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A Preliminary Investigation Of Three Advanced Wind Energy Systems For Residential And Farm Applications

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A PRELIMINARY INVESTIGATION OF THREE ADVANCED WIND ENERGY SYSTEMS FOR RESIDENTIAL AND FARM APPLICATIONS

TECHNICAL REPORT

by

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ABSTRACT

This report is primarily concerned with an analysis of advanced wind driven energy systems. Three such systems, the Improved Wind Furnace System and the Wind Driven Total Energy Systems, Types I and II, for the supply of energy to electrical, space heating and domestic hot water loads are considered for New England residential and farm applications. These systems are studied with the aid of an interactive digital computer simulation (WDTES1) and an economics program (WSDECO). Although the programs incorporate some idealizations, they represent a necessary preliminary investigation of the total system and its components. The computer models are designed to be general enough to allow for wide variations of loads, component sizes, working fluids and energy costs, but specific enough to approach an optimum design point based on maximum energy efficiency or minimum total system costs.

Results indicate that the Wind Driven Total Energy System, Type II model requires the least amount of auxiliary energy input to the system for all three residential and farm settings considered. However, it was found that the higher capital costs of the Wind Driven Total Energy System, Type II, did not justify its use when compared to the less energy efficient but also less expensive Improved Wind Furnace System. All systems studied though, if mass produced, were found to be less expensive annually than the conventional electric, oil and gas energy supply systems, provided that the capital costs are amortized over a twenty year period.

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CHAPTER I

INTRODUCTION

Energy and its means of supply have become commodities of increasingly greater importance on the world market and a major political and economic consideration for every nation of the world. An abundant supply of energy at a low cost is basic to an industrial society to insure a higher net economic welfare for all and to preclude the possibility of conflict over decreasing resources.

The realization that energy is a precious and dwindling resource has given rise to the examination of energy conservation and renewable energy systems to help solve the energy problem. The United States is not only the largest energy consuming nation in the world, consuming some 30 percent of the world's energy production, but it is essentially the largest per capita user (with the exception of some small countries, such as Luxembourg [1]), since it has less than six percent of the world's population. This large per capita energy requirement is not only due to its large gross national product, but also due to the lack of an efficient energy conservation program. Nations such as Sweden, West Germany and Canada, which have approximately the same per capita GNP as the United States use less energy to achieve it. For example, the average Canadian uses 85 percent of the energy used by his American counterpart and the average Swede and West German uses 50 percent [2].

Obviously, much can be accomplished, in solving the energy problem, by wise use of energy resources which are already available, but still more energy will be required in the future. Hard choices, which have both economic and political ramifications, will have to be made between various conventional (fossil fuel, nuclear, etc.) and non-conventional (solar, hydrogen, biomass, etc.) energy systems. Solar energy, with its subdivision wind energy, represents a viable alternative socially, politically and aesthetically, and most importantly, for certain applications, economically, to the conventional methods·of energy supply.

Approximately 20 percent of the energy used in the United States annually is for heating and cooling of buildings and residences [3] and approximately three percent of the total energy is consumed for hot water. Therefore, by reducing residential and building energy requirements, the total annual energy consumption can be reduced significantly. The application of wind energy to residential heating can be advantageous since the greatest wind resource is generally during the late autumn, winter and spring months in New England, a time when the heating load is the greatest. This is graphically represented in Figure 1.1.

Farms, by virtue of their location in areas of sparse population, are also an application for wind energy that should be redeveloped. Before rural electrification projects, farms in the U.S. relied heavily on wind energy to mill grain and pump water. With the advent of inexpensive electrical and petroleum energy, windmills were phased out. Wind to electrical energy conversion, if properly developed, could supply energy to run appliances, milking machines, tools, etc. and liberate rural farms from electrical utility lines, thus saving the very expensive costs of running transmission lines to a rural setting.

Fortunately, as shown in Figure 1.2,the United States is blessed with a huge wind resource in various portions of the country [4]. Since most of the Northeast, Northwest and the Plains region lie in areas where the average annual wind resource at a relatively low height is 125 watts per

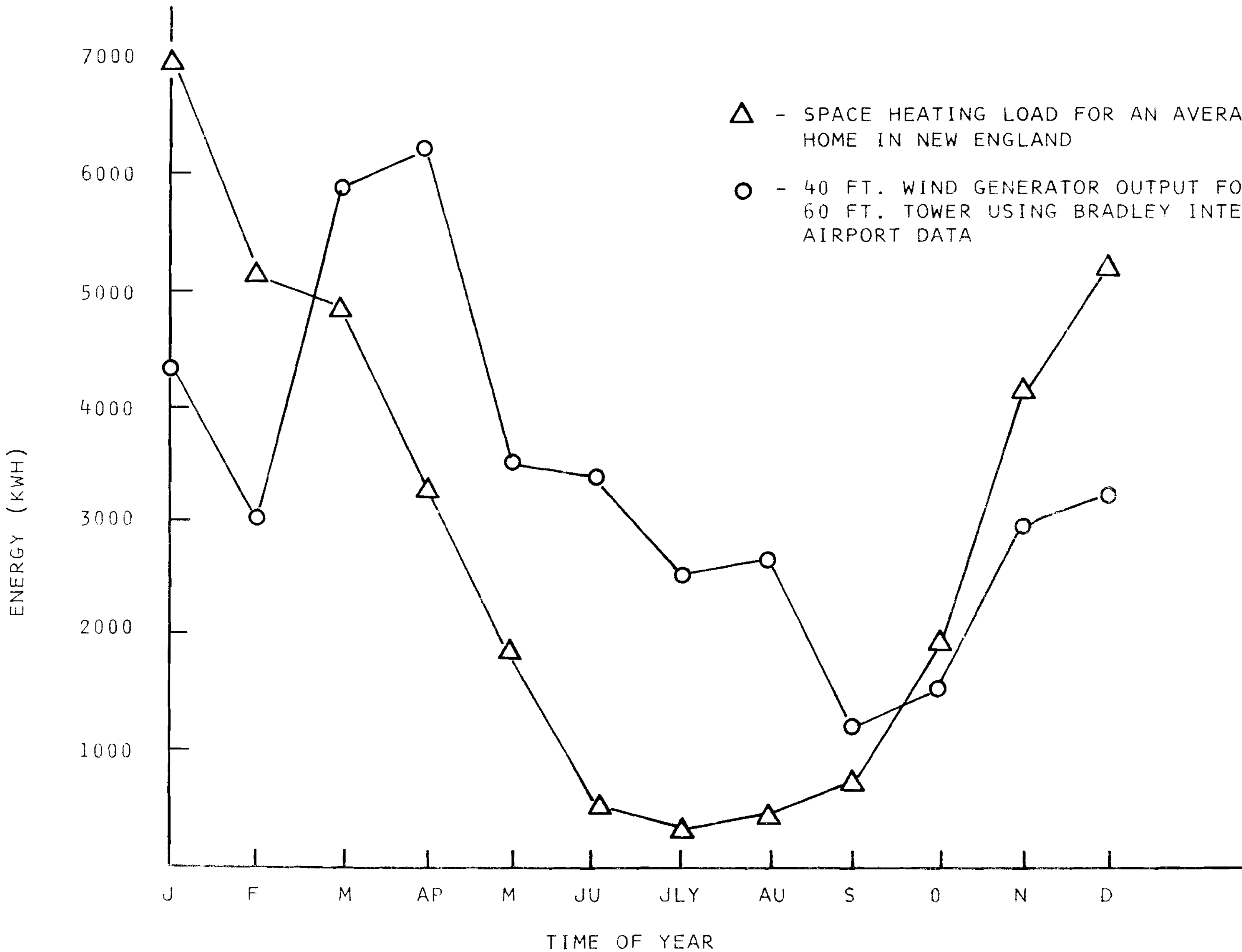


FIGURE 1.1. SPACE HEATING LOAD AND 40 FT. WIND GENERATOR OUTPUT VS. TIME OF YEAR

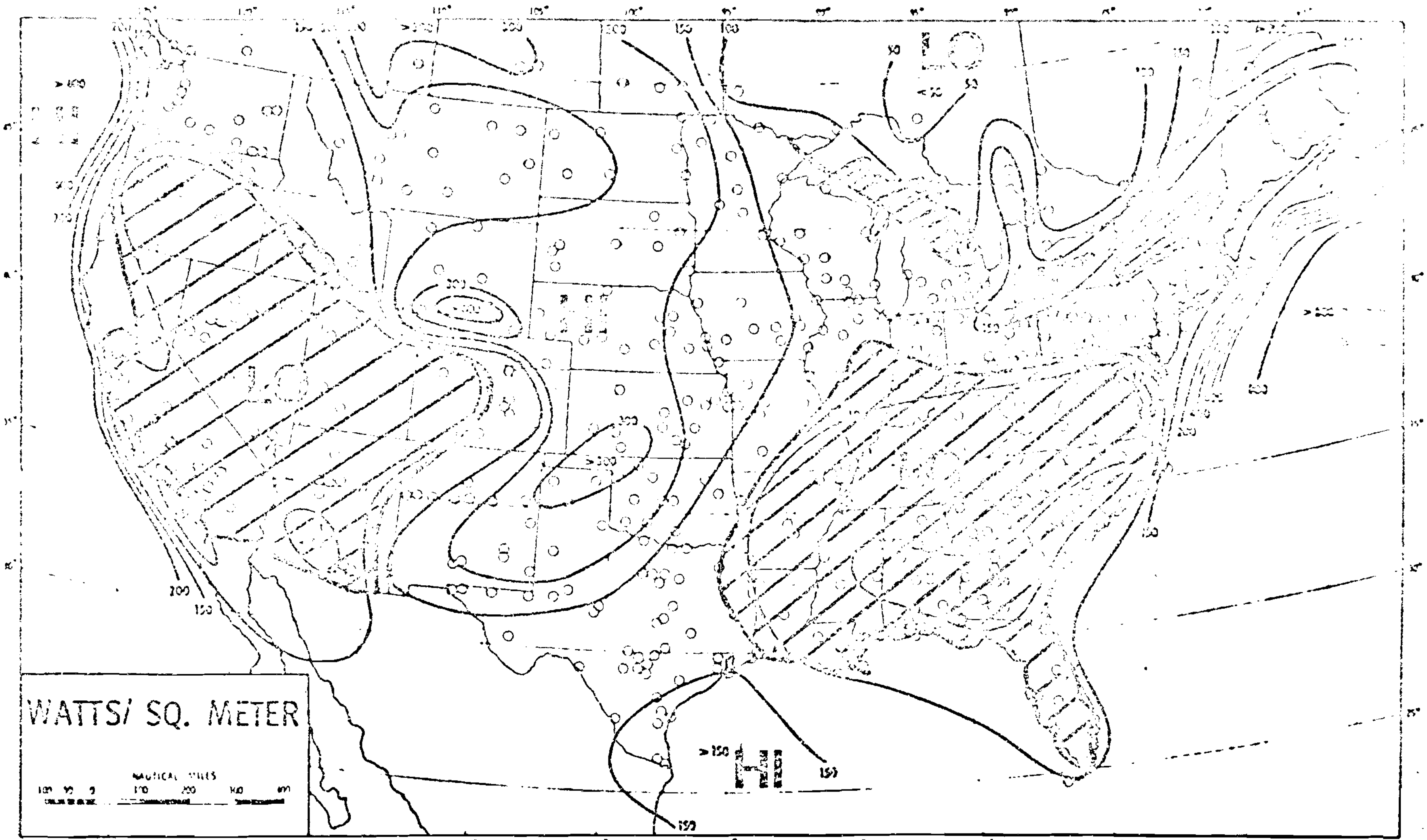


FIGURE 1.2. UNITED STATES WIND RESOURCE. WIND ENERGY UTILIZATION IS PROBABLY NOT ECONOMICALLY FEASIBLE IN THE CROSSHATCHED REGIONS. (HERONEMUS - ADAPTED FROM REFERENCE 4)

square meter or greater, investigations at the University of Massachusetts suggest that these are viable wind use areas.

Wind energy, along with other forms of solar energy, due to its variable intensity must be stored to insure distribution to residential and farm energy loads as it is required. Unfortunately, the electrical, domestic hot water and space heating loads of a typical New England residence or farm are also variable. Thus, any well designed wind energy storage and distribution system must consider the variability of the energy inputs and outputs for the most efficient design. Thermodynamically, the most efficient energy use is possible when high grade energy, such as electricity, is used for a high grade application, such as the electrical load, and similarly, when low grade energy, such as waste heat, is used for a low grade application , such as space heating.

With these considerations in mind, as a part of on-going work in the Energy Alternative Program at the University of Massachusetts, Solar Habitat 1, the wind furnace was designed and put into operation [5-8]. As a logical extension of this program and to exploit the system more efficiently in a thermodynamic sense, three advanced wind furnace concepts are considered in this work. These three concepts are the Improved Wind Furnace System (IWFS) and two Wind Driven Total Energy Systems (WDTES) all of which are designed for residential or farm applications.

CHAPTER II

DESCRIPTION OF SYSTEM CONFIGURATIONS

In the following sections, a description of the proposed advanced wind energy systems and their mode of operational logic is provided. Since the systems studied are quite complex, the effects of all system parameters capable of being varied in the digital computer simulation could not be studied due to time and computer useage restraints. Instead, key system variables were identified and varied to give insight into system performance. These key variables are: 1) the high temperature storage (HTS) tank capacity, 2) the heating load, 3) the electrical load, 4) Rankine Cycle efficiency, and, for the Improved Wind Furnace System, 5) the low temperature storage (LTS) tank capacity. Although wind turbine generator (WTG) blade diameter is also a key system variable and WDTES1 allows the choice of six blade diameter sizes ranging from 20 to 40 feet, only the 40 ft. size wind machine was considered. It is believed that a single 40 ft. WTG is a size well suited to match the loads under consideration and, with its 25 kw generator, represents the largest sized reasonably priced (if mass produced) unit for a farm or residence. (Future work may consider multiple arrays of 40 ft. WTG's).

2.1 The Improved Wind Furnace System (IWFS)

The first advanced wind furnace system considered was the Improved Wind Furnace System (IWFS). The Improved Wind Furnace, shown schematically, in Figure 2.1 includes these subsystems:

a) A 40 ft. diameter pitch controlled, horizontal axis, wind turbine generator.

b) A sensible thermal energy storage tank, using water as an energy storage medium.

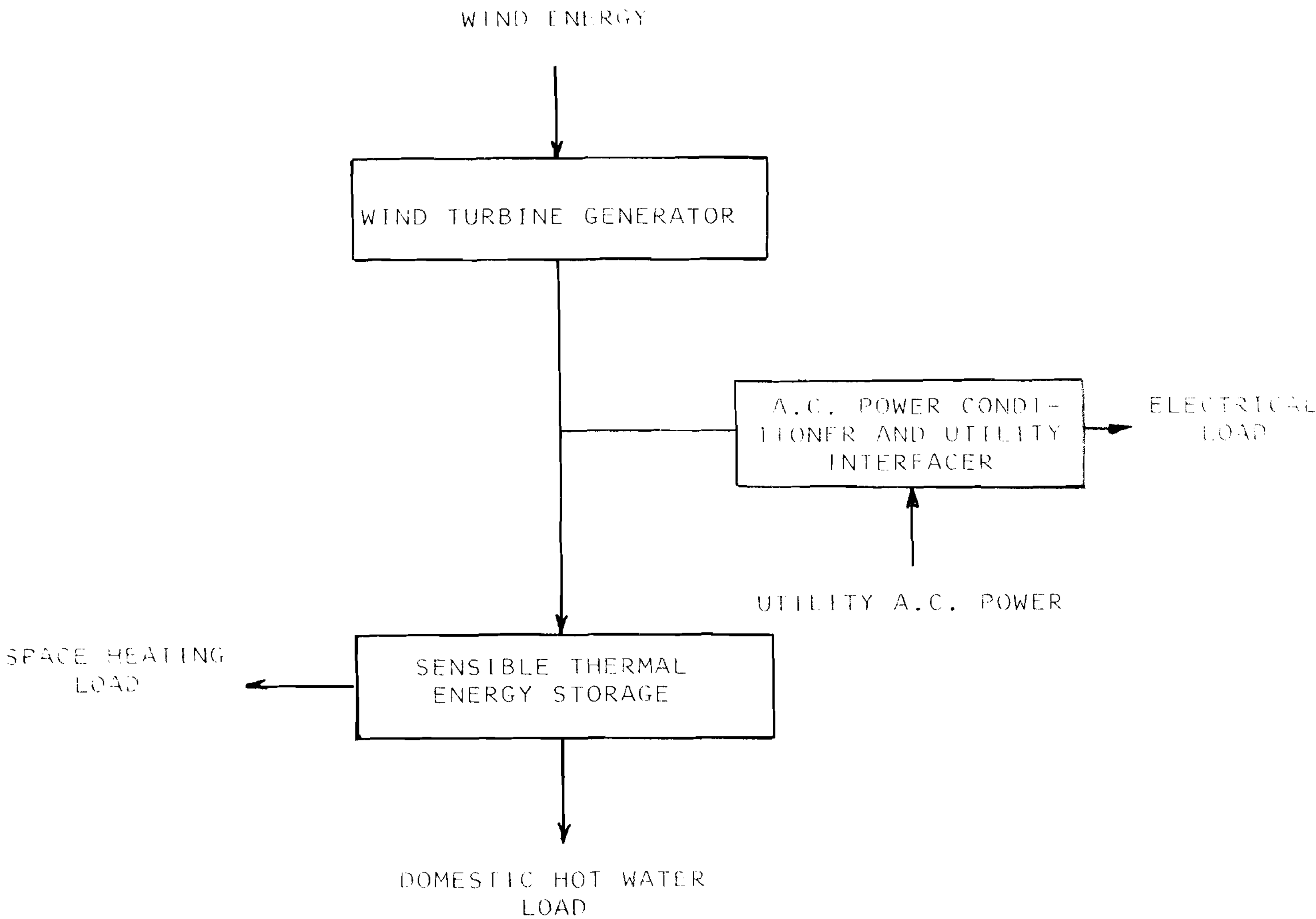


FIGURE 2.1. SCHEMATIC OF THE IMPROVED WIND FURNACE SYSTEM (IWFS)

c) An electricity power conditioner and utility interfacer. Wind turbine electricity would be fed through this unit to satisfy, with the help of utility power, the electrical load. In the case of surplus wind generated electricity, the excess would be channeled into the thermal storage. The technology for those units has already been established [9].

d) The switching logic and controls to facilitate the above operations.

A more detailed schematic of the IWFS is given in Figure 2.2. A description of its components, operation and proposed control follows.

1. Wind turbine generator, A, delivers three phase AC current at 1 whenever wind is above generator cut in speed. A is controlled constantly in pitch to optimum tip-speed ratio, or furled in dangerously high winds. A is also protected from stalling by a field controller.

2. Component C represents the connected 120/140 volt, single phase 60 Hz electrical load which follows a daily residential or farm demand pattern. When A has power to deliver to the demand at C, switching logic, K, will allow power conditioner, B, to provide as much of the demand as A is capable of supplying. Should the demand at C be greater than that supplied at A, utility AC supply, N, will be used to supply the balance. If the demand at C is less than the supply at A, K will send the difference to the sensible thermal energy storage, E, through storage tank resistance heaters, D.

3. Component G represents the space heating load. If the thermostat at G requires heat, heat is transferred from storage tank E

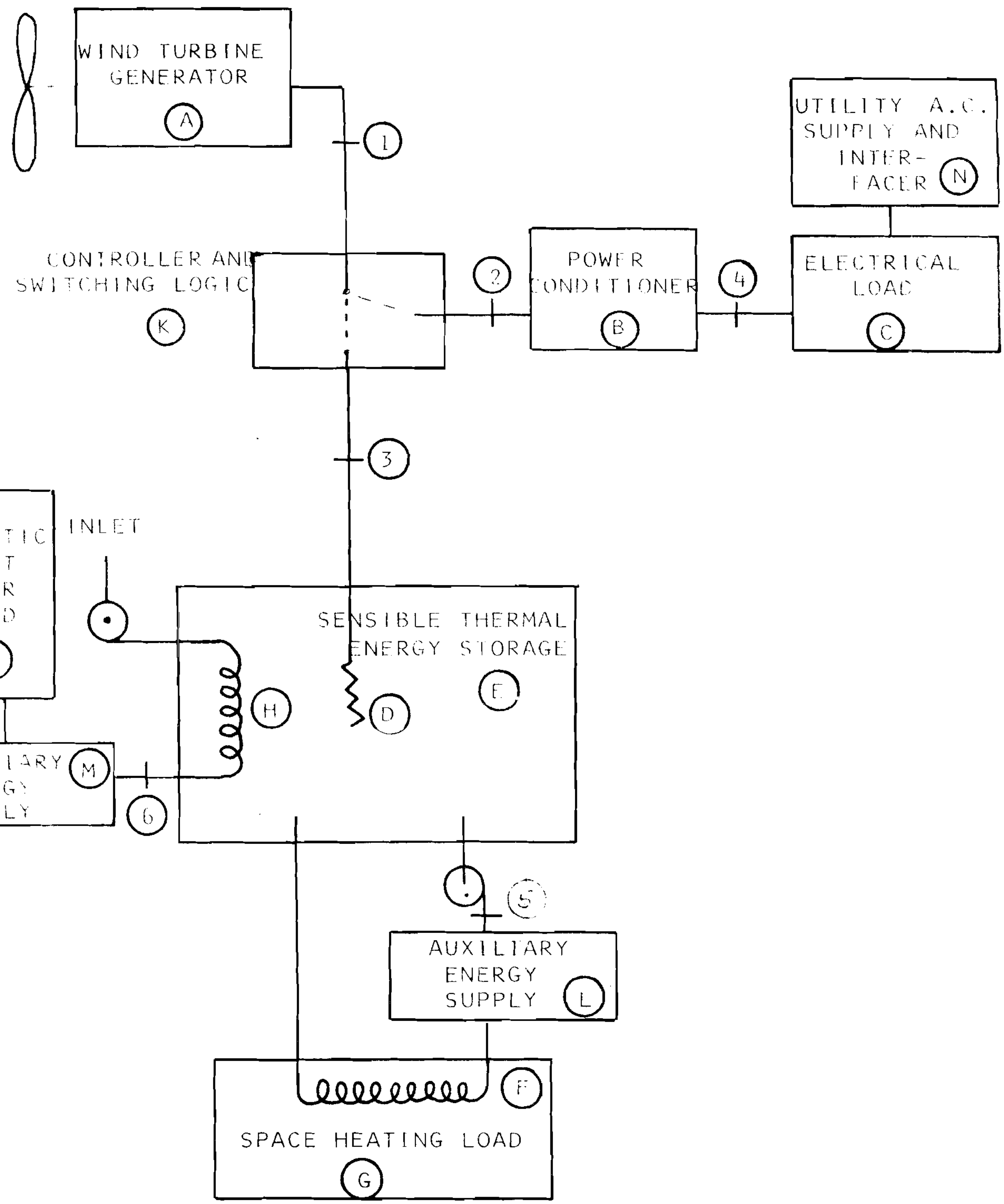


FIGURE 2.2. DIAGRAM OF THE IMPROVED WIND FURNACE SYSTEM

through heat exchanger F to the load. If the temperature at 5 is too low for heat delivery in sufficient quantities, auxiliary energy supply, L, supplies the balance.

4. Component I represents the domestic hot water load. If I requires hot water and the temperature at E is greater than the hot water delivery temperature, 140°F, energy is supplied through heat exchanger H. If the temperature at E is less than the delivery temperature and I requires hot water, the water is preheated through heat exchanger H and auxiliary energy supply, M, supplies the balance.

5. If the temperature at E is near the boiling temperature (200°F), and the energy input at 3 is greater than the loads at 5 and 6, the blades at A are controlled to allow the energy at 3 to be equal to the loads at 5 and 6 to prevent boiling of the storage medium.

The major advantage of the Improved Wind Furnace System is its relatively low cost and simplicity when compared to the other wind generator systems. With the IWFS, energy storage must be large enough to insure that the wind turbine will not have to be feathered and that the temperature of the storage material will be high enough to supply energy to the thermal loads. Also, with the IWFS, all electricity which is not supplied directly from the wind generator must be supplied by the utility. Since electricity is by far the most expensive form of energy, it is imperative to keep this utility electricity demand low.

2.2 <u>The Wind Driven Total Energy System, Type I (WDTES, Type I)</u>

The second advanced wind furnace system considered was the Wind Driven Total Energy System, Type I, which features a direct wind energy input to a high temperature storage material. The WDTES, Type I model, shown schematically in Figure 2.3 includes these subsystems:

a) A 40 ft. diameter, pitch controlled, horizontal axis WTG.

b) A low temperature thermal storage tank (LTS) using water as a storage material, from which space heating is supplied.

c) A high temperature thermal storage tank (HTS), which uses sodium hydroxide (NaOH), a phase change material, for energy storage. From this tank, domestic hot water is supplied, as well as heat for the Rankine Cycle power plant.

d) A Rankine Cycle power system. This component employs a drying fluid, toluene, as a working fluid. The heat source for this heat engine is the HTS and the heat sink is the LTS. Via the turbine shaft and an alternator, the energy produced is converted to electricity to satisfy the electrical load.

e) The utility interfacer. Electrical energy, not supplied to the electrical load by the Rankine Cycle power system would be supplied, through this unit, by the utility.

f) The switching logic and controls to facilitate the above operations.

A more detailed schematic of the WDTES Type I system is shown in Figure 2.4. A description of its components, their operation and controls follows.

1. Wind turbine generator, A, delivers three phase AC current at 1 whenever wind is above the generator cut in speed. A is controlled constantly in pitch to optimum tip-speed ratio or furled in dangerously high winds. A is also protected from stalling by a field controller.

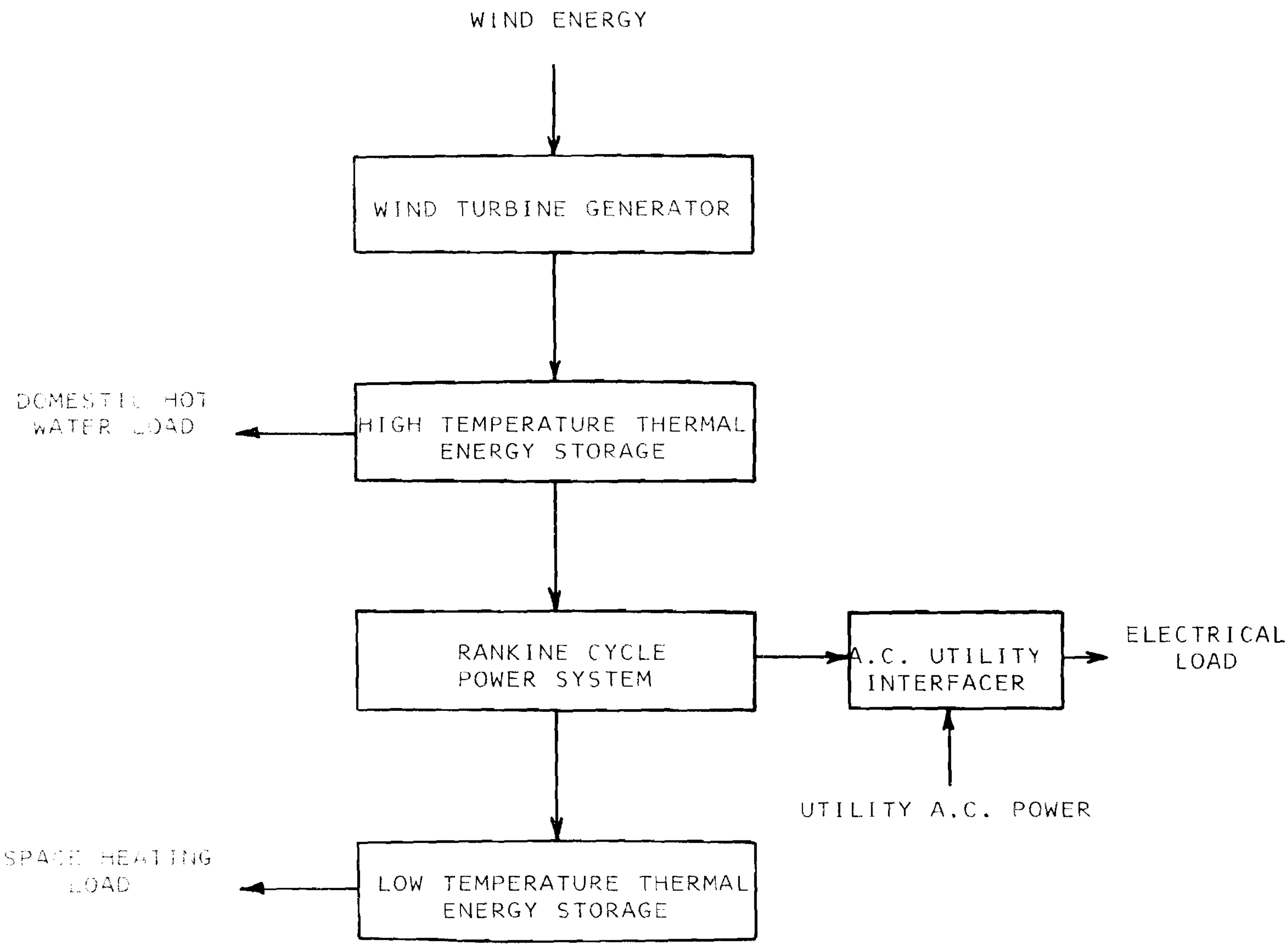


FIGURE 2.3. SCHEMATIC OF THE WIND DRIVEN TOTAL ENERGY SYSTEM, TYPE I

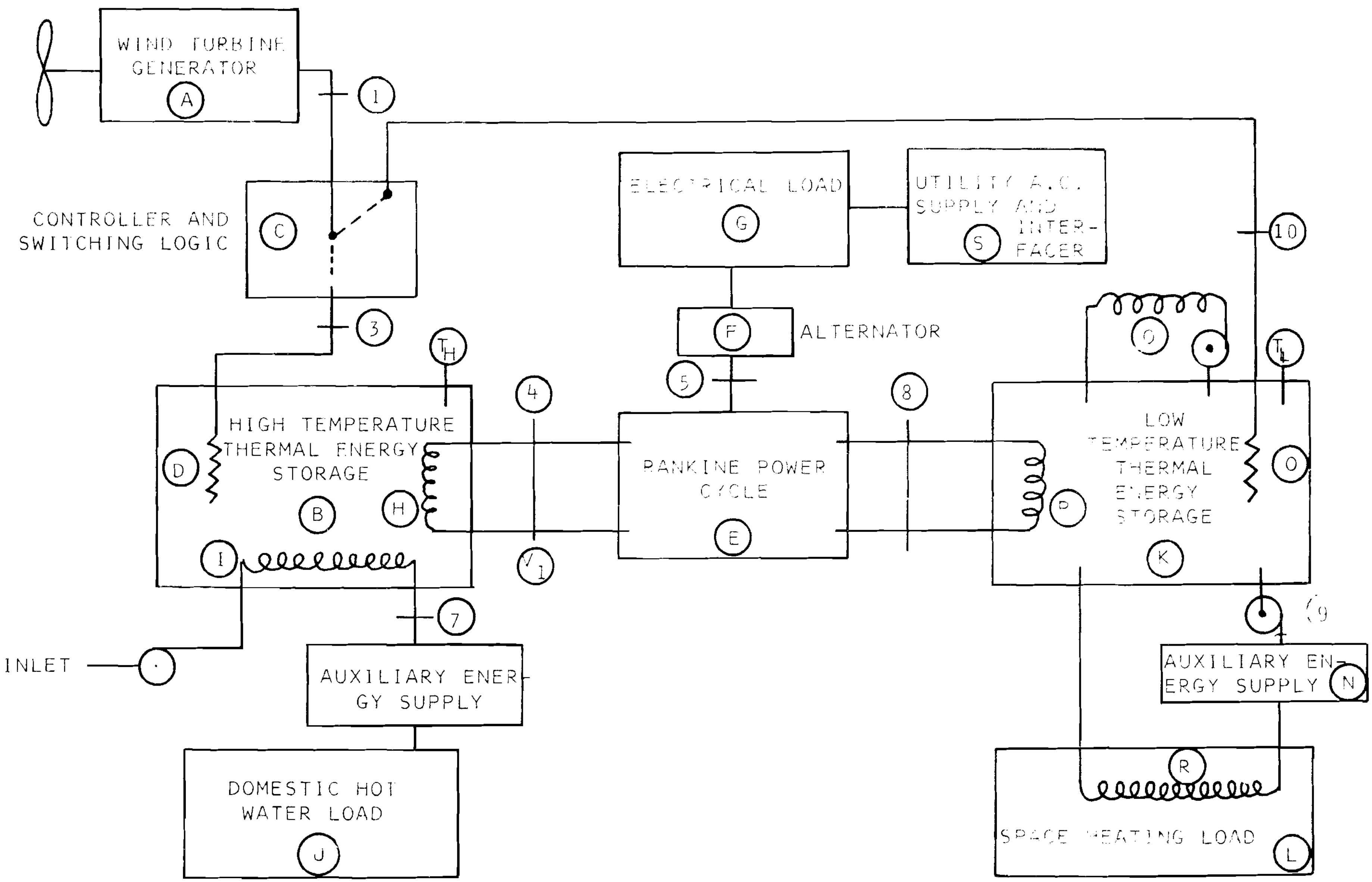


FIGURE 2.4. DIAGRAM OF THE WIND DRIVEN TOTAL ENERGY SYSTEM (WDTES), TYPE I

2. Component B represents the sodium hydroxide high temperature thermal storage. When A has power to deliver and the temperature at TH is less than the critical value (800^{0}F), switching logic, C, allows the electrical energy to flow through resistance heater, D, immersed in the tank.

3. Component G is the connected 120/140 volt single phase, 60 Hz electrical load which follows a daily residential or farm demand pattern. When electricity is required by G and TH is above the minimum Rankine Cycle operation temperature (400^{0}F), Rankine Power Cycle, E, is activated and the power output at 5 goes through alternator, F, to supply power to G. If TH is less than the minimum RC operation temperature and electricity is required by G, electricity is supplied via the utility AC supply, S.

4. The Rankine Power Cycle is represented by component E in Figure 2.4. The closed Rankine Cycle, which drives alternator, F, derives its heat from high temperature thermal storage, B, through heat exchanger, H. Heat is rejected into the low temperature thermal storage K, through heat exchanger, P. When power is required, switching logic, C, opens valve V_1 to allow E to operate. The amount of working fluid passing through heat exchanger H will be controlled by C, setting valve V_1, such that the power output of F matches the demand at G.

5. Component K is the low temperature thermal storage (LTS) which utilizes water as an energy storage medium. When energy is available at 1, but the temperature at TH is greater than or equal to the critical value, switching logic, C, allows the excess energy produced at A, to pass through resistance heater, O, immersed in the LTS. If the temperature at TL is near the boiling temperature of 200^{0}F or greater, a

small pump, which is controlled by switching logic C, allows the storage material to flow through air cooled heat exchanger, Q, thereby preventing boiling. If energy is available at I and TH and TL are at their critical values (800^{O}F and 200^{O}F respectively), the blades at A are controlled to allow only enough energy to flow through C to keep the storage tanks at these critical temperature values.

6. The domestic hot water load is represented by component J. A small pump allows the inlet water from a main to pass through heat exchanger, I, situated in the high temperature thermal storage, B. If the outlet temperature from I is less than the hot water delivery temperature (140^{O}F) at 7, auxiliary energy supply, M, is activated to heat the water to the delivery temperature.

7. Component L is the space heating load. A small pump allows water from the thermal storage tank to pass through baseboard heaters, R. If the temperature at 9 is too low to satisfy heating load, L, auxiliary energy supply, N, is activated to supply the remainder.

The main advantage of WDTES Type I, when compared to the IWFS is the small amount of electricity which has to be supplied by the utility to the electrical load. By minimizing utility supplied electricity, the most expensive auxiliary energy requirement of the system can be eliminated, provided that the space heating and domestic hot water auxiliary energy supplies are not electric. This leaves open the possibility, mentioned earlier, that this system can be left independent of transmission lines.

The basic disadvantage of this system is that the electricity produced by the wind generator is not utilized, thermodynamically, in the best manner possible. Losses occur in the conversion of electrical energy to heat energy and back again to electrical energy. A conceptually more efficient system could be designed which eliminates this electricity to heat to electricity energy conversion loss. This is the basis for the Wind Driven Total Energy Type II System.

2.3 The Wind Driven Total Energy System, Type II (WDTES, Type II)

The final advanced wind furnace system considered was the Wind Driven Total Energy System, Type II, which features a system by which electrical energy produced by the wind generator is supplied to the electrical load as a top priority and the excess is supplied to the high temperature storage material [10]. The WDTES Type II system shown schematically in Figure 2.5, utilizes these subsystems:

a) A 40 ft. diameter, pitched controlled, horizontal axis, wind generator.

b) A low temperature thermal storage tank with water as a storage medium, from which space heating is supplied.

c) A high temperature thermal storage tank which uses the phase change material, sodium hydroxide, for energy storage. This tank is utilized for the supply of domestic hot water as well as a heat source for the Rankine Cycle heat engine.

d) A Rankine Cycle Power System. This subsystem uses toluene as a working fluid and rejects heat into the low temperature thermal storage tank. By way of the turbine shaft and an alternator, the energy produced is converted into electricity to satisfy the electrical load.

e) The utility interfacer. Electrical energy, not supplied to the electrical load by the Rankine Cycle or by the wind generator directly, is supplied, through this unit by the utility.

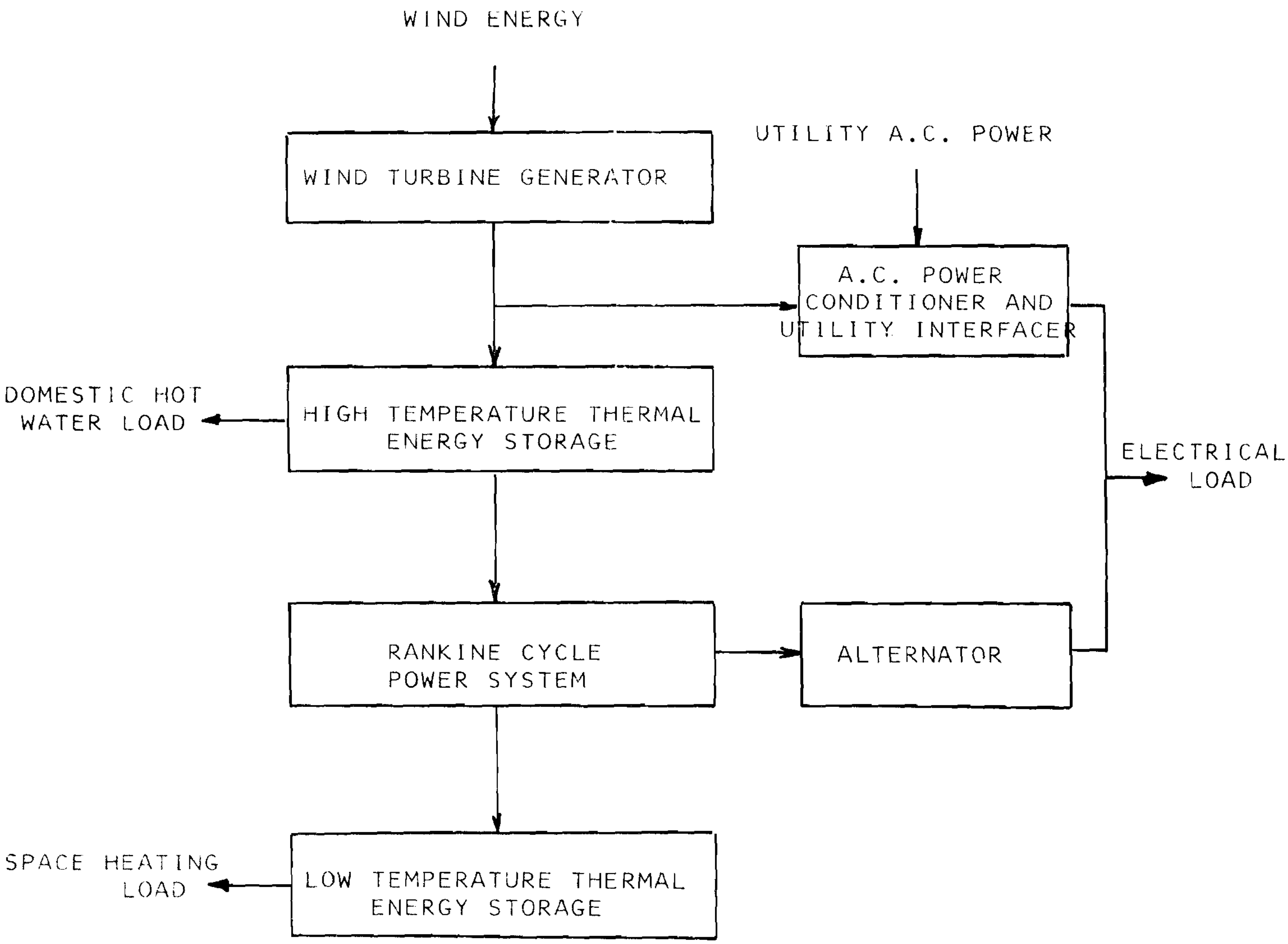


FIGURE 2.5. SCHEMATIC OF THE WIND DRIVEN TOTAL ENERGY SYSTEM, TYPE II

f) The necessary switching logic and controls.

A more detailed schematic for WDTES II is given in Figure 2.6. A description of the components, its operation and the proposed controls follow.

1. Wind turbine generator, A, delivers three phase AC current at 1 whenever wind speed is above the generator cut in speed. A is controlled constantly in pitch to optimum tip-speed ratio or furled in dangerously high winds. A is protected from stalling by a field controller.

2. The electrical load is represented by component G. This is a 120/140 volt, single phase, 60 Hz electrical load which follows a daily residential or farm demand pattern. Whenever A has power to deliver and G shows a demand, switching logic, C, will allow power conditioner, S, to supply as much of the demand as possible. If the demand at G is less than the available energy at 1, C will satisfy the demand at G and allow the remainder of the energy to pass to the high temperature thermal storage, B. If, in this case, B is at its critical value of 800°F or higher, C, will pass the energy to low temperature thermal storage tank, K, through resistance heater, O.

3. Component B represents the sodium hydroxide high temperature thermal storage. When A has satisfied the electrical load, and TH is less than its critical value, switching logic, C, allows the electrical energy to flow through resistance heater, D, immersed in the tank.

4. The Rankine Power Cycle is represented by component E.

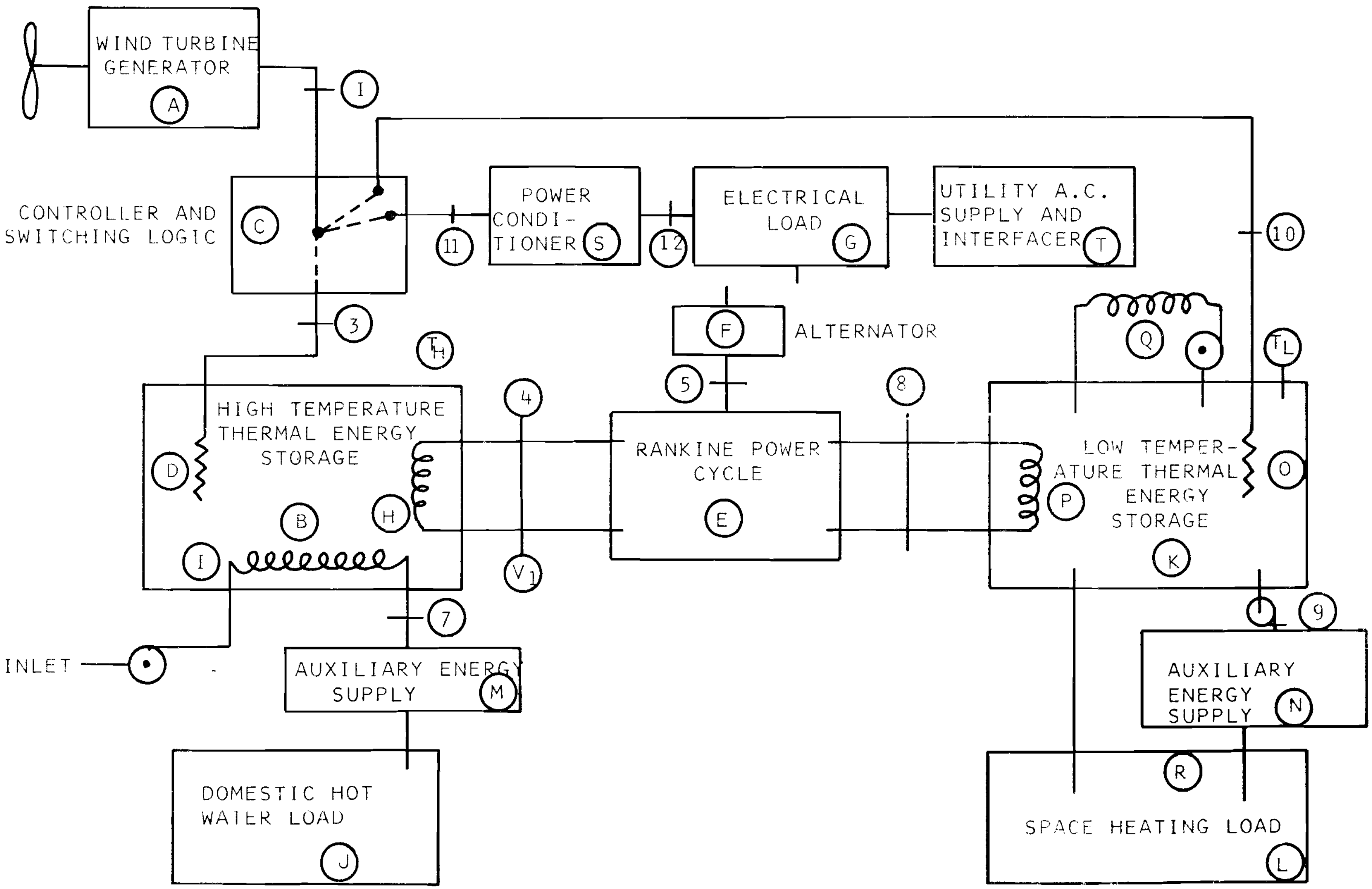


FIGURE 2.6. DIAGRAM OF THE WIND DRIVEN TOTAL ENERGY SYSTEM, TYPE II

The closed Rankine Cycle, which drives alternator, F, uses B as a heat source and H as its hot side heat exchanger. Heat is rejected into the low temperature thermal storage, K, through heat exchanger, P. When power is required from E, switching logic, C, opens valve V_1, allowing the working fluid to flow and E to operate. The amount of working fluid passing through H will be controlled by C, setting valve V_1 such that the power out of F matches the part of the demand at G which is nct satisfied via A.

5. Component K is the low temperature, sensible, thermal storage, which uses water as an energy storage material. When energy is available at ', but the temperature at TH is greater than or equal to its critical value, switching logic, C, channels the excess electrical energy through resistance heater, O, immersed in the LTS. If the temperature, TL, of K is near the boiling temperature 200^{o}F or greater, a small pump, controlled by C, allows the storage material to flow through Q, an air cooled heat exchanger, preventing boiling. If energy is available at 1 and TH and TL are at their critical values, the blades at A are controlled to allow only enough energy to flow through C to keep the storage tanks at these temperatures, with B given first priority.

6. The domestic hot water load is represented by component J. A small pump allows the inlet water from a main to pass through heat exchanger, I, situated in the high temperature thermal storage, B. If the outlet temperature from I is less than the hot water delivery temperature of 140^{o}F at 7, auxiliary energy supply, M, is allowed heat the water to the delivery temperature.

7. Component L is the space heating load. A small pump

allows water from the thermal storage tank to pass through baseboard heaters, R. If the temperature at 9 is too low to satisfy L, auxiliary energy supply, N, is activated to supply the remainder of the space heating.

The advantage of the WDTES Type II, compared to the IWFS and the WDTES Type I, is that this system requires the minimum amount of utility electricity and the minimum total auxiliary energy of all the systems. Thermodynamically, due to efficient energy use and the least amount of energy conversion, this should be the system least wasteful in energy use. Unfortunately, this high efficiency must be coupled with favorable economics to make the system practical. The concept will be considered in later chapters.

CHAPTER III

DESCRIPTION OF SUBSYSTEMS AND MODELS

In this chapter, analyses of the important subsystems and models related to the three advanced wind furnace systems are performed. Subsystems previously investigated by Darkazalli [11], which are in common with his work, are dealt with briefly, while the subsystems exclusive to the advanced wind furnace systems are treated in greater detail. The governing equations and their limitations will be shown, while the mathematical simulation for each subsystem will be provided in Chapter IV.

3.1 The Wind Turbine Generator

The wind turbine generator envisaged for use with the advanced wind furnace systems which was designed [12,13] at the University of Massachusetts, is 40 ft. diameter, three bladed, horizontal axis wind turbine, mounted on a 60 ft. tower, which is coupled with a 25 kw generator. With the use of wind speed data, measured at nearby Bradley International Airport using an anemometer at 10 meter/height, the expected electrical output from the generator is approximately 40,000 kWh per year. This is roughly equivalent to the yearly total energy requirements for a home in the New England area.

The power output of the 40 ft. wind turbine generator considered, and also the 20, 25, 30, 32.5 and 35 ft. wind machines which the main simulation program, WDTES1, is capable of analyzing is given in Figure 3.1. This set of performance curves is given as a function of

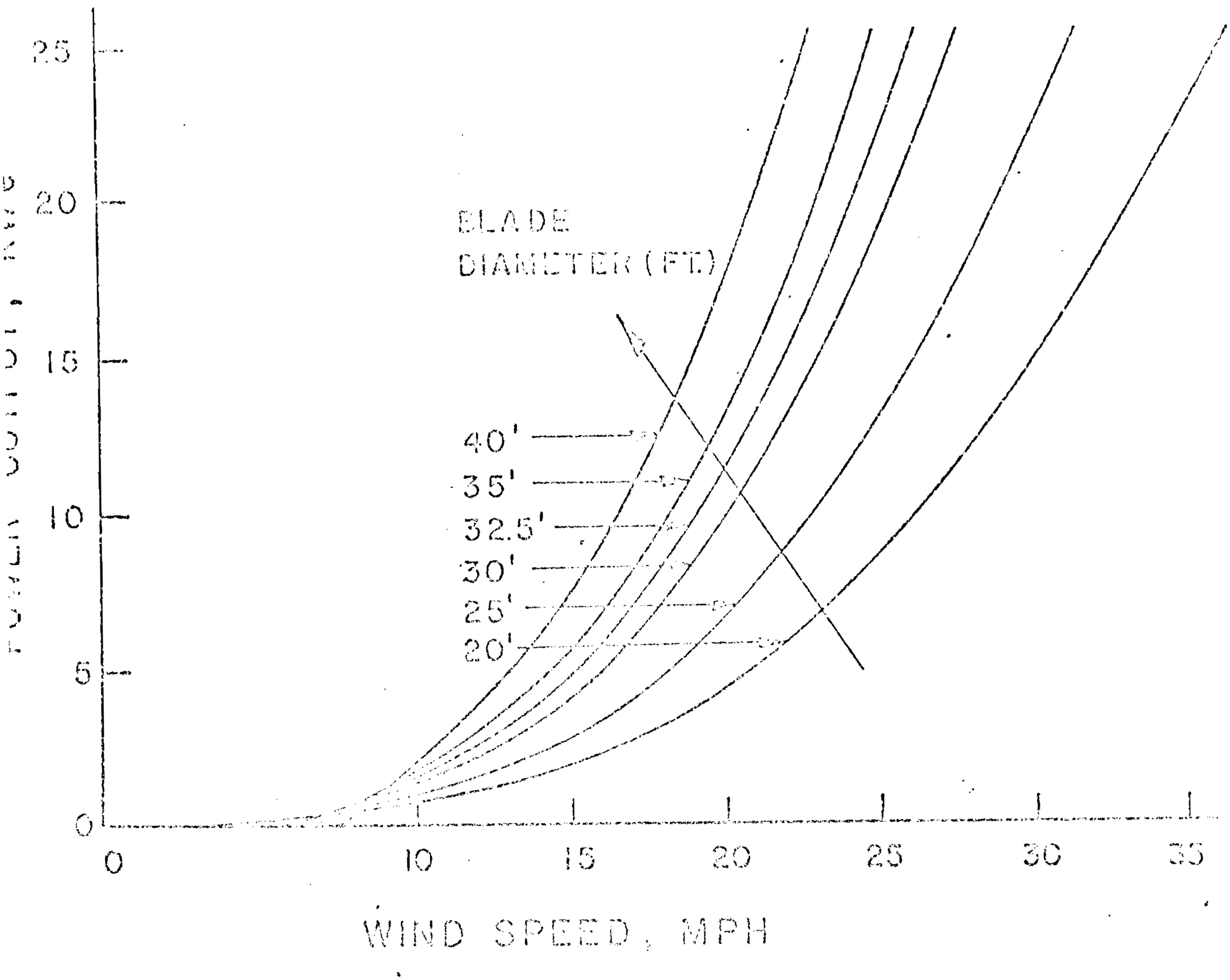


Figure 3.1. Wind Generator Performance Curves.

wind speed for the various blade diameters. These curves were generated using three analytical programs which considered blade element theory and the wind generator, and are the result of previous investigations at the University of Massachusetts [13].

To convert the wind data from its 10 meter reference height to the wind tower height of 60 ft., Hellman's relation, which follows, was employed.

$$V_T = V_{10} [0.2337 + 0.656 \log_{10}(HT + 4.75)] \qquad (3.1)$$

where V_T is the wind speed at the tower height, V_{10} is the wind speed at 10 meters and HT is the tower height in meters.

3.2 The High Temperature Thermal Storage Subsystem

The High Temperature Thermal Storage (HTS) subsystem is the key element in both WDTES systems. By virtue of its capacity, one is able to control the distribution of energy to the various energy loads. The optimum sized HTS is crucial to the Wind Driven Total Energy Systems. An HTS which is too large will maintain a lower temperature, thus decreasing Rankine Cycle efficiency, while an HTS that is too small will exhibit wild temperature fluctuations, inhibiting the performance of the Rankine Cycle turbine. The HTS used in the WDTES Model is similar to the heat storage unit in the "Therm-Bank" water heater developed by Comstock & Wescott, Inc. [14], shown in Figure 3.2. The HTS, whose optimum size will be calculated in Chapters V and VI, consists of a non-corrosive steel containment tank of cylindrical shape and of minimum surface area, a hot water coil, a resistance

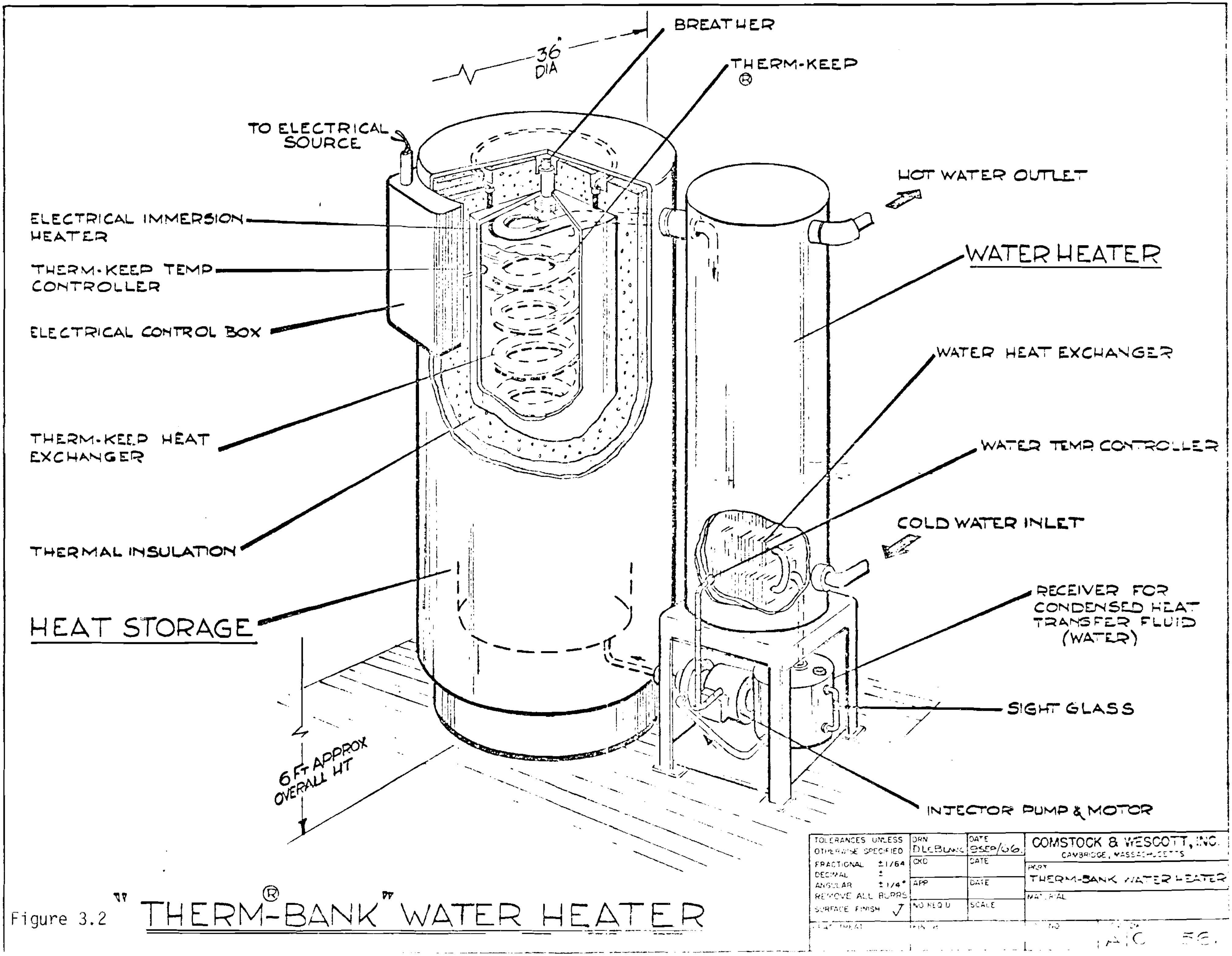


Figure 3.2 "THERM®-BANK" WATER HEATER

heater for electrical energy input from the wind turbine generator, 1.5 ft. of glass wool insulation (k=.022 Btu/hr ft °F) and a sodium hydroxide (NaOH) storage medium.

Sodium hydroxide was chosen as a storage medium for three reasons. First, it can be used to store energy up to a relatively high temperature (900°F) and can be cooled and reheated without chemically breaking down. Second, by virtue of its fairly high specific heat (C_p = .4157 Btu/lbm°R up to 560°F, C_p = .575 Btu/lbm°R from 560°F to 600°F, and C_p = .500 from 600°F to 900°F) and its two large latent heat phase changes, a solid to solid phase change at 560°F which liberates 67 Btu/lbm and a solid to liquid phase change at 600°F which releases 70 Btu/lbm, it is capable of storing large amounts of energy at high temperature [15]. This is graphically displayed in the temperature enthalpy graph, Figure 3.3. (Note that since NaOH is incompressible $\Delta H = \Delta U$.) Since the phase changes are at a high temperature, if the proper Rankine Cycle working fluid is selected, a high Rankine Cycle efficiency is possible due to the ample temperature difference between the high and low temperature thermal storage materials. Finally, of great importance, are the possible effects of stratification in the HTS [16]. As shown in Figure 3.2, the Rankine Cycle working fluid inlet is at the bottom of the HTS. This, along with density changes in the storage material and its latent heat, causes a wide temperature stratification in the HTS. At the inlet and through the first section of the heat exchanger, the working fluid is preheated by the portion of the tank which is at the lowest temperature. As the working fluid travels up the heat exchanger, a continually decreasing amount of heat

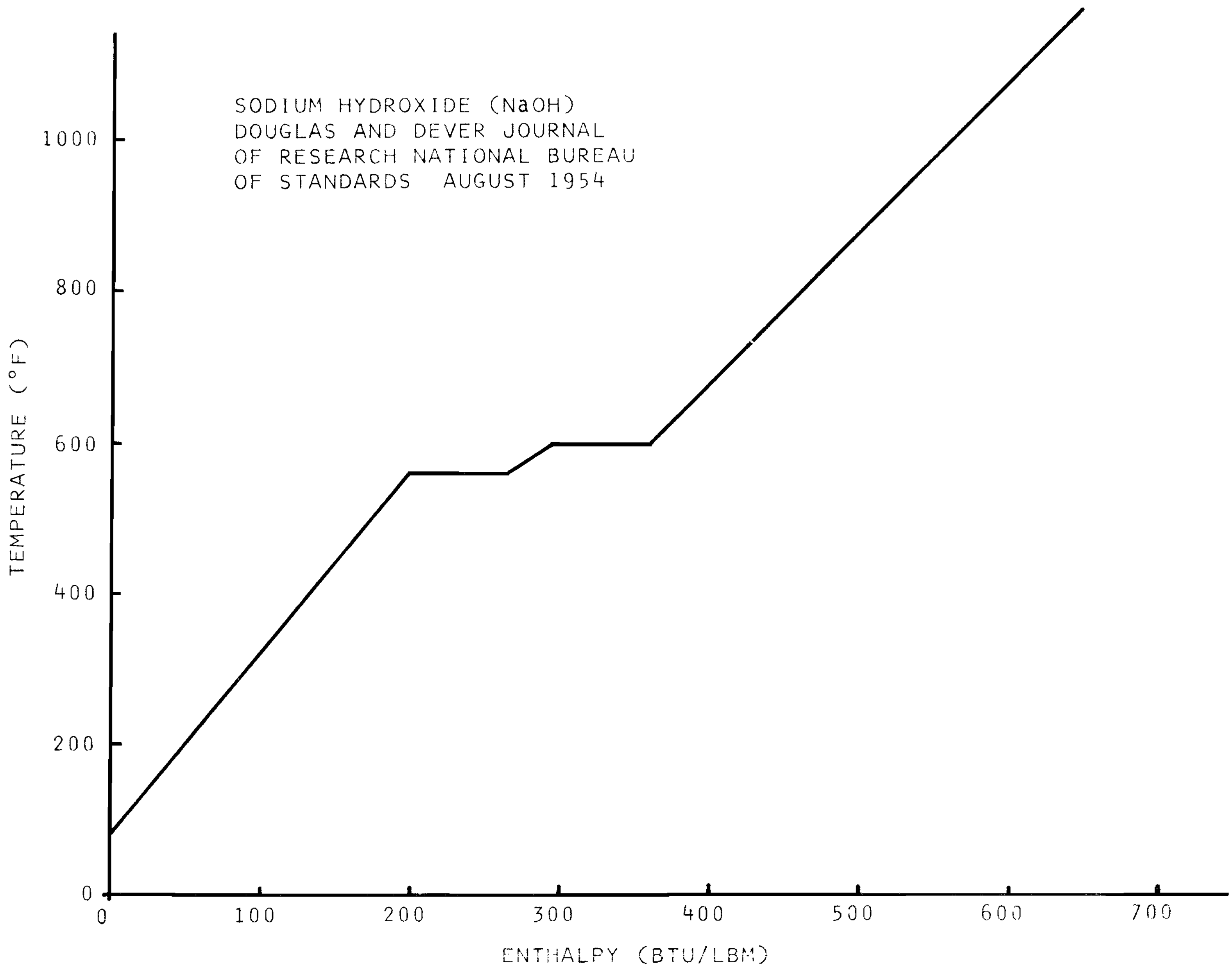


FIGURE 3.3. TEMPERATURE-ENTHALPY DIAGRAM FOR SODIUM HYDROXIDE

is transferred to it per unit length due to the decreasing temperature difference between the NaOH and the working fluid. Also, as the tank discharges, a phase front forms which moves vertically up the tank. This has the effect of insuring that the top section of the tank will remain at a high temperature for long periods of time, and in turn, will insure that the working fluid outlet temperature and the Rankine Cycle efficiency are high.

Results from a detailed computer simulation [16] showing the combination of high fluid outlet temperature and high thermodynamic availability are shown in Figures 3.4 and 3.5 [16], for a 100 and 250 gallon HTS respectively. Also shown is the comparison of fluid outlet temperatures for the well mixed and stratified models as a function of time in Figure 3.6. For this analysis, a strip method was used to simulate differential volumes of storage material which yielded energy to the working fluid through a thin walled heat exchanger of finite surface area. The two phase changes were considered as one at 600°F and heat balances were performed on the differential volumes of storage material and the working fluid. Also, heat conduction in the vertical direction was considered. Heat losses from the HTS, the effects of natural convection, and the vaporization of the working fluid were effects that were neglected in that simulation [16].

Although the effects of stratification are quite important, they were not considered in this preliminary investigation of these systems due to the prohibitively large amounts of computer time for such as simulation, and the fact that a more detailed analysis of the Rankine Cycle subsystem would have been required. Instead, a well-mixed model,

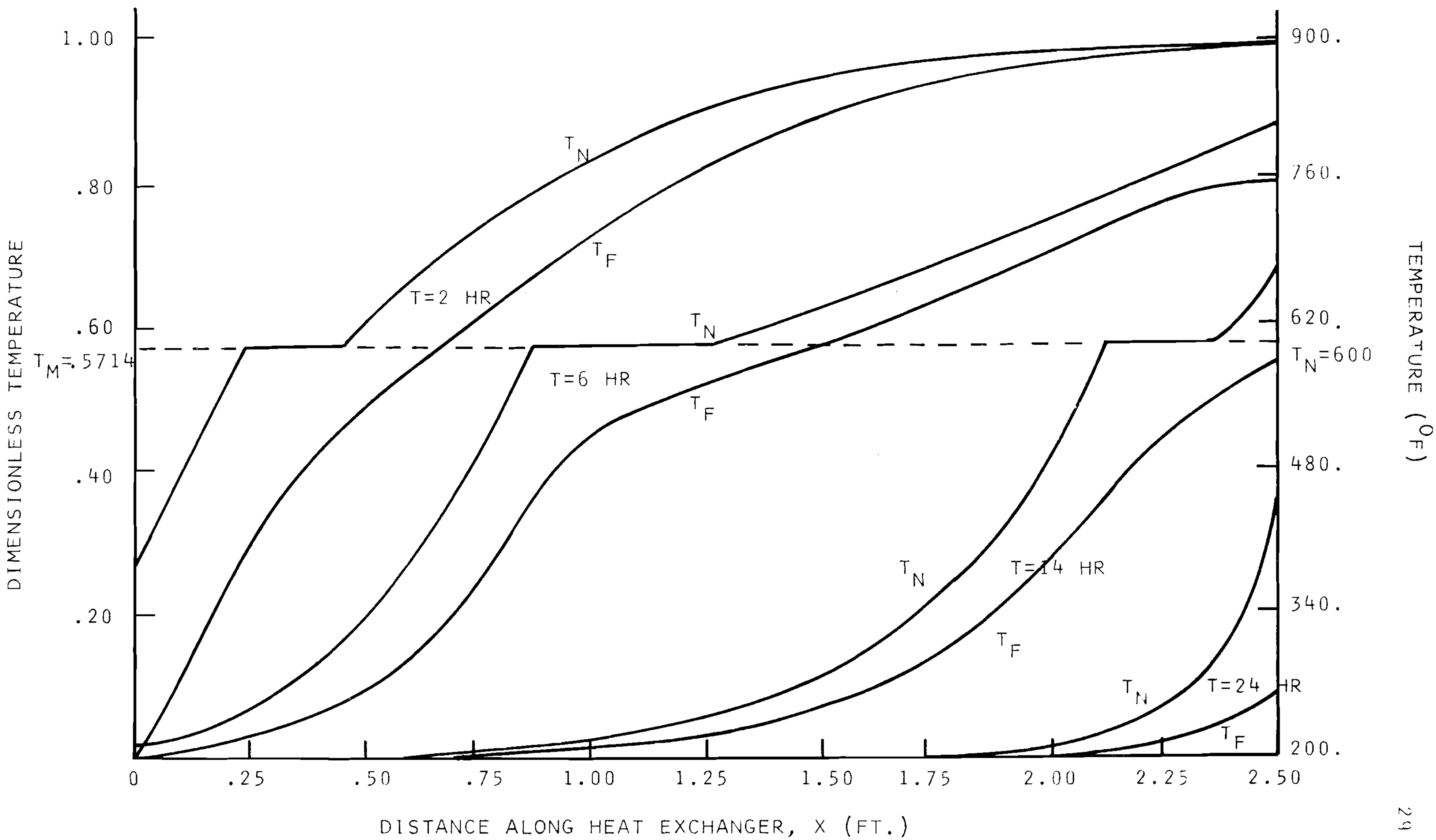


FIGURE 3.4. STORAGE MATERIAL TEMPERATURE, T_N, AND WORKING FLUID TEMPERATURE, T_F, AS A FUNCTION OF HEAT EXCHANGER DISTANCE FOR 100 GAL. HTS.

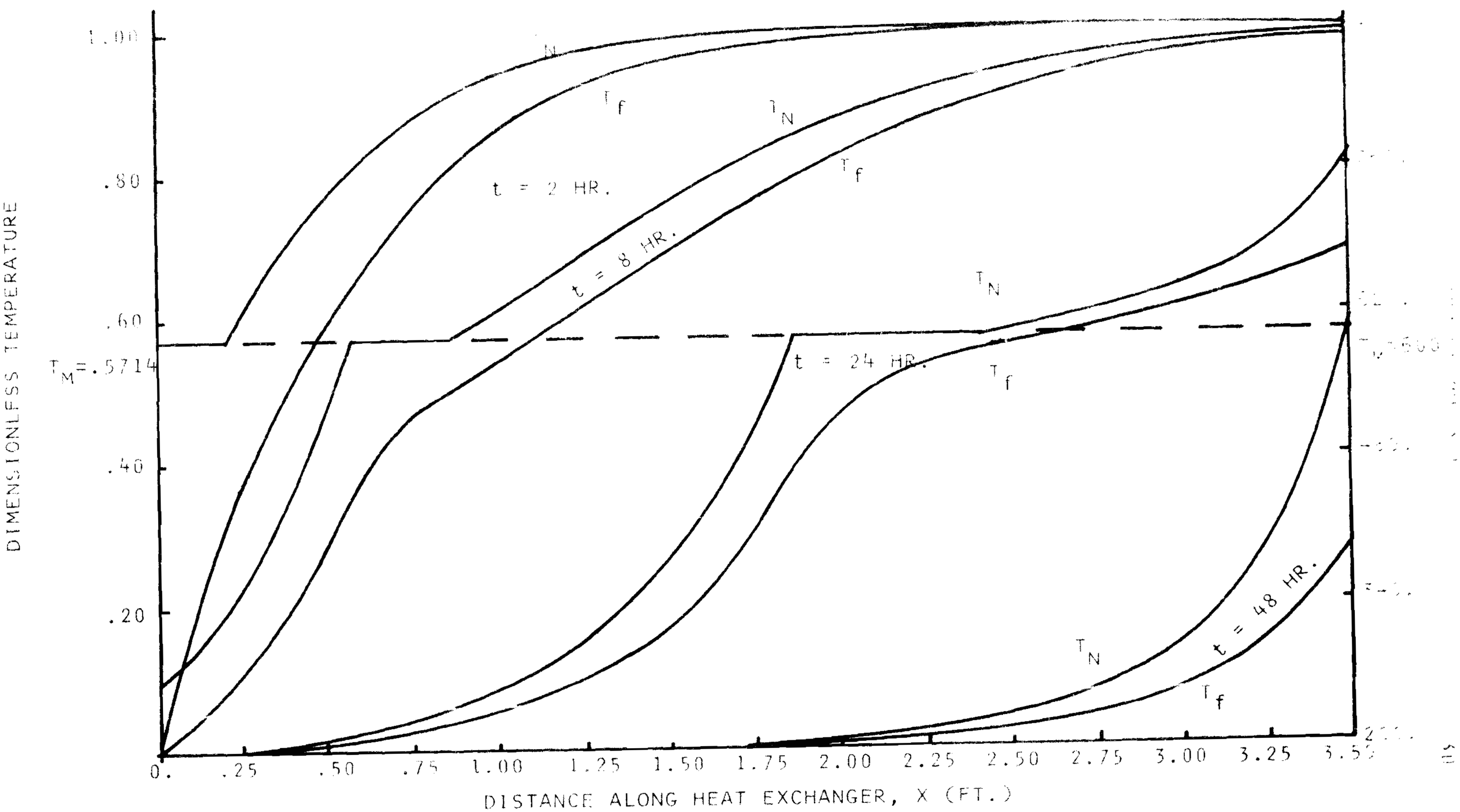


FIGURE 3.5. STORAGE MATERIAL TEMPERATURE, T_N, AND WORKING FLUID TEMPERATURE, T_f, AS A FUNCTION OF HEAT EXCHANGER DISTANCE FOR 250 GAL. TANK.

which represents the most conservative case, was used. In this model, heat transferred to the working fluid is released by the tank as a whole and thus, the internal energy of the whole tank decreases by this amount and follows the temperature-enthalpy plot in Figure 3.3. A comparison between the well-mixed and stratified models is shown graphically in Figure 3.6. It can be inferred from this figure that for a discharge time of up to 12 hours that the 100 gallon stratified tank will allow an outlet temperature equal to or greater than the 250 gallon well-mixed tank.

In the HTS model, the hot side heat exchanger for the Rankine Cycle is assumed to have a 50°F temperature difference across it. The domestic hot water coil is assumed to be a controlled heat exchanger which allows the water to rise to the hot water delivery temperature of 140°F if the storage material is at 140°F or greater, and to the storage temperature if it is less than 140°F.

The energy balance on a control volume around the tank follows and is based on the schematic shown in Figure 3.7. The energy stored in the tank per unit time, $\frac{dE_{HTS}}{dt}$, is given by:

$$\frac{dE_{HTS}}{dt} = \dot{W}_{ADD} - \dot{Q}_{H} - \dot{Q}_{HW} - \dot{Q}_{HTSHL} - \dot{Q}_{NTHL} - \dot{Q}_{LB} \qquad (3.2)$$

where $\dot{W}_{ADD}$ is the electrical power intput from the wind turbine generator, $\dot{Q}_H$ is the rate of energy added to the working fluid, $\dot{Q}_{HW}$ is the rate of energy given up to the hot water load, $\dot{Q}_{HTSHL}$ is the rate of energy lost by the HTS which contributes to the home heating load, $\dot{Q}_{NTHL}$ is the rate of energy lost by the HTS that occurs when space heating is not required (this contributes to the cooling load) and

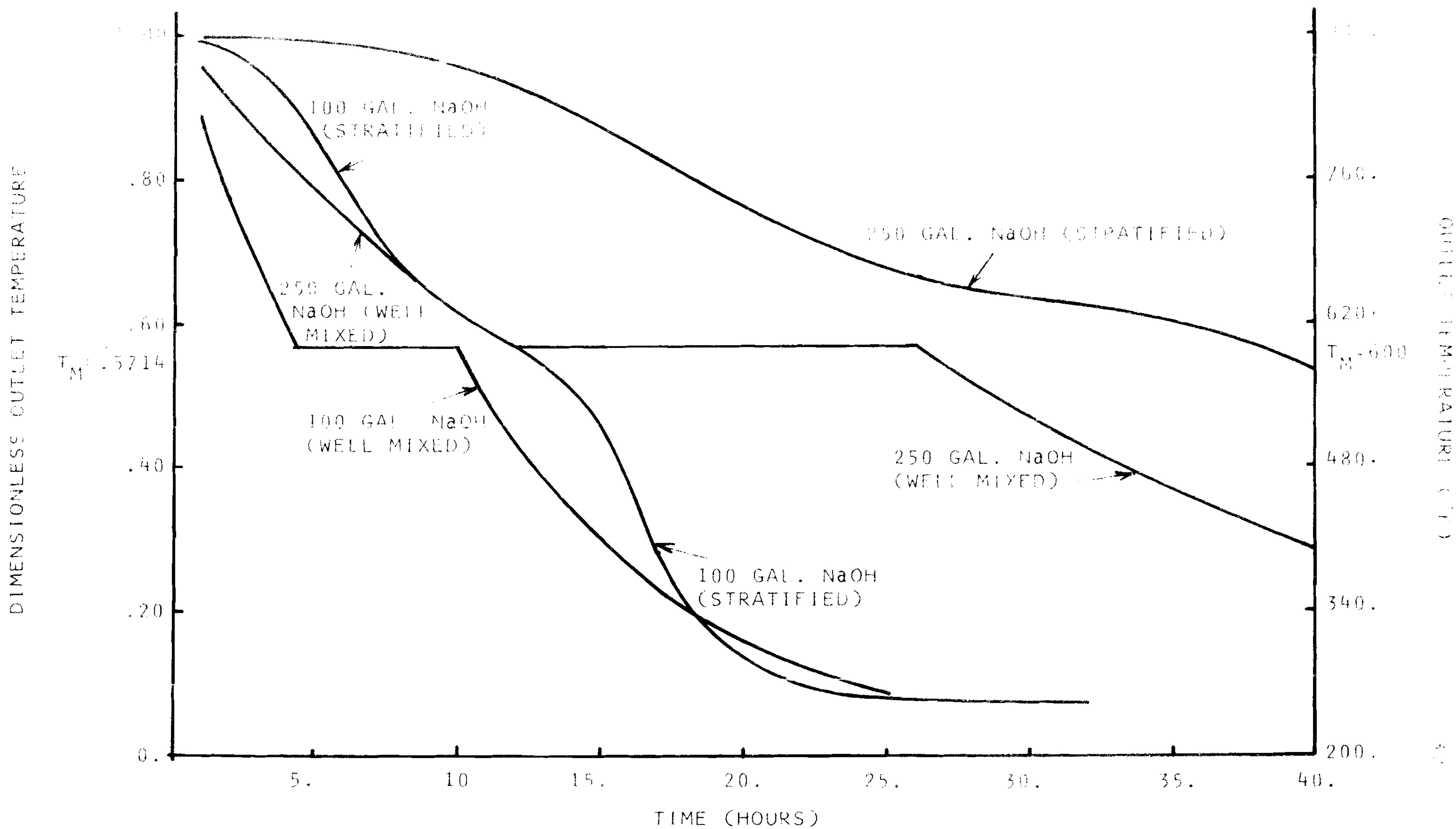


FIGURE 3.6. WORKING FLUID OUTLET TEMPERATURE AS A FUNCTION OF TIME FOR THE WELL-MIXED AND STRATIFIED MODELS.

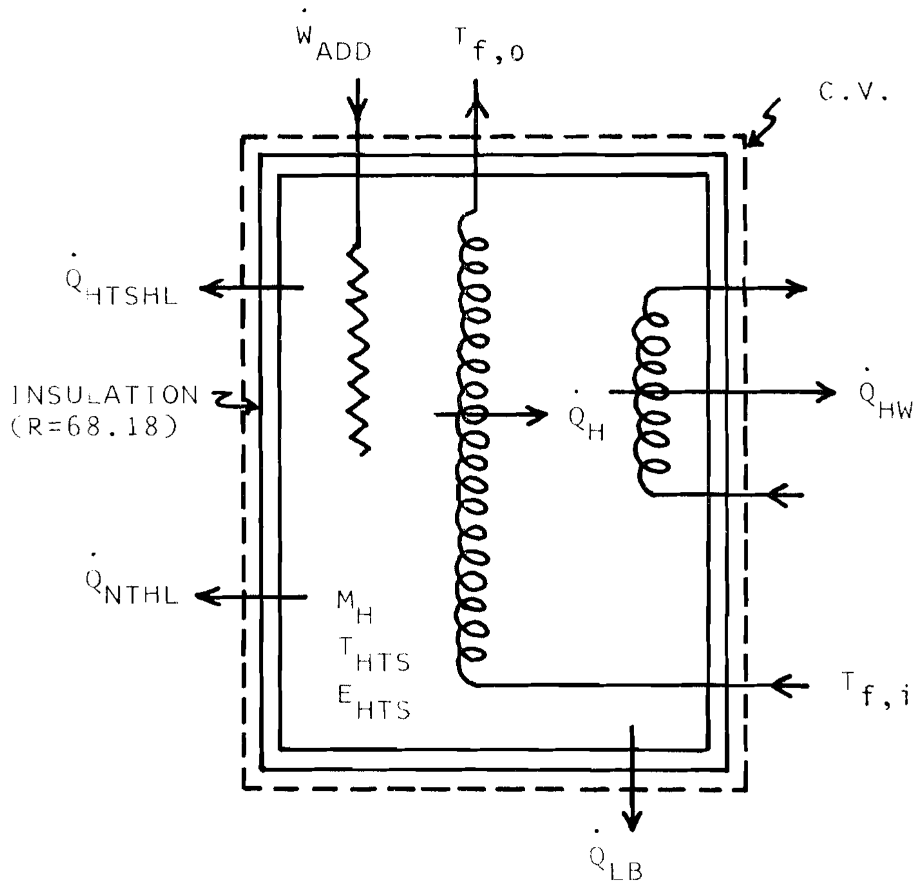


FIGURE 3.7. CONTROL VOLUME FOR THE HTS

$\dot{Q}_{TB}$ is the rate of energy lost by the HTS through the floor to the ground. $\dot{Q}_{HTSHL}$ is calculated using the equation:

$$\dot{Q}_{HTSHL} = U_{LW}\, AWI\, (T_{HTS} - T_B) + U_{LT}\, A_T\, (T_{HTS} - T_B) \qquad (3.3)$$

where Awi is the wall surface area of the HTS, U_{LW} is the overall heat transfer coefficient for the walls, T_{HTS} is the temperature of the storage medium and T_B is the temperature of the surroundings. U_{LT} is the overall heat transfer coefficient for the top of the tank, and A_T is the area of the top of the tank. U_{LW} is calculated using the equation:

$$U_{LW} = \left[\frac{R_i\, LN(R_o/R_i)}{k_{ins}} + \frac{R_i}{R_o(h_o)}\right]^{-1} \qquad (3.4)$$

where R_i is the inside radius of the HTS, R_o is the radius to the edge of the insulation, k_{ins} is the thermal conductivity of the insulation and h_o is the outside convective heat transfer coefficient. The term h_o was calculated using the following equation from Holman [17]:

$$h_o = 0.19\,(T_W - T_B)^{1/3} \qquad (3.5)$$

where h_o has units of Btu/hr ft^3 °F, T_W is the temperature at the surface of the insulation in °F and T_B is the temperature of the surroundings in °F.

U_{LT} is found by using the equation:

$$U_{LT} = \left[\frac{X_{ins}}{k_{ins}} + \frac{1}{h_{ot}}\right]^{-1} \qquad (3.6)$$

where X_{ins} is the thickness of the insulation and h_{ot} is the outside convection heat transfer coefficient for the top of the tank and is given by the equation also from Holman [17]:

$$h_{ot} = 0.22 \ (T_T - T_B)^{1/3} \tag{3.7}$$

where h_{ot} has units of Btu/hr ft °F and T_T is the temperature at the surface of the top insulation and has units of °F.

Q_{NTHL} is calculated in the same manner as Q_{HTSHL}, but occurs only when the home heating load is zero. Q_{LB} is found by using the equation:

$$Q_{LB} = \left(\frac{k_{ins}}{X_{ins}}\right) A_B \ (T_{HTSI} - T_B) \tag{3.8}$$

where A_B is the surface area of the bottom of the tank.

The computerized analytical model for the HTS is presented in Chapter IV.

3.3 The Low Temperature Thermal Storage Subsystem

The Low Temperature Thermal Storage (LTS) Subsystem is as important to the performance of the IWFS as the HTS is to the two WTDES schemes. However, the effects of varying its size in the WDTES model is minimal and thus, its size was considered a key variable only to the IWFS model. In the WDTES model, the LTS acts mainly as an energy sink for the Rankine Cycle and an energy storage and delivery system for the space heating load. For the IWFS scheme, the LTS is the storage and distribution system for all the energy inputs and outputs of the system, except the electrical load.

In the WDTES scheme, the LTS subsystem, into which heat is rejected from the Rankine Cycle, is made up of a steel containment tank of cylindrical shape and minimum surface area, 1 ft. of glass wool insulation and a resistance heater, which is coupled to the controller and switching logic. Also included in this subsystem is the sensible thermal energy storage medium, water, and the necessary tubing to allow the delivery of the storage medium to the baseboards of the home for heating. In the IWFS model, the LTS subsystem consists of a steel containment tank of cylindrical shape and minimum surface area with 1 ft. of glass wool insulation, a resistance heater through which excess energy from the wind turbine generator is supplied to the tank, a hot water coil for the delivery of heat to the domestic hot water load, and tubing to allow the delivery of the water storage to the baseboards of the home.

With the WDTES simulation, the storage tank capacity was assumed to be 2000 gallons (16,076 lbm @200°F), or 7 ft. in diameter and 7 ft. in height, since it was found that the effect of increasing this size had marginally advantageous effects on the systems energy efficiency. For the IWFS model, the size of the LTS was varied to find the optimum size based on minimum total system costs of maximum system energy efficiency. In both models, the stratification effects were neglected since it was assumed that pumping the working fluid through the baseboards would cause the tank to become well mixed.

The control volume for the LTS, using the WDTES model, is shown in Figure 3.8. The energy stored in the LTS per unit time, $\frac{dE_{LTS}}{dt}$, is given by

$$\frac{dE_{LTS}}{dt} = \dot{W}_{ADDL} + \dot{Q}_L - \dot{Q}_{ACHX} - \dot{Q}_{L3L} - \dot{Q}_{LTSHL} - \dot{Q}_{LNTHL} - \dot{Q}_{FLTS} \quad (3.9)$$

where $\dot{W}_{ADDL}$ is the energy added through the resistance heater, $\dot{Q}_L$ rate of heat rejection from the Rankine Cycle, $\dot{Q}_{ACHX}$ is the rate of heat

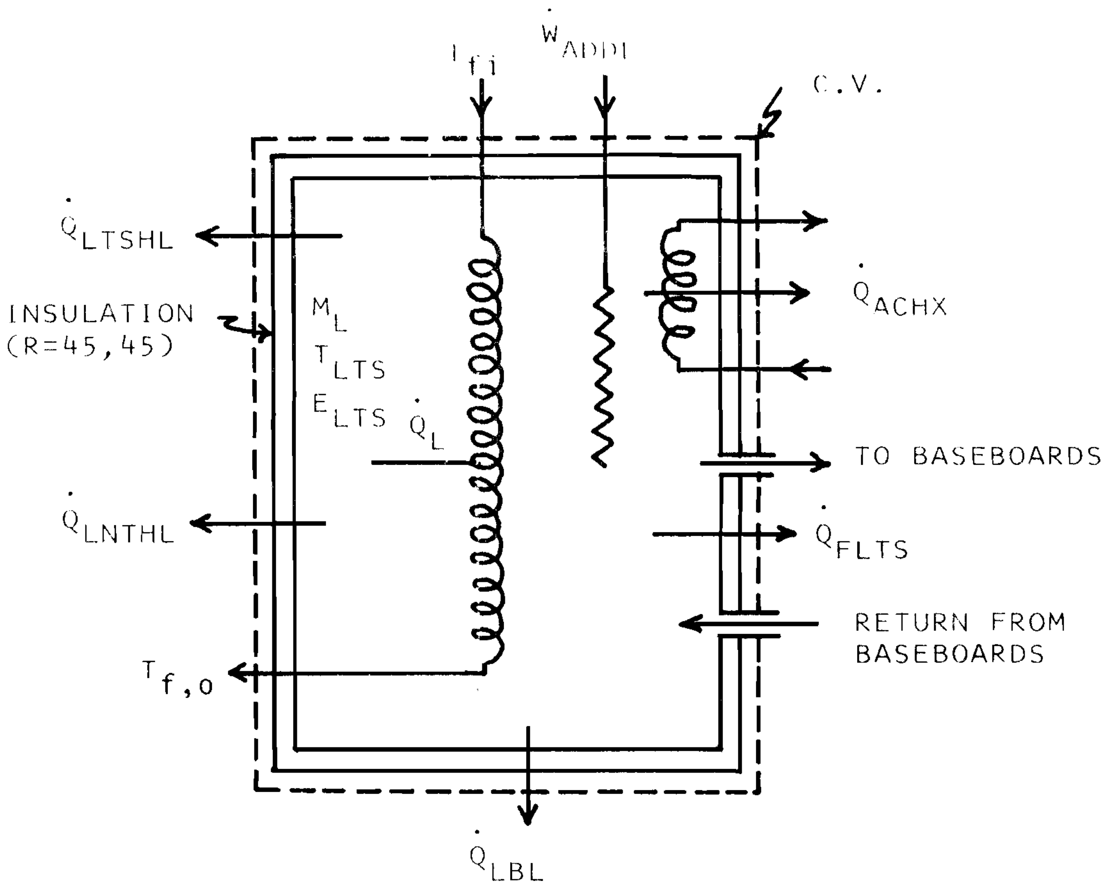


FIGURE 3.8. CONTROL VOLUME FOR THE LTS, WDTES APPLICATION.

rejected to the ambient through the air cooled heat exchanger to prevent boiling, $\dot{Q}_{LBL}$ represents the rate of heat loss through the bottom of the tank to the ground, $\dot{Q}_{LTSHL}$ is the rate of thermal loss through the walls and top of the tank to the heating load, $\dot{Q}_{LNTHL}$ represents the rate of heat loss through the tank walls and top when heating is not required for the home and $\dot{Q}_{FLTS}$ is the rate of heat transferred to the space heating load through the baseboards.

The control volume for the LTS used in the IWFS is shown in Figure 3.9. An energy balance on this control volume yields:

$$\frac{dE_{LTS}}{dt} = \dot{W}_{ADDL} - \dot{Q}_{LBL} - \dot{Q}_{LTSHL} - \dot{Q}_{LNTHL} - \dot{Q}_{FLTS} - \dot{Q}_{HW} \qquad (3.10)$$

where $\dot{Q}_{HW}$ is the rate of heat transfer to the hot water coil.

$\dot{Q}_{LTSHL}$ and $\dot{Q}_{LBL}$ were calculated in exactly the same manner as $\dot{Q}_{HTSHL}$ and $\dot{Q}_{LB}$ respectively.

3.4 The Rankine Cycle Subsystem

The ability to supply electrical energy to the electrical load when sufficient wind energy is not available is an important feature of the two WHECS schemes. Electrical energy supply is accomplished by utilizing a four or six kilowatt output Rankine Cycle Power System for the residence or farm application, respectively. Rankine Cycle Power Systems of small size have been considered and built in the past [18,19,20], and should be commercially available in the near future.

The Rankine Cycle subsystem, shown in Figure 3.10 consists of a preheater, through which the working fluid is heated to the boiling temperature, a boiler (or boiler/superheater combination), through

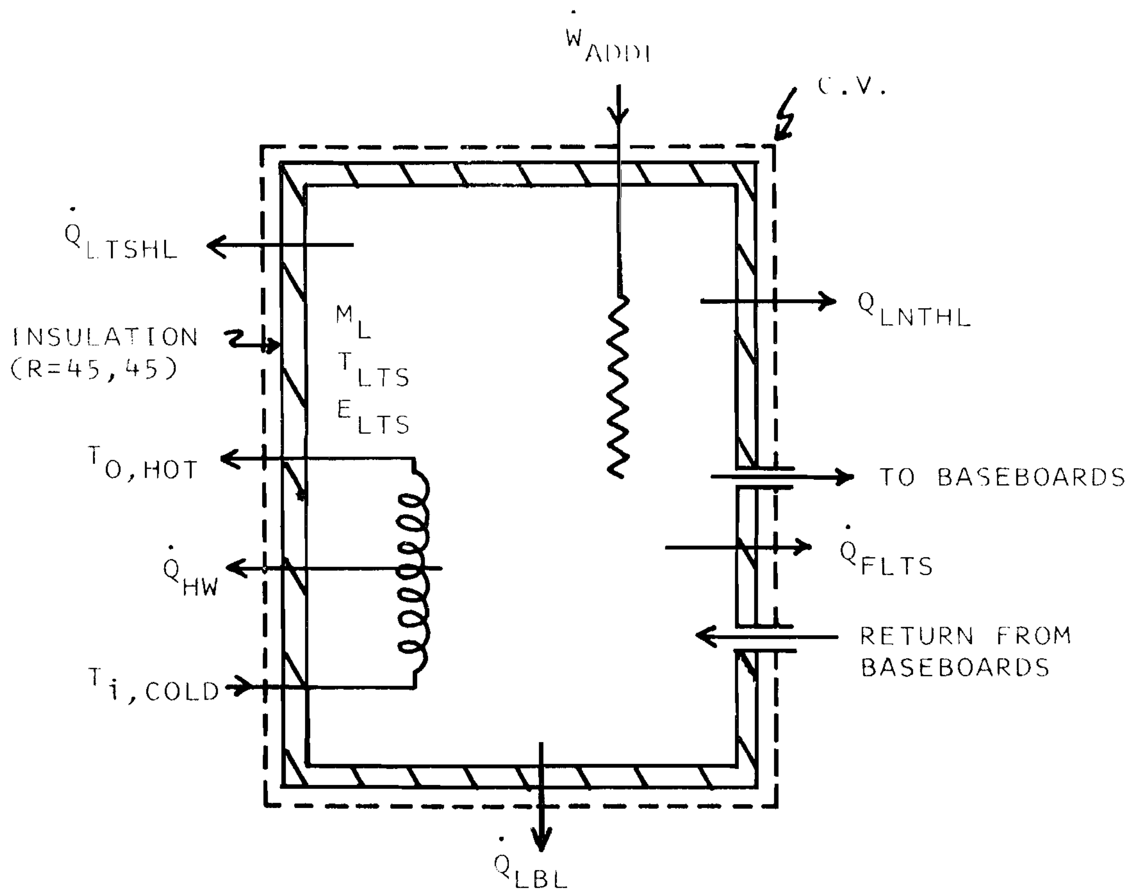


FIGURE 3.9. CONTROL VOLUME FOR THE LTS, IWFS APPLICATION

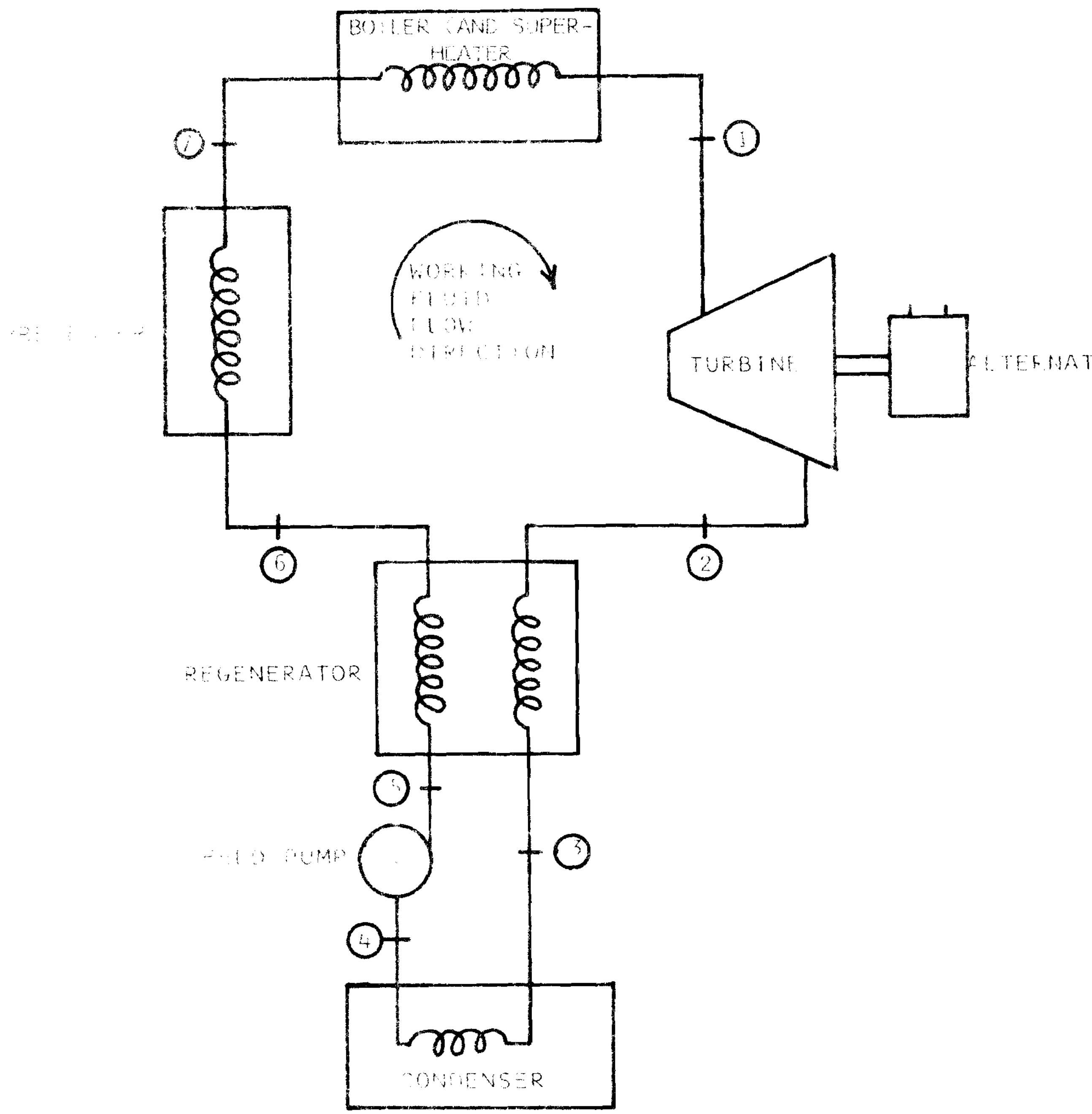


FIGURE [illegible].10. THE RANKINE CYCLE POWER SYSTEM which the working fluid is vaporized or superheated, a turbine (expander) which, due to the expansion of the working fluid produces shaft work to drive the alternator, a regenerator for the recovery of some heat which would otherwise be rejected, a condenser which rejects heat to the LTS, and a small feed pump.

A temperature - entropy diagram for the cycle using toluene as a working fluid is shown as Figure 3.11. The state points shown on the diagram also represent the state points superimposed on Figure 3.10. The superheat option is shown by the dashed lines. If the maximum working fluid temperature for the cycle is above 550°F, it is advantageous to slightly decrease the boiler operating pressure (and the boiler temperature) and then to superheat the working fluid to state 1', the maximum working fluid temperature, before expansion in the turbine to state 2'. This has the effect of slightly increasing cycle efficiency at maximum fluid temperatures of about 550°F, and this increased efficiency becomes more significant with higher maximum working fluid temperatures.

Toluene ($CH_3C_6H_5$) which is a "drying" fluid as shown by the positive slope of its saturated vapor line, was chosen as the Rankine Cycle working fluid for various reasons. First, Rankine Cycle efficiency using toluene as a working fluid is high, provided that a regenerator is used to take advantage of the waste superheat after expansion in the turbine. This high Rankine Cycle efficiency is important to the system to maintain high HTS availability. As shown by Miller [21], toluene, which has maximum and minimum use temperatures of 750°F and

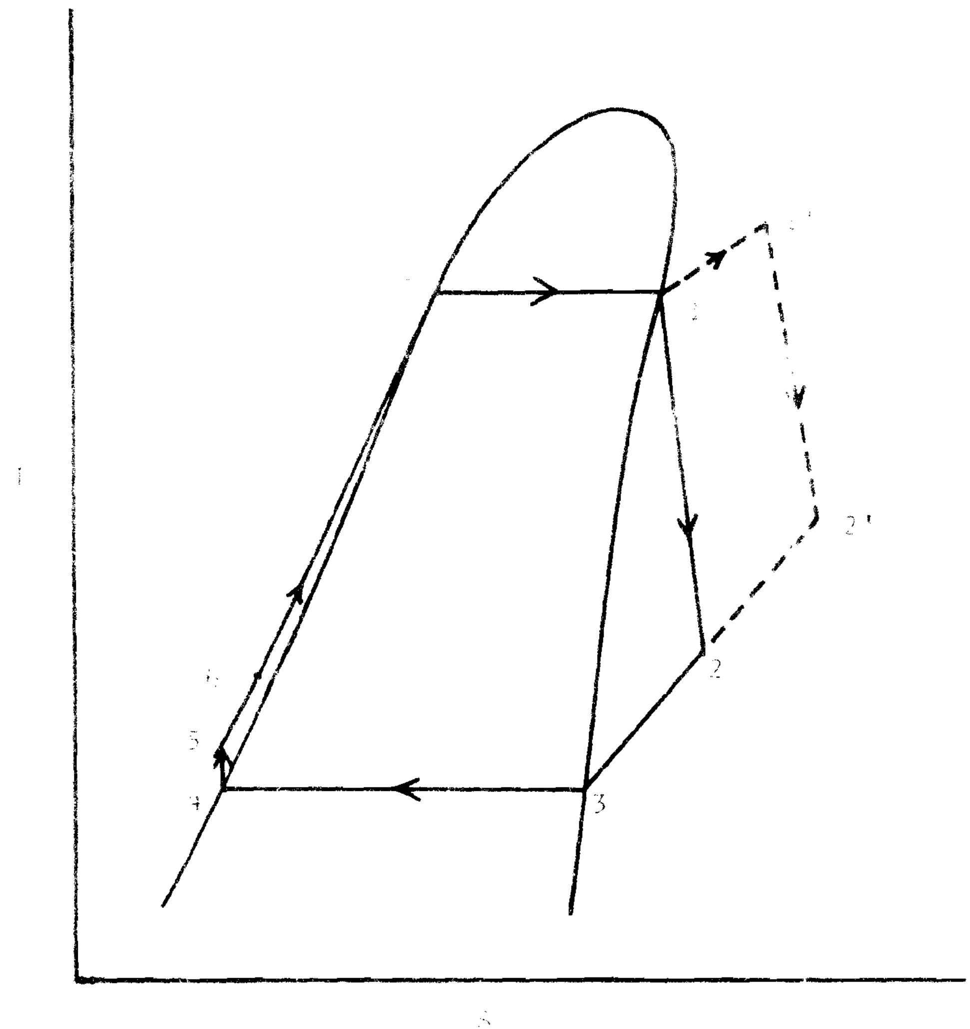


FIGURE 3.11. TEMPERATURE-ENTROPY DIAGRAM FOR A REGENERATIVE RANKINE CYCLE WITH TOLUENE AS A WORKING FLUID.

-139°F, respectively, offers a high Rankine Cycle efficiency over the range of temperatures to be used in the WDTES System. This is in part due to the high turbine efficiency possible (expansion through the turbine results in the working fluid at a superheated state, and not in the two phase region as with a "wetting" fluid, where moisture droplets decrease turbine efficiency.) The only other working fluid considered by Miller [21] that has approximately the same high efficiency over this temperature range is benzene, which has recently been called a carcinogenic material by the Environmental Protection Agency. Finally, toluene is also a common industrial solvent and therefore has the advantage of being readily available and having its characteristics well documented [22].

In the WDTES scheme, the temperature of both the HTS and the LTS may vary widely with time, therefore, the thermodynamic state of the working fluid in all the components of the Rankine Cycle is also a variable in time. For this reason, an in depth investigation of the off-design performance of specific Rankine Cycle components is important for the detailed analysis of the Rankine Cycle subsystem. Since the main thrust of this work was the preliminary investigation of IWFS and WDTES schemes, a more detailed, off-design analysis of the Rankine Cycle was not used. Instead, a shorter and more readily available method of Rankine Cycle analysis was adopted for use. Program Cycle, an interactive, digital computer program, developed at Sandia Laboratories [23] and written in Fortran was used to perform a series of steady state analyses of the Rankine Cycle model. The use of this program requires the input of eight working fluid properties, Rankine [illegible] component efficiencies and the maximum and minimum working fluid temperatures (also pressures at superheating) for the cycle being considered. Although the output from the program includes a large amount of information on the characteristics and state points of the various components in the steady state model, only the thermal efficiency of the cycle was used for this study.

Since the temperature difference between the working fluid in the two heat exchangers and the storage material in their respective thermal energy storage tanks was not known, an assumption of 50°F less than the storage material temperature in the HTS and 25°F greater than the LTS storage tank temperature was made for the temperature of the working fluid at the heat exchanger outlets. Component efficiencies were assumed to be as follows:

Combined alternator/generator efficiency	=	.95
Turbine efficiency	=	.8
Regenerator efficiency	=	.8
Nozzle efficiency	=	.95
Pump efficiency	=	.5

In off-design operation, the efficiencies of these components (especially the turbine) would be affected by the variation of the storage tank temperatures. However, for this analysis, these values were assumed constant.

With these assumptions, Program Cycle could now be utilized to obtain a series of curves of maximum Rankine Cycle efficiency (assuming the previous component efficiencies) as a function of maximum working fluid temperature (T_{H1}) for a series of minimum working fluid temperatures

(T_{LO}). This is shown, for tolulene, in Figure 3.12. These curves were produced by varying T_{HI} and T_{LO} and also the boiler pressure (for superheat only) to obtain values of maximum cycle efficiency. These curves were fitted for use with WDTES1, by an eighth order polynomial along lines of constant T_{LO}, so that linear interpolations for intermediate values of T_{LO} could be made accurately.

Since Rankine Cycle efficiency is now known for all possible storage tank temperature combinations, for a given required electrical energy output from the Rankine Cycle, W_{REQ}, the rate of heat transfer required from the HTS, $\dot{Q}_H$, can be found as follows:

$$\dot{Q}_H = W_{REQ}/(\eta_{th}\eta_{AG}) \qquad (3.10)$$

where η_{th} is the thermal efficiency of the Rankine Cycle and η_{AG} is the combined alternator/generator efficiency. The rate of heat transfer to the LTS, $\dot{Q}_L$ can be found using the following equation:

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{REQ}/\eta_{AG} \qquad (3.11)$$

An attempt was made to show the effect of decreased turbine efficiency on the WDTES model by introducing the Rankine Cycle efficiency factor, RNKFCT. Since turbine inefficiency is the main source of cycle inefficiency for the Rankine Cycle, it was assumed that decreasing η_{th} by 75% would have the effect of reducing turbine efficiency by approximately 25% to 60% that would yield a range of WDTES performance that may duplicate the effects of off-design Rankine Cycle operation.

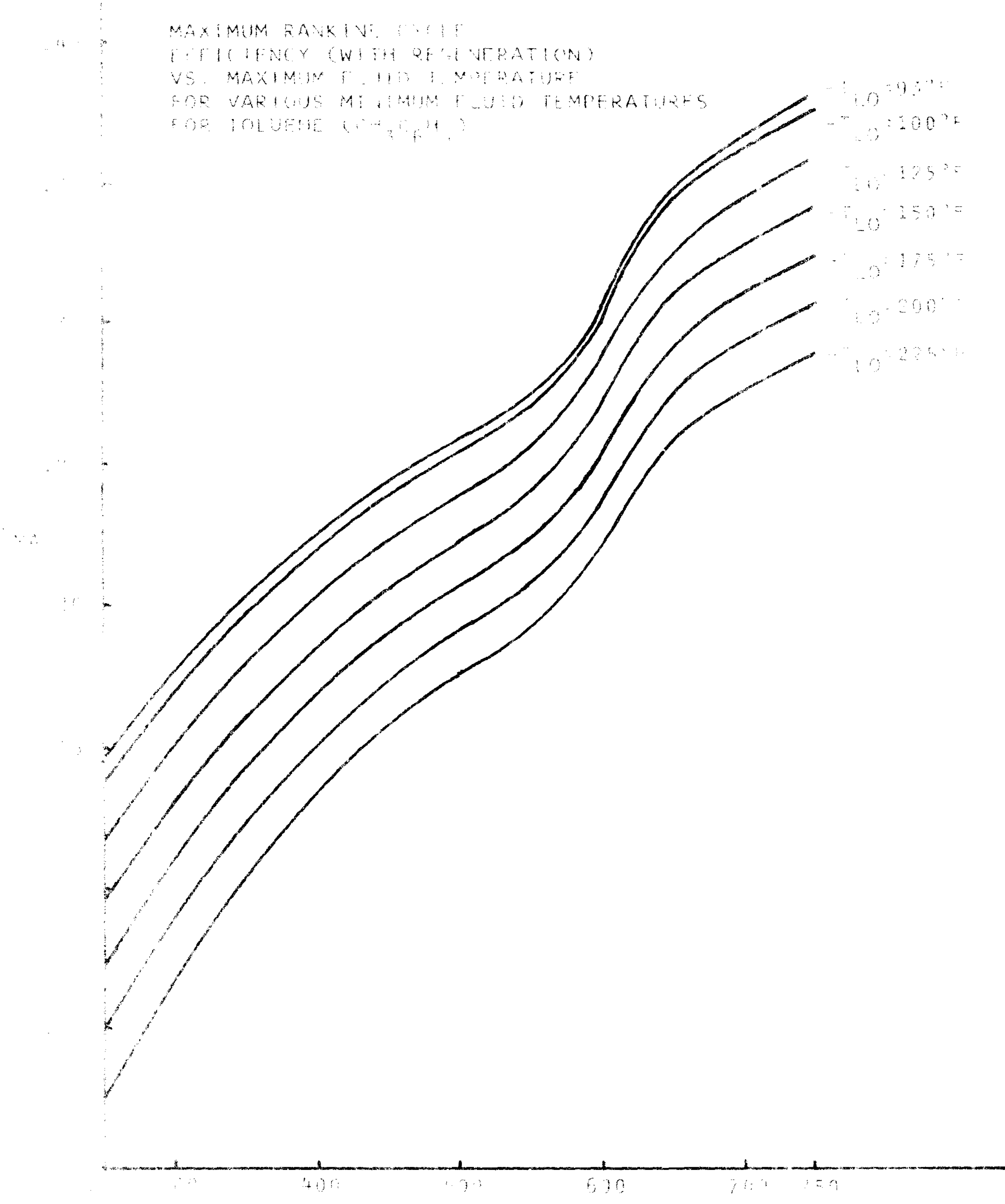


FIGURE . MAXIMUM RANKINE CYCLE EFFICIENCY (WITH REGENERATION) VS MAXIMUM WORKING FLUID TEMPERATURES FOR VARIOUS MINIMUM WORKING FLUID TEMPERATURES.

3.5 The House Model

The space heating load represents the largest single energy requirement for the systems being considered. For this reason, a detailed computer subprogram, based on ASHRAE design practice [24], developed by Darkazalli [11] for the previous wind and solar heating studies at Solar Habitat I was used for this study. Using this program, the simulated 35,383 kWL yearly heating load of Solar Habitat I represents the heating load of an average home in the New England area. Also considered in WDTES1, by modeling a house with no basement, was a 17,166 kWh yearly heating load result which is indicative of the heating load of a well-insulated home in the New England region. The monthly variations of these heating loads are shown in Figure 3.13.

A steady state energy balance on the home, which has an assumed constant residence temperature of 68°F, is given by the equation:

$$\dot{Q}_{HL} = \dot{Q}_s + \dot{Q}_{inf} \qquad (3.12)$$

where $\dot{Q}_{HL}$ represents the space heating load of the home, $\dot{Q}_s$ is the rate of energy loss through the walls, roof, floor, windows and doors of the home and $\dot{Q}_{inf}$ represents the infiltration losses. $\dot{Q}_s$ is calculated by:

$$\dot{Q}_s = \sum_i U_i A_i \, (T_{in} - T_{out}) \qquad (3.13)$$

where U_i and A_i are the overall heat transfer coefficient and the surface area, respectively, of the i^{th} heat transfer surface, such as wall, roof, window, etc. and T_{in} and T_{out} are the inside and outside temperatures for that surface. U_i is found from equations of the form:

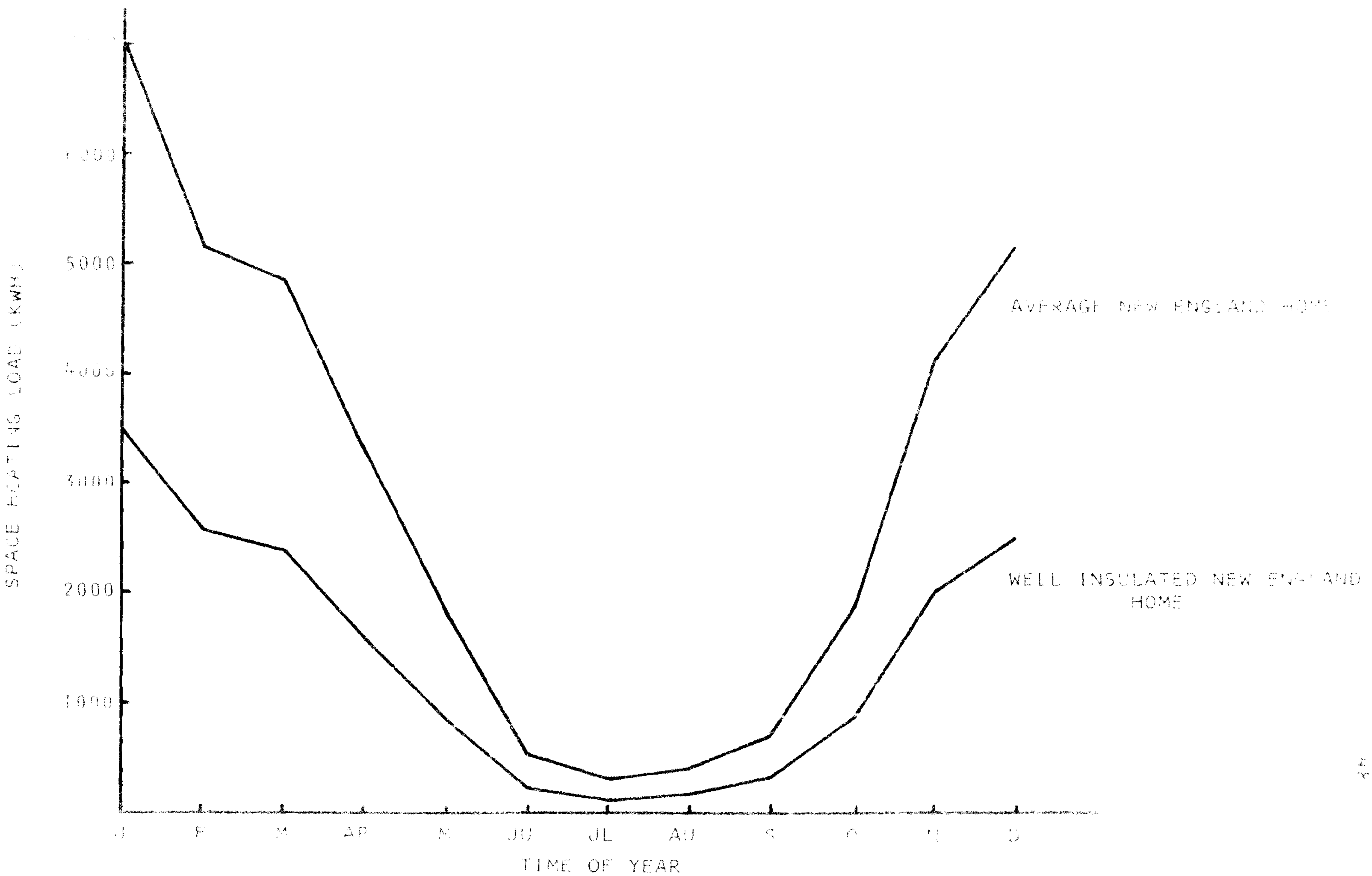


FIGURE 3.15. PLOT OF SPACE HEATING LOAD AS A FUNCTION OF TIME OF YEAR FOR AVERAGE AND WELL INSULATED NEW ENGLAND HOMES

$$U_i = \left[\frac{1}{h_o} + \frac{x}{k} + \frac{1}{h_i}\right]^{-1} \quad (3.14)$$

where h_i and h_o are the inside and outside convective heat transfer coefficients, x is the thickness and k is the thermal conductivity of the surface under consideration. Q_{inf} in Equation 3.12 is found from:

$$\dot{Q}_{inf} = \rho \, C_{air} \, V \, (T_{in} - T_{out}) \quad (3.15)$$

ρ is the density of the air and C_{air} is its specific heat, while V represents the volumetric flow rate of the air. A volumetric flow rate, recommended by ASHRAE [24], of one volume change per hour was used in the present heating load model.

Although $\dot{Q}_{HL}$ does represent the space heating load of the homes under consideration, some heat losses from the storage tanks being used and also the solar energy gain through the windows of the homes must be considered for an accurate heating load model. $\dot{Q}_{HLACT}$, which is the actual heating load for the homes that must be supplied either by the system or by auxiliary means, is given by:

$$\dot{Q}_{HLACT} = \dot{Q}_{HL} - \dot{Q}_{HTSHL} - \dot{Q}_{LTSHL} - \dot{Q}_{SOL} \quad (3.16)$$

where $\dot{Q}_{LTSHL}$ and $\dot{Q}_{HTHSL}$ are the rate of heat loss from the LTS and the HTS (with the WDTES models), respectively. $\dot{Q}_{LTSHL}$ and $\dot{Q}_{HTSHL}$ only diminish the heating load when heating is required in the home. $\dot{Q}_{sol}$ represents the rate of solar energy gain through the windows of the home and is given by the equation:

$$\dot{Q}_{sol} = q_A A_{win} (1\text{-SHADE}) \qquad (3.17)$$

where q_A is the absorbed solar energy per unit area, A_{win} is the area of the window receiving the solar energy and SHADE is the shading factor. $\dot{Q}_{sol}$, like $\dot{Q}_{HTSHL}$ and $\dot{Q}_{LTSHL}$ only decreases the heating load when the temperature indoors is higher than the ambient temperature, otherwise, these terms would add to the cooling load.

3.6 The Electrical Load Model

Two different models of the electrical load were studied for use with the WDTESI computer simulation. The first model represents a simulation of an average U.S. home electrical load and was adapted from recent work by Wolf [25]. The second model was chosen to represent an average U.S. farm electrical load and is similar to the average home electrical load. It includes a farm machinery electrical load term, to take into account the electrical energy consumption of milking machines, farm tools, etc.

The average U.S. home electrical load is based on a yearly annual electrical load of 5785 kwh as given by Wolf [25]. He also presented a hourly nominal electrical load, as shown in Table 3.1. Since the consumption of electrical energy by a residential unit in the Northeast varies seasonally from a high of 19.7 kwh/day during December and January to a low of 12.0 kwh/day during June and July, Wolf [25] proposed the following modification to calculate the actual hourly electrical energy consumption, WE:

Time (hr.)	Nominal Electrical Consumption (W_{NOM}) In Preceding Hour (kWh)
1	0.8
2	0.5
3	0.4
4	0.3
5	0.3
6	0.3
7	0.4
8	0.6
9	0.9
10	1.2
11	0.9
12	0.8
13	0.7
14	0.6
15	0.6
16	0.7
17	0.7
18	1.3
19	1.7
20	1.6
21	1.4
22	1.3
23	1.1
24	0.9
TOTAL	20.0

Table 3.1 Hourly Nominal Electrical Load for a Single Family Residence [Wolf: 1975)

$$W = W_{NOM} \left[\frac{0.985 + 0.600}{2} + \frac{0.985 - 0.600}{2} \cos \left(2\pi \frac{day}{365} \right) \right] \quad (3.18)$$

where day represents the day of year, and is measured from January 1. A slight modification of this equation was used in WDTES1 to coincide with the inputted meteorlogical data which starts on September 1. This modification of Equation 3.18 was made by substituting (day + 243) for the day term, resulting in essentially the same equation, but using September 1 as day 1. Although the highest nominal hourly electrical consumption by the average U.S. home for this model was 1.7 kWh, the instantaneous rate of electrical energy consumption can be greater than 1.7 kW. For this reason, a 4 kW size electrical energy system is provided for the residence.

The average U.S. farm electrical load was modeled by superimposing a portable electrical machinery load on the average U.S. home electrical load to make up a total yearly electrical load of 16,736 kWh [16]. This machinery load, W_{MECH}, which is given in Table 3.2, was not assumed to vary seasonally. As with the average U.S. residence, the average U.S. farm can instantaneously use more electrical energy than the 1.7 kW maximum hourly average, therefore, it was assumed that the farm must be provided with a 6 kW size electrical energy system.

The Domestic Hot Water Load Model

The domestic hot water load, which represents the smallest energy load on the systems under consideration, when compared to the electrical and space-heating loads, follows an assumed hourly load pattern shown

Time (hr.)	Electrical Consumption For Machinery (W_{MECH}) in Preceding Hour (kWh)
1	0.667
2	0.667
3	0.667
4	0.667
5	2.000
6	2.000
7	2.000
8	1.000
9	1.000
10	1.000
11	1.000
12	2.000
13	2.000
14	2.000
15	1.000
16	1.000
17	2.000
18	2.000
19	2.000
20	0.667
21	0.667
22	0.667
23	0.667
24	0.667
TOTAL	30.003

Table 3.2 Hourly Electrical Load for Machinery for an Average U.S. Farm

in Table 3.3. This distribution pattern is based on work by Mutch [3].

For the WDTES schemes, cold inlet water at 60°F from the main is supplied to a heat exchanger coil immersed in the HTS. If the outlet temperature from the coil is less than the assumed hot water supply temperature, THWR of 140°F, extra energy supplied by an auxiliary source is required to raise the temperature of the water to THWR. The heat exchanger is assumed to be controlled to allow the water temperature to reach 140°F, if the HTS tank temperature is at 140°F or greater, but does not allow it to reach a temperature greater than 140°F. This same logic is followed in the IWFS scheme, except the heat exchanger coil is immersed in the LTS.

The equation for the heat required for the domestic hot water supply, Q_{HW}, follows:

$$Q_{HW} = \rho_{water} \; H_W \; C_{PW} \; (T_{HWR}-T_{CW}) \qquad (3.19)$$

where ρ_{water} is the density of water, H_W is the amount of hot water required, shown in Table 3.3, C_{PW}, is the specific heat of water and T_{CW} is the inlet water temperature.

In the WDTES schemes, if the HTS is at a temperature lower than T_{HWR}, the auxiliary energy required to heat the water to T_{HWR} is given by the equation:

$$Q_{HWAUX} = \rho_{water} \; H_W \; C_{PW} \; (T_{HWR} - T_{HTSI}) \qquad (3.20)$$

where T_{HTSI} is the temperature of the high temperature storage material. Similarly, in the IWFS model, the auxiliary energy required is given by

Time (hr.)	Gallons of Hot Water Required
1	1.12
2	0.0
3	0.0
4	0.0
5	0.0
6	0.0
7	0.75
8	2.32
9	3.62
10	4.20
11	3.45
12	2.25
13	1.80
14	2.55
15	1.35
16	1.20
17	1.05
18	1.88
19	3.38
20	5.80
21	4.80
22	3.45
23	2.73
24	2.32
TOTAL	50.02

Table 3.3 The Hourly Domestic Hot Water Load [Mutch: 1974]

$$W_{HWAUX} = \rho_{water} H_W C_{PW} (T_{HWR} - T_{LTSI}) \qquad (3.21)$$

where T_{LTSI} is the temperature of the low temperature storage material. Since auxiliary energy is being used to raise the water temperature from the associated storage tank temperatures, the amount of energy supplied to the domestic hot water load by the HTS and LTS for the different schemes can be found by substituting T_{HTSI} for T_{HWR} in Equation 3.19 for the WDTES models, and by substituting T_{LTSI} for T_{HWR} for the IWFS model.

3.8 The Power Conditioner and the Alternator Subsystems

The conditioning of the electrical energy output from the wind turbine generator to useful single phase, 60 HZ, 120/140 volt electricity is required by the IWFS and WDTES, Type II schemes. Because the AC generator in the current design WTG produces electricity of variable frequency and voltage, a rectifier must be employed to convert this electrical energy to DC power. This rectifier can be quite inexpensive, and in fact, the unit presently in use at the University of Massachusetts for the 32.5 ft. WTG consists of only six diodes. After the conversion to DC current, the output from the rectifier must be inverted to produce the desired A.C. current for the residence or farm. Inverters in the four and six kilowatt size, as required, are presently quite expensive, but decreasing costs and increasing efficiency [9,26] are beginning to make these units practical for wind turbine generator applications.

In the WDTES Type I and Type II units, the electrical energy produced by the alternator connected to the constant speed turbine of the Rankine Cycle is of constant voltage and 60 Hz frequency. For this reason, a rectifier and inverter system is not required.

CHAPTER IV

MAIN PROGRAM ANALYTICAL MODELS

Digital computer simulation is an integral part in the analysis of the WDTES or IWFS models' performance characteristics. These systems, due to their ever changing imposed loads, energy inputs and modes of operation, also require that this simulation be rather lengthy. For this reason, the main thrust of this chapter is devoted to the description of the logic required in the analyses of the various subsystems, while the detailed program is included, line by line, in Appendix B.

The computer model, WDTES1, which is general enough to simulate both of the WDTES models and the IWFS model, consists of the main program and the subprograms which follow: 1) the main program, which, through its interactive input format allows the user to input the system desired, start up conditions, component sizes, and the output format. The main program is also responsible for the main mode of operations switching logic and the energy distribution to the various loads; 2) the data input subprogram, which comprises pertinent meteor-logical data such as solar insolation, cloud cover, wind velocity and direction, and air temperature all for specific sites; 3) the wind turbine generator subprogram that calculates the windpower output of the WTG; 4) the high temperature thermal storage subprogram (for the WDTES models), which calculates the energy stored in and the thermal losses of the HTS; 5) the electrical load subprogram which calculates either the residence or the average U.S. farm electrical load; 6) the space heating load subprogram; 7) the domestic hot water subprogram that calculates the hot water load; 8) the low temperature thermal storage subprogram that calculates the energy stored in and the thermal losses of the LTS; 9) the solar energy subprogram, that gives the solar energy gain through the windows; 10) the Rankine Cycle subprogram, which calculates the thermal efficiency of the Rankine Cycle power system and also the source and sink heat rate requirements, and finally 11) the output subprograms which provides useable system performance data in either hourly, daily or monthly format. All the subprograms which are pertinent to the system being simulated are examined hour by hour for the duration of one year's meteorlogical data.

4.1 The Main Program

The main program contains all program inputs, except meteorlogical data, and also provides the main simulation of the various operational modes and the energy distribution to the various loads of the three systems under consideration. A flow diagram of the logic used in the main program appears in Figure 4.1. Initially, the system configuration, components (and thereby the model), start up conditions and desired output must be selected. This is accomplished by means of an interactive format for time-sharing systems or by a batch format which allows the program to be submitted as a card deck. The meteorlogical data is read and corrected for the desired system configuration and the correct units. The wind turbine generator subprogram then calculates the wind energy produced by the WTG. The electric, space

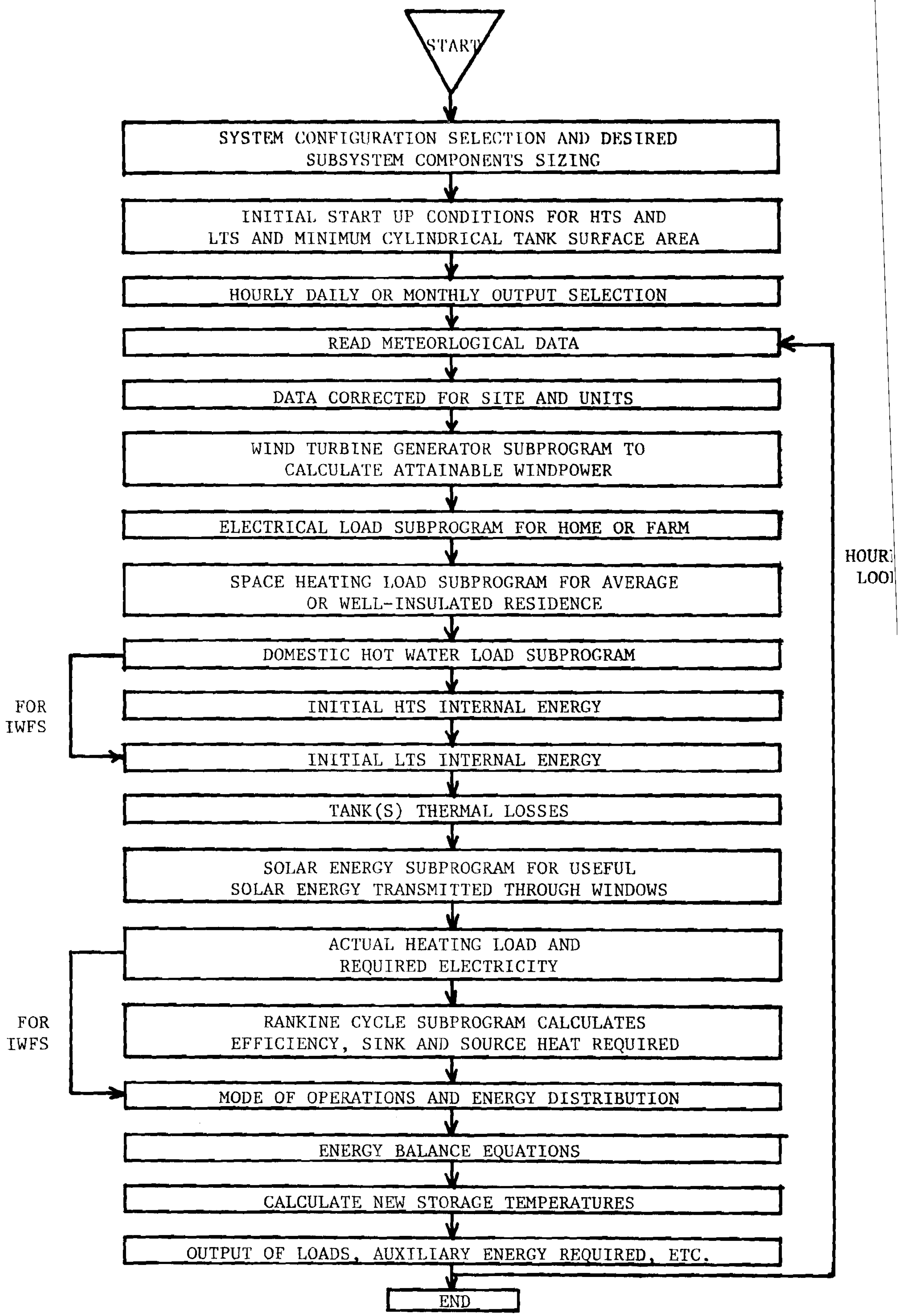


FIGURE 4.1 MAIN PROGRAM FLOW DIAGRAM

heating and domestic hot water loads are calculated using their respective subprograms. Following that, the initial high temperature thermal storage internal energy is calculated. If the WDTES models are under consideration, the calculation of the initial low temperature thermal storage internal energy follows. The thermal losses from the LTS and HTS (if the WDTES models are being used) are then calculated. The solar energy subprogram then calculates the useful solar energy gain through the windows. The actual heating load, which takes into account the useful solar energy and tank losses is calculated along with the actual electricity required, which is different than the electrical load in the WDTES schemes due to alternator efficiency. The Rankine Cycle subprogram follows for the WDTES models and calculates the thermal efficiency of the cycle, the required heat input and the required heat rejection for the amount of electrical output needed from the alternator. Next comes the mode of operations and energy distribution logic which specifies the flow of energy in the systems being considered to the various system components based on storage tank temperatures, prescribed priorities and energy requirements. This section follows the logic that is presented for each system in Chapter II and will be considered in detail in Section 11 of this chapter. An energy balance is then performed on the energy storage unit(s) and the new tank temperature(s) and internal energy is calculated. Finally, the desired outputs of loads, the auxiliary energy requirements and the energy distribution via specific modes is given in either an hourly, daily or monthly format. The control then shifts back to the meteorlogical data which is read and the calculations for the next hour are performed until the final hour of the year's duration is considered. The following sections will consider some of these subprograms in greater detail.

4.2 The Data Input Subprogram

The data input subprogram was adapted for the WDTES1 program from previous work by Darkazalli [11]. The subprogram shown in Figure 4.2 is made up of six separate data banks, each of which contains two months of meteorlogical data. Each data bank has a line for each hour of the two month period, and five pieces of information are on each line. A sample of the data is shown in Figure 4.3. The first column represents the solar insolation (SUN) on a surface tilted 60° from the horizontal and has units of Btu/ft^2 hr. The second column represents the cloud cover (NCC) and is based on a scale from 0 to 10. The third column is the wind speed (NV) in knots and the fourth is ambient temperature (NTA) in degrees Fahrenheit. The final column represents wind direction (NDW), measured in tens of degrees from due north, where 09 = east, 18 = south, 27 = west, 36 = north and 00 = calm. For the runs made, the solar insolation and the cloud cover are based on data taken hourly at Blue Hills, Mass. in 1958 and the wind speed, wind direction and air temperature were recorded once every three hours at Bradley International Airport, Conn. in 1971. These data banks are read by the program one line at a time and stored in a two dimensional array as a function of NHR, the hour of the day, and NDAY, the day of the two month data bank interval.

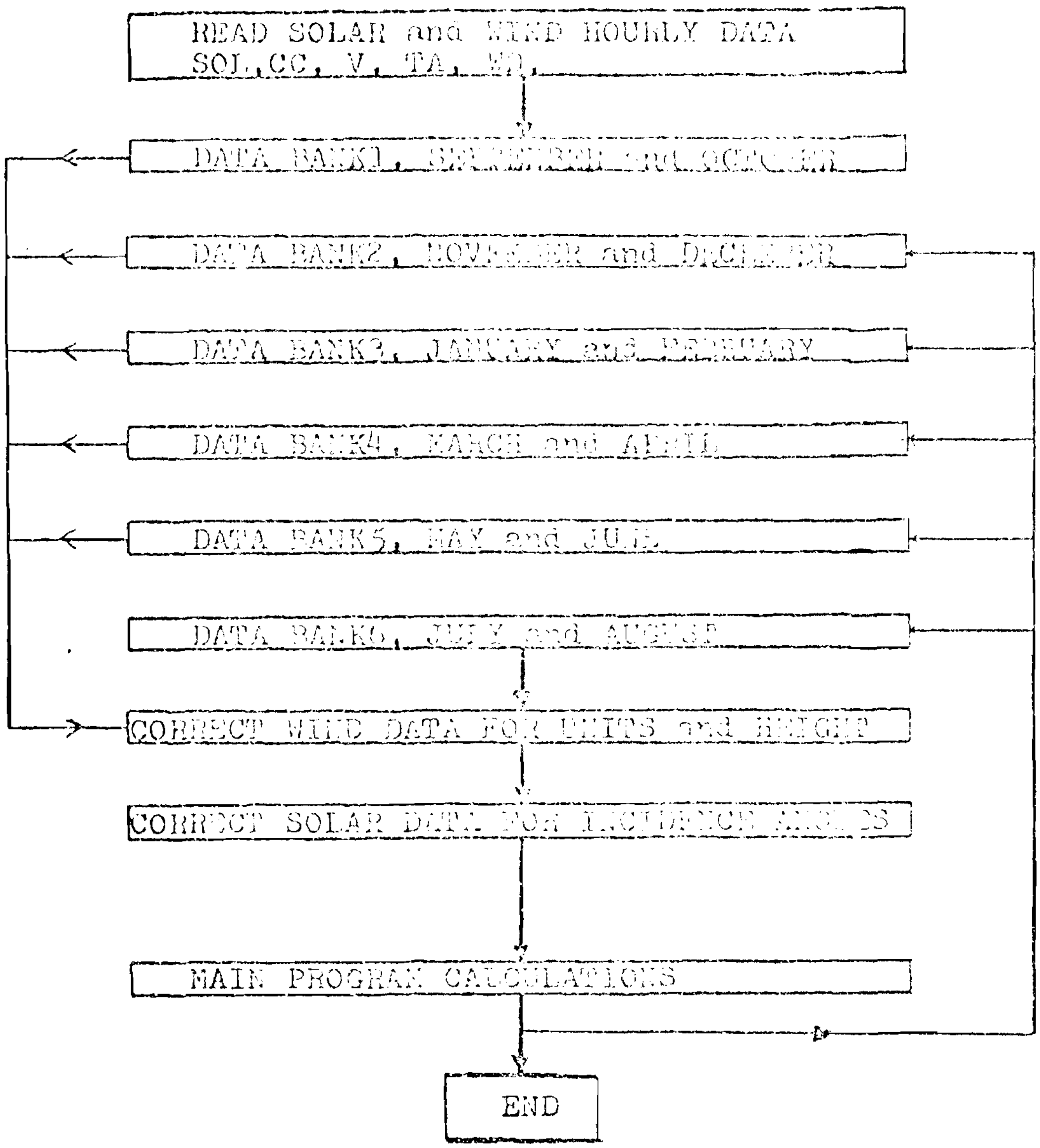


Figure 4.2. Flow Diagram of the Data Input Subprogram

	Solar Insolation, Btu/ft^2 hr	Cloud Cover, 0 to 10 scale	Wind Speed, knots	Ambient Temperature, F	Wind Direction
1096	0	9	04	62	29
1098	0	2	04	62	29
1100	0	0	04	62	29
1102	0	0	00	56	00
1104	0	0	00	56	00
1106	0	0	00	56	00
1108	0	0	00	51	00
1110	136.	0	00	51	00
1112	216.	0	00	51	00
1114	257.	2	01	58	07
1116	258.	7	01	58	07
1118	295.	8	01	58	07
1120	278.	0	04	56	04
1122	237.	0	04	56	04
1124	181.	2	04	56	04
1126	94.	3	03	53	33
1128	10.	8	03	53	33
1130	0	8	03	53	33
1132	0	9	03	53	28
1134	0	10	03	53	28
1136	0	10	03	53	28
1138	0	10	08	50	27
1140	0	10	08	50	27
1142	0	10	08	50	27

Figure 4.3. Sample Data for One Day

4.3 The Wind Turbine Generator Subprogram

The flow diagram for the wind turbine generator subprogram is shown in Figure 4.4 and is also based on previous work by Darkazalli (11). Because the wind velocity data was not taken at the height of the wind turbine generator or the house, the data has to be modified using Hellman's relation, Equation 3.1. The correction factor for the WTG and the house are called COF and COH, respectively. By employing the COF term and the curve fitted WTG output equations, shown in Figure 3.1, the harvested wind energy can be calculated.

4.4 The High Temperature Thermal Storage Subprogram

The high temperature thermal storage subprogram is shown as a logic flow diagram in Figure 4.5. Inputted to the subprogram are the desired mass of NaOH (EM) to be considered, its specific heats (CPS1, CPS2, CPS3) and latent heat characteristics, the initial HTS temperature (THTSI), the solid-solid phase change fraction (X1I) or the solid-liquid phase change fraction (X2I), (if THTSI is at 560°F or 600°F, respectively), and the home basement temperature T_B. Via the main program, the subprogram then requires the user to either input a specific tank height and radius for the cylindrical tank, or to allow the program itself to calculate the tank height and radius corresponding to minimum surface area. The subprogram then requires the user to input the HTS insulation thickness and thermal conductivity. Next, the routine calculates the HTS initial internal energy (EHI) and the tank losses for the hour (QLTOT). After the input and outputs on the tank are considered, in the main program an energy balance is performed on the tank and the final internal energy of the HTS at the end

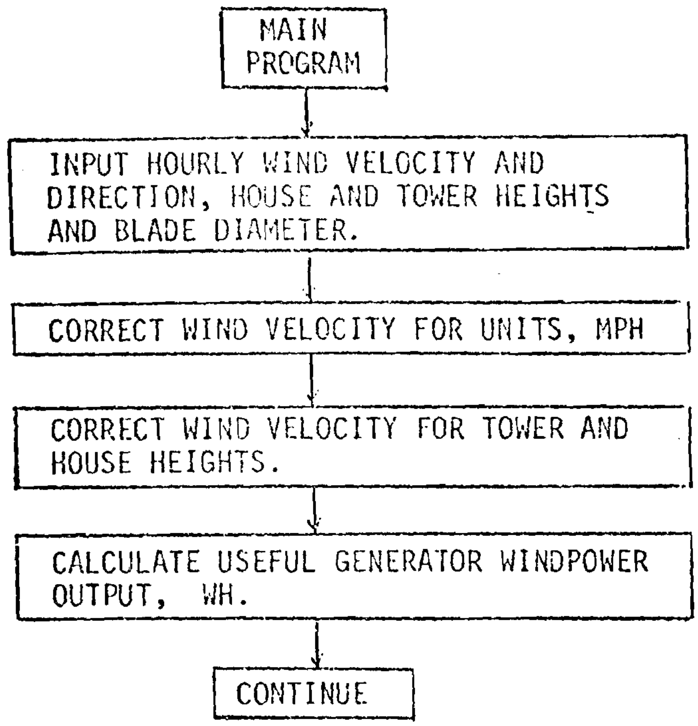


Figure 4.4. The Wind Turbine Generator Subprogram Flow Diagram

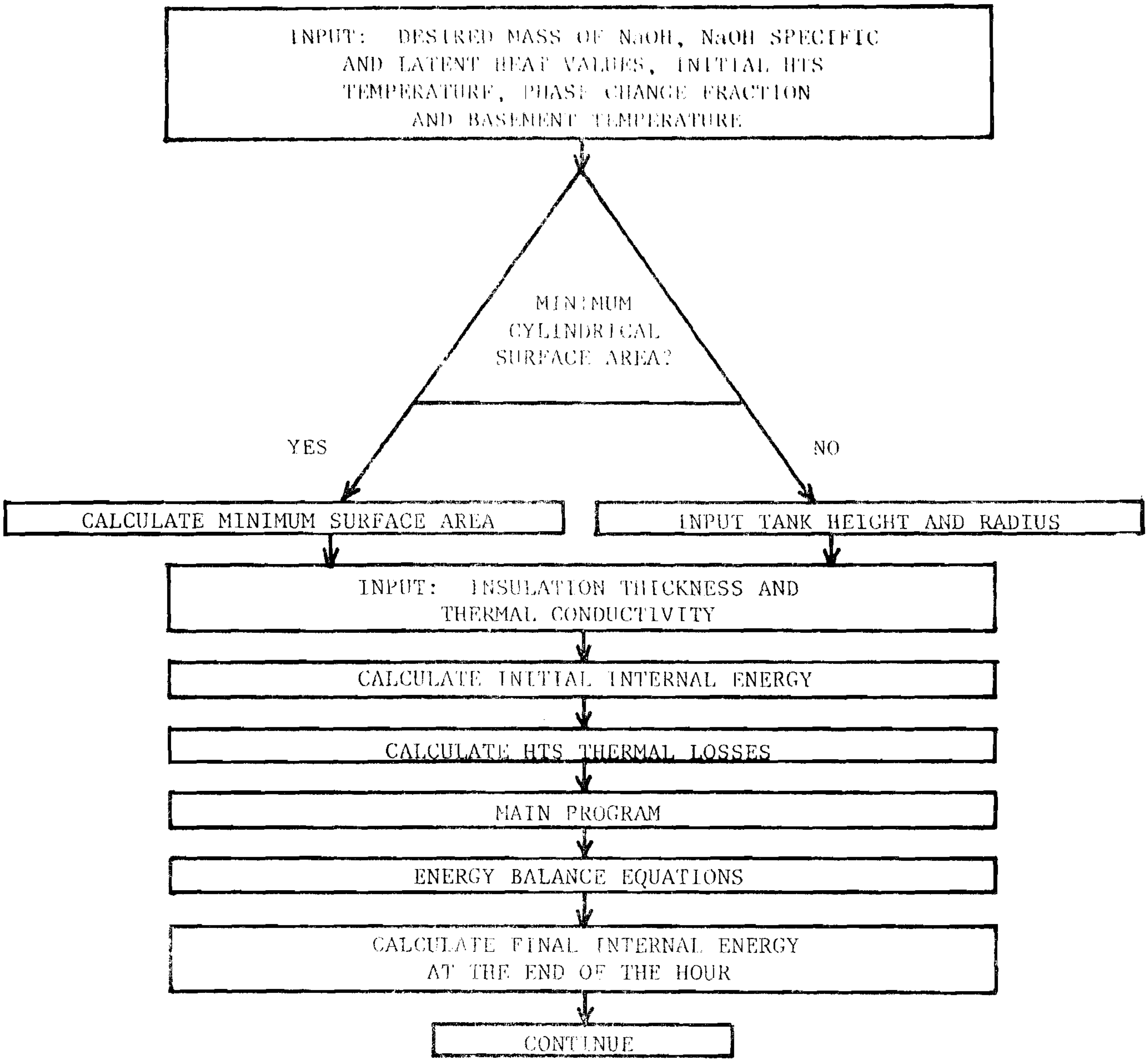


FIGURE 4.5. THE HIGH TEMPERATURE THERMAL STORAGE SUBPROGRAM FLOW DIAGRAM.

of the hour is calculated.

4.5 The Electrical Load Subprogram

The electrical load subprogram depicted as a block diagram in Figure 4.6, requires an input, from the main program, of the time of day and the day of year (day). The nominal (WNOM) and the seasonally adjusted residential electrical loads (WE) are calculated according to Table 3.1 and Equation 3.18, respectively. The subprogram then asks the user to type 1 for the average U.S. farm electrical load. An input of any number but 1 will result in the residential electrical load. If a 1 is inputted, the farm machinery load (WMECH) is found according to Table 3.2 and summed with the residential load to get the total electrical load.

4.6 The Space Heating Load Subprogram

The space heating load subprogram (11), shown in block diagram form in Figure 4.7, calculates the heating load for an average or well-insulated New England home based on air temperature, wind velocity and wind direction. For the well-insulated home, conductive, convective and infiltrative heat losses are calculated from the first floor of the home through the walls, floors, ceiling, doors and windows. For the average New England home, the heat losses through the basement walls, floors and doors are also taken into consideration. Each of the various heat transfer surfaces is considered independently and, therefore, modification of this program to fit other residential models is easily accomplished.

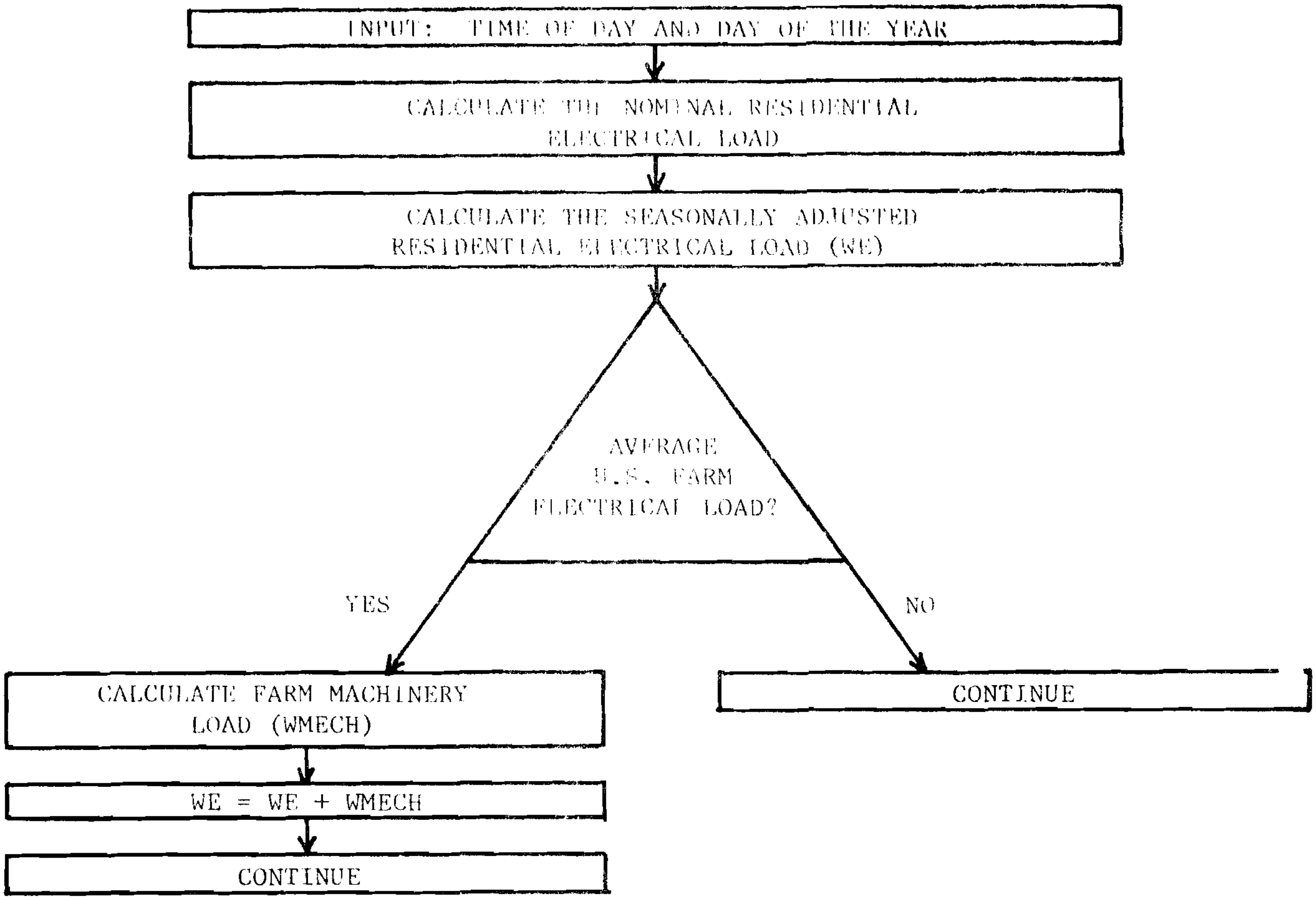


FIGURE 4.6. BLOCK DIAGRAM OF THE ELECTRICAL LOAD SUBPROGRAM.

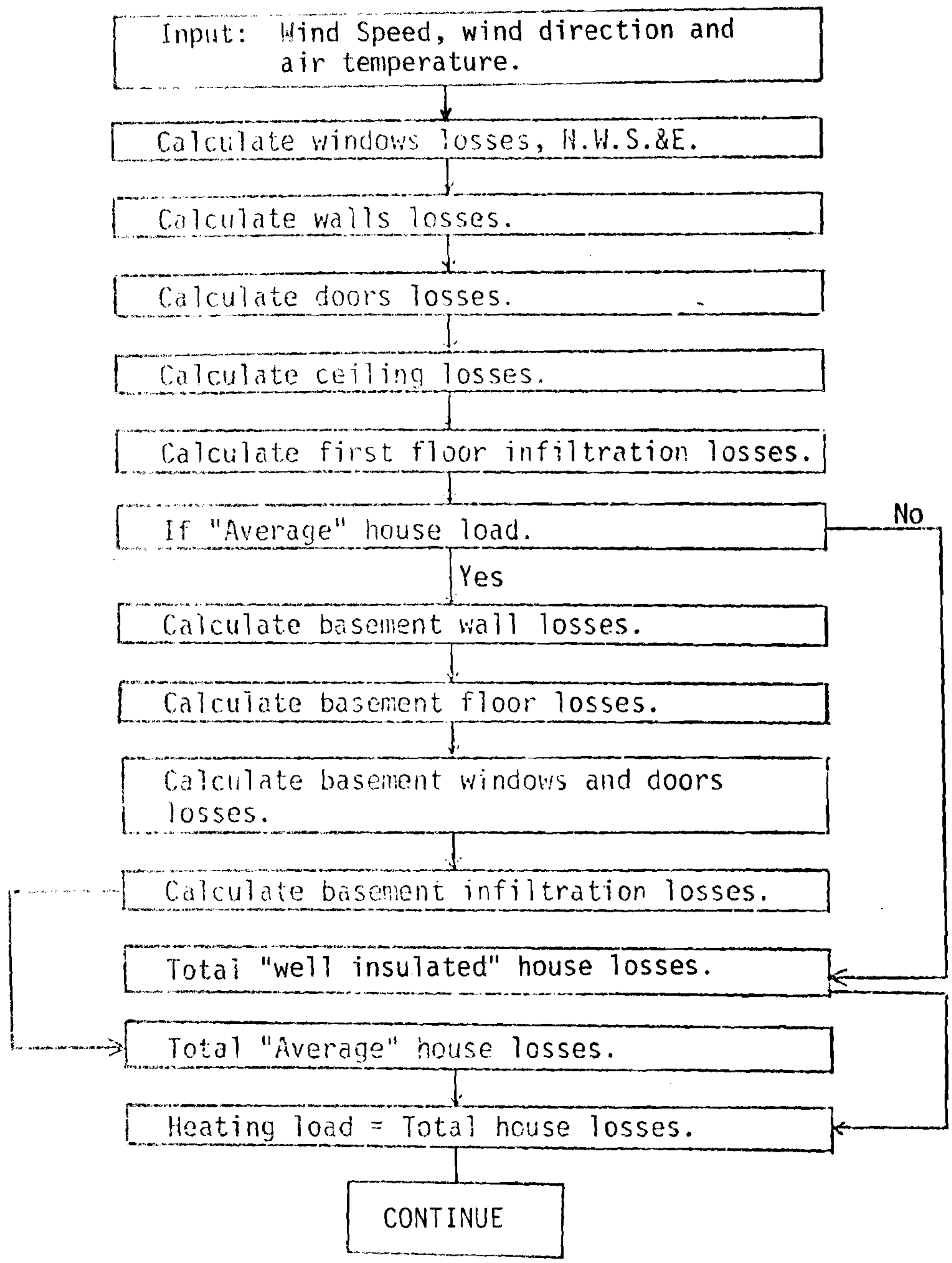


Figure 4.7. Block Diagram of the Space Heating Load Subprogram

4.7 The Domestic Hot Water Subprogram

The domestic hot water (DHW) subprogram, shown as a block diagram in Figure 4.8, is used in basically the same form for both the WDTES models and the IWFS model, except that in the WDTES models, energy is supplied from the HTS and in the IWFS model, by the LTS. The data input to the subprogram consists of the hour of day, the inlet water temperature from the main (TCW) and the desired hot water outlet temperature (THWR). The WDTES or IWFS models and the HTS or LTS tank capacity model has been previously specified in the main program and this, in turn, specifies whether the DHW energy is to be supplied by the HTS or the LTS in the DHW subprogram. The hourly DHW demand and the energy required to supply this demand is then calculated. If this energy is available in the storage tank and the storage temperature is greater or equal to THWR, the total DHW energy requirement is supplied by the storage. If not, energy is supplied by the storage to raise the hot water temperature to the storage temperature and the remainder is supplied by an auxiliary source.

4.8 The Low Temperature Thermal Storage Subprogram

The low temperature thermal storage subprogram, shown as a flow diagram in Figure 4.9, is quite similar to the HTS subprogram. The inputs into the subprogram are the desired mass of H_2O (EML) under examination, the specific heat (CPW), the initial LTS temperature (TLTSI) and the home basement temperature. The main program has already required the user to input specific tank dimensions or to allow the program to calculate the minimum cylindrical surface area. The insulation thickness and its thermal conductivity are then inputted

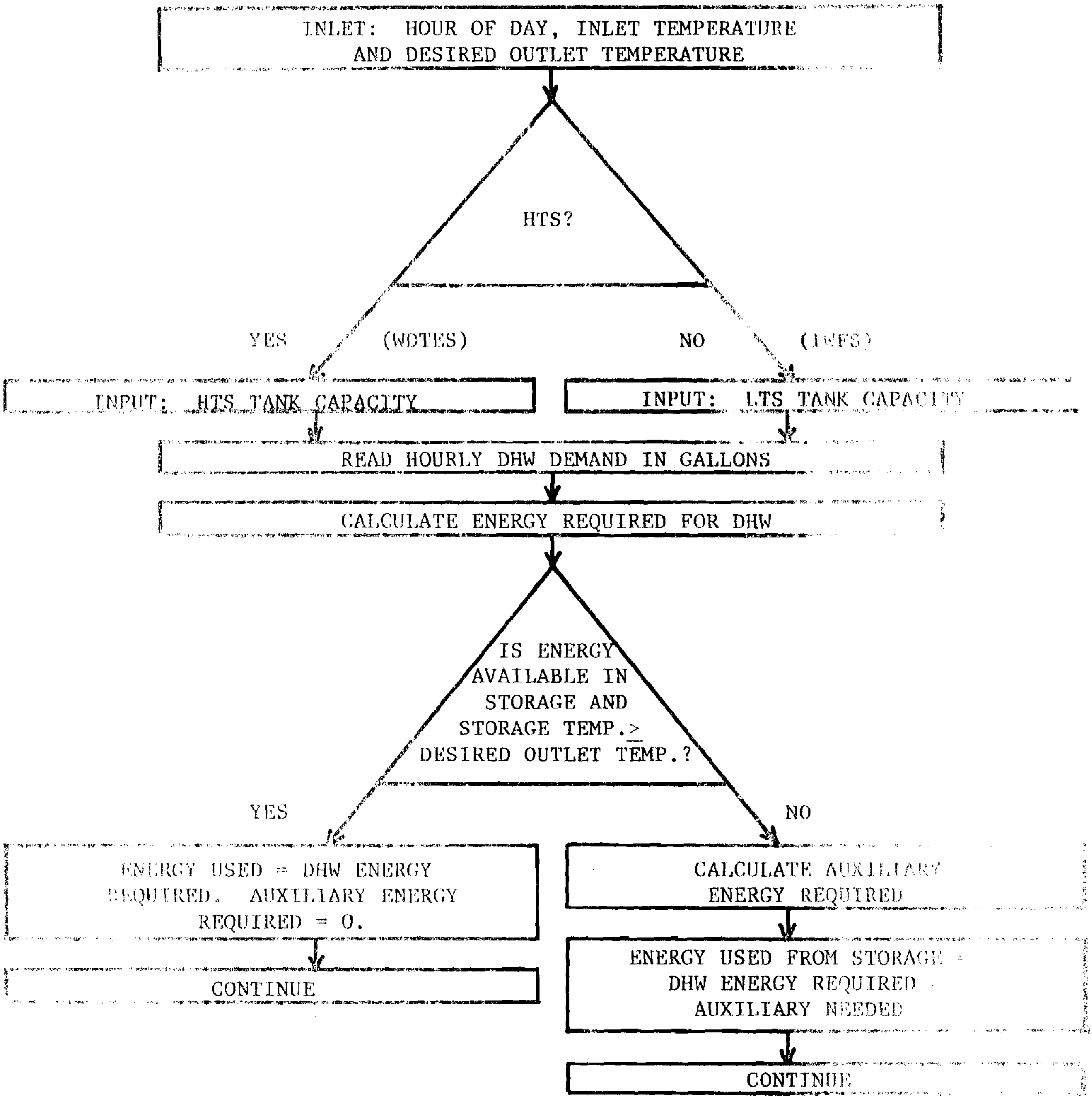


FIGURE 4.8. THE DOMESTIC HOT WATER BLOCK DIAGRAM.

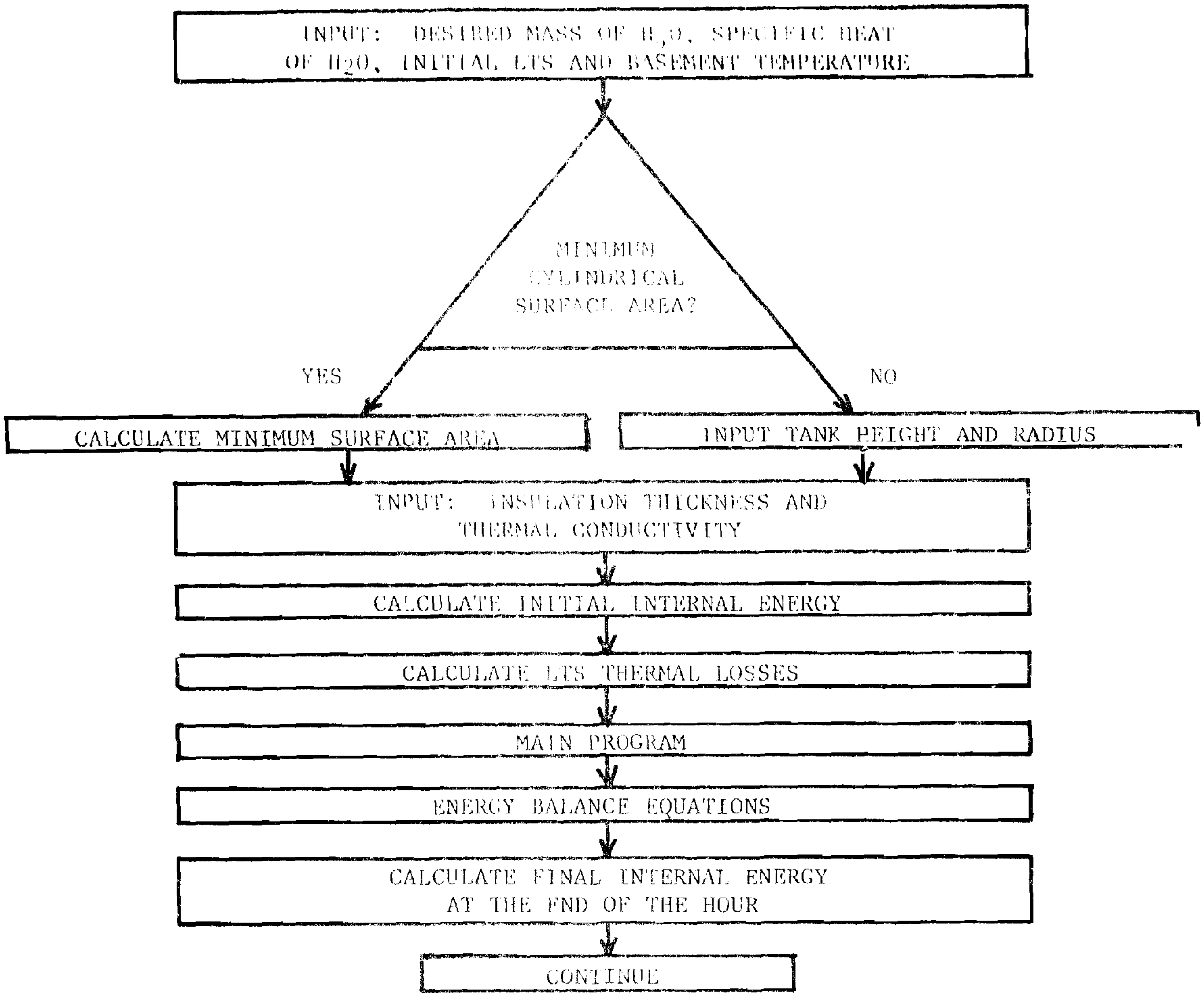


FIGURE 4.9. THE LOW TEMPERATURE THERMAL STORAGE SUBPROGRAM FLOW DIAGRAM.

and the program calculates the initial LTS internal energy (ELI) and the thermal losses (QLTOTL). Then, after the system analysis is performed in the main program, an energy balance on the LTS is made, the energy removal from the LTS is calculated and the LTS temperature is decreased by this amount.

4.9 The Solar Energy Subprogram

The solar energy subprogram [11] calculates the useful solar energy gain through the windows. As shown in logic flow diagram, Figure 4.10, the method of calculation is straightforward and requires no convergence techniques. The inputs to the subprogram are the hour of day, the day of the year, the solar insolation and the cloud cover. If solar radiation is available, the subprogram calculates the angle of incidence of the beam solar radiation on the first window and determines if the window is receiving solar radiation and the amount of shading that is taking place. The absorptance of the window as a function of incidence angle is then calculated. The solar radiation is then divided into its beam and diffuse components, and the beam attenuation is converted from its 60° collection orientation to the orientation of the window. The total solar energy input through the window is then calculated and the control returns to perform the calculation on the next window until the analysis is performed on all sunlit windows.

4.10 The Rankine Cycle Subprogram

The Rankine Cycle (RC) subprogram, shown in Figure 4.11, is easily programmable once the series of curves representing maximum RC

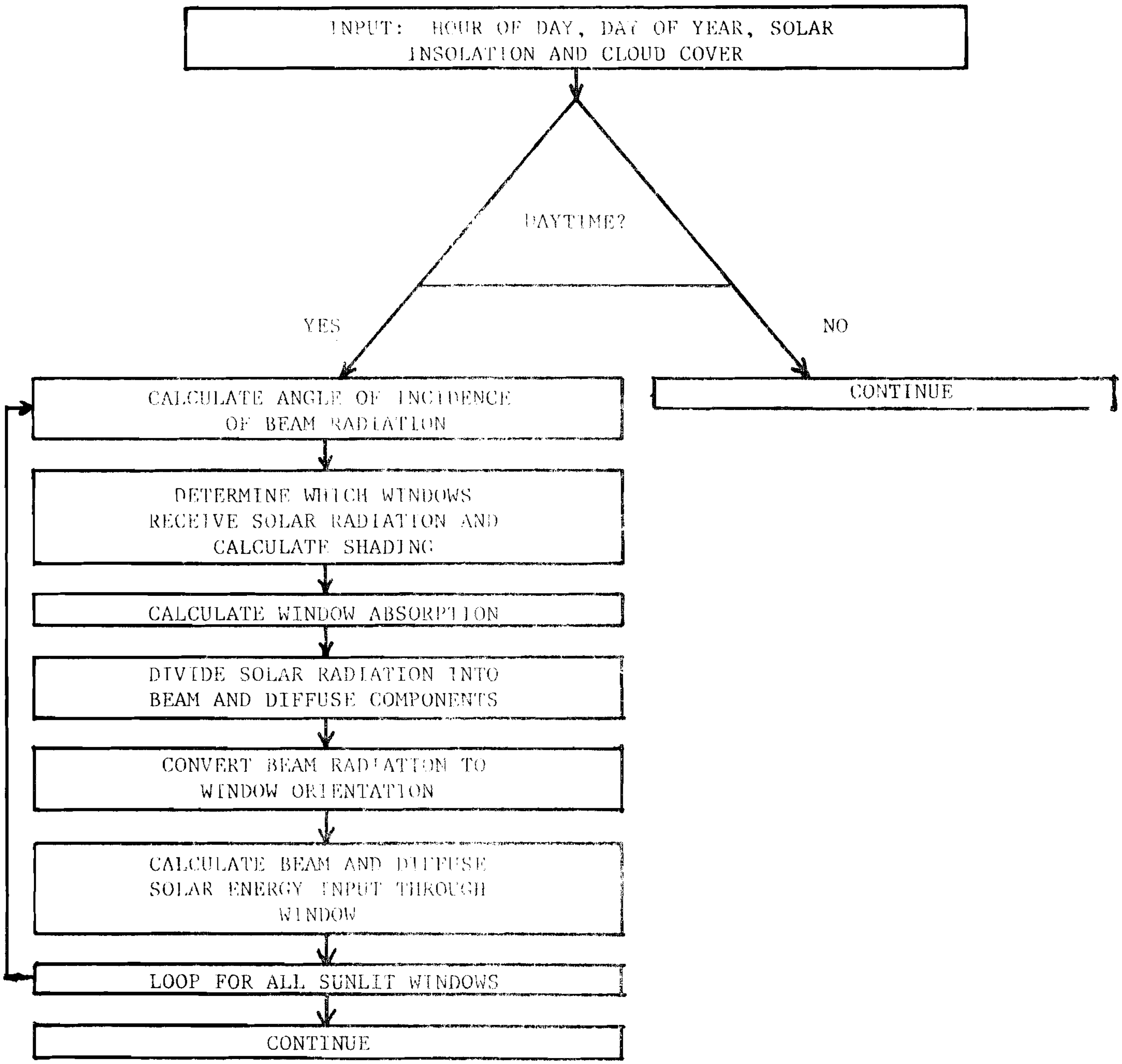


FIGURE 4.10. FLOW DIAGRAM OF THE SOLAR ENERGY SUBPROGRAM.

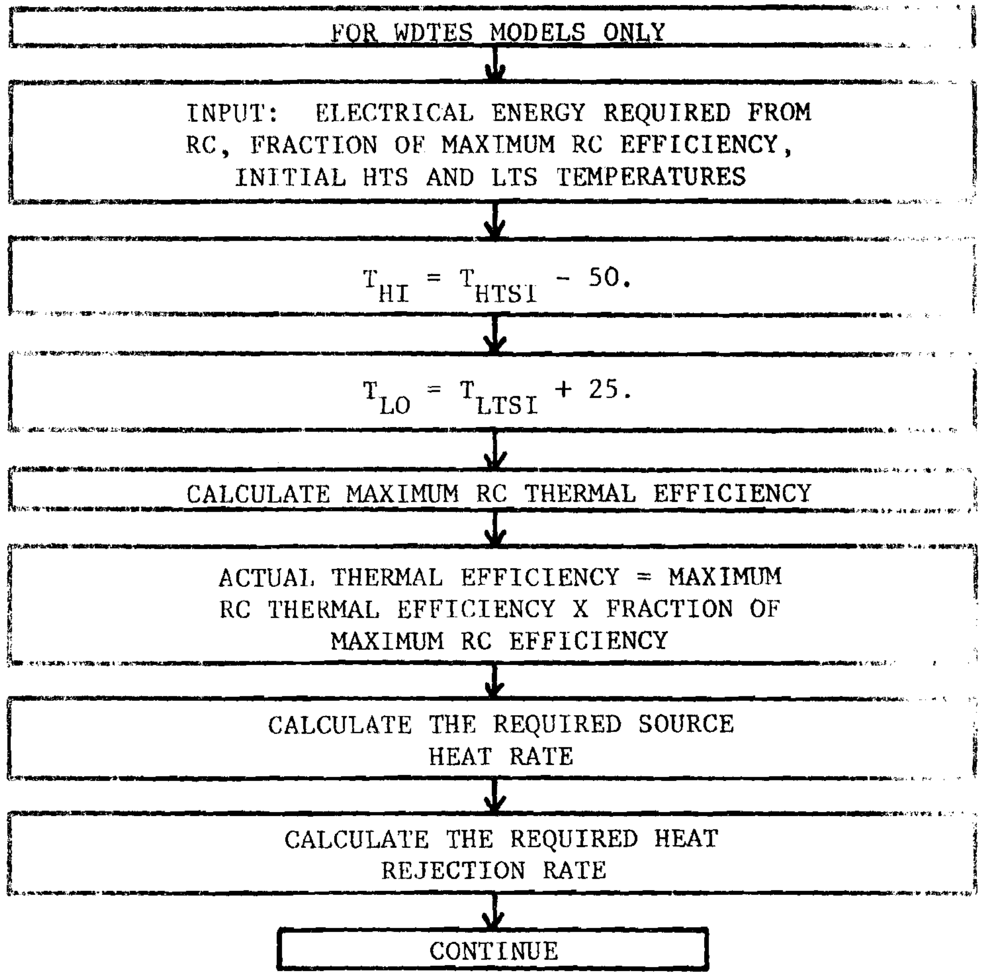


FIGURE 4.11. BLOCK DIAGRAM FOR THE RANKINE CYCLE SUBPROGRAM.

efficiency as a function of maximum working fluid temperature shown in Figure 3.12 are curve fitted. The RC Subprogram, which is for the WDTES models only, has as inputs, the electrical energy required from the RC (WREQ), the fraction of maximum Rankine Cycle thermal efficiency (RNKFCT) and the initial HTS and LTS temperatures. The assumed temperature difference across the HTS and LTS, 50°F and 25°F, respectively, are then used to calculate the maximum working fluid temperature (T_{HI}) and the minimum working fluid temperature (T_{LO}). Then, by regarding the curve fit equations represented in Figure 3.12 and by linear interpolation for values of T_{LO} between these curves, the maximum Rankine Cycle thermal efficiency (ETA) is calculated. The actual RC thermal efficiency is then calculated by multiplication of ETA by the RNKFCT. Since the actual thermal efficiency and the required electrical energy output are known, the required heat transfer Q_H from the HTS source and the required rate of heat transfer to the LTS sink Q_{ETAL} can now be determined.

4.11 The Mode of Operations and Switching Logic Model

The switching and operational mode model is technically a part of the main program, but, because it is the central controlling logic for all three systems, it requires close consideration. The model is based on the energy flow logic which appears in Chapter II for each system. The model for the IWFS scheme is, by far, the most straightforward due to the fact that there is no Rankine Cycle or high temperature thermal storage for this system. A diagram of this logic is included in Figure 4.12. The model for the WDTES Type I and Type II schemes is included in Figure 4.13 and 4.14 respectively. The models for the

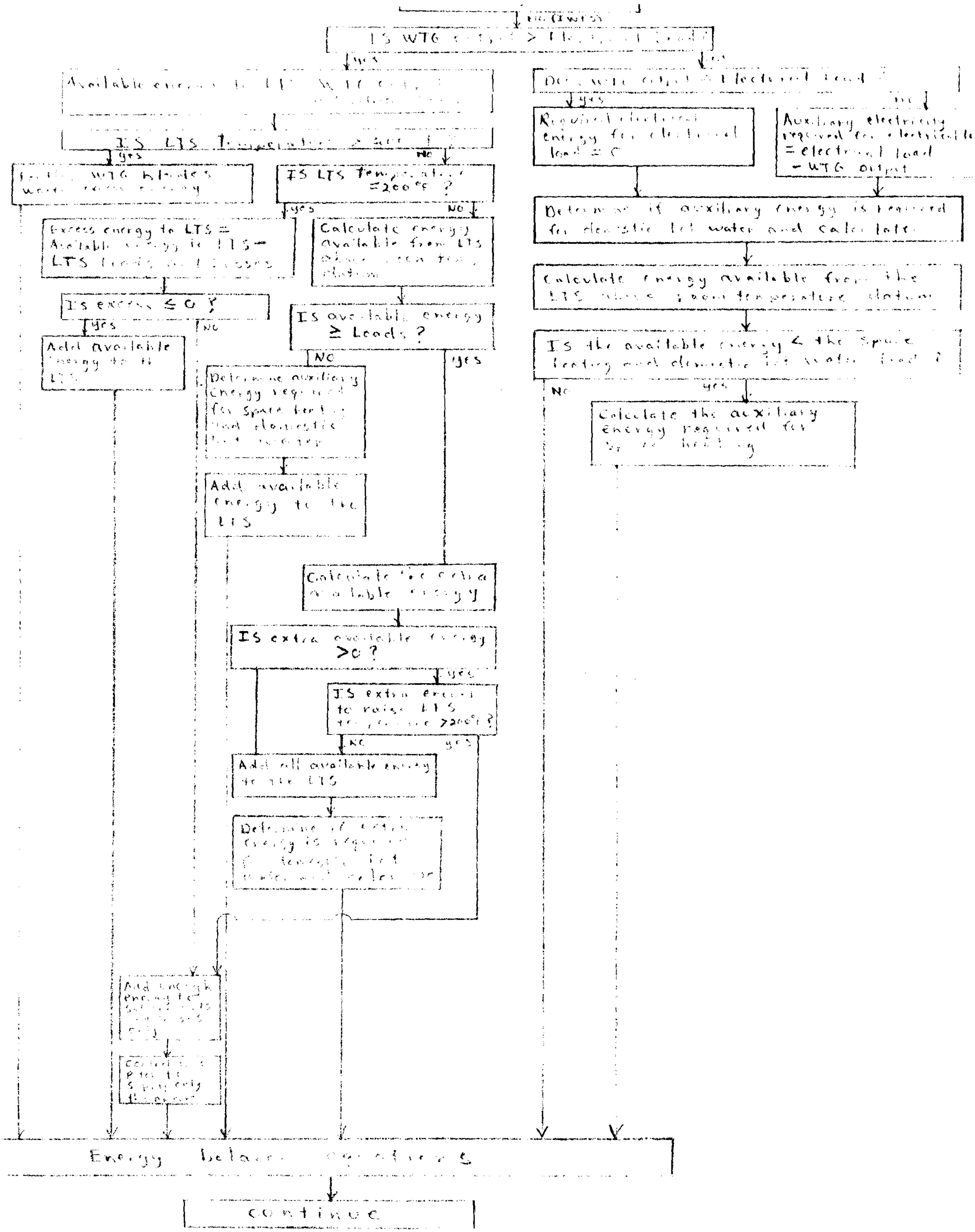


Figure 4.? ... Logic for the IWFS

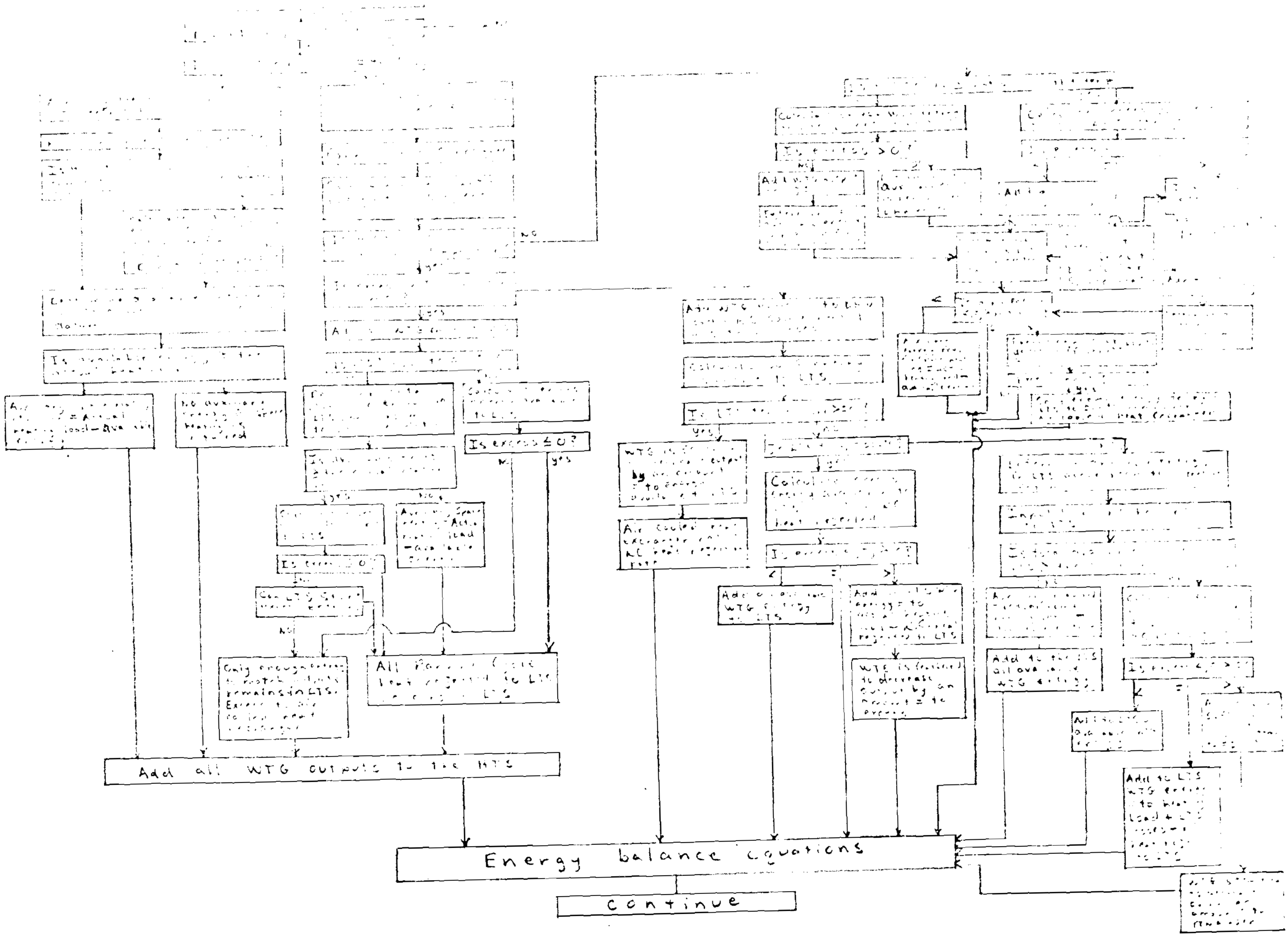


Figure 4.13. Switching and Mode of Operations Logic for WDTES, Type I

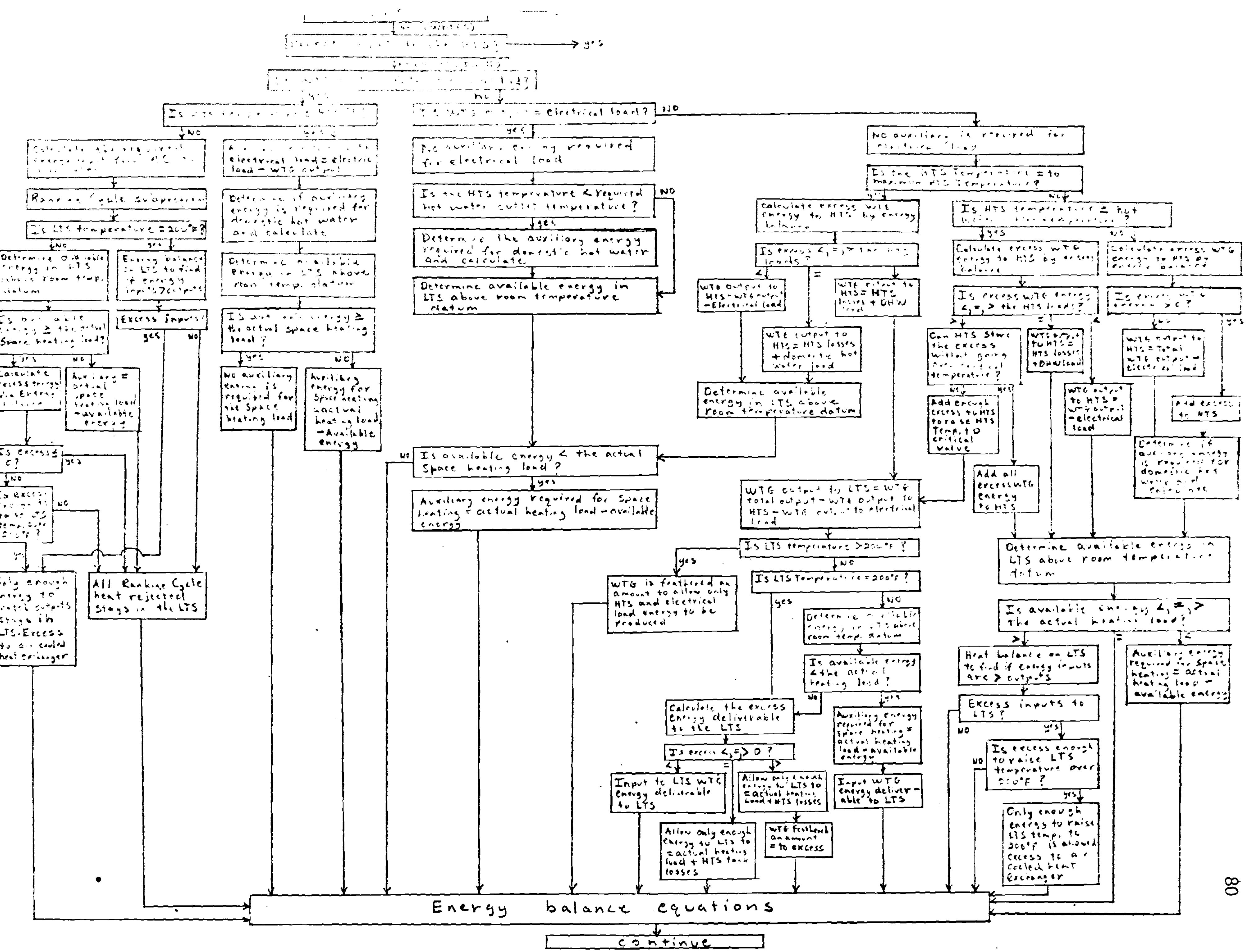


Figure 4.14. Switching and Mode of Operations Logic for WDTES Two II

WDIES systems are more complex than the IWFS and require far greater amounts of computer time to process. Although the basic logic for these systems is actually quite simple to understand, the sheer volume of conditions that must be examined makes careful testing of the models essential to minimize errors.

4.12 The Output Subprogram

The output subprogram allows each subsystem, relevant to a particular model, to be examined individually hour by hour. The output subprogram then prints and formats the resulting calculations in either an hourly, daily, or monthly fashion. The output results printed include the input conditions, various energy loads, energy distribution throughout the system under consideration, and most importantly, the auxiliary space heating, electrical and domestic hot water loads.

A sample hourly run, showing the inputs and outputs from the program, is given in Figures 4.15 and 4.16, respectively. (Temperatures are in degrees Farenheit and energy values are in kilowatt-hours.)

```
RNH,MA=100000
 WIND ROTOR DIAMETER (FT) =
? 40.
              40.00
 FOR AVERAGE U.S. FARM ELECTRICAL LOAD TYPE 1.
? 1.
               1.00
 FOR NO HTS TYPE 0
 FOR HTS TYPE 1
? 1
                 1
 FOR DIRECT INPUT TO HTS TYPE 1.
 TO SATISFY ELECTRICAL LOAD FIRST ,TYPE 0.
? 0.
            0.
 MASS OF HIGH TEMP STORAGE MATERIAL (NAOH) (LBM) =
? 1437.5
            1437.50
 FOR MIN. HTS TANK SURF. AREA TYPE 1.
 TO INPUT SPECIFIC TANK DIMENSIONS TYPE 0.
? 1.
               1.00
 HTS INSUL. THICKNESS (FT) =,THERMAL COND. (B/HR FT F) =
? 1.5,.022
               1.50        .22000E-01
 LTS INSUL. THICKNESS (FT) =,THERMAL COND. (B/HR FT F) =
? 1.,.022
               1.00        .22000E-01
 TO INCLUDE BASEMENT TYPE 1
? 1
                 1
 MASS OF LOW TEMP STORAGE MATERIAL (H2O) (LBM) =
? 16076.
           16076.00
 FOR MIN. LTS TANK SURF. AREA TYPE 1.
 TO INPUT SPECIFIC LTS TANK DIMENSIONS TYPE 0.
? 1.
               1.00
 THE INITIAL LTS TEMPERATURE (F) =
? 68.
              68.00
 INITIAL HTS TEMPERATURE (F) =
? 68.
              68.00
 MAXIMUM ALLOWABLE HTS TEMPERATURE =
? 800.
             800.00
 FRACTION OF MAXIMUM RANKINE CYCLE EFFICIENCY =
? 1.
               1.00
 FOR HOURLY OUTPUT LET RR=0.,MON=0
 FOR DAILY OUTPUT LET RR=1.,MON=0
 FOR MONTHLY OUTPUT LET RR=1.,MON=1
 RR=
? 0.
            0.
 MON=
? 0
```

Figure 4.15. Inputs for WDTES1 Program

HTS TANK RADIUS - 1.2663 FT.
HTS TANK HEIGHT - [illegible] FT.
LTS TANK RADIUS - 3.4907 FT.
LTS TANK HEIGHT - 6.9814 FT.
SEPTEMBER

NHR	WW[illegible]	WI	QHLACT	QHW	QH	QL	QACHX	WWASTE	THISF	TLISF	QAUX	WEAUX	WHWAUX	[illegible]	WREG
1	0.	1.226	[illegible]	.022	0.	0.	0.	0.	67.9	68.0	[illegible]	1.226	[illegible]	0.	0.
2	0.	1.016	3.[illegible]91	0.	0.	0.	0.	0.	67.9	68.0	3.[illegible]91	1.016	0.	0.	0.
3	0.	.946	3.[illegible]91	0.	0.	0.	0.	0.	67.9	68.0	3.[illegible]91	.946	0.	0.	0.
4	0.	.[illegible]	3.[illegible]50	0.	0.	0.	0.	0.	67.9	68.0	3.950	[illegible]	0.	0.	0.
5	0.	2.209	3.[illegible]50	0.	0.	0.	0.	0.	67.9	68.0	3.[illegible]50	2.209	0.	0.	0.
6	0.	2.209	3.[illegible]50	0.	0.	0.	0.	0.	67.9	68.0	3.950	2.209	0.	0.	0.
7	0.	2.279	3.235	.014	0.	0.	0.	0.	67.8	68.0	3.2[illegible]	2.279	.172	0.	0.
8	0.	1.419	3.092	.044	0.	0.	0.	0.	67.[illegible]	68.0	3.0[illegible]	1.419	.40[illegible]	0.	0.
9	0.	1.628	2.676	.067	0.	0.	0.	0.	67.[illegible]	68.0	2.6[illegible]	1.628	.[illegible]0	0.	0.
10	0.	1.838	0.	.073	0.	0.	0.	0.	66.7	68.0	0.	1.8[illegible]	.7[illegible]	0.	0.
11	0.	1.628	0.	.057	0.	0.	0.	0.	66.4	68.0	0.	1.[illegible]	.617	0.	0.
12	0.	2.5[illegible]	0.	.035	0.	0.	0.	0.	66.2	68.0	0.	2.5[illegible]	.40[illegible]	0.	0.
13	6.370	2.489	0.	.027	0.	0.	0.	0.	88.2	68.0	0.	0.	.324	3.881	0.
14	6.370	2.419	0.	.175	0.	0.	0.	0.	109.6	68.0	0.	0.	.423	3.947	0.
15	6.370	1.419	0.	.164	0.	0.	0.	0.	136.8	68.0	0.	0.	.1[illegible]	4.944	0.
16	1.884	1.489	0.	.225	0.	0.	0.	0.	137.7	68.0	0.	0.	.[illegible]09	.393	0.
17	1.884	2.489	0.	.199	0.	0.	0.	0.	136.[illegible]	68.0	0.	.605	.[illegible]5	0.	0.
18	1.884	2.908	0.	.[illegible]	0.	0.	0.	0.	134.4	68.0	0.	1.024	.016	0.	0.
19	0.	3.187	0.	.714	0.	0.	0.	0.	130.8	68.0	0.	3.187	.0[illegible]	0.	0.
20	0.	1.784	0.	1.[illegible]	0.	0.	0.	0.	1[illegible].1	68.0	0.	1.7[illegible]	.1[illegible]	0.	0.
21	0.	1.644	0.	.762	0.	0.	0.	0.	120.7	68.0	0.	1.644	.1[illegible]	0.	0.
22	0.	1.575	2.170	.[illegible]11	0.	0.	0.	0.	117.7	68.0	2.170	1.575	.1[illegible]	0.	0.
23	0.	1.4[illegible]	2.170	.384	0.	0.	0.	0.	115.5	68.0	2.170	1.4[illegible]	.14[illegible]	0.	0.
24	0.	1.[illegible]	2.171	.314	0.	0.	0.	0.	113.6	68.0	2.171	1.[illegible]	.1[illegible]	0.	0.

KDAY	WWSD	WLD	QHLACD	QHWD	QACHXD	WWASTD	QAUXD	WEAUXD	WHWAUXD	THCRIT	TLCRIT	[illegible]	QHP	WREQD	FREQP
1	24.760	43.966	38.137	[illegible].042	0.	0.	38.137	32.384	[illegible].725	[illegible]	[illegible]	13.[illegible]	0.	0.	0

NHR	WWS	WI	QHLACT	QHW	QH	QL	QACHX	WWASTE	THISF	TLISF	QAUX	WEAUX	WHWAUX	[illegible]	WREG
1	0.	1.[illegible]	3.044	.147	0.	0.	0.	0.	112.7	68.0	[illegible]044	1.[illegible]	.0[illegible]	0.	0.
2	0.	1.0[illegible]	3.044	0.	0.	0.	0.	0.	112.7	68.0	3.044	1.0[illegible]	0.	0.	0.
3	0.	.947	3.044	0.	0.	0.	0.	0.	112.7	68.0	3.044	.9[illegible]	0.	0.	0.
4	0.	.877	3.577	0.	0.	0.	0.	0.	112.6	68.0	3.577	.8[illegible]	0.	0.	0.
5	0.	2.210	3.577	0.	0.	0.	0.	0.	112.6	68.0	3.577	2.210	0.	0.	0.
6	0.	2.210	3.577	0.	0.	0.	0.	0.	1[illegible].5	68.0	3.577	2.21[illegible]	0.	0.	0.
7	0.	2.[illegible]	3.050	.096	0.	0.	0.	0.	111.9	68.0	3.0[illegible]	2.[illegible]	.050	0.	0.
8	0.	1.421	2.487	.294	0.	0.	0.	0.	110.2	68.0	2.4[illegible]	1.[illegible]	.15[illegible]	0.	0.
9	0.	1.631	1.843	.444	0.	0.	0.	0.	107.6	68.0	1.843	1.[illegible]	.1[illegible]	0.	0.
10	0.	1.841	0.	.488	0.	0.	0.	0.	104.[illegible]	68.0	0.	1.841	.3[illegible]	0.	0.
11	0.	1.631	0.	.377	0.	0.	0.	0.	102.6	68.0	0.	1.631	.2[illegible]	0.	0.
12	0.	2.561	0.	.234	0.	0.	0.	0.	101.7	68.0	0.	2.5[illegible]	.205	0.	0.
13	3.164	2.421	0.	.181	0.	0.	0.	0.	104.0	68.0	0.	0.	.1[illegible]	.668	0.
14	3.164	2.421	0.	.274	0.	0.	0.	0.	106.6	68.0	0.	0.	.2[illegible]4	.738	0.
15	3.164	1.421	0.	.154	0.	0.	0.	0.	115.6	68.0	0.	0.	.1[illegible]	1.737	0.
16	6.370	1.[illegible]1	0.	.1[illegible]	0.	0.	0.	0.	142.4	68.0	0.	0.	.071	4.871	0.
17	6.370	2.491	0.	.20[illegible]	0.	0.	0.	0.	163.2	68.0	0.	0.	0.	[illegible]	0.
18	[illegible]	2.911	0.	.367	0.	0.	0.	0.	180.8	68.0	0.	0.	0.	3.458	0.
19	3.164	3.192	0.	.660	0.	0.	0.	0.	176.9	68.0	0.	.027	0.	0.	0.
20	3.164	1.789	0.	1.132	0.	0.	0.	0.	178.2	68.0	0.	0.	0.	1.376	0.
21	3.164	1.648	0.	.937	0.	0.	0.	0.	181.3	68.0	0.	0.	0.	1.516	0.
22	[illegible]	1.528	1.126	.674	0.	0.	0.	0.	194.[illegible]	68.0	1.126	0.	0.	3.[illegible]	0.
23	4.[illegible]	1.458	1.124	.533	0.	0.	0.	0.	209.8	68.0	1.124	0.	0.	3.1[illegible]	0.
24	[illegible]	[illegible]	1.121	.4[illegible]	0.	0.	0.	0.	[illegible]	68.0	1.12[illegible]	0.	0.	[illegible]	0.

KDAY	WWSD	WLD	QHLACD	QHWD	QACHXD	WWASTD	QAUXD	WEAUXD	WHWAUXD	THCRIT	TLCRIT	[illegible]	QHP	WREQD	FREQP
2	[illegible]	44.024	30.812	7.914	0.	0.	[illegible]	19.[illegible]	1.954	101.3	[illegible]	[illegible]	0.	0.	0

Figure 4.10 WDTES1 Output in Hourly Format

CHAPTER V

ANALYTICAL SYSTEM PERFORMANCE

To represent the IWFS and WDTES models' analytical performance characteristics in a coherent fashion, the relationship between each system under investigation and its imposed loads must first be established. Only then can the relative merits and drawbacks of each system be determined. Therefore, in this chapter, each advanced wind furnace system was first considered relative to the imposed loads of a well-insulated New England residence, an average New England residence and an average New England farm. Then a comparison between systems was made.

The imposed loads on the system were modeled relative to three different values. The load for the well-insulated New England residence included domestic hot water, a residential electrical load, and its space heating load. The average New England residence is similar to the well-insulated one except that the space heating load was about twice the well-insulated residence's value. The average New England farm was taken to have a similar domestic hot water load, the average New England residence space heating load, and an average farm electrical load. In summary the total annual energy loads for the well-insulated home, the average home and the average farm in New England are 26,516kWh, 44,733kWh, and 55,684kWh, respectively.

Important parameters studied for the IWFS and WDTES systems were the total auxiliary energy required, the auxiliary space heating and electricity required, the mean LTS temperature, the WTG electricity added to the LTS via the resistance heaters, and the WTG energy lost due to the feathering of the blades when there was no system storage capacity remaining. In addition to those, certain parameters were studied with the IWFS or WDTES models only. With the WDTES schemes, the Rankine Cycle operation time, the mean HTS tank temperature, the mean HTS and LTS tank temperatures when the Rankine Cycle is operating, and the WTG electricity added to the HTS were calculated for both 100% and 75% of the "maximum" Rankine Cycle efficiency values. In the IWFS scheme the only additional parameter considered was the auxiliary domestic hot water energy required.

Each parameter was considered to be a function of at least one design variable for each system. For the WDTES models, the key variable was considered to be the HTS tank size and similarly, for the IWFS model the LTS tank size. The effects of those two key variables on their respective system parameters were found by varying their magnitudes for each set of imposed loads. It should be pointed out, that because the systems are started with the tank(s) at 68°F, the auxiliary energy requirements of the systems will tend to be overestimated and thus in some cases a significant fraction of the auxiliary energy requirements come during start up.

Detailed energy flow diagrams for all three systems depicting each computer run made are summarized in Appendix D.

5.1 Improved Wind Furnace System Results

Analytical results for the Improved Wind Furnace System used in conjunction with the well insulated New England residence are shown in Figures 5.1 through 5.4. As can be seen in Figures 5.1 and 5.2 where auxiliary energy requirements are shown as a function of LTS tank size, the total auxiliary energy and the auxiliary space heating required by the

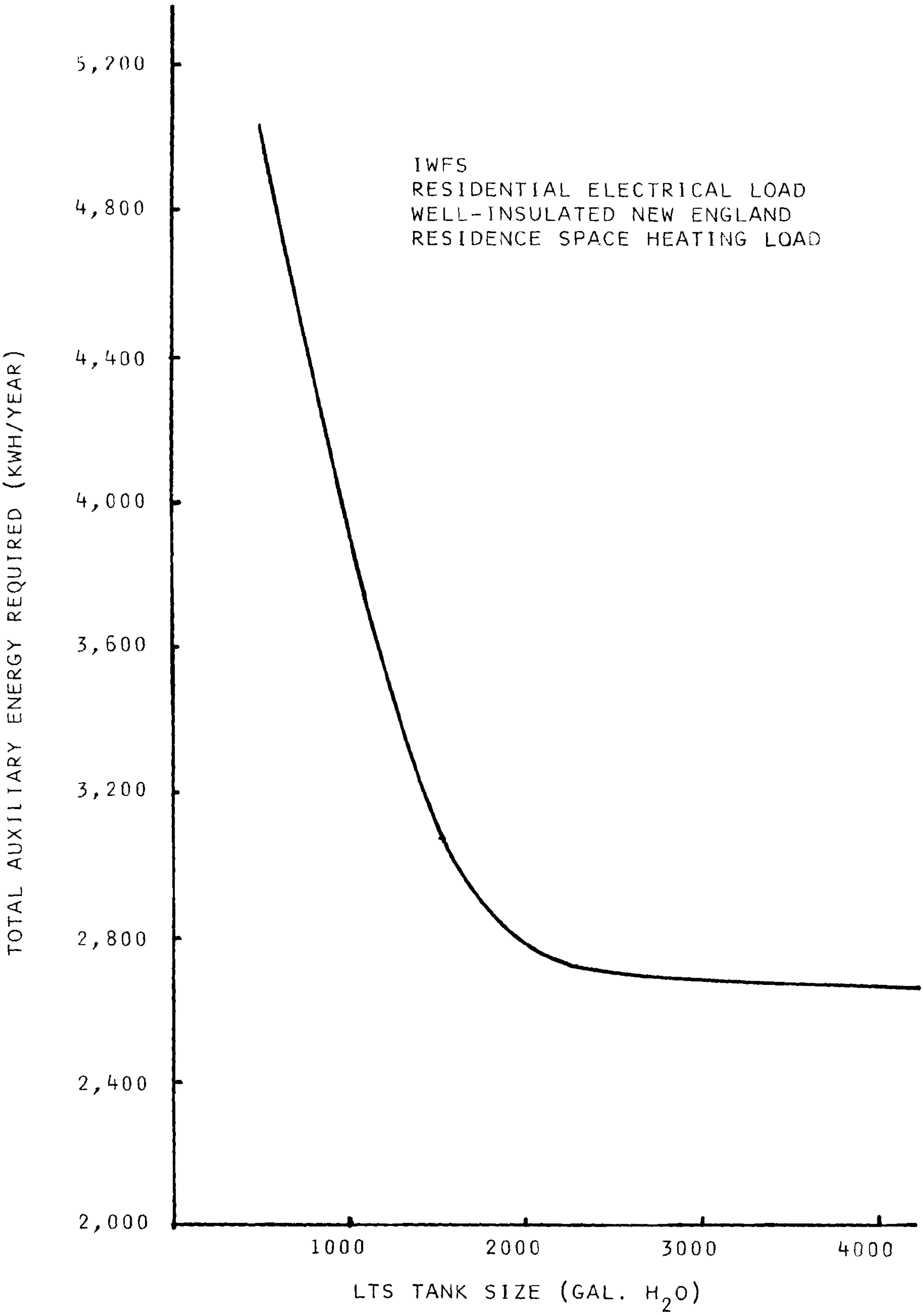


FIGURE 5.1. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF LTS TANK SIZE.

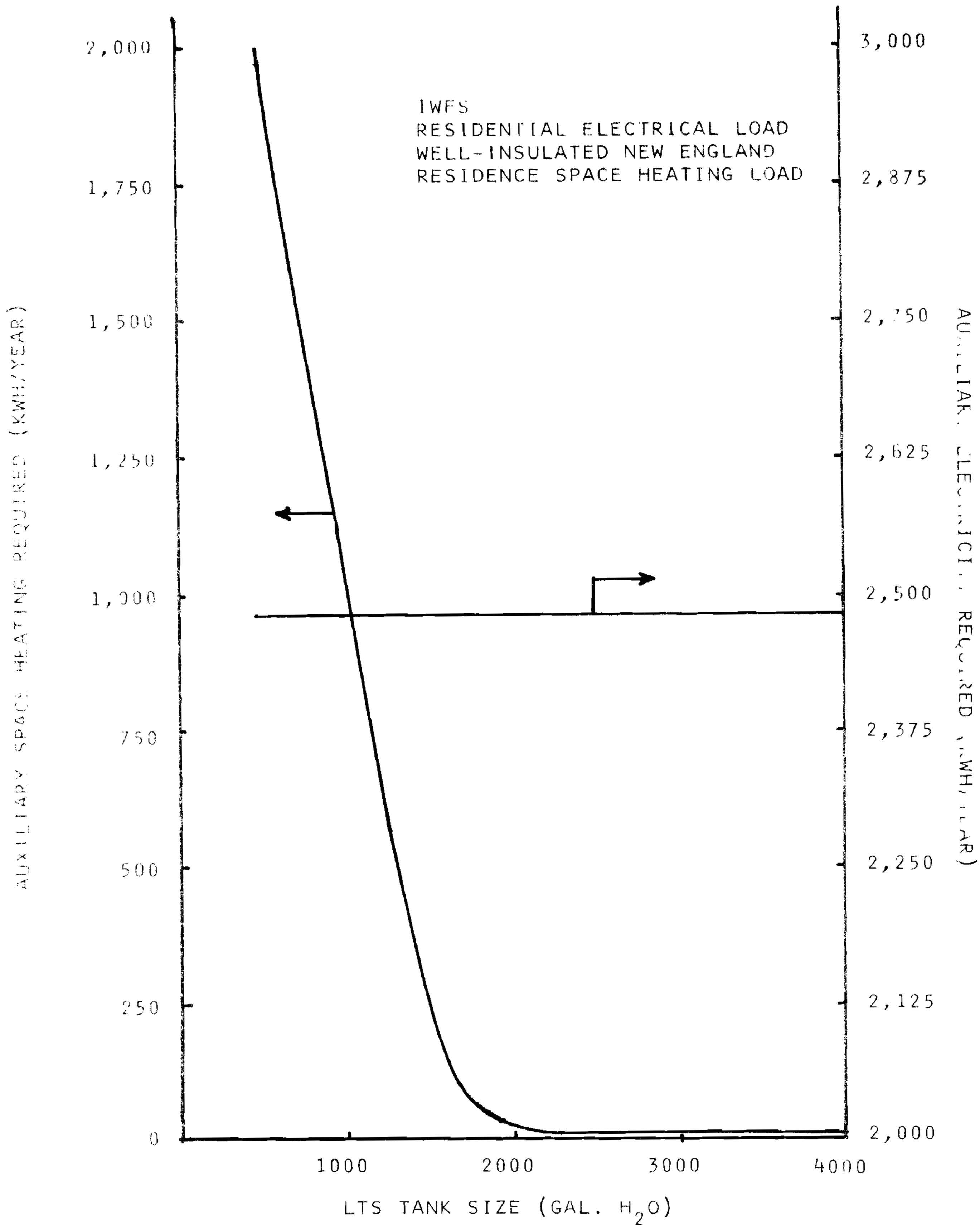


FIGURE 5.2. AUXILIARY SPACE HEATING AND AUXILIARY ELECTRICITY REQUIRED AS A FUNCTION OF LTS TANK SIZE.

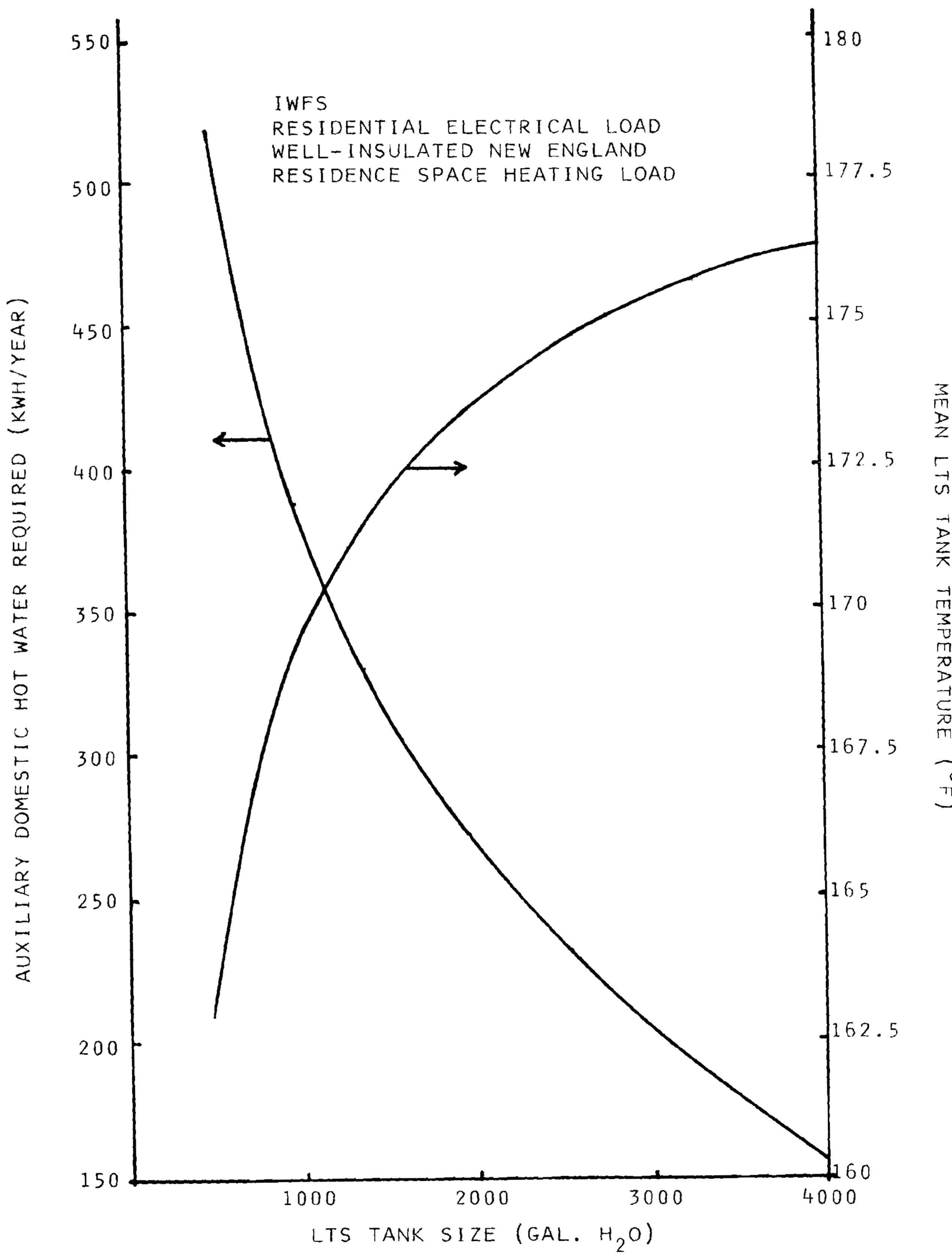


FIGURE 5.3. AUXILIARY DOMESTIC HOT WATER REQUIRED AND MEAN LTS TANK TEMPERATURE AS A FUNCTION OF LTS TANK SIZE.

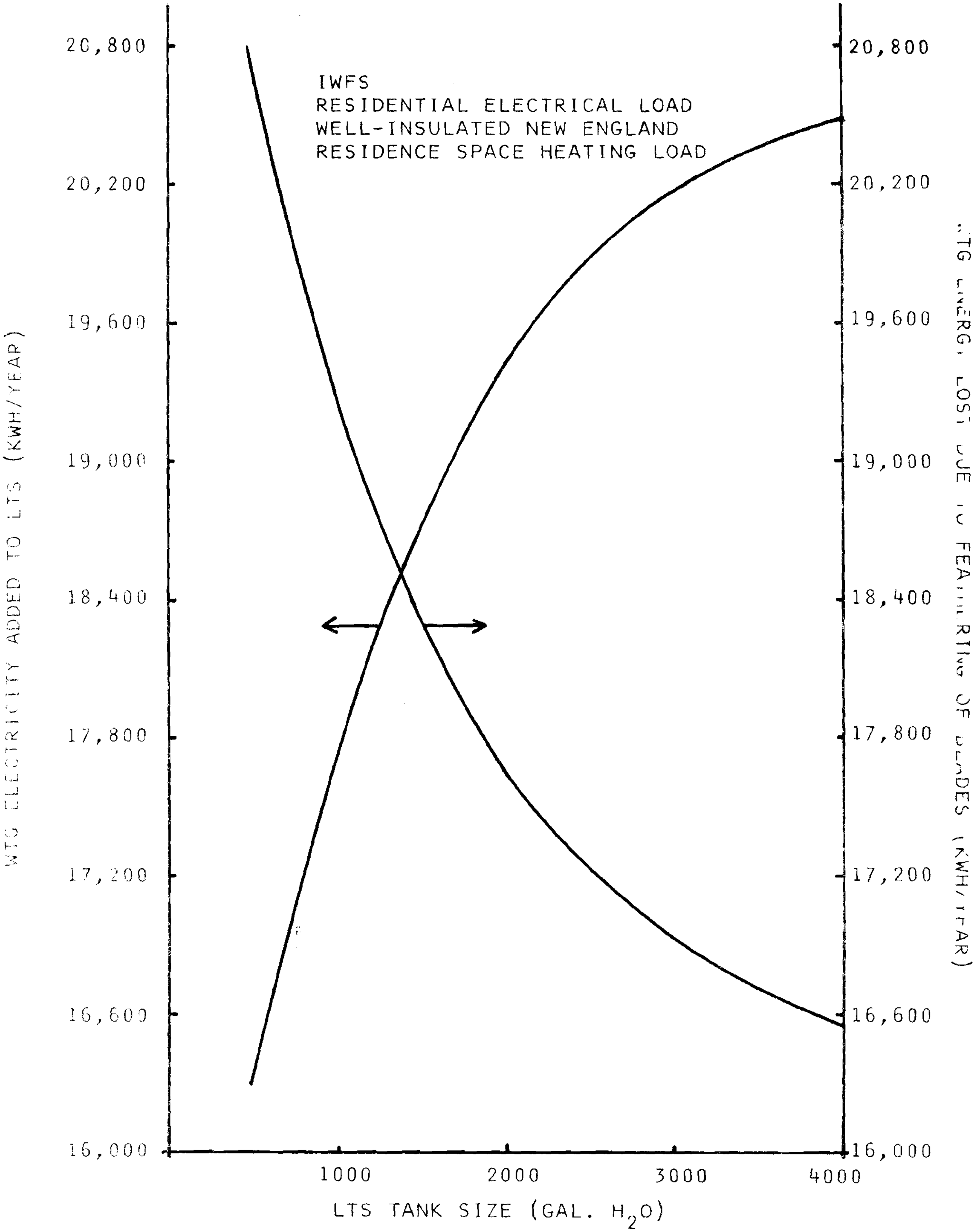


FIGURE 5.4. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE LTS AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF LTS TANK SIZE.

IWFS decrease rapidly until a 2,000 gal. tank storage size is reached. Once this size tank is used, the auxiliary space heating requirement decreases virtually to zero and the total auxiliary energy requirement decreases to approximately 10% of the total energy load. Also of interest in Figure 5.2 is the auxiliary electricity required which remains constant for all LTS tank sizes. This is due to the fact that in the IWFS model, electricity is the first priority of the WTG output, and there is no provision in the system for another electrical energy source, such as the Rankine Cycle in the WDTES models. This constant auxiliary electricity requirement is a feature with all the IWFS imposed load combinations although the amount of the requirement will change with different electrical loads. Figures 5.3 and 5.4 show the strong interdependence, as a function of LTS tank size, of the auxiliary domestic hot water requirement, the mean LTS tank temperature, the WTG energy lost due to feathering. As the LTS tank size increases, its capacity to store energy also rises. This allows more WTG electricity to be added to the LTS and less loss due to feathering. Because so much more energy remains in the system, the average LTS tank temperature increases even though the tank size has also. The higher average temperature and the greater stored energy volume make the stored energy more able to supply energy to the domestic hot water load and the space heating load, causing the auxiliary requirements to decrease.

The IWFS model results using the average New England residence energy requirements are shown in Figures 5.5 to 5.8. As in Figure 5.1, Figure 5.5 shows a minimum total auxiliary energy requirement after the 2,000 gal. LTS storage size is reached. (This minimum represents approximately 28% of the 44,733kWh imposed loads on the system.) In Figure 5.6, the auxiliary

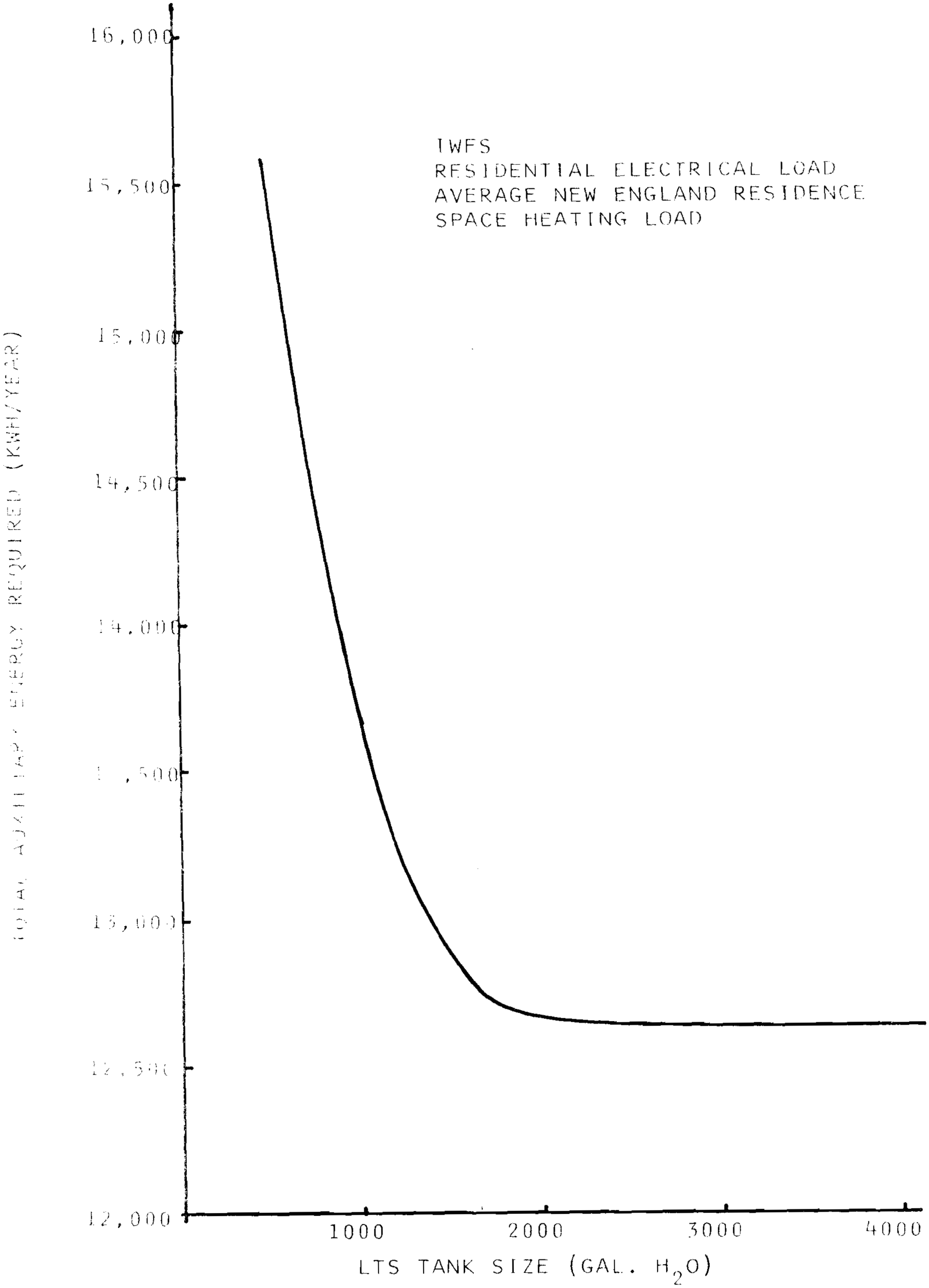


FIGURE 5.5. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF LTS TANK SIZE.

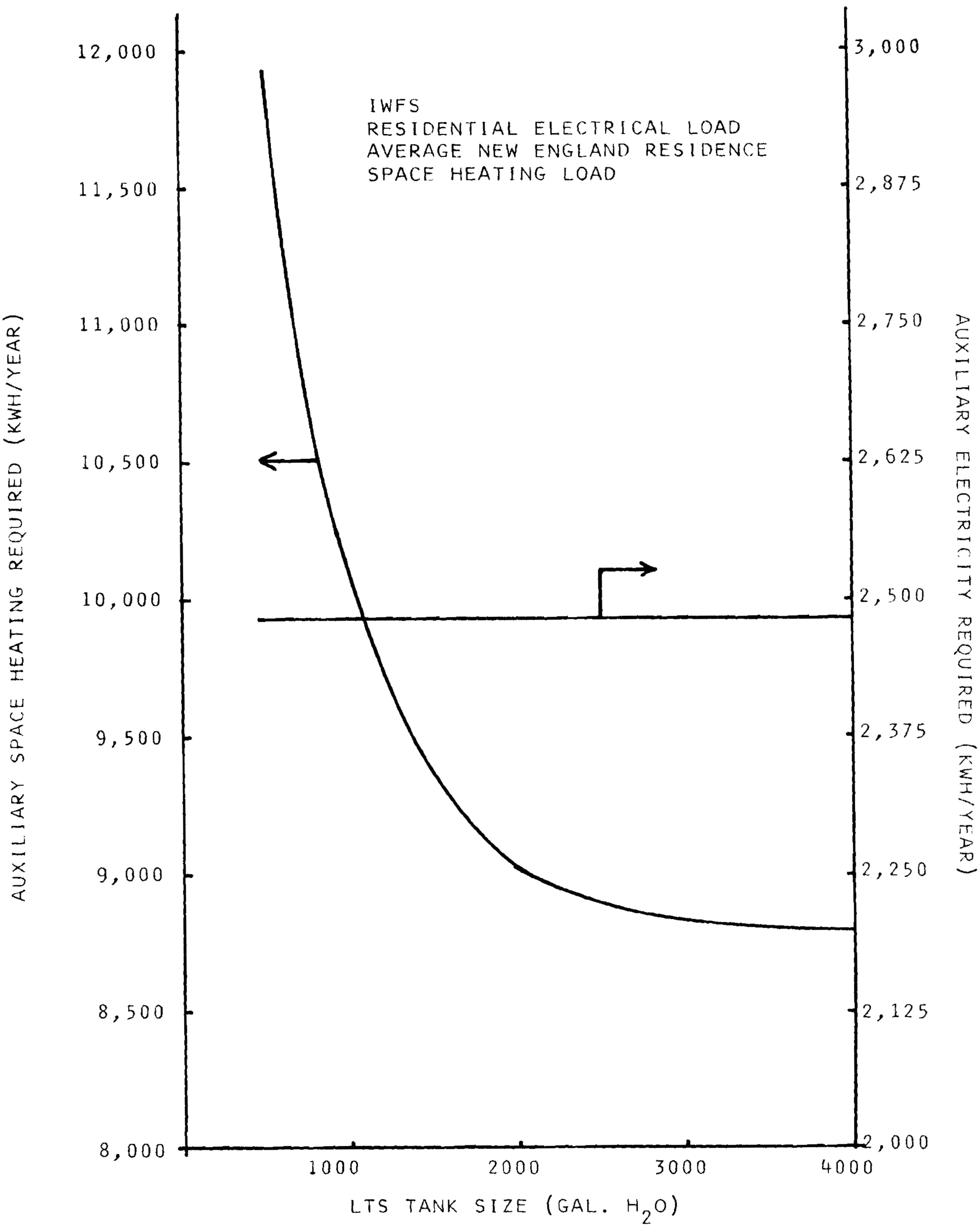
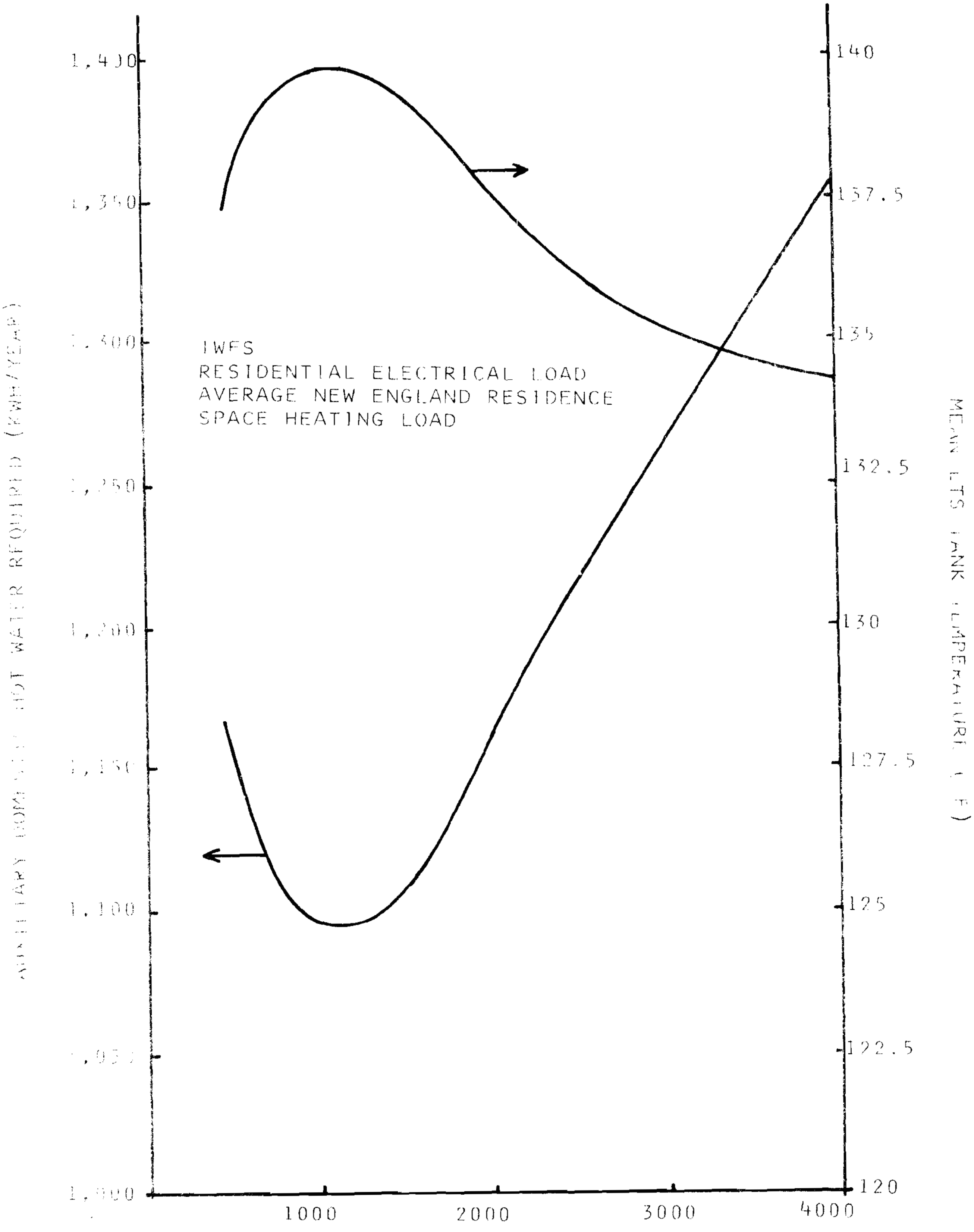


FIGURE 5.6. AUXILIARY SPACE HEATING AND AUXILIARY ELECTRICITY REQUIRED AS A FUNCTION OF LTS TANK SIZE.



LTS TANK SIZE (GAL. H_2O)

FIGURE 5.7. AUXILIARY DOMESTIC HOT WATER REQUIRED AND MEAN LTS TANK TEMPERATURE AS A FUNCTION OF LTS TANK SIZE.

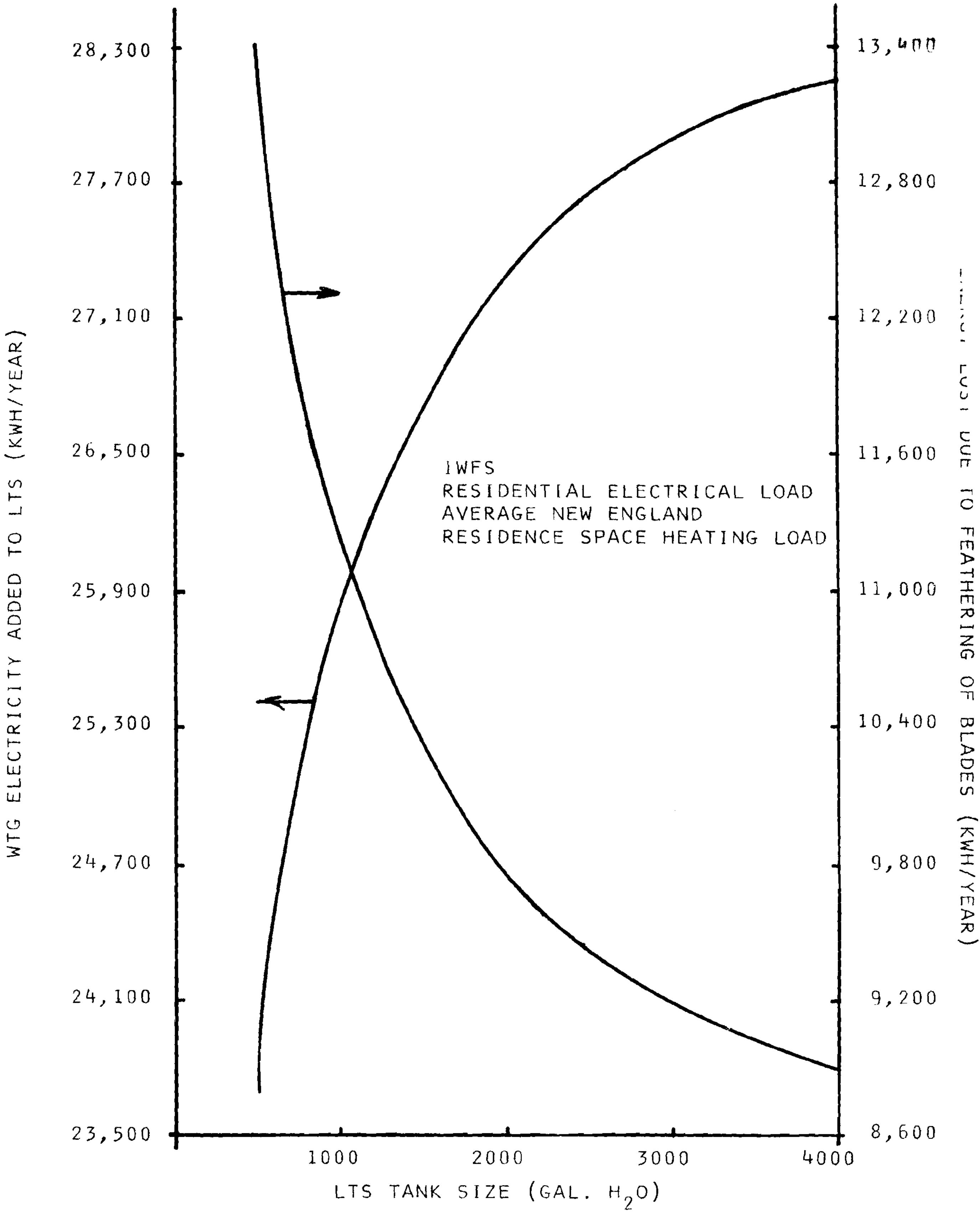


FIGURE 5.8. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE LTS AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF LTS TANK SIZE

space heating and electricity requirements are shown. It should be noted that the auxiliary electricity requirement is exactly the same for the average New England residence and the well insulated residence. However, the auxiliary domestic hot water requirements and the mean LTS tank temperature curves shown in Figure 5.7 show a marked dissimilarity to the curves in Figure 5.3 for the well-insulated home. Figure 5.8 can give insight into the reasons for these differences. In Figure 5.8 as LTS tank size increases, more WTG electricity is supplied to the LTS and less is lost due to feathering of the blades. However, this increase in added energy is not large enough to increase the mean tank temperature of the LTS at sizes over 1000 gallons as shown in Figure 5.7 because of the large space heating load and the greater LTS mass. This causes the maximum mean LTS tank temperature to occur at a tank size of approximately 1000 gallons and also sets a minimum auxiliary domestic hot water requirement at that point.

The performance of the average New England farm application of the IWFS model is shown in Figures 5.9 to 5.12. As can be seen in Figure 5.9, the minimum total auxiliary energy requirement for the farm occurs again at the 2000 gallon LTS tank size, and represents about 37% of the total energy requirements of the farm. Since the farm model has greater electrical energy requirements than does the residence, more WTG electricity must be first supplied to the electrical load, leaving less for the space heating and domestic hot water loads. This causes all the farm auxiliary energy requirements, shown in Figures 5.10 and 5.11, to increase over the corresponding requirements in Figures 5.6 and 5.7 for the average residential

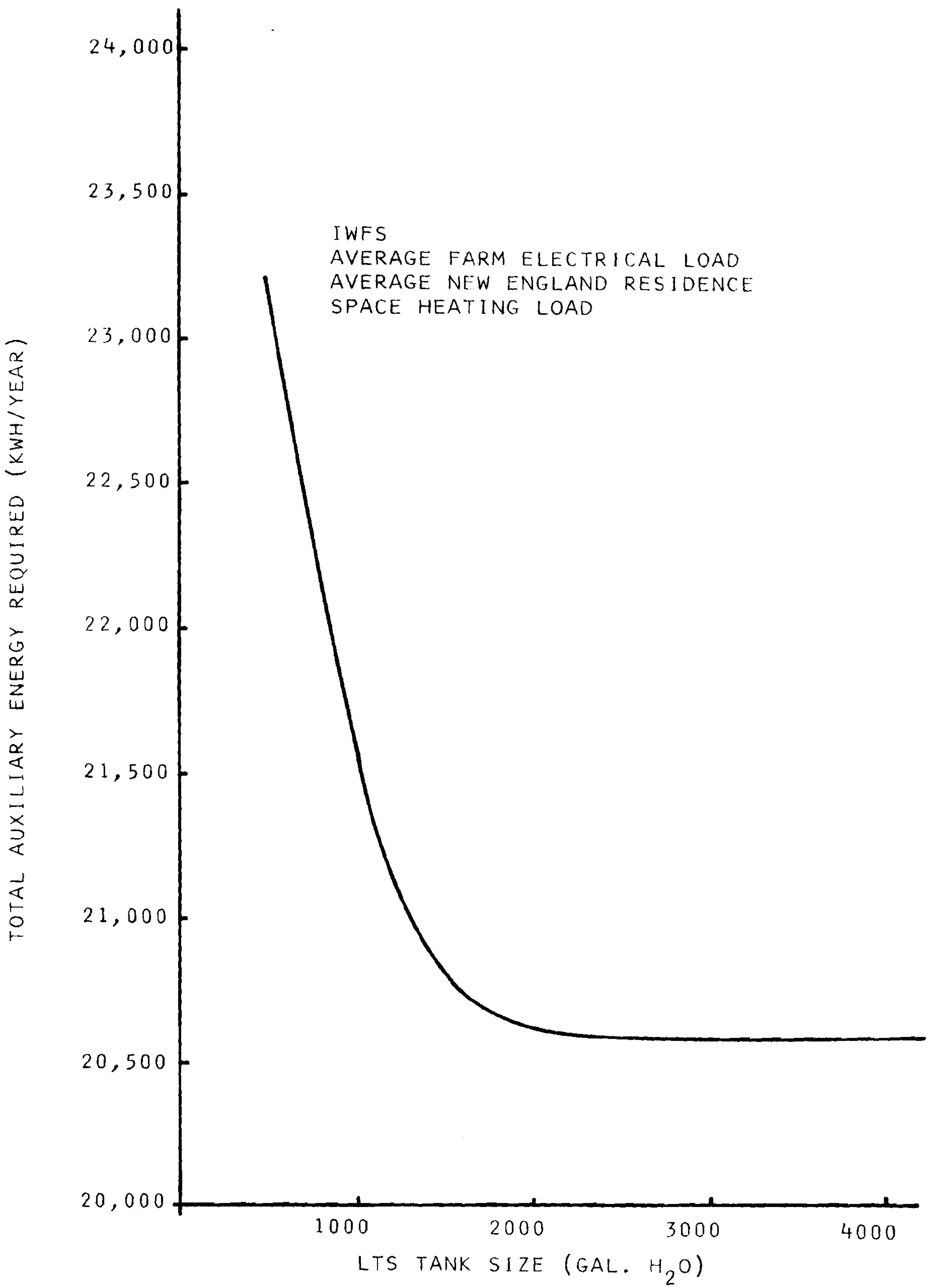


FIGURE 5.9. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF LTS TANK SIZE.

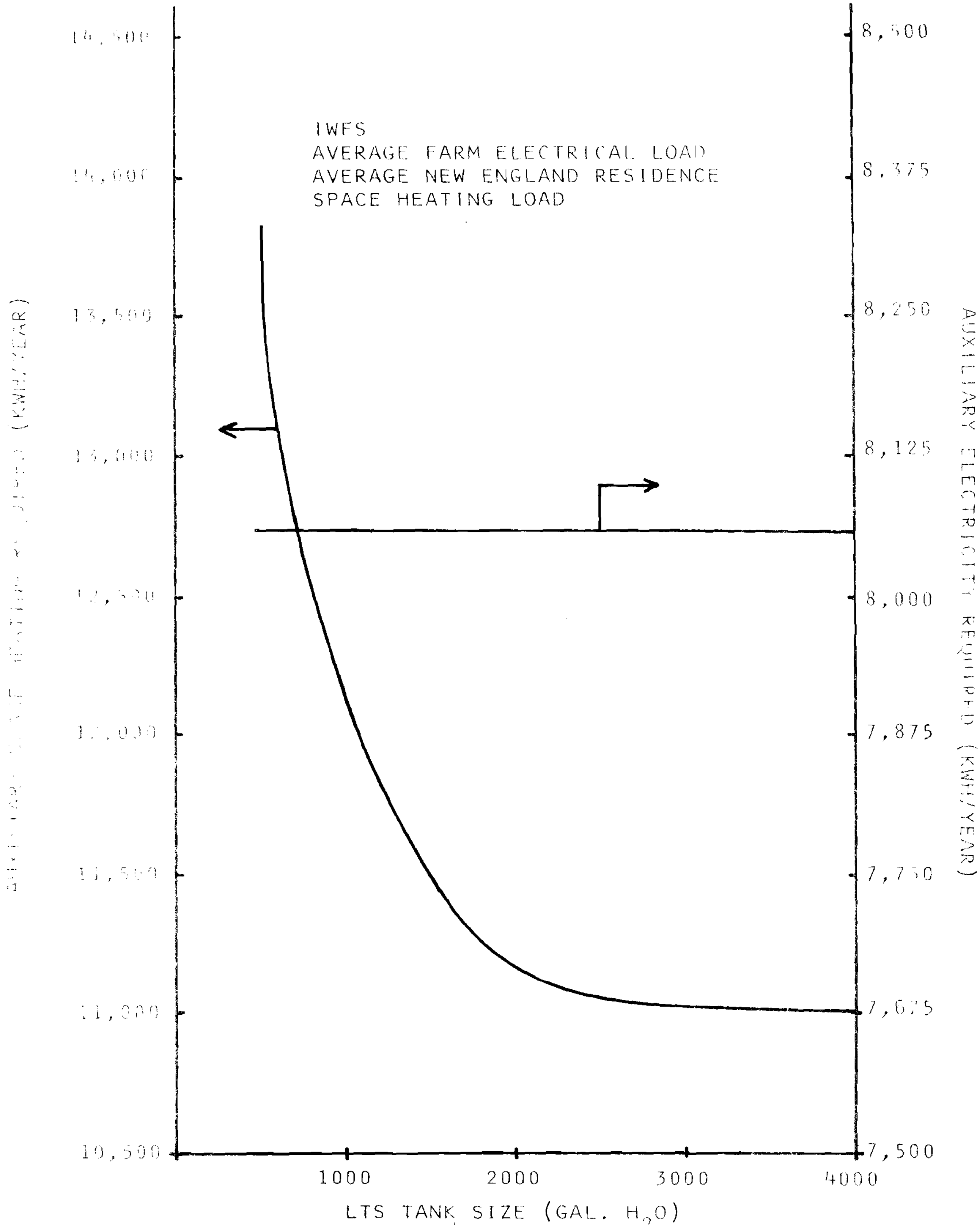


FIGURE 5.10. AUXILIARY SPACE HEATING AND AUXILIARY ELECTRICITY REQUIRED AS A FUNCTION OF LTS TANK SIZE.

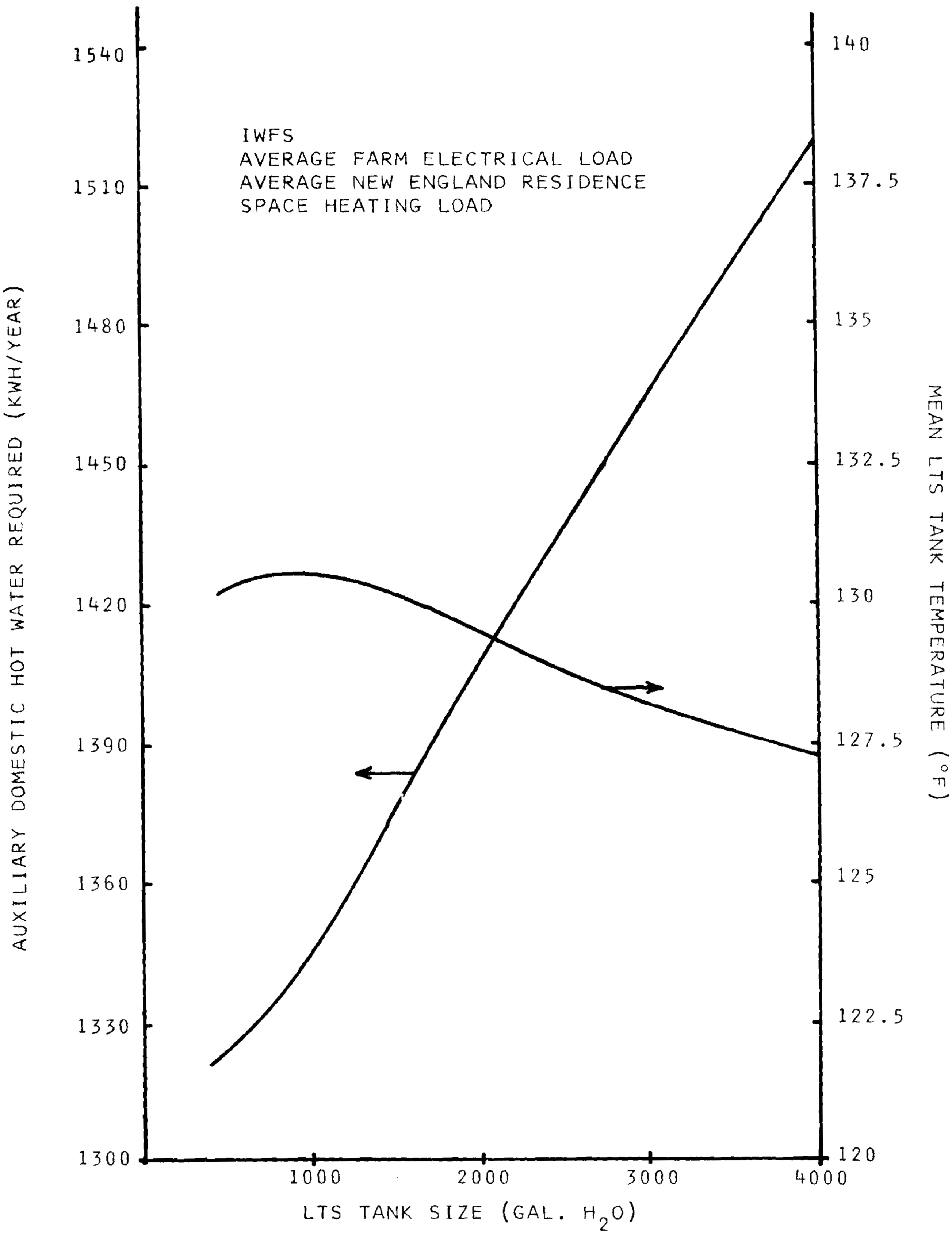


FIGURE 5.11. AUXILIARY DOMESTIC HOT WATER REQUIRED AND MEAN LTS TANK TEMPERATURE AS A FUNCTION OF LTS TANK SIZE.

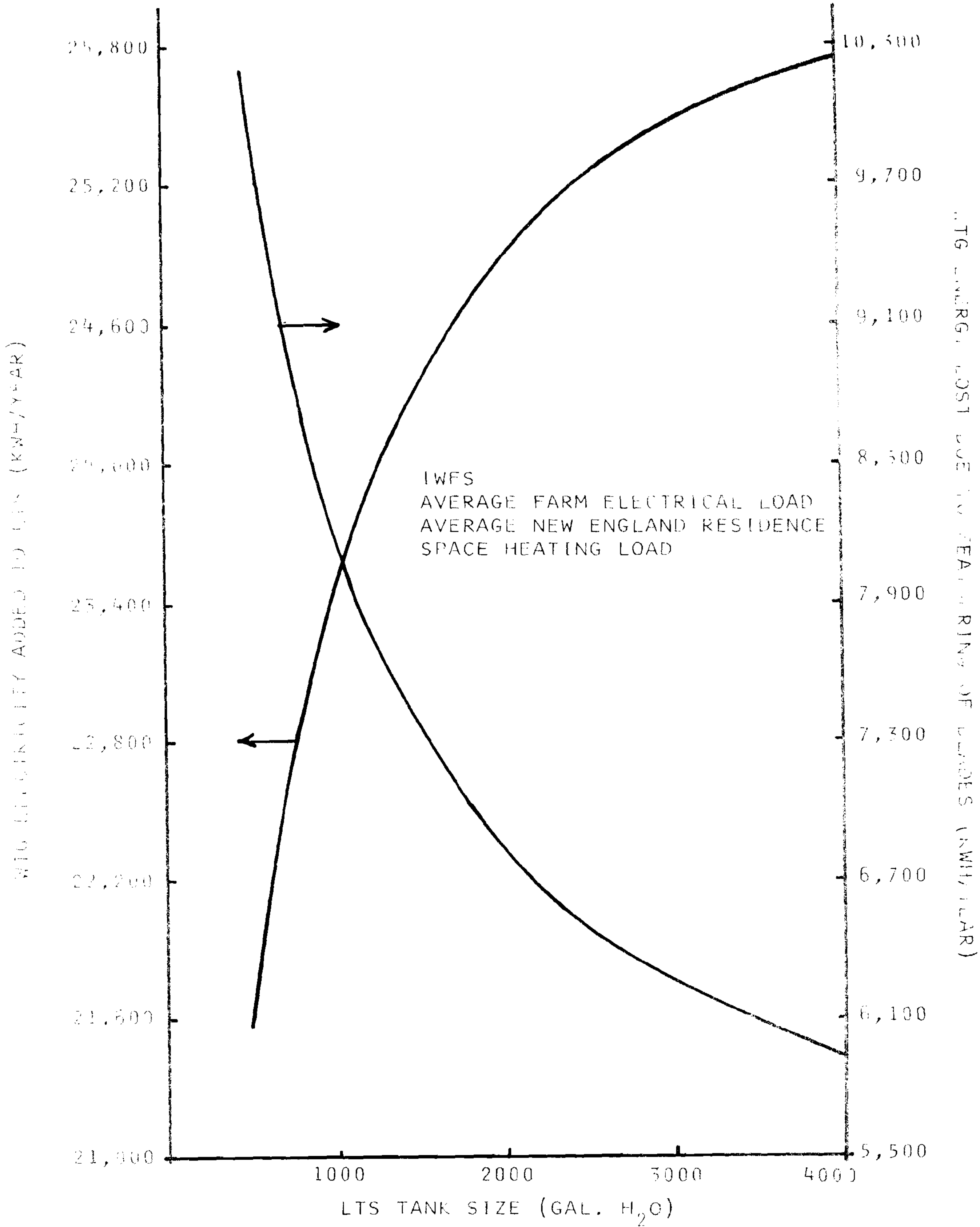


FIGURE 5.12. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE LTS AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF LTS TANK SIZE.

application. Although more of the WTG energy is utilized, as can be seen by comparing Figures 5.12 and 5.8, the mean LTS tank temperature is still less, as seen in Figures 5.11 and 5.7, for the farm application due to the diversion of WTG energy to the much larger electrical load.

5.2 Wind Driven Total Energy System, Type I Results

The Wind Driven Total Energy System, Type I performance results for the well-insulated New England residence setting are represented in Figures 5.13 through 5.19. For all WDTES runs made, it was found that increasing the LTS tank size over 2000 gallons would not increase system performance significantly, but that decreasing LTS tank size to 1000 gallons would decrease performance. As shown in Figure 5.13, the minimum total auxiliary energy requirement for the WDTES, Type I system with a 100% and 75% "maximum" efficiency Rankine Cycle subsystem are approximately 6% and 7% of the 26,516kWh imposed load, respectively, with the minimum occuring at the 250 gallon HTS tank size with "maximum" RC efficiency. Of this percentage, a large portion of the space heating and the domestic hot water auxiliary energy is required during the start up period, and thus the system once in operation in this setting should only require some utility supplied electricity occasionally. This is corroborated by Figures 5.14 and 5.15. It should be noted that the effects of decreased Rankine Cycle efficiency cause the system to require less low grade space heating energy but more high grade electrical energy. Also, as seen in Figures 5.15 through 5.18, the decreased RC efficiency for the given HTS tank size causes the HTS to operate at a lower mean tank temperature annually and during the RC operation periods. This lower mean HTS temperature causes

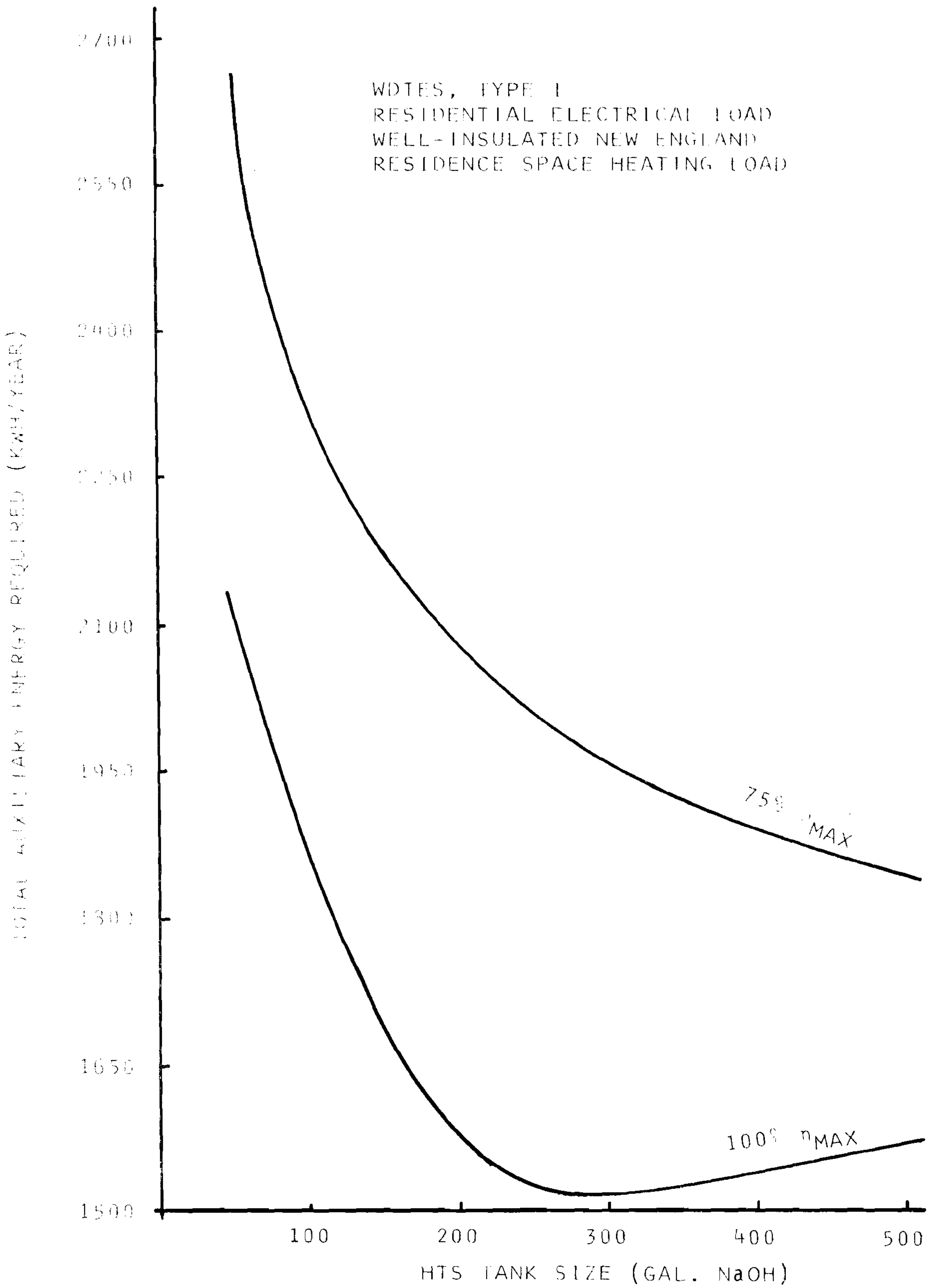


FIGURE 5.13. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

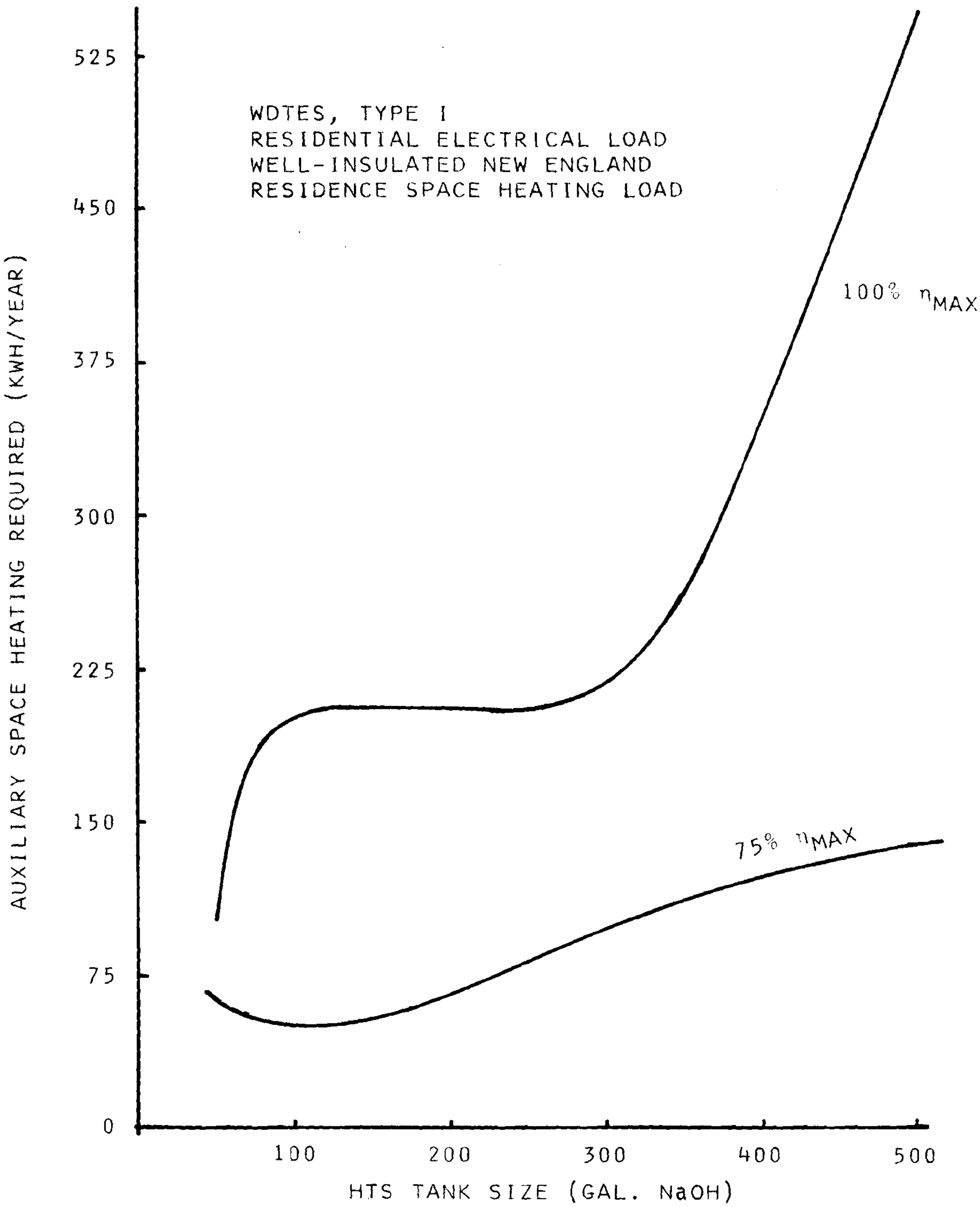


FIGURE 5.14. AUXILIARY SPACE HEATING REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

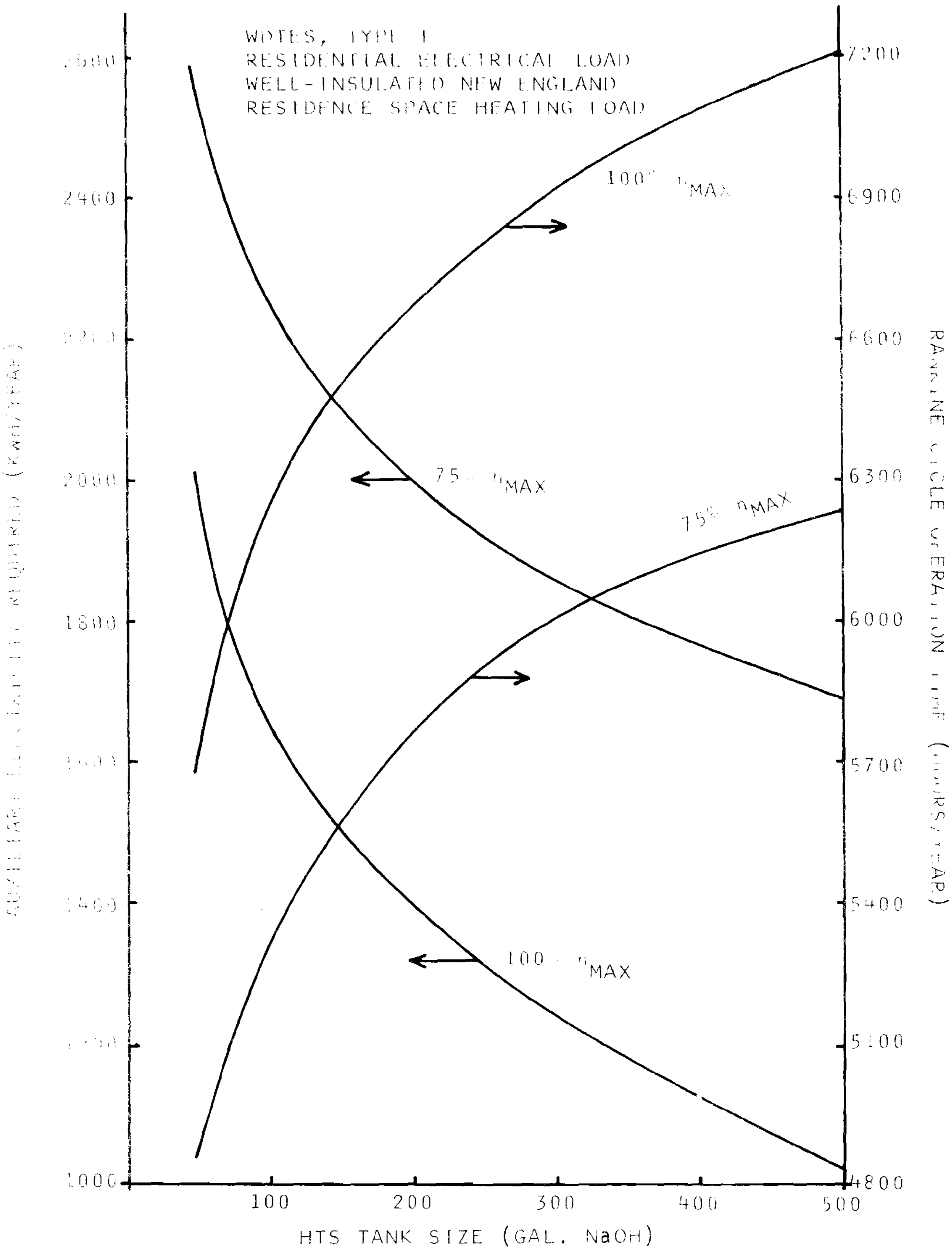


FIGURE 5.15. AUXILIARY ELECTRICITY REQUIRED AND RANKINE CYCLE OPERATION TIME AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES

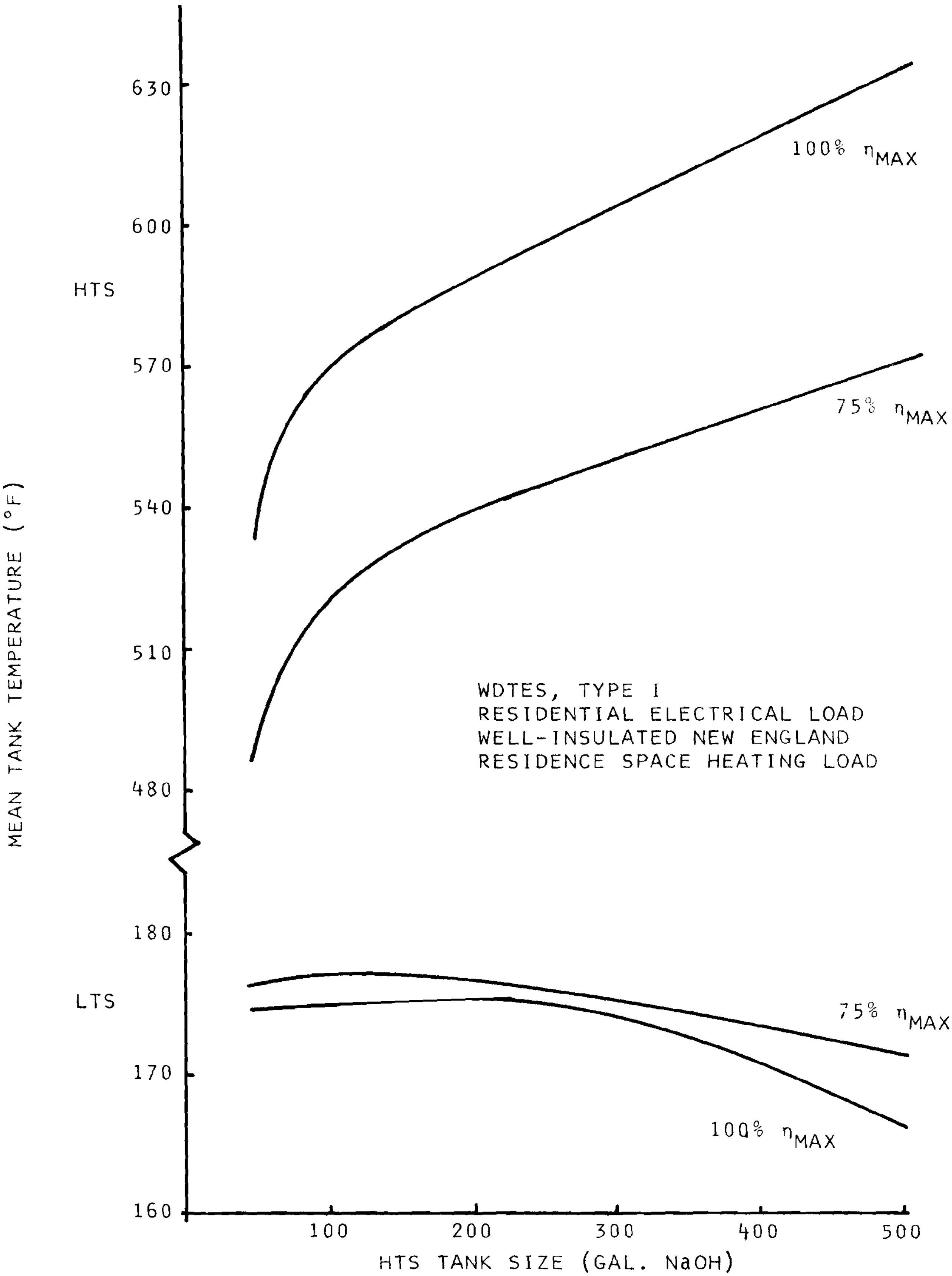


FIGURE 5.16. HTS AND LTS MEAN TANK TEMPERATURES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

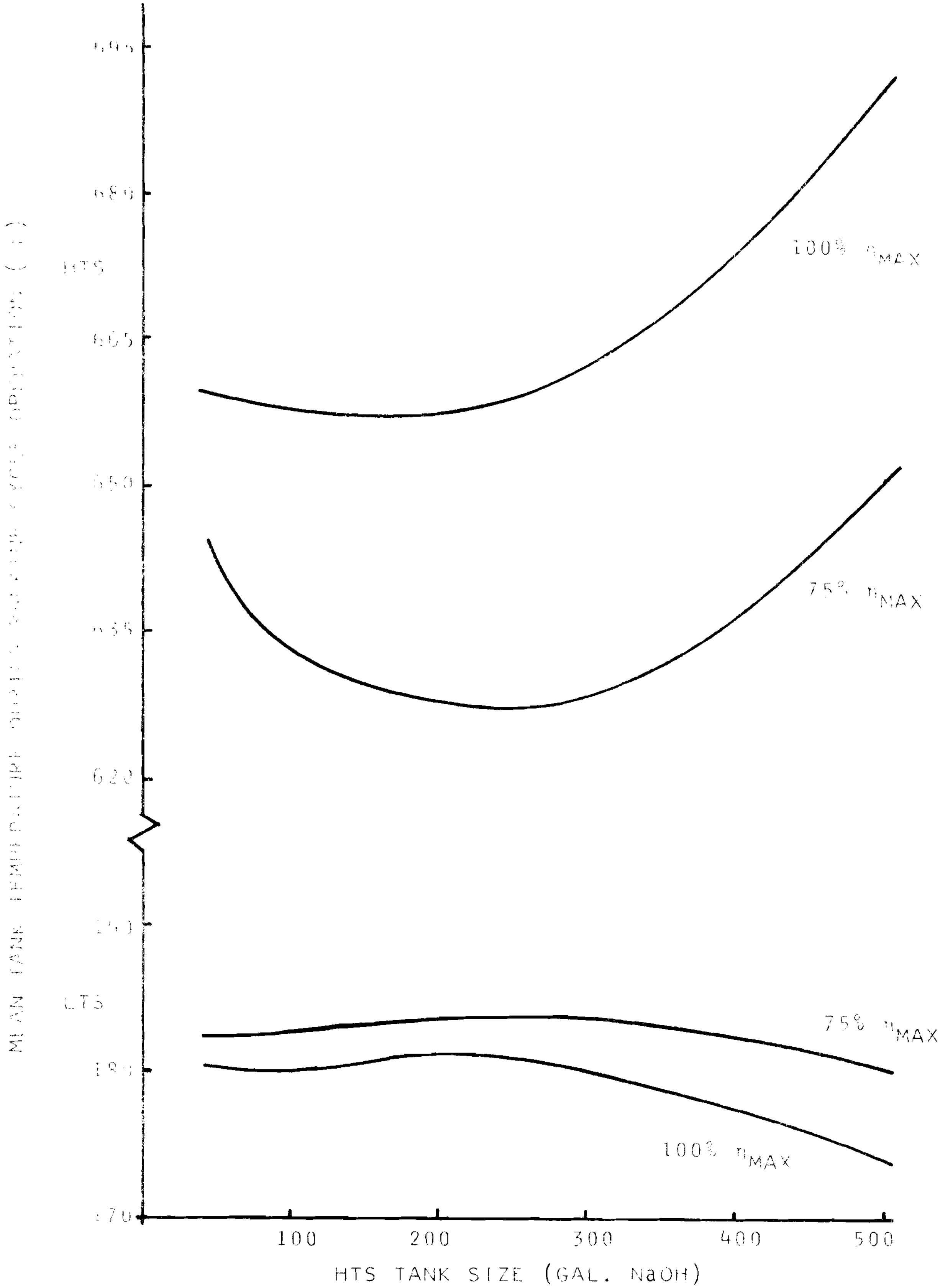


FIGURE 5.17. HTS AND LTS MEAN TANK TEMPERATURES DURING RANKINE CYCLE OPERATION AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

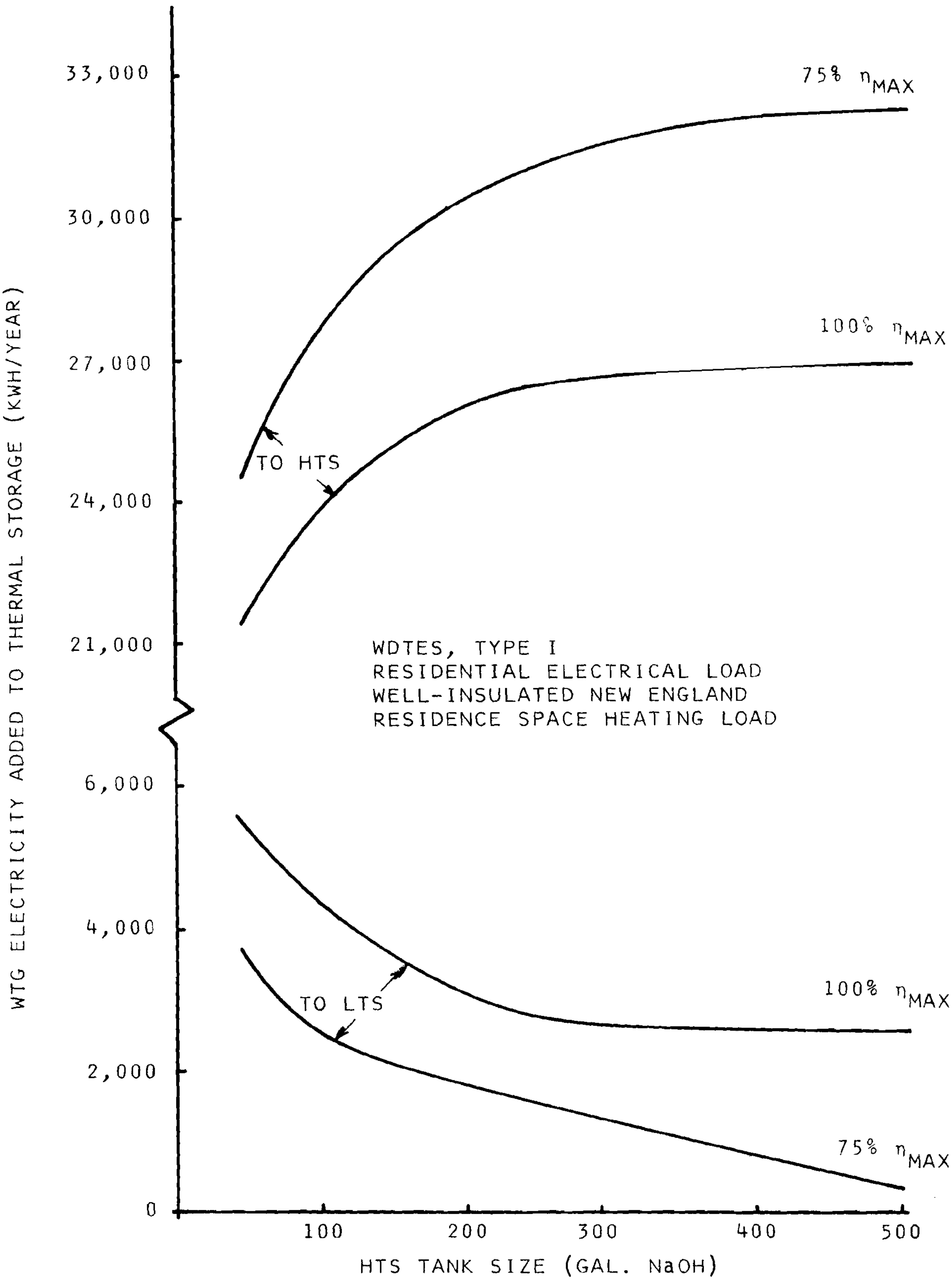


FIGURE 5.18. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE HTS AND LTS AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

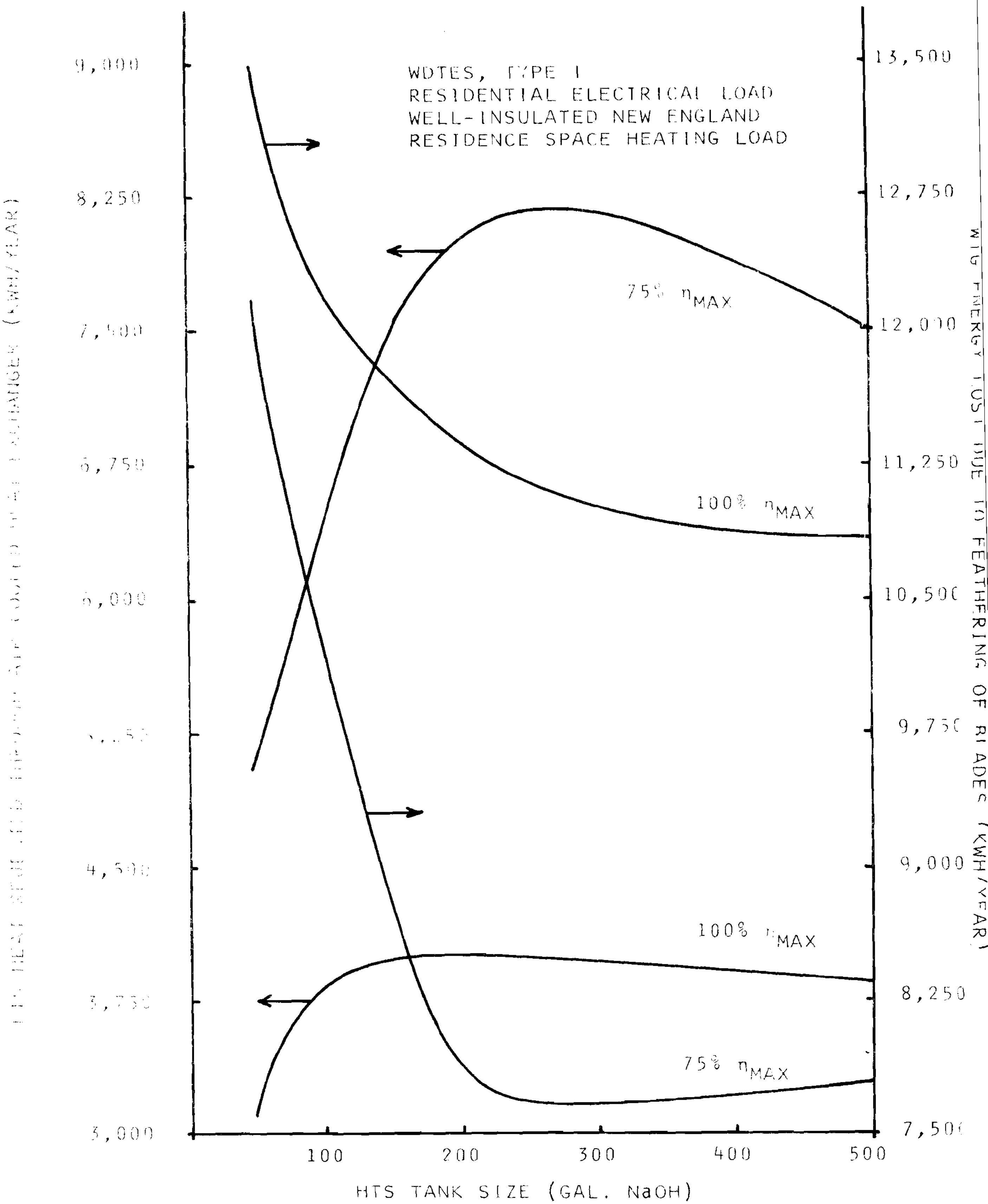


FIGURE 5.19. LTS HEAT REJECTED THROUGH THE AIR COOLED HEAT EXCHANGER AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

more of the WTG energy to be added to the HTS and less to the LTS, but it also keeps the HTS temperature below the minimum 400°F temperature required for RC operation more of the time and thus the Rankine Cycle does not operate as frequently. The annual mean tank temperature and the mean tank temperature during RC operation shown in Figures 5.16 and 5.17, can give an indication to the design temperatures requirements of the Rankine Cycle components such as the heat exchangers and the turbine and also can help in the choice of baseboards and hot water coils for the system. Figure 5.18 shows that with increasing HTS tank size, more WTG energy is added to the HTS, leaving less available for the LTS. Another important effect of decreased Rankine Cycle efficiency is shown in Figure 5.19. For a given HTS tank size, the amount of heat which must be rejected from the LTS to prevent boiling is greater with decreased RC efficiency. This is due to the fact that the amount of heat rejected from the condenser of the Rankine Cycle must be greater for a given required RC output with a less efficient Rankine Cycle.

The analytical results for the WDTES, Type I system when used in conjunction with the average New England residence model are shown in Figures 5.20 through 5.26. As indicated in Figure 5.20, the minimum total auxiliary energy requirement for the ssytem, with maximum Rankine Cycle efficiency, is less than 28% of the 44,733kWh total energy requirements for a 100 gallon HTS. The use of the WDTES, Type I scheme for this application does not significantly affect the auxiliary electricity requirements, the Rankine Cycle operation time, the WTG electricity added to the HTS thermal storage and the HTS temperatures when compared to the well-insulated home

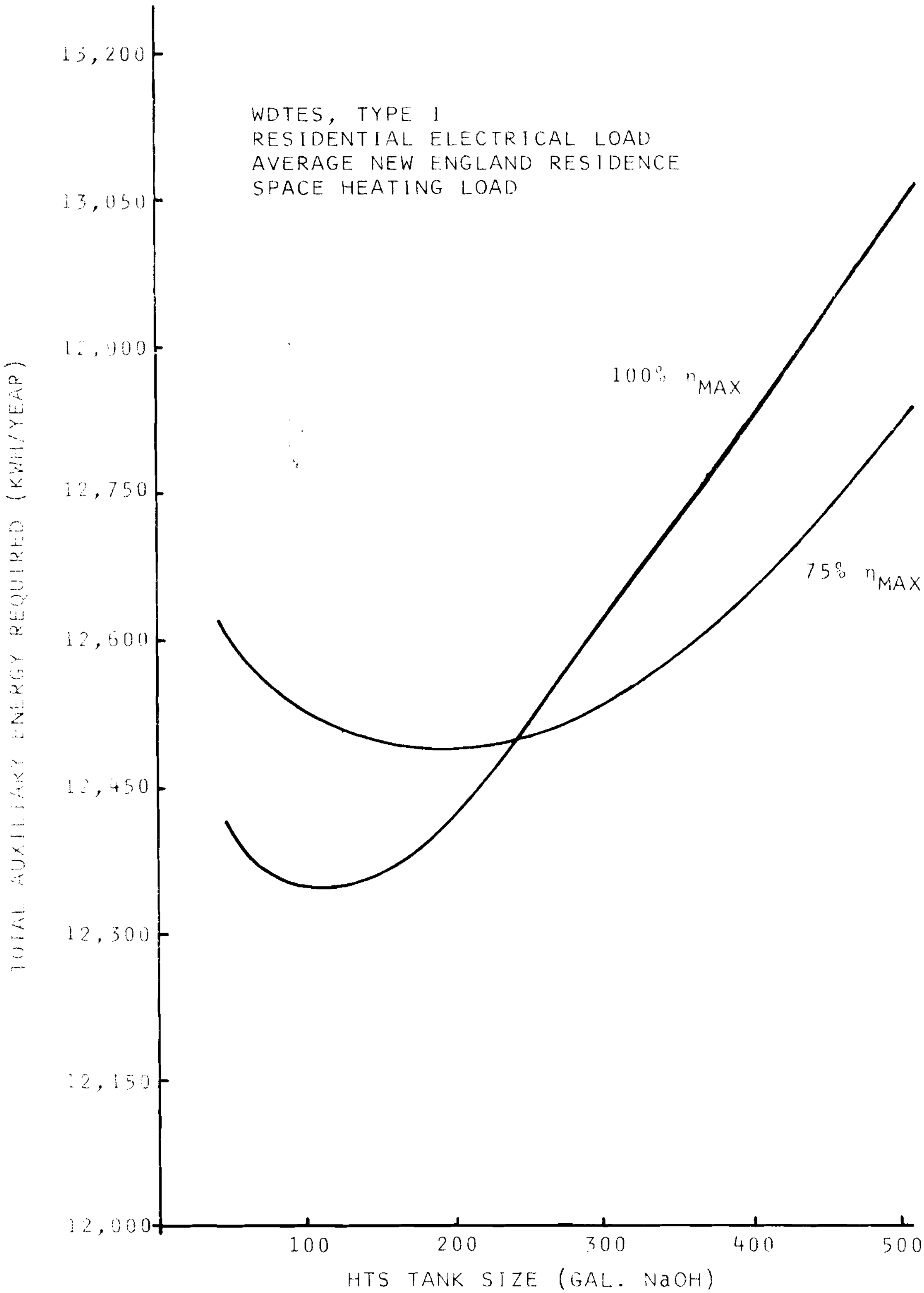


FIGURE 5.20. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

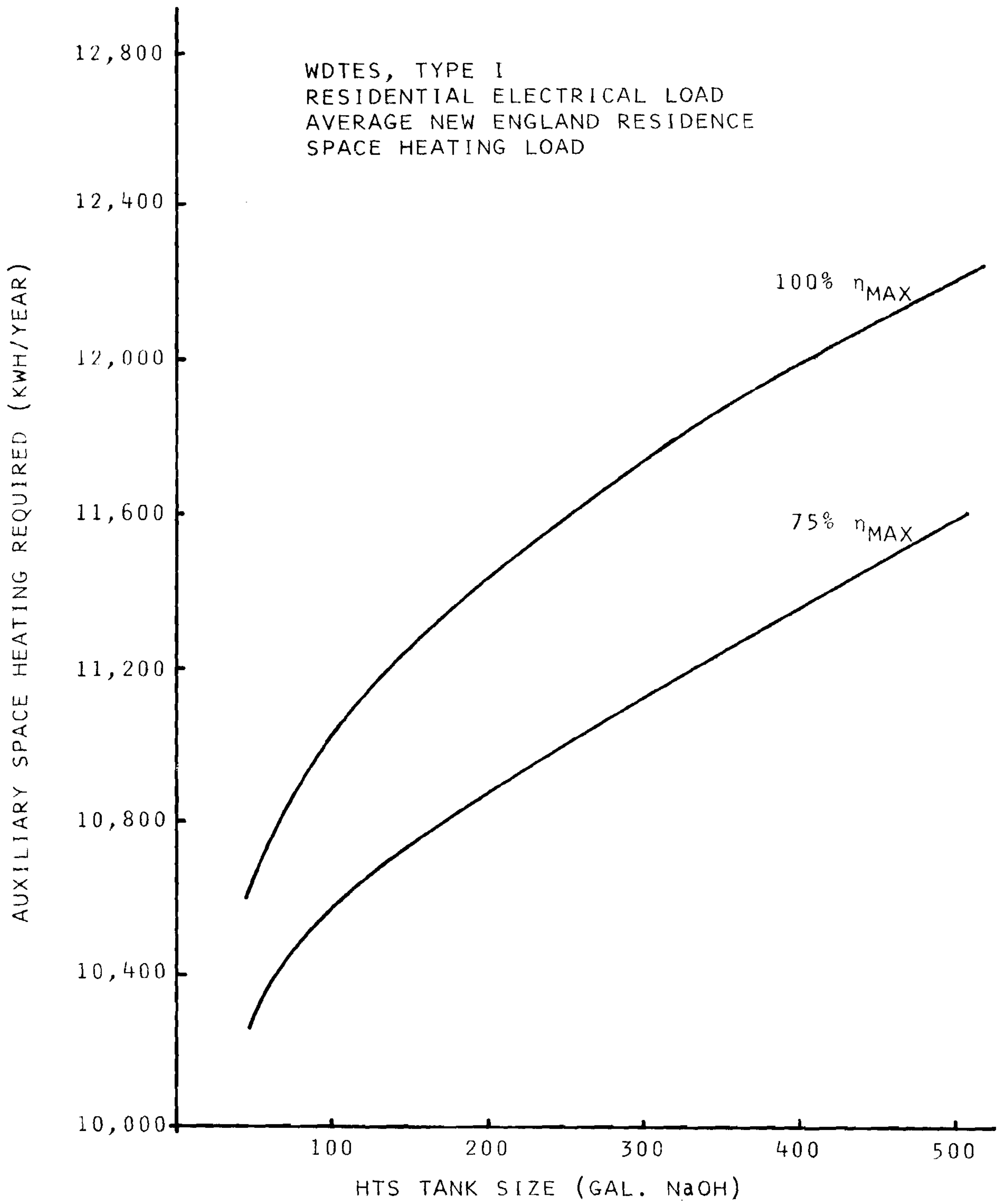


FIGURE 5.21. AUXILIARY SPACE HEATING REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

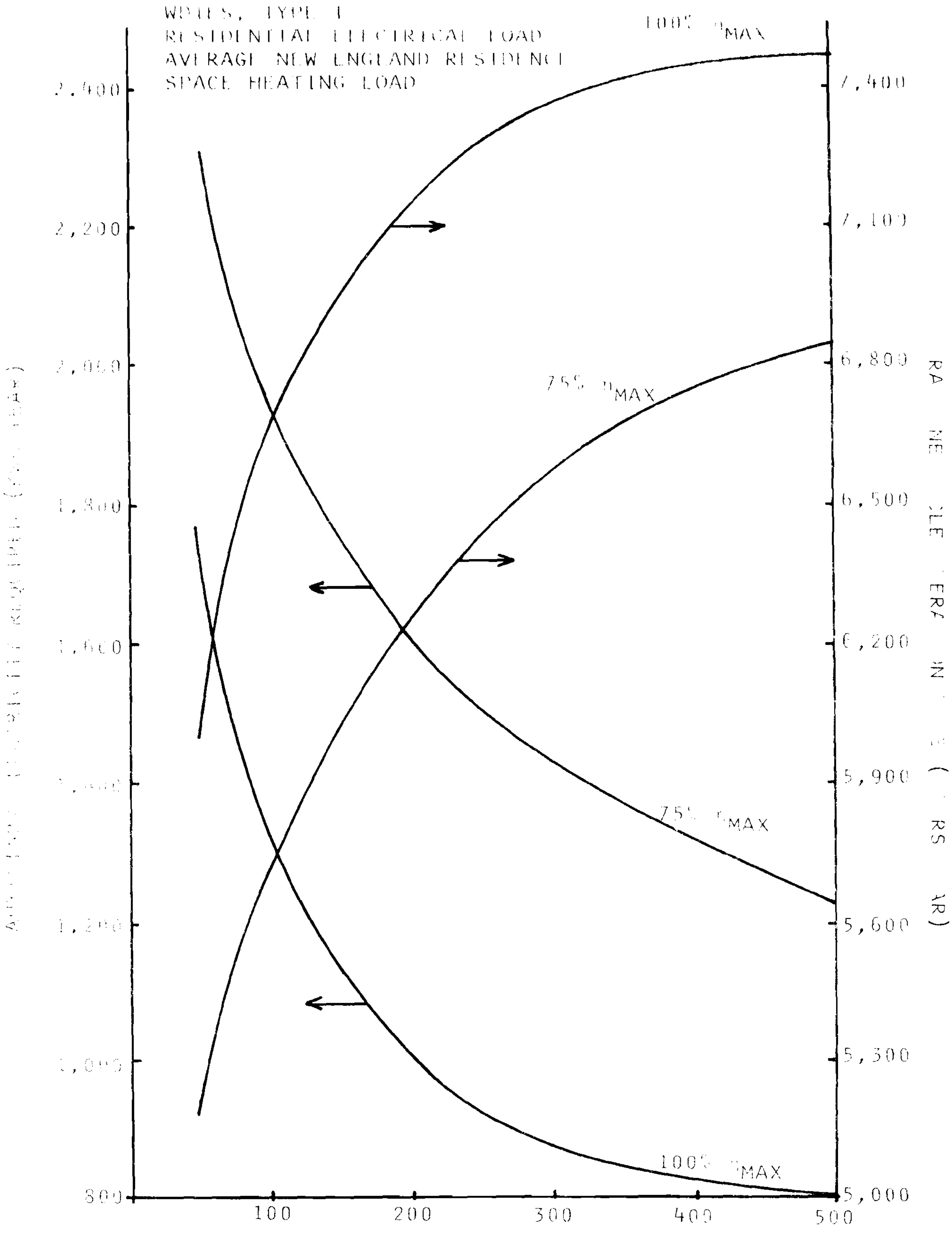


FIGURE 5.22. AUXILIARY ELECTRICITY REQUIRED AND RANKINE CYCLE OPERATION TIME AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

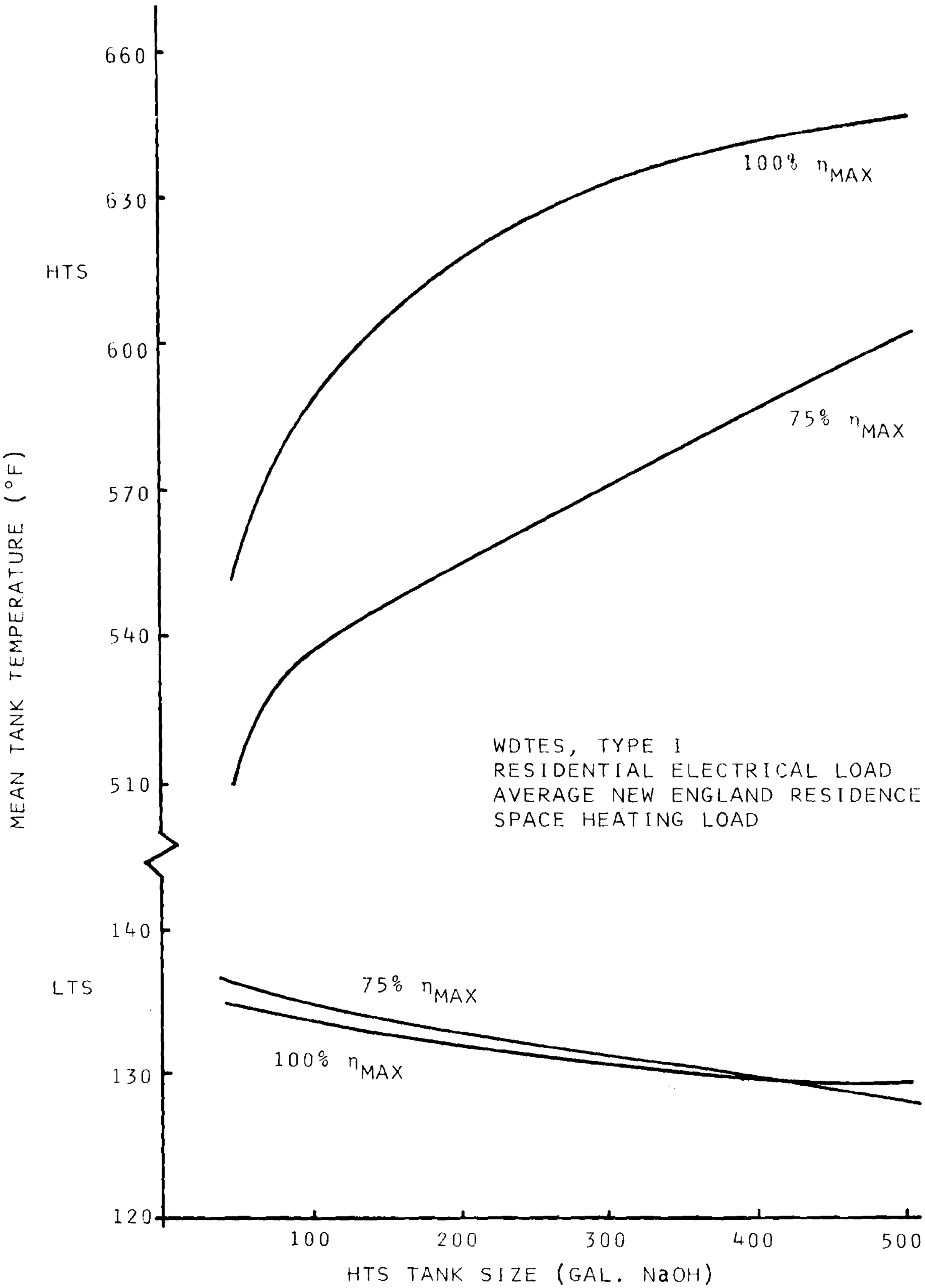


FIGURE 5.23. HTS AND LTS MEAN TANK TEMPERATURES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

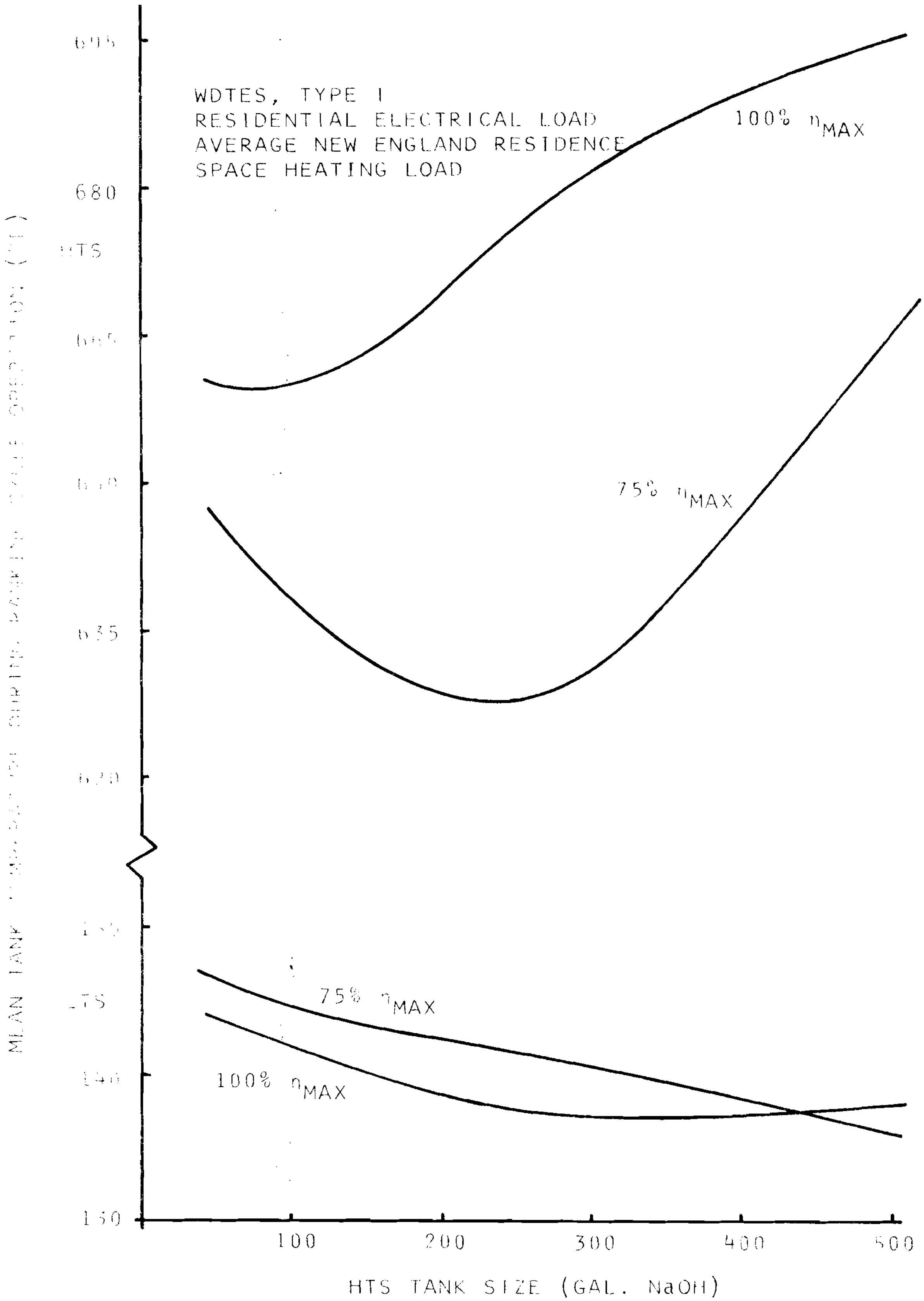


FIGURE 5.24. HTS AND LTS MEAN TANK TEMPERATURES DURING RANKINE CYCLE OPERATION AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

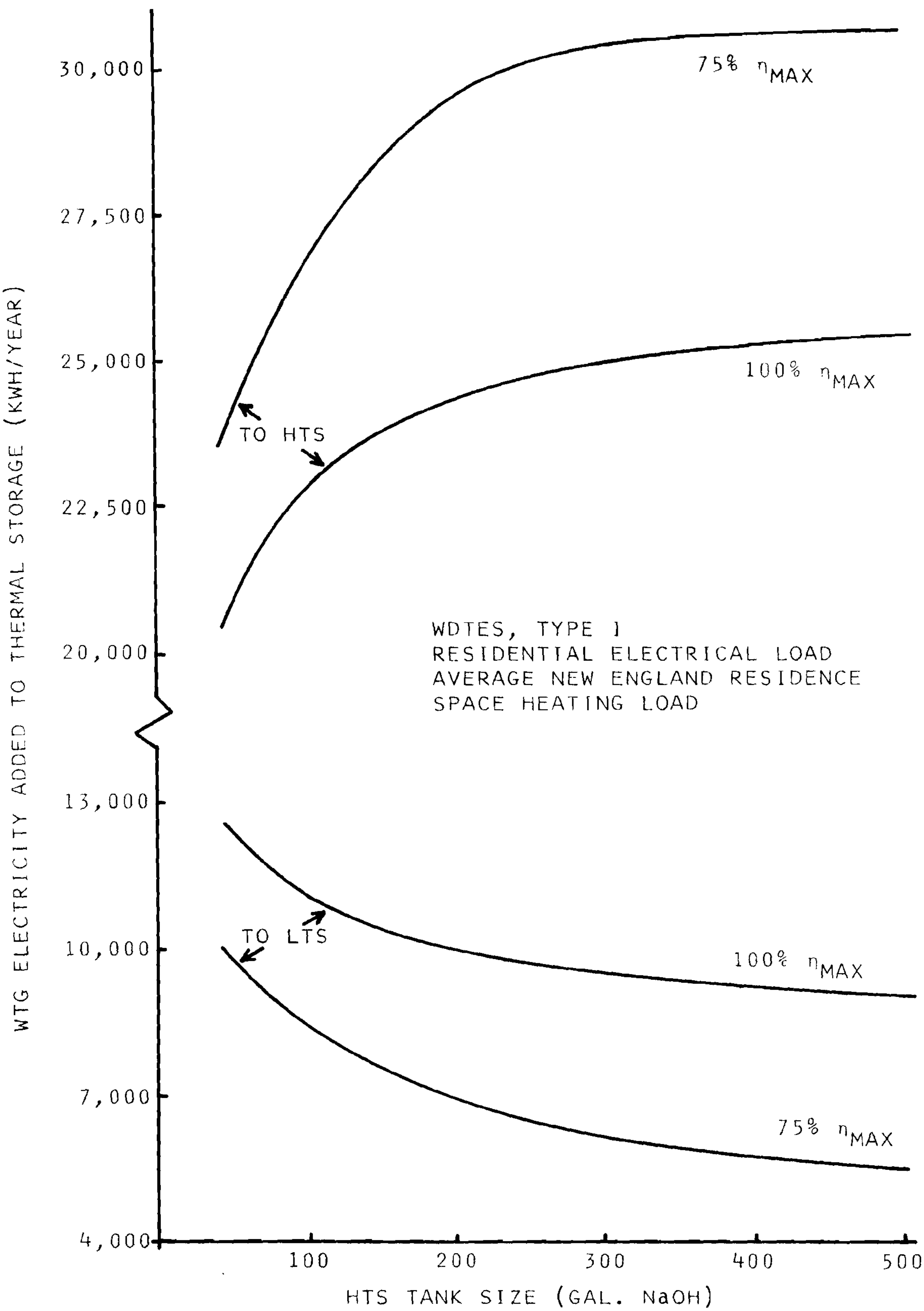


FIGURE 5.25. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE HTS AND LTS AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

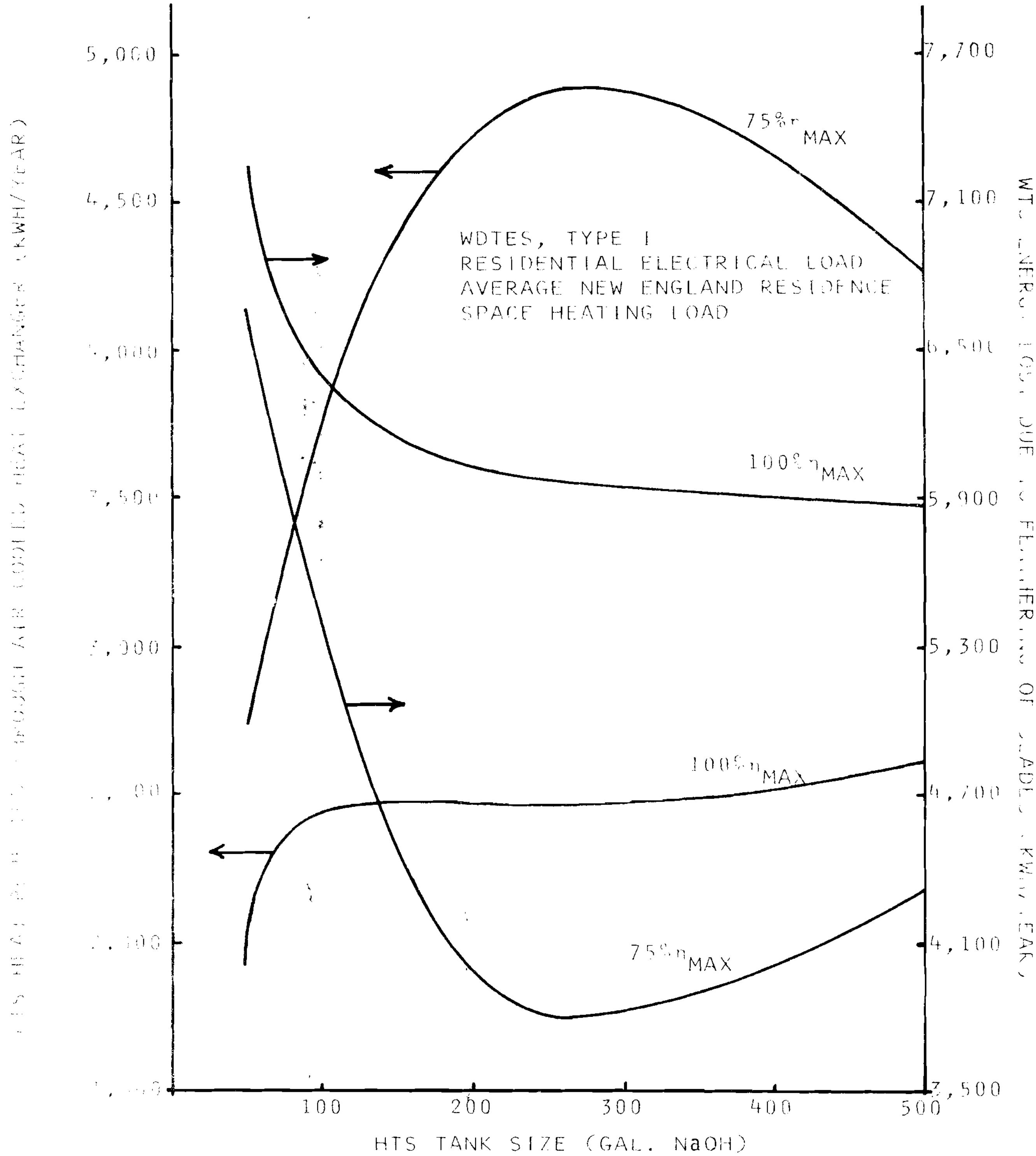


FIGURE 5.26 LTS HEAT REJECTED THROUGH THE AIR COOLED HEAT EXCHANGER AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

application. This can be inferred if Figures 5.22 through 5.25 are compared with Figures 5.15 through 5.18. The main differences between the system's performance in the two applications is in the effects of the higher space heating load which can be seen by comparing the auxiliary requirements in Figures 5.21 and 5.14. Because the energy sent to the space heating load is removed from the LTS, the temperature in this tank is much lower, as shown by comparing Figures 5.23 and 5.24 with 5.16 and 5.17, than it would be with the lower heating load model. This effect takes place in spite of the fact that more of the WTG electricity is added to the LTS and less system energy is wasted from the LTS through the air-cooled heat exchanger and from the WTG by feathering the blades as shown in Figures 5.25, 5.26, 5.18 and 5.19.

The use of the WDTES, Type I model with the average New England farm is depicted by Figures 5.27 to 5.33. These Figures reveal the effects of higher electrical energy demands on the system, which has a minimum total auxiliary energy requirement of about 49% of the 55,684kWh imposed loads with a 100 gallon HTS. Although a 50 gallon HTS may require slightly less auxiliary energy, large fluctuations in the RC turbine inlet temperature make this impractical. The auxiliary space heating requirements and the mean LTS tank temperature for the well insulated home and the farm application are virtually the same as seen in a comparison of Figures 5.28 and 5.21, or 5.30 and 5.23. The auxiliary electrical requirements for the two uses vary greatly however, with the farm application requiring a much greater auxiliary electricity supply as can be seen in a comparison of Figures 5.29 and 5.22. This high auxiliary requirement is due to the rapid depletion of the energy stored in the HTS, which is indicated in Figures

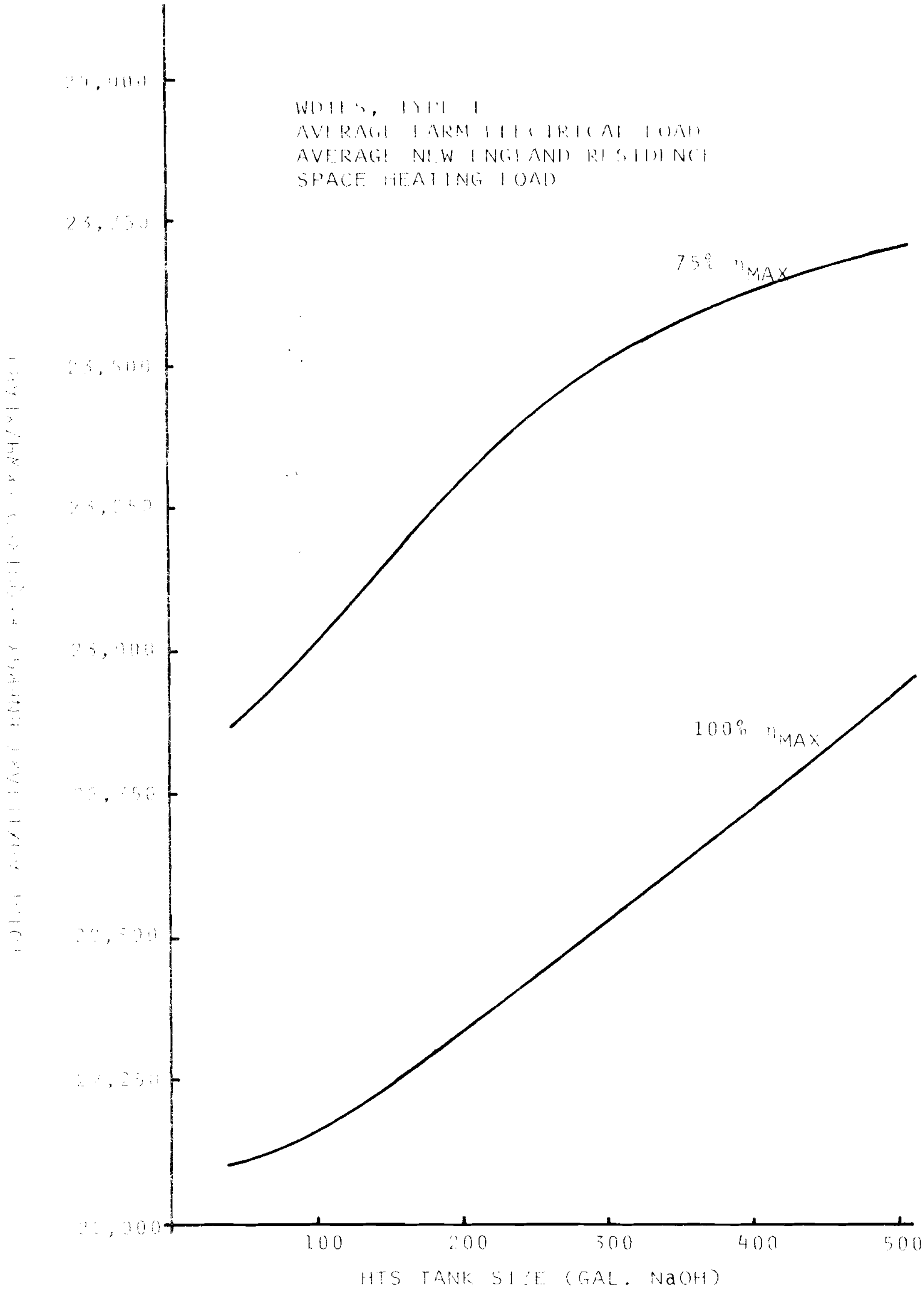


FIGURE 5.27. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

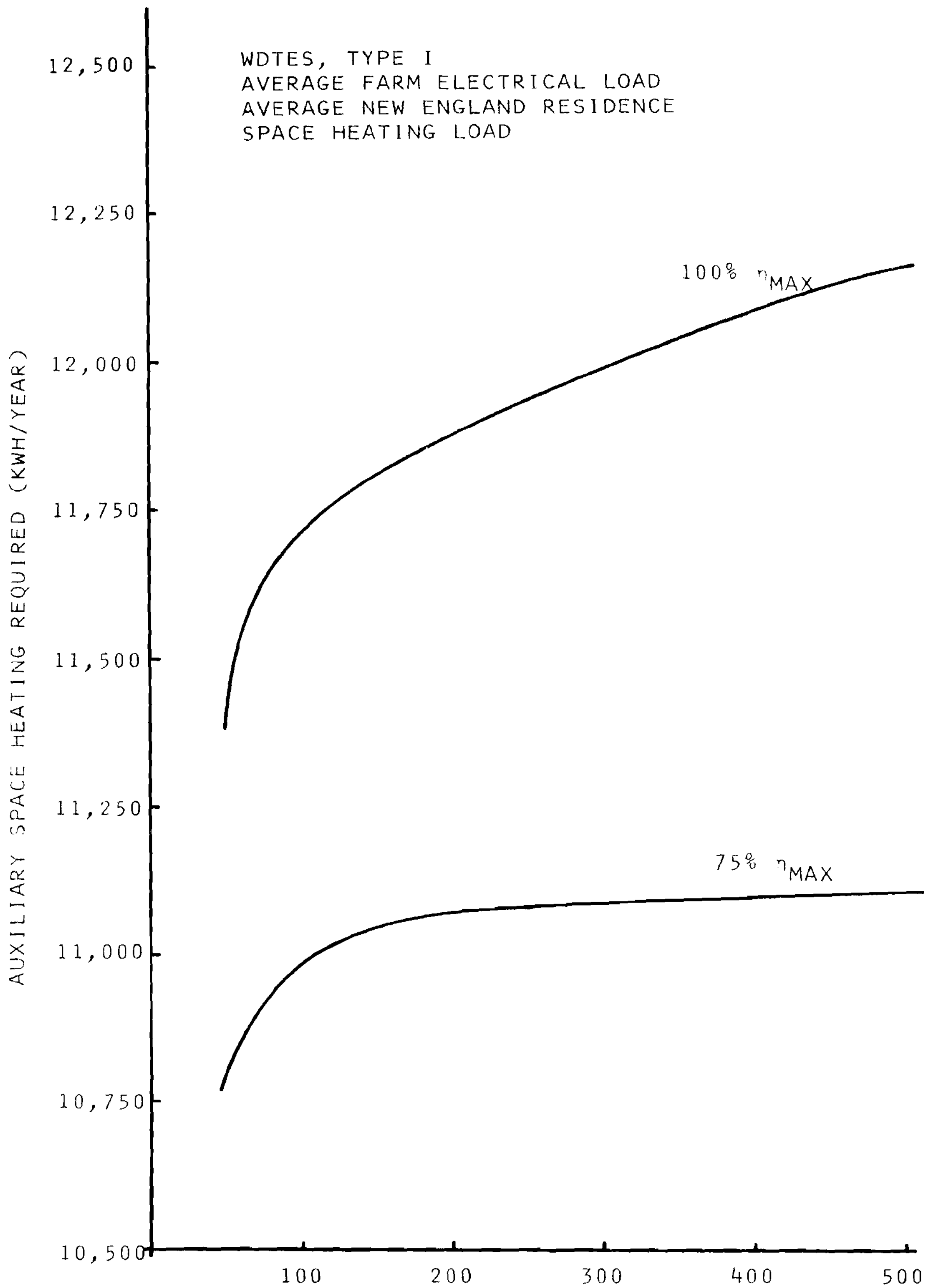


FIGURE 5.28. AUXILIARY SPACE HEATING REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

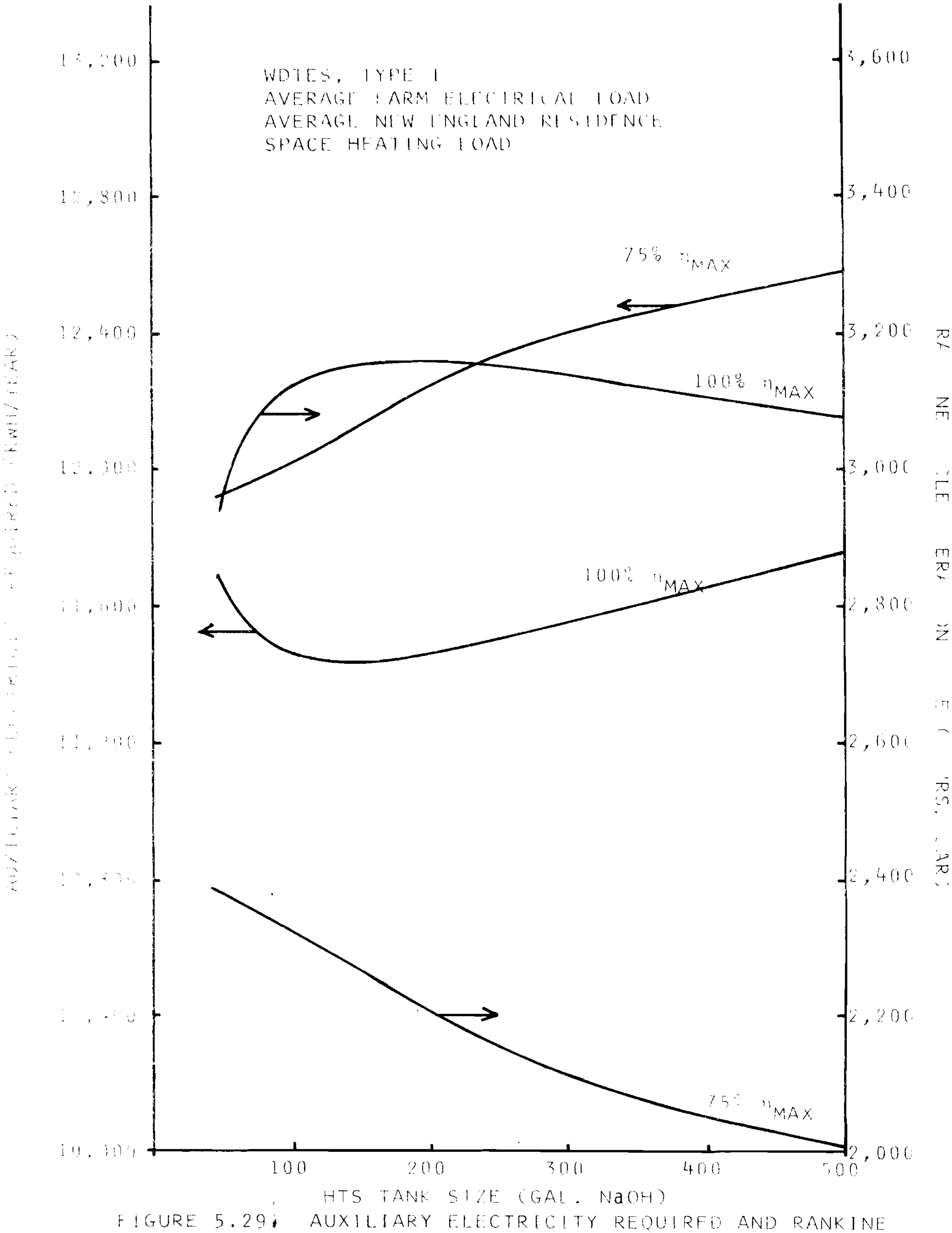


FIGURE 5.29 AUXILIARY ELECTRICITY REQUIRED AND RANKINE CYCLE OPERATION TIME AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

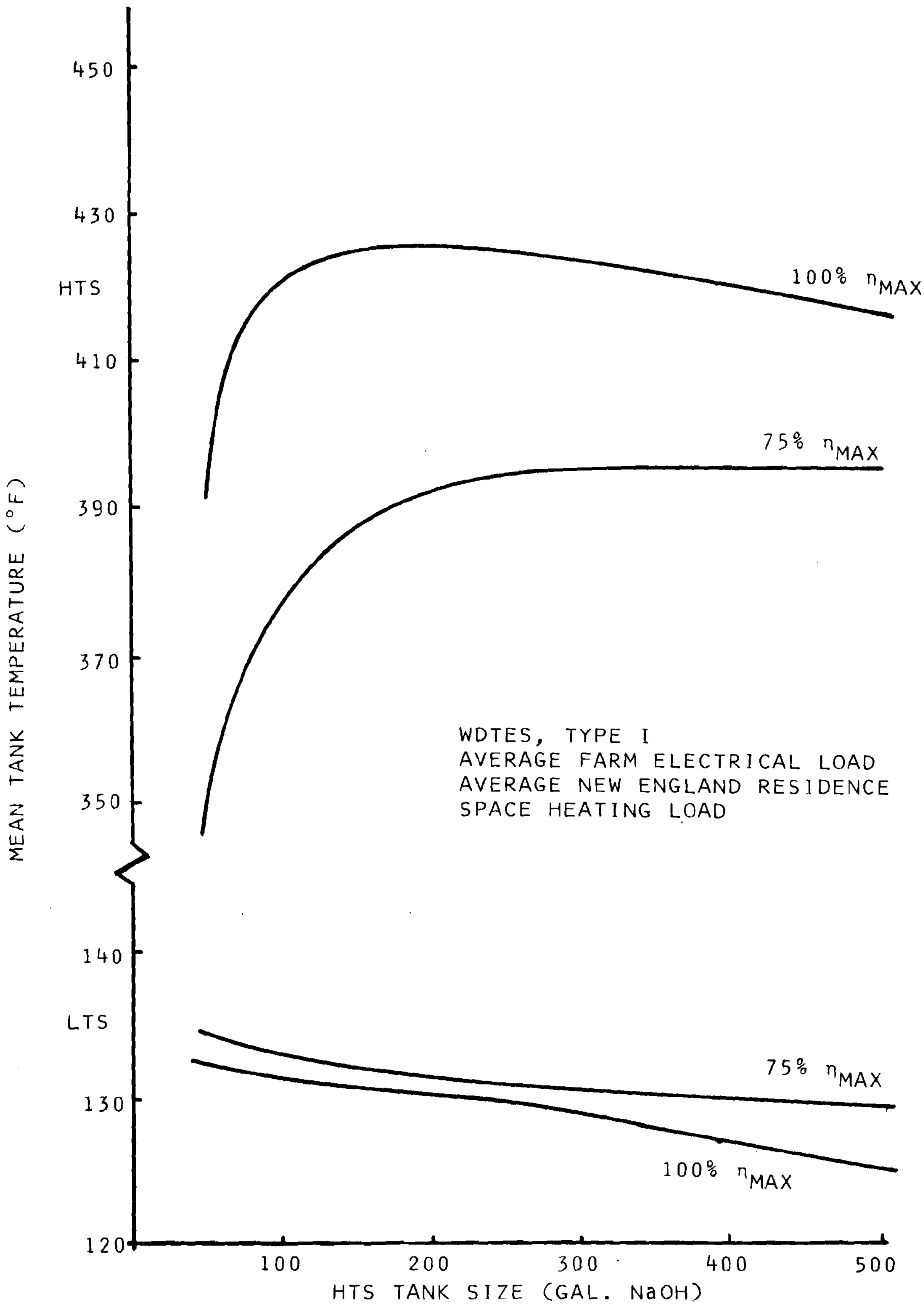


FIGURE 5.30. HTS AND LTS MEAN TANK TEMPERATURES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

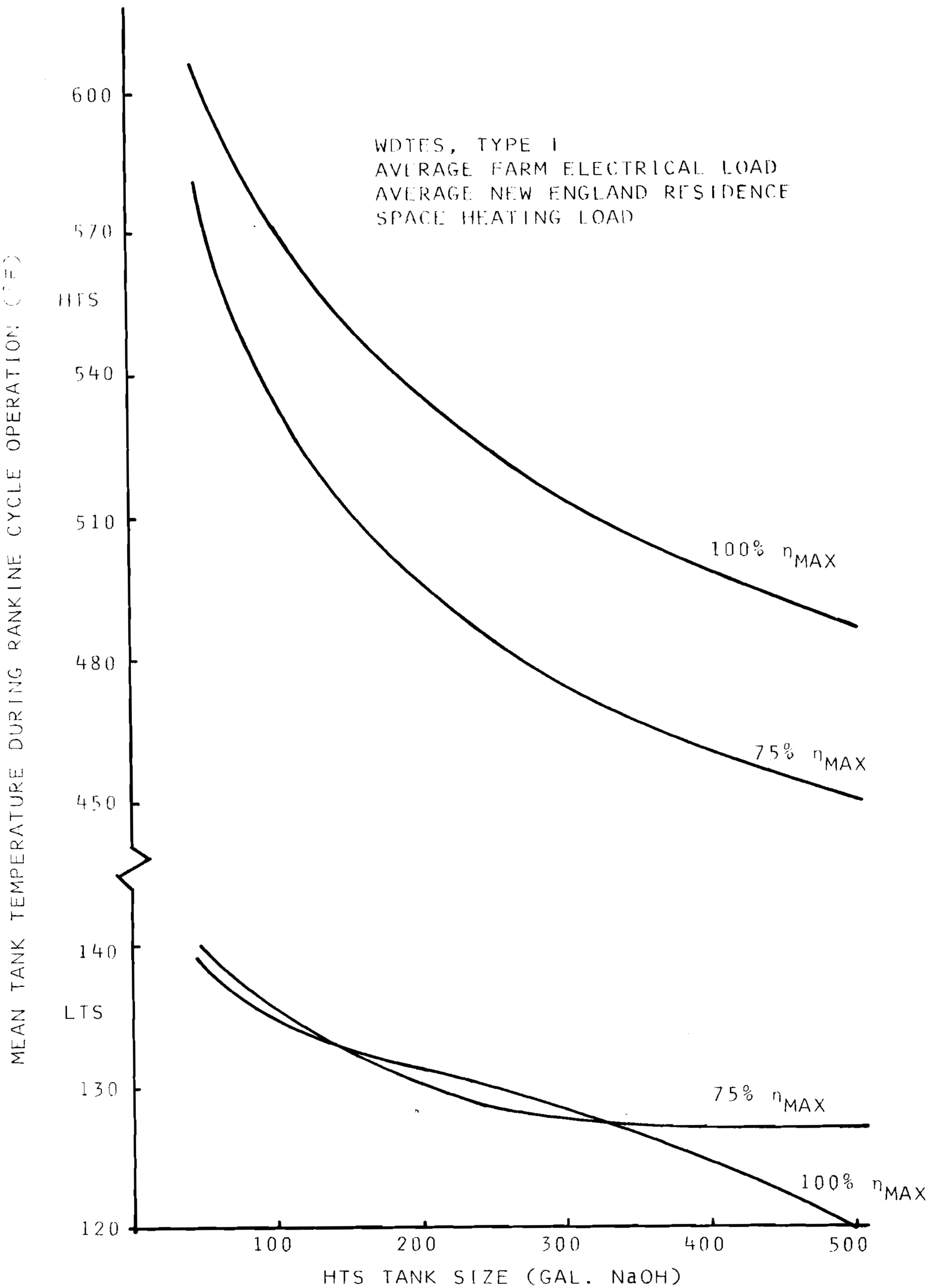


FIGURE 5.31. HTS AND LTS MEAN TANK TEMPERATURES DURING RANKINE CYCLE OPERATION AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

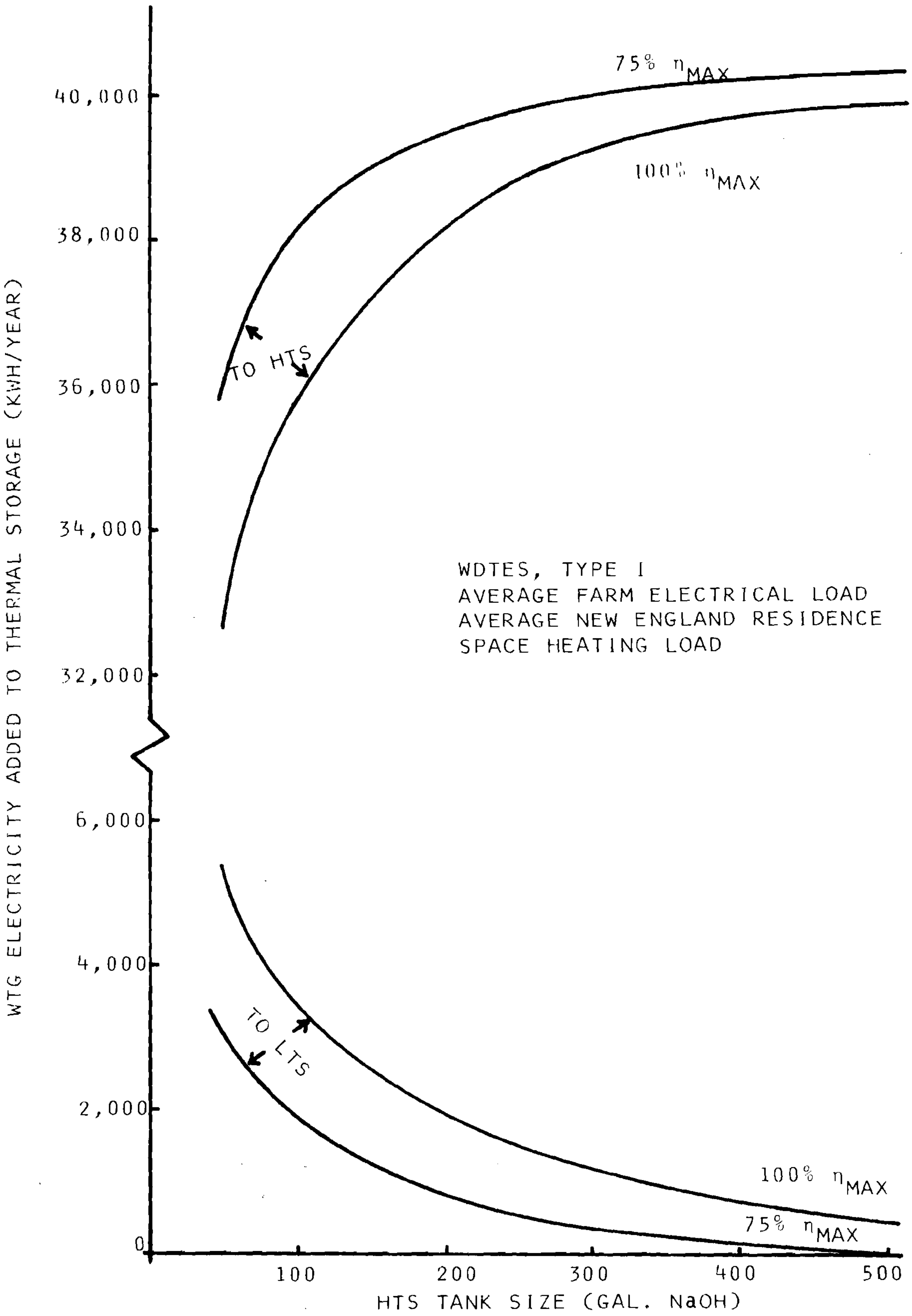


FIGURE 5.32 WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE HTS FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

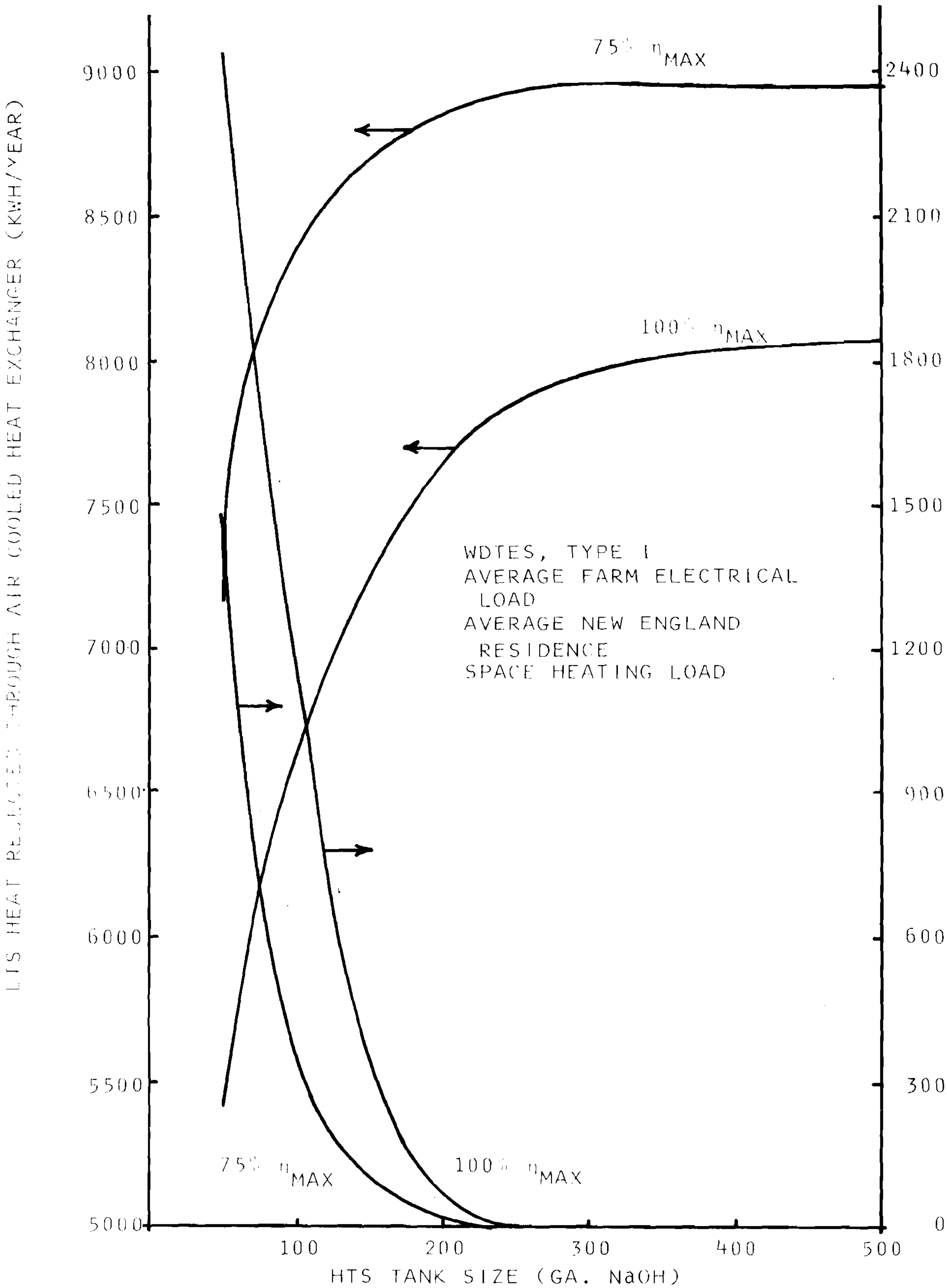


FIGURE 5.33 LTS HEAT REJECTED THROUGH THE AIR COOLED HEAT EXCHANGER AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF HTS TAB SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

5.30 and 5.31 by the low mean HTS temperature and the low HTS temperature when the Rankine Cycle is operated. Even though little WTG energy is wasted by the system in this setting as shown by Figures 5.32 and 5.33, the HTS temperature is at a low level when RC operation is required. This low HTS temperature causes a low thermal efficiency during RC operation, causing a huge heat rejection rate in the condenser and in turn requiring the waste of LTS heat rejected through the air cooled heat exchanger, shown in Figure 5.33. Also, because of this low RC efficiency, the HTS is drained of so much energy that the temperature drops below the required 400°F for RC operation and the Rankine Cycle operates infrequently as shown in Figure 5.29.

5.3 Wind Driven Total Energy System, Type II Results

The application of the WDTES, Type II scheme to the well-insulated New England residence model is a striking example of how Wind Turbine Generator energy can be utilized in an efficient manner to supply virtually all of the energy requirements of a residence. As can be seen in Figure 5.34 the minimum total auxiliary energy required by the system is only about 4% of the 26,516kWh total energy requirements of this home if a 100 gallon HTS tank is employed. The division of this total load into its auxiliary space heating and electricity requirements is shown in Figures 5.35 and 5.36. As with the WDTES, Type I model, the auxiliary domestic hot water requirements of this system are virtually zero. (Since most of the auxiliary energy requirement takes place during the start up interval, this system in the well-insulated home setting can truly be considered as a total energy system.) The high efficiency of the system is shown in Figure 5.40. Out of the 40,361kWh of electricity capable of being produced

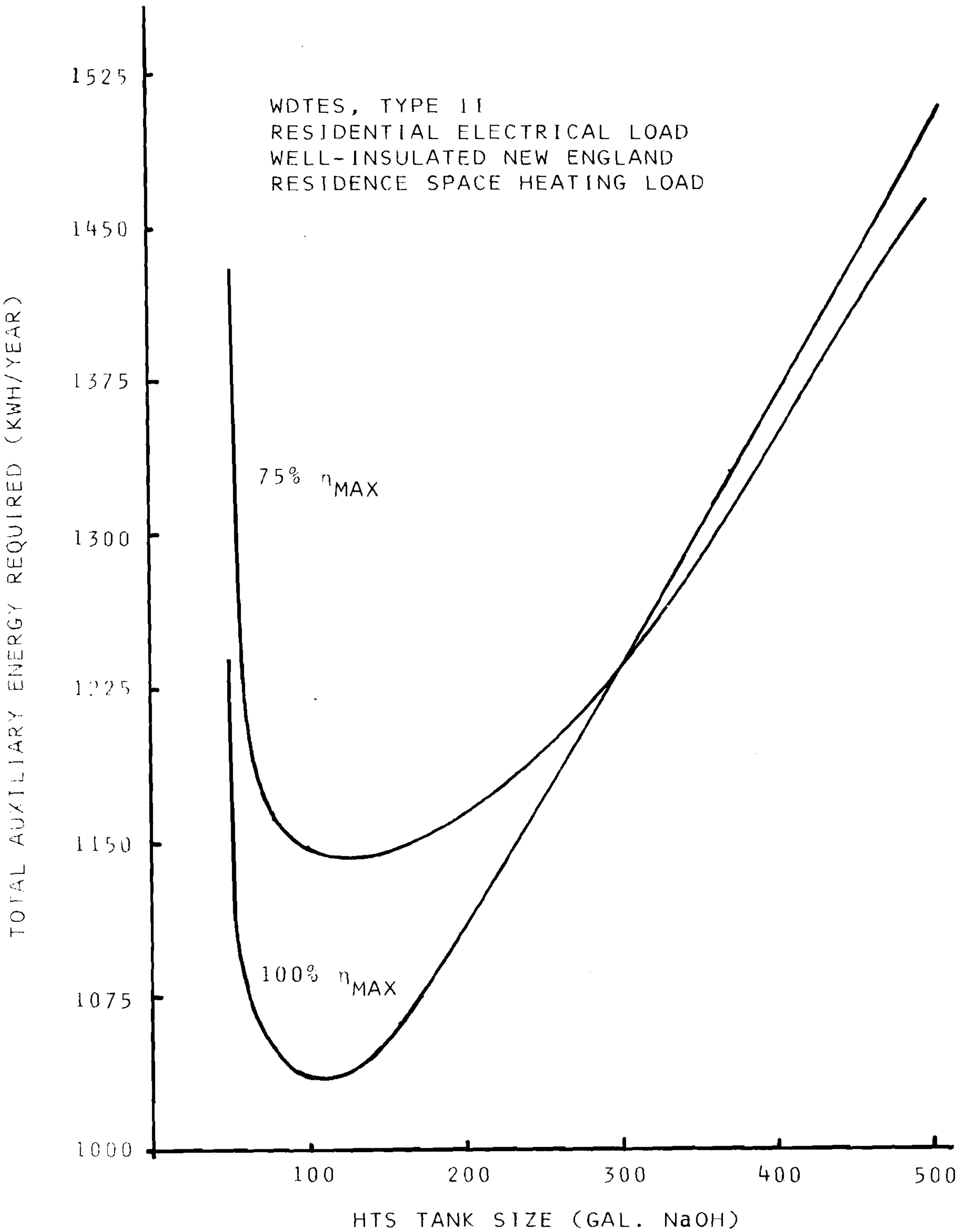


FIGURE 5.34. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

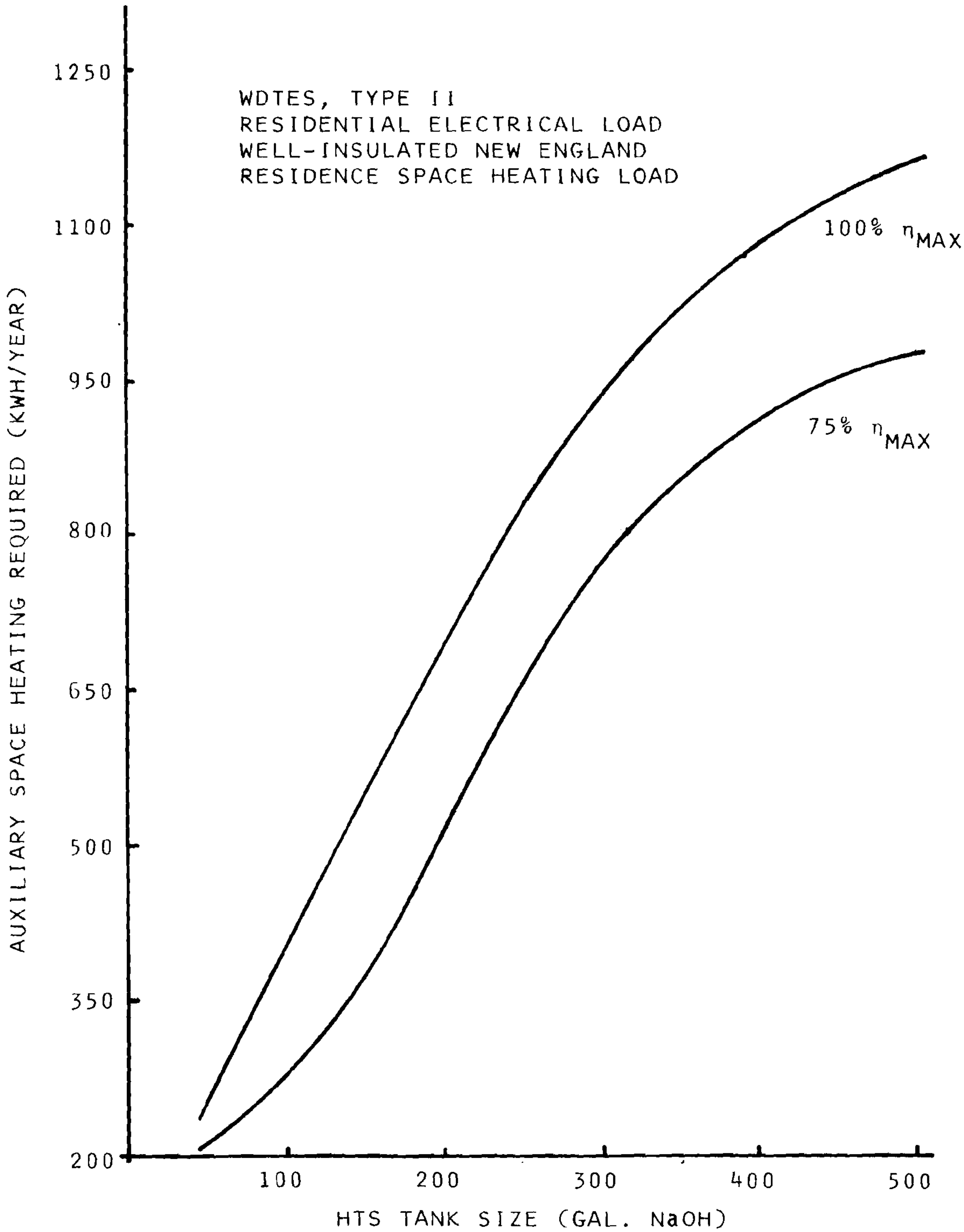


FIGURE 5.35. AUXILIARY SPACE HEATING REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

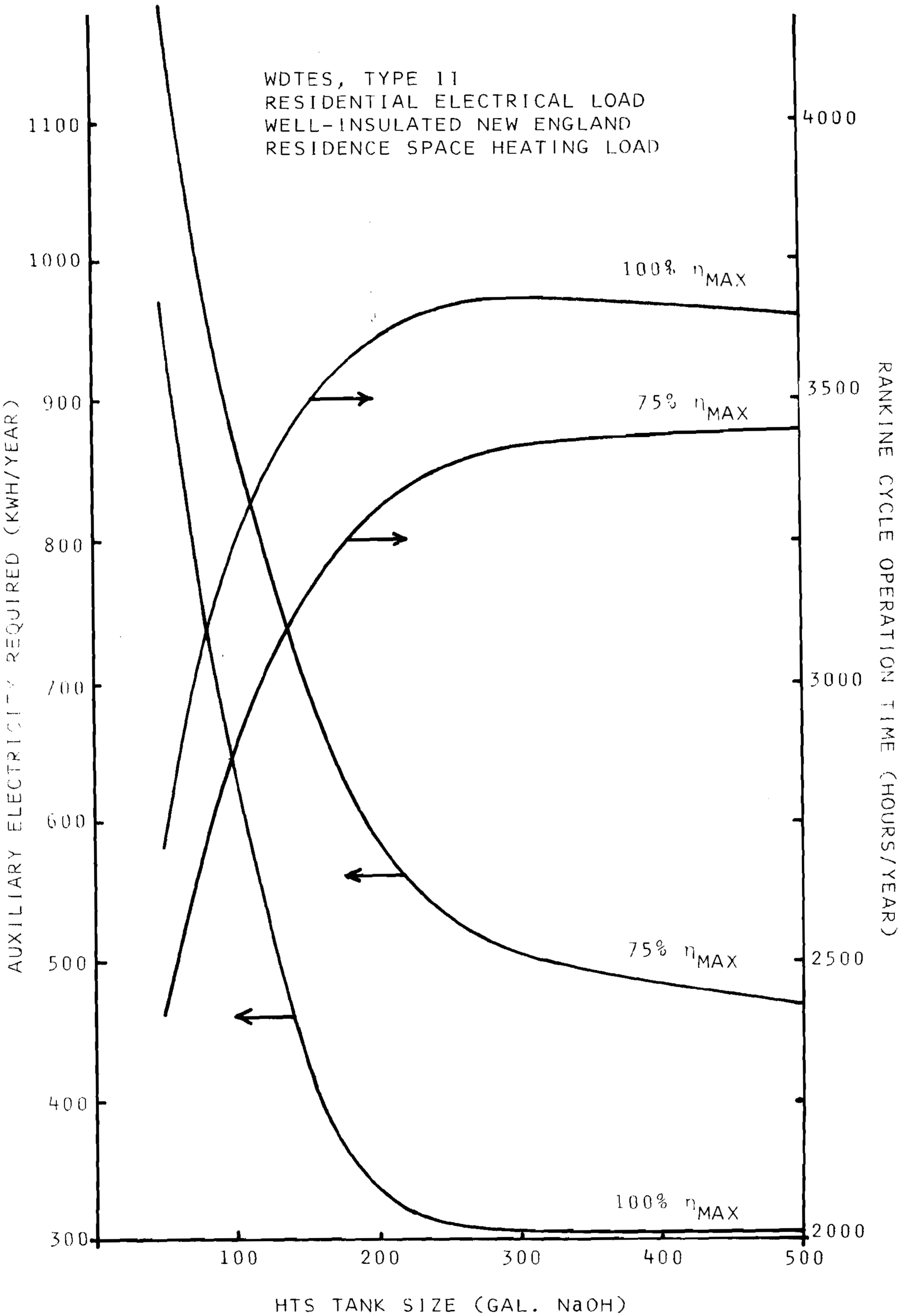


FIGURE 5.36. AUXILIARY ELECTRICITY REQUIRED AND RANKINE CYCLE OPERATION TIME AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY

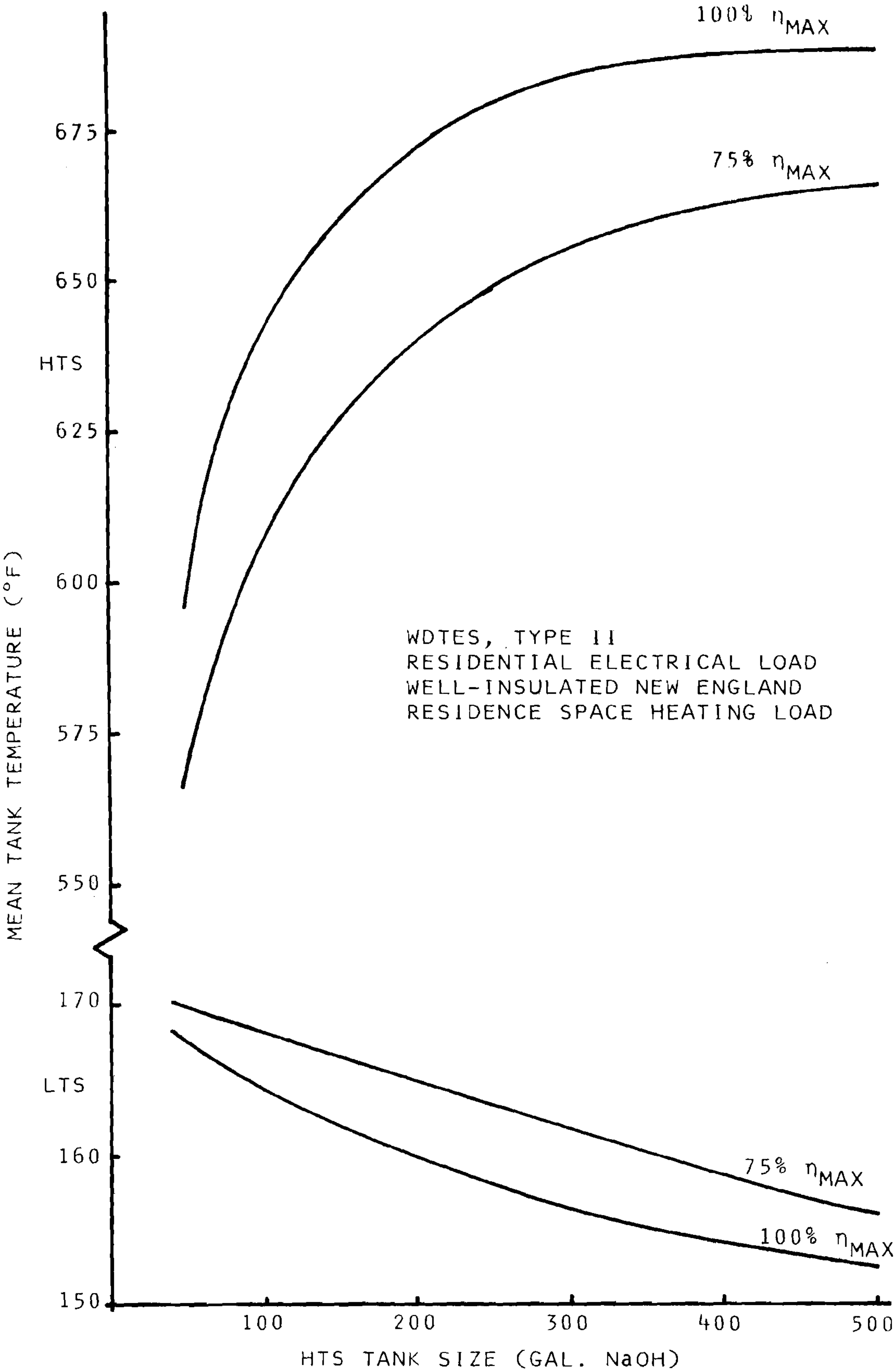


FIGURE 5.37. HTS AND LTS MEAN TANK TEMPERATURES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

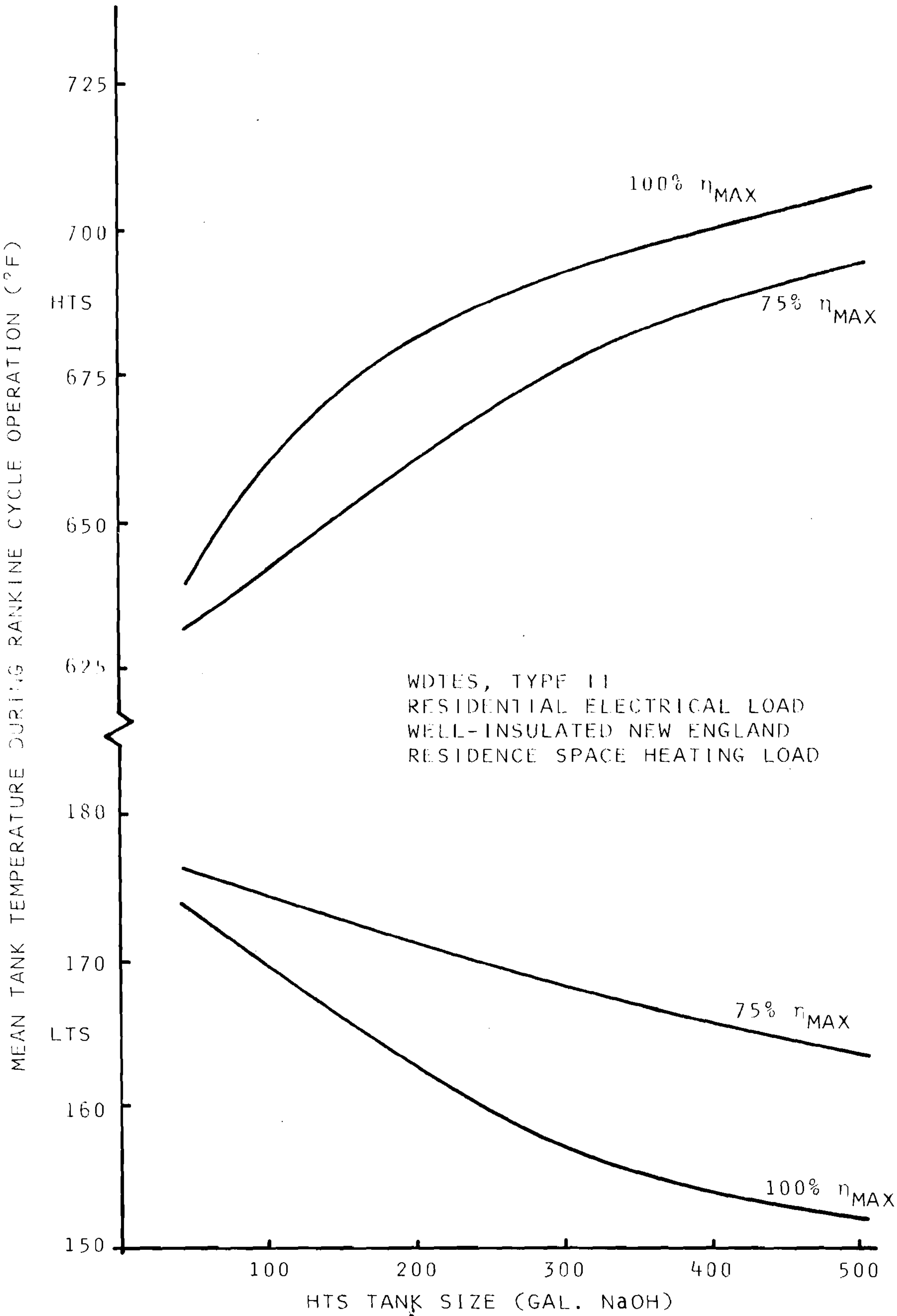


FIGURE 5.38. HTS AND LTS MEAN TANK TEMPERATURES DURING RANKINE CYCLE OPERATION AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

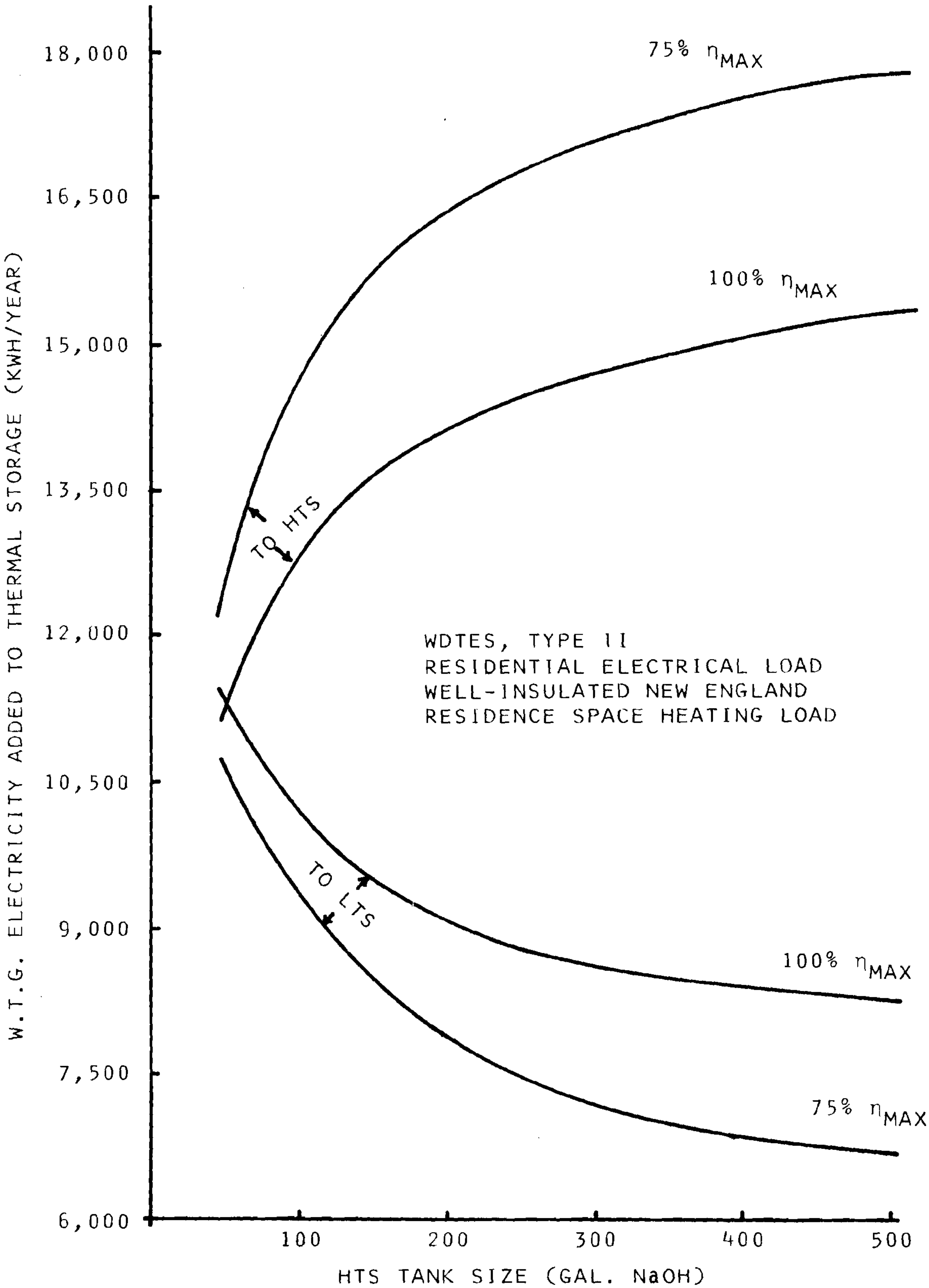


FIGURE 5.39. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE HTS AND LTS AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

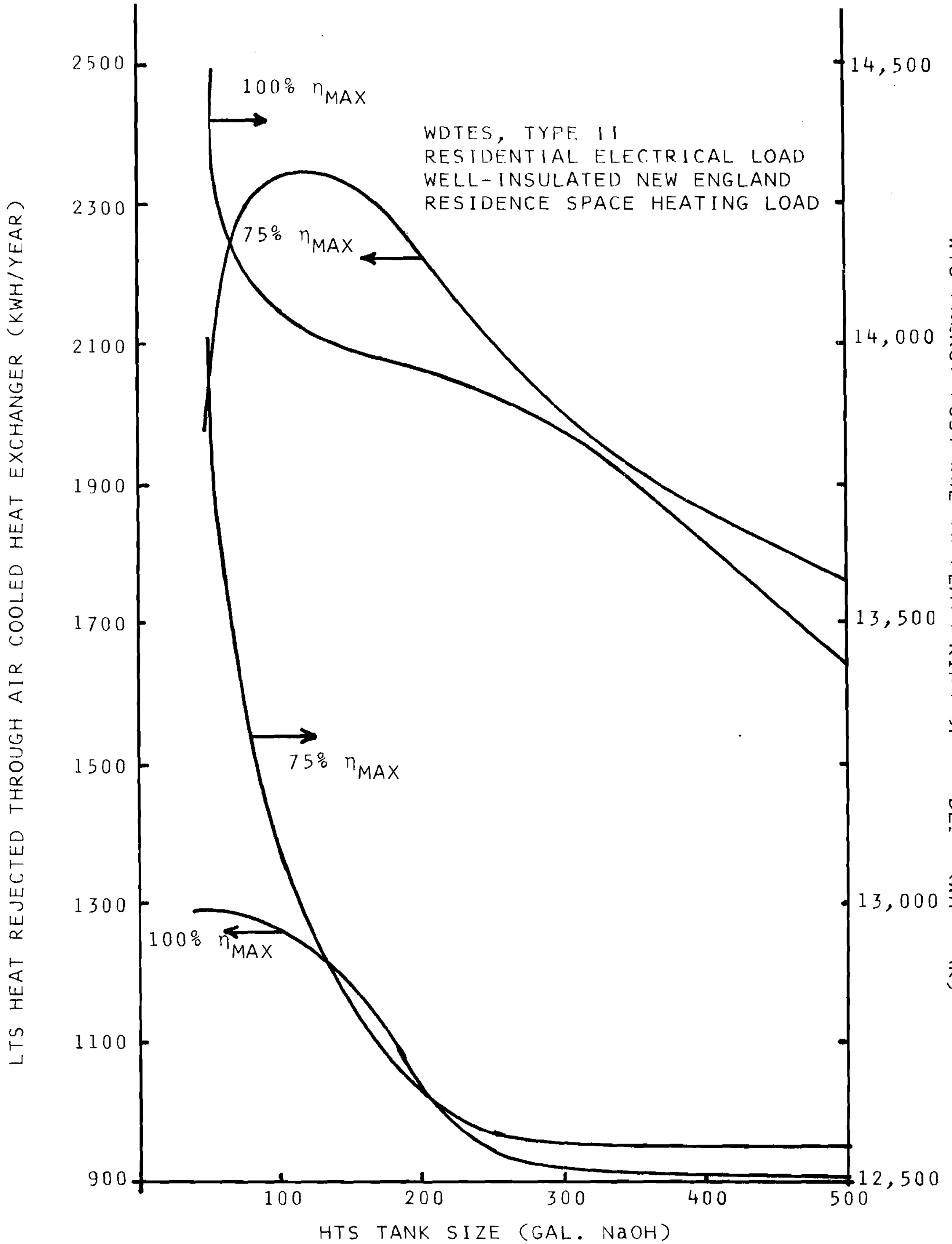


FIGURE 5.40. LTS HEAT REJECTED THROUGH THE AIR COOLED HEAT EXCHANGER AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

annually by the WTG about 14,000kWh is not used by the system due to feathering of the blades (assuming maximum RC efficiency and 100 gallon HTS) and could be used for other purposes such as a return to the utility grid. The remaining 26,600kWh, along with the very small total auxiliary requirement supplies the 25,516kWh total energy load of the home in a very efficient manner. Also, as shown in Figures 5.37 and 5.38, the mean annual tank temperatures and the mean tank temperatures when the Rankine Cycle is on, for both the HTS and the LTS, are at sufficiently high temperatures to allow high RC efficiency and readily available energy distribution to the space heating and domestic hot water loads. The effects of increasing HTS tank size and turbine efficiency can be seen in Figure 5.39. As HTS tank size increases, more energy can be added to the HTS, leaving less to be diverted to the LTS. Lower turbine efficiency (as shown by the 75% η_{max} lines) causes a higher source heat requirement from the RC, depleting the HTS more rapidly and hence, allowing more WTG energy to be supplied to the HTS.

The application of the WDTES, Type II system to the average New England residence is shown in Figures 5.41 to 5.47. This system requires a minimum total auxiliary energy requirement of 27% of the total energy load of 44,733kWh, as seen in Figure 5.41. Because the largest portion of this requirement is for auxiliary space heating, as shown in Figure 5.42, and a minimal amount is for auxiliary electricity, shown in Figure 5.43, an interesting possibility arises. As previously noted, a large portion of the small auxiliary electricity requirement takes place during the start up duration. For this reason, the WDTES, Type II system in an average,

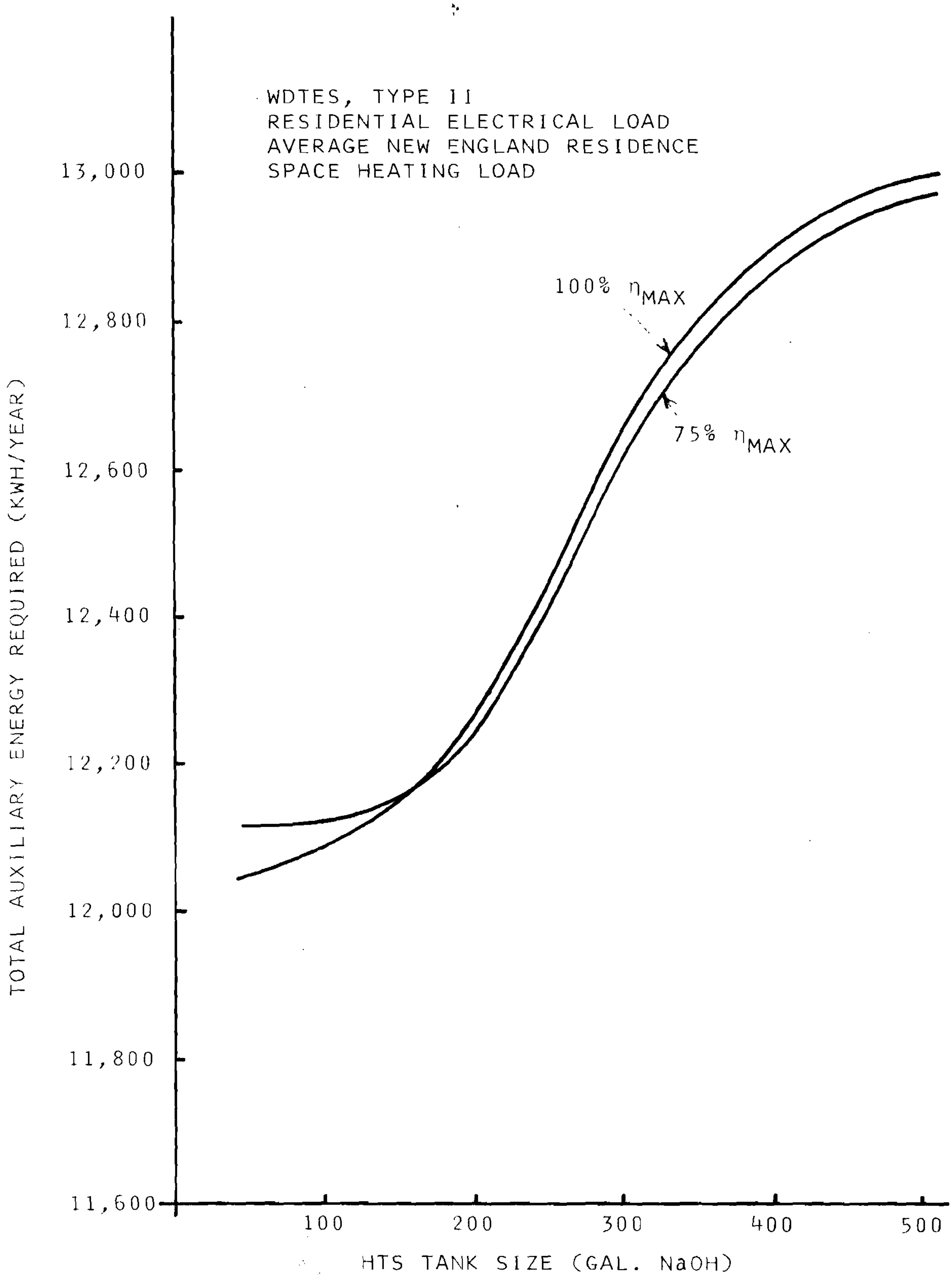


FIGURE 5.41. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

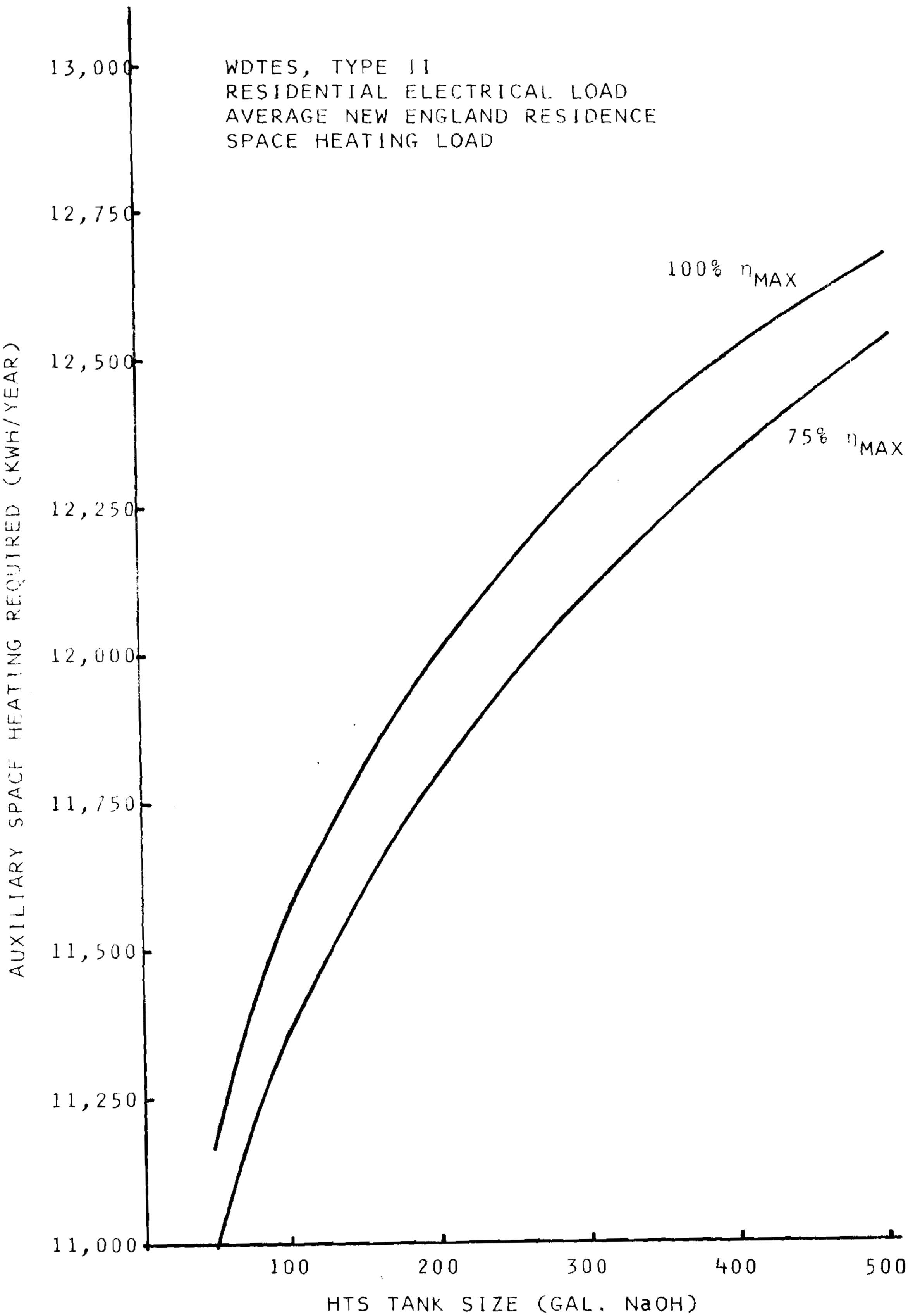


FIGURE 5.42. AUXILIARY SPACE HEATING REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

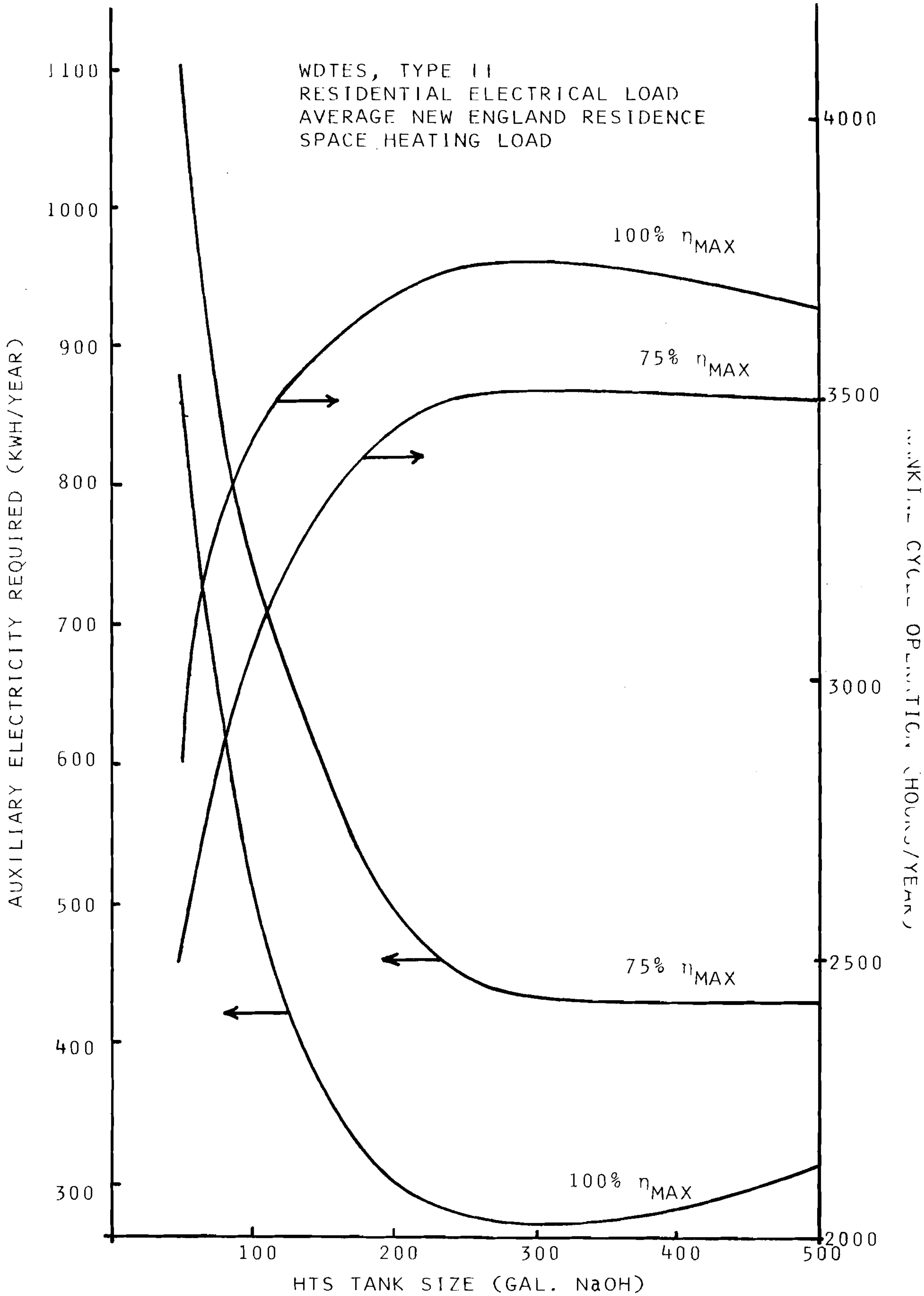


FIGURE 5.43. AUXILIARY ELECTRICITY REQUIRED AND RANKINE CYCLE OPERATION TIME AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

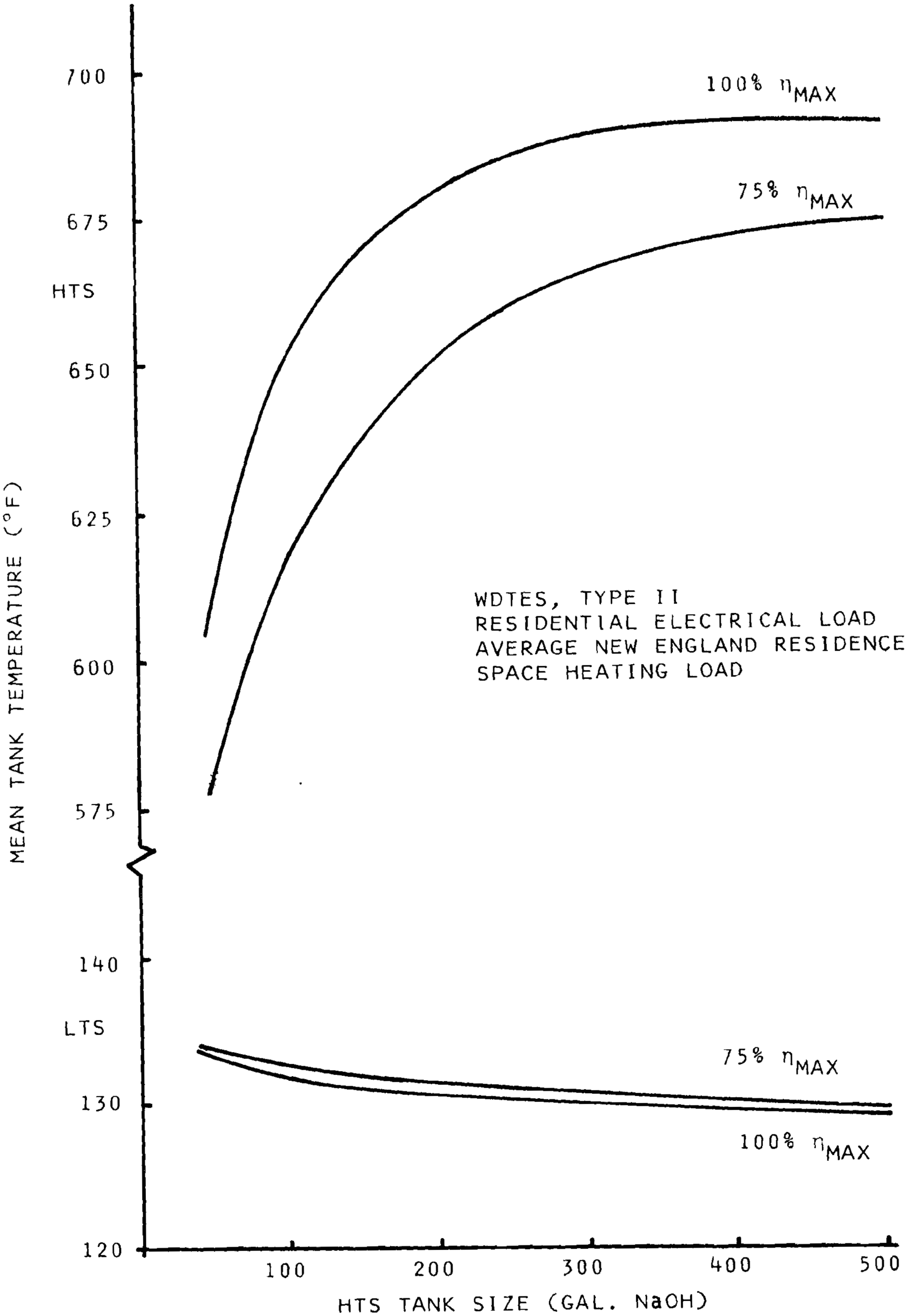


FIGURE 5.44. HTS AND LTS MEAN TANK TEMPERATURES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

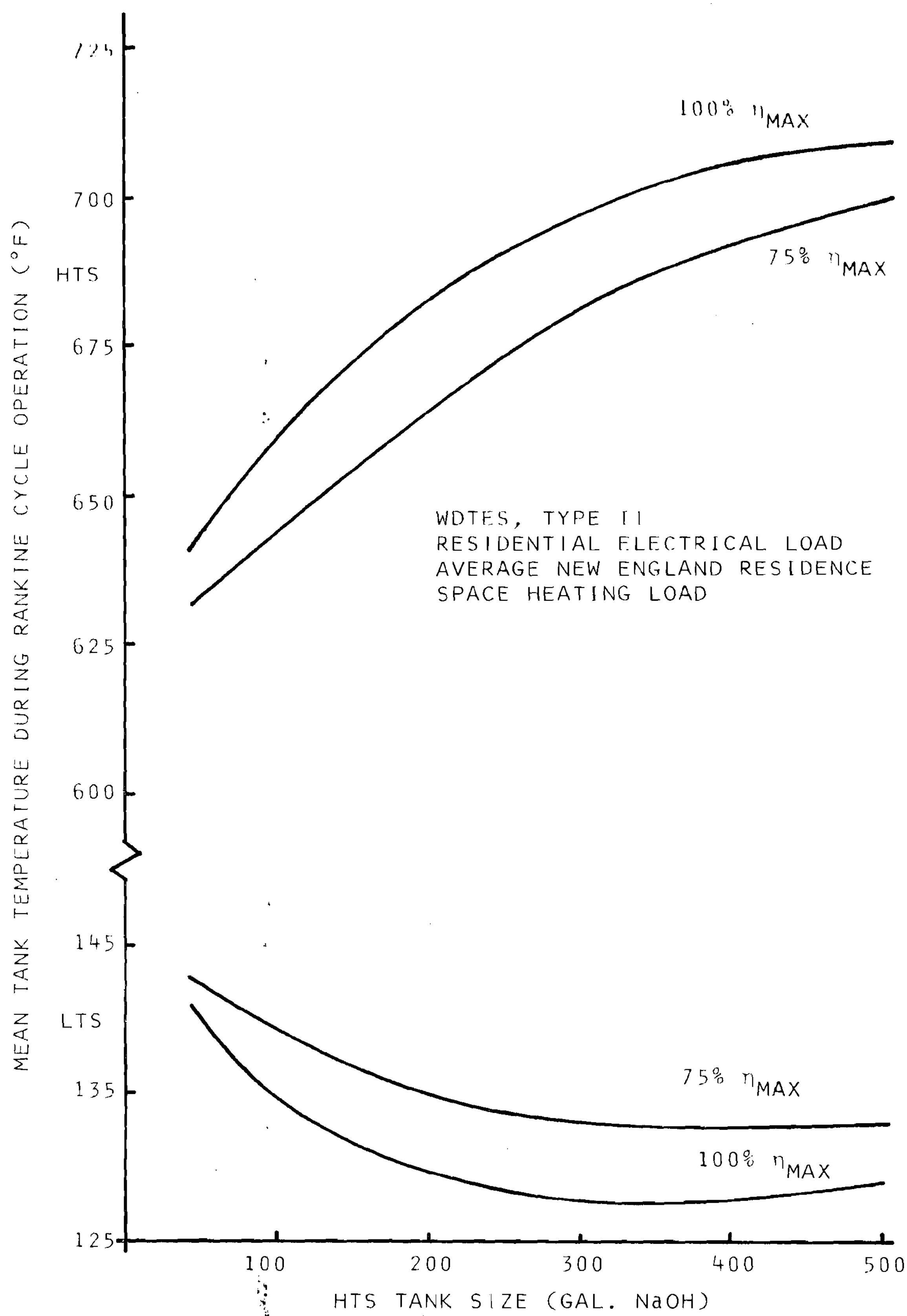


FIGURE 5.45. HTS AND LTS MEAN TANK TEMPERATURES DURING RANKINE CYCLE OPERATION AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

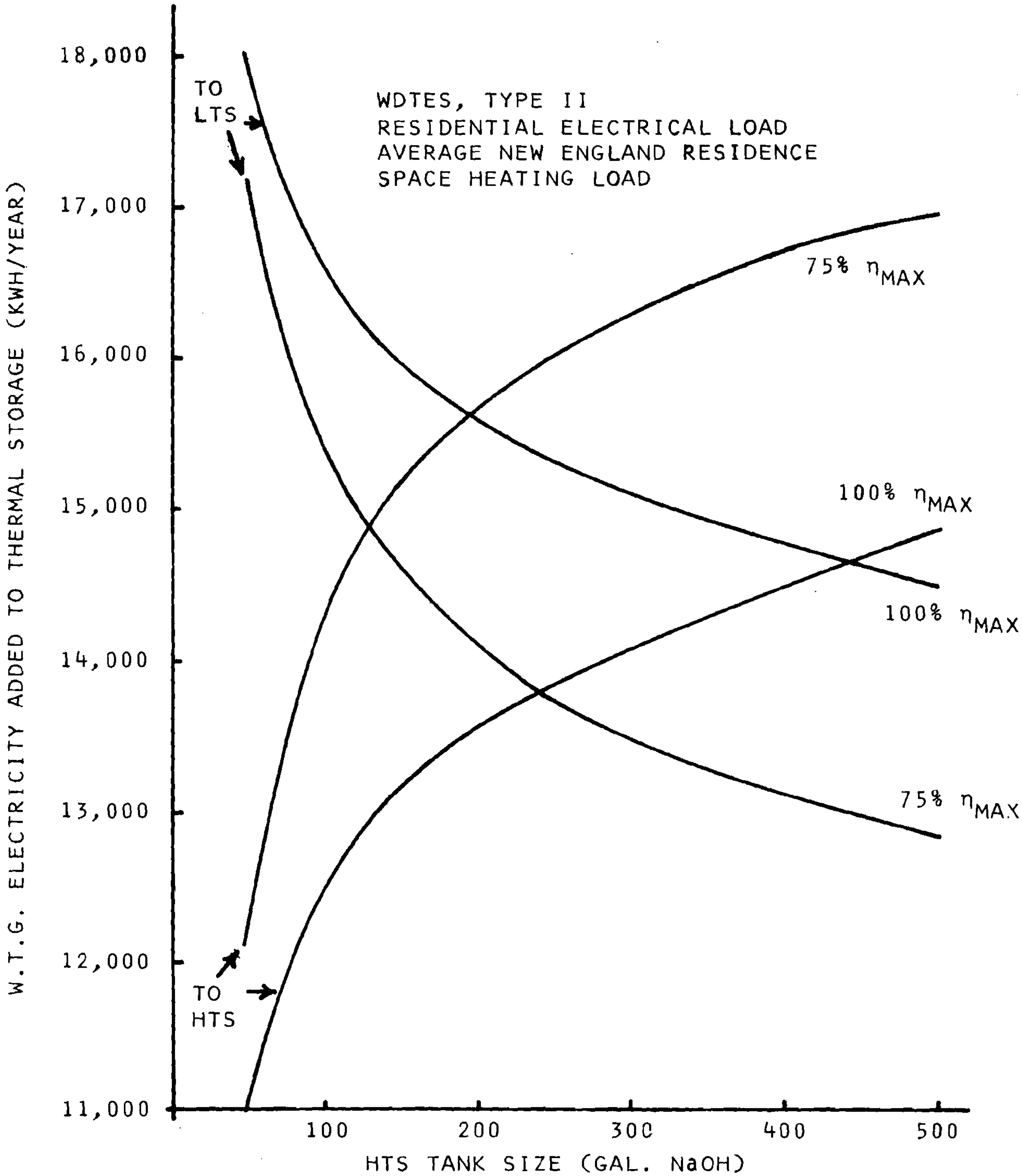


FIGURE 5.46. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE HTS AND LTS THERMAL STORAGE VIA RESISTANCE HEATERS AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

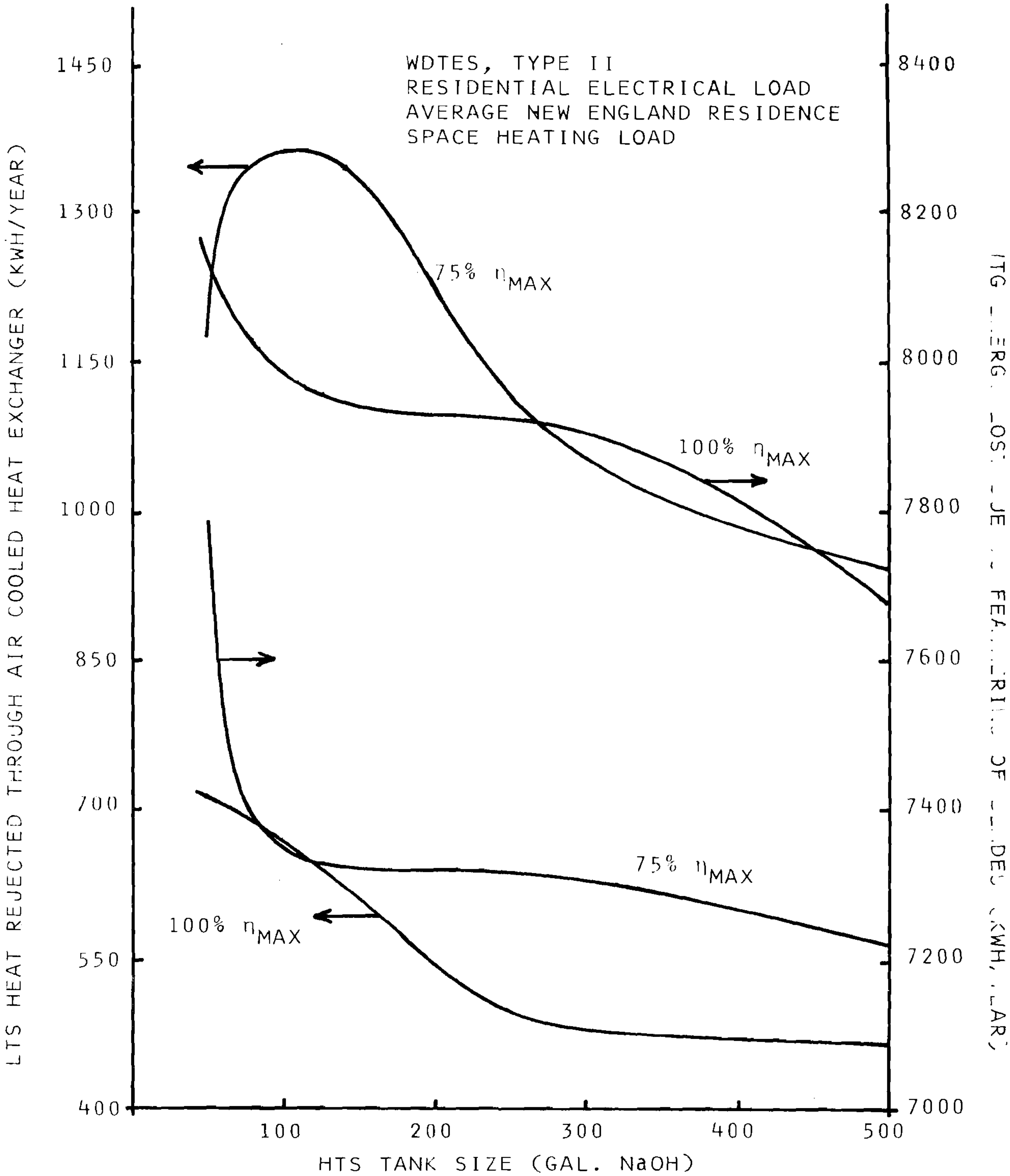


FIGURE 5.47. LTS HEAT REJECTED THROUGH THE AIR COOLED HEAT EXCHANGER AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

and also a well insulated residential setting could be made independent of utility transmission lines. If the auxiliary space heating requirement of the system could be supplied by non-conventional means (i.e. solar collectors) the whole residence could be made completely independent of all utilities, insulating the resident from escalating fuel prices, conventional installation costs and possible black-outs and brown-outs. As can be seen in Figures 5.44 and 5.45, the HTS and LTS mean tank temperatures both annually and during Rankine Cycle operation are at acceptable levels for high RC efficiency and space heating and domestic hot water supply, although the LTS temperatures are somewhat lower than for the well-insulated home application, shown in Figures 5.37 and 5.38.

Even with the higher electrical load of the average New England farm setting, the WDTES, Type II scheme requires only about 34% of the 55,684kWh total farm energy loads as an auxiliary requirement, if a 250 gallon HTS tank is used, as shown in Figure 5.48. The auxiliary space heating and electrical requirements of the system in the farm application are shown in Figures 5.49 and 5.50 respectively. It should be noted that in the farm application the auxiliary electricity required, at all HTS tank sizes considered, is significant and must be supplied by the utility. The effect on the system of the large electrical load, when compared to the average residence is that when the Rankine Cycle is operating, although it operates less frequently as shown in Figures 5.50 and 5.43, a large electrical output is required from it. This lowers the HTS tank temperature both annually and when the RC is operating shown by comparing Figures 5.51 and 5.52 to 5.44 and 5.45. Because the HTS temperatures are lower, a larger amount of WTG electricity is supplied to the HTS and less to the LTS as

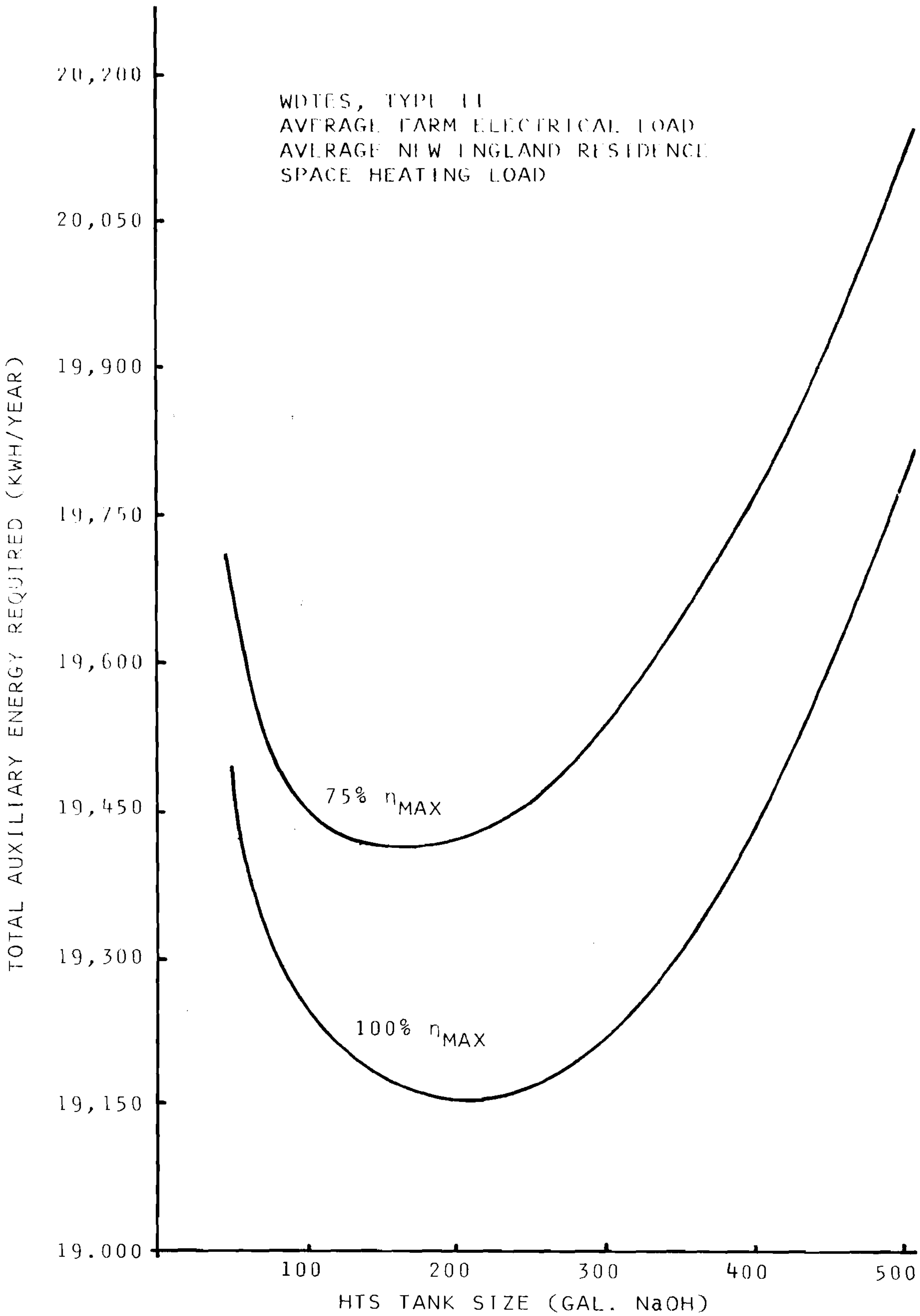


FIGURE 5.48. TOTAL AUXILIARY ENERGY REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

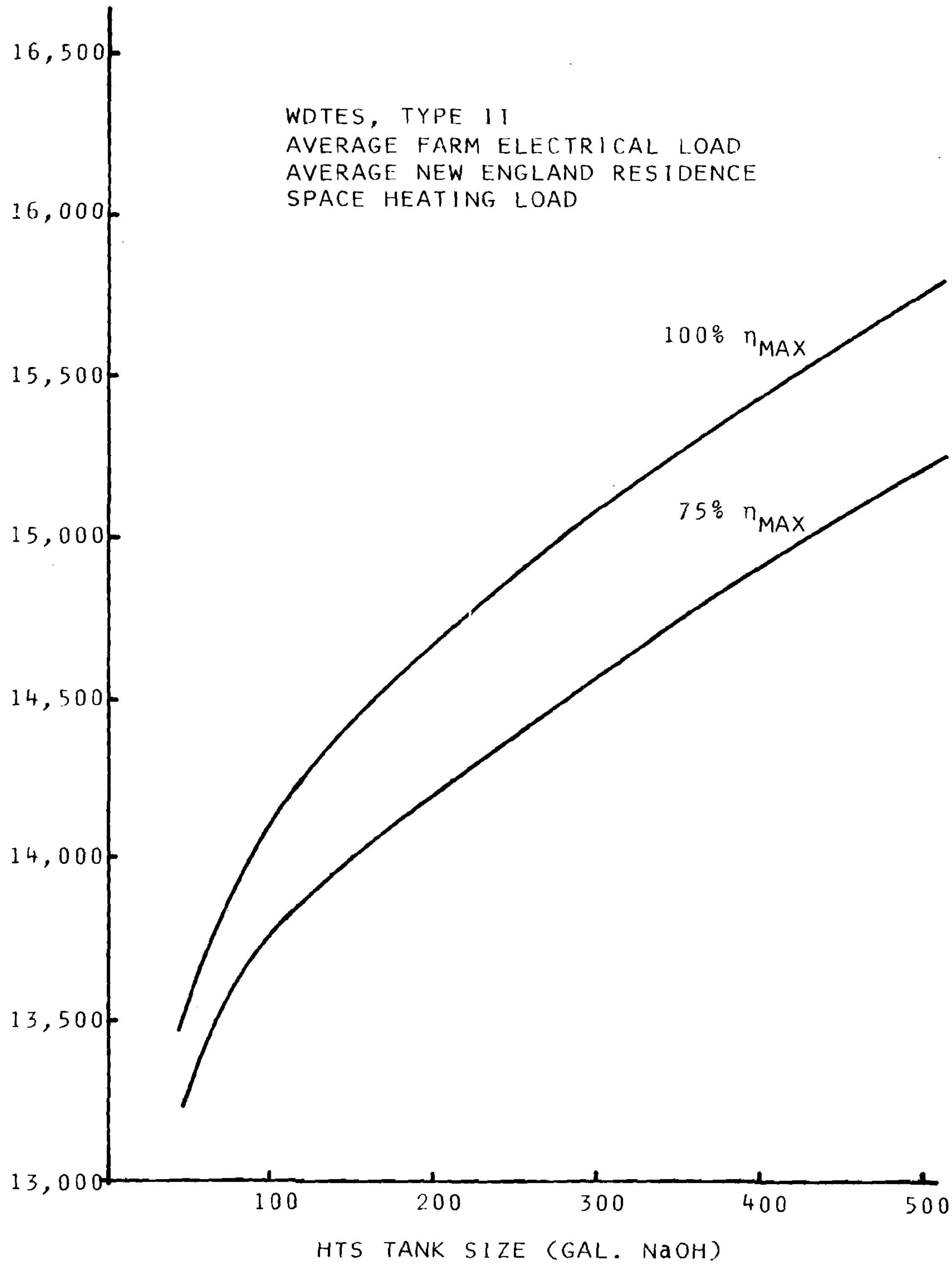


FIGURE 5.49. AUXILIARY SPACE HEATING REQUIRED AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

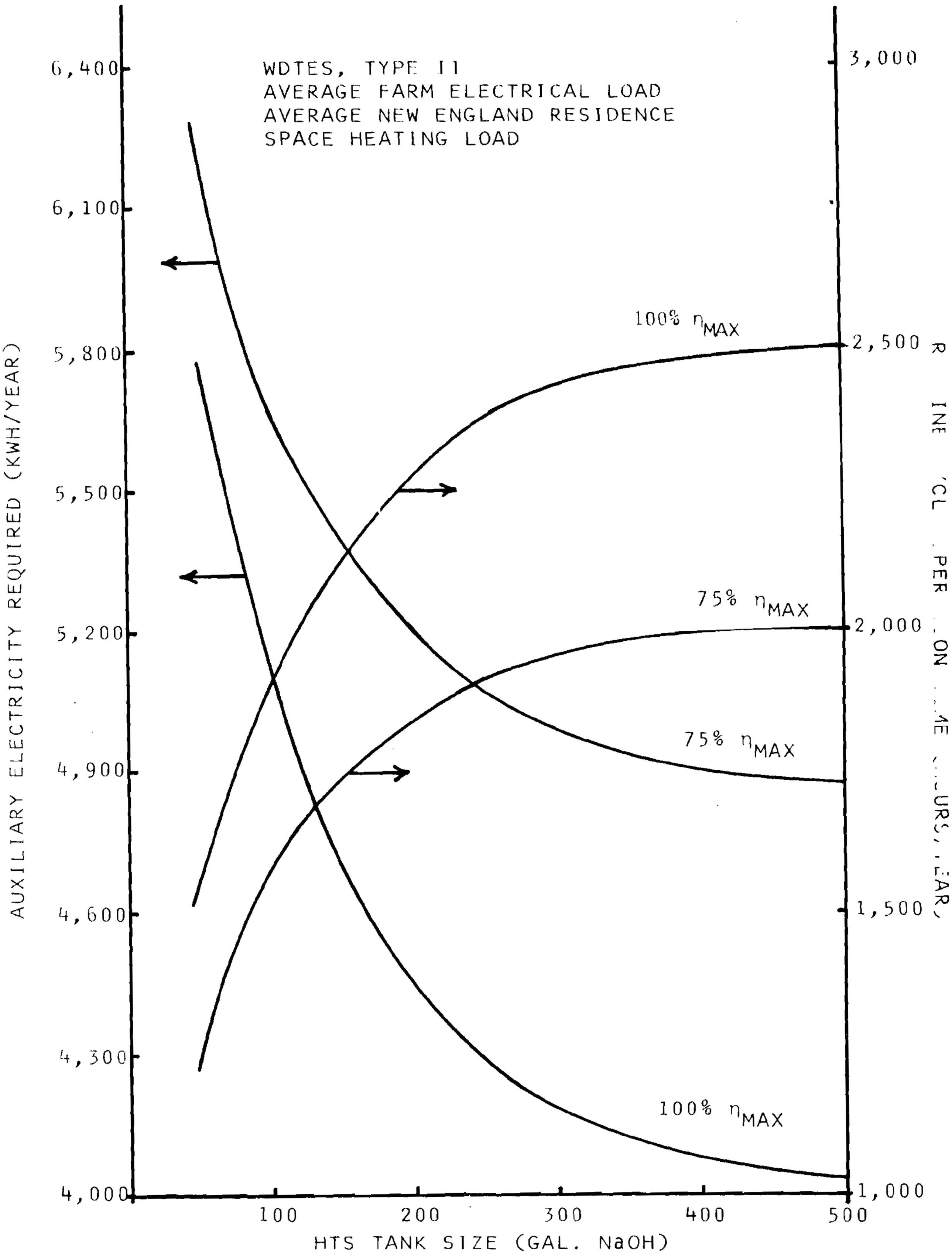


FIGURE 5.50. AUXILIARY ELECTRICITY REQUIRED AND RANKINE CYCLE OPERATION TIME AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY.

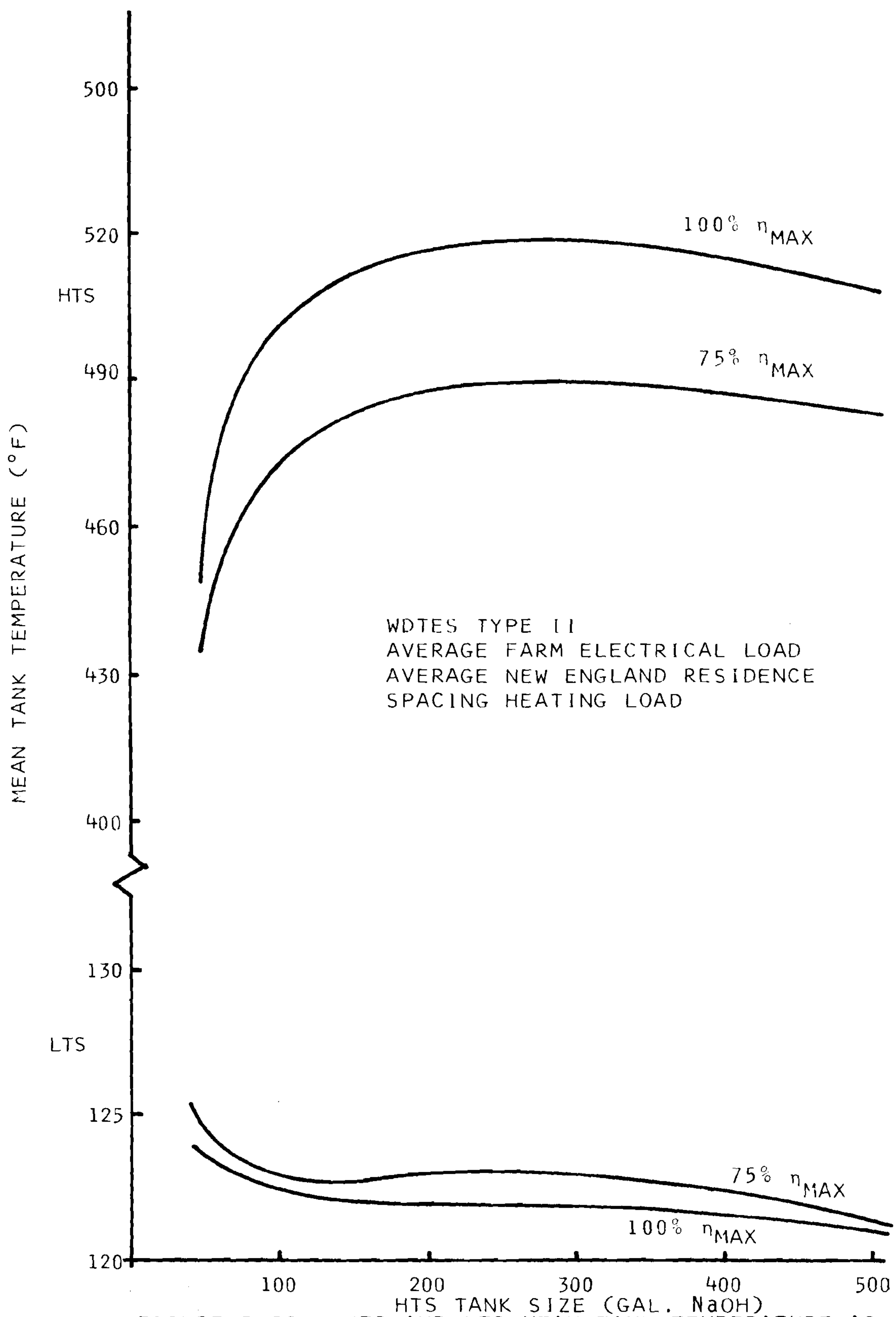


FIGURE 5.52. HTS AND LTS MEAN TANK TEMPERATURE AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

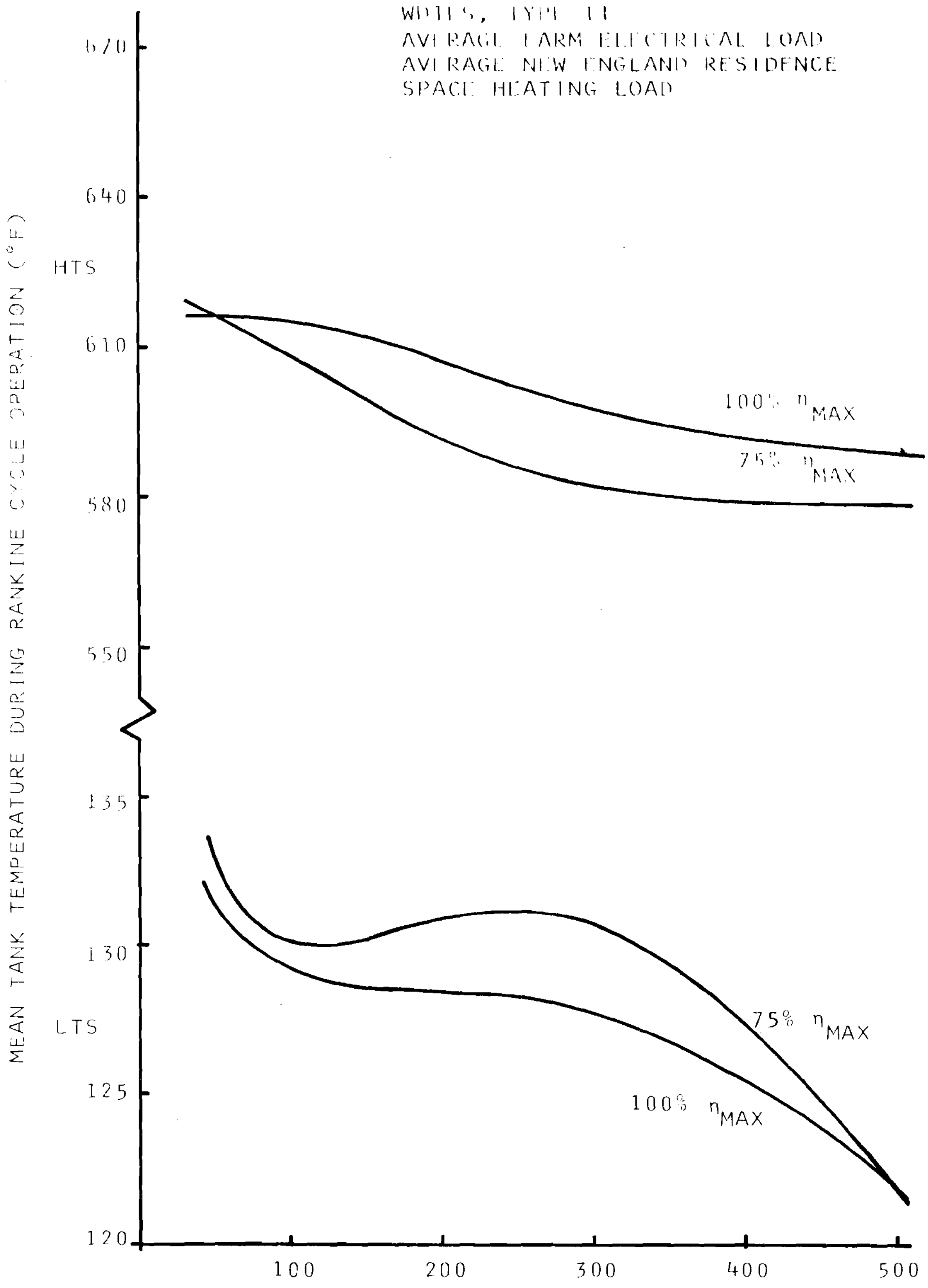


FIGURE 5.52. HTS AND LTS MEAN TANK TEMPERATURE DURING RANKINE CYCLE OPERATION AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

shown in Figures 5.53 and 5.46. This also tends to keep LTS temperature low, as given in Figures 5.51 and 5.52. And, since a large output is required from the RC when it operates, the heat rejected from the condenser tends to overheat the LTS at times causing a larger energy flow through the air cooled heat exchanger, seen by comparing Figures 5.54 and 5.47. This also tends to keep average annual LTS temperatures lower because the energy is not stored over a period of time in the LTS but rejected to the outside air through the air cooled heat exchanger, thus leaving the system.

5.4 System Performance Comparisons

A comparison of system performance for the three advanced wind furnace systems is best accomplished by examining the performance trends of all systems when the same load models are applied to them. In this way, favorable trends in the performance characteristics of each system can become apparent.

The well-insulated New England residence model is shown with the three systems in Figures 5.1 through 5.4, 5.13 through 5.19 and 5.34 through 5.40. As seen in Figures 5.1, 5.13 and 5.34, both WDTES models offer a lower total auxiliary energy requirement than the IWFS model, with the WDTES, Type II model, using a 100 gallon HTS, being the best of these. An examination of Figures 5.2, 5.14, 5.15, 5.35 and 5.36 shows that for LTS tank sizes greater than 2000 gallons, the IWFS uses the least auxiliary space heating and also that the WDTES, Type II model uses the least auxiliary electricity by far. These conclusions are also corroborated by Figures 5.55 and 5.56 which show the fraction of the space heating load and the fraction of the electrical load to be supplied by the auxiliary for each of the systems. Rankine Cycle operation time for

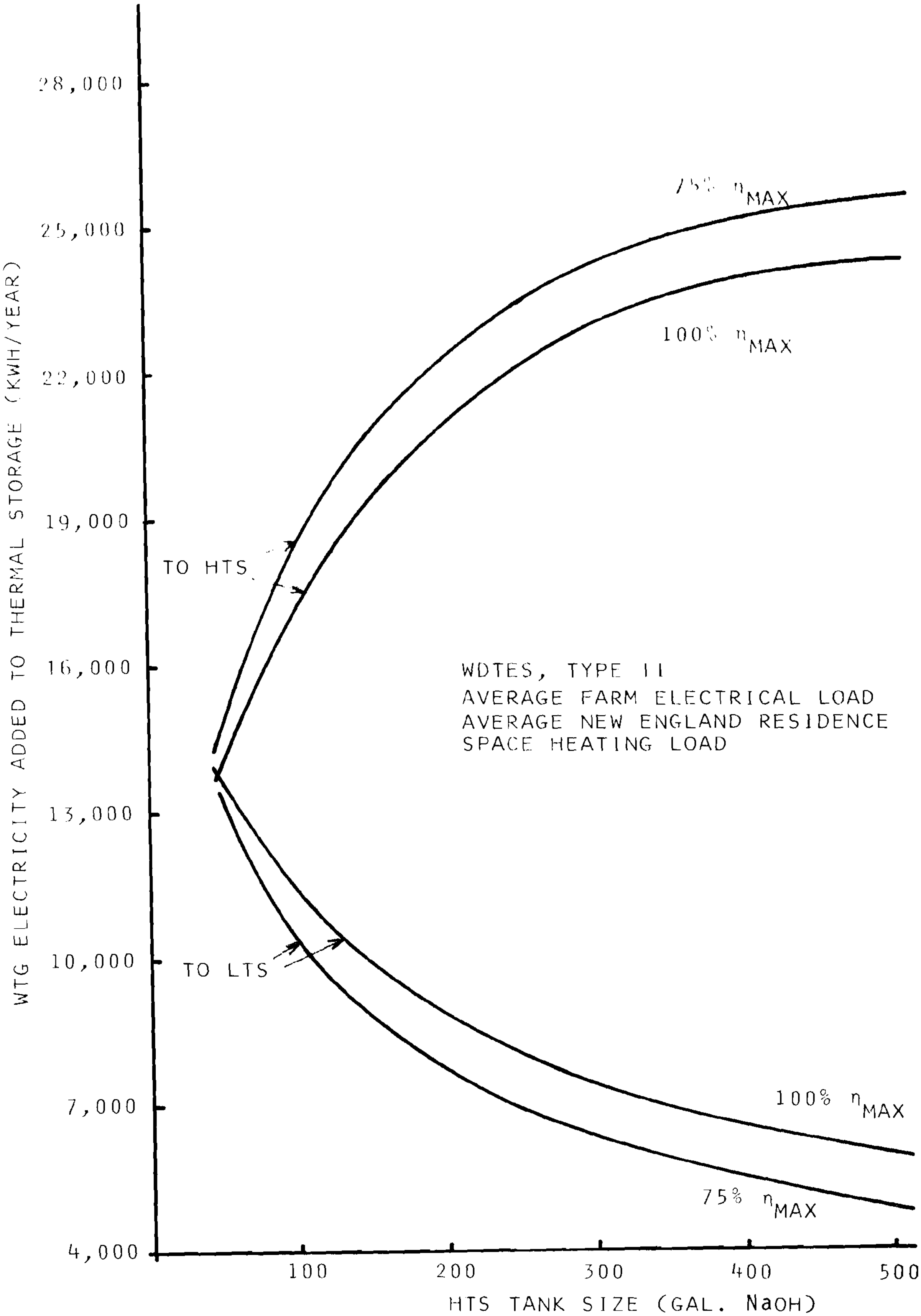


FIGURE 5.53. WIND TURBINE GENERATOR ELECTRICITY ADDED TO THE HTS AND LTS THERMAL STORAGE VIA RESISTANCE HEATERS AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKINE CYCLE EFFICIENCY VALUES.

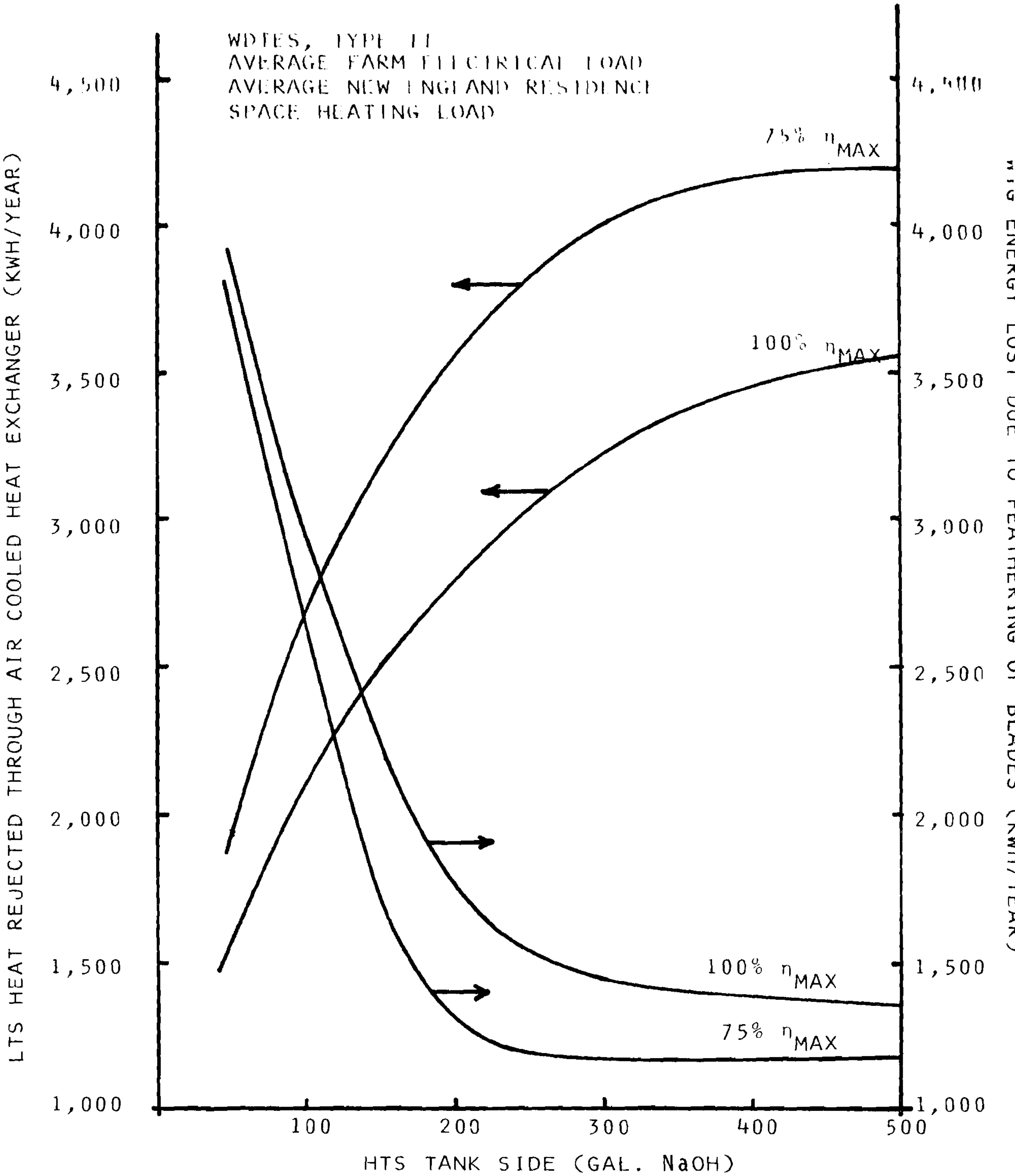


FIGURE 5.54. LTS HEAT REJECTED THROUGH THE AIR COOLED HEAT EXCHANGER AND WTG ENERGY LOST DUE TO FEATHERING OF BLADES AS A FUNCTION OF HTS TANK SIZE FOR BOTH 100% AND 75% "MAXIMUM" RANKE CYCLE EFFICIENCY VALUES.

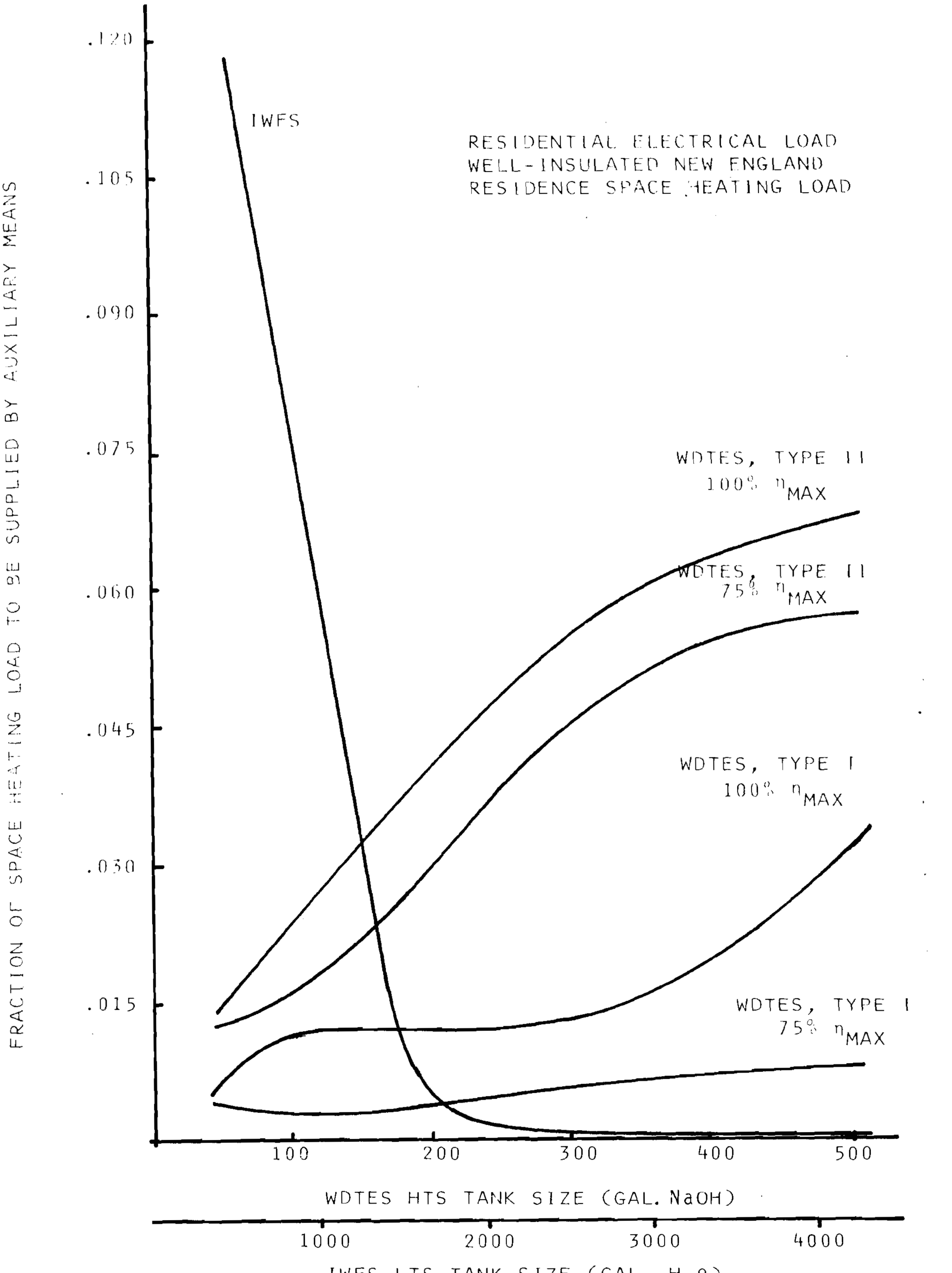


FIGURE 5.55. FRACTION OF SPACE HEATING LOAD TO BE SUPPLIED BY AUXILIARY MEANS AS A FUNCTION OF WDTES HTS TANK SIZE OR IWFS LTS TANK SIZE.

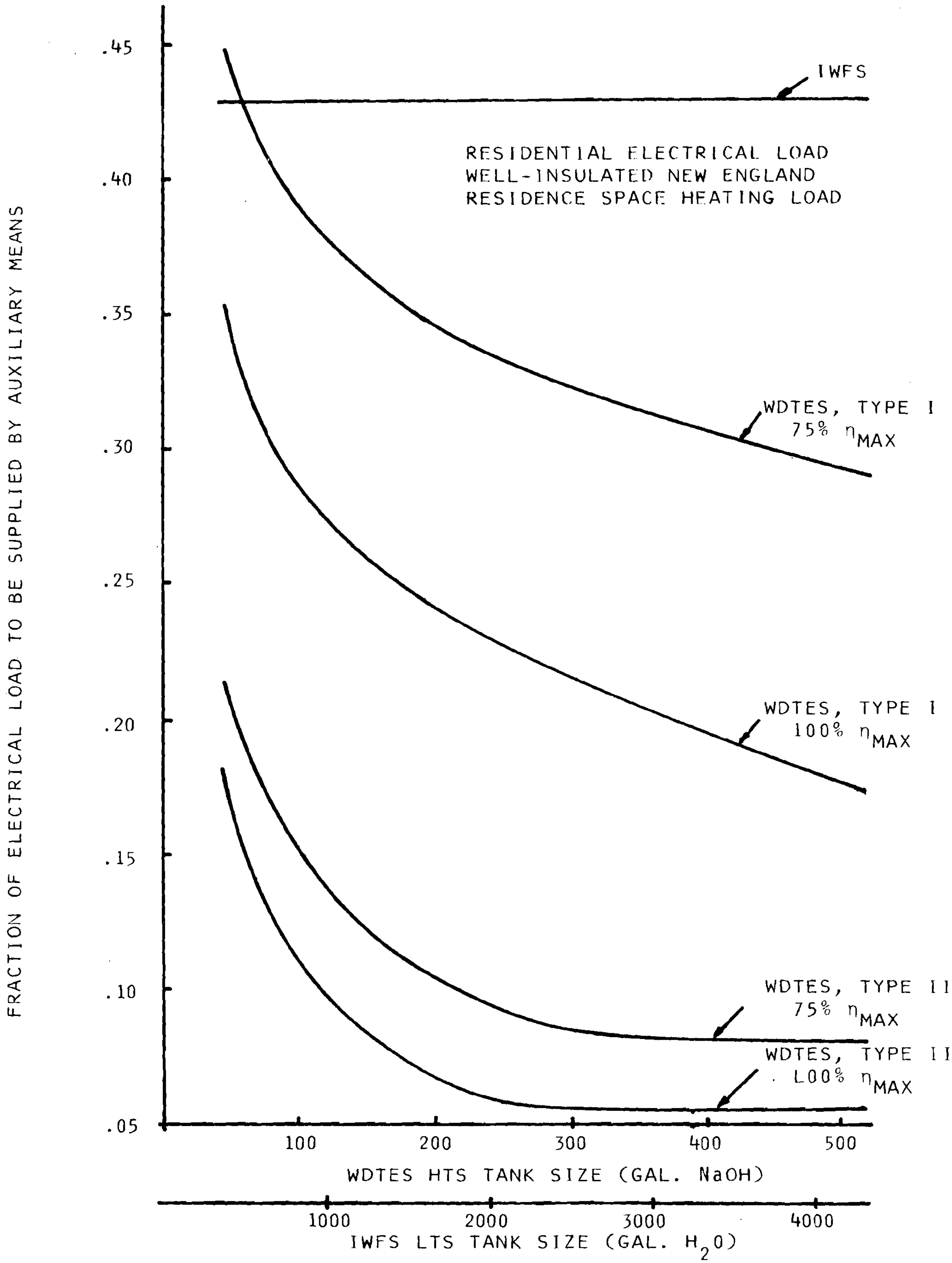


FIGURE 5.56. FRACTION OF ELECTRICAL LOAD TO BE SUPPLIED BY AUXILIARY MEANS AS A FUNCTION OF WDTES HTS TANK SIZE OR IWFA LTS TANK SIZE.

the WDTES schemes, as shown in Figures 5.15 and 5.36, are much less for the WDTES, Type II model because with this system a direct supply of WTG electricity, via the power conditioner, to the electrical load is possible. Unlike the WDTES models, the auxiliary domestic hot water requirement for the IWFS model is significant, as given by Figure 5.3. Because of the load model's low space heating load, the average LTS tank temperature for all three models at all tank sizes considered are sufficiently high for the supply of forced hot water to baseboards, as given in Figures 5.3, 5.16 and 5.37. By examining Figures 5.16, 5.17, 5.37 and 5.38, it can be shown that the mean HTS tank temperature is higher for the WDTES, Type II scheme, but that the HTS tank temperature during RC operation is higher for the WDTES, Type I model. This result is brought about because the Rankine Cycle in the WDTES, Type I model operates more frequently and at a higher output level than on the Type II model. This tends to deplete the energy in the tank more quickly, and causes it to drop below the 400°F minimum RC operation temperature more often. An example of the high energy output levels required from the WDTES, Type I Rankine Cycle can be seen by comparing Figures 5.19 and 5.40. With the Type II model, the RC is only used to augment the WTG electrical output to the electrical load and therefore the condenser heat rejected is small and requiring the air cooled heat exchanger to operate infrequently. Conversely, the RC in the Type I model is the sole supplier of electricity for the system and therefore rejects a larger amount of heat through the condenser, requiring more air cooled heat exchanger heat rejection to prevent boiling. Also to be considered is the WTG energy lost due to feathering of blades, shown in Figures 5.4, 5.19 and 5.40. The IWFS loses the most energy in this way, and the WDTES, Type I model, the least. If a battery storage subsystem were employed with the IWFS model, the possibility would arise for storing some of that overflow energy rather than feathering the blades, thus decreasing the system's high auxiliary electricity requirement.

The application of the three systems to the average New England residence load model is shown in Figures 5.5 to 5.8, 5.20 to 5.26 and 5.41 to 5.47. As given by Figures 5.5, 5.20 and 5.41, the total auxiliary energy requirement of the three systems is virtually the same, with the WDTES, Type II scheme having the lower value by a small amount. Figures 5.6, 5.7, 5.21, 5.22, 5.42 and 5.43 show these energy requirements broken down into their space heating, electrical and domestic hot water (for the IWFS) auxiliary energy components. A comparison of the fraction of the space heating load to be supplied by auxiliary means for each of the systems is shown in Figure 5.57. This figure shows that for LTS tank sizes of 1000 gallons or greater, the IWFS model requires the least amount of auxiliary space heating of any of the systems. Because utility electricity is the most expensive auxiliary energy supply and a very small auxiliary electricity requirement may indicate the possibility of electrical utility independence, the WDTES, Type II model (which has its auxiliary electrical energy requirements compared to the other systems in Figure 5.58), has the best auxiliary energy requirement characteristics. A comparison of Figures 5.25 and 5.46 show graphically a basic difference between the WDTES schemes. The Type I system inputs a far greater amount of WTG electricity to the HTS, in all cases, than the Type II system, because the Type II system only inputs excess WTG electricity after satisfying the

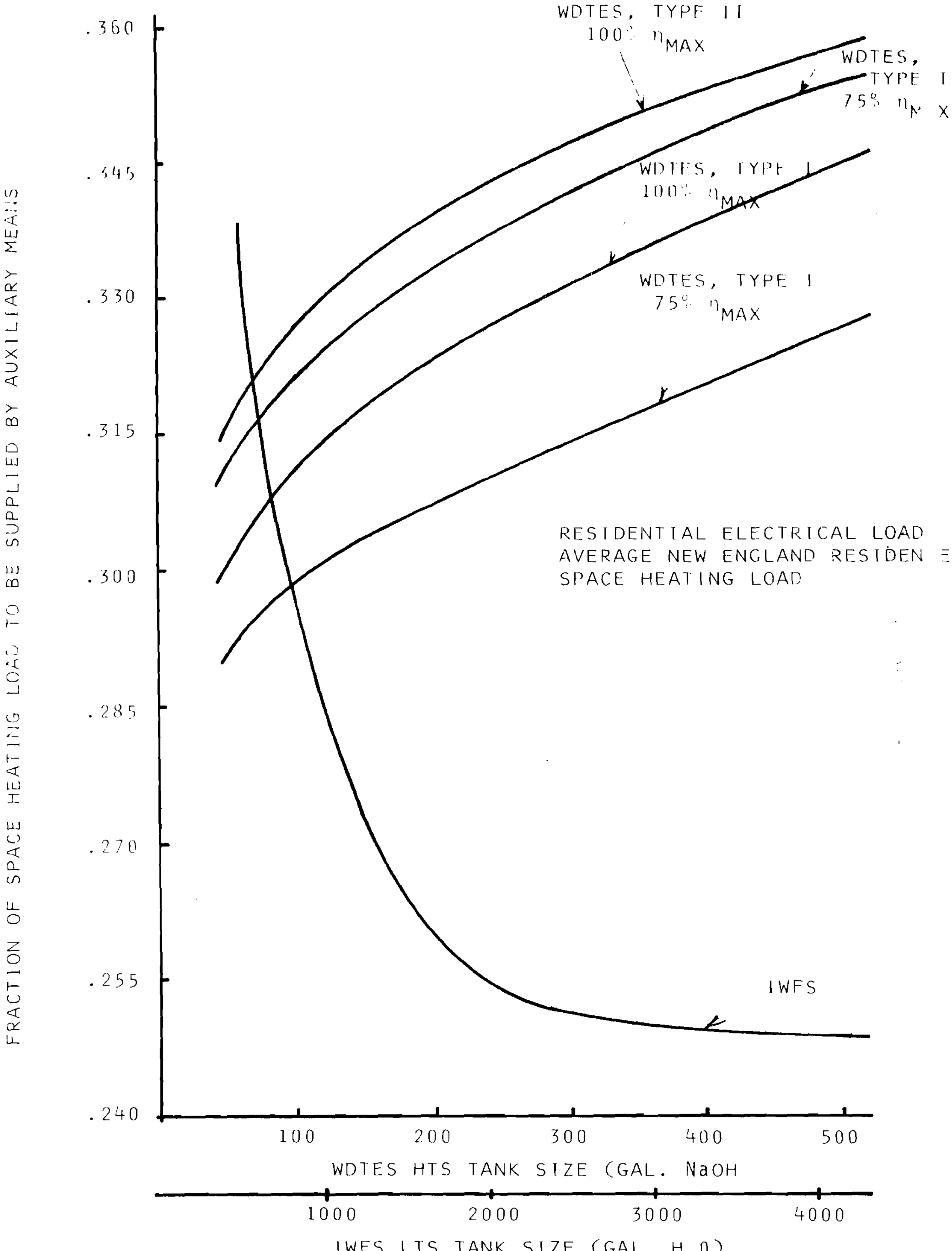


FIGURE 5.57. FRACTION OF SPACE HEATING LOAD TO BE SUPPLIED BY AUXILIARY MEANS AS A FUNCTION OF WDTES HTS TANK SIZE OR IWFS LTS TANK SIZE.

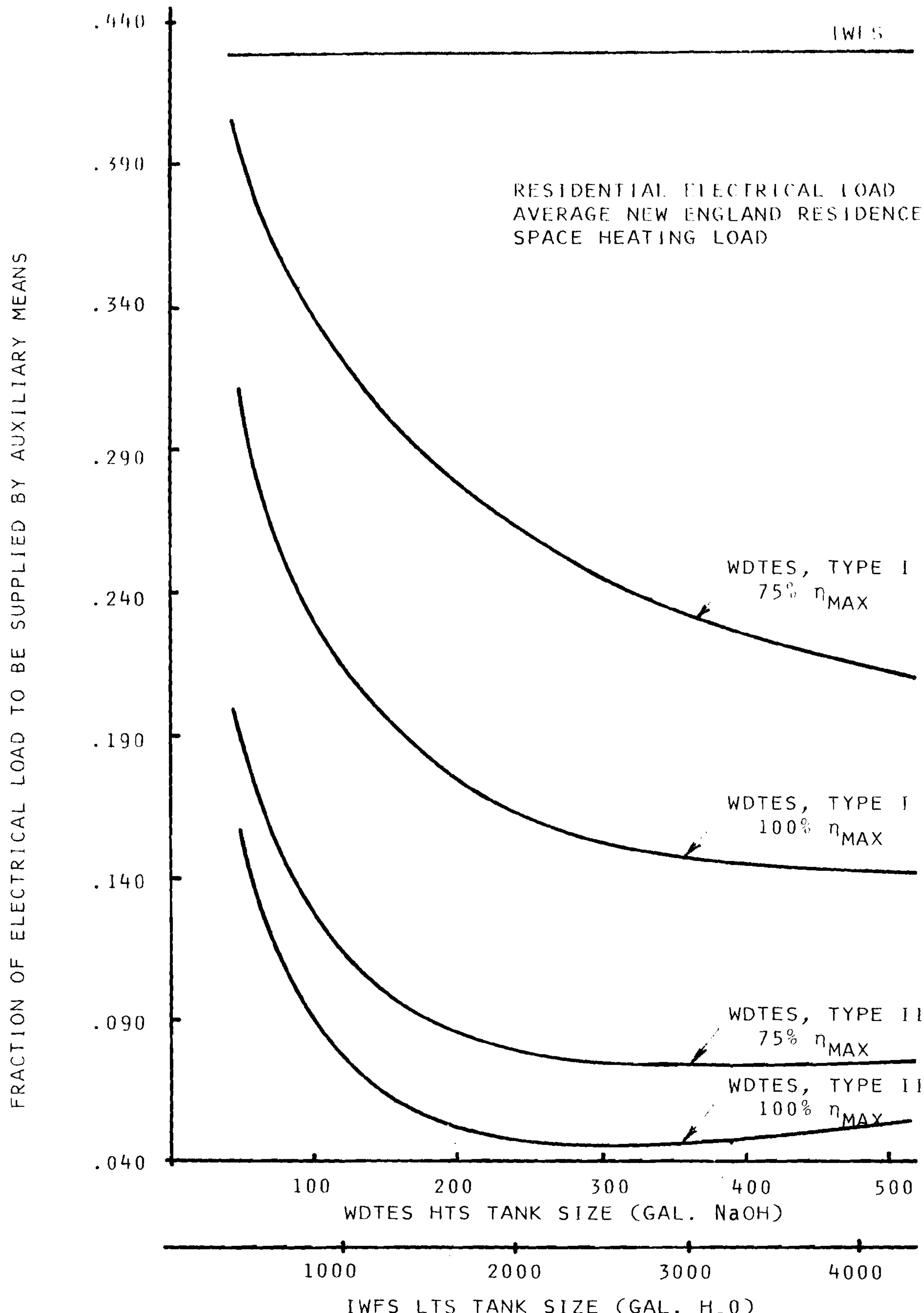


FIGURE 5.58. FRACTION OF ELECTRICAL LOAD TO BE SUPPLIED BY AUXILIARY MEANS AS A FUNCTION OF WDTES HTS TANK SIZE OR IWFS LTS TANK SIZE.

electrical load. Also shown in these figures is that the Type II system inputs a greater amount of WTG electricity to the LTS than the Type I system. The higher mean HTS temperature with the Type II system, as shown in Figures 5.23 and 5.44 makes that happen. Because of that, the HTS in the Type II system goes over 800°F more often allowing WTG electricity to flow to the LTS tank resistance heaters.

The effects that the large electrical load of the average New England farm model has on the three systems are shown in Figures 5.9 through 5.12, 5.27 through 5.33 and 5.48 through 5.54. A comparison of Figures 5.9, 5.27 and 5.48 shows that the WDTES, Type II model requires the least auxiliary energy input to the various imposed loads. Although the Type II system does not supply as much of the space heating load as the Type I system or the IWFS does, as shown in absolute values in Figures 5.10, 5.28 and 5.49 or in Figure 5.59 for a comparison in terms of fraction of space heating load supplied by auxiliary, the ability of the system to supply the electrical requirements is by far the best. As given in Figures 5.10, the IWFS model has no electrical supply subsystem other than the WTG and the utility, and thus is dependent on the WTG output coinciding with the electrical load. The WDTES, Type I model's inability to supply the electrical load effectively in this high electrical load case is shown graphically in Figure 5.60. Because of the huge RC output required by the Type I system, the HTS tank is continually depleted. When the HTS is able to input energy to the RC it is generally at a low temperature causing low RC efficiency and hence high condenser heat rejection rates and high air cooled heat exchanger discharge as can be inferred from

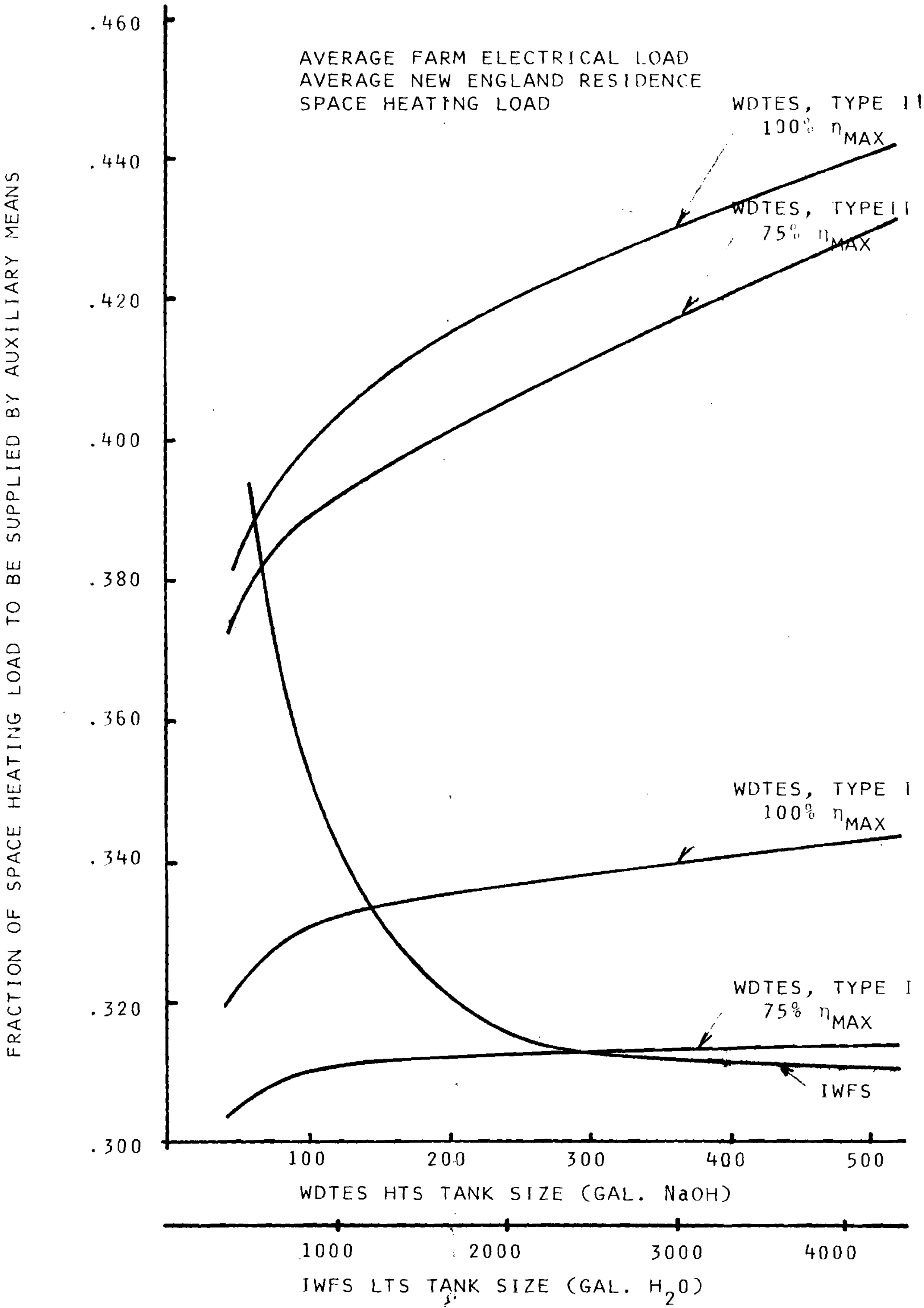


FIGURE 5.59. FRACTION OF SPACE HEATING LOAD TO BE SUPPLIED BY AUXILIARY MEANS AS A FUNCTION OF WDTES HTS TANK SIZE OR IWFS FTS TANK SIZE

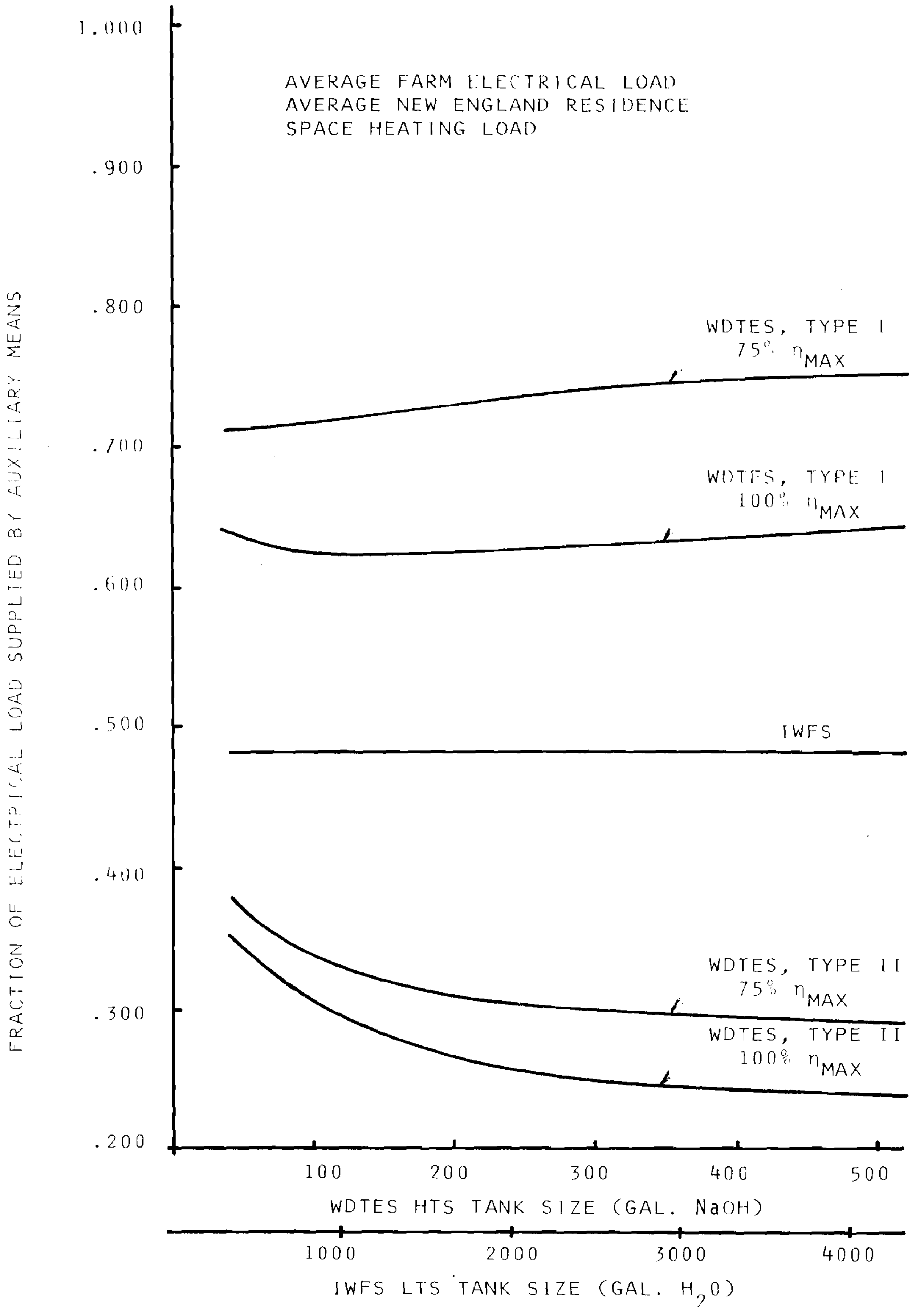


FIGURE 5.60. FRACTION OF ELECTRICAL LOAD TO BE SUPPLIED BY AUXILIARY MEANS AS A FUNCTION OF WDTES HTS TANK SIZE OR IWFS LTS TANK SIZE.

Figures 5.31 and 5.33. The Type II system, because the RC is only required to augment the WTG output to the electrical load, has a higher HTS mean temperature annually and during RC operation which is shown by comparing Figures 5.52 and 5.31. This gives rise to higher thermal efficiency for the Rankine Cycle. These two effects couple to yield low condenser heat rejection rates and thus, lower use of the air cooled heat exchanger, as shown by comparing Figure 5.54 with Figure 5.33. Finally, even though the IWFS model requires a large amount of auxiliary energy, it wastes an amount of WTG energy many times greater than both the WDTES models do, as shown in Figures 5.12, 5.33 and 5.54. This basic drawback of the IWFS model occurs with all the imposed load combinations considered and implies that changes in the model design, such as the use of batteries for electrical energy storage, mentioned earlier, may improve the performance of the system.

The WDTES, Type II scheme is the optimum system considered for all three imposed energy load models. For the well insulated New England residence setting, assuming "maximum" Rankine Cycle efficiency, a 100 gallon HTS tank should be used with the system for minimum auxiliary energy requirements. Although a close examination of Figure 5.41 would seem to indicate that a 50 gallon HTS should be used with the Type II system in the average New England residence setting, it was found that so small an HTS tank produced wild turbine inlet temperature fluctuations, making the 100 gallon HTS more desirable. Finally, for use with the average New England farm setting, the 250 gallon HTS tank size, assuming "maximum" Rankine Cycle efficiency, requires the least auxiliary energy input to the system, making it the most desirable tank size based on energy efficiency.

It has been shown that the WDTES, Type II model, using a different HTS tank size for different settings is the most energy efficient system considered. Energy efficiency, though, is not the only criteria that dictates the use of an alternative energy system in place of a conventional one. Economic feasibility is the greatest obstacle to the implementation of such systems. For this reason, an economic analysis of the systems under consideration is performed in the following chapter.

CHAPTER VI

SYSTEM ECONOMICS MODEL AND RESULTS

The high initial capital costs of the systems under study must be weighed against the savings in energy use, with respect to conventional systems, to justify their implementation. Although the value of saving a barrel of fuel oil is greater than its cost, when national GNP is under consideration, a prospective user of IWFS or WDTES units will not be concerned with U.S. GNP (unless, of course, government subsidy is allowed), but rather net dollar savings.

This chapter is devoted to an economic analysis of the capital costs and fuel requirements of the IWFS and WDTES models when compared against conventional electric, oil and natural gas systems. Each IWFS of WDTES scheme considered will also have, as a back up system, the same conventional heating system. For a comparison with a total electric system, the electric conventional system is assumed to satisfy all electrical, space heating and domestic hot water requirements. Gas and oil systems supply only space heating and domestic hot water with the electrical load being supplied from the electric utility.

Total costs for the conventional and non-conventional systems were considered to be made up of component costs (which are assumed to also include labor) and fuel costs. Previous work by Darkazalli [11] was used as a basis for many of the component costs. Costs of the complete wind turbine generator and low temperature thermal storage subsystems were updated from the 1975 dollars used in his work to 1977 dollars by the consumer price index ratio of the past two years [27]. Other component capital costs were estimated by the methods that follow.

6.1 Component Costs

The component economics model for the wind energy system is based on an initial capital outlay in 1977 for a prototype system or a mass-produced system (if this were possible today) with its lower costs. This non-conventional system, as well as its conventional counterpart, is assumed to be amortized over a 20 year period with an annual inflation rate of 8%.

Costs of the wind turbine generator, the low temperature thermal storage and the conventional systems, already considered in detail by Darkazalli [11] will not be presented. However, costs of the high temperature thermal storage, the Rankine Cycle, the power conditioner (rectifier and inverter), the alternator and miscellaneous items (field controller, switching logic and thermocouples) will be discussed.

The assumed high temperature thermal storage cost (C_{THTS}) is shown in Table 6.1 for both the 250 gallon and the 1000 gallon sizes. The sodium hydroxide storage material cost is based on information from a recent report by Bundy, Herrick and Kosky [28], while the costs of the other HTS components were estimated on the basis of past UMass Wind Furnace experience. A HTS tank cost per gallon as a function of HTS tank size was found by assuming that the costs varied linearly as a function of HTS tank lateral area. Using this plot, shown in Figure 6.1, the HTS tank costs per gallon for all sizes considered could be found for a prototype unit. The total HTS cost (C_{THTS}) was

	250 Gallon	1000 Gallon
1) Storage material NaOH, @ $3.60/gallon	$900	$3,600
2) Carbon Steel tank	$300	$600
3) Resistance Heaters (25kW)	$400	$400
4) Thermal Insulation	$200	$400
5) Fittings and Hot Water Coil	$200	$250
TOTAL	$2000	$5,250

Table 6.1 Assumed High Temperature Thermal Storage Prototype Costs.

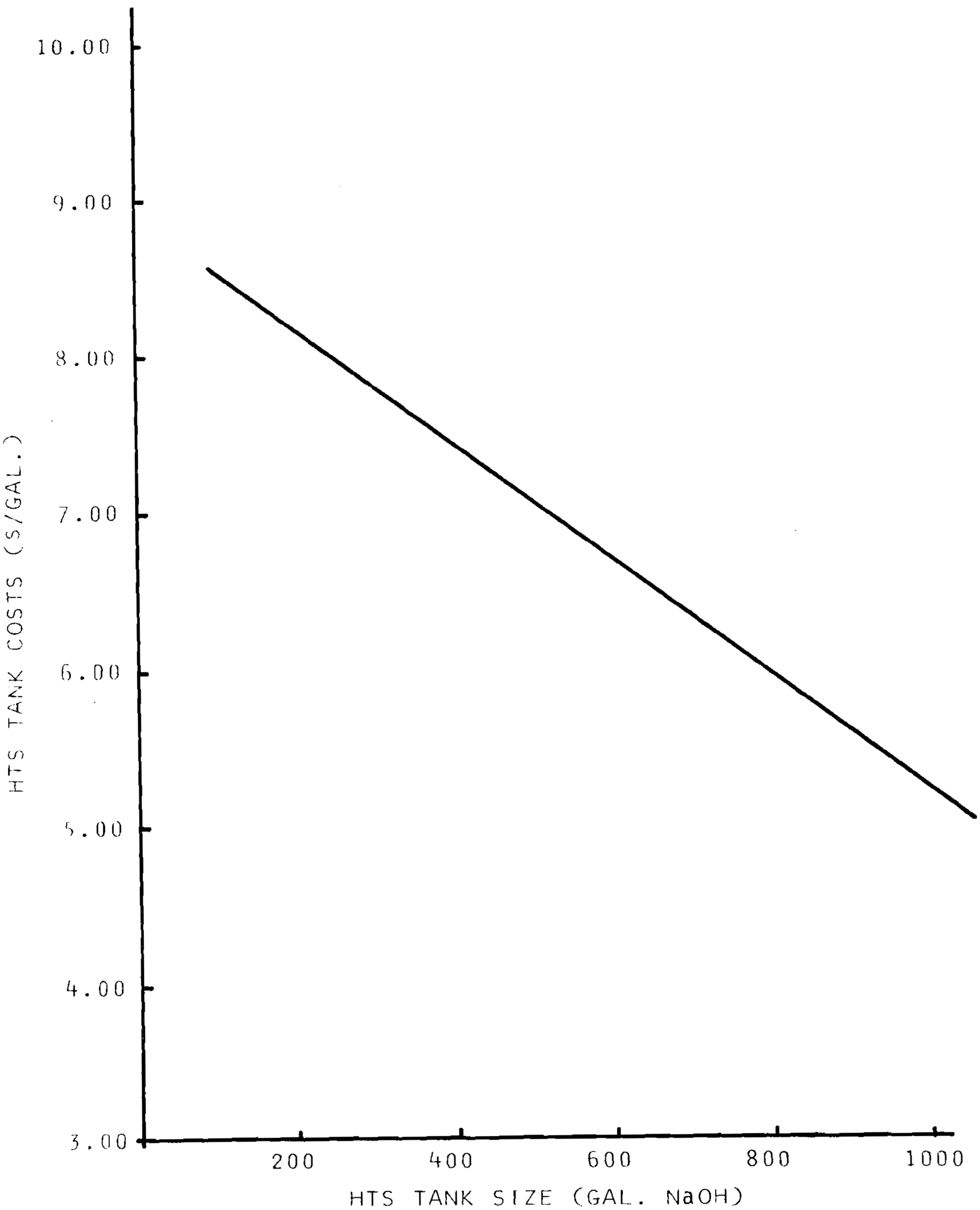


FIGURE 6.1. HTS TANK COSTS AS A FUNCTION OF HTS TANK SIZE FOR A PROTOTYPE UNIT.

found using the equation:

$$C_{THTS} = C_{HTS} \text{ HTS} \tag{6.1}$$

where HTS is the HTS tank size in gallons of NaOH.

Furthermore, it was assumed that if the HTS were mass-produced (in a thousand unit volume or greater), the cost of each unit would decrease to 75% of the prototype cost.

The cost of the Rankine Cycle Subsystem, (C_{RC}), which includes heat exchangers and installation, is based on a relationship as given by Curran [29]:

$$C_{RC} = 135\ [7 + 1.5\ (\text{RCHP} - 1)] \tag{6.2}$$

where C_{RC} is in dollars and RCHP is the Rankine Cycle output capacity in horsepower. Although there is some discrepancy between the costs estimated by this equation and cost projections made by Barber (30), because actual costs for specific systems of the small sizes required were not available, it was assumed that Equation 6.2 would suffice for this preliminary economic analysis. This same value of C_{RC} was used for both the prototype and mass produced costs.

The power conditioner subsystem is actually made up of two components, a rectifier for the conversion of three phase, variable frequency, AC power to DC power and an inverter for the conversion of the DC power to single phase, 60 Hertz, 120 volt AC power. The rectifier, which could be made simply by using only six diodes, was assumed to cost $100 for both the prototype and mass produced units. The inverter, however, is neither a simple component, nor an inexpensive one when compared against the rectifier.

The inverter represents one of the greatest capital expenditures of the IWFS or the WDTES, Type II models. Two types of inverters were found to be available for use with these systems. The first of these is the Gemini Synchronous Inverter System, marketed by the Windworks Company of Mukwonago, Wis. [9]. This unit, via interfacing with the utility grid, sends DC electricity from the rectifier into the utility power lines, which it views as an infinite electrical sink. AC electricity from the utility is actually exchanged with the DC energy input to the grid, to supply the required current. The Gemini system has the disadvantage of being dependent on the local utility lines, but is quite inexpensive in the four and six kilowatt sizes required for the electrical loads under consideration, as shown in Figure 6.2 [31].

The second type of inverter available is a type identical to the Abacus Inverter System, marketed by Abacus Controls, Inc. of Somerville, N.J. [26]. The Abacus unit has the advantage of requiring only a DC input from the rectifier to produce single phase, 120 volt AC current. For this reason, by using this inverter, a system could be made independent of utility electricity, unless of course it is needed as an auxiliary energy source. Unfortunately, the prototype Abacus unit costs of $5600 and $7900 for the four and six kilowatt sizes are quite expensive [32]. Also, as shown in Figure 6.3, the mass-produced Abacus unit is still much more expensive when compared against the cost of the mass-produced Gemini unit in Figure 6.2. It must be taken into consideration, however, that if a system can be made independent of the electrical transmission lines (this is a distinct possibility with the WDTES, Type II model in certain applications), the cost of erecting transmission lines to the

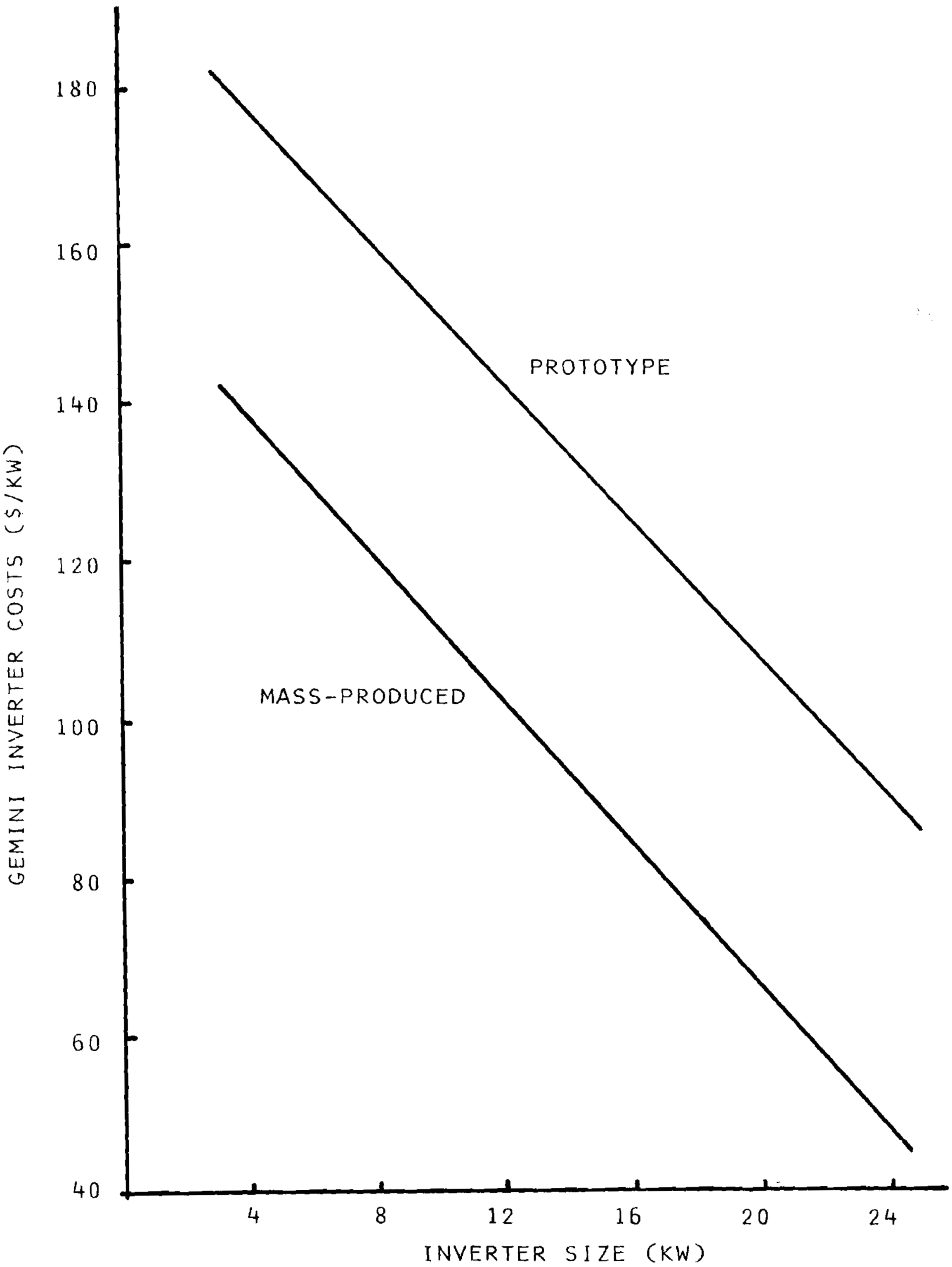


FIGURE 6.2. GEMINI INVERTER COSTS AS A FUNCTION OF INVERTER SIZE FOR PROTOTYPE AND MASS-PRODUCED UNITS.

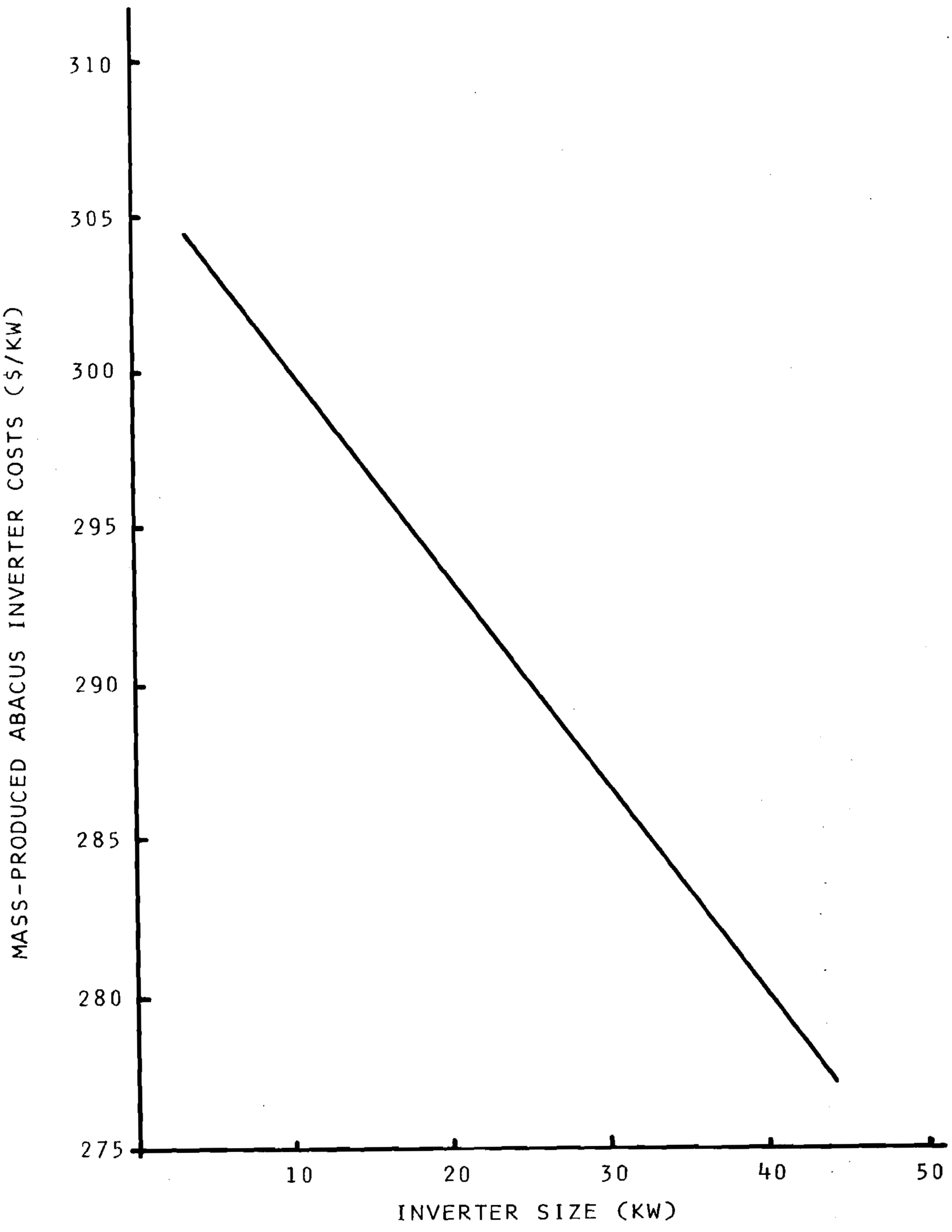


FIGURE 6.3. MASS PRODUCED ABACUS INVERTER COSTS AS A FUNCTION OF INVERTER SIZE.

residence or farm would be saved. For this reason, the cost of the Abacus unit was included in the cost analysis of the WDTES, Type II model for the cases when gas or oil are used for auxiliary space heating and domestic hot water. It should also be pointed out that, since the money saved by not having to erect electrical transmission lines varies widely for different locations, this was not taken into account in the economic analysis.

For the two WDTES systems, alternator costs must be taken into account. It was found that alternators of the four and six kilowatt size are produced by the Lima Electric Company, Inc. of Lima, Ohio. This is the same company that produced the generator for the WTG that is a part of the UMass wind furnace system. The cost of the four and six kilowatt prototype units, C_{ALT}, as found in a price listing from the company, are \$1020 and \$1135, respectively. It was assumed that if these units were mass produced in a volume of a thousand or more that the cost per unit, C_{ALTF}, would drop to 65% of this.

The field controller, switching logic and thermocouples were lumped under miscellaneous costs. The prototype costs for the miscellaneous item (C_{MISC}) were assumed to include \$150 each for the field controller and the switching logic, and \$50 for thermocouples, for a total of \$350. Mass produced costs for the miscellaneous items (C_{MISCF}) included \$100 each for the field controller and switching logic, and \$50 for the thermocouples, for a \$250 total.

The annual cost of the advanced wind furnace and the conventional systems was calculated by first determining the total cost of the systems. The total cost was then multiplied by the annual cost factor, R, to find the yearly cost. The factor, R, is given by the equation:

$$R = \frac{I}{(1 - \frac{1}{(1 + I)^n})} \qquad (6.3)$$

where I is the annual interest rate and N represents the amortization period.

6.2 Fuel Costs and Conventional System Efficiencies

Fuel costs for both the auxiliary requirements of the advanced wind furnace systems and the conventional systems were adopted from actual New England energy costs. An assumed electricity cost of $.045/kWh was based on an updated version of the electricity cost assumed by Darkazalli [11]. The natural gas cost was found by using the rate structure provided by the Baystate Gas Company of Northampton, Mass., which appears in Table 6.2. From this rate structure, an average cost of $.012/kWh was derived assuming a 4,400 kWh combined space heating and domestic hot water load and a 100,000 Btu/CCF heating value of the fuel [33]. The cost of No. 2 heating oil was found to be $.479/gallon in the Amherst area. Assuming a heating value of the fuel of 139,600 Btu/gallon yielded a cost of $.0117/kWh.

The rapid escalation of fuel prices in recent years indicates that those fuel costs will not remain at these values. To take rising fuel costs into account, annual price escalation rates of 6% for electricity, 7% for oil and 8% for natural gas were assumed for the 20 year amortization period [33].

The average fuel costs (C_{FAVE}) were calculated over the amortization period using the equation:

First CCF	-	\$3
Next 9 CCF	-	\$.311/CCF
Next 15 CCF	-	\$.271/CCF
Next 25 CCF	-	\$.231/CCF
Over 50 CCF	-	\$.1542/CCF
Adjustment price for each CCF		\$.1370/CCF

(1 CCF = 100 ft^3)

Table 6.2 Typical New England Natural Gas Rate Structure (1977)

$$C_{FAVE} = \frac{\sum_{i=1}^{N} (1+RI)^{N} C_{FI}}{N} \tag{6.4}$$

where C_{FAVE} has units of \$/kWh, N is the amortization period in years, C_{FI} is the initial fuel cost in \$/kWh, and RI is the annual fuel escalation rate.

Conventional electrical, space heating and domestic hot water systems have inherent inefficiencies due to losses in the baseboard resistance heaters or the fossil-fuel furnace. Because this tends to increase conventional and auxiliary fuel consumption costs, this effect was included in the economic analysis. Although the losses for fossil fuel furnaces can vary widely, as shown in Dunning [34], average fossil-fuel furnace efficiencies were derived based on information found in his paper. The efficiencies of the natural gas and oil fired furnaces were assumed to be 65% and 55% respectively. For the electrical model, baseboard resistance heaters were assumed to have an efficiency of 95%.

6.3 The Computer Economic Model

A digital computer simulation WSDECO, which appears as a logic flow chart in Figure 6.4, was written to facilitate the economic analysis of the conventional and non-conventional systems. As in the main program simulation, WSDECO features an interactive format to simplify its use. A line by line listing of this computer program is located in Appendix C.

Initially, as shown in Figure 6.4, the program requires the user to input the electrical, space heating and domestic hot water loads for the residential or farm setting. It then asks the operator to input the auxiliary energy requirements for the non-conventional system, the type

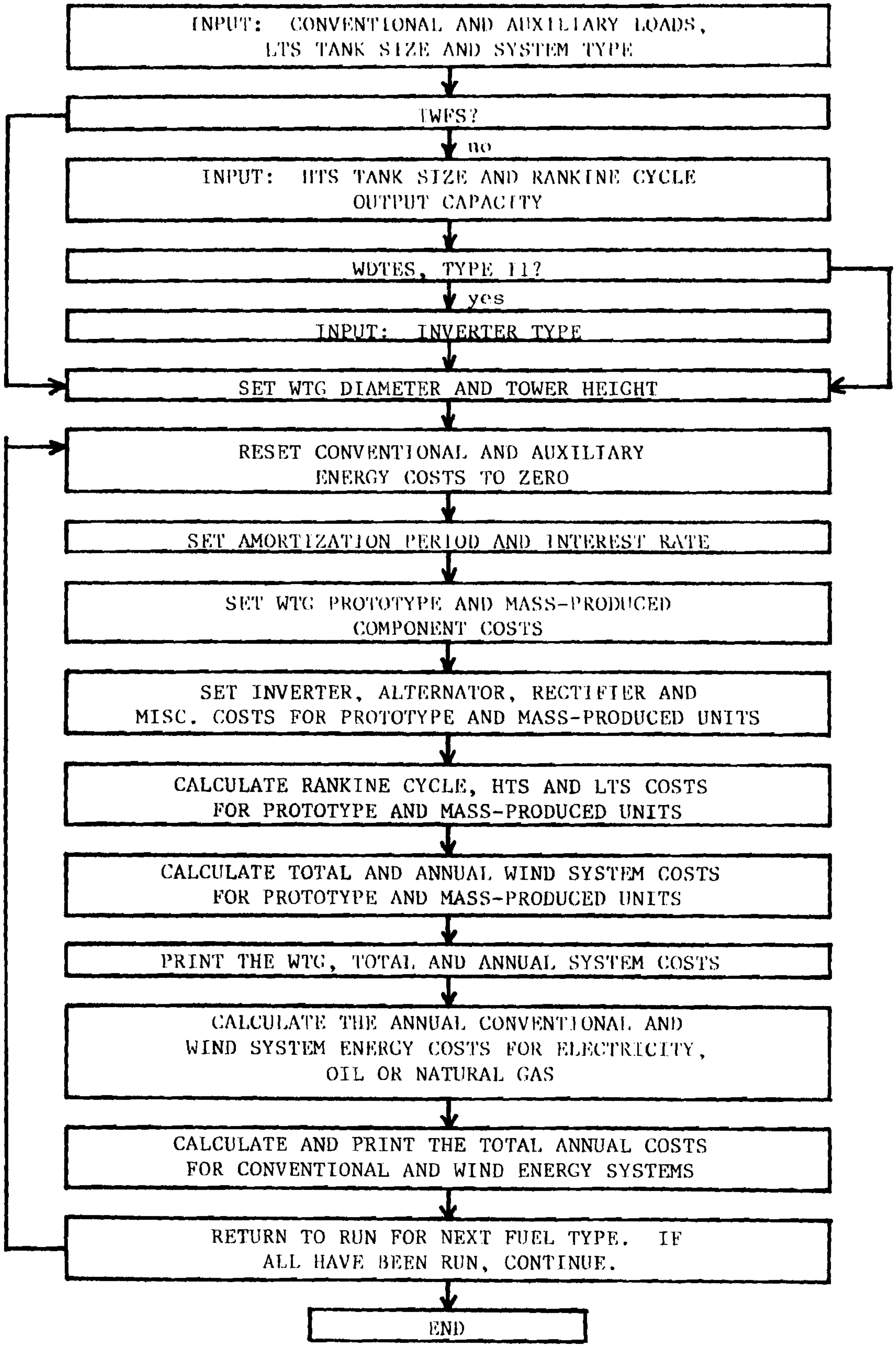


FIGURE 6.14. LOGIC FLOW DIAGRAM FOR THE ECONOMICS PROGRAM

of system to be studied and the LTS tank size. If the system under consideration is a WDTES scheme the user is then asked to input the HTS tank size and the Rankine Cycle size. If the WDTES, Type II model is being investigated, the user is asked to input the inverter type, either Gemini or Abacus. Next, for all systems, the WTG diameter and tower height is set. The amortization period and the interest rate is then assigned. WTG and advanced wind furnace component costs are then either set or calculated for both the prototype and mass-produced units and the total non-conventional system costs are calculated and printed out. Annual costs for the units are then found by using the annual cost factor, R. Next, the annual conventional and non-conventional fuel costs are determined. Since the system costs and the fuel costs are now known, total annual costs are then calculated and outputted by the program. Finally, if all three fuels have not been considered, all costs are reset to zero and the program is initiated again. Once electricity, oil and natural gas have been considered for auxiliary fuels, the program terminates.

A sample run of WSDECO showing both inputs and outputs is included in Figure 6.5 and an explanation of the variables given in the output is located in Appendix A. A breakdown of the total costs of the prototype WTG(CWND), the total system (CTOT) and their corresponding mass-produced costs (CWNDF) and CTOTF) are shown for all three systems in Table 6.3. The non-conventional component costs for the systems are shown for the average New England residence application with a 2000 gallon LTS for the IWFS model and also a 100 gallon HTS and a 4 kw Rankine Cycle for the WDTES models. It should be noted that although

```
      CWND          CTOT          ACST
     15669.00      22292.71      2270.56
     CWNDF         CTOTF         ACSTF
      7078.00      12209.96      1243.61
ELECTRICITY
    CECONV        COCONV        CGCONV        TCCONV
     2448.80        0.            0.           2448.80
     CEAUX         COAUX         CGAUX         TCAUX
       95.57        0.            0.             95.57
    CANCOV        CANSDS        CANSDSF
     2616.86      2534.18       1507.23
OIL
    CECONV        COCONV        CGCONV        TCCONV
      534.28       967.23         0.           1501.51
     CEAUX         COAUX         CGAUX         TCAUX
       58.23        18.86         0.             77.09
    CANCOV        CANSDS        CANSDSF
     1703.18      2549.32       1522.37
GAS
    CECONV        COCONV        CGCONV        TCCONV
      534.28        0.           945.77        1480.05
     CEAUX         COAUX         CGAUX         TCAUX
       58.23        0.            18.44          76.67
    CANCOV        CANSDS        CANSDSF
     1670.51      2537.70       1510.75
 END.

SRU       1.662 UNTS.

RUN COMPLETE.
```

Figure 6.5 Sample Run of Economics Program WSDECO

Component	IWFS Prototype	IWFS Mass Produced	WDTES, Type I Prototype	WDTES, Type I Mass Produced	WDTES, Type II Gemini Inverter Prototype	WDTES, Type II Gemini Inverter Mass Produced	WDTES, Type II Abacus Inverter Prototype	WDTES, Type II Abacus Inverter Mass Produced
(3) 40 ft. Blades	$5852	$3228	$5852	$3228	$5852	$3228	$5852	$3228
25 kW Generator	2270	880	2270	880	2270	880	2270	880
Stationary Parts	4547	1650	4547	1650	4547	1650	4547	1650
60 ft. Tower	3000	1320	3000	1320	3000	1320	3000	1320
TOTAL WTG COSTS	$15669	$7078	$15669	$7078	$15669	$7078	$15669	$7078
2000 gal. LTS	$1760	$1100	$1760	$1100	$1760	$1100	$1760	$1100
100 gal. HTS	-	-	855	641	855	641	855	641
4 kW Gemini Inverter	710	552	-	-	710	552	-	-
4 kW Abacus Inverter	-	-	-	-	-	-	5600	1216
4 kW Alternator	-	-	1020	660	1020	660	1020	660
4 kW Rectifier	100	100	-	-	100	100	100	100
4 kW Rankine Cycle	-	-	1829	1829	1829	1829	1829	1829
Miscellaneous	350	250	350	250	350	250	350	250
TOTAL SYSTEM COST	$18589	$9080	$21483	$11558	$22293	$12210	$27183	$12874

Table 6.3. Breakdown of Typical Non-Conventional Component Costs

these costs are shown to the dollar, those figures are not that accurate due to the assumptions made for this preliminary study and therefore should only be considered to represent price trends and not actual dollar costs.

6.4 Economics Analytical Results

In this section, the results obtained from the systems simulation model (WDTES1) are used in conjunction with the economics model (WSDECO) to evaluate the economic feasibility of the three advanced wind furnace systems. The economic potential of each prototype or mass produced system was determined with respect to each of the three residential or farm applications by comparing its total annual cost with the conventional systems annual cost.

Economic results were derived for the IWFS model in each of the applications by varying the key system variable, the low temperature thermal storage, from 500 to 4000 gallons. With the IWFS model, the only inverter type considered was the Gemini model, since utility lines would be imperative due to the large electrical auxiliary requirements of the system and also that inverter's low cost.

With the WDTES models, which assumed maximum Rankine Cycle efficiency, economic results for each setting were obtained by varying the high temperature thermal storage size from 50 to 500 gallons. In the case of the WDTES, Type I and the WDTES, Type II model in the farm setting, the only inverter type considered was the Gemini model because the high auxiliary electrical requirement dictates accessibility to utility lines. However, with the WDTES, Type II scheme in the well-insulated and average New England residence settings, the auxiliary electrical requirement was considered to be low enough that independence from the utility lines was possible. Thus, under these conditions, the feasibility of the more expensive Abacus inverter was appraised.

The economic results for the well-insulated New England residence are given in Figures 6.6 through 6.9. As shown in all four graphs, with each mass-produced advanced wind furnace system, the lowest total annual system costs are achieved by using the electric utility as a backup system. Although the difference in total annual system costs are small for the three auxiliary systems, due to the low auxiliary energy requirement for the advanced furnace systems in this setting, the low component costs of the auxiliary electrical system make it economically advantageous. The IWFS model, shown in Figure 6.6, represents the system with the lowest annual costs for both the prototype and mass-produced units. Although auxiliary energy requirements of the system are high, the relatively low component costs of the IWFS when compared against the WDTES models in Figures 6.7 through 6.9 make the prototype model less expensive than the conventional electric system, and the mass-produced model cheaper than the conventional oil and gas systems. Figures 6.7 and 6.8, for the WDTES, Type I and the Type II model with a Gemini inverter, show the costs of the two prototype and mass produced systems to be approximately equal. This is caused by the lower auxiliary energy costs of the Type II scheme with a Gemini inverter being able to offset its greater system component costs when compared against the Type I model in that setting. The increase in the WDTES, Type II model costs when the Abacus inverter is introduced is depicted in Figure 6.9. As can be inferred from Figure 6.9, only mass production of the

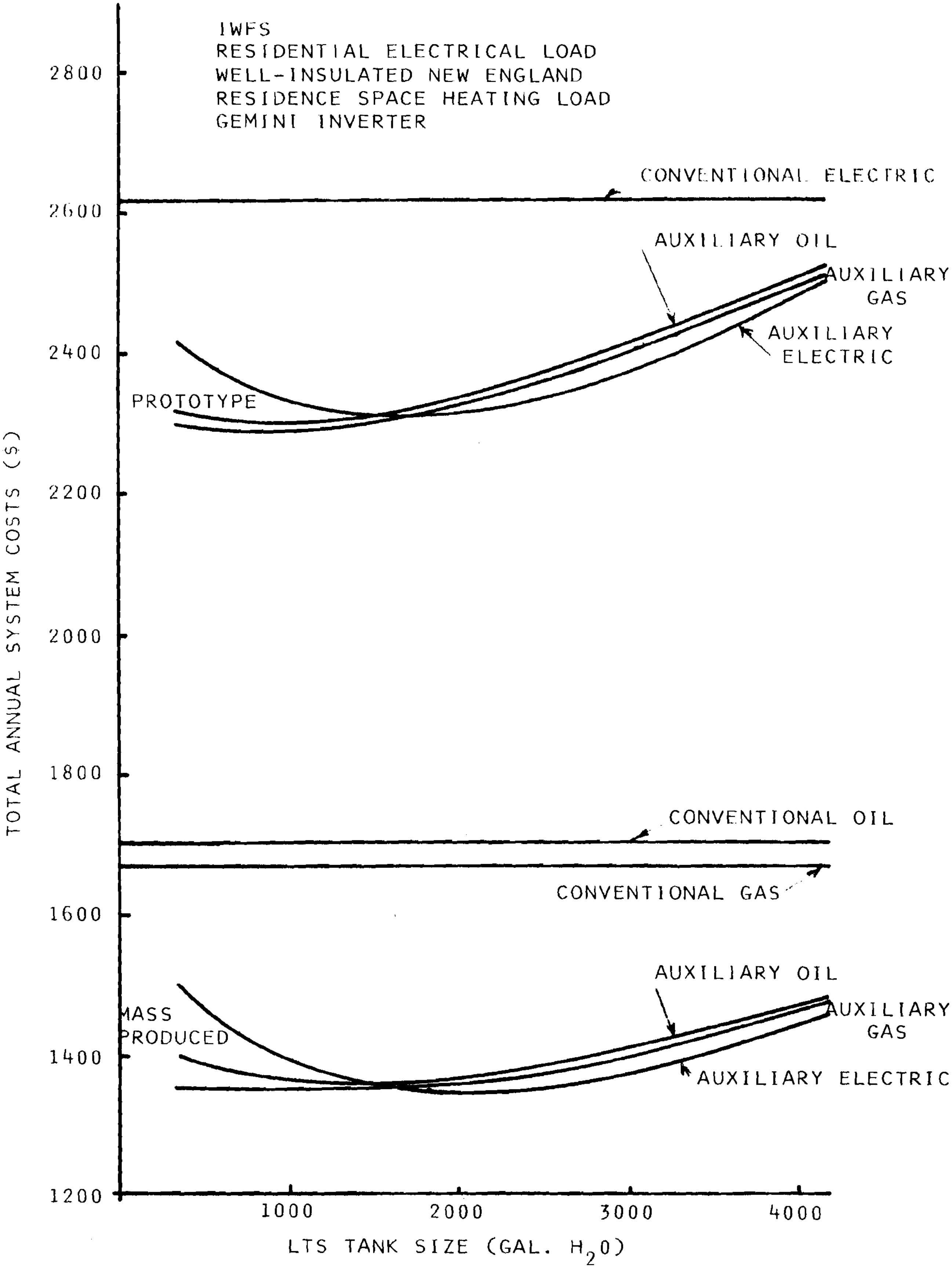


FIGURE 6.6. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF LTS TANK SIZE FOR CONVENTIONAL PROTOTYPE AND MASS PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

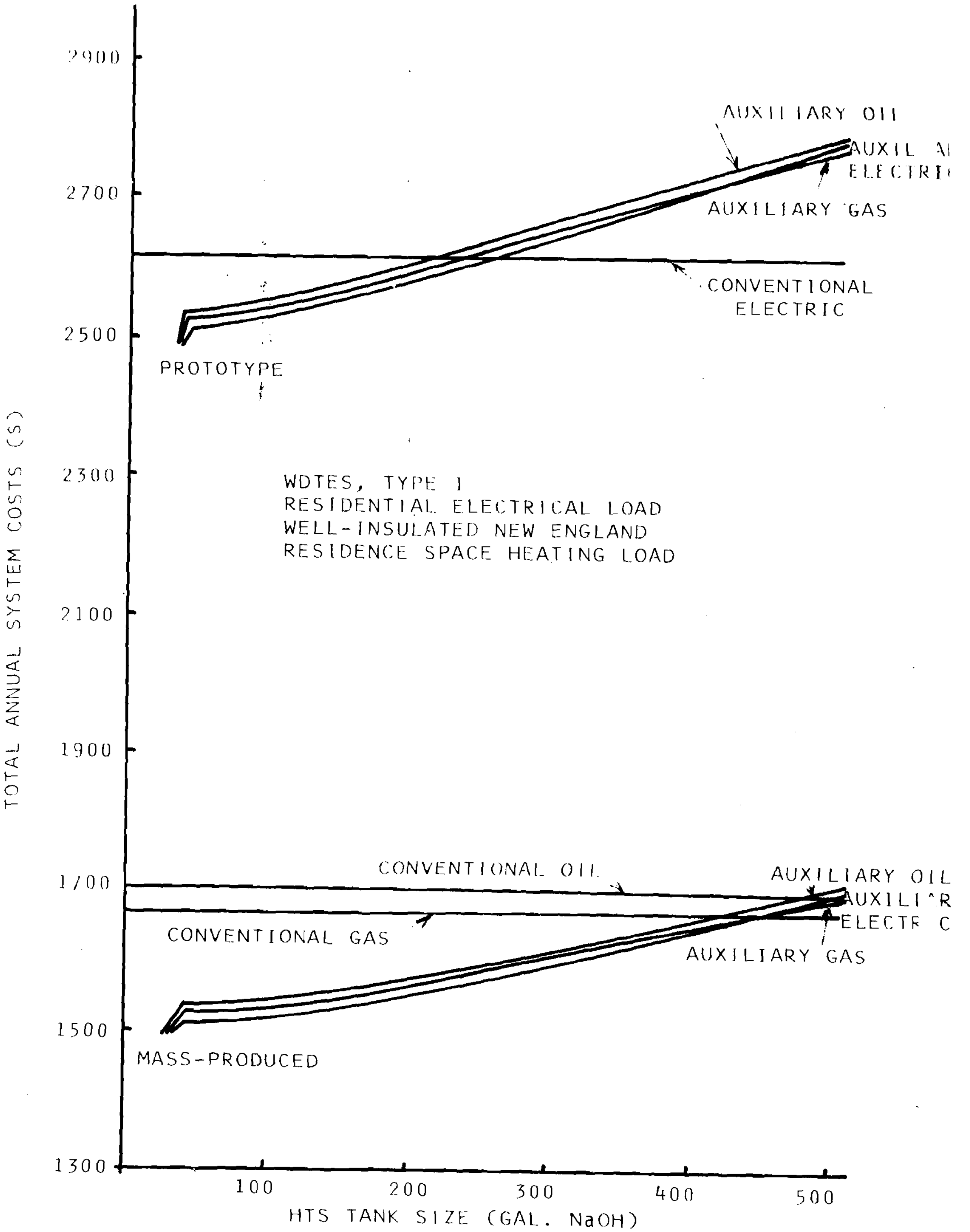


FIGURE 6.7. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

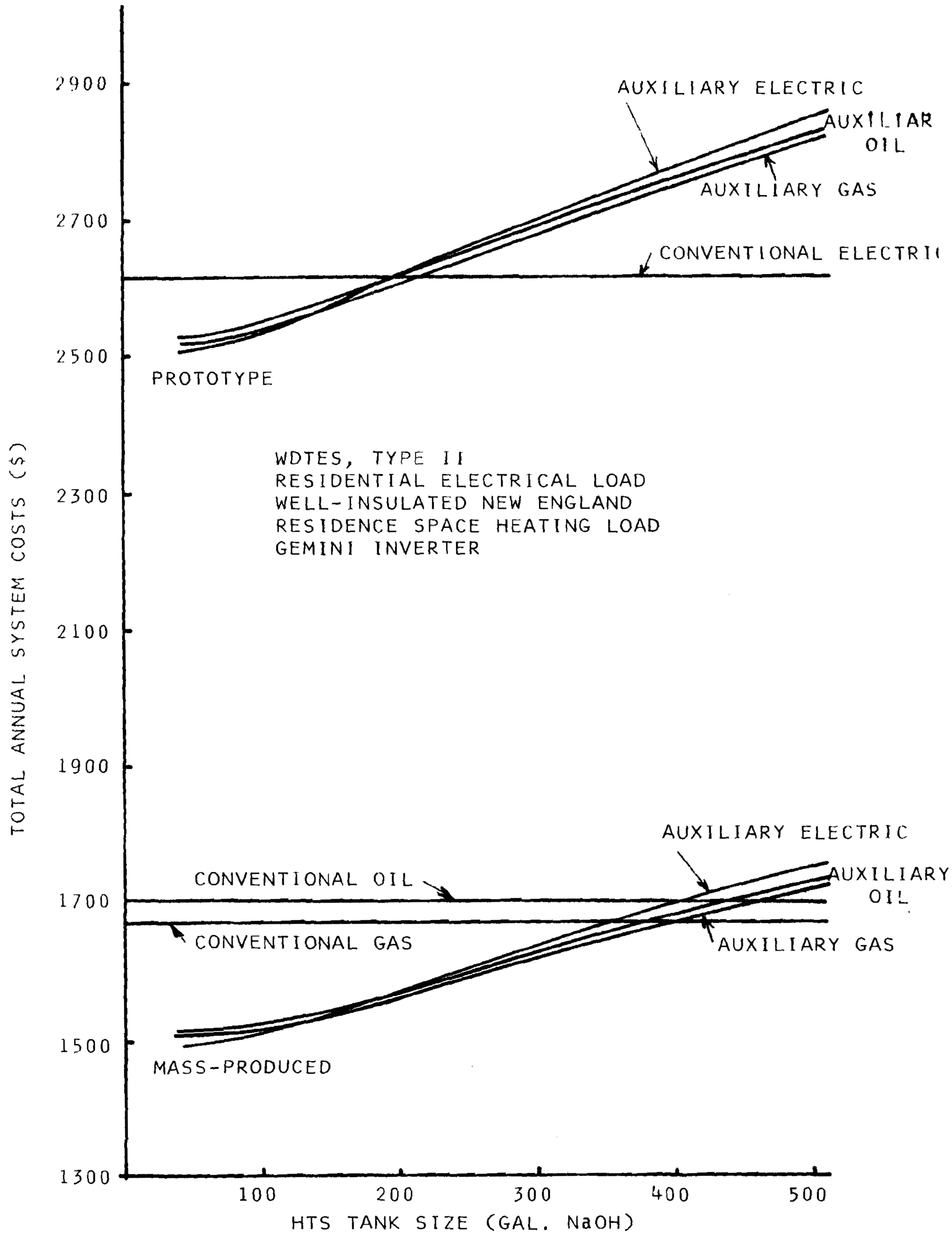


FIGURE 6.8. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

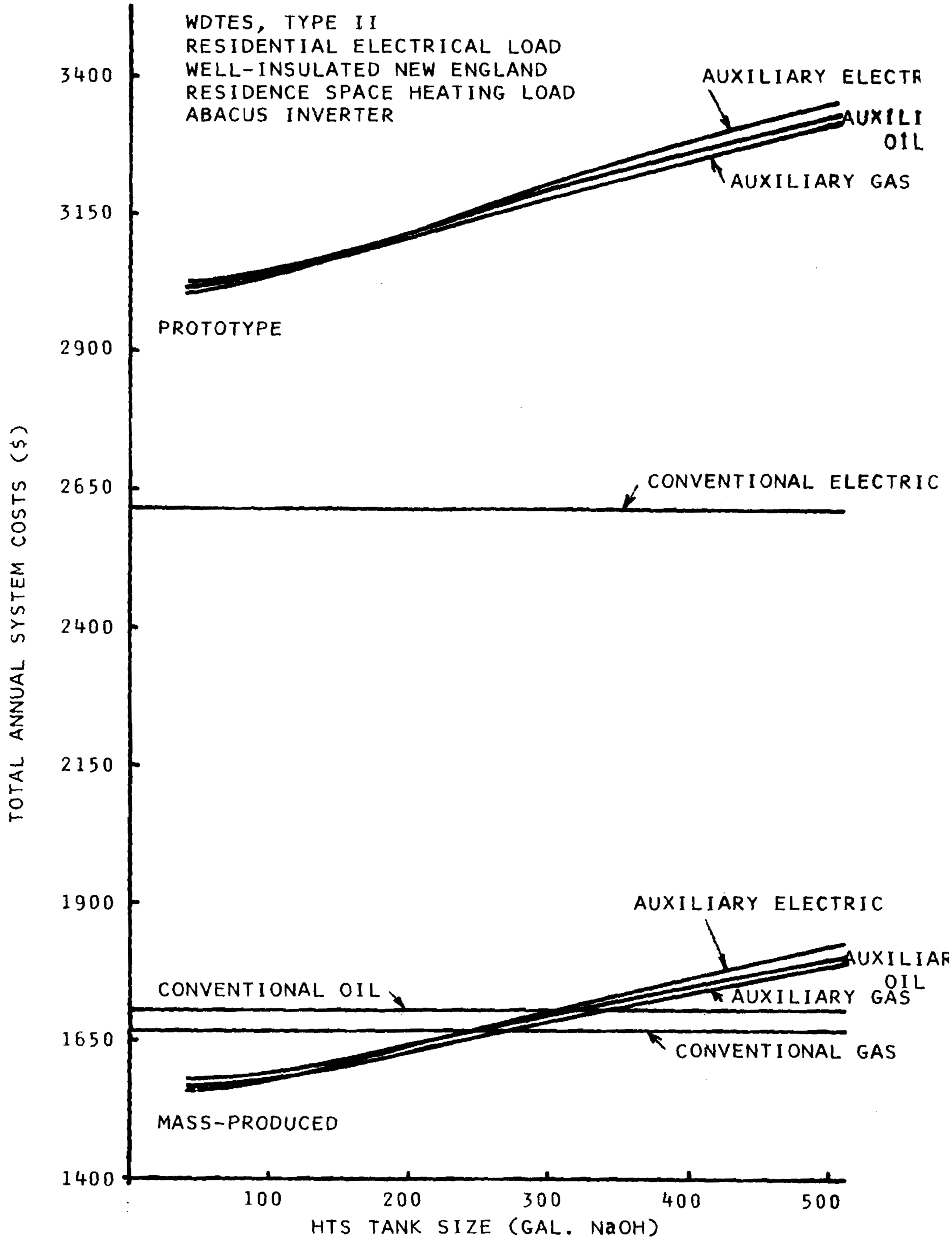


FIGURE 6.9. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

components could make this model less expensive annually than the conventional systems.

As shown in Figures 6.10 through 6.13, for the average New England Residence, the application of any of the prototype systems, using the proper storage tank size, can be justified economically when compared to conventional electric systems. Furthermore, if gas is used as an auxiliary all the advanced mass produced wind furnace systems compare favorably economically to the conventional oil and gas system costs. Also of interest with this application is the large difference for all models in annual costs between auxiliary electric and auxiliary fossil fuels. This is due to the relatively large (when compared to the well-insulated residence) auxiliary energy requirements of all the systems in this application and the difference between electrical and fossil fuel costs. With the IWFS model (shown in Figure 6.10), which represents the lowest priced non-conventional system, an annual savings of approximately $700 over the conventional gas costs can be realized. Unlike the well-insulated setting, a comparison of Figures 6.11 and 6.12, representing the WDTES, Type I model and the Type II model with a Gemini inverter both in the average N.E. residence setting, indicates that the higher energy efficiency of the Type II system is not great enough to justify higher component costs. This trend is corroborated further, as seen in the still greater annual costs in Figure 6.14, when the Abacus inverter is employed.

The economic results for the average New England farm setting are shown in Figures 6.14 through 6.16. In the farm setting, the auxiliary electrical requirements for the IWFS and WDTES, Type II were so large

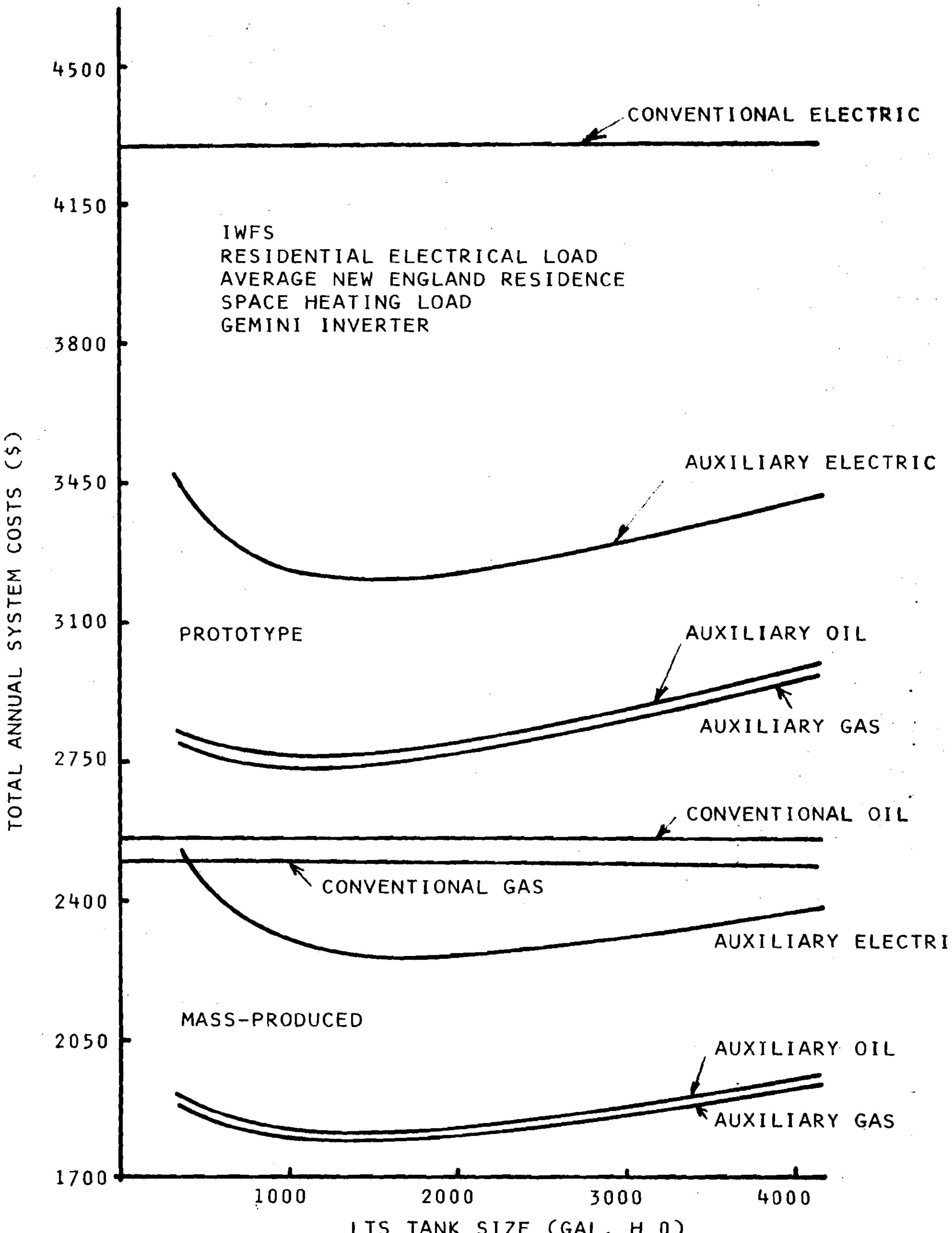


FIGURE 6.10. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF LTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

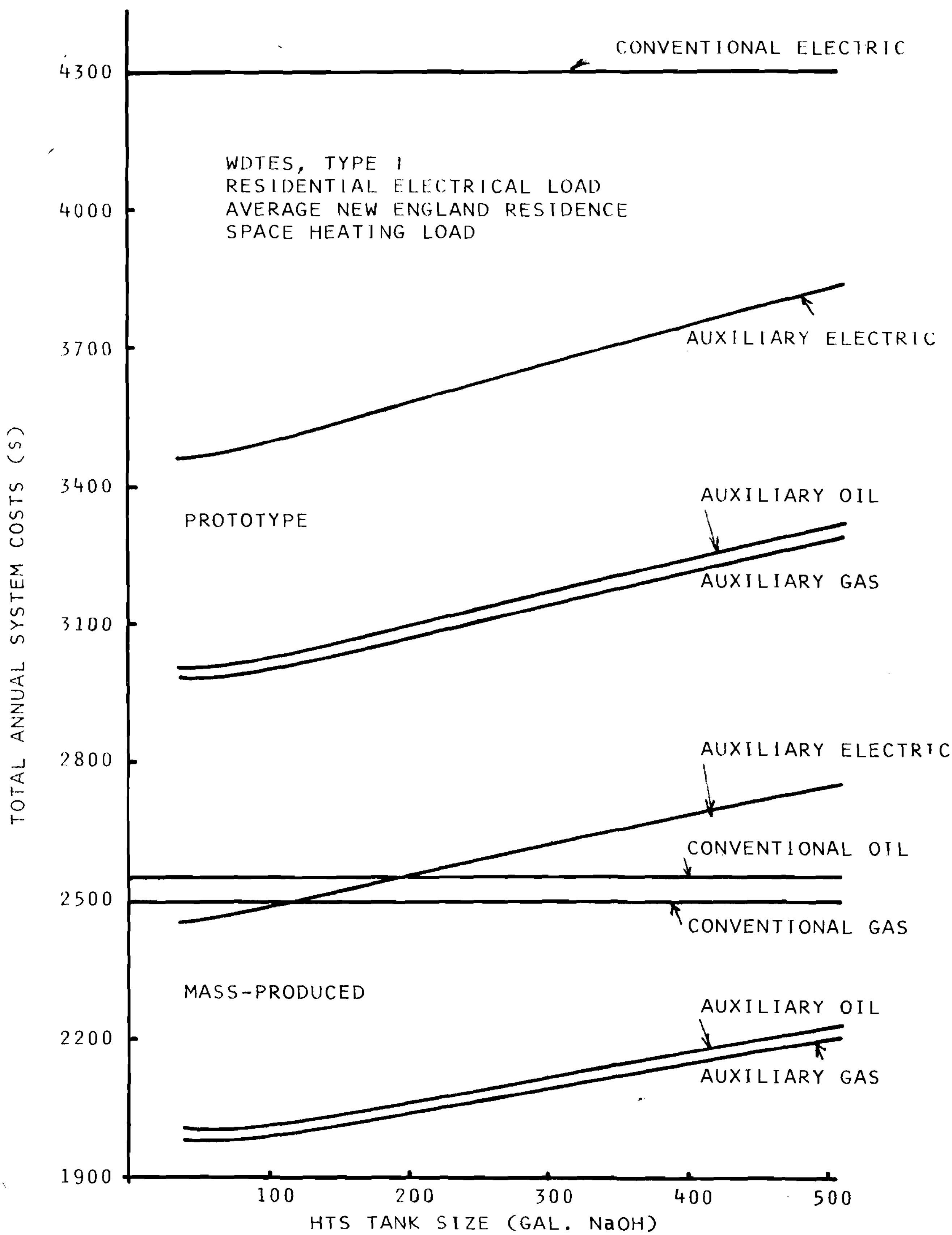


FIGURE 6.11. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

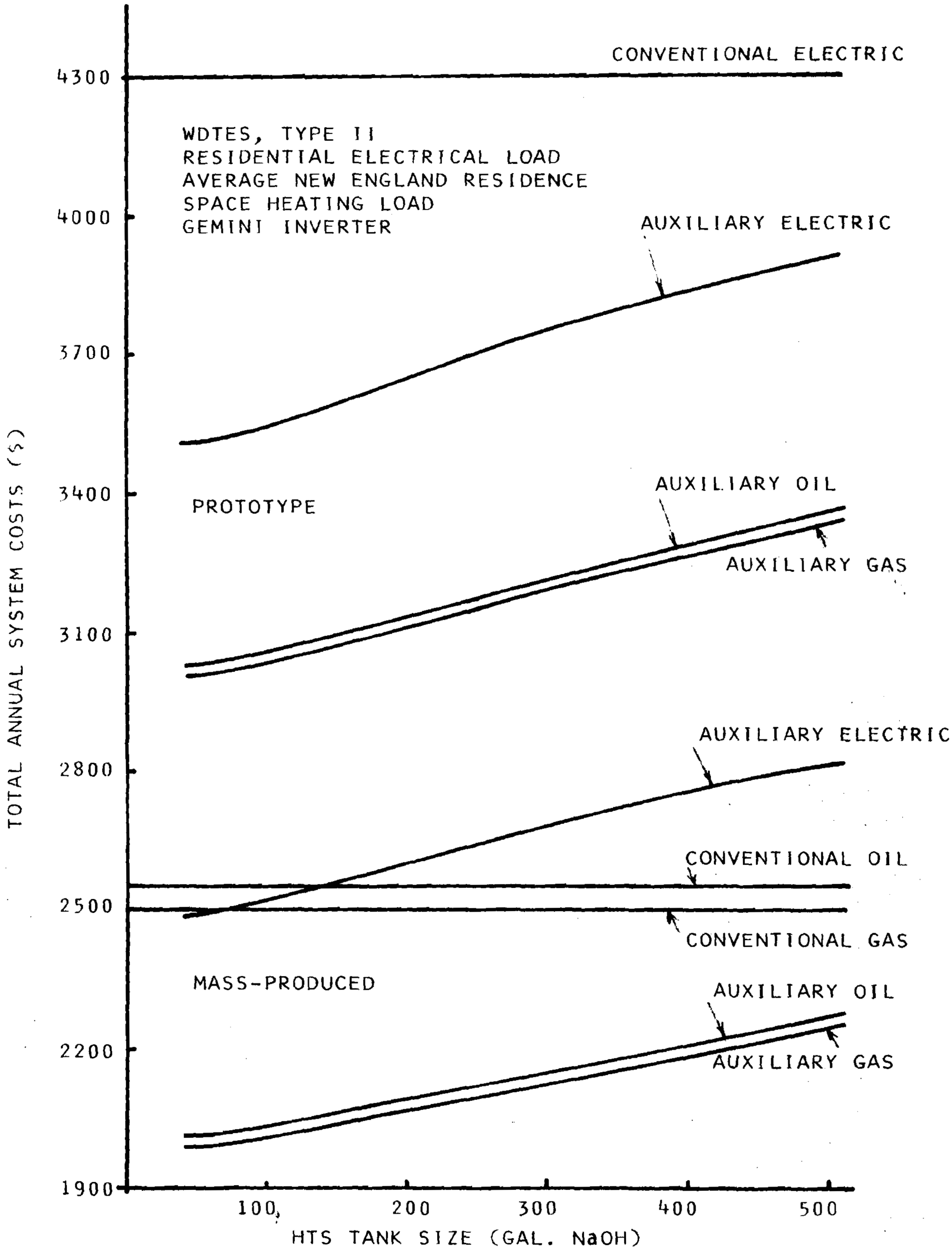


FIGURE 6.12. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL, PROTOTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

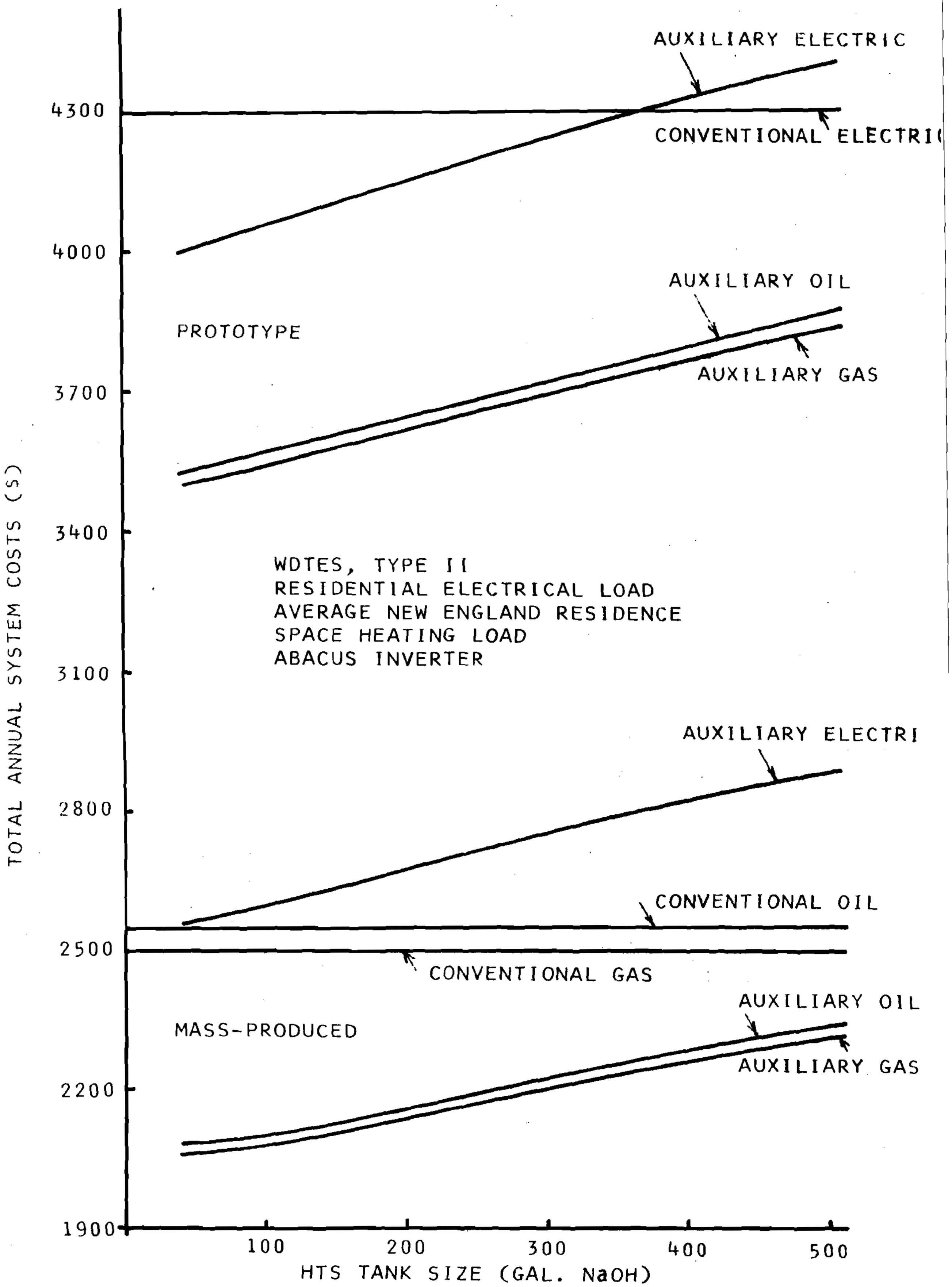


FIGURE 6.13. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

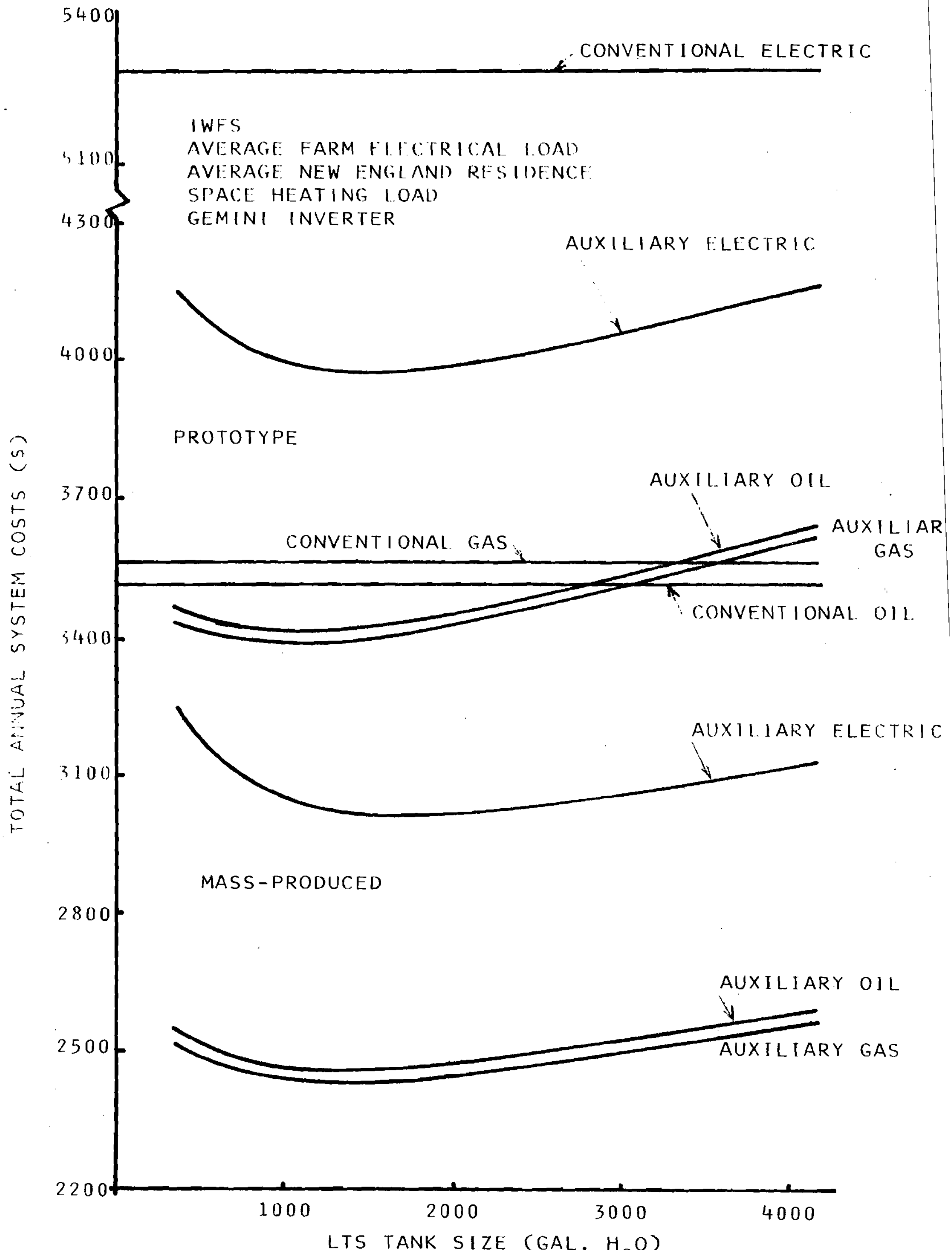


FIGURE 6.14. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF LTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

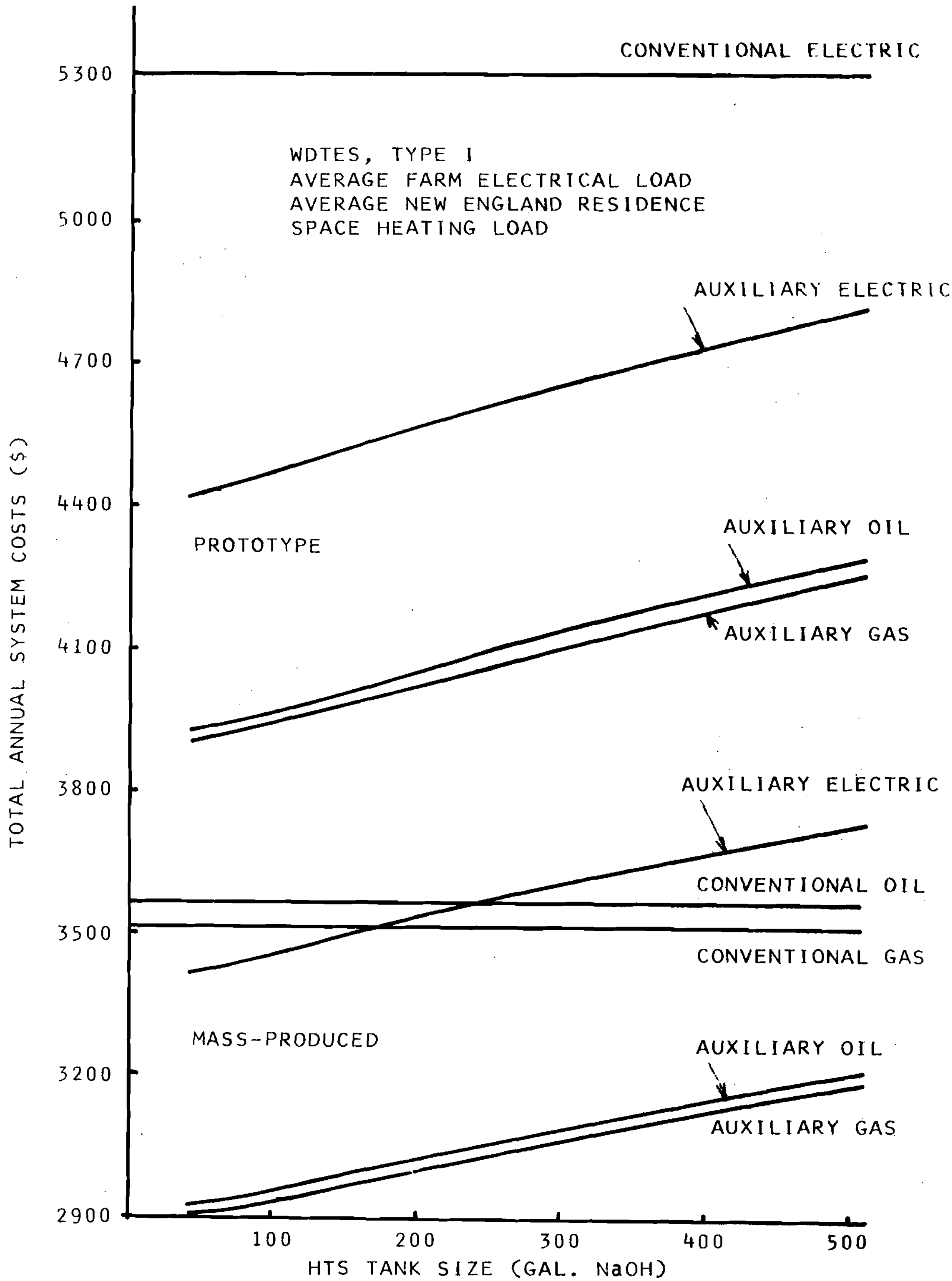


FIGURE 6.15. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL,PROTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

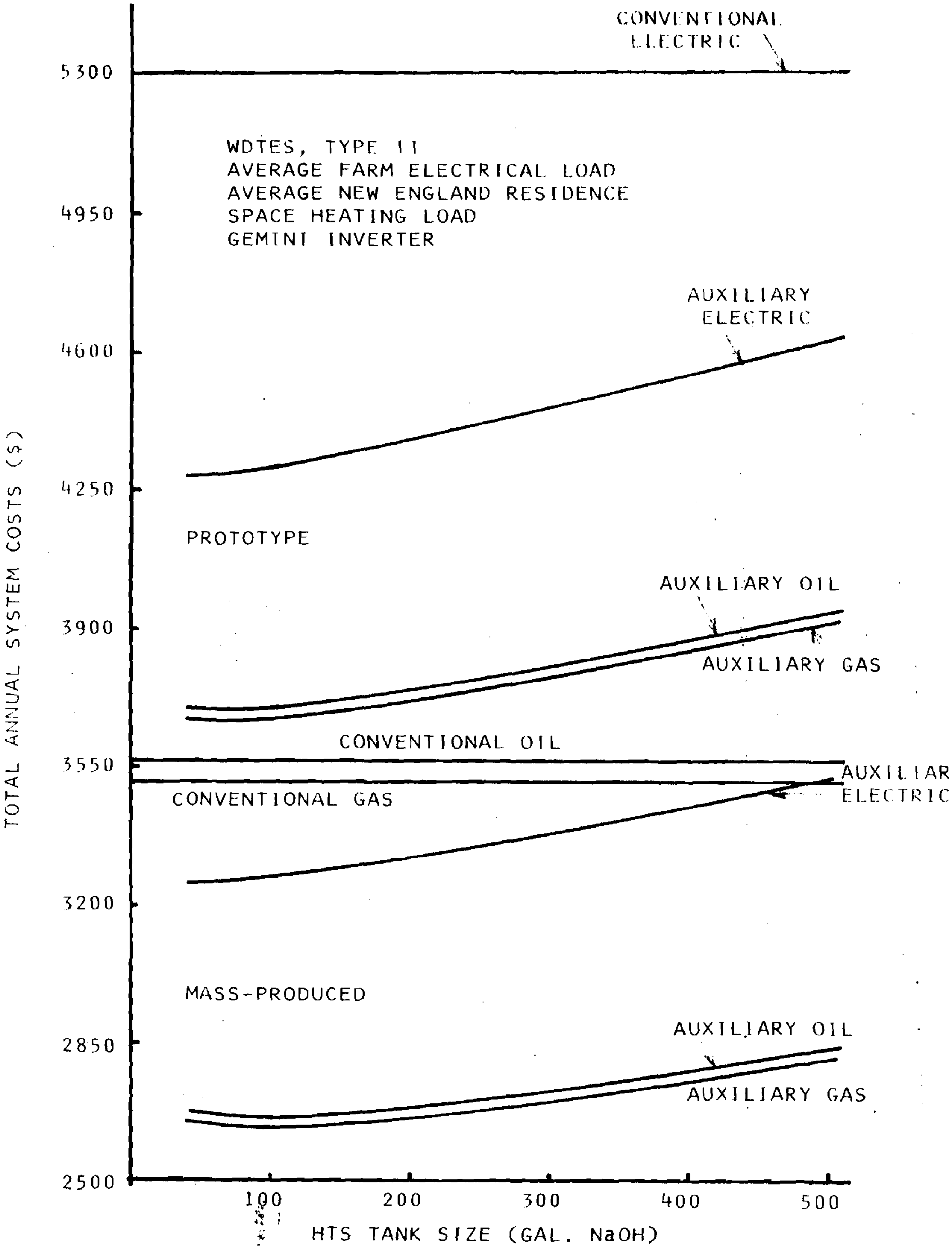


FIGURE 6.16. TOTAL ANNUAL SYSTEM COSTS AS A FUNCTION OF HTS TANK SIZE FOR CONVENTIONAL, PROTOTYPE AND MASS-PRODUCED SYSTEMS. INTEREST RATE = 8% LOAN PERIOD = 20 YEARS.

that independence from utility lines was not deemed possible, and therefore only the Gemini inverter was considered. As in the other two settings, results shown by comparing Figures 6.14, 6.15 and 6.16 indicate that the IWFS model is the least expensive of the three advanced wind furnace systems. Results for the IWFS scheme shown in Figure 6.14 indicate that the mass produced unit and even the prototype unit, if gas or oil is used as an auxiliary fuel, are economically justifiable when compared to conventional electric, oil and gas systems. In fact, with a 1000 gallon LTS tank and gas as an auxiliary fuel, an annual savings of over $1000 can be realized as compared to a conventional gas system, once the units are mass produced. Figures 6.15 and 6.16 show that large savings over conventional systems costs can also be achieved by mass-produced WDTES, Type I and Type II units. A comparison of Figures 6.15 and 6.16 also reveal an interesting trend between the two WDTES units with regard to higher electrical loads. As previously stated in Chapter V, the WDTES, Type II unit has the advantage over the Type I unit of being able to supply electricity directly from the WTG when wind energy is available. This results in far lower auxiliary electrical consumption. By comparing Figures 6.15 and 6.16 it can be inferred that this lower electrical consumption does justify the higher component costs of the WDTES, Type II model when compared to the Type I system. Also, as shown by comparing Figures 6.14 and 6.16 it becomes apparent that the WDTES, Type II model with all its expensive components, is almost as inexpensive as the IWFS model, if mass-produced. This leaves open the possibility that in an application that requires an even larger electrical load than the average New England farm, the WDTES, Type II system may not only be less expensive than the conventional system, but it could also become less expensive than the IWES model.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The previous chapters have yielded preliminary findings regarding the performance and economic feasibility of the IWFS and WDTES models with respect to three residential and farm applications. In this chapter, conclusions based on these findings will be used to evaluate the realistic potential of these alternative energy systems to decrease the total energy requirements of the residential or farm environs. In addition to this, more in-depth analytical and experimental means of system analysis for these and other applications of such systems will be proposed for future research.

7.1 Conclusions

Optimum system configuration and component sizes for each of the three applications can be made either on the basis of minimum auxiliary energy requirements or minimum annual system costs.

For the well-insulated New England residence, results shown in Figure 5.34 indicate that the minimum total auxiliary energy requirements occur when the WDTES, Type II scheme, with a 100 gallon HTS is used. This system would supply over 95% of the 26,516kWh total energy loads of the home, even with a turbine efficiency of 60%. However, it is not economical to use such an expensive system for energy supply. As indicated by comparing Figures 6.6 through 6.9, the minimum annual system costs for this application occur when the mass produced IWFS model with electric auxiliary and a 2000 gallon LTS is used. This system offers an annual savings of over $300 in total expense with respect to conventional gas systems.

With the average New England residence, as indicated in Figure 5.41, the WDTES, Type II scheme represents the most energy efficient model of the three, allowing about 73% of the total residential energy requirement of 44,733kWh to be supplied. Again, though, the mass-produced IWFS system provides the least expensive means of energy supply. For the residence, a minimum system cost which is over $700 less than the conventional gas system cost annually, is achieved annually by using the IWFS with a 1000 gallon LTS and a gas auxiliary energy supply.

In the average New England farm setting, again the WDTES, Type II unit as seen in Figure 5.48 provides the most efficient means of wind energy supply examined, supplying some 66% of the 55,684kWh total farm energy requirements if a 250 gallon HTS is used. By regarding Figure 6.14, it can be shown that the annual savings over conventional gas costs by using a mass-produced IWFS with a 1000 gallon LTS and an auxiliary gas system, is almost $1000.

What needs to be provided to the home or farm owner is more economic incentive to increase the return on investment in these systems even though after the 20 year amortization period, total annual system costs will drop significantly. This has been proposed for some alternative energy systems by the government [2], in the form of rebates for installation of such systems and higher taxes on energy. During the Arab oil embargo and the natural gas shortage of the winter of 1976-77, the economic dependence of the U.S. on energy, because of loss of growth potential and foreign balance of payments, was realized. Therefore, it is in the national interest for the government to provide such incentives. If these economic incentives are provided, the so-far small return on investment potential of these systems should be increased sufficiently to provide for their eventual widespread use.

7.2 Recommendations

Two avenues of research, both analytical and experimental, should be followed to augment the findings of this preliminary investigation into the IWFS and WDTES models. Future analytical studies should include an in-depth investigation into the effects of thermal stratification in the HTS and LTS for the WDTES and IWFS models, respectively. In addition to this, a more detailed analysis of the WDTES model should consider the off-design analysis of the Rankine Cycle subsystem, especially its turbine and heat exchangers. Also, an optimization scheme, based on maximum energy efficiency or minimum total costs, for WTG sizes and multiple WTG arrays, should be derived for different wind regimes and load applications. Another useful endeavor may be the analysis of the three systems with the addition of storage batteries. Because a large amount of WTG energy is not allowed into the system due to the feathering of the blades, the possibility that this electrical energy could be stored for later distribution to the electrical load remains. If a battery subsystem could be incorporated into these advanced wind furnace systems, the storage of the high grade energy could allow smaller HTS and LTS tanks to be used and may decrease utility electrical requirements significantly. This could allow the possibility of a lower cost system independent from electrical transmission lines. As far as economics are concerned, a more detailed economic analysis, comparing the costs of many different sets of components and component sizes, fuel costs, fuel escalation rates, interest rates and amortization periods should be performed. Also, the economic potential of these systems should be studied with respect to any major government alternative energy funding or tax on heating fuels.

Because of the complex nature of the advanced wind furnace systems, a fully accurate simulation of these systems will never be possible, although it can be approached. Therefore, a well instrumented pilot plant operation should be attempted at an already existing wind furnace facility. Solar Habitat I, the existing wind furnace system at the University of Massachusetts offers an opportunity to further evaluate these systems. Using its 32.5 ft. diameter 25 kw WTG, the IWFS model could be added at a low cost by the addition of a rectifier, Gemini inverter, switching logic and controls. A comparison of the actual performance of this system could then be made to the WDTES1 computer simulation to determine the program's validity and justify its use as an engineering tool. Finally, the addition of a high temperature thermal storage, a Rankine Cycle subsystem and a more sophisticated switching logic and controls would allow for the investigation of the WDTES, Type II system in this well-insulated New England residence.

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APPENDIX A

NOMENCLATURE

A_B	:	Surface area of HTS tank bottom	ft^2
ACST	:	Annual prototype system costs	$
ACSTF	:	Annual mass produced system costs	$
C_{air}	:	Specific heat of air	$Btu/lb_m{}^oF$
C_{ALT}	:	Alternator cost	$
CANCOV	:	Annual conventional system costs	$
CANSDS	:	Annual prototype wind system costs	$
CANSDSF	:	Annual mass-produced wind system costs	$
CEAUX	:	Annual cost of auxiliary electricity	$
CECONV	:	Annual conventional electric cost	$
C_{FAVE}	:	Average annual fuel cost	$
C_{FI}	:	Initial fuel cost	$/kWh
CGAUX	:	Annual cost of auxiliary gas	$
CGCONV	:	Annual conventional gas cost	$
C_{HTS}	:	High temperature thermal storage cost	$/gallon
C_{INV}	:	Inverter cost	$
C_{MISC}	:	Miscellaneous costs	$
COAUX	:	Annual cost of auxiliary oil	$
COCONV	:	Annual conventional oil cost	$
CPW	:	Specific heat of water	$Btu/lb_m{}^oF$
C_{RC}	:	Cost of Rankine Cycle subsystem	$
C_{THTS}	:	Total high temperature thermal storage cost	$
CTOT	:	Total prototype wind system costs	$

CTOTF	:	Total mass-produced wind system costs	\$
CWND	:	Prototype WTG costs	\$
CWNDF	:	Mass-produced WTG costs	\$
day	:	Day of year	---
E_{HTS}	:	HTS tank internal energy	Btu
E_{HI}	:	Initial HTS internal energy	Btu
E_{LTS}	:	LTS tank internal energy	Btu
E_M	:	Mass of HTS storage material	lb_m N_aOH
E_{ML}	:	Mass of LTS storage material	lb_m H_2O
h_o	:	HTS tank wall convective heat transfer coefficient	Btu/hr ft^2 ^oF
h_{ot}	:	HTS tank top convective heat transfer coefficient	Btu/hr ft^2 ^oF
H_T	:	WTG tower height	meters
HTS	:	HTS tank size	gallons
H_W	:	Amount of hot water required	gallons
I	:	Interest rate	---
K_{ins}	:	Tank insulation thermal conductivity	Btu/hr ft ^oF
N	:	Amortization period	years
q_A	:	Absorbed solar energy	Btu/hr ft^2
$\dot{Q}_{ACHX}$	:	Heat rejection rate through the air cooled heat exchanger	Btu/hr
Q_{AUX}	:	Auxiliary energy required for space heating load	Btu
Q_{ETAL}	:	Required heat rejection from the Rankine Cycle	Btu
Q_{FLTS}	:	Rate of heat transferred to the space heating load through the baseboards	Btu/hr

$\dot{Q}_H$	:	Rate of energy added to Rankine Cycle working fluid	Btu/hr
$\dot{Q}_{HL}$	:	Space heating load	Btu/hr
$\dot{Q}_{HLACT}$	:	Actual home space heating load	Btu/hr
$\dot{Q}_{HTSHL}$	:	Rate of energy lost by the HTS that decreases the heating load	Btu/hr
$\dot{Q}_{HW}$	:	Rate of energy supplied to domestic hot water load	Btu/hr
$\dot{Q}_{inf}$	:	Infiltrative heating losses	Btu/hr
$\dot{Q}_L$	:	Rate of energy rejected from the Rankine Cycle working fluid	Btu/hr
$\dot{Q}_{LB}$	:	Rate of energy lost by the HTS through the basement floor	Btu/hr
$\dot{Q}_{LBL}$	:	Rate of energy lost by the LTS through the basement floor	Btu/hr
$\dot{Q}_{LNTHL}$	:	Rate of energy lost by the LTS when space heating is not required	Btu/hr
Q_{LTOT}	:	HTS tank thermal losses	Btu
$\dot{Q}_{LTSHL}$	:	Rate of energy lost by the LTS that decreases the heating load	Btu/hr
$\dot{Q}_{NTHL}$	:	Rate of energy lost by the HTS when space heating is not required	Btu/hr
$\dot{Q}_{SOL}$	:	Rate of solar energy gain through windows	Btu/hr
R	:	Annual cost factor	---
RCHP	:	Rankine Cycle output capacity	HP
RI	:	Annual fuel cost escalation rate	---

R_i	:	HTS tank inside radius	ft
RNKFCT	:	Fraction of maximum Rankine Cycle efficiency	---
R_o	:	HTS tank radius to edge of insulation	ft
SHADE	:	Shading factor	---
T_B	:	Basement temperature	^oF
TCAUX	:	Total annual costs for auxiliary energy	$
TCCONV	:	Total annual conventional energy costs	$
T_{CW}	:	Cold water inlet temperature	^oF
T_{HI}	:	Rankine Cycle maximum working fluid temperature	^oF
T_{HTS}	:	HTS storage medium temperature	^oF
T_{HWR}	:	Domestic hot water delivery temperature	^oF
T_{in}	:	Indoor temperature	^oF
T_{LO}	:	Rankine Cycle minimum working fluid temperature	^oF
T_{out}	:	Ambient temperature	^oF
T_W	:	Temperature at the surface of the HTS tank insulation	^oF
U_{LT}	:	Overall heat transfer coefficient for the HTS tank top	Btu/hr ft^2 ^oF
U_{LW}	:	Overall heat transfer coefficient for the HTS tank walls	Btu/hr ft^2 ^oF
V	:	Volumetric flow rate of infiltrative air	ft^3/hr
V_{10}	:	Wind speed at 10 meter height	mph
V_T	:	Wind speed at tower height	mph
$\dot{W}_{ADD}$	:	Electric power input to the HTS from the WTG	kW
$\dot{W}_{ADDL}$	:	Electrical power input to the LTS from the WTG	kW

WE	:	Seasonally adjusted electrical load	kWh
W_{EAUX}	:	Auxiliary energy required for the electrical load	kWh
W_{HWAUX}	:	Auxiliary energy required for domestic hot water	kWh
W_{MECH}	:	Average U.S. farm machinery load	kWh
W_{NOM}	:	Nominal electrical load	kWh
W_{REQ}	:	Required electrical energy output from the Rankine Cycle	kWh
X1I	:	Solid-solid phase change fraction	---
X2I	:	Solid-liquid phase change fraction	---
X_{ins}	:	Tank insulation thickness	ft
η_{AG}	:	Alternator efficiency	---
η_{th}	:	Rankine Cycle thermal efficiency	---
ρ	:	Density of air	ft^3/lb_m
ρ_{water}	:	Density of water	$gallons/lb_m$

APPENDIX B

THE MAIN PROGRAM

The main computer program (WDTES1) was written in Fortran IV language for the Control Data Cyber 70 time sharing computer system located at the University of Massachusetts. WDTES1 features an interactive input format for ease of operation and a choice of hourly, daily or monthly output formats. To use the WDTES1 program, the operator is required to first get the data banks to be used and then to run the program. System control parameters and component sizes will then be inputted via the interactive input format.

A listing of the system control parameters, the WDTES1 Fortran variable assignments and the WDTES1 computer program follow. The Fortran variable assignments previously used by Darkazalli (11) are not shown since these same subprograms are used in WDTES1. The D, M and Y suffixes for variables in WDTES1, are used to denote daily, monthly or yearly values while hourly values have no suffix (i.e. WE, WED, WEM, WEY represent hourly, daily, monthly and yearly values of the electrical load.)

WDTES1 SYSTEM CONTROL PARAMETERS

DIRHTS	=	1.	For WDTES, Type I option
	=	0.	For WDTES, Type II option
EEJ	=	1.	For minimum LTS tank surface area
	=	0.	To input specific LTS tank dimensions
EJ	=	1.	For minimum HTS tank surface area
	=	0.	To input specific HTS tank dimensions
MON	=	1	For monthly output
	=	0	For hourly or daily output
NFLR	=	1	For average New England residence
	=	0	For well-insulated New England residence
NOHTS	=	1	For WDTES option
	=	0	For IWFS option
RR	=	1.	For daily or monthly output
	=	0.	For hourly output
USAVFM	=	1.	For average U.S. farm electrical load
	=	0.	For residential electrical load

WDTESI FORTRAN VARIABLES

AT	: Surface area of HTS tank top	ft^2
ATL	: Surface area of LTS tank top	ft^2
AWI	: Inside surface area of HTS tank wall	ft^2
AWIL	: Inside surface area of LTS tank wall	ft^2
AWO	: Outside surface area of HTS tank wall	ft^2
AWOL	: Outside surface area of LTS tank wall	ft^2
CPS1	: Specific heat of NaOH up to 560^o	$Btu/lb_m\,^oF$
CPS2	: Specific heat of NaOH from 560^o to 600^oF	$Btu/lb_m\,^oF$
CPS3	: Specific heat of NaOH above 600^oF	$Btu/lb_m\,^oF$
D	: Diameter of WTG blades	ft
DAY	: Day of year	---
E93	: Rankine Cycle efficiency for TLO = 93^oF	---
E100	: Rankine Cycle efficiency for TLO = 100^oF	---
E125	: Rankine Cycle efficiency for TLO = 125^oF	---
E150	: Rankine Cycle efficiency for TLO = 150^oF	---
E175	: Rankine Cycle efficiency for TLO = 175^oF	---
E200	: Rankine Cycle efficiency for TLO = 200^oF	---
E225	: Rankine Cycle efficiency for TLO = 225^oF	---
EHF	: Final specific internal energy in the HTS	Btu/lb_m
EHI	: Initial specific internal energy in the HTS	Btu/lb_m
EHLF	: Final specific internal energy in the LTS	Btu/lbm
EHLI	: Initial specific internal energy in the LTS	Btu/lbm
EHTAIR	: Heat transfer coefficient at the top of the HTS tank	$Btu/hr\ ft^2\ ^oF$

EHTL	: Heat transfer coefficient at the top of the LTS tank	Btu/hr ft^2 ^oF
EHTSY	: HTS internal energy at the end of the year period	kWh
EHWAIR	: Heat transfer coefficient at the HTS tank wall	Btu/hr ft^2 ^oF
EHWL	: Heat transfer coefficient at the LTS tank wall	Btu/hr ft^2 ^oF
EKINS	: Thermal conductivity of HTS tank insulation	Btu/hr ft ^oF
EKINSL	: Thermal conductivity of LTS tank insulation	Btu/hr ft ^oF
EL	: HTS tank height	ft
ELL	: LTS tank height	ft
ELNTHL	: LTS tank thermal losses when there is no heating load	kWh
ELTELDY	: WTG output supplied to electrical load via the power conditioner	kWh
ELTSY	: LTS internal energy at the end of the year period	kWh
EM	: Mass of high temperature storage material (NaOH)	lb_m
EMH	: Critical specific HTS internal energy	Btu/lb_m
EMHL	: Critical specific LTS internal energy	Btu/lb_m
EML	: Mass of low temperature storage material (H_2O)	lb_m
ENERGY	: Total annual auxiliary energy required	kWh
ETA	: Rankine Cycle efficiency	---
FREQ	: Period of Rankine Cycle operation	hr
HNTHL	: HTS tank thermal losses when there is no heating load	kWh
KDAY	: Day of the month	---
KK	: Number of days in the two month data tape period	days

N	: Meteorlogical data tape number	---
ND	: Number of days in the month	days
NDAY	: Day of the two month data tape period	---
NHR	: Hour of the day	---
NM	: Month of the year	---
QACHX	: Heat rejected from the LTS through the air cooled heat exchanger	Btu/hr
QAUX	: Auxiliary energy required for space heating	Btu/hr
QAVAIL	: Available energy in the LTS above the room temperature datum	Btu
QE	: Heat added to the HTS via the resistance heaters	Btu/hr
QEL	: Heat added to the LTS via the resistance heaters	Btu/hr
QETAL	: Required heat rejection from the Rankine Cycle	Btu/hr
QFLTS	: Annual amount of heat delivered to the heating load from the LTS	kWh
QH	: Source heat required for the Rankine Cycle	Btu/hr
QHL	: Space heating load	Btu/hr
QHLACT	: Space heating load minus the tank(s) thermal losses and the solar energy input	Btu/hr
QHLMS	: Space heating load minus the tank(s) thermal losses	Btu/hr
QHTSHL	: Thermal losses from the HTS that decrease the space heating load	Btu/hr
QHW	: Domestic hot water load	Btu/hr
QL	: Heat rejected from the Rankine Cycle to the LTS which does not when the air cooled heat exchanger is not required	Btu/hr

QLB	: Thermal losses from the HTS tank bottom	Btu/hr
QLBL	: Thermal losses from the LTS tank bottom	Btu/hr
QLT	: Thermal losses from the HTS tank top	Btu/hr
QLTL	: Thermal losses from the LTS tank top	Btu/hr
QLTOT	: Total thermal losses from the HTS tank	Btu/hr
QLTOTL	: Total thermal losses from the LTS tank	Btu/hr
QLTSHL	: Thermal losses from the LTS that decrease the space heating load	Btu/hr
QLW	: Thermal losses from the HTS tank walls	Btu/hr
QLWL	: Thermal losses from the LTS tank walls	Btu/hr
QLX	: Excess heat available to the LTS	Btu/hr
QLXT	: Specific excess energy available to the LTS	Btu/lbm
QMH	: Specific electrical energy available to the HTS minus the HTS loads	Btu/lbm
QML	: Specific electrical energy available to the LTS minus the LTS loads	Btu/lbm
QSOL	: Useful solar radiation through the windows	Btu/hr
RATIO	: Space heating load multiplication factor	---
RI	: HTS tank radius	ft
RIL	: LTS tank radius	ft
RNKFCT	: Fraction of "maximum" Rankine Cycle efficiency	---
RO	: Radius of the HTS to the edge of the insulation	ft
ROL	: Radius of the LTS to the edge of the insulation	ft
THAVRY	: Average annual HTS temperature during Rankine Cycle operation	^oF
THAVY	: Average annual HTS temperature	^oF

THCRIT	: Critical HTS temperature	^oF
THEDA	: Time increment	hr
THI	: Maximum Rankine Cycle working fluid temperature	^oF
THMAX	: Maximum allowable HTS temperature	^oF
THTSF	: Final HTS temperature	^oF
THTSI	: Initial HTS temperature	^oF
TLAVRY	: Average annual LTS temperature during Rankine Cycle operation	^oF
TLAVY	: Average annual LTS temperature	^oF
TLCRIT	: Critical LTS temperature	^oF
TLO	: Minimum Rankine Cycle working fluid temperature	^oF
TLTSF	: Final LTS temperature	^oF
TLTSI	: Initial LTS temperature	^oF
TT	: Temperature of HTS tank top	^oF
TTL	: Temperature of LTS tank top	^oF
TW	: Temperature of HTS tank wall	^oF
TWL	: Temperature of LTS tank wall	^oF
ULT	: HTS tank top overall heat transfer coefficient	Btu/hr ft^2 ^oF
ULTL	: LTS tank top overall heat transfer coefficient	Btu/hr ft^2 ^oF
ULW	: HTS tank wall overall heat transfer coefficient	Btu/hr ft^2 ^oF
ULWL	: LTS tank wall overall heat transfer coefficient	Btu/hr ft^2 ^oF
WADD	: Electrical energy added to the HTS via the resistance heaters	kW
WADDL	: Electrical energy added to the LTS via the resistance heaters	kW
WE	: Electrical load	kW

WEAUX	: Auxiliary electrical energy required for electrical load	kW
WEXT	: Excess electrical energy available to the HTS after HTS tank loads (and electrical load for WDTES) are met	kW
WEXTL	: Excess electrical energy available to the LTS after LTS tank loads are met	kW
WHWAUX	: Auxiliary energy required for domestic hot water	kW
WLTS	: Electrical energy available to the LTS	kW
WMECH	: Farm machinery electrical load	kW
WNOM	: Nominal electrical load	kW
WR05	: Alternator losses	kW
WR95	: Electricity delivered via alternator	kW
WREQ	: Electricity required from Rankine Cycle	kW
WWASTE	: Electrical energy lost from WTG due to feathering of blades	kW
WWG	: WTG electrical output	kW
X1F	: Final solid-solid phase change fraction	---
X1I	: Initial solid-solid phase change fraction	---
X2F	: Final solid-liquid phase change fraction	---
X2I	: Initial solid-liquid phase change fraction	---
XINS	: HTS insulation thickness	ft
XINSL	: LTS insulation thickness	ft

```
PROGRAM WDTES1(INPUT,OUTPUT,B1,TAPE1=B1,B2,TAPE2=B2,
+B3,TAPE3=B3,B4,TAPE4=B4,B5,TAPE5=B5,B6,TAPE6=B6)
*    THE FOLLOWING LINES ARE PROGRAM INPUTS AND START UP CONDITIONS
PRINT 60
60 FORMAT(27H WIND ROTOR DIAMETER (FT) =)
READ,D
PRINT,D
THEDA=1.
PRINT 1505
1505 FORMAT(46H FOR AVERAGE U.S. FARM ELECTRICAL LOAD TYPE 1.)
READ,USAVFM
PRINT,USAVFM
PRINT 1101
1101 FORMAT(18H FOR NO HTS TYPE 0)
PRINT 1102
1102 FORMAT(15H FOR HTS TYPE 1)
READ,NOHTS
PRINT,NOHTS
IF(NOHTS.EQ.0)GO TO 1103
PRINT 1300
1300 FORMAT(32H FOR DIRECT INPUT TO HTS TYPE 1.)
PRINT 1301
1301 FORMAT(42H TO SATISFY ELECTRICAL LOAD FIRST ,TYPE 0.)
READ,DIRHTS
PRINT,DIRHTS
PRINT 64
64 FORMAT(50H MASS OF HIGH TEMP STORAGE MATERIAL (NAOH) (LBM) =)
READ,EM
PRINT,EM
PRINT 92
92 FORMAT(37H FOR MIN. HTS TANK SURF. AREA TYPE 1.)
PRINT 94
94 FORMAT(42H TO INPUT SPECIFIC TANK DIMENSIONS TYPE 0.)
READ,EJ
PRINT,EJ
IF(EJ.EQ.1.)96,98
96 CONTINUE
RI=(EM/(2.*3.1416*107.5))**0.3333
EL=2.*RI
GO TO 100
98 PRINT 68
68 FORMAT(39H TANK RADIUS (FT) =, TANK HEIGHT (FT) =)
READ,RI,EL
PRINT,RI,EL
GO TO 100
100 PRINT 70
70 FORMAT(56H HTS INSUL. THICKNESS (FT) =,THERMAL COND. (B/HR FT F) =)
READ,XINS,EKINS
PRINT,XINS,EKINS
1103 CONTINUE
PRINT 158
158 FORMAT(56H LTS INSUL. THICKNESS (FT) =,THERMAL COND. (B/HR FT F) =)
READ,XINSL,EKINSL
PRINT,XINSL,EKINSL
PRINT 72
72 FORMAT(27H TO INCLUDE BASEMENT TYPE 1)
READ,NFLR
PRINT,NFLR
PRINT 144
144 FORMAT(48H MASS OF LOW TEMP STORAGE MATERIAL (H2O) (LBM) =)
```

```
READ,EML
PRINT,EML
PRINT 146
146 FORMAT(37H FOR MIN. LTS TANK SURF. AREA TYPE 1.)
PRINT 148
148 FORMAT(46H TO INPUT SPECIFIC LTS TANK DIMENSIONS TYPE 0.)
READ,EEJ
PRINT,EEJ
IF(EEJ.EQ.1.)150,152
150 CONTINUE
RIL=(EML/(2.*3.1416*60.13))**0.3333
ELL=2.*RIL
GO TO 154
152 PRINT 156
156 FORMAT(39H TANK RADIUS (FT) =, TANK HEIGHT (FT) =)
READ,RIL,ELL
PRINT,RIL,ELL
154 CONTINUE
PRINT 112
112 FORMAT(34H THE INITIAL LTS TEMPERATURE (F) =)
READ,TLTSI
PRINT,TLTSI
IF(NOHTS.EQ.0)GO TO 1104
PRINT 74
74 FORMAT(30H INITIAL HTS TEMPERATURE (F) =)
READ,THTSI
PRINT,THTSI
IF(THTSI.EQ.560.)10,11
10 PRINT 76
76 FORMAT(24H SOLID - SOLID QUALITY =)
READ,X1I
PRINT,X1I
11 IF(THTSI.EQ.600.)12,13
12 PRINT 78
78 FORMAT(25H SOLID - LIQUID QUALITY =)
READ,X2I
PRINT,X2I
13 CONTINUE
PRINT 110
110 FORMAT(36H MAXIMUM ALLOWABLE HTS TEMPERATURE =)
READ,THMAX
PRINT,THMAX
PRINT 1501
1501 FORMAT(47H FRACTION OF MAXIMUM RANKINE CYCLE EFFICIENCY =)
READ,RNKFCT
PRINT,RNKFCT
1104 CONTINUE
PRINT 586
586 FORMAT(34H FOR HOURLY OUTPUT LET RR=0.,MON=0)
PRINT 587
587 FORMAT(33H FOR DAILY OUTPUT LET RR=1.,MON=0)
PRINT 588
588 FORMAT(35H FOR MONTHLY OUTPUT LET RR=1.,MON=1)
PRINT 589
589 FORMAT(4H RR=)
READ,RR
PRINT,RR
PRINT 591
591 FORMAT(5H MON=)
READ,MON
```

```
PRINT,MON
DIMENSION NV(25,62),SUN(25,62),NTA(25,62),NCC(25,62),NDW(25,62)
FREQ=0.
N=1
ND=30
MM=1
KDAY=1
KK=61
NHR=1
DAY=1.
NDAY=1
IF(NOHTS.EQ.0)GO TO 1105
PRINT 102,RI
102 FORMAT(18H HTS TANK RADIUS =,F8.4,4H FT.)
PRINT 104,EL
104 FORMAT(18H HTS TANK HEIGHT =,F8.4,4H FT.)
1105 CONTINUE
PRINT 168,RIL
168 FORMAT(18H LTS TANK RADIUS =,F8.4,4H FT.)
PRINT 170,ELL
170 FORMAT(18H LTS TANK HEIGHT =,F8.4,4H FT.)
550 CONTINUE
READ(N,504)(((SUN(II,JJ),NCC(II,JJ),NV(II,JJ),NTA(II,JJ),
+NDW(II,JJ)),II=1,24),JJ=1,KK)
504 FORMAT(5X,F5.0,4(1X,I2))
IF(MM.EQ.1)PRINT 601
610 WWGD=0.
WED=0.
QHLD=0.
QHLACD=0.
QHWD=0.
QAUXD=0.
QACHXD=0.
WWASTD=0.
WHWAUXD=0.
WADDD=0.
QHD=0.
WREQD=0.
FREQD=0.
IF(NOHTS.EQ.0)THTSI=0.
THCRIT=THTSI
TLCRIT=TLTSI
WEAUX=0.
500 V=NV(NHR,NDAY)
SOL=SUN(NHR,NDAY)
CC=NCC(NHR,NDAY)
TA=NTA(NHR,NDAY)
WD=NDW(NHR,NDAY)
*   THE FOLLOWING LINES CALCULATE WTG OUTPUT
HT=60.
HTR=20.
CON=1.15
COF=(.2337+.656*ALOG10(.3048*HT+4.75))/(.2337+.656*ALOG10(.3048
+ *HTR+4.75))
WV=V*CON*COF
IF(D.EQ.20.) GO TO 320
IF(D.EQ.25.) GO TO 330
IF(D.EQ.30.) GO TO 340
IF(D.EQ.32.5) GO TO 350
IF(D.EQ.35.) GO TO 360
```

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IF(D.EQ.40.) GO TO 370
320 IF(WV.LE.3.5.OR.WV.GE.36.1)322,324
324 WP=-.4182+.1843*WV-.02348*WV**2+.00165*WV**3-.0000168*WV**4
322 IF(WV.LE.3.5) WP=0.0
IF(WV.GE.36.1) WP=25.0
GO TO 380
330 IF(WV.LE.4.42.OR.WV.GE.31.1)334,332
332 WP=-.9273+.32*WV-.0347*WV**2+.00232*WV**3-.0000217*WV**4
334 IF(WV.LE.4.42) WP=0.0
IF(WV.GE.31.1) WP=25.0
GO TO 380
340 IF(WV.LE.5.0.OR.WV.GE.27.5)344,342
342 WP=-1.599+.4956*WV-.05136*WV**2+.0034*WV**3-.0000334*WV**4
344 IF(WV.LE.5.0) WP=0.0
IF(WV.GE.27.5) WP=25.0
GO TO 380
350 IF(WV.LE.5.46.OR.WV.GE.26.1)356,354
354 WP=-1.874+.521*WV-.05*WV**2+.0035*WV**3-.3069E-4*WV**4
356 IF(WV.LE.5.46) WP=0.0
IF(WV.GE.26.1) WP=25.0
GO TO 380
360 IF(WV.LE.6.55.OR.WV.GE.24.8)364,362
362 WP=-6.599+1.821*WV-.1798*WV**2+.00926*WV**3-.000117*WV**4
364 IF(WV.LE.6.55) WP=0.0
IF(WV.GE.24.8) WP=25.0
GO TO 380
370 IF(WV.LE.7.73.OR.WV.GE.22.7)374,372
372 WP=-13.1071+3.177*WV-.2887*WV**2+.01396*WV**3-.000182*WV**4
374 IF(WV.LE.7.73) WP=0.0
IF(WV.GE.22.7) WP=25.0
GO TO 380
380 WWG=WP*1000.
*    THE FOLLOWING LINES CALCULATE THE ELECTRICAL LOAD
IF(NHR.EQ.1.OR.NHR.EQ.12) WNOM=800.
IF(NHR.EQ.2) WNOM=500.
IF(NHR.EQ.3.OR.NHR.EQ.7) WNOM=400.
IF(NHR.GE.4.AND.NHR.LE.6) WNOM=300.
IF(NHR.EQ.8.OR.NHR.EQ.14.OR.NHR.EQ.15) WNOM=600.
IF(NHR.EQ.9.OR.NHR.EQ.11.OR.NHR.EQ.24) WNOM=900.
IF(NHR.EQ.10) WNOM=1200.
IF(NHR.EQ.13.OR.NHR.EQ.16.OR.NHR.EQ.17) WNOM=700.
IF(NHR.EQ.18.OR.NHR.EQ.22) WNOM=1300.
IF(NHR.EQ.19) WNOM=1700.
IF(NHR.EQ.20) WNOM=1600.
IF(NHR.EQ.21) WNOM=1400.
IF(NHR.EQ.23) WNOM=1100.
WE=WNOM*((0.985+0.600)/2.+((0.985-0.600)/2.)
+*COS(2.*3.14159*(DAY+243.)/365.))
IF(USAVFM.EQ.1.)1509,1511
1509 IF(NHR.LE.4.OR.NHR.GT.19) WMECH=667.
IF(NHR.GT.4.AND.NHR.LE.7) WMECH=2000.
IF(NHR.GT.7.AND.NHR.LE.11) WMECH=1000.
IF(NHR.GT.11.AND.NHR.LE.14) WMECH=2000.
IF(NHR.GT.14.AND.NHR.LE.16) WMECH=1000.
IF(NHR.GT.16.AND.NHR.LE.19) WMECH=2000.
WE=WE+WMECH
1511 CONTINUE
*    THE FOLLOWING LINES CALCULATE THE SPACE HEATING LOAD
RATIO=1.0
COH=0.871
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WL=48.7
VSCAIR=0.000012
PR=.72
RDR=25.24
RIN=0.68
WW=32.07
HV=V*CON*COH
RWL=29.0
RWIN=16.11
RBW1=41.4
TR=68.
TB=68.
TG=50.
ABWW1=WW*1.
ABWE1=WW*1.
ABWS1=WL*1.
ABWN1=WL*1.
ABW2=(WW+2.*WL)*5.5
ABW1=(WW+2.*WL)*3.
UBW2=1./17.23
ABWW2=WW*5.5-8.0*5.5
DATA AWE,AWW,AWN,AWS/24.,24.,72.,48./
DATA ADE,ADW,ADN,ADS/21.,21.,0.0,21./
AWALLE=WW*8.-AWE-ADE
AWALLW=WW*8.-AWW-ADW
AWALLN=WL*8.-AWN-ADN
AWALLS=WL*8.-AWS-ADS
UCEIL=0.0192
ACEIL=WW*WL
UBASEF=1./16.605
ABASEF=ACEIL
AGRND=ACEIL
ABASDR=56.
VOLUMB=13340.
VOLUMF=12500.
CP=0.24
UGRND=0.0192
IF(TA.LT.68.)402,400
400 QHL=0.0
GO TO 420
402 CONTINUE
RHOAIR=0.086*460./(460.+TA)
IF(HV.EQ.0.0) GO TO 404
RE=RHOAIR*HV*1.47*WL/VSCAIR
IF(RE.LT.500000.) GO TO 406
GO TO 408
406 HC=0.014*.664*RE**.5*PR**.33
GO TO 410
408 HC=0.014*0.036*PR**.33*(RE**.8-23200.)
410 HW=0.014*1.025*RE**.5/2.
HCE=HCW=HCS=HCN=HC
IF(WD.GT.4.5.AND.WD.LE.13.5) HCE=HW
IF(WD.GT.13.5.AND.WD.LE.22.5) HCS=HW
IF(WD.GT.22.5.AND.WD.LE.31.5) HCW=HW
IF(WD.GT.31.5.OR.WD.LE.4.5) HCN=HW
UDOORE=1./(3./HCE+RDR+RIN)
UDOORW=1./(3./HCW+RDR+RIN)
UDOORS=1./(3./HCS+RDR+RIN)
UBASDR=1./(8./HCW+RDR+RIN)
UWALLE=1./(WW/HCE+RWL+RIN)
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UWINE=1./(6./HCE+RWIN+RIN)
UWALLW=1./(WW/HCW+RWL+RIN)
UWINW=1./(6./HCW+RWIN+RIN)
UWALLN=1./(WL/HCN+RWL+RIN)
UWINN=1./(18./HCN+RWIN+RIN)
UWALLS=1./(WL/HCS+RWL+RIN)
UWINS=1./(15./HCS+RWIN+RIN)
UBWW2=1./(WW/HCW+17.23+RIN)
UBWE1=1./(WW/HCE+RBW1+RIN)
UBWW1=1./(WW/HCW+RBW1+RIN)
UBWS1=1./(WL/HCS+RBW1+RIN)
UBWN1=1./(WL/HCN+RBW1+RIN)
GO TO 412
404 UDOORE=1./(RDR+RIN)
UDOORW=UDOORN=UDOORS=UDOORE
UBASDR=UDOORE
UWALLE=1./(RWL+RIN)
UWALLW=UWALLN=UWALLS=UWALLE
UWINE=1./(RWIN+RIN)
UWINW=UWINS=UWINN=UWINE
UBWW2=1./(17.23+RIN)
UBWW1=1./(RBW1+RIN)
UBWE1=UBWS1=UBWN1=UBWW1
412 DT=TR-TA
DTB=TB-TA
UBW1=1./(RBW1+RIN)
QBW1=(ABWW1*UBWW1+ABWE1*UBWE1+ABWS1*UBWS1+ABWN1*UBWN1)*DTB
QBW2=(ABW2*UBW2+ABW1*UBW1)*(TB-(TA+TG)/2.)
QBWW2=(ABWW2*UBWW2+(WW*3.-8.*1.5)*UBWW1)*DTB
QWALLE=UWALLE*AWALLE*DT
QWALLW=UWALLW*AWALLW*DT
QWALLN=UWALLN*AWALLN*DT
QWALLS=UWALLS*AWALLS*DT
QCEIL=UCEIL*ACEIL*DT
QWINE=UWINE*AWE*DT
QWINW=UWINW*AWW*DT
QWINN=UWINN*AWN*DT
QWINS=UWINS*AWS*DT
QWINT=QWINE+QWINW+QWINN+QWINS
QWALLT=QWALLE+QWALLS+QWALLW+QWALLN
QDOORE=UDOORE*ADE*DT
QDOORW=UDOORW*ADW*DT
QDOORS=UDOORS*ADS*DT
QDOORT=QDOORE+QDOORW+QDOORS
QBASEF=UBASEF*ABASEF*(TB-TG)
QBASDR=UBASDR*ABASDR*DTB
QBASET=QBASEF+QBASDR+QBW2+QBWW2+QBW1
QINFB=VOLUMB*CP*RHOAIR*DTB
QINFF=VOLUMF*CP*RHOAIR*DT
QGRND=AGRND*UGRND*(TR-TG)
IF(NFLR.EQ.1) GO TO 414
QHL=QINFF+QWINT+QDOORT+QWALLT+QCEIL+QGRND
QHL=QHL*RATIO
GO TO 416
414 QHL=QBASET+QINFF+QINFB+QWINT+QWALLT+QDOORT+QCEIL
QHL=QHL*RATIO
416 IF(QHL.LT.0.0) QHL=0.0
420 CONTINUE
*   THE FOLLOWING LINES CALCULATE THE DOMESTIC HOT WATER LOAD
THWR=140.
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TCW=60.
CPW=1.
ROWTR=8.33
IF(NHR.EQ.1) HW=1.12
IF(NHR.GT.1.AND.NHR.LT.7) HW=0.0
IF(NHR.EQ.7) HW=.75
IF(NHR.EQ.8.OR.NHR.EQ.24) HW=2.32
IF(NHR.EQ.9) HW=3.62
IF(NHR.EQ.10) HW=4.2
IF(NHR.EQ.11.OR.NHR.EQ.22) HW=3.45
IF(NHR.EQ.12) HW=2.25
IF(NHR.EQ.13) HW=1.8
IF(NHR.EQ.14) HW=2.55
IF(NHR.EQ.15) HW=1.35
IF(NHR.EQ.16) HW=1.20
IF(NHR.EQ.17) HW=1.05
IF(NHR.EQ.18) HW=1.88
IF(NHR.EQ.19) HW=3.38
IF(NHR.EQ.20) HW=5.80
IF(NHR.EQ.21) HW=4.8
IF(NHR.EQ.23) HW=2.73
HWM=ROWTR*HW
QHW=HWM*CPW*(THWR-TCW)
IF(THTSI.LT.THWR) QHW=HWM*CPW*(THTSI-TCW)
IF(NOHTS.EQ.0.AND.TLTSI.LT.THWR)QHW=HWM*CPW*(TLTSI-TCW)
IF(NOHTS.EQ.0.AND.TLTSI.GE.THWR)QHW=HWM*CPW*(THWR-TCW)
IF(NOHTS.EQ.0)GO TO 1160
*   THE FOLLOWING LINES CALCULATE THE INITIAL HTS AND LTS TANK
*   INTERNAL ENERGY
DATA CPS1,CPS2,CPS3/.4167,.575,.500/
IF(THTSI.LT.560.)1,2
1 EHI=CPS1*THTSI-33.336
2 IF(THTSI.EQ.560.)3,4
3 EHI=200.+X1I*67.
4 IF(THTSI.GT.560..AND.THTSI.LT.600.)5,6
5 EHI=267.+CPS2*(THTSI-560.)
6 IF(THTSI.EQ.600.)7,8
7 EHI=290.+X2I*70.
8 IF(THTSI.GT.600.)9,15
9 EHI=360.+CPS3*(THTSI-600.)
15 CONTINUE
IF(DAY.EQ.1..AND.NHR.EQ.1)EHIY=EHI
IF(KDAY.EQ.1.AND.NHR.EQ.1)EHIM=EHI
1160 CONTINUE
EHLI=CPW*TLTSI
IF(DAY.EQ.1..AND.NHR.EQ.1)EHLIY=EHLI
IF(KDAY.EQ.1.AND.NHR.EQ.1)EHLIM=EHLI
IF(NOHTS.EQ.0)GO TO 489
*   THE FOLLOWING LINES CALCULATE THE HTS AND LTS TANK THERMAL LOSSES
IF(THTSI.LE.TB)491,493
491 QLTOT=0.
GO TO 489
493 Z=0.
TW=THTSI
39 Z=Z+1.
EHWAIR=0.19*((TW-TB)**.33333)
AWI=2.*3.1416*RI*EL
RO=RI+XINS
AWO=2.*3.1416*RO*EL
ULW=1./(RI*ALOG(RO/RI)/EKINS+RI/(RO*EHWAIR))
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QLW=ULW*AWI*(THTSI-TB)
IF(XINS.EQ.0.)GO TO 40
TW=QLW/(AWO*EHWAIR)+TB
IF(Z.EQ.100.)40,39
40 CONTINUE
AT=3.1416*(RI**2)
ZZ=0.
TT=THTSI
49 ZZ=ZZ+1.
EHTAIR=0.22*((TT-TB)**.33333)
ULT=1./(XINS/EKINS+1./EHTAIR)
QLT=ULT*AT*(THTSI-TB)
IF(XINS.EQ.0.)GO TO 50
TT=QLT/(AT*EHTAIR)+TB
IF(ZZ.EQ.100.)50,49
50 CONTINUE
QLB=(EKINS/XINS)*AT*(THTSI-TB)
QLTOT=QLW+QLT+QLB
489 CONTINUE
IF(TLTSI.LE.TB)481,483
481 QLTOTL=0.
GO TO 479
483 W=0.
TWL=TLTSI
134 W=W+1.
EHWL=0.19*((TWL-TB)**0.33333)
AWIL=2.*3.1416*RIL*ELL
ROL=RIL+XINSL
AWOL=2.*3.1416*ROL*ELL
ULWL=1./(RIL*ALOG(ROL/RIL)/EKINSL+RIL/(ROL*EHWL))
QLWL=ULWL*AWIL*(TLTSI-TB)
IF(XINSL.EQ.0.)GO TO 132
TWL=QLWL/(AWOL*EHWL)+TB
IF(W.EQ.100.)132,134
132 CONTINUE
ATL=3.1416*(RIL**2)
WW=0.
TTL=TLTSI
138 WW=WW+1.
EHTL=0.22*((TTL-TB)**.33333)
ULTL=1./(XINSL/EKINSL+1./EHTL)
QLTL=ULTL*ATL*(TLTSI-TB)
IF(XINS.EQ.0.)GO TO 136
TTL=QLTL/(ATL*EHTL)+TB
IF(WW.EQ.100.)136,138
136 CONTINUE
QLBL=(EKINSL/XINSL)*ATL*(TLTSI-TB)
QLTOTL=QLWL+QLTL+QLBL
479 CONTINUE
*   THE FOLLOWING LINES CALCULATE THE USEFUL SOLAR ENERGY GAIN
*   THROUGH THE WINDOWS AND THE USEFUL HTS AND LTS TANK LOSSES
ALONG=72.
TIMECOR=(ALONG-75.)*3.14159/180.
PE=3.14159/2.
PS=0.
PW=3.14159/2.
PCOL=0.
SHADE=0.1
AE=AWE*(1.-SHADE)
AW=AWW*(1.-SHADE)
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AS=AWS◆(1.-SHADE)
A1=60.
A2=42.33
AL=A2◆3.14159/180.
BA=A1◆3.14159/180.
GN=2.
IF(NHR.GT.6..AND.NHR.LT.19.)903,970
970 EE=0.
EW=0.
ES=0.
GO TO 998
903 HR=NHR
HR=HR+TIMECOR
DA=23.367/180.◆3.14159◆SIN(2.◆3.14159/365.◆(DAY+163.))
HA=(HR-12.)◆3.14159/12.
JWND=1
IF(HA.EQ.0.)GO TO 980
IF(HA.GT.0.)GO TO 972
P=PE
GO TO 999
960 EE=AE◆Y
EW=0.
GO TO 990
972 JWND=2
P=PW
GO TO 999
975 EW=AW◆Y
EE=0.0
GO TO 990
980 EE=0.
EW=0.
990 JWND=3
P=PCOL
999 COSI1=(SIN(AL)◆COS(BA)-COS(AL)◆SIN(BA)◆COS(P))◆SIN(DA)
++(COS(AL)◆COS(BA)+SIN(AL)◆SIN(BA)◆COS(P))◆COS(DA)◆COS(HA)
++SIN(BA)◆SIN(P)◆COS(DA)◆SIN(HA)
COSI=SIN(P)◆COS(DA)◆SIN(HA)+SIN(AL)◆COS(P)◆COS(DA)◆COS(HA)
+-COS(AL)◆COS(P)◆SIN(DA)
AI1=ACOS(COSI1)
IF(AI1.GT.1.5708) AI1=1.5707
AI=ACOS(COSI)
IF(AI.GT.1.5708) AI=1.5707
SINR=SIN(AI)/1.52
R=ASIN(SINR)
RL=.5◆((SIN(AI-R)◆SIN(AI-R))/(SIN(AI+R)◆SIN(AI+R))+(TAN(AI-R)
+◆TAN(AI-R))/(TAN(AI+R)◆TAN(AI+R)))
RLN=1.-((1.-RL)/(1.+(2.◆GN-1.)◆RL))
IF(GN.EQ.1.) RD=0.16
IF(GN.EQ.2.) RD=0.24
IF(GN.EQ.3.) RD=0.29
IF(AI.LT..5236) ABS=0.96
IF(AI.GE..5236.AND.AI.LT..698) ABS=0.95
IF(AI.GE..698.AND.AI.LT..8726) ABS=0.93
IF(AI.GE..8726.AND.AI.LT.1.0472) ABS=0.91
IF(AI.GE.1.0472.AND.AI.LT.1.2217) ABS=0.88
IF(AI.GE.1.2217.AND.AI.LT.1.3963) ABS=0.81
IF(AI.GE.1.3963.AND.AI.LE.1.5708) ABS=0.66
SINAA=SIN(AL)◆SIN(DA)+COS(AL)◆COS(DA)◆COS(HA)
AA=ASIN(SINAA)
DFSOL=0.78+61.3◆AA+6.17◆CC
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IF(DFSOL.LT.0.0) DFSOL=0.0
DRSOLT=SOL-DFSOL
IF(DRSOLT.LT.0.0)993,996
993 DRSOLT=0.0
DFSOL=SOL
996 CONTINUE
DRSOLV=DRSOLT*COSI/COSI1
SOLV=DRSOLV+DFSOL
Y=DRSOLV*(1.-RLN)*ABS+DFSOL*(1.-RD)*0.90
IF(Y.LT.0.0) Y=0.0
IF(JWND.EQ.1)GO TO 960
IF(JWND.EQ.2)GO TO 975
IF(JWND.EQ.3) ES=Y*AS
998 QSOL=EE+ES+EW
IF(NOHTS.EQ.0)QLW=0.
IF(NOHTS.EQ.0)QLT=0.
IF(QHL.EQ.0.)1200,1202
1200 QSOL=0.
QHTSHL=0.
QLTSHL=0.
QHLACT=0.
GO TO 1204
1202 QHLMS=QHL-(QLW+QLT)-(QLWL+QLTL)
IF(QHLMS)1206,1208,1210
1206 QSOL=0.
QHLACT=0.
QHTSHL=(QHL/(QLW+QLT+QLWL+QLTL))*(QLW+QLT)
QLTSHL=(QHL/(QLW+QLT+QLWL+QLTL))*(QLWL+QLTL)
GO TO 1204
1208 QSOL=0.
QHTSHL=QLW+QLT
QLTSHL=QLWL+QLTL
QHLACT=0.
GO TO 1204
1210 QHLACT=QHLMS-QSOL
IF(QHLACT.LE.0.)1212,1214
1212 QSOL=QHLMS
QHLACT=0.
QLTSHL=QLWL+QLTL
QHTSHL=QLW+QLT
GO TO 1204
1214 QSOL=QSOL
QLTSHL=QLWL+QLTL
QHTSHL=QLW+QLT
GO TO 1204
1204 CONTINUE
*   THE FOLLOWING LINES CALCULATE THE RANKINE CYCLE EFFICIENCY,SOURCE
*   AND SINK HEAT REQUIREMENTS
IF(NOHTS.EQ.0)GO TO 1100
IF(DIRHTS.EQ.1.)1304,1306
1306 IF(WWG.LT.WE)114,116
114 IF(THTSI.LE.400.)725,727
727 WREQ=(WE-WWG)/.95
GO TO 1310
1304 IF(THTSI.LE.400.)725,1308
1308 WREQ=WE/.95
1310 FREQ=1.
THI=THTSI-50.
TLO=TLTSI+25.
IF(TLO.LT.100.)801,809
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 801 E93=59.3209745-1.12178996*THI+9.09939924E-3*THI**2
+-4.13082443E-5*THI**3+1.14908972E-7*THI**4
+-2.00655919E-10*THI**5+2.14863798E-13*THI**6
+-1.29031498E-16*THI**7+3.32830628E-20*THI**8
 IF(TLD.LE.93.)803,805
 803 ETA=E93
 GO TO 900
 805 E100=57.7564004-1.09305596*THI+8.87246906E-3*THI**2
+-4.03052230E-5*THI**3+1.12194103E-7*THI**4
+-1.96043954E-10*THI**5+2.10057039E-13*THI**6
+-1.26218589E-16*THI**7+3.25747644E-20*THI**8
 XINP=(TLD-93.)/(100.-93.)
 ETA=XINP*(E100-E93)+E93
 GO TO 900
 809 IF(TLD.GE.100..AND.TLD.LT.125.)811,819
 811 E100=57.7564004-1.09305596*THI+8.87246906E-3*THI**2
+-4.03052230E-5*THI**3+1.12194103E-7*THI**4
+-1.96043954E-10*THI**5+2.10057039E-13*THI**6
+-1.26218589E-16*THI**7+3.25747644E-20*THI**8
 IF(TLD.EQ.100.)813,815
 813 ETA=E100
 GO TO 900
 815 E125=46.8825955-.892124881*THI+7.28082422E-3*THI**2
+-3.32586585E-5*THI**3+9.31144512E-8*THI**4
+-1.63661167E-10*THI**5+1.76377178E-13*THI**6
+-1.06571413E-16*THI**7+2.76476625E-20*THI**8
 XINP=(TLD-100.)/(125.-100.)
 ETA=XINP*(E125-E100)+E100
 GO TO 900
 819 IF(TLD.GE.125..AND.TLD.LT.150.)821,829
 821 E125=46.8825955-.892124881*THI+7.28082422E-3*THI**2
+-3.32586585E-5*THI**3+9.31144512E-8*THI**4
+-1.63661167E-10*THI**5+1.76377178E-13*THI**6
+-1.06571413E-16*THI**7+2.76476625E-20*THI**8
 IF(TLD.EQ.125.)823,825
 823 ETA=E125
 GO TO 900
 825 E150=43.0557333-.82440575*THI+6.76493741E-3*THI**2
+-3.10603739E-5*THI**3+8.73783178E-8*THI**4
+-1.54260201E-10*THI**5+1.66910432E-13*THI**6
+-1.01207575E-16*THI**7+2.63366589E-20*THI**8
 XINP=(TLD-125.)/(150.-125.)
 ETA=XINP*(E150-E125)+E125
 GO TO 900
 829 IF(TLD.GE.150..AND.TLD.LT.175.)831,839
 831 E150=43.0557333-.82440575*THI+6.76493741E-3*THI**2
+-3.10603739E-5*THI**3+8.73783178E-8*THI**4
+-1.54260201E-10*THI**5+1.66910432E-13*THI**6
+-1.01207575E-16*THI**7+2.63366589E-20*THI**8
 IF(TLD.EQ.150.)833,835
 833 ETA=E150
 GO TO 900
 835 E175=43.7793859-.836999466*THI+6.85176225E-3*THI**2
+-3.13756142E-5*THI**3+8.80182741E-8*THI**4
+-1.54943917E-10*THI**5+1.67167541E-13*THI**6
+-1.01076881E-16*THI**7+2.62309330E-20*THI**8
 XINP=(TLD-150.)/(175.-150.)
 ETA=XINP*(E175-E150)+E150
 GO TO 900
 839 IF(TLD.GE.175..AND.TLD.LT.200.)841,849
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841 E175=43.7793859-.836999466*THI+6.85176225E-3*THI**2
+-3.13756142E-5*THI**3+8.80182741E-8*THI**4
+-1.54943917E-10*THI**5+1.67167541E-13*THI**6
+-1.01076881E-16*THI**7+2.62309330E-20*THI**8
IF(TLD.EQ.175.)843,845
843 ETA=E175
GO TO 900
845 E200=43.7050821-.836486411*THI+6.84957070E-3*THI**2
+-3.13706102E-5*THI**3+8.80144539E-8*THI**4
+-1.54952439E-10*THI**5+1.67192202E-13*THI**6
+-1.01101470E-16*THI**7+2.62401012E-20*THI**8
XINP=(TLD-175.)/(200.-175.)
ETA=XINP*(E200-E175)+E175
GO TO 900
849 IF(TLD.GE.200..AND.TLD.LT.225.)851,859
851 E200=43.7050821-.836486411*THI+6.84957070E-3*THI**2
+-3.13706102E-5*THI**3+8.80144539E-8*THI**4
+-1.54952439E-10*THI**5+1.67192202E-13*THI**6
+-1.01101470E-16*THI**7+2.62401012E-20*THI**8
IF(TLD.EQ.200.)853,855
853 ETA=E200
GO TO 900
855 E225=44.0832228-.844013486*THI+6.90719943E-3*THI**2
+-3.16095795E-5*THI**3+8.86069329E-8*THI**4
+-1.55853373E-10*THI**5+1.68012248E-13*THI**6
+-1.01509300E-16*THI**7+2.63246945E-20*THI**8
XINP=(TLD-200.)/(225.-200.)
ETA=XINP*(E225-E200)+E200
GO TO 900
859 IF(TLD.EQ.225.)861,900
861 E225=44.0832228-.844013486*THI+6.90719943E-3*THI**2
+-3.16095795E-5*THI**3+8.86069329E-8*THI**4
+-1.55853373E-10*THI**5+1.68012248E-13*THI**6
+-1.01509300E-16*THI**7+2.63246945E-20*THI**8
ETA=E225
GO TO 900
900 ETA=ETA*RNKFCT
QH=(WREQ/0.293)/ETA
QETAL=QH-(WREQ/0.293)
*   THE FOLLOWING LINES REPRESENT THE MODE OF OPERATION AND SWITCHING
*   LOGIC
IF(DIRHTS.NE.1.)GO TO 1314
WEXT=WWG-0.293*(QLTOT+QHW+QH)
IF(THTSI.EQ.THMAX)1320,244
1320 IF(WEXT.LE.0.)1324,1326
1324 WADD=WWG
WADDL=0.
GO TO 1314
1326 WADD=0.293*(QLTOT+QHW+QH)
GO TO 265
1314 IF(TLTSI.EQ.200.)290,292
290 QLX=QETAL-QLTOTL-QHLACT
IF(QLX)294,294,296
294 QL=QETAL
QACHX=0.
GO TO 300
296 QL=QLTOTL+QHLACT
QACHX=QLX
GO TO 300
292 IF(TLTSI.LT.200.)298,300
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298 QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL+QETAL
IF(QAVAIL-QHLACT)562,561,561
561 QLX=QETAL-QLTOTL-QHLACT
IF(QLX)306,306,308
308 QLXT=QLX*THEDA/EML
EMHL=CPW*200.
IF((QLXT+EHLI).LE.EMHL)302,304
302 QL=QETAL
QACHX=0.
GO TO 300
304 CONTINUE
QL=(EMHL-EHLI)*EML/THEDA+QLTOTL+QHLACT
QACHX=QETAL-QL
GO TO 300
306 QL=QETAL
QACHX=0.
GO TO 300
562 QAUX=QHLACT-QAVAIL
QL=QETAL
QACHX=0.
GO TO 300
725 WEAUX=WE-WWG
IF(DIRHTS.EQ.1.)WEAUX=WE
QH=0.
QL=0.
IF(THTSI.LT.THWR)  WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL
IF(QAVAIL-QHLACT)729,731,731
731 QACHX=0.
QAUX=0.
 GO TO 300
729 QAUX=QHLACT-QAVAIL
QACHX=0.
GO TO 300
300 WADD=0.
IF(DIRHTS.EQ.1.)WADD=WWG
WADDL=0.
GO TO 182
116 IF(WWG.EQ.WE)118,120
118 WREQ=0.
QH=0.
QL=0.
WADD=0.
WADDL=0.
IF(THTSI.LT.THWR)1011,1012
1011 WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
1012 QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL
IF(QAVAIL-QHLACT)552,551,551
551 GO TO 554
552 QAUX=QHLACT-QAVAIL
554 CONTINUE
120 IF(WWG.GT.WE)122,182
122 QH=0.
QL=0.
IF(THTSI.EQ.THMAX)188,190
188 WEXT=WWG-WE-0.293*QLTOT-0.293*QHW
IF(WEXT)192,194,196
192 WADD=WWG-WE
GO TO 247
194 WADD=0.293*QLTOT+0.293*QHW
```

```
GO TO 247
247 QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL
IF(QAVAIL-QHLACT)249,240,240
249 QAUX=QHLACT-QAVAIL
GO TO 240
196 WADD=0.293*QLTOT+0.293*QHW
265 CONTINUE
WLTS=WWG-WE-WADD
IF(DIRHTS.EQ.1.)WLTS=WWG-WADD
IF(TLTSI.GT.200.)198,200
198 WWASTE=WLTS
IF(DIRHTS.EQ.1.)QACHX=QETAL
200 IF(TLTSI.EQ.200.)202,214
202 WEXTL=WLTS-0.293*QHLACT-0.293*QLTOTL
IF(DIRHTS.EQ.1.)WEXTL=WEXTL+0.293*QETAL
IF(DIRHTS.EQ.1.)QL=QETAL
IF(WEXTL)204,206,208
204 WADDL=WLTS
GO TO 210
206 WADDL=0.293*QHLACT+0.293*QLTOTL
IF(DIRHTS.EQ.1.)WADDL=WADDL-0.293*QETAL
GO TO 210
208 WADDL=0.293*QHLACT+0.293*QLTOTL
IF(DIRHTS.EQ.1.)WADDL=WADDL-0.293*QETAL
WWASTE=WEXTL
GO TO 210
210 CONTINUE
214 IF(TLTSI.LT.200.)216,218
216 QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL+WLTS/0.293
IF(DIRHTS.EQ.1.)QL=QETAL
IF(QAVAIL-QHLACT)572,570,570
572 QAUX=QHLACT-QAVAIL
WADDL=WLTS
GO TO 235
570 WEXTL=WLTS-0.293*QHLACT-0.293*QLTOTL
IF(DIRHTS.EQ.1.)WEXTL=WEXTL+0.293*QETAL
IF(WEXTL)220,222,224
220 WADDL=WLTS
GO TO 235
222 WADDL=0.293*QHLACT+0.293*QLTOTL
IF(DIRHTS.EQ.1.)WADDL=WADDL-0.293*QL
GO TO 235
224 QML=(WEXTL/0.293)*THEDA/EML
EMHL=CPW*200.
IF((QML+EHLI).GT.EMHL)226,228
226 CONTINUE
WADDL=(EMHL-EHLI)*EML*0.293/THEDA+0.293*QHLACT+0.293*QLTOTL
IF(DIRHTS.EQ.1.)WADDL=WADDL-0.293*QL
WWASTE=WLTS-WADDL
228 IF((QML+EHLI).LE.EMHL)230,232
230 WADDL=WLTS
232 CONTINUE
235 CONTINUE
218 CONTINUE
240 CONTINUE
IF(THTSI.LT.THMAX)GO TO 267
190 IF(THTSI.LT.THMAX)244,182
244 IF(THTSI.GE.THWR)1005,1006
1006 WEXT=WWG-WE-0.293*QLTOT
IF(WEXT)1007,1008,1009
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1007 WADD=WWG-WE
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
GO TO 273
1008 WADD=0.293*QLTOT
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
GO TO 273
1009 WADD=WEXT
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
GO TO 273
1005 WEXT=WWG-WE-0.293*QLTOT-0.293*QHW
IF(DIRHTS.EQ.1.)WEXT=WWG-0.293*(QLTOT+QHW+QH)
IF(DIRHTS.EQ.1.)QL=QETAL
IF(WEXT)248,250,252
248 WADD=WWG-WE
IF(DIRHTS.EQ.1.)WADD=WWG
GO TO 273
250 WADD=0.293*QLTOT+0.293*QHW
IF(DIRHTS.EQ.1.)WADD=WADD+0.293*QH
GO TO 273
273 QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL
IF(DIRHTS.EQ.1.)QAVAIL=QAVAIL+QETAL
IF(QAVAIL-QHLACT)277,272,1410
277 QAUX=QHLACT-QAVAIL
GO TO 272
1410 IF(DIRHTS.EQ.1.)1412,272
1412 QLX=QETAL-QLTOTL-QHLACT
IF(QLX.LE.0.)272,1455
1455 QLXT=QLX*THEDA/EML
EMHL=CPW*200.
IF((QLXT+EHLI).LE.EMHL)272,1414
1414 QL=(EMHL-EHLI)*EML/THEDA+QLTOTL+QHLACT
QACHX=QETAL-QL
GO TO 272
252 QMH=(WEXT/0.293)*THEDA/EM
EMH=360.+CPS3*(THMAX-600.)
IF((QMH+EHI).LE.EMH)254,256
254 WADD=WWG-WE
IF(DIRHTS.EQ.1.)WADD=WWG
QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL
IF(DIRHTS.EQ.1.)QAVAIL=QAVAIL+QL
IF(QAVAIL-QHLACT)534,270,1412
534 QAUX=QHLACT-QAVAIL
GO TO 270
256 IF((QMH+EHI).GT.EMH)258,260
258 WADD=(EMH-EHI)*EM*0.293/THEDA+0.293*QLTOT+0.293*QHW
IF(DIRHTS.EQ.1.)WADD=WADD+0.293*QH
GO TO 265
267 CONTINUE
260 CONTINUE
270 CONTINUE
272 CONTINUE
GO TO 182
1100 IF(WWG.GT.WE)1111,1113
1111 QH=0.
QL=0.
WLTS=WWG-WE
IF(TLTSI.GT.200.)1115,1117
1115 WWASTE=WLTS
GO TO 182
1117 IF(TLTSI.EQ.200.)1119,1121
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1119 WEXTL=WLTS-0.293*(QHLACT+QHW+QLTOTL)
IF(WEXTL)1123,1123,1125
1123 WADDL=WLTS
GO TO 182
1125 WADDL=0.293*(QHLACT+QHW+QLTOTL)
WWASTE=WEXTL
GO TO 182
1121 IF(TLTSI.LT.200.)1127,182
1127 QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL+WLTS/0.293
IF(QAVAIL-QHLACT-QHW)1129,1131,1131
1129 QAUX=QHLACT-(QAVAIL-QHW)
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
WADDL=WLTS
GO TO 182
1131 WEXTL=WLTS-0.293*(QHLACT+QHW+QLTOTL)
IF(WEXTL)1133,1133,1135
1133 WEXTL=WLTS
WADDL=WLTS
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
GO TO 182
1135 QML=(WEXTL/0.293)*THEDA/EML
EMHL=CPW*200.
IF((QML+EHLI).LE.EMHL)1137,1139
1137 WADDL=WLTS
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
GO TO 182
1139 IF((QML+EHLI).GT.EMHL)1141,182
1141 WADDL=(EMHL-EHLI)*EML*0.293/THEDA+0.293*(QHLACT+QHW+QLTOTL)
WWASTE=WLTS-WADDL-0.293*(HWM*CPW*(THWR-TCW)-QHW)
GO TO 182
1113 IF(WWG.EQ.WE)1145,1147
1145 WREQ=0.
QH=0.
QL=0.
WADDL=0.
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL
IF(QAVAIL-QHLACT-QHW)1149,182,182
1149 QAUX=QHLACT-(QAVAIL-QHW)
GO TO 182
1147 IF(WWG.LT.WE)1151,182
1151 WREQ=WE-WWG
WEAUX=WREQ
QH=0.
QL=0.
WADDL=0.
WHWAUX=0.293*(HWM*CPW*(THWR-TCW)-QHW)
QAVAIL=EML*CPW*(TLTSI-TR)-QLTOTL
IF(QAVAIL-QHLACT-QHW)1153,182,182
1153 QAUX=QHLACT-(QAVAIL-QHW)
182 CONTINUE
*    THE FOLLOWING LINES REPRESENT ENERGY BALANCE EQUATIONS
IF(NOHTS.EQ.0)GO TO 1107
QE=WADD/0.293
EHF=(QE-QH-QLTOT-QHW)*THEDA/EM+EHI
1107 CONTINUE
QEL=WADDL/0.293
IF(NOHTS.EQ.0)1109,1108
1108 EHLF=(QL+QEL+QAUX-QHLACT-QLTOTL)*THEDA/EML+EHLI
GO TO 1162
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1109 EHLF=(QEL+QAUX-QHLACT-QLTOTL-QHW)*THEDA/EML+EHLI
1162 CONTINUE
*   THE FOLLOWING LINES CALCULATE THE FINAL HTS AND LTS TANK
*   INTERNAL ENERGY
IF(NOHTS.EQ.0)GO TO 32
IF(EHF.LT.200.)20,21
20 THTSF=(EHF+33.336)/CPS1
21 IF(EHF.GE.200..AND.EHF.LE.267.)22,23
22 THTSF=560.
X1F=(EHF-200.)/67.
23 IF(EHF.GT.267..AND.EHF.LT.290.)25,26
25 THTSF=(EHF-267.)/CPS2+560.
26 IF(EHF.GE.290..AND.EHF.LE.360.)28,29
28 THTSF=600.
X2F=(EHF-290.)/70.
29 IF(EHF.GT.360.)31,32
31 THTSF=(EHF-360.)/CPS3+600.
32 CONTINUE
*   THE FOLLOWING LINES PERFORM CONVERSIONS OF UNITS AND OUTPUT
*   INFORMATION IN THE DESIRED FORMAT
TLTSF=EHLF/CPW
WWG=WWG/1000.
WE=WE/1000.
QHLACT=QHLACT*.293/1000.
QHL=QHL*.293/1000.
QHW=QHW*.293/1000.
QH=QH*.293/1000.
QL=QL*.293/1000.
QACHX=QACHX*.293/1000.
WWASTE=WWASTE/1000.
QAUX=QAUX*.293/1000.
WEAUX=WEAUX/1000.
WHWAUX=WHWAUX/1000.
WADD=WADD/1000.
WREQ=WREQ/1000.
QLB=QLB*.293/1000.
QLBL=QLBL*.293/1000.
QSOL=QSOL*.293/1000.
QHTSHL=QHTSHL*.293/1000.
QLTSHL=QLTSHL*.293/1000.
IF(RR.EQ.1.)620,622
622 IF(NHR.EQ.1)623,625
623 PRINT 650
625 PRINT 652,NHR,WWG,WE,QHLACT,QHW,QH,QL,QACHX,WWASTE,THTSF,TLTSF,
+QAUX,WEAUX,WHWAUX,WADD,WREQ
620 NHR=NHR+1
IF(THTSF.LT.THCRIT)THCRIT=THTSF
IF(TLTSF.LT.TLCRIT)TLCRIT=TLTSF
IF(FREQ.EQ.1.)THRAVD=THRAVD+THTSI
IF(FREQ.EQ.1.)TLRAVD=TLRAVD+TLTSI
TAVHD=TAVHD+THTSI
TAVLD=TAVLD+TLTSI
WWGD=WWG+WWGD
WED=WE+WED
QHLD=QHL+QHLD
QHWD=QHW+QHWD
QHLACD=QHLACT+QHLACD
QAUXD=QAUX+QAUXD
WEAUXD=WEAUX+WEAUXD
QACHXD=QACHX+QACHXD
```

```
WWASTD=WWASTE+WWASTD
WHWAUXD=WHWAUX+WHWAUXD
WADDD=WADD+WADDD
QHD=QH+QHD
WREQD=WREQ+WREQD
FREQD=FREQ+FREQD
QLBD=QLB+QLBD
QLBLD=QLBL+QLBLD
QSOLD=QSOL+QSOLD
QHTSHLD=QHTSHL+QHTSHLD
QLTSHLD=QLTSHL+QLTSHLD
IF(NHR.LE.24)624,626
624 THTSI=THTSF
TLTSI=TLTSF
X1I=X1F
X2I=X2F
QACHX=0.
QAUX=0.
WEAUX=0.
WHWAUX=0.
WADD=0.
WADDL=0.
WWASTE=0.
WEXT=0.
WEXTL=0.
QH=0.
WREQ=0.
FREQ=0.
QLB=0.
QLBL=0.
QSOL=0.
QHTSHL=0.
QLTSHL=0.
QETAL=0.
GO TO 500
626 NDAY=NDAY+1
DAY=DAY+1.
IF(MON.EQ.1)630,632
632 IF(KDAY.EQ.1)GO TO 634
IF(RR.EQ.1.)GO TO 636
634 PRINT 640
636 PRINT 642,KDAY,WWGD,WED,QHLACD,QHWD,QACHXD,WWASTD,
+QAUXD,WEAUXD,WHWAUXD,THCRIT,TLCRIT,WADDD,QHD,WREQD,FREQD
630 KDAY=KDAY+1
NHR=1
WWGM=WWGD+WWGM
WEM=WED+WEM
QHLM=QHLD+QHLM
QHWM=QHWD+QHWM
QHLACM=QHLACD+QHLACM
QAUXM=QAUXD+QAUXM
WEAUXM=WEAUXD+WEAUXM
WHWAUXM=WHWAUXD+WHWAUXM
QACHXM=QACHXD+QACHXM
WWASTM=WWASTD+WWASTM
WADDM=WADDD+WADDM
QHM=QHD+QHM
WREQM=WREQD+WREQM
FREQM=FREQD+FREQM
QLBM=QLBD+QLBM
```

```
QLBLM=QLBLD+QLBLM
QSOLM=QSOLD+QSOLM
QHTSHLM=QHTSHLD+QHTSHLM
QLTSHLM=QLTSHLD+QLTSHLM
THRAVM=THRAVD+THRAVM
TLRAVM=TLRAVD+TLRAVM
TAVHM=TAVHD+TAVHM
TAVLM=TAVLD+TAVLM
WWGD=0.
WED=0.
QHLD=0.
QHWD=0.
QHLACD=0.
QAUXD=0.
WEAUXD=0.
WHWAUXD=0.
QACHXD=0.
WWASTD=0.
QLBD=0.
QLBLD=0.
QSOLD=0.
QHTSHLD=0.
QLTSHLD=0.
THRAVD=0.
TLRAVD=0.
TAVHD=0.
TAVLD=0.
THTSI=THTSF
TLTSI=TLTSF
X1I=X1F
X2I=X2F
QACHX=0.
QAUX=0.
WEAUX=0.
WADD=0.
WADDL=0.
WWASTE=0.
WEXT=0.
WEXTL=0.
QH=0.
WREQ=0.
FREQ=0.
QLB=0.
QLBL=0.
QSOL=0.
QHTSHL=0.
QLTSHL=0.
QETAL=0.
IF(KDAY.LE.ND)GO TO 610
KDAY=1
NHR=1
NM=NM+1
IF(FREQM.EQ.0.)GO TO 1400
THAVRM=THRAVM/FREQM
TLAVRM=TLRAVM/FREQM
1400 CONTINUE
THAVM=TAVHM/(ND*24.)
TLAVM=TAVLM/(ND*24.)
EHTSM=0.293*EM*(EHF-EHIM)/1000.
ELTSM=0.293*EML*(EHLF-EHLIM)/1000.
```

```
11500 PRINT 644
11510 PRINT 646,WWGM,WEM,QHLM,QHLACM,QHWM,QACHXM,WWASTM,QAUXM,WEAUXM,WHWAUXM
11520+,WADDM,QHM,WREQM,FREQM
11530 PRINT 1079
11540 PRINT 1081,QLBM,QLBLM,QSOLM,EHTSM,ELTSM,QHTSHLM,QLTSHLM
11550+,THAVRM,TLAVRM,THAVM,TLAVM
11560 WWGY=WWGM+WWGY
11570 WEY=WEM+WEY
11580 QHLY=QHLM+QHLY
11590 QHWY=QHWM+QHWY
11600 QHLACY=QHLACM+QHLACY
11610 QAUXY=QAUXM+QAUXY
11620 WEAUXY=WEAUXM+WEAUXY
11630 WHWAUXY=WHWAUXM+WHWAUXY
11640 QACHXY=QACHXM+QACHXY
11650 WWASTY=WWASTM+WWASTY
11660 WADDY=WADDM+WADDY
11670 QHY=QHM+QHY
11680 WREQY=WREQM+WREQY
11690 FREQY=FREQM+FREQY
11700 QLBY=QLBM+QLBY
11710 QLBLY=QLBLM+QLBLY
11720 QSOLY=QSOLM+QSOLY
11730 QHTSHLY=QHTSHLM+QHTSHLY
11740 QLTSHLY=QLTSHLM+QLTSHLY
11750 THRAVY=THRAVM+THRAVY
11760 TLRAVY=TLRAVM+TLRAVY
11770 TAVHY=TAVHM+TAVHY
11780 TAVLY=TAVLM+TAVLY
11790 WWGM=0.
11800 WEM=0.
11810 QHLM=0.
11820 QHWM=0.
11830 QHLACM=0.
11840 QAUXM=0.
11850 WEAUXM=0.
11860 WHWAUXM=0.
11870 QACHXM=0.
11880 WWASTM=0.
11890 WADDM=0.
11900 QHM=0.
11910 WREQM=0.
11920 FREQM=0.
11930 QLBM=0.
11940 QLBLM=0.
11950 QSOLM=0.
11960 QHTSHLM=0.
11970 QLTSHLM=0.
11980 THRAVM=0.
11990 TLRAVM=0.
12000 TAVHM=0.
12010 TAVLM=0.
12020 THAVRM=0.
12030 TLAVRM=0.
12040 THAVM=0.
12050 TLAVM=0.
12060 IF(NM.EQ.2)GO TO 660
12070 IF(NM.EQ.3)GO TO 662
12080 IF(NM.EQ.4)GO TO 664
12090 IF(NM.EQ.5)GO TO 666
```

```
IF(NM.EQ.6)GO TO 668
IF(NM.EQ.7)GO TO 670
IF(NM.EQ.8)GO TO 672
IF(NM.EQ.9)GO TO 674
IF(NM.EQ.10)GO TO 676
IF(NM.EQ.11)GO TO 678
IF(NM.EQ.12)GO TO 680
IF(NM.GT.12)GO TO 682
660 ND=31
PRINT 690
GO TO 610
662 N=2
ND=30
KK=61
NDAY=1
PRINT 692
GO TO 550
664 ND=31
PRINT 694
GO TO 610
666 N=3
ND=31
KK=59
NDAY=1
PRINT 696
GO TO 550
668 ND=28
PRINT 698
GO TO 610
670 N=4
ND=31
KK=61
NDAY=1
PRINT 700
GO TO 550
672 ND=30
PRINT 702
GO TO 610
674 N=5
ND=31
KK=61
NDAY=1
PRINT 704
GO TO 550
676 ND=30
PRINT 706
GO TO 610
678 N=6
ND=31
KK=62
NDAY=1
PRINT 708
GO TO 550
680 ND=31
PRINT 710
GO TO 610
682 EHTSY=0.293*EM*(EHF-EHIY)/1000.
ELTSY=0.293*EML*(EHLF-EHLIY)/1000.
IF(FREQY.EQ.0.)GO TO 1401
THAVRY=THRAVY/FREQY
```

```
TLAVRY=TLRAVY/FREQY
1401 CONTINUE
THAVY=TAVHY/(365.*24.)
TLAVY=TAVLY/(365.*24.)
WR95=.95*WREQY
IF(NOHTS.EQ.0)WR95=0.
WR05=.05*WREQY
IF(NOHTS.EQ.0)WR05=0.
ELTELDY=WEY-WEAUXY-WR95
WADDLY=WWGY-ELTELDY-WADDY-WWASTY
HNTHL=WADDY-QLBY-QHY-QHWY-QHTSHLY-EHTSY
IF(NOHTS.EQ.0)HNTHL=0.
QLY=QHY-WREQY
IF(NOHTS.EQ.0)QLY=0.
QFLTS=QHLY-QAUXY-QSOLY-QLTSHLY-QHTSHLY
ELNTHL=QLY+WADDLY-ELTSY-QACHXY-QLBLY-QLTSHLY-QFLTS
IF(NOHTS.EQ.0)ELNTHL=WADDLY-ELTSY-QACHX-QLBLY-QLTSHLY-QFLTS-QHWY
ENERGY=QAUXY+WEAUXY+WHWAUXY
PRINT 712
PRINT 714,WWGY,WEY,QHLY,QHLACY,QHWY,QACHXY,WWASTY,QAUXY,WEAUXY,WHWAUXY
PRINT 1021
PRINT 1023,WADDY,QHY,WREQY,FREQY,QLBY,QLBLY,QSOLY,EHTSY,ELTSY
PRINT 1225
PRINT 1227,QHTSHLY,QLTSHLY,THAVRY,TLAVRY,THAVY,TLAVY
PRINT 2051
PRINT 2053,WR95,WR05,ELTELDY,WADDLY,HNTHL,QLY,QFLTS,ELNTHL,ENERGY
601 FORMAT(10H SEPTEMBER)
640 FORMAT(4HKDAY,3X,4HWWGD,6X,3HWED,4X,6HQHLACD,
+4X,4HQHWD,4X,6HQACHXD,3X,6HWWASTD,3X,5HQAUXD,3X,6HWEAUXD,2X,
+7HWHWAUXD,2X,6HTHCRIT,2X,6HTLCRIT,3X,5HWADDD,5X,3HQHD,3X,5HWREQD,
+1X,5HFREQD)
642 FORMAT(1X,I2,9(1X,F8.3),2(2X,F5.1),3(1X,F8.3),1X,F3.0)
644 FORMAT(4X,4HWWGM,6X,3HWEM,5X,4HQHLM,4X,6HQHLACM,
+4X,4HQHWM,4X,6HQACHXM,3X,6HWWASTM,4X,5HQAUXM,3X,6HWEAUXM,
+2X,7HWHWAUXM,4X,5HWADDM,6X,3HQHM,4X,5HWREQM,1X,5HFREQM)
646 FORMAT(13(1X,F8.2),1X,F5.0)
1079 FORMAT(4X,4HQLBM,4X,5HQLBLM,4X,5HQSOLM,4X,5HEHTSM,4X,
+5HELTSM,3X,7HQHTSHLM,3X,7HQLTSHLM,3X,6HTHAVRM,3X,6HTLAVRM,
+4X,5HTHAVM,4X,5HTLAVM)
1081 FORMAT(7(1X,F8.2),4(4X,F5.1))
650 FORMAT(1X,3HNHR,3X,3HWWG,6X,2HWE,3X,6HQHLACT,4X,3HQHW,
+5X,2HQH,6X,2HQL,4X,5HQACHX,3X,6HWWASTE,2X,5HTHTSF,2X,5HTLTSF,
+3X,4HQAUX,3X,5HWEAUX,2X,6HWHWAUX,4X,4HWADD,4X,4HWREQ)
652 FORMAT(1X,I2,8(1X,F7.3),2(1X,F6.1),5(1X,F7.3))
690 FORMAT(8H OCTOBER)
692 FORMAT(9H NOVEMBER)
694 FORMAT(9H DECEMBER)
696 FORMAT(8H JANUARY)
698 FORMAT(9H FEBRUARY)
700 FORMAT(6H MARCH)
702 FORMAT(6H APRIL)
704 FORMAT(4H MAY)
706 FORMAT(5H JUNE)
708 FORMAT(5H JULY)
710 FORMAT(7H AUGUST)
712 FORMAT(7X,4HWWGY,8X,3HWEY,7X,4HQHLY,5X,6HQHLACY,7X,4HQHWY,
+5X,6HQACHXY,5X,6HWWASTY,6X,5HQAUXY,5X,6HWEAUXY,4X,7HWHWAUXY)
714 FORMAT(10(1X,F10.1))
1021 FORMAT(6X,5HWADDY,8X,3HQHY,6X,5HWREQY,6X,5HFREQY,
+7X,4HQLBY,6X,5HQLBLY,6X,5HQSOLY,6X,5HEHTSY,6X,5HELTSY)
```

```
 1023 FORMAT(9(1X,F10.1))
 1225 FORMAT(4X,7HOHTSHLY,4X,7HOLTSHLY,5X,6HTHAVRY,5X,6HTLAVRY,
+6X,5HTHAVY,6X,5HTLAVY)
 1227 FORMAT(2(1X,F10.1),4(6X,F5.1))
 2051 FORMAT(7X,4HWP95,7X,4HWR05,4X,7HELTELDY,5X,6HWADDLY,6X,
+5HANTHL,8X,3HOLY,6X,5HOFLTS,5X,6HELNTHL,5X,6HENERGY)
 2053 FORMAT(9(1X,F10.1))
 STOP
 END
```

APPENDIX C

THE ECONOMICS PROGRAM

The economics program (WSDECO) was also written in Fortran IV language. WSDECO features an interactive format and enables the user to compare the economic feasibility of the IWFS, WDTES, Type I and WDTES, Type II models with the conventional electrical, gas and oil energy systems. This comparison can also be made for both prototype and mass-produced advanced wind furnace systems using 1977 dollars.

The WSDECO system control parameters and Fortran variables are given in the following sections along with a listing of WSDECO.

WSDECO SYSTEM CONTROL PARAMETERS

AUXOPT	=	1	For electric auxiliary system
	=	2	For oil auxiliary system
	=	3	For gas auxiliary system
SYST	=	1	For IWFS
	=	2	For WDTES, TYPE I
	=	3	For WDTES, TYPE II
TYPINV	=	1	For Gemini inverter
	=	2	For Abacus inverter

WSDECO FORTRAN VARIABLES

ACST	:	Annual prototype system costs	$
ACSTF	:	Annual mass-produced system costs	$
ACONVE	:	Annual cost of conventional electric system	$
ACONVG	:	Annual cost of conventional gas system	$
ACONVO	:	Annual cost of conventional oil system	$
BINCT	:	Fixed cost of prototype WTG blades	$
BINCTF	:	Fixed cost of mass-produced WTG blades	$
BLCT	:	Prototype WTG blade cost	$/ft^3
BLCTF	:	Mass-produced WTG blade cost	$/ft^3
CALT	:	Prototype alternator cost	$
CALTF	:	Mass-produced alternator cost	$
CANCOV	:	Annual conventional system costs	$
CANSDS	:	Annual prototype wind system costs	$
CANSDSF	:	Annual mass-produced wind system costs	$
CEAUX	:	Annual cost of auxiliary electricity	$
CECONV	:	Annual conventional electric cost	$
CELAV	:	Average undelivered electricity cost based on escalation rate over amortization period	$/kWh
CELECT	:	Undelivered electricity cost	$/kWh
CGAS	:	Undelivered gas cost	$/kWh
CGASAV	:	Average undelivered gas cost based on escalation rate over amortization period	$/kWh
CGAUX	:	Annual cost of auxiliary gas	$/kWh
CGCONV	:	Annual conventional gas cost	$
CGEN	:	Prototype generator cost	$

CGENF	:	Mass-produced generator cost	\$
CHTS	:	Prototype HTS cost	\$/gallon
CHTSF	:	Mass-produced HTS cost	\$/gallon
CINV	:	Prototype inverter cost	\$
CINVF	:	Mass-produced inverter cost	\$
CLTS	:	Prototype LTS cost	\$/gallon
CLTSF	:	Mass-produced LTS cost	\$/gallon
CMISC	:	Prototype miscellaneous costs	\$
CMISCF	:	Mass-produced miscellaneous costs	\$
COAUX	:	Annual cost of auxiliary oil	\$
COCONV	:	Annual conventional oil cost	\$
COIL	:	Undelivered oil cost	\$/kWh
COILAV	:	Average undelivered oil cost based on escalation rate over amortization period	\$/kWh
CONVE	:	Conventional electric system costs	\$
CONVG	:	Conventional gas system costs	\$
CONVO	:	Conventional oil system costs	\$
CRC	:	Cost of Rankine Cycle subsystem	\$
CRECT	:	Rectifier cost	\$
CSTAT	:	Prototype WTG stationary parts cost	\$
CSTATF	:	Mass-produced WTG stationary parts cost	\$
CTHTS	:	Total prototype HTS cost	\$
CTHTSF	:	Total mass-produced HTS cost	\$
CTLTS	:	Total prototype LTS cost	\$
CTLTSF	:	Total mass-produced LTS cost	\$
CTOT	:	Total prototype wind system costs	\$

CTOTF	:	Total mass produced wind system costs	$
CTWR	:	Prototype tower costs	$/ft
CTWRF	:	Mass produced tower costs	$/ft
CWND	:	Prototype WTG costs	$
CWNDF	:	Mass-produced WTG costs	$
D	:	WTG blade diameter	ft
EAUX	:	Auxiliary energy to be supplied electrically	kWh
ECNV	:	Conventional system energy to be supplied electrically	kWh
EFF	:	Efficiency of fuel heat delivery system	---
GAUX	:	Auxiliary energy to be supplied by gas	kWh
GCONV	:	Conventional system energy to be supplied by gas	kWh
HTS	:	HTS tank size	gallons
HT	:	WTG tower height	ft
I	:	Interest rate	---
LTS	:	LTS tank size	gallons
N	:	Amortization period	yrs
OAUX	:	Auxiliary energy to be supplied by oil	kWh
OCONV	:	Conventional system energy to be supplied by oil	kWh
QAUXY	:	Annual auxiliary space heating load	kWh
QHLY	:	Annual space heating load	kWh
R	:	Annual cost factor	---
RC	:	Rankine Cycle output capacity	kW
RCHP	:	Rankine Cycle output capacity	HP
RI	:	Annual fuel cost escalation rate	---
TCAUX	:	Total annual costs for auxiliary energy	$

TCCONV	:	Total annual conventional energy costs	$
TQHWY	:	Annual domestic hot water load	kWh
WEAUXY	:	Annual auxiliary electrical load	kWh
WEY	:	Annual electrical load	kWh
WHWAUXY	:	Annual auxiliary domestic hot water load	kWh
Z	:	Sums to 20 year electricity costs	$
ZZ	:	Sums to 20 year oil costs	$
ZZZ	:	Sums to 20 year gas costs	$

```
PROGRAM WSDECO(INPUT,OUTPUT)
INTEGER AUXOPT,SYST,TYPINV
REAL LTS,N,I
PRINT 510
510 FORMAT(*INPUT ELECTRICAL, SPACE HEATING *
+*AND DOMESTIC HOT WATER LOADS*)
READ,WEY,QHLY,TQHWY
PRINT 512
512 FORMAT(*INPUT AUXILIARY ELECTRICAL, SPACE HEATING *
+*AND DOMESTIC HOT WATER LOADS*)
READ,WEAUXY,QAUXY,WHWAUXY
PRINT 514
514 FORMAT(*INPUT LTS TANK SIZE*)
READ,LTS
PRINT 516
516 FORMAT(*INPUT SYSTEM USED, 1-IWFS, 2-WDTES,TYPE I, *
+*3-WDTES,TYPE II*)
READ,SYST
IF(SYST.EQ.1)GO TO 109
PRINT 518
518 FORMAT(*INPUT HTS TANK SIZE AND RANKINE *
+*CYCLE SIZE (4.KW OR 6.KW)*)
READ,HTS,RC
IF(SYST.NE.3)GO TO 109
PRINT 552
552 FORMAT(*INPUT INVERTER TYPE, 1=GEMINI, 2=ABACUS*)
READ,TYPINV
109 CONTINUE
AUXOPT=0
D=40.
HT=60.
1000 AUXOPT=AUXOPT+1
CEAUX=0.
COAUX=0.
CGAUX=0.
CECONV=0.
COCONV=0.
CGCONV=0.
TCAUX=0.
TCCONV=0.
N=20.
I=.08
CLTS=.88
CLTSF=.55
CHTS=-3.6667E-3*HTS+8.91667
CHTSF=CHTS*.75
BINCT=220.
BINCTF=220.
BLCT=.088
BLCTF=.047
CGEN=2270.
CGENF=880.
CSTAT=4547.
CSTATF=1650.
IF(SYST.EQ.1)315,316
315 IF(WEY.LT.10000.)317,318
317 CINV=710.
CINVF=552.
GO TO 536
318 CINV=1013.
```

```
CINVF=774.
GO TO 536
516 IF(RC.EQ.4.)520,522
520 CINV=710.
CINVF=552.
IF(TYPINV.EQ.2)524,522
524 CINV=5600.
CINVF=1216.
522 IF(RC.EQ.6.)526,528
526 CINV=1013.
CINVF=774.
IF(TYPINV.EQ.2)530,528
530 CINV=7900.
CINVF=1816.
528 IF(RC.EQ.4.)532,534
532 CALT=1020.
CALTF=660.
GO TO 536
534 IF(RC.EQ.6.)538,536
538 CALT=1135.
CALTF=740.
536 CONTINUE
IF(RC.EQ.4.)540,542
540 CRECT=100.
GO TO 544
542 CRECT=100.
544 CONTINUE
CMISC=350.
CMISCF=250.
CTWR=50.
CTWRF=22.
RCHP=RC*1.341
CRC=135.*(7.+1.5*(RCHP-1.))
IF(RC.EQ.0.)CRC=0.
R=I/(1.-1./(1.+I)**N)
CWND=BINCT+BLCT*D**3+CSTAT+CTWR*HT+CGEN
IF(D.EQ.0.)CWND=0.
CTLTS=CLTS*LTS
CTHTS=CHTS*HTS
CTOT=CWND+CTLTS+CTHTS+CRC+CINV+CALT+CRECT+CMISC
IF(SYST.EQ.1)CTOT=CWND+CTLTS+CINV+CRECT+CMISC
IF(SYST.EQ.2)CTOT=CWND+CTLTS+CTHTS+CRC+CALT+CMISC
ACST=CTOT*R
CWNDF=BINCTF+BLCTF*D**3+CSTATF+CTWRF*HT+CGENF
IF(D.EQ.0.)CWNDF=0.
CTLTSF=CLTSF*LTS
CTHTSF=CHTSF*HTS
CTOTF=CWNDF+CTLTSF+CTHTSF+CRC+CINVF+CALTF+CRECT+CMISCF
IF(SYST.EQ.1)CTOTF=CWNDF+CTLTSF+CINVF+CRECT+CMISCF
IF(SYST.EQ.2)CTOTF=CWNDF+CTLTSF+CTHTSF+CRC+CALTF+CMISCF
ACSTF=CTOTF*R
N=20.
IF(AUXOPT.GT.1)GO TO 427
PRINT 632
632 FORMAT(8X,4HCWND,11X,4HCTOT,11X,4HACST)
PRINT 110,CWND,CTOT,ACST
PRINT 634
634 FORMAT(7X,5HCWNDF,10X,5HCTOTF,10X,5HACSTF)
PRINT 120,CWNDF,CTOTF,ACSTF
427 CONTINUE
```

```
CELECT=.045
RI=.06
EFF=.95
CONVE=1650.
ACONVE=CONVE*R
IF(AUXOPT.EQ.1)EAUX=WEAUXY+QAUXY+WHWAUXY
IF(AUXOPT.EQ.1)ECNV=WEY+QHLY+TQHWY
IF(AUXOPT.EQ.2)EAUX=WEAUXY
IF(AUXOPT.EQ.2)ECNV=WEY
IF(AUXOPT.EQ.3)EAUX=WEAUXY
IF(AUXOPT.EQ.3)ECNV=WEY
Z=0.
EJ=0.
249 EJ=EJ+1.
CELCTI=((1.+RI)**EJ)*CELECT
Z=Z+CELCTI
IF(EJ.EQ.N)250,249
250 CONTINUE
CELAV=Z/N
CEAUX=EAUX*CELAV/EFF
CECONV=ECNV*CELAV/EFF
IF(AUXOPT.EQ.1)GO TO 500
IF(AUXOPT.EQ.3)GO TO 400
COIL=.0117
RI=.07
EFF=.55
CONVO=1980.
ACONVO=CONVO*R
OAUX=QAUXY+WHWAUXY
OCONV=QHLY+TQHWY
ZZ=0.
EJG=0.
299 EJG=EJG+1.
COILI=((1.+RI)**EJG)*COIL
ZZ=ZZ+COILI
IF(EJG.EQ.N)300,299
300 CONTINUE
COILAV=ZZ/N
COAUX=OAUX*COILAV/EFF
COCONV=OCONV*COILAV/EFF
GO TO 500
400 CGAS=.012
RI=.08
EFF=.65
CONVG=1870.
ACONVG=CONVG*R
GAUX=QAUXY+WHWAUXY
GCONV=QHLY+TQHWY
ZZZ=0.
EJGM=0.
409 EJGM=EJGM+1.
CGASI=((1.+RI)**EJGM)*CGAS
ZZZ=ZZZ+CGASI
IF(EJGM.EQ.N)410,409
410 CONTINUE
CGASAV=ZZZ/N
CGAUX=GAUX*CGASAV/EFF
CGCONV=GCONV*CGASAV/EFF
500 TCAUX=CEAUX+COAUX+CGAUX
TCCONV=CECONV+COCONV+CGCONV
```

```
IF(AUXOPT.EQ.1)PRINT 600
IF(AUXOPT.EQ.2)PRINT 601
IF(AUXOPT.EQ.3)PRINT 602
PRINT 611
611 FORMAT(6X,6HCECONV,9X,6HCOCONV,9X,6HCGCONV,
+9X,6HTCCONV)
PRINT 610,CECONV,COCONV,CGCONV,TCCONV
PRINT 621
621 FORMAT(7X,5HCEAUX,10X,5HCOAUX,10X,5HCGAUX,
+10X,5HTCAUX)
PRINT 620,CEAUX,COAUX,CGAUX,TCAUX
IF(AUXOPT.EQ.1)700,710
700 CANCOV=ACONVE+CECONV
CANSDS=ACST+ACONVE+CEAUX
CANSDSF=ACSTF+ACONVE+CEAUX
GO TO 800
710 IF(AUXOPT.EQ.2)720,730
720 CANCOV=CECONV+ACONVO+COCONV
CANSDS=ACST+CEAUX+ACONVO+COAUX
CANSDSF=ACSTF+CEAUX+ACONVO+COAUX
GO TO 800
730 CANCOV=CECONV+ACONVG+CGCONV
CANSDS=ACST+CEAUX+ACONVG+CGAUX
CANSDSF=ACSTF+CEAUX+ACONVG+CGAUX
800 CONTINUE
PRINT 801
801 FORMAT(6X,6HCANCOV,9X,6HCANSDS,9X,7HCANSDSF)
PRINT 900,CANCOV,CANSDS,CANSDSF
IF(AUXOPT.LT.3)GO TO 1000
110 FORMAT(4(5X,F10.2))
120 FORMAT(4(5X,F10.2))
600 FORMAT(◆ELECTRICITY◆)
601 FORMAT(◆OIL◆)
602 FORMAT(◆GAS◆)
610 FORMAT(4(5X,F10.2))
620 FORMAT(4(5X,F10.2))
900 FORMAT(3(5X,F10.2))
END
```

APPENDIX D

ENERGY FLOW DIAGRAMS

Energy flow diagrams for each run of the WDTES1 program are shown in this appendix. The variables listed are defined in Appendix B, and the yearly values given for them represent energy flow in kWh unless otherwise stated. The flow of energy to the various components and loads was beneficial in determining the effects on a specific system, of variations in the parameters considered (i.e. HTS tank size, electrical load, fraction of maximum Rankine Cycle efficiency, etc.). Because of this and because a large amount of information can be represented in a fairly simple form, diagrams of this type should be used to study advanced wind furnace and possibly other types of solar energy systems.

Only one example output form is shown - the others are kept on file in the Mechanical Engineering Department at the University of Massachusetts.

IWFS
500 GAL. LTS
Home ELECTRICAL LOAD
40 FT. WIND MACHINE
TOTAL AUXILIARY ENERGY
REQUIRED = 4968.0