CHAPTER 4. SCREENING ANALYSIS

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CHAPTER 4. SCREENING ANALYSIS

4.1 INTRODUCTION

The screening of design options is the first step in the water heater rulemaking process. The purpose of screening is to identify those design options that the Department will consider for the engineering analysis. The screening analysis also provides a discussion of the criteria for eliminating certain design options from further consideration. On July 15, 1996, the Department issued the Process Improvement (Interpretive) Rule.[1] Section 4 of the Interpretive Rule articulates factors to take into account in screening design options. These factors are as follows:

- Technological feasibility,
- Practicability to manufacture, install and service,
- Adverse impacts on product utility or product availability,
- Adverse impacts on health and/or safety.

This chapter discusses various design options for improving the energy efficiency of electric, gas-fired (natural gas and LPG),[a] and oil-fired storage-type water heaters. Building on past analysis and incorporating public comments to the 1994 NOPR, a draft screening analysis was prepared and presented at the Water Heater Standards Rulemaking Workshop held in Washington, D.C., on June 24, 1997, for review and comment from stakeholders. This chapter addresses comments received at three different stages of the rulemaking process since that initial draft was issued. These later comments have been incorporated into the technical review of all design options. Based on this technical review, the design options have been screened and pared down to a list of options used by DOE for the engineering and economic analyses.

4.1.1 Stakeholder Comments

Section 4 of the Interpretive Rule, which establishes the process for developing energy conservation standards, provides for greater and more productive interaction between DOE and stakeholders throughout the process. It is also designed so that key analysis is performed earlier in the process, with early opportunities for public review and comment on that analysis. The process is consistent with the procedural requirements of the law, but adds some important enhancements.

There have been several opportunities for public comment on the residential water heating standards process. DOE has considered all the comments it has received and presents below those

[a] Water heaters fueled by natural gas and LPG are considered as one product class for the purpose of identifying design options. They are treated separately with respect to manufacturing cost, markup, retail price, and fuel price in the Life-Cycle Cost and subsequent analyses.

comments that specifically discuss DOE's screening of design options.

After the June 1997 workshop, DOE received several written comments from stakeholders pertaining directly to the design options discussed. There were a total of 15 sets of comments from manufacturers, associations, gas and electric utilities, a consumer group, and a consumer. (All comments are available for viewing in DOE's Freedom of Information Reading Room.)

Laclede Gas Company and the American Gas Association (AGA) advised DOE to follow statutory requirements and not to screen out any design options.[2, 3] Section 4 of the Interpretive Rule articulates factors DOE will take into account in screening design options, selecting candidate standard levels for further analysis, and selecting proposed and final standard levels. Therefore, DOE is following the criteria listed in the Interpretive Rule and will proceed to reject certain design options from the analysis based on these considerations. In reference to Section 4(a) of the Interpretive Rule, the Gas Appliance Manufacturers Association (GAMA) provided a list of design options to keep and a list to screen out and included reasons for screening them out.[4] Bradford White Corporation supported the GAMA design options discussed at the workshop.[5] Edison Electric Institute (EEI), Southern Company, and Virginia Power supported DOE's screening analysis and list found in *Appendix B, Supplement to the Water Heater Rulemaking Framework.*[6, 7, 8, 9]

In accordance with the Interpretive Rule, the Department published the results of a preliminary screening of the water heater design options in *Technology Assessment and Screening Analysis, Appendix B Supplement to the Water Heater Rulemaking Framework*, in January 1998.[9] Stakeholders were notified of the availability of this document in the Federal Register on January 14, 1998.[10] The Notice further requested comments on the *Technology Assessment and Screening Analysis* document.

DOE received 28 comments on the *Technology Assessment and Screening Analysis* document. Six stakeholders including GAMA supported, with modifications, the Department's position regarding the screened design options. These comments addressed air atomized oil burners, power vents, and tank bottom insulation for gas- or oil-fired water heaters.

The majority of comments dealt with the Department's decision to eliminate the heat pump water heater design option from consideration. AGA claims DOE must consider all design options because DOE is mandated by law to consider all technologically feasible design options. AGA further claims that DOE disregarded the position it took in 1994 on heat pump water heaters.[11] Okaloosa Gas District, Clearwater Gas System, the City of Mesa, Arizona, Milza S. Barley and thirteen gas utilities recommend that DOE consider all design options, including heat pump water heaters.[12, 13, 14, 15, 16] Laclede Gas objects to the elimination of the heat pump water heater from standards consideration because it claims that DOE is protecting electric utility market dominance and it could lead to fuel substitution away from gas water heaters.[17] Laclede Gas further claims that heat pump water heaters should be considered as a design option because DOE is introducing a new heat pump water heater which may overcome several critical market barriers including cost.[18] Okaloosa Gas District believes that DOE should screen-in heat pump water heaters because a recently published GAMA directory lists five models.[12] AGA and Okaloosa Gas District claim that DOE relied on unsubstantiated statements by Southern Company regarding product reliability and inadequate infrastructure to eliminate heat pump water heaters.[11, 12] AGA claims that heat pump water heaters are technically feasible and that reliability and infrastructure issues are not a sufficient reason to eliminate them.[19] DOE eliminated design options based on the criteria in the process improvement rule (see the 61 FR 36974, section III. 4).[1] DOE believes that the heat pump water heater is technically feasible but DOE eliminated the heat pump water heater design option because it is not practicable to manufacture, install, and service heat pump water heaters on the scale necessary at the time of the effective date of this standard and because of adverse impacts on product utility.

GAMA claims DOE was justified in screening out heat pump water heaters and the decision is supported by criteria listed in 42 USC 6295(o).[20] Furthermore, GAMA supports DOE's decision to eliminate specific design options.[4, 21]. EEI, Southern Company and Virginia Power agree with DOE's decision to screen out heat pump water heaters.[7, 22, 23, 24] DOE has continued to screen out heat pump water heaters and several other design options listed in the screening document.

In October, 1998, DOE published *Results and Methodology of the Engineering Analysis for Residential Water Heater Efficiency Standards.*[25] This document, an overview of the preliminary engineering analysis for Residential Water Heater Efficiency Standards, was available to the public prior to the November 1998 Water Heater Rulemaking Workshop. The document contained a section updating the design options screening process based on comments received on the *Technology Assessment and Screening Analysis*. DOE did not revise its position on heat pump water heaters, but further elaborated on the rationale for eliminating heat pump water heaters as a design option.

4.2 DISCUSSION OF DESIGN OPTIONS

The design options considered here are grouped in two categories. The first category is design options used by DOE in the engineering and economic analyses. The second category contains design options that have been eliminated from further consideration. The discussion under this second category also includes the screening criteria used by DOE.

4.2.1 Design Options Used in the Engineering Analysis

DOE used the nine design options listed below in the engineering and economic analyses because they are currently (or have been recently) applied to commercial or residential water heaters and pass all of the screening criteria. In the engineering analysis phase, certain of these design options were combined to meet an efficiency level based on a simple payback estimate.

- Heat Traps
- Plastic Tank
- Increased Jacket Insulation
- Insulating the Tank Bottom (Electric Only)
- Improved Flue Baffle/Forced Draft
- Increased Heat Exchanger Surface Area
- Flue Damper (Electromechanical)
- Side Arm Heater
- Electronic (or Interrupted) Ignition.

4.2.1.1 Heat Traps

The heat conducted and convected through the fittings (water pipes, drain valve, pressure relief valve, and thermostat) accounts for about 15% of the total standby loss in a typical residential-size gas-fired water heater.[26] A heat trap is a device or arrangement of piping that keeps the buoyant hot water from circulating through the piping distribution system because of natural convection. When there is no draw of hot water, this device prevents water in the hot water outlet line from getting back into the tank as it cools off; and prevents hot water in the tank from circulating back into the cold water inlet line. Thus, by containing the hot water in the storage tank, the heat trap minimizes standby loss. These devices can be integral to the tank design or independently attached to the inlet and outlet pipes during installation at the site. Paul *et al*. have shown that heat traps can increase the energy factor (EF) of residential-size water heaters by 1%.[26] Also, the effectiveness of a heat trap can be increased by insulating its exposed portion.

Conventional heat traps are currently made in two styles. In the first style, a floating plastic ball blocks the cold water inlet. The buoyancy of the plastic holds it in place until water is drawn. The force of water is strong enough to push the ball out of the way as water enters the tank. The second style is used for the hot water outlet. In this heat trap, the ball is denser than water, and the weight of the ball seals the outlet until hot water is drawn and the water pressure lifts it out of the way.[27] A small bypass channel is left for water to escape back into the inlet line from the tank as it expands after a large draw fills the tank with cold water. Heat traps could also be of metallic design. Manufacturing costs appear to be roughly comparable between the metal and plastic heat traps, but plastic heat traps are considerably more effective in reducing water heater standby losses.

Other heat trap designs have also been invented and produced. These include U-shaped pipes,[28] flexible seals,[29] flaps, springs, and other mechanisms.

Bradford White Corporation concludes that heat traps are not a design option because they are noisy and viewed as a deterrent for product utility by consumers and cost more than the energy savings can repay.[5] On the other hand, GAMA recommends that heat traps be considered in the DOE analysis because this technology is already implemented in most models.[30]

DOE agreed with GAMA's comment and considered this design option in the engineering analysis.

4.2.1.2 Plastic Tank

Plastic water heater tanks can be constructed using a seamless, blow-molded polybutylene inner tank with a filament-wound fiberglass outer tank, similar to the fabrication of tanks for water softeners.[31] A second method consists of constructing a thin steel shell with an internal plastic tank. The steel exterior is constructed first; then, plastic powder is injected into the shell, and the tank is rotated in a furnace to coat the interior with the plastic. The steel exterior serves as the primary structural support for the tank. The lower heat conductivity of plastic compared to metal reduces the amount of heat conducted through the tank wall to the insulation and to the feed-throughs.

However, the plastic tank cannot be used with standard center-flue gas-fired water heaters or with oil-fired water heaters, because the plastic cannot withstand the high temperatures produced by the flames. This option can be used only with electric water heaters or with indirect water heating techniques (e.g., the side arm water heater or heat pipe technologies) that avoid flame temperature problems.

GAMA recommends eliminating plastic tank water heaters because it is not an efficiency improving design option. GAMA believes DOE should rely on increased insulation thickness for efficiency improvements.[4]

DOE believes that the plastic tank construction method enables an improved process of insulating the tank bottom. Therefore, this design option may, in fact, reduce standby losses in certain applications and should be investigated further. DOE considered this design option in the engineering analysis.

4.2.1.3 Increased Jacket Insulation

Manufacturers insulate water heaters by filling the cavity between the jacket and the tank (top and sides) with polyurethane foam insulation or fiberglass insulation. Because polyurethane foam is a more effective insulation than fiberglass, it is more widely used. Most water heaters on the market today have at least 1-inch thick foam insulation, while some models have 2- or 3-inch thick insulation. The baseline electric unit for the present analysis has 1.5 inches of insulation in order to achieve the minimum EF levels..

The Gas Research Institute (GRI) reports that for a gas-fired water heater with a 40-gallon storage tank with 1-inch polyurethane foam insulation around the jacket and fiberglass insulation around the combustion chamber, the jacket losses are about 50% of the total standby losses.[32] For a tank with more than 40 gallons of storage volume, the jacket losses as a percent of the total standby losses will be even higher. Although increasing the insulation thickness reduces the standby loss, the increase in the overall diameter of the water heater may pose some installation problems. There may also be an increase in shipping costs because fewer water heaters will fit in a truck.

Bradford White Corporation commented that the uncertainty over the blowing agent for foam insulation be handled by limiting the cavity size.[5] DOE has limited cavity size to 3 inches.

DOE has used the blowing agent HFC-245fa in its analysis. On September 13, 1999, Allied Signal[a] announced in a press release that it was planning to manufacture HFC-245fa at its Geismar, Louisiana facility.[35] Allied Signal has received EPA approval for HFC-245fa. At the July 23, 1999 workshop Allied Signal announced a plant would be online by mid 2002.[36] It appears that HFC-245fa will be available by the effective date of this rulemaking, therefore, DOE chose this blowing agent for the engineering and economic analyses.

4.2.1.4 Insulating the Tank Bottom (Electric Only)

The bottom of the tank of an electric water heater can be insulated as an alternative design option to reduce the standby heat loss. This is not conventionally done. As evidence see the losses visible in the infrared thermograph presented by NIST at the November 1998 workshop.[37] DOE believes tank bottom insulation will significantly reduce these losses. DOE included this design option in the engineering and economic analyses.

4.2.1.5 Improved Flue Baffle/Forced Draft

The standard flue baffle is a twisted strip of metal inserted into the flue that increases the turbulence of flue gases and improves heat transfer to the walls of the flue. The geometry of the flue baffle can be modified to increase its effectiveness. One manufacturer uses a flue with many small rectangular fins attached on its inside surface. The arrangement and size of the fins in various models increases the recovery efficiency of the water heater. Other baffle configurations that increase recovery efficiency are also available.

A research project funded by the GRI reviewed technical literature, manufacturers' literature, and patents to determine what new technologies are applicable to heat exchangers that involve flue gases from combustion of natural gas.[38] The conclusion was that significant increases in the convective heat transfer coefficient could be achieved with the use of heat transfer enhancement devices. The study suggested that in some cases, an increase in heat transfer coefficient might be accompanied by an increase in the pressure drop (due to an increase in the friction factor). The study identified twisted-tape inserts as a potential heat transfer enhancement device for water heaters.

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[a] In June 1999, Allied Signal and Honeywell announced their merger; in October 2000, GE acquired the newly combined company.[33, 34]

Beckermann and Goldschmidt [39] investigated experimentally and empirically the effects of velocity of the flue gases, the twist (i.e., number of turns) of the tape, and the surface emissivities on the total heat transfer (convection and radiation) in a fuel-fired water heater. They reported that compared to an empty tube, the flue tube with twisted tape enhances the overall heat transfer performance by as much as 50%.

This design option of an improved flue baffle can increase the recovery efficiency to about 80-85%, depending on the specific geometry. At the upper end of the recovery efficiency range, the water heater would require power venting or induced draft and corrosion resistant flues for safe operation. Because of the potential for condensation caused corrosion, recovery efficiencies above 80% were not considered in this analysis.

In addition to an increase in efficiency, there is also a reduction in standby loss. The off-cycle standby loss is reduced by the additional restrictions to airflow due to the increased baffling.

Several manufacturers currently make water heaters with induced-draft blowers. However, this feature is usually added to allow sidewall venting and may not be accompanied by any increase in flue baffling.

Some manufacturers make water heaters with induced draft fans that, in addition to pulling the combustion products through the water heater, also draw excess air into the flue gases prior to venting. The additional air cools flue gases leaving the water heater to a low enough temperature so standard plastic piping can be used for venting. This eliminates any problems with corrosion. Plastic piping is often cheaper and easier to install than sheet metal or masonry chimneys.

While this technique of flue gas dilution does not necessarily increase water heater efficiency by itself, when combined with an improved flue baffle that increases recovery efficiency, it can help avoid venting problems. DOE included the improved flue baffle/forced draft design option in the engineering analysis.

4.2.1.6 Increased Heat Exchanger Surface Area

There are two fundamental ways to improve the heat transfer from the flue gas to the water including the use of increased heat exchanger surface area and improved flue baffle. The improved heat transfer leads to an increase in the thermal efficiency of the water heater. However, the thermal efficiency is limited to about 84%, at which point condensation of the flue gases begins to occur in the flue or vent pipe that may cause corrosion of the surfaces. To avoid such problems, use of this design option will be limited to an 80% recovery efficiency (or about 82% thermal efficiency) level.

The design option of increased heat exchanger surface area can be achieved using, among others, the following two modifications of the basic design of the standard gas-fired storage water heater: (1)

submerged combustion chamber and (2) multiple flues. The first is to surround the combustion chamber with water; the other is to use a number of smaller flue tubes instead of one large flue to vent the exhaust gases from the combustion process. This design option can increase recovery efficiency sufficiently so that condensation (and hence corrosion) is likely to occur in venting systems so in our analysis we limited the recovery efficiency to 80% or lower.

Submerged Combustion Chamber. The combustion chamber in a standard gas-fired storage water heater is below the water tank, and the bottom of the tank (below the burners) is seldom insulated. Therefore, the water heater loses heat from the bottom of the tank. The sides and bottom of the combustion chamber are not surrounded by water. By inserting the combustion chamber into the storage tank, more of the combustion energy can be recovered. Standby losses are reduced somewhat because of restrictions on the air flow through the combustion chamber and flue.

Multiple Flues. The multiple-flue design uses several smaller flues in place of one large central flue in the middle of the storage tank. The increased surface area for heat exchange between the flue gases and the water in the tank yields an increase in recovery efficiency. One manufacturer is currently offering this design in a residential gas-fired water heater.

DOE considered the use of these design modifications in the engineering analysis.

4.2.1.7 Flue Damper (Electromechanical)

Gas-fired storage water heaters are equipped with a draft hood connecting the flue pipes to a vent pipe or chimney. During off-cycle, the water heater loses heat by natural convection and conduction through the vent pipe or chimney. A damper can be installed either at the flue exit or in the vent pipe to minimize the off-cycle heat losses. A flue damper is installed upstream of the draft diverter, while the vent damper is installed downstream of the draft diverter.

Electric flue dampers are activated by an external source of electricity. The dampers open when combustion starts and close immediately after combustion stops. Therefore, there is a greater reduction in off-cycle losses compared to buoyancy activated dampers [see Flue Damper (Buoyancy Operated)]. When the damper reaches the open position, an interlock switch energizes the solenoid and enables the gas ignition circuit. Therefore, the burner cannot be ignited when the damper is in the closed position. Because the dampers open and close immediately, no bypass is needed. A knockout is provided to vent the flue gases from a standing pilot. The electric flue damper needs a 24-volt electric source and consumes about 5W when the gas supply is off.

Flue/vent dampers have no effect on the steady-state performance of the water heater. However, in a field test of a 70-gallon gas-fired storage water heater with rated input capacity of 36,000 Btu/h, the addition of an electric flue damper reduced the standby loss from 113,000 Btu/day to 46,000 Btu/day. The overall system service efficiency increased from 61% to 65%, a significant increase in energy efficiency.[40]

It should be noted there is an increased installation cost for electrical supply and maintenance costs are expected to be higher. DOE included the design option of the electromechanical flue damper in the engineering analysis.

4.2.1.8 Side Arm Heater

The side arm heater design avoids large flue losses by removing the flue from the center of the tank. Water is withdrawn from the bottom of the tank and heated over a burner in a small, separate heat exchanger. Water is returned to the top of the tank. A small circulation pump moves water through the heat exchanger when the burner is on. The burner could have electronic ignition, which would reduce the pilot light losses. Auxiliary power is supplied by a low-voltage plug-in transformer.

A water heater using this design in combination with electronic ignition and a plastic tank was commercially available until 1999. DOE included this design option in the engineering analysis.

4.2.1.9 Electronic (or Interrupted) Ignition

The most commonly used ignition system in storage water heaters is a standing pilot ignition system. The disadvantage is it burns gas continuously at a rate of about 450 Btu/h, and only part of this heat is converted to useful energy. In addition to a standing pilot, three electronic ignition devices are commonly used in gas-fired equipment:

Intermittent Pilot Ignition. This is a device that lights a pilot by generating a spark, which in turn lights the main burner.

Intermittent Direct Ignition. This system lights the main burner directly by generating a spark.

Hot Surface Ignition. This is a system that lights the main burner directly from a very hot surface.

Unlike standing pilot ignition systems that consume gas continuously, these devices operate only at the beginning of each on-period. Although there is no increase in the steady-state efficiency with use of electronic ignition devices, the overall fuel consumption may be reduced. Burner on-time may increase to make up for the heat the standing pilot would have supplied during standby periods.

The "interrupted ignition" system for an oil-fired burner activates the spark only until a steady flame is established. The oil consumption is not affected by interrupted ignition, nor is there an improvement in the recovery efficiency of the water heater. However, this design option not only reduces the igniter's electricity consumption, but also reduces its maintenance costs because the electrodes do not have to be replaced as often. In addition to changes in controls, the igniter can be made from solid-state electronics, instead of an iron core transformer. This improves performance and also reduces power consumption.

DOE included the electronic ignition design option in the engineering analysis.

4.2.2 Design Options Eliminated from Further Consideration

DOE may eliminate design options in accordance with the mandate of the process improvement (Section 4 of the Interpretive Rule, "Process for Developing Efficiency Standards and Factors to be Considered") per the Interpretive Rule.[1] Technologically feasible design options (i.e., those design options that are already in use by industry or options that are proven by research and progressing towards the development of a prototype) have been identified in this report. In addition to technological feasibility, the other screening criteria for the design options are:

- Practicability to manufacture, install, and service,
- Impacts on product utility or product availability, and
- Impacts on health and safety.

If production of a technology in commercially available products and reliable installation and servicing of the technology could be achieved on the scale necessary to serve the relevant market at the time of the effective date of the standard, then that technology will be considered practicable to manufacture, install and service. If a technology is determined to have significant adverse impact on the utility of the product to significant subgroups of consumers, or if adoption of a technology results 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. at the time, it will not be considered further. If it is determined that a technology will have significant adverse impacts on health or safety, it will not be considered further.

DOE eliminated the following design options from further consideration because they do not meet the screening criteria as described in each of their individual discussions. Some of the issues are highlighted by the fact that the design options, if implemented, can conflict with national building codes, plumbing codes, or other technical testing criteria. Also, in some cases, they do not meet the criteria of practicability to install and service, they have adverse impact on product utility or product application, or they are not an efficiency improvement feature.

- Flue Damper (Buoyancy Operated)
- Submerged Combustion
- Directly Fired
- Condensing Option
- Condensing Pulse Combustion
- Advanced Forms of Insulation

- U-Tube Flue
- Thermophotovoltaic and Thermoelectronic Generators
- Reduced Burner Size (Slow Recovery)
- Heat Pump Water Heater Options
- Timer Controlled
- System Application Options
- Sediment Removal Features
- Two-Phase Thermosiphon (TPTS) Design
- Air-Atomized Burner (Oil-Fired Only)

4.2.2.1 Flue Damper (Buoyancy Operated)

This flue damper is a small, very lightweight aluminum dome-shaped poppet that slides up and down in an enclosure placed at the top of the flue of a gas-fired water heater. The buoyancy of the combustion products lifts the poppet, allowing flue gases to enter the venting system. Working prototypes have been tested by AGA.

This design option would reduce off-cycle standby losses, but would have no effect on recovery efficiency. This flue damper may not work with high recovery efficiency water heaters because there may not be enough waste heat in the combustion products to provide sufficient buoyancy to lift the poppet.

The standard for gas water heaters [41] requires the burner to shut off if the flue gets blocked for some reason. Thus the effects of a failure of the flue damper to open should be mitigated by the burner controls. More field tests, however, are planned to address other safety and operational concerns.

GAMA states that the buoyancy operated flue damper is only a concept that needs more research and testing to determine that it will not cause safety problems. A water heater with a buoyancy operated flue damper must also demonstrate compliance with existing appliance safety standards.[4]

DOE agreed with GAMA and believes that additional information on safety issues and long-term use is required.

4.2.2.2 Submerged Combustion

In this design option, the flue products are bubbled through a small volume of water by the pressure from the burner blower. This small amount of water is heated by direct contact with the flue products. The heated water is re-pressurized by a circulating pump and returned to the storage tank.

The direct contact heat exchange process as described above is a more efficient means of transferring heat than in a conventional tube-and-shell heat exchanger, but can also lead to the contamination of the domestic water by the flue products. This can cause health and safety problems for the end users. This design option can also cause conflict with local plumbing codes (e.g., International Association of Plumbing and Mechanical Officials (IAPMO) 1991[42]) with respect to water quality. Local code restrictions for health reasons may also conflict with the atmospheric emissions from the unit. Therefore, DOE eliminated this design option because of its likely adverse impacts on health and safety.

4.2.2.3 Directly Fired

In this design option, water is sprayed through a series of baffles above the burner. Flue products are in direct contact with the water, which is re-pressurized by a circulating pump and returned to the storage tank.

The direct contact heat exchange process as described above is a more efficient means of transferring heat than in a conventional tube-and-shell heat exchanger, but can also lead to the contamination of the domestic water by the flue products. This can cause health and safety problems for the end users. This design option can also cause conflict with local plumbing codes (e.g., IAPMO 1991) with respect to water quality. Therefore, DOE eliminated this design option because of its likely adverse impacts on health and safety.

4.2.2.4 Condensing Option

Condensing the combustion products in the flue gas extracts more heat in the form of latent energy, leading to an increase in the thermal efficiency of the water heater. The flue-gas condensate is corrosive and often contains acids. Therefore, special corrosion resistant heat exchangers and vent linings are required for safe and reliable operation of the water heater. A number of studies and field tests have been conducted to quantify the corrosion characteristics of condensing gas appliances. [43] Since 1979, Battelle has conducted research on corrosion-resistant heat exchangers for condensing appliances for GRI and DOE. Based on this research, a set of guidelines was developed for the design of condensing heat exchangers. The guidelines consist of minimizing condensation in noncondensing regions of heat exchangers, reducing the corrosiveness of flue-gas condensate and using materials having a high corrosion resistance to flue-gas condensate in the condensing region.[44] European experience with condensing appliances has also shown that in addition to metal corrosion, problems could occur in rubber seals and in flue pipes.[45] Corrosion due to condensation of combustion gases limits the thermal efficiency of a fuel-fired water heater with a standard flue and vent system to 84%. Using corrosion resistant heat exchangers or side-wall venting, or lining the vent/masonry systems with corrosion resistant material, can extend the thermal efficiency limit beyond 84%.

Condensing gas appliances can be of two types: fully-condensing or near-condensing. Fully-condensing appliances will have flue gas temperatures less than the dew point (130°F to 140°F) of the flue products. Condensation is expected in both the heat exchanger and the vent system. Near-condensing appliances will have flue gas temperatures greater than the dewpoint of the flue gas. Condensation is expected in the vent system but not in the heat exchangers. The thermal efficiency of fully condensing water heaters can be as high as 99%; for near condensing water heaters, it is generally between 84% and 90%.

Several manufacturers offer near-condensing water heaters and a few offer fully-condensing types. Currently these are all commercial water heaters. A large-scale field test, sponsored by GRI, compared the performance characteristics of condensing with conventional non-condensing commercial water heaters [46]. A detailed inspection of the nine prototype units after 2 years of field operation uncovered no serious concerns regarding reliability or durability. The overall results confirmed the technical feasibility of the condensing design and that it provided a substantial efficiency improvement over conventional equipment.

Although the field test showed no corrosion in the heat exchangers after 2 years of field operation, Lennox Industries noted, for certain regions of the country, a high incidence of problems with heat exchangers in their condensing pulse combustion warm-air furnaces.[47] The secondary heat exchangers (primarily used to extract latent heat) had very high sulfur concentrations because of the high sulfur content in the supply fuel. Similar limitations may exist in gas-fired condensing water heaters. DOE is co-funding, with GRI and American Water Heater Products, a research project into inexpensive residential-sized condensing water heaters. The objective of the research is to find a low cost method to resolve problems with corrosion in the condensing heat exchangers. Completion date for this research is April 2001.

There are also limitations with respect to the servicing and maintenance infrastructure in retrofit situations. To install a condensing flue gas water heater, the vent systems have to be replaced or modified to prevent corrosion or damage from flue-gas condensate. When two or more gas appliances are vented through the same flue, replacing the standard gas water heater with a condensing gas water heater could orphan a standard gas furnace. Essentially, the flue becomes oversized for the remaining appliance.

DOE is not aware of any commercially available residential size condensing water heaters, or of any prototypes and doesn't expect information on whether commercially viable products are possible until its research project is completed in April 2001. Mass production of this technology in commercial products on the scale necessary to serve the gas-fired residential water heater market at the time of effective date of this standard is not possible. Therefore, this product is not considered further.

4.2.2.5 Condensing Pulse Combustion

Pulse combustion burners are another condensing technology. 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 produced, the process becomes self-sustaining.[48] 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 inside. The emissions from pulse combustion burners are 50% to 66% lower than those of a conventional burner.[48] Because the pulse combustion process is highly efficient, the burners are generally used with condensing appliances. AGA Laboratories built several prototypes as part of a study of pulse combustion residential water heaters.[49] They reported that the prototype models had a recovery efficiency of more than 90%. However the costs of pulse combustion control systems and condensing heat exchanger materials were too high for manufacturing water heaters for the residential market, and no further development activities were considered.

This technology has not been developed for oil-fired equipment. Also, as noted in the condensing option discussion, Lennox Industries has experienced problems with heat exchangers in their condensing pulse combustion warm-air furnaces. The primary concerns with using this design option are the likely condensation of flue gases and the need to reline or replace vent systems to prevent corrosion.

While prototype residential size pulse condensing water heaters have been built, DOE is not aware of any commercially available residential size pulse condensing water heaters, or of any plans to develop them. Without further research and development mass production of this technology in commercial products on the scale necessary to serve the gas-fired residential water heater market at the time of effective date of this standard is not possible. Therefore, this product is not considered further.

4.2.2.6 Advanced Forms of Insulation

Alternate ways of reducing the jacket losses without increasing the diameter of the water heater include the use of advanced insulation materials or the use of evacuated panels. Some of the advanced materials or methods of insulation considered here involve the use of vacuum, inert gases, aerogel, or partial vacuums.

Vacuum Insulation. A "hard" vacuum between internal reflective surfaces is a very good insulator. It has been used for years in Thermos bottles and Dewar tanks for cryogenic applications. Durability and the difficulty of maintaining the seal over the life of the water heater are some problems with this technology that have to be resolved.

Gas-filled Panels. Gas-filled panels are thermal insulating devices that retain a high concentration of a low-conductivity gas, at atmospheric pressure, within a multilayer infrared reflective baffle. The thermal performance of the panels depends on the type of gas fill and the baffle configuration. Calorimetric measurements have shown total resistance levels of about R-12.6 for a 1-inch thick krypton panel, R-25.7 for a 2-inch krypton panel, and R-18.4 for a 1-inch xenon panel. Gas-filled panels are flexible, self-supporting, and can be made in a variety of shapes and sizes to thoroughly fill most types of cavities. This technology has not been demonstrated for water heater applications.

Aerogel Insulation. An example of advanced insulation materials is silica aerogel, which is composed of 96% air and the remaining 4% of a wispy matrix of silica (silicon dioxide). Aerogels are more efficient and weigh less than the polyurethane foam that is currently used in most water heaters. The R-value of the aerogel at atmospheric pressure is comparable to that of the polyurethane foam, but when 90% of the air is evacuated from a plastic-sealed aerogel packet, its resistance nearly triples. Another advantage of the aerogel insulation over foam insulation is avoiding the use of chlorofluorocarbons to blow the polyurethane foam into the heater jacket. New manufacturing processes have been developed that can produce flexible blankets or clamshell forms of this material. The aerogel material is vulnerable to shock and vibration, however, and material handling becomes an issue. Because it is hygroscopic, it also requires a thorough sealing of the cavity between the water heater tank and the outside cover. The material has not been demonstrated for use with water heaters.

Evacuated Panels. In addition to aerogels, other materials with a lightweight open structure can create very good insulators at "soft" or low vacuums. The materials can be enclosed with metals or plastic. At least one company sells evacuated panels for use with special purpose, marine applications, refrigerators.[50] A vacuum (10^{-3} torr[a]) is drawn in this panel before sealing, and a lightweight, rigid foam keeps the vacuum from compressing the panel. This technology has not been demonstrated for curved surface applications, such as water heater tanks.

GAMA recommends elimination of advanced insulation materials because it would require the industry to completely restructure their production lines to accommodate a radically different way of insulating water heaters. GAMA claimed that manufacturers have not established methods to manufacture water heaters with these types of materials.[4] DOE agrees with GAMA on the issue of manufacturability, particularly in the context of restructuring water heater production lines. Moreover, reliability and durability over the life of the water heater of some of these advanced forms of insulation for water heater applications have not been demonstrated. Nor has such insulation been applied to water heaters as prototypes or in commercially available products. Therefore, these have not been demonstrated to be technically feasible.

4.2.2.7 U-Tube Flue

One comment on the 1994 NOPR mentioned an old water heater design that used an inverted U-shaped flue within the tank of the water heater[51]. This design could increase the recovery efficiency and would reduce standby losses. No working prototypes or commercially available products are currently available and DOE believes that this design would not meet modern safety standards, because of possible flue-gas condensation in the U-tube. Lack of working prototypes precludes DOE from testing the option further and validating the applicability or usefulness of this particular design option. Therefore, this design option is considered not technologically feasible.

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[a] A torr is a unit of measure for vacuum levels. 1 torr equals 133 Pascals (0.0193 psi).

4.2.2.8 Thermophotovoltaic and Thermoelectronic Generators

A thermophotovoltaic water heater uses a special light-emitting burner coupled with silicon photovoltaic cells that generate auxiliary power to run a fan, operate the electronic ignition and controls, and charge a battery. This avoids the requirement of auxiliary electrical supply, while offering the efficiency advantages of electronic ignition and forced-draft combustion. DOE has funded the development of prototypes of this design option in the past, but there has been no recent activity. This technology has not been demonstrated for widespread applications, such as in water heaters.

Another method of generating electricity at the water heater is based on thermocouple technology. Thermoelectric generators are available, but none has been used in water heaters. Furthermore, DOE understands this option and the thermophotovoltaic generator option need further development for common day-to-day applications before prototypes for water heaters can be developed and tested. Therefore, this design option is considered not technologically feasible.

4.2.2.9 Reduced Burner Size (Slow Recovery)

Reducing burner size while keeping flue baffle and tank geometry the same will increase the ratio of heat transfer surface area per Btu of input, thereby increasing the recovery efficiency. The lower input means that recovery would be slower than with conventional burners. The first hour rating would probably be reduced, as well, although some of this first hour rating reduction could possibly be offset by changing the dip tube design, to better stratify the water in the tank and thereby reduce mixing. Slower recovery also implies reduced product utility by the consumer and hence will not meet one of the key screening criteria.

GAMA believes that slow recovery is another name for derating.[4] By derating, the water heater is not able to provide as much hot water. This is particularly an issue for households larger than three persons because normal hot water use may result in frequently running out of hot water. Therefore, DOE eliminated this design option from further consideration because of the adverse impact on product utility.

4.2.2.10 Heat Pump Water Heater Options

Because the vast majority of electric water heaters use resistance elements to heat the water, there are few available options for substantially improving efficiency. With current technology, a heat pump can achieve the greatest efficiency improvement for heating water. A heat pump water heater can double the EF of a resistance water heater but it uses heat from the surrounding air, which, depending on the location of the air heat source, may need to be made up by the household heating system.

In its *Technology Assessment and Screening Analysis, Appendix B Supplement to the Water Heater Rulemaking Framework* of January 1998, DOE eliminated heat pump water heaters as a design option based on poor reliability and lack of an infrastructure for servicing of heat pump water heaters.[9]

DOE received the following comments on heat pump water heaters from the Technology Assessment and Screening Analysis document. AGA claimed DOE must consider all technologically feasible design options.[11] Okaloosa Gas District, Clearwater Gas System, the City of Palo Alto, the City of Mesa Arizona, Milza S. Barley and 13 gas utilities recommended that DOE consider heat pump water heaters in its standards analysis.[12, 13, 14, 15, 16] LaClede Gas claimed DOE is protecting electric utility market dominance and it could lead to fuel substitution away from gas water heaters.[17] LaClede Gas further claimed that heat pump water heaters should be considered as a design option because DOE is researching a new heat pump water heater which may overcome several critical market barriers including cost. [18] Okaloosa Gas District claimed DOE must explain why it eliminated heat pump water heaters since the recent GAMA directory lists five models.[12] Following the November 1998 workshop, AGA claimed that neither Electric Power Research Institute (EPRI) nor American Council for an Energy-Efficient Economy (ACEEE) identified any infrastructure or reliability problems in their public information on heat pump water heaters and that reliability and infrastructure issues are not a sufficient reason to eliminate them.[19]

GAMA, EEI, Southern Company and Virginia Power agreed with DOE's decision to screen out heat pump water heaters.[4, 7, 8, 20, 21, 22, 23] Southern Company claimed that heat pump water heaters should be eliminated as a design option because of product reliability issues and an inadequate infrastructure.[7]

The 1994 rulemaking process produced a litany of comments describing problems with establishing an electric water heater standard based on heat pump water heaters (see docket EE-RM-90-201). Many of the comments discussed issues that the screening process was designed to address early in the rulemaking process. Among the comments received:

- 216 comments cited the immature infrastructure for manufacturing, sales and repair, especially in rural areas.
- 107 comments feared increased electric rates due to loss of revenues in rural electric cooperatives.
- 66 comments questioned the inconvenience and possible price hikes for larger tank size due to the lower recovery rate, 40 % slower than conventional electric water heaters.
- 33 comments questioned the reliability of heat pump water heaters.
- 33 comments expressed concerns about increased noise.
- 22 comments claimed under-the-counter applications would not be cost effective.
- 21 comments believed it would distort the marketplace and lessen competition among fuel sources.
- 15 comments cited the space restrictions of small homes, and the increased payback time due to reduced electricity use.

DOE has reviewed these comments as well as other issues associated with the installation and use of residential heat pump water heaters. The following issues form the basis of DOE's decision to screen out heat pump water heaters as a design option pursuant to10 CFR 430, Subpt. C, App. A Section 5(b):[52]

- Practicability to Manufacture (on the scale necessary to serve the relevant market at the time of the effective date of the standard),
- Practicability to Install (reliably on the scale necessary to serve the relevant market at the time of the effective date of the standard),
- Practicability to Service (reliably on the scale necessary to serve the relevant market at the time of the effective date of the standard), and
- Impacts on Product Utility to Consumers (significant adverse impact to significant subgroups of consumers).

Description of Technology. A heat pump water heater represents a merging of two otherwise unrelated technologies: an electric resistance water heater with tank and controls, and a refrigeration circuit similar to that found in a residential air-conditioner. To understand the issues confronting manufacturers in bringing a heat pump water heater into the market, it is important to understand how the heat pump water heater is similar to and how it is different from other residential appliances. What follows is a description of how a heat pump water heater works and how it differs from the standard electric resistance water heater.

Heat pump water heaters transfer heat from air, typically at room temperature, to water at a higher temperature. The heated water can then be used to provide the residential hot water supply. Since heat does not naturally transfer from a low temperature to a higher temperature, a "heat pump" is used. The terminology "heat pump" is used here to mean a mechanical system consisting primarily of a closed refrigeration loop containing a refrigerant vapor compressor, an evaporator (a type of heat exchanger), a condenser (another heat exchanger), and an expansion device. These are the four basic components of standard vapor-compression refrigerant circuitry that exist in any household refrigeration or air-conditioning system.

The refrigeration process normally removes heat from a heat source and pushes that heat to another location. A good example is the household refrigerator. The refrigerator removes heat from the contents of the refrigerator box and rejects it to the surrounding kitchen air. In common parlance, we refer to the system as a refrigerator, but the thermodynamic cycle upon which it is based is often referred to as a "heat pump." A heat pump is a system which can extract heat from a low temperature heat source (i.e., the refrigerator contents) and reject it to a higher temperature "sink" (the surrounding air). Note that the heat pump is usually designed to help in moving heat from a low temperature heat source to a higher temperature heat sink. However, it can also be used to simply speed up the rate of heat transfer from a high temperature heat source to a low-temperature heat sink.

So, how does the system work? The refrigeration process relies on the behavior of the refrigerant fluids. Like most fluids, refrigerants can exist as both a liquid and as a vapor. Which state they are in depends on their temperature and the pressure to which they are subjected.

A common starting point in analyzing the refrigerant loop is the compressor. The compressor uses electrical energy to turn the compressor motor and compress refrigerant vapor. As the compressor does mechanical work on the refrigerant vapor, the vapor's temperature rises. The refrigerant leaves the compressor as a hot, high pressure gas. This gas moves to the condenser. The condenser is a heat exchanger which allows the hot gas to lose heat to a heat sink. Typically, it does this by passing the gas along one side of a metal wall while some other, cooler fluid (air or water depending on the appliance in question) absorbs the heat across the metal wall. As the high pressure refrigerant vapor is cooled in the condenser, it condenses into a liquid. This high pressure liquid moves from the condenser to the expansion device.

As the high pressure liquid flows through the expansion device, it quickly moves from a region of high pressure to low pressure. Some of the liquid evaporates in the process, drastically cooling the rest of the liquid to the liquid's saturation temperature. The saturation temperature is the temperature at which liquids evaporate or condense at a specified pressure. Since the suction side of the compressor keeps the pressure low at this point, the saturation temperature will also be correspondingly low (typically below 20˚F in a household appliance). The mixture of cold, saturated liquid and vapor moves onto another heat exchanger, the evaporator.

In the evaporator, heat transfers from a warmer surrounding fluid to the cold refrigerant liquid, which causes the remaining refrigerant to evaporate. The temperature of the refrigerant remains approximately constant until all the refrigerant is evaporated, and the heat transfer takes place as long as the heat source is at a higher temperature than the saturation temperature of the refrigerant. Thus the evaporator is what is used to remove heat from the heat source (like the air inside a refrigerator), with the heat absorbed by the refrigerant.

The vaporization in the evaporator occurs under low pressure and the volume of the resultant vapor is high and the temperature relatively cool. The cool, low pressure vapor flows from the evaporator to the suction side of the compressor. As it enters the compressor, it is recompressed again, restarting the refrigeration cycle. Throughout the operation of the system, heat is transferred from the fluid surrounding the evaporator to the fluid surrounding the condenser.

In a heat pump water heater, the evaporator is a refrigerant-to-air heat exchanger and the condenser is a refrigerant-to-water heat exchanger. The refrigeration cycle is used to remove heat from ambient, household air at room temperature and use that heat to heat a tank of stored water to a much higher temperature (typically 120˚F or greater). Electricity powers the compressor which enables the heat pump water heater to operate. At the evaporator and condenser temperatures used for a typical heat pump water heater, the "heat pump" extracts approximately twice as much energy from the air (in the form of heat) as is used to operate the compressor (in the form of electricity). Additionally, much of the electrical energy used to operate the compressor eventually winds up heating the refrigerant directly and is transferred to the water in the condenser. When used continuously, typical heat pumps appear to heat water at roughly 2.5 to 3 times the rate of energy input (in the form of electricity).

Electric resistance water heaters, in contrast, directly *produce* heat in electric resistance elements. The conversion from electrical energy to heat energy occurs at essentially 100% efficiency, i.e., the energy leaving the electric resistance elements in the form of heat is essentially equal to the electrical energy input to the elements. This is in contrast with what appears to be greater efficiency in the heat pump water heater. However, the fundamental difference between the two designs is that the majority of heat that enters the tank from a heat pump water heater is heat that has been extracted from some other source such as room air. Comparison of the apparent efficiency of the two products is not possible without establishing the cost to heat the air that the heat pump water heater eventually transferred to the hot water.

Note, in practice, actual tested residential heat pump water heater designs typically yield an energy factor of about 2.0. This lower energy factor accounts for cycling losses, heat escaping from the heat pump water heater system, piping, or storage tank, and any use of backup electric resistance heat in the system. This compares with typical energy factors of about 0.86 for electric resistance systems. Note the EF of 2.0 in the heat pump water heater design does not account for where the original heat came from. A direct comparison of the EFs of the two water heater designs only makes sense if the heat extracted from the air by the heat pump water heater is free and extracting this heat does not produce another energy penalty on the household. This is the case in some very warm climates (e.g., Hawaii). In most of the U.S., homes are heated for substantial portions of the year and operating a heat pump water heater that extracts heat from the household air increases the load on the home heating system during these periods. For this reason, accounting for the net energy or energy cost impact of the heat pump water heater requires analyzing the energy cost impact on the entire house, not just the electrical energy input to the water heater.

There are two basic designs for residential heat pump water heaters: add-on and integral. An add-on heat pump water heater is a product designed to be added to a separately manufactured storage-tank, often a standard electric resistance water heater. A small pump circulates water from the tank through the heat pump.

The second type of heat pump water heater is an integral heat pump water heater. In an integral design, the heat exchanger (condenser) is built into the storage tank. This eliminates the need for a circulation pump and increases efficiency.

Both designs have a refrigeration subsystem composed of, at a bare minimum, an expansion device, evaporator, compressor, and a fan (to force air over the evaporator and enhance heat transfer). The refrigerant condenser, also part of the refrigeration loop, can be located with the rest of the subsystem as a separate unit (as is done with the add-on type heat pump water heater) or located integral to the tank as with the integral heat pump water heater design. In the add-on heat pump water heater, cold water is removed from the tank, heated and pumped back into the tank. In the integral design, the heat pump compressor moves refrigerant from the condenser coil, located in the tank to the evaporator coil located outside the tank. Regardless of design, the expansion device, evaporator, fan and compressor have to be located outside the tank proper. With the integral design, these components are most commonly located on top of the water tank. With the add-on design, they can be mounted on top of the tank or as a completely separate unit that can be placed on the floor or hung on the wall. For good efficiency, the add-on heat pump water heater should be placed relatively close to the tank. As the unit is placed farther from the tank, the water heating efficiency is degraded due to piping losses, predominantly the result of warm water left in the piping between on-cycles.

Another component that is incorporated in most residential heat pump water heater designs is electric resistance heating elements. These are needed because, for cost and space considerations with practical residential heat pump water heaters, the heating capacity of the refrigeration system in heat pump water heaters is limited. Existing residential designs have between 40% and 80% of the heating capacity of typical electric resistance water heaters. To compensate for this and allow faster water heating and shorter recovery periods for the heat pump water heater during periods of high use, electric resistance heaters are employed that can heat the water in the tank faster than the heat pump unit. Larger capacity heat pump systems can be constructed, but the cost of larger systems generally outweighs the energy efficiency benefits to the average consumer. Instead, practical systems are designed to heat water gradually using the higher efficiency heat pump, but can, when required by the heating load, use a higher capacity electric resistance backup.

Practicability to Manufacture. From our analysis of the water heater industry, DOE has determined that water heater manufacturers would not have the lead time to ramp up heat pump water heater production to present sales levels in the three-year time frame established by the NOPR. Since the late 1970s, sales of heat pump water heaters have not exceeded 10,000 per year (<0.33% of electric water heater sales, <0.17% of all water heater sales). Sales have declined drastically since the mid-1980s. Presently, two manufacturers of residential heat pump water heaters produce less than 4,000 residential water heaters a year in categories covered by the present rulemaking. None of the five major manufacturers of residential water heaters currently have a heat pump design in their residential product line, and only two (State and Rheem) have had a heat pump water heater in their product lines in the last 10 years.

Reliability issues are an ongoing concern that have not yet been adequately solved by manufacturers. As evidence of reliability problems, Northeast Utilities (NU) claims they are the only utility to place a substantial (2,000 units) order (in 1996) for heat pump water heaters in the last five years. NU states it has only installed 600 heat pump water heaters because of a failure rate in excess of 10%.[53]

Although most manufacturers could develop, either alone or in partnership with others, a working heat pump water heater design in the next few years, there are significant difficulties in capitalizing and building heat pump water heater manufacturing facilities to provide for the present 4 million plus electric water heater sales annually.

Heat pump water heaters would require the introduction of a completely new product to the market with a market volume greater than that of all room air-conditioner shipments in the U.S.[54] In a 1994 Arthur D. Little report, the estimated investment cost to convert to heat pump water heaters was $750 million.

Given the current levels of profitability of the water heater industry and the limited capital resources, some manufacturers will not be able to finance these costs.[55]

In addition, given the high initial cost for heat pump water heaters, poor reliability with past heat pump water heater designs, and anticipated impact on consumer utility, initial sales of electric water heaters after a heat pump water heater standard may be low as consumers look for other alternatives. These alternatives could be switching to gas or oil-fired or solar or photovoltaic water heaters or simply replacing the existing tank with a replacement electric resistance storage tank as allowed in the current DOE test procedure.

With a government imposed time frame for shifting all production to heat pump water heaters and a shifting market size, it is unclear how the electric water heater industry could plan to satisfy an unknown final market volume.

The gas industry has commented that DOE should not screen heat pump water heaters out as a design option because it is presently supporting the development of a residential heat pump water heater product.[18] The heat pump water heater design being pursued by DOE is an integral heat pump water heater design which uses a small compressor with 40% less heating capacity than any used in existing heat pump water heater products (and has about 25% of the heating capacity of a typical electric resistance hot water heater). This should assist in installation in smaller spaces as it will physically use smaller components (particularly the compressor and evaporator/fan system), and will likely be quieter in operation. Present designs re-inject condensate back into the air to be recondensed in the evaporator. This may simplify installation, at some expense to system capacity, efficiency and dehumidification of the residence. The integral heat pump water heater design proposed by DOE uses a 50-gallon tank, but even the small compressor and heat exchanger used in that design adds approximately a foot in height to that tank. The attached 50-gallon storage tank is sized to provide ample water for a typical day's use in most residences. Smaller tank sizes are not being proposed, as the cost effectiveness of the heat pump decreases rapidly with smaller tank sizes and characteristic lower water usage. Presently, the smallest integral heat pump water heater design available in the U.S. is an 80-gallon unit. The design proposed by DOE would still need access to the same amount of household heat any heat pump water heater would require to serve the residence load, however the lower heat extraction rate of the DOE unit may allow for installation in locations with smaller surrounding air volume than is required for existing designs.

The unit is being developed with input from DOE, Arthur D. Little, and Oak Ridge National Laboratory and has been designed from the outset to address many of the known market barriers facing the adoption of residential heat pump water heaters. Preliminary field tests of the DOE design are likely to start in the spring of 2000. Larger scale utility testing is slated for late 2000 to 2001. Accelerated reliability testing is also scheduled sometime after initial field testing has resulted in a more or less stable product. If field and reliability testing are positive, limited commercial production and sales are possible by 2003. Actual production and sales would be through an existing air-conditioning equipment manufacturer who would likely purchase storage tanks from an existing water heater manufacturer.

Because of the issues that have plagued heat pump water heaters in the past, DOE is requiring its partners to introduce the product cautiously, correcting problems encountered during field testing and fully testing the corrections. A market study done by Arthur D. Little projected potential sales for the DOE design up to 300,000 units/year 10 years after commercial introduction, or 7.5% of present electric water heater sales.[56] It is important to note that the time scales established for the DOE development effort represent typical product design and production ramp-up schedules for newly introduced residential appliances.

Whether this unit is successful will depend on how well it addresses both the marketplace and technical issues facing heat pump water heater products and the final cost to the consumer. However, at no time did developers believe this design to be a replacement for all electric water heater applications. Its future marketplace success will save some energy directly, but more importantly will serve to introduce consumers to benefits and successful applications of the technology, will begin the development of a limited installation and service infrastructure for heat pump water heaters, and may point other manufacturers to successful product designs and marketing niches for heat pump water heaters.

There is also the additional cumulative burden on the manufacturers of both gas and electric water heaters who have to redesign and retool their manufacturing processes to address the issues of preventing ignition of flammable vapors (for gas units) and the phaseout of HCFC-141b insulation blowing agent.

Considering these issues with regard to manufacturability and achieving a scale of production necessary to serve the electric water heater market at the time of the effective date of the standard, DOE has concluded that the screening criterion of "practicability to manufacture" will not be met and has eliminated heat pump water heaters as a design option from further consideration.

Practicability to Install. Heat pump water heaters cannot be used as direct replacements for existing electric water heaters in many applications. For example, small electric resistance water heaters are often used in mobile homes, under-counter applications, apartments, small condos and other applications where space is limited. Approximately 30% of all electric water heater installations are in residences smaller than 1,000ft^2 in size (average size: approximately 760 ft^2).[57] In many of these installations, space restrictions would make it impossible to simply replace the existing electric resistance water heater with any of the existing heat pump water heater designs sold today or with future designs, such as that being proposed by DOE.

The physical size of the heat pump water heater is necessarily larger to accommodate the placement of the heat pump unit. A small (4,000-6,000 Btu/h) heat pump unit mounted on top of a tank will add approximately 8-12 inches on top of the tank for compressor, evaporator coils, and evaporator fan. In addition, to match the same water use profiles, the size of the storage tank itself may need to be larger to compensate for the smaller heat input rate of the heat pump water heater and the particular control strategy used in the heat pump water heater design. Even assuming no change in tank size from the electric resistance model, this extra height of the heat pump design will present installation problems where the existing water heater enclosure is height limited, such as is the case with many existing lowboy water heater installations. It is estimated that lowboy electric water heaters make up approximately 18% of all water heater sales according to GAMA estimates,[58] and may make up as much as 25% of the market in particular regions.[59] Since there is a cost premium attached to a lowboy design, it is believed that most of these sales reflect some type of height restriction in the space. Additionally, the space in which the heat pump water heater is located must be large and must provide ready access to change the air filters on the heat pump evaporator coil. Lack of regular filter changes has been reported as a primary reason for product failure in field studies of heat pump water heaters.[60]

As mentioned previously, it is possible to install the heat pump components of the add-on heat pump water heater away from the tank and pipe water between the heat pump unit and the tank. In practice, this introduces efficiency losses from the connecting piping and does not remove the need for a place to put the heat pump unit.

Hiding the plumbing between tank and heat pump unit may require extensive remodeling expenses for many residences, and cannot be considered a practical installation. In addition, finding a location for the refrigeration subsystem is more complicated than simply finding the physical space to place the unit. The refrigeration subsystem of a heat pump water heater needs sufficient flow of warm air across the evaporator coils to serve as a heat source. Without this heat source, the heat pump cannot function and must revert to electric resistance operation. Placing the heat pump water heater in a non-ventilated closet will not provide an adequate heat source. Operation in heat pump mode will generally require on the order of 100 cfm or more of warm air turnover between house and closet; unlikely to be achieved with natural ventilation through a closet door. A heat pump water heater installed behind even a fully louvered closet door is likely to experience short cycling of cold exhaust air, affecting efficiency and capacity, and thus performance of the unit.

Additionally, one must deal with condensate produced at the evaporator coil. Like all refrigeration devices, the temperature of the evaporator coil must be cold to extract heat from the surrounding air. When air blows across the coil, moisture in the air is condensed to liquid. The amount of liquid produced is a function of the humidity in the air blown across the coil, the temperature of the evaporator coil, and the hot water load. Heat pump water heaters installed in unconditioned spaces in the south, east, and midwestern U.S. can be expected to produce between several quarts to several gallons of condensate per day during the cooling season. Locating the heat pump in the conditioned space will not eliminate all the condensate buildup unless the air conditioning system can be counted on to dehumidify all house air, to a dewpoint below the coil temperature. Since this is hard to ensure in practice, a condensate drain is essentially required in present heat pump water heater designs. The need for a drain complicates installations where the existing water heater is located in a hall closet, attic, garage, or other location where access to a plumbing drain is not readily available. A pump can be used to move condensate to a drain if needed. However, this represents not only added expense, but a potential source of failure and consequent household damage.

There has been some discussion of techniques for re-evaporating the condensate, but no existing heat pump water heater models incorporate this option and no prototypes exist. While perhaps simple in concept, re-boiling of the condensate may dramatically reduce (by as much as 30-50%) the efficiency of the heat pump water heater under humid conditions. The extent that this impacts the annual average efficiency will depend on climate; however, the above figures could represent a common performance degradation in southern and coastal regions of the U.S.

Siting constraints are expected to be less severe with larger apartments, where it is anticipated that the greater available space has encouraged both larger rooms and more "traditional" looking water heater design and placement, such as separate laundry/utility rooms.

Siting of heat pump water heaters is expected to be less of a problem with traditional single family housing. With single family housing, the water heater is commonly installed in a basement or garage, or, when installed inside the residence, in a utility room where access to condensate drainage is available and where cool air from the heat pump water heater is not likely to negatively impact the main living space. However, installations under stairwells and in closets remain common and are expected to generate installation and performance problems. Since these locations may be centrally located in the residence, condensate pumps may be a necessary part of heat pump water heater installations in these areas.

With manufactured housing, condensate drainage is generally not a problem, however finding workable locations for the water heater and a heat pump unit may be difficult. This is particularly true in smaller, older manufactured housing units, where the housing design focused on optimal use of space and height- restricted closet installations were common. More modern manufactured housing relies on full-height closets or utility rooms. Approximately 62% of existing manufactured housing less than 1000 ft^2 in size was built before 1980.[50]

Surveys from the Georgia Power and Alabama Power companies reported that between 20% and 30% of water heaters in their service territory are installed in locations unacceptable for heat pump water heaters, primarily due to air volume constraints.[55] It is anticipated that specific subgroups, such as apartment units, should expect even higher incidence of installation problems.

DOE believes that heat pump water heaters can be installed in most locations. However, 18% of sales of electric water heaters, or about 700,000 per year, are lowboy models. An integral heat pump water heater would not fit into these locations. Perhaps 50% of the lowboy sales are for new construction leaving 350,000 units per year that would require an add-on heat pump unit. Additionally, over one million standard sized electric water heaters per year are installed in residences of 1,000 ft^2 or less. Perhaps as many as 500,000 of these installations would also require an add-on heat pump unit. This is a total of 850,000 add-on heat pump water heaters per year. These add-on heat pump units require a space with at least 100 cubic feet per minute of warm air and wiring and plumbing connections (probably through one or more walls) for water pipes and a condensate drain. We would characterize this installation as "difficult." Without an extensive survey, we are unable to determine how many of these difficult installations would be feasible, although costly, and how many would result in loss of product utility as discussed later in this section.

Since we have determined that almost a million households could be affected each year, we eliminated heat pump water heaters as a design option from further consideration because of issues concerning practicability to install on the scale necessary to serve the relevant market at the time of the effective date of the standard.

Practicability to Service. Two hundred sixteen comments to the 1994 rulemaking process (docket EE-RM-90-201) claimed that " . . . the infrastructure to service heat pump water heaters is not capable of handling a large quantity of heat pump water heater units." The issues faced in service and maintenance of heat pump water heaters have not changed since 1994.

The present service and maintenance infrastructure for electric resistance water heaters, consists, for the most part, of plumbers. Service and maintenance of a heat pump water heater is, however, more complex than service and maintenance of an electric resistance water heater. In addition, where most electric resistance water heaters are similar in design, there are several different classes of heat pump designs (integral versus add-on designs, ambient air versus exhaust air heat source) that all have different service and maintenance requirements and are likely to be available in a mature market.

A plumber will likely be the primary installer of a residential heat pump water heater. Any water heater installation typically utilizes a plumber to attach the plumbing to the water heater. In most jurisdictions, the electrical connection (a hard-wired 220 Volt connection) requires either a separate electrician or a plumber with some electrical wiring skill and certification.

However, if there is a problem with an installed heat pump water heater unit, a plumber may currently not have the background to troubleshoot either the refrigeration system or controls. Note that you really cannot reliably test the refrigeration system or controls of an integrated heat pump water heater until the tank is full of water and the plumbing is connected, which means that replacement with a new water heater is also an expensive option at that point.

A further complication with heat pump water heater products is the distribution structure for residential water heaters. Presently, several of the major residential water heater manufacturers distribute their products through a distribution chain that extends through wholesale suppliers directly to plumbers installing their products. Approximately 50% of the residential water heater market follows this pattern. This distribution method provides a natural link from the manufacturer to the installation and product service personnel through which training could be accomplished.

The other 50% of water heaters are sold primarily through retail outlets (hardware stores and some major department stores). Particularly for sales through hardware stores, there is little link between the manufacturer and the product service personnel. This will complicate training of product service personnel for any given manufacturer's products.

The distribution through hardware stores would also complicate repair and service of heat pump water heaters. Heat pump water heaters are more complex in design and based on fundamentally different technology from electric resistance water heater designs. Because of this, they require a broader range of skills to service the units. The typical electric water heater requires two screw-in electric resistance elements, a tank, and thermostat controls. The add-on heat pump water heater, the most common design produced in the past, is composed of a refrigerant compressor, expansion device, water pump, piping, refrigerant-to-air heat exchanger (evaporator), refrigerant-to-water heat exchanger (condenser), fan, sensors and controls that can: turn the pump, compressor, and fan on together or independently, defrost the evaporator, or even to provide freeze protection. This is in addition to the need for electric resistance backup elements and controls that have to operate in conjunction with the heat pump controls. In addition to the mechanical components, there is the refrigerant itself, which can leak out from the system gradually, resulting in poor performance, or leak out of the system catastrophically, resulting in system failure.

Any one of these system components can fail and cause the water heater to stop functioning as a heat pump water heater. This is in contrast to the simple, relatively maintenance-free, gas or electric water heater. Once installed, the most likely failure mode of either electric or gas water heaters is a leak from the tank wall, leading to complete replacement of the water heater. There is little "service" necessary.

The add-on heat pump water heater, however, would arguably be one of the more mechanically complex, and possibly more expensive, appliances found in a residence. The integral heat pump water heater design simplifies the system by dispensing with the pump, water piping, and pump controls; however, they are still substantially more complex than an electric resistance water heater. For these reasons, where repair of heat pump water heater components is possible, it may be an attractive alternative to simple replacement. Repair of heat pump water heaters, however, will likely be costly. Since the heat pump water heater is plumbed and hardwired into the residence, and since there really isn't a "down period" for hot water consumption in a residence, most repairs will have to be made in the field. This is particularly true of existing integrated heat pump water heaters, where it may be impossible to separate the upper heat pump section from the tank itself without breaking into the refrigeration circuitry.

Plumbers generally do not have training or background in repair of appliances like a failing heat pump water heater, nor would plumbers likely be a logical source of labor to do these repairs since they are among the highest paid residential contractors. Premature (non-tank) heat pump water heater failures are typically caused by the electrical components (fans, pumps, electronic controls, or wiring) or through loss of refrigerant. Generally, this type of repair work is done by small appliance repair personnel who repair refrigerators, freezers, room air conditioners, and other "white" goods (e.g., washing machines). These repair personnel have backgrounds in troubleshooting fans, pumps, wiring and controls and are often certified to repair low and high pressure, hermitically sealed, refrigeration equipment. According to the Bureau of Labor and Statistics, of the approximately 71,000 home appliance repair workers in the U.S., 2 out of 3 work directly for department stores or household appliance stores, where they service the same products that they sell retail.[61] These stores represent a fraction of sales of water heaters, but might be logical sales outlets for heat pump water heaters. However, for some existing water heater manufacturers, this would require opening up new distribution channels for electric water heater products.

Another possible option for repair and service of heat pump water heaters is air-conditioning contractors. This is a vertically oriented industry that is completely separate and distinct from the water heater industry. However, if the residential air-conditioning industry chose to build heat pump water heaters, they could choose to sell these products through their already established distribution channels. This would simplify the service and maintenance infrastructure for these companies. Installation, however, would require contracting with or hiring of local plumbing professionals. It is unknown if present water heater manufacturers could have access through these same residential air conditioning industry distribution channels to distribute and service their own heat pump water heater designs.

To date, long term reliability in add-on heat pump water heater products has not been well established in field studies of available products. In the U.S., the greatest field experience with residential heat pump water heaters has been through utility demand side management or U.S. military housing programs. In both cases, poor reliability, in programs and product designs going back 20 years has been the single biggest reason for the demise of virtually all such programs. Additionally, NU claims they have trained over 80 installers during two years of the program but only 19 continue to install the units at reasonable prices. NU lists number of call-backs because of failures among the reasons contractors have dropped out of the program.[53]

Presently, no mass-market installation and servicing infrastructure for heat pump water heaters exists. It is noted that while there are several potential candidate industries who could provide servicing capabilities, none have relationships with major water heater manufacturers or with plumbers who install water heaters. There is no precedent in the history of the U.S. major appliance industries to suggest that a new service and repair infrastructure could develop, on the scale of several million units per year, in a roughly three-year time frame. This is particularly true given the virtual absence of available products in the next two years from major manufacturers, the radical changes required in the existing water heater market simply to develop heat pump water heater products, and the absence of any present consumer demand for such products. A complete reversal of this situation would be required for an energy efficiency standard at the heat pump water heater level to succeed.

Therefore, DOE eliminated heat pump water heaters as a design option from further consideration because of problems concerning practicability to service on the scale necessary to serve the relevant market at the time of the effective date of the standard.

Impacts on Product Utility to Consumers. Manufacturers of present ambient-air heat pump water heaters recommend locating the evaporators in spaces of at least 1,000 ft^3 in volume to provide adequate air circulation and minimize overcooling of the space which can impact performance. Approximately 14% of all residences are smaller than 1000 ft^2 and presently use electric water heaters. A 10' x 12' room with an 8' ceiling (1,000 ft^3) is 12% or more of the floor area in a 1,000 ft^2 residence. For many residences of this size, this would force evaporators to be located in what is presently living space of the residence, causing additional fan, compressor, and pump noise. Cold air from the heat pump water heater located in the living space may also cause some dissatisfaction. This is particularly a concern in small, slab-on-grade housing, mobile/manufactured homes, or apartments.

If there is no space to incorporate both the water tank and the refrigeration subsystem in the same location, a reduced tank size may have to be installed. This could cause a 20% to 25 % loss of tank volume on a standard 50 gallon water heater. Any substantial reduction in the tank size to accommodate the heat pump would reduce the first hour rating, since first hour rating depends on tank size and reheat capacity. The first hour rating is, "an estimate of the maximum volume of "hot" water that a storage-type water heater can supply within an hour that begins with the water heater fully heated.".[62] We interpret lost first hour rating as a loss of product utility.

Because of this significant adverse impact to significant subgroups of consumers, the Department has concluded that the screening criterion of "impacts on product utility to consumers" will not be met and eliminated heat pump water heaters as a design option from further consideration.

In summary, DOE has eliminated residential heat pump water heaters as a design option for this rulemaking. It fails to meet the screening criteria listed earlier, namely, practicability to manufacture, install, and service and it has adverse impacts on product utility. There is no foreseeable means for the technology to advance enough in the short term to allow heat pump water heaters to fill market needs and to continue to provide a reasonable level of consumer utility.

4.2.2.11 Timer Controlled

This design option limits the time of day when the elements of an electric storage-type water heater may be energized. This is most often used as part of an electric utility demand-side management program for load shifting ("demand avoidance strategy"). Field tests show a few percent energy savings, because the water in the tank remains at a reduced temperature for part of the day. However, the actual energy savings will depend on the end-use profile, lifestyle of the consumer, and a basic desire to save energy.

GAMA claims that timer controls are used as a demand avoidance device to allow consumers to use lower priced electricity.[4] Although this design reduces standby losses, it does not improve efficiency because it only shifts the electric consumption from on-peak to off-peak times. Therefore, DOE did not include this in its analysis.

4.2.2.12 System Application Options

The following three techniques are applicable to the water heating system rather than to individual water heaters and, as such, are not considered in DOE's definition of water heaters. Therefore, DOE does not consider these add-ons as design options and hence, they are not relevant for the present screening considerations.

Solar Pre-Heat. This and the following two techniques may be relevant on a site-specific basis, and are applied at a system level as opposed to an equipment level. Individual water heater manufacturers do not control their use. This technique uses solar collectors as pre-heaters for a standard electric storage-type water heater. Many designs are currently available, with a wide range of installed costs.

Drain Water Heat Recovery System. This technique uses a heat exchanger to recover waste heat from the drain. In effect, this becomes a pre-heater for a standard storage type water heater. A few designs are currently available. [63, 64] However recent water conservation measures, such as low-flow showerheads, may lead to fewer benefits than previously thought.

Tempering Tank. A tempering tank is an un-insulated storage tank plumbed in the water line before the water heater. When installed in a conditioned or semi-conditioned space, it may raise the inlet water temperature to the ambient temperature.

GAMA states that solar pre-heat, drain water heat recovery systems, and tempering tanks are installation options independent of the water heater design.[4] DOE agrees with GAMA and considers these as system installation features and not necessarily as enhancing the design nor the individual appliance efficiency.

4.2.2.13 Sediment Removal Features

Several manufacturers offer models with dip-tubes designed to create turbulent water flow that prevents or reduces the buildup of sediment on the bottom of the tank. This may reduce the degradation of efficiency and prolong the life of the water heater. This design feature relates more to equipment reliability than efficiency improvement.

GAMA claims that sediment removal features are not a design option applicable to meeting a minimum efficiency specification.[4] DOE agrees with the comment and believes this only preserves as-designed efficiency over time but does not increase energy efficiency of the water heater. Therefore, DOE did not consider this design option for engineering analysis.

4.2.2.14 Two-Phase Thermosiphon (TPTS) Design

This is a heat-pipe mechanism to transfer heat from the burner to the storage tank. The TPTS is a closed loop device consisting of an evaporator in which the working fluid (water) is heated, percolating liquid and vapor into the condenser where heat is transferred into the water storage tank.[65] At the condenser, the vaporized working fluid is condensed and drains back through a separate restricted tube to the evaporator, where it is reheated. The restriction prevents the heated vapor and liquid from flowing to the condenser through the return path. During off-cycle, there is very little heat transfer through the TPTS system. This reduces standby losses to levels similar to those of electric water heaters.

GAMA believes the TPTS system would cause a drastic redesign of all gas water heaters with little increase in efficiency.[4] DOE understands that working prototypes of the heat exchanger design have been developed and delivered to Rheem Corporation for detailed performance and life testing. However, DOE is aware that some designs of heat pipes used in furnace applications posed safety problems due to contamination of the working fluid. DOE concludes that large scale production of these devices has not been satisfactorily demonstrated. Therefore, DOE did not include this design option in the engineering analysis on the basis of practicality to manufacture.

4.2.2.15 Air-Atomized Burner (Oil-Fired Only)

This is a different type of burner for oil-fired equipment. Instead of relying on pressure to create a spray of fine oil droplets prior to combustion, this burner uses a stream of air to atomize the oil. Compared to conventional burners, this design allows better control of droplet size and mixing with air at lower oil flow rates. Downsizing the burner with the same flue and baffle geometry will give a higher recovery efficiency.[66] The combustion process is also cleaner with this burner.

Furnace prototypes have been made with this design option. There could be a slight improvement from cleaner combustion. Even if the first hour rating were reduced because of the smaller burner, it would still be larger than that of a gas-fired water heater. Other impacts on manufacturability, installation, and service of a water heater are yet to be determined.

GAMA believes that air-atomized burner technology is not yet sufficiently developed, especially for a water heater application, to include it as a design option.[4] DOE agrees and did not include this design option in the engineering analysis on the basis of practicality to manufacture.

4.3 RESULTS

Based on the above discussion, the design options used in the Engineering Analysis are listed in Table 4.1, and those that have been eliminated from further consideration are listed in Table 4.2.

Table 4.1 Design Options Used in the Engineering Analysis

Design Option Description	Electric	Gas	Oil
Heat Traps	X	X	X
Plastic Tank	X	X*	
Increased Jacket Insulation	X	X	X
Insulating the Tank Bottom (Electric Only)	X		
Improved Flue Baffle/Forced Draft		X	X
Increased Heat Exchanger Surface Area		X	X
Flue Damper (Electromechanical)		X	
Side Arm Heater		X	
Electronic (or Interrupted) Ignition		X	X

* used in conjunction with the Side Arm Heater option

Table 4.2 Design Options Eliminated from Further Consideration

Design Option Description	Criteria for Elimination
Flue Damper (Buoyancy Operated)	Safety issues and lack of long-term use data
Submerged Combustion	Conflict with health and safety codes
Directly Fired	Conflict with health and safety codes
Condensing Option	Fails practicability to manufacture test
Condensing Pulse Combustion	Fails practicability to manufacture test
Advanced Forms of Insulation	Not technically feasible within next few years
U-Tube Flue	Not technically feasible within next few years
Thermophotovoltaic and Thermoelectronic Generators	Not technically feasible within next few years
Reduced Burner Size (Slow Recovery)	Adverse impact on product utility
Heat Pump Water Heater Options	Fails practicability to manufacture, fails practicability to install, fails practicability to service, and has negative impacts on product utility to consumers
Timer Controlled	Not an efficiency improvement option
System Application Options	System installation feature
Sediment Removal Features	Not an efficiency improvement option
Two-Phase Thermosiphon (TPTS) Design	Fails practicability to manufacture test
Air-Atomized Burner (oil-fired units)	Fails practicability to manufacture test

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