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BROOKHAVEN NATIONAL LABORATORY BURNER-BOILER/FURNACE EFFICIENCY TEST PROJECT

ANNUAL FUEL USE AND EFFICIENCY REFERENCE MANUAL HYDRONIC EQUIPMENT

J. Batey, R. Hoppe, A.L. Berlad, T. Allen, and R. McDonald

December 1977

DEPARTMENT OF ENERGY AND ENVIRONMENT

BROOKHAVEN NATIONAL LABORATORY

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Abstract

A procedure for calculating the annual fuel use and seasonal efficiency of a particular heating unit has been developed at Brookhaven National Laboratory based upon laboratory measurement of steady state and part-load efficiency. The Annual Fuel Use and Efficiency (AFUE) calculation procedure provides a simple and direct method by which detailed efficiency measurements can be translated to annual fuel use data for ranges of field variables including: geographic location, building design heat load, domestic hot water usage, and design fuel firing rate. The direct efficiency measurements performed in the laboratory in conjunction with the AFUE procedure provide a standard quantitative method for comparison of heating units on a common and realistic basis.

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ANNUAL FUEL USE AND EFFICIENCY

A. GENERAL DISCUSSION

A simple computational procedure has been devised at Brookhaven National Laboratory to evaluate annual fuel consumption for hydronic heating equipment tested in the laboratory. The computer-based calculation relies on precise measurement of the "intrinsic merits" of a particular heating unit expressed in terms of steady state efficiency and cycle efficiencies over the entire range of heating loads. The annual fuel consumption for the heating unit under investigation varies as a function of several key parameters including: geographic location, building design heat load, outside design temperature, room temperature, domestic hot water use, and design fuel firing rate. Each of these parameters can be varied over a range of practical values in order to determine the resulting change in overall seasonal efficiency and fuel consumption for a particular heating unit. The output of these calculations is expressed as a matrix of overall seasonal efficiency and fuel consumption values (gallons of fuel oil per year) as a function of the important variables (see Figure 1).

The Annual Fuel Use and Efficiency calculation utilizes hourly outside temperature information averaged over a ten-year period for a particular geographic location, and the overall efficiencies measured in the laboratory (including burner on-cycle and off-cycle heat losses) are related to the outside temperatures. Fuel consumption at each outside temperature is calculated, and the total quantity of fuel consumed per year is evaluated by summing fuel usage over all outside temperatures during the heating season. Hourly temperature calculations are considered to be superior to methods utilizing degree-day temperature data because of the large temperature variations possible during a 24-hour period. The averaging process inherent

HEATING UNIT	
LOCATION	
DESIGN HEAT LOAD (BTUH)	
OUTSIDE DESIGN TEMP (°F)	
ROOM TEMP (°F)	

HOT WATER \ α		1	2	3	4
0 GAL PER DAY	SEAS EFF				
	GAL PER YEAR				
	GPH				
40 GAL PER DAY	SEAS EFF				
	GAL PER YEAR				
	GPH				
80 GAL PER DAY	SEAS EFF				
	GAL PER YEAR				
	GPH				
120 GAL PER DAY	SEAS EFF				
	GAL PER YEAR				
	GPH				

Figure 1. AFUE Output Format

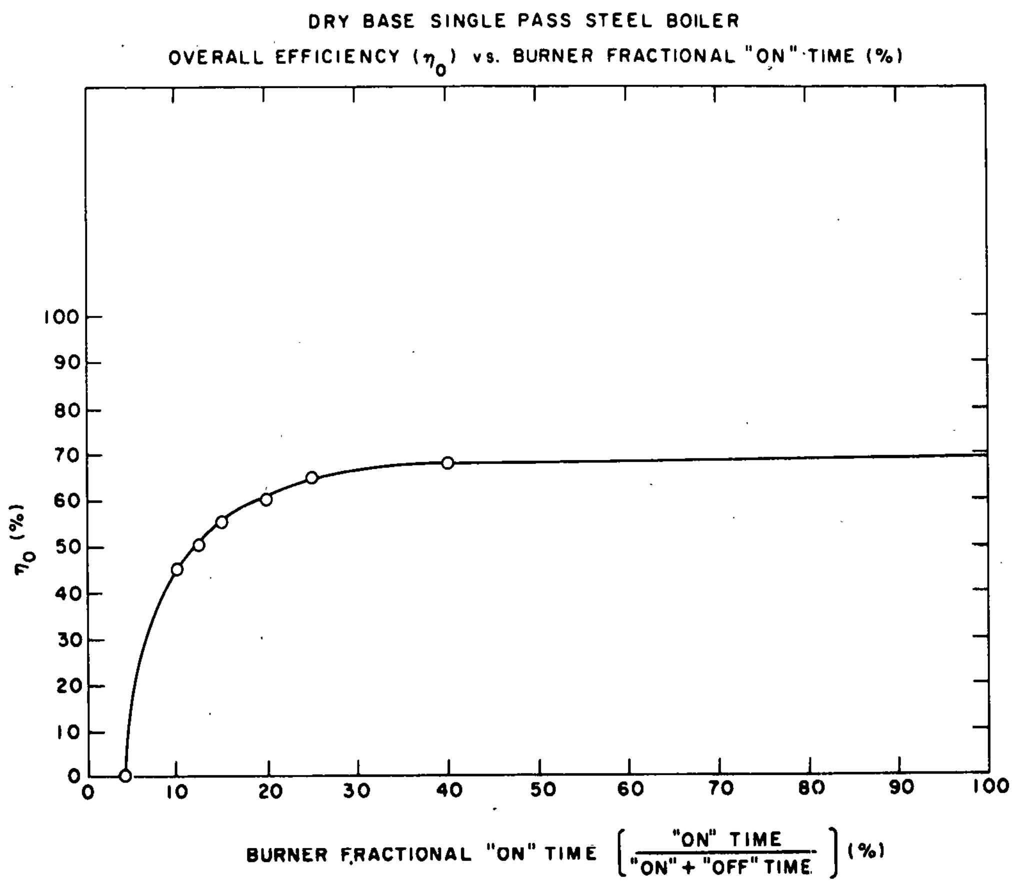

Figure 2. Typical efficiency results measured in the laboratory.

in degree-day calculations can introduce unnecessary error in the determination of fuel use. Hourly information and calculations can follow the thermal response of conventional residential structures, and the corresponding change in heating system overall efficiency.

In the computational program for boilers, the design heat load of the building (Btu per hour), the outside design temperature, and the inside design temperature can all be varied by changing the corresponding input values. Each computer output presents values of seasonal efficiency and gallons of fuel consumed per year for a range of domestic hot water loads and design fuel firing rates. The nondimensional fuel firing rate is expressed in terms of α (the overfiring ratio) such that α equal to one is a properly sized unit, α equal to two is 100% oversized, and so on. The domestic hot water load is an average value, and it is assumed that there is sufficient storage capacity in the system to satisfy peak instantaneous hot water needs. In boilers using "tankless coils" to supply domestic hot water, fuel firing rates generally above 1.1 gallons per hour must be maintained to satisfy the peak domestic hot water demand.

The laboratory efficiency measurements and BNL computational procedures provide the technical bases by which the annual fuel consumption of heating units can be quantitatively compared, assuming a structure with known thermal features and a properly installed and serviced heating unit. The actual annual fuel consumption of field installed heating units cannot be predicted on the basis of laboratory measurements and computer programs alone. It is ultimately influenced by many parameters affecting the heat load of a specific house, in a specific city, during a specific heating season, and subject to an infinitude of variables including: house size, shape, quality of insulation, wind exposure, solar exposure, air-tightness, internal heat sources, site topography, landscaping effects, and conditioned room air venting (through exhaust fans and chimneys via barometric dampers or draft diverters and fireplace flues). Additional variables include those pertaining to heating system installation such as distribution losses, design firing rate, location of heating equipment in the building, (use/nonuse of conditioned air for combustion) and servicing (cleanliness and adjustment of boiler and burner components.

For example, the design heat load of a well studied structure could be significantly increased by unwise use of bathroom and kitchen exhaust fans that are dependent on the individual life styles of residents. The warm air exhausted by these fans increases the air infiltration and heat load of the building. Also, long uninsulated runs of piping (or ducting) of boiler (or furnace) heat transfer fluid in unheated portions of the building could lead to substantial heat loss and degradation of operating efficiency. This factor is solely dependent on the wisdom of the equipment installer. The list of possible schemes by which one may degrade efficiency performance of an individual building is almost without limit.

Another feature of building structures that has received considerable attention is the contribution of fuel-fired (air-consuming) heating equipment to the building infiltration heat load. There are many variables that will affect this factor including the precise heating unit location within the structure, and local building air-tightness in the vicinity of the heating unit. A heater located within the conditioned space in a central area of the structure would have a larger impact on infiltration than a unit located in a laundry room on an outside wall, in a "drafty" unheated basement, or in an unheated garage. The total impact of oil-fired hydronic heating units on building infiltration must be considered to be small, and vary by a factor between zero and 100 percent depending on the specifics of the individual installation.

One additional feature that should be mentioned is the degree to which jacket losses from the boiler contribute to the heating load of the structure. The BNL computational program assumes that jacket losses are not available for space heating. As previously mentioned, many heating units are located in unheated and drafty portions of the building where boiler heat loss cannot directly contribute to heating the structure. Also, while jacket losses may produce locally elevated temperatures in the boiler room, it is unlikely that the majority of this heat is distributed evenly throughout the structure. Combustion air and draft diverter air flows incurred by the heating unit continually exhaust the heat from jacket losses up-the-stack during both burner "on" and "off" cycles. In addition, conduction losses through building walls can increase in the vicinity of the heating unit in response to localized high temperature. Of course, there are cases in which jacket losses may supply useful heat to the building. The BNL laboratory measurement procedure includes the measurement of jacket losses, and it is possible through the computation program to evaluate the effect of this heat source on seasonal efficiency for specific cases.

B. ANNUAL FUEL USE AND EFFICIENCY CALCULATION PROCEDURE

1. Introduction

The AFUE calculation provides the procedure by which detailed laboratory efficiency measurements for a particular heating unit can be expressed in terms of annual fuel use and seasonal efficiency over a range of operating conditions. Annual fuel use is determined directly by totaling hourly fuel consumption over the entire year. The calculation depends on precise measurement of burner on-cycle and burner off-cycle heat losses for the heating unit to be evaluated. Annual fuel use and seasonal efficiency results can be presented for a variety of design firing rates, domestic hot water loads, building design heat loads, and geographic locations.

AFUE results for a specified heating unit can be applied to field situations, provided that the design heat load of the structure is known. Presently, precise design heat loads of structures are not easily determined under field conditions. However, work is being performed at BNL in conjunction with the State University of New York at Stony Brook to develop a procedure for accurate field measurement of building heat loads, and this will enable AFUE results to be applied to specific field-installed heating equipment. In all cases, the results of AFUE analysis can be used to compare the relative merits of various heating units on a common basis. Precise efficiency measurements that are performed in the laboratory are translated to annual fuel consumption data for identical operating conditions. The AFUE calculation is useful as both an absolute and relative measure of heating equipment efficiency performance.

2. Heat Balances and Computer Calculation of Annual Fuel Use

Conventional residential heating units generally feature on-off control modes. That is, the burner is capable of firing at only one fuel flow rate and the burner firing period reduces to satisfy reduced heating requirements, resulting in burner on-off cycling. Accordingly, thermal efficiency can be divided into two distinct parts. Heat losses arising during burner operation are generally characterized by a steady state efficiency (η_s). Heat losses occurring during the burner off-period are accounted for by a cycle efficiency (η_c). Total heat losses during both "on" and "off" periods can be accounted for by an overall efficiency (η_o) which is the product of steady state and cyclic components.

$$\eta_o = \eta_s \eta_c$$

For example, with a steady state efficiency of 70% and cyclic efficiency of 80%, the overall efficiency is 56%.

To determine annual fuel use it is necessary to calculate the design firing rate (nozzle size) of the heating unit. Optimally, at design conditions (as the outside temperature reaches the design temperature) the burner should operate continuously for properly sized equipment as the total heat supply is balanced by the total heating requirement. Heat supplied by the burner is the product of the design oil flow rate, $\dot{m}_{oil}$ (nozzle size), steady state efficiency ($\eta_c = 1$ for continuous operation) and the heating value of the fuel, h. The total design heating requirement is the sum of the design load, L_d, and the domestic hot water load, H_o. An equation can be written to equate these two quantities, where steady state design load conditions are exactly met by the steady state heat output of the heating unit.

$$\dot{m}_{oil}\ \eta_s\ h = L_d + H_o \qquad (1)$$

It has been observed by field investigators that many heating units are installed with firing rates in excess of the design value. We can define an overfiring ratio (α) to account for the factor by which the heating equipment is overdesigned beyond peak conditions:

$$\dot{m}_{oil}\ \eta_s\ h = (L_d + H_o)\alpha \qquad (2)$$

In field installations, α equal to two is not uncommon, corresponding to systems overfired by 100 percent. One factor contributing to overfiring is the rate at which domestic hot water is used. The total daily heat load resulting from domestic hot water use is small compared to the instantaneous rate at which the hot water is utilized. Larger nozzles are often installed to satisfy the peak usage. An obvious solution to this problem is the use of domestic hot water storage tanks used in conjunction with reduced firing rate.

After the design fuel flow rate has been determined, fuel use can be calculated for each hour of the year based on hourly outside temperature data. Each outside temperature (provided in one degree F intervals) corresponds to a specific space heat load that is less than the design heat load, L_d. Therefore, the burner will operate for less than 100 percent of the time, and burner off-cycle heat loss must be incorporated into the heat balance. The laboratory cycle efficiency data provide the functional relationship between burner fractional on-time (F) and cycle efficiency (η_c).

$$\eta_c = f\ (F)$$

where f is a non-linear function measured in the laboratory, (see Figure 2).

We can write a heat balance for the system at various outside temperatures by including the burner cycle efficiency. Cycle efficiency, η_c, is a function of the burner fractional on-time, F, which can be related to the outside temperature. As the outside temperature increases, the heat load decreases producing smaller values of F and smaller values of η_c. The heat balance can be expressed as:

$$\dot{m}_{oil}\ F\ \eta_s\ \eta_c\ h = L_d \left[\frac{T_{in} - T}{T_{in} - T_d}\right] + H_o \qquad (3)$$

where: T is the variable outside temperature

T_{in} is the inside temperature

T_d is the outside design temperature

The quantity in brackets is a non-dimensional temperature, corresponding to the fraction of design-inside temperature differential. Note that for T greater than T_d, F (the burner fractional on-time) becomes smaller than 1, and $\eta_c = f(F)$ also becomes smaller than one. At design conditions, F and η_c equal one, the quantity in brackets goes to one, and equation (3) reduces to equation (1).

The overfiring ratio can be incorporated by solving equation (2) for L_d and combining the results with equation (3):

$$\dot{m}_{oil}\, F\, \eta_s\, \eta_c\, h = \left[\frac{\dot{m}_{oil}\, \eta_s\, h}{\alpha} - H_o\right]\left[\frac{T_{in} - T}{T_{in} - T_d}\right] + H_o$$

solving for the product of F and η_c:

$$F\, \eta_c = \left[\frac{1}{\alpha} - \frac{H_o}{\dot{m}_{oil}\, \eta_s\, h}\right]\left[\frac{T_{in} - T}{T_{in} - T_d}\right] + \frac{H_o}{\dot{m}_{oil}\, \eta_s\, h}$$

For each outside temperature (T_i) there is a unique burner fractional on-time (F_i) corresponding to a unique cycle efficiency ($\eta_{c,i}$).

$$F_i\, \eta_{c,i} = \left[\frac{1}{\alpha} - \frac{H_o}{\dot{m}_{oil}\, \eta_s\, h}\right]\left[\frac{T_{in} - T_i}{T_{in} - T_d}\right] + \frac{H_o}{\dot{m}_{oil}\, \eta_s\, h} \qquad (4)$$

Thus, we have obtained an equation in which each outside temperature (T_i) can be used to solve the right-hand side of the equation. H_o α, $\dot{m}_{oil}$, η_s, h, T_{in} and T_d are all known quantities. The left-hand side of the equation is the product of laboratory measured quantities.

Solving the right-hand side of equation (4) for a specific outside temperature (T_i) determines a unique value for the product $F_i\ \eta_{c,i}$ which corresponds to a unique value for the burner fractional on-time, F_i. Once F_i is determined, fuel consumption in gallons (M_i) can be calculated for that outside temperature by multiplying F_i by the design fuel flow rate, $\dot{m}_{oil}$.

$$M_i = F_i\ \dot{m}_{oil}$$

For each outside temperature T_i there is a corresponding fuel consumption M_i. The total fuel consumed at temperature T_i is the product of M_i and N_i, the number of hours per year during the heating season at temperature T_i.

$$M_{i,t} = N_i\ F_i\ \dot{m}_{oil}$$

To obtain the total fuel use for the heating season, M, we sum over all outside temperatures.

$$M = \sum_i M_{i,t} = \sum_i N_i\ F_i\ \dot{m}_{oil}$$

For example, with an outside design temperature of $0^{\circ}F$ and an inside temperature of $68^{\circ}F$, the summation would be:

$$M = \sum_{i=o}^{68} M_{i,t} \qquad (5)$$

where M is the total volume (in gallons) of fuel used during the heating season for space heating and domestic hot water generation.

Fuel use during the non-heating season (summer months) for production of domestic hot water can be calculated by:

$$F' \eta_c = \frac{H_o}{\dot{m}_{oil} \eta_s h}$$

Once F' is determined fuel use during the non-heating season, M', can be found by summation:

$$M' = \sum_{\substack{\text{summer}\\ \text{hours}}} F' \dot{m}_{oil} \qquad (6)$$

Total annual fuel consumption M_{annual} is equal to the sum of heating season and non-heating season fuel use:

$$M_{annual} = M + M' \qquad (7)$$

The AFUE Computer Program uses equation (2) to calculate the design fuel flow rate ($\dot{m}_{oil}$) once L_d has been chosen, for a variety of α and H_o values. η_s is determined by laboratory measurement. During the computational process, the overfiring ration (α) and the domestic hot water load (H_o) are varied to monitor equipment performance under various operating conditions. The AFUE program calculates M_{annual} by use of equations (4), (5), (6) and (7) for each value of α (corresponding to a specific design fuel flow rate), and for each value of domestic hot water load (H_o). Ten-year averaged hour-by-hour weather data for each specified geographic location provide the values for N_i, the number of hours per year at each outside temperature.

The seasonal efficiency is calculated based on the total heat available from the quantity of fuel that is consumed. The "ideal" annual fuel use is recalculated for a "perfect system" in which both steady state and cycle efficiencies are taken to equal 100 percent. The resulting annual fuel use is divided by the actual fuel use to provide a value for seasonal efficiency.

$$\text{Seasonal Efficiency} = \frac{\text{Perfect System Fuel Use}}{\text{Actual Fuel Use}}$$

Manual fuel use calculations could be used instead of a computer to obtain the same fuel use results. A computer program is used because of the substantial savings in time compared to manual methods.

C. EXAMPLE OF LABORATORY TEST RESULTS AND ANNUAL FUEL USE EFFICIENCY COMPUTATION

Results of laboratory tests performed on a dry-base, single-pass, vertical fire-tube boiler, equipped with a conventional non-retention head burner are presented in Figure 2. As the burner fractional "on" time is reduced (burner "off" time is increased) the overall efficiency decreases corresponding to larger off-cycle boiler heat losses. The overall efficiency includes burner on-cycle and off-cycle heat losses and is plotted for the entire range of heating unit loads from standby to full load (steady state operation). Annual fuel consumption and seasonal efficiencies have been calculated by the AFUE procedure and the results are provided in matrix form (see Table 1a and 1b) for a variety of domestic hot water loads and design fuel firing rates.

Table 1a provides the computed fuel use and efficiency for a building located in the New York City area with a design heat load of 50,000 Btu per hour, while Table 1b is calculated for the same location and a design load of 25,000 Btu per hour. Each of the parameters at the top of the output page can be varied. The seasonal efficiency is abbreviated S.E., and is presented together with the annual fuel use as a function of the domestic hot water load (gallons of water per day) over a range of overfiring ratios (α). Each α corresponds to a unique design oil flow rate (firing rate in gallons of oil per hour), and as the overfiring ratio is increased, the seasonal efficiency drops and annual fuel use increases. For example, in Table 1a at 40 gallons per day of domestic hot water, increasing α from 2 to 3 corresponds to increasing the design firing rate from 1.07 to 1.61 gph, and a resulting decrease in seasonal efficiency from .567 to .502. The corresponding increase in fuel consumption is 186 gallons per year from 1437 to 1623 - a 13% increase in annual fuel use. This example demonstrates the significant effect of overfiring on the quantity of fuel required to satisfy the same heat load for the particular heating unit being considered. All equipment that has been tested at BNL substantiate this result with varying degrees of performance degradation depending on the particular heating unit, and its part-load efficiency performance. It has been observed that both steady state and cyclic efficiencies vary over a wide range of values for commercially available equipment of various design.

D. SUMMARY

The BNL Annual Fuel Use Efficiency calculation in conjunction with precise laboratory measurements, provide the basis by which the intrinsic merits of individual heating units can be compared under a full range of "standard" conditions. "Standard" conditions include any given design heat load, any given hour-by-hour weather pattern for the heating season, any given range of domestic hot water requirements, and any given cycle characteristics which may be employed in a home heating strategy. AFUE analysis cannot be used to evaluate the annual fuel consumption of a particular building/heating unit system, unless all specific building heat sources and losses can be incorporated into a total heat load. Instead, the strength of the procedure is its simplicity and ability to provide a quantitative measure by which equipment of various designs can be compared on a realistic and common basis.

HEATING UNIT: DRY-BASE SINGLE PASS STEEL BOILER
LOCATION: NEW YORK CITY
DESIGN HEAT LOAD: 50000.0 BTU PER HOUR
ROOM TEMP: 68.0°
OUTSIDE DESIGN TEMP: 0.0°

DOMESTIC HOT WATER (GAL PER DAY)		1.	2.	3.	4.
0.	SEASONAL EFFICIENCY	.631	.555	.488	.435
	ANNUAL FUEL USAGE (GAL/YEAR)	1156.	1316.	1497.	1680.
	DESIGN OIL FLOW RATE (GPH)	.521	1.042	1.563	2.085
40.	SEASONAL EFFICIENCY	.639	.567	.502	.450
	ANNUAL FUEL USAGE (GAL/YEAR)	1274.	1437.	1623.	1812.
	DESIGN OIL FLOW RATE (GPH)	.536	1.071	1.607	2.143
80.	SEASONAL EFFICIENCY	.646	.577	.514	.463
	ANNUAL FUEL USAGE (GAL/YEAR)	1393.	1558.	1749.	1942.
	DESIGN OIL FLOW RATE (GPH)	.550	1.100	1.650	2.200
120.	SEASONAL EFFICIENCY	.652	.586	.525	.475
	ANNUAL FUEL USAGE (GAL/YEAR)	1511.	1679.	1874.	2073.
	DESIGN OIL FLOW RATE (GPH)	.565	1.129	1.694	2.258

Table 1a: (Dry-base single pass steel boiler with non-retention head burner) 50,000 btu per hour

HEATING UNIT: DRY-BASE SINGLE PASS STEEL BOILER
LOCATION: NEW YORK CITY
DESIGN HEAT LOAD: 25000.0 BTU PER HOUR
ROOM TEMP: 68.0°
OUTSIDE DESIGN TEMP: 0.0°

DOMESTIC HOT WATER (GAL PER DAY)		1.	2.	3.	4.
0.	SEASONAL EFFICIENCY	.631	.555	.488	.435
	ANNUAL FUEL USAGE (GAL/YEAR)	578.	658.	748.	840.
	DESIGN OIL FLOW RATE (GPH)	.261	.521	.782	1.042
40.	SEASONAL EFFICIENCY	.646	.577	.514	.463
	ANNUAL FUEL USAGE (GAL/YEAR)	696.	779.	874.	971.
	DESIGN OIL FLOW RATE (GPH)	.275	.550	.825	1.100
80.	SEASONAL EFFICIENCY	.656	.594	.535	.485
	ANNUAL FUEL USAGE (GAL/YEAR)	815.	900.	1000.	1102.
	DESIGN OIL FLOW RATE (GPH)	.290	.579	.869	1.158
120.	SEASONAL EFFICIENCY	.664	.607	.551	.503
	ANNUAL FUEL USAGE (GAL/YEAR)	934.	1020.	1125.	1232.
	DESIGN OIL FLOW RATE (GPH)	.304	.608	.912	1.216

Table 1b: (Dry-base single pass steel boiler with non-retention head burner) 25,000 btu per hour

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