates that are typically too high to be effective in a staged-firing application.[14]

Summary. Modulating gas furnaces and boilers, both two-stage and step, are currently on the market, which demonstrates the technological feasibility and the practicability to manufacture, install, and service them. There are no known published discussions on adverse impacts on product utility. In fact, one of the advantages of modulating furnaces and boilers is that they provide additional utility to consumers (e.g., quieter operation, less variation in air temperatures). Based on the fact that most major furnace manufacturers currently market modulating models, which use standard technologies and production processes, there are no adverse impacts on product availability. This technology appears to have no adverse impacts on health or safety. Thus, two-stage modulating and continuous modulating technologies, as applied to gas-fired equipment, pass all the screening criteria.

4.2.1.3 Increased or Improved Insulation

Many furnaces and boilers are equipped with a layer of insulation designed to reduce the amount of heat transferred to the appliance's environment through the jacket. Increasing the thickness of the insulation layer reduces the jacket losses in isolated combustion systems (ICS) (outdoor installations). For indoor installations, jacket losses are considered useful heat and do not affect the product’s efficiency. Fiberglass is the most commonly used insulation material. Using materials with a higher R-value (i.e., thermal resistance, the measure of how quickly heat can be lost through the insulation) would further reduce the jacket losses.

An increase in insulation affects the width but not the height of the furnace. Whereas an increase in height can present a problem in some installations, the increase in width considered for this design option does not pose any problems with respect to product utility.

Many ICS and weatherized furnaces (and outdoor boilers) already include the jacket insulation design option, so adding or improving jacket insulation is technologically feasible. Similarly, the capability to manufacture, install, and service equipment with increased or improved jacket insulation is practical using today's processes. Jacket insulation is already used in existing products and it is therefore a technologically feasible design option. Jacket insulation poses no health or safety risks. Increasing or improving jacket insulation would not have any adverse impacts on health or safety. Therefore, the jacket insulation design option passes all the criteria.

4.2.1.4 Condensing Secondary Heat Exchanger

While a primary heat exchanger captures most of the heat available in the combustion process, a secondary heat exchanger is designed to condense the water vapor in the flue gas, thus harnessing the latent heat associated with the phase change of the water. The heat of vaporization of water in the combustion products of natural gas represents about 9 percent of the total energy in the gas.

This analysis focuses on the most common way to condense water vapor in the flue gases, by adding a secondary condensing heat exchanger to the dry primary heat exchanger. Because sulfur, chlorine, and other impurities can combine with water vapor to create acids and may be present in the gas and combustion air, it is essential that the condensing heat exchanger materials be highly corrosion-resistant. Most designs that meet this criterion use stainless steel. Another solution is to use low-cost carbon steel with a plastic coating that is impervious to condensate and to the flue gas.

The water vapor in the flue gases condenses if the temperature of the heat exchanger is sufficiently low. The heat exchanger area of a condensing furnace must be about double that of the heat exchanger of an 80 percent AFUE furnace having equivalent heating capacity. Most condensing furnaces operate with higher inducer pressure than non-condensing furnaces, because of the higher density of the low-temperature flue products going through the inducer fan and the greater pressure drop across the larger heat exchanger.

Another way to condense flue gases is to increase the heat-transfer coefficient in the heat exchanger. In a condensing heat exchanger, mass transfer (condensing water vapor) takes place simultaneously with heat transfer, which improves the heat-transfer coefficient.

Operating in a condensing mode is not a practical near-term option for oil-fired furnaces. The use of low-sulfur fuel oil may make this a more attractive option in the future, but considerable research that includes evaluation of safety concerns is needed.

Condensing gas furnaces account for nearly one quarter of annual gas furnace shipments. Condensing hot-water boilers are also available from several manufacturers. The high volume of shipments demonstrates the technological feasibility of condensing secondary heat exchangers. Likewise, the ready availability of models of condensing non-weatherized gas furnaces and hot-water boilers confirms the practicability to manufacture, install, and service this design option, and indicates no adverse impact on product availability from an increased reliance on this technology. Condensing technology seems to pose no adverse impacts on product utility or on health and/or safety. Therefore, the Department determined that this technology option meets all screening criteria for the non-weatherized gas furnace and hot-water boiler product classes.

4.2.1.5 Electronic Ignition

The baseline model ignition system used in hot-water gas boilers and mobile home furnaces (MHFs) is a standing pilot. A type of electronic ignition system, the hot-surface ignitor (HSI), is also available for these products. Unlike standing-pilot ignition systems that consume gas continuously, HSI devices operate only at the beginning of each “on” period. Although electronic ignition devices do not increase the steady-state efficiency, burner on-time may increase slightly to make up for the heat the standing pilot would have supplied during standby periods. HSIs use a hot surface to ignite the main burners. This type of igniter uses 400 Watts (w) for 37 seconds during startup and 2.5 W continuously during on-cycle. This design does not require maintenance. However, because the igniter itself does not last indefinitely, igniter replacement is occasionally necessary.

A design option that DOE considered, the “hot-surface pilot,” is a modification of the HSI system. It is a small, hot-surface igniter that lights a pilot, which in turn lights the main burner. It uses much less electrical power than the typical HSI and is much more reliable (i.e., less likely to burn out).

Residential oil burners are currently ignited using an intermittent-duty ignition. Underwriters Laboratories, Inc. (UL) defines intermittent-duty ignition as "ignition by an energy source that is continuously maintained throughout the time the burner is firing.”[15] This design has been the standard of the industry for many years. Reductions in electric consumption are possible through “interrupted ignition,” which is available for residential oil burners.[14] The UL defines interrupted-duty ignition as an "ignition system that is energized each time the main burner is to be fired and de-energized at the end of a timed trial period or after the main burner is proven to be established.[15] In other words, the ignitor comes on to light the flame, and then, after the flame is established, the ignitor is turned off and the flame keeps burning.

The burner industry promotes the interrupted-duty ignition strategy. The industry is currently transitioning away from electromechanical controls and iron core transformers, and toward solid-state controls with interrupted-duty capability and electronic igniters. So far, the reaction from installers and consumers has been positive, since these devices are smaller, weigh less, offer improved performance with cold-oil or delayed-spark conditions, are less sensitive to line voltage fluctuations, and extend the life of the igniter and the electrodes.[16, 17]

Since this design option is already being used, it is clearly technologically feasible and practical to manufacture, install, and service. There is no reason to expect that widespread adoption of this design option would have an adverse impact on product availability. No adverse impacts on product utility or on health and/or safety have been reported. This design option passes all the screening criteria.

4.2.1.6 Induced and Forced-Draft Combustion Systems

Induced-draft and forced-draft combustion systems are two alternatives to natural-draft systems. Induced- and forced-draft systems use a fan to provide the air flow necessary for combustion, without the need for a draft hood or draft diverter.

The combustion-air blower in an induced-draft system is located downstream from the burner and heat exchanger. This is the safest way to obtain the advantages of a power-draft furnace. An induced-draft system maintains negative pressures throughout the flue gas stream within the appliance, thus ensuring that any leakages will be directed into the flue gas stream and away from the surroundings. This provides an added measure of safety, because a negative pressure is established in the heat exchanger as well, preventing the combustion gases inside the heat exchanger from contaminating the conditioned air, should the heat exchanger develop a crack or opening during its lifetime.

The forced-draft combustion system provides almost the same efficiency advantages as an induced-draft furnace. The difference is that the combustion-air blower in a forced-draft system is located upstream of the burner. This difference may affect heat loss from the collector box assembly because the combustion-air blower is not located in the flue-gas stream in forced-draft systems. Although once more common, forced-draft systems are not widely used today, as they cannot maintain negative pressures in the flue-gas stream.

The induced-draft technology is commonly used for non-weatherized and weatherized gas furnaces. Oil-fired furnaces and oil-fired boilers typically use forced-draft combustion. Mobile home furnaces and gas hot water boilers typically use natural draft systems. Therefore, the Department considers induced-draft combustion as a design option for mobile home furnaces and gas hot-water boilers.

In the case of gas-fired furnaces, both the induced and forced-draft combustion technology have a significant efficiency advantage compared to the natural draft combustion system. A Gas Research Institute (GRI) study[6] points out that using an induced draft system increases efficiency by 6.6 AFUE points compared to the natural draft system. Electricity consumption increases slightly, but the total site energy consumption decreases considerably.

In the case of gas-fired boilers, the induced-draft combustion technology also has an efficiency advantage compared to the natural draft combustion system. The GRI study[6] points out that using the natural draft system instead of induced draft system would increase the efficiency by 2.3 AFUE points. Electricity consumption increases, but the total site energy consumption decreases considerably.

Induced-draft combustion systems are used in most gas furnaces currently sold in the U.S., and forced-draft systems were once common, demonstrating that this technology is feasible and practical to manufacture, install, and service. The Department is aware of no reports of adverse impacts on product utility or product availability, or of adverse impacts on health and/or safety, that are attributable to the use of these technologies. This design option passes all of the screening criteria.

4.2.1.7 Infrared Burner

Infrared burners are a design option for gas-powered burners in furnaces and boilers. Infrared burners are typically premix burners that produce a high radiant-heat flux with low emissions. Infrared burners have a small efficiency advantage over blue-flame burners because they can operate at lower levels of excess air. However, because these burners use 100 percent primary air, they are susceptible to uneven operation (flashback). To prevent this from becoming a safety problem, flashback-sensing devices must be added to each burner, thus increasing the cost. Low nitrogen oxides (NO_x) production is a strong advantage of all infrared burners.[4]

Several infrared burner materials have been developed, including ceramic, stainless steel, and glass fiber. Most ceramic burners are flat plates and have not been used in gas furnaces, although they have been used in boilers. Recently, a ceramic burner design that consists of ceramic fibers formed into a mat structure has been reported.[18] This design satisfies the heating load requirements for residential furnaces, has very low NO_x emissions, and is capable of operating within a very wide turndown ratio (the ratio of the maximum to minimum output). Perforated high-temperature stainless steel and woven high-temperature wire are formable and adaptable to various configurations. However, metal gets brittle with time, creeps out of shape, and cracks. Glass fiber is the most successful material, since it can be formed and it reliably maintains its shape.

Infrared burners are currently used in many applications, demonstrating technological feasibility and practicability to manufacture, install, and service. Experience shows no adverse impacts on product utility. The existence of several technological options to produce infrared burners (as described above) indicates that there are no adverse impacts on product availability. No reports have been found indicating adverse impacts on health and/or safety attributable to infrared burners. None of the criteria would screen out this design option.

The infrared burner design option is not currently applicable to oil burners, because the oil fuel requires fuel atomization and vaporization prior to combustion. Ongoing research on alternative fuel-oil atomization and combustion methods may someday permit the development of radiant oil burners. However, due to the lack of current technological feasibility, this is not a viable option for oil-burning appliances at this time.[14]

4.2.1.8 Direct Vent

Direct-vent appliances use ducts to provide outdoor air for combustion. Non-direct-vent appliances typically use air from the appliance's environment for combustion. Direct-vent systems may use a combustion-air preheat system that passes the outdoor combustion air through a heat exchanger in contact with the flue gases. The combustion air does not mix with the flue gases. The so-called direct-vent with preheat design uses a concentric vent/combustion air system in which the flue gases pass through a central-vent pipe and the combustion air passes through a concentric duct surrounding it. This arrangement creates a counter-flow heat exchanger that recovers some heat from the flue gases to preheat the combustion air.

The direct vent with preheat technology provides an efficiency advantage compared to non-direct vent systems. The GRI study[6] points out that using the combustion air preheat technology instead of non-direct vent system would increase the AFUE by 3.4 AFUE points.[a]

The direct-vent-without-preheat design is the same as the direct-vent-with-preheat design, except that the combustion air is not preheated by the flue gases. There are separate vent and combustion air systems and the combustion air is not preheated. The current test procedure does not differentiate between the performance of direct-vent with and without preheat technology; both are evaluated as ICS installations.

The fact that direct-vent designs are currently available for many models of furnaces and boilers shows that this design option is technologically feasible and practical to manufacture, service, and install. Long experience with direct-vent systems has shown no adverse impacts on product utility, product availability, or health or safety. Thus, this design option meets all of the screening criteria.

4.2.1.9 Fuel Filtration

An option for oil-fired equipment is the use of modern fuel-filtration technology to improve system efficiency by maintaining clean flames and reducing the rate of fouling in the heat exchanger.[14]

Fuel filtration is currently available for some models of oil-fired furnaces and boilers, and therefore this design option is technologically feasible and practical to manufacture. The Department is aware of no reports of adverse impacts on product utility, on product availability,

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[a] These results are obtained under the current DOE test procedure conditions, which specify relatively short vent runs (five-foot venting section). These conditions reflect the installations of mobile home furnaces and do not require the concentric vent to be made of special stainless material. However, relatively longer venting sections are required in most homes, which may cause condensate problems in a concentric vent system in the colder parts of the country. Therefore, corrosion-resistant vent materials should be considered with this design option for applications other than mobile homes.

or on health or safety that are attributable to the use of fuel filtration technology. This design option meets the screening criteria.

4.2.1.10 Pulse Combustion

Pulse-combustion burners operate on self-sustaining resonating pressure waves that alternately rarefy the combustion chamber (drawing a fresh fuel/air mixture into the chamber) and pressurize it (causing ignition by compression heating of the mixture to its flash point). This process is initiated by a blower supplying an initial fuel-and-air mixture to the combustion chamber. The mixture is ignited with a spark. Once resonance is initiated, the process becomes self-sustaining.[19] Pulse frequencies are on the order of 100 cycles per second. Pulse combustion systems feature high heat-transfer rates, are capable of self-venting, and can draw outside air for combustion even when installed indoors. The CO emissions from pulse combustion burners are 50–66 percent lower than those of a conventional burner.[19] Because the pulse combustion process is highly efficient, the burners generally are used with condensing appliances.

In contrast to other forced-air furnaces utilizing natural draft and induced draft technologies, pulse-combustion furnaces generate positive pressure on the flue side of the heat exchanger. This creates a potential safety problem, because any leak in the heat exchanger results in the potential for combustion products contaminating the circulation-air stream.

Pulse-combustion gas furnaces were available in the United States for more than two decades, but they were withdrawn from the market because the manufacturers found that competing technologies such as condensing flue gases using a secondary heat exchanger cost significantly less to manufacture and operate. Regarding oil-fired pulse combustion of boilers and furnaces, at least one prototype version has been developed, but no commercially available units have been introduced for residential applications in the United States.

The length of time this technology was available demonstrates the technological feasibility and the practicability to manufacture, install, and service products with this design option. The Department is not aware of any adverse impacts on product utility or health or safety that are attributable to the use of pulse combustion technology. Given the long years of production of this design option, there is enough experience available to assure product availability. For gas furnaces, this design option passes all the screening criteria.

4.2.1.11 Dampers

Burner-box dampers and flue dampers restrict the exhaust gas flow on the flue-gas side of the heat exchanger during the off cycle, thereby trapping residual heat in the heat exchanger. Burner-box dampers are installed at the combustion-air inlet to the appliance and flue dampers are installed in the flue, where the flue gases leave the appliance. Stack dampers may be used with appliances equipped with draft hoods; they are installed downstream of the draft hood. The stack damper closes during the off cycle to restrict the flow of dilution air through the vent system when the appliance is off. The dampers are most useful with natural-draft combustion systems.[6]

A high-quality flue damper may be used in lieu of a fan-assisted design.[6] In order for such a furnace to achieve performance which matches or exceeds the current minimum efficiency requirements, the damper closure ratio must be close to 100 percent.

Dampers currently are installed on many models of gas boilers, which demonstrates the technological feasibility of this design option and its practicability to manufacture, install, and service. Since the design option is not a complicated technology and has been produced for at least two decades, there is no reason to expect adverse impact on product availability. The Department is not aware of any adverse impacts on product utility, or on health or safety, from damper designs. This design option meets all the criteria.

4.2.1.12 Air-atomized Burner with Modulation

The residential oil burner market is currently dominated by the pressure-atomized retention head burner. At low firing rates, pressure-atomizing nozzles suffer rapid fouling of the small internal passages, leading to bad spray patterns and poor combustion performance.

To overcome the low input limitations of conventional burners, a low-pressure air-atomized burner has been developed that can operate at firing rates as low as 0.25 gallons of oil per hour (10 kW). In addition, the burner can be operated in a high/low-firing rate mode. This burner is currently being commercialized. It can operate with almost no excess combustion air (less than 10 percent) with lean-burning, ultra-clean combustion. This burner design is capable of firing fuel at low input rates to closely match the smaller heating loads of well-insulated modern homes. Tests performed at the Brookhaven National Laboratory have demonstrated that the use of this technology produces significant reductions in emission of nitrogen oxides (NO_X) and particulates.[20]

This burner design has been available for more than a decade. The results from long-term tests at Brookhaven National Laboratory indicate that there are no problems with technological feasibility or practicability to manufacture, install, or service this technology. There are no reasons to expect adverse impacts on product utility, and no indications of adverse impacts on health or safety. This design option passes all the screening criteria.

4.2.1.13 Delayed-Action Oil-Pump Solenoid Valve

Delayed-action oil-pump solenoid valves can improve overall efficiency and lower particulate emissions during burner on-off cycling. This device is installed to supplement the fuel pump regulator; by delaying the fuel release by several seconds, it allows the pressure to build to the required level and to be fully discharged in the combustion chamber without dripping. Testing at Brookhaven National Laboratory indicates that the typical efficiency benefit of delayed-action solenoid valves is expected to be less than 1 percent.

Delayed-action oil-pump solenoid valves for oil-fired equipment are already offered in at least two fuel-pump models (Valcor Scientific and Taisan), which indicates the technical feasibility of this design option. It also indicates the practicability to manufacture, install, and service products incorporating this design option. The Department is aware of no reports of adverse impacts on product utility or adverse impacts on health or safety caused by this design option. Therefore, this design option passes all the screening criteria.

4.2.1.14 Increased Motor Efficiency

More-efficient electric motors could be used in furnace blowers, hot-water boiler pumps, and draft inducers.

Most furnace-blower motors and hot-water boiler pumps use a permanent split capacitor (PSC) design. PSC motors are reasonably efficient (above 70 percent) when operating at high speed. However, when these motors are operated at low speed, their efficiencies may drop into the 20 percent range. The circulating blower for most gas furnaces is also used to circulate the supply air when the air conditioner is operating. The air-conditioner evaporator coil needs a higher airflow than the furnace heat exchanger; therefore, the blower motors operate at low speed, and thus inefficiently, for the furnace operation.

Technologies that use power electronics offer dramatic improvements in efficiency at low speeds. In the ECM—also known as the brushless, permanent-magnet motor—the rotor is a permanent magnet. A rotating magnetic field is created in the armature by switching current in a coordinated manner among six coils. This creates a three-phase motor with essentially no losses in the rotor. The speed and torque of the motor can be accurately varied by controlling the frequency and voltage applied to the armature coils. ECMs can operate at efficiencies above 80 percent across a very wide range of speeds. A similar, slightly-the-less-efficient motor technology, the switched-reluctance motor, has a solid-steel rotor instead of a permanent magnet. The power electronics are more complicated than for the ECM.

Designs to increase PSC motor efficiency are currently available; about 5 percent of furnace shipments currently use ECMs, so there is apparently no issue with technological feasibility or practicability to manufacture, install, and service. There have been no reports of adverse impacts on product utility or availability. In fact, the electronic controls on ECMs allow manufacturers to offer additional features such as continuous ventilation, reduced noise, and better control of air flow, which improve the utility of furnaces. There have been no reports of adverse impacts on health or safety. In fact, improvements that become possible with electronic controls may lead to a healthier indoor environment due to the lower temperature variations, and also reduce noise. Increased motor efficiency passes the screening criteria.

4.2.1.15 Increased Blower Impeller Efficiency

This technology discussion applies to furnaces only, since boilers do not have blowers. Improving the efficiency of the blower impeller (wheel) lowers the power requirements of the motor. The maximum efficiency of the commonly used forward-curved fan impellers is 65 percent, although efficiency in operation may be much lower. A viable alternative design is a backward-curved impeller, which has a maximum efficiency of 78 percent. It has been available in larger blowers for decades.

Impellers with improved efficiency are technologically feasible and practical to manufacture, install, and service. As long as the blower moves the same amount of air as current designs, there will be no impact on product utility, health, or safety. The improved designs are not expected to be appreciably different to manufacture, so product availability will not be a problem. This design option passes all the screening criteria.

4.2.2 Design Options Eliminated from Further Consideration

The Department eliminated the following design options from further consideration because they do not meet the screening criteria as described in section 4.1.

4.2.2.1 Self-Generation of Electric Power

It may be possible to use the heat generated by a furnace's combustion system to generate the electricity needed to operate the various electrical components.[21, 22] Known methods include thermophotovoltaic (TPV) generators, thermoelectric generators, and thermionic conversion. Other techniques use engines based on the Rankine cycle, Brayton cycle, Stirling cycle, or Otto cycle, where the engine drives an electrical generator or provides direct mechanical power and the waste heat from the engine is used for space heating. Several references provide detailed discussion of the self-powered heating appliance technologies.[21, 22]

TPV devices convert radiant heat directly into electrical power by using a semiconductor cell situated inside of the combustion zone. Currently, TPV systems are not available for oil- or gas-fired equipment. Preliminary testing at Brookhaven National Laboratory has not yet produced an effective prototype. Future advances in TPV technology may allow incorporation of this new technology into control systems and power generation for residential equipment. However, this technology is not yet available for residential use, and considerable research is needed before its potential savings and costs can be evaluated.

Thermoelectric generators are thermocouples made from semiconducting alloys with power conversion efficiencies capable of small-scale power generation. A thermocouple is a circuit formed by two wires of dissimilar metals, where the junctions are kept at different temperatures, producing an electromotive force in the circuit, also known as the Seebeck effect. For furnace designs, the thermoelectric generator would form a cylinder around a firing flame. A rechargeable battery would start the thermoelectric generator but, once hot, the thermoelectric generator would provide sufficient excess capacity to recharge the battery.[23] With no moving parts, a thermoelectric generator is maintenance-free and can last the life of the furnace.

No self-powered furnaces or boilers are currently on the market. While there has been research and development work that looks promising, at this point the Department is not convinced that this design option is technologically feasible. There are no data to indicate the practicability to manufacture, install, and service products incorporating this design option. The Department is aware of no reports assessing the impacts on product utility or impacts on health or safety resulting from this design option. Therefore, the Department excluded this design option from further consideration for the purposes of this rulemaking.

4.2.2.2 Fuel-Driven Heat Pumps

Heat pumps extract heat from outdoor air or the ground and thus offer the potential for greater heating output than energy input. This technology takes advantage of the thermodynamic principle that energy can be extracted from the appliance's environment and delivered to the conditioned space.

It is possible to manufacture fuel-fired heat pumps that use engine-driven vapor compression cycles. The fact that, in the past, several manufacturers marketed this type of equipment shows that this design is technologically feasible. Other designs use absorption cycles and adsorption cycles. (Several manufacturers sold air conditioners utilizing an aqua-ammonia-based absorption cycle from the late 1960s up to the 1990s, but the reliability problems and related service costs were prohibitive, and the manufacturers took these models off the market.) This option uses a fundamentally different thermodynamic phenomenon from the process of convective and conductive heat exchange that occurs in furnaces and boilers, and would require a complete redesign of the appliance.

Fuel-driven heat pump technology appears to be technologically feasible and has no adverse impact on product utility or on health and safety. During the 1990s, one manufacturer marketed, in limited localities, a design for a fuel-driven heat pump, but withdrew it after a few years. Based on the past experience with fuel-driven technology,[24] the Department found that residential fuel-driven heat pumps would not be able to be mass-produced and be reliable to install and service on the scale necessary to serve the relevant market at the time of the effective date of the standard. Therefore, the Department excluded this option from further consideration.

4.2.2.3 Flue-Gas Recirculation

Flue-gas recirculation (FGR) design allows a fraction of the flue gas to be recirculated to the inlet and mixed with the combustion air so that some of the products of combustion pass through the burner more than once. This process reduces NO_x, but potentially increases CO production. The flame temperature and the temperature of the flue products are also reduced. This technology has been implemented for pollution control in automobiles and large commercial boilers.

Computer simulations of furnace performance show that FGR with the current furnace design improves the AFUE by 0.3 percent, due to the reduction of the excess air. However, the combustion fan would consume 10 percent more electricity in order to overcome the pressure drop associated with the flue-gas recirculation.[6]

In the case of boilers, a study showed that the addition of NO_x-control systems, such as FGR and low NO_x burners, can reduce combustion efficiency (due to lower combustion temperatures), resulting in higher CO and organic emissions relative to uncontrolled boilers. The FGR process reduces the peak flame temperature because the flue gas that is reintroduced into the furnace's combustion and flame zones is at a lower temperature and has a lower oxygen concentration.[25] This process reduces excess air (free oxygen) fractions, potentially compromising the furnace's ability to meet the requirements of the American National Standards Institute (ANSI) Z21.47 overfire test, which stipulates that the carbon monoxide level in the flue products must remain below 0.04 percent when the furnace is fired at 12 percent over its rated input. Incorporating the FGR process would make it more difficult for furnace (and boiler) manufacturers, who currently design their equipment to operate with excess air fractions that are sufficiently high enough to account for the practical aspects of field operations and maintain safe operation, to meet the ANSI CO limit.[6, 26]

Furnaces with FGR design are technologically feasible and practical to manufacture, install, and service. This design is used extensively in commercial-sized equipment and, therefore, the product availability is not a problem. There are no known negative impacts on the product utility. However, this design may result in higher CO production, and therefore, given the potential negative impact on health and safety due to an increased potential for CO production, the Department excluded this technology from further consideration.

4.2.2.4 Smart Valve

One option for oil-fired furnaces and boilers is a “smart valve” or positive shut-off valve on the fuel nozzle, which reduces smoke and soot production during burner start-up and shut-down. This valve is generally installed directly in the nozzle tip and prevents oil from dripping into the combustion chamber. This option can also be retrofitted on existing burners. Smart-valve design for oil-fired equipment does not affect the efficiency of the appliance, but plays a role as an emission-control device.

Smart valve design has no known adverse impact on product utility or on health and safety. Although this technology has been offered by at least one oil-burner manufacturer for commercial-sized equipment, the Department is not aware of any prototypes for use in residential-sized equipment. Since there is no proof that smart valve design would be able to be mass-produced and be reliable to install and service on the scale necessary to serve the relevant market at the time of the effective date of the standard, the Department excluded it from further consideration.

4.2.2.5 Design Options Yielding 82 Percent and Higher AFUE for Non-condensing Non-weatherized Gas Furnaces

Technologies for producing non-condensing non-weatherized gas furnaces can yield efficiency of up to 89 percent AFUE. At levels of 82 percent AFUE and above, however, there are concerns regarding corrosion in vents and condensation that could pose risk to the consumer. According to the National Fuel Gas Code, condensation occurs at 83 percent steady-state efficiency, which is close to 82 percent AFUE.[4] Based on comments received at and after the ANOPR public meeting, the Department believes that non-condensing non-weatherized furnaces with necessary venting systems at AFUE levels of 82 percent and higher would not be able to be mass-produced and be reliable to install and service on the scale necessary to serve the relevant market at the time of the effective date of the standard. Further, there are safety issues related to venting at these AFUE levels. Therefore, DOE discontinued consideration of non-condensing non-weatherized gas furnaces at 82 percent AFUE and higher.

4.3 SUMMARY OF SCREENING

Table 4.3.1 presents the results of the screening of design options by product class. The design options showing a “Y” (for “yes”) pass all of the screening criteria. Some options are not applicable (n/a) for certain product classes. For example, improved or increased insulation is not applicable for boilers because boilers are tested as indoor appliances according to the DOE test procedure.

Table 4.3.1 Screening Results for Design Options by Product Class

	Gas Furnaces		Oil-fired furnaces	Mobile- Home Gas Furnaces	Hot Water Boilers	
	Non-weatherized	Weatherized				
Design Option					**Gas**	**Oil**
Improved Heat Exchanger Effectiveness	Y	Y	Y	Y	Y	Y
Modulating Operation	Y	Y	Y	Y	Y	Y
Increased or Improved Insulation	Y	Y	Y	Y	n/a	n/a
Condensing Secondary Heat Exchanger	Y	N	N	Y	Y	Y
Electronic Ignition	b	b	b	Y	Y	b
Induced or Forced Draft	b	b	b	Y	Y	b
Infrared Burner	Y	Y	Y	Y	Y	Y
Direct Vent	Y	Y	Y	Y	Y	Y
Fuel Filtration	n/a	n/a	Y	n/a	n/a	Y
Pulse Combustion	Y	Y	N	Y	Y	N
Dampers	n/a	b	n/a	Y	Y	n/a
Air-Atomized Burner with Modulation	n/a	n/a	Y	n/a	n/a	Y
Delayed Action Oil Pump Solenoid Valve	n/a	n/a	Y	n/a	n/a	Y
Increased Motor Efficiency	Y	Y	Y	Y	Y	Y
Increased Blower Impeller Efficiency	Y	Y	Y	Y	n/a	n/a
Self-Generation of Electricity	N	N	N	N	N	N
Fuel-Driven Heat Pumps	N	N	N	N	N	N
Flue Gas Recirculation	N	N	N	N	N	N
Smart Valve	n/a	n/a	N	n/a	n/a	N

Y = The design option is applicable to this product class and passes screening.
N = The Department screened out this design option from further analysis for this product class.
b = The design option is already in the baseline model of this product class.
n/a = The design option is not applicable to this product class.

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