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Load Research Manual

Volume 3: Load Research for Advanced Technologies

U. S. Department of Energy
Economic Regulatory Administration
Office of Utility Systems

Argonne National Laboratory
Energy and Environmental Systems Division

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LOAD RESEARCH MANUAL

Volume 3: Load Research for Advanced Technologies

prepared by

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C. Grund, Jr.	Southern Company Services, Inc.
J. Leo	Middle South Services, Inc.

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FOREWORD

This manual will assist electric utilities and state regulatory authorities in investigating customer electricity demand as part of cost-of-service studies, rate design, marketing research, system design, load forecasting, rate reform analysis, and load management research. Load research also can be useful in determining the cost-effectiveness of time-of-day rates and load management. These types of studies and other conservation-related measures are being encouraged by the Department of Energy's Economic Regulatory Administration. The manual reviews the state of the art of load research and presents technical guidelines for implementing a load research study. Special attention is given to the concerns of small utilities that have no previous load research experience and to issues raised by the reporting requirements of Section 133 of the Public Utility Regulatory Policies Act (PURPA) of 1978, described in the Code of Federal Regulations (CFR), Title 18, Chapter 1, Subchapter K, Part 290,* Subpart D.

Volume 1 of this three-volume manual, entitled Load Research Procedures, includes an Executive Summary that presents an overview of load research procedures and PURPA requirements. Chapter 1 of this volume reviews the state of the art of load research techniques and describes a procedural framework within which load research can be conducted. An interpretation of PURPA requirements for reporting load data is presented in Chapter 2. Chapter 3 discusses load research problems faced by small utilities, which generally are relatively inexperienced in load research.

Volume 2, Fundamentals of Implementing Load Research Procedures, describes load research procedures in detail (Chapter 1). Chapter 2 of this volume compares ongoing load research programs at three utilities: Carolina Power and Light Company, Long Island Lighting Company, and Southern California Edison Company. Chapter 3 presents conclusions and suggestions regarding the implementation of load research programs. A load research bibliography and glossaries of load research and statistical terms are also included in Vol. 2.

Volume 3, Load Research for Advanced Technologies, deals with solar, wind, and cogeneration technologies. This volumes takes an engineering approach to load research for these emerging technologies.

Those inexperienced in load research should benefit from first obtaining an overview of the state of the art (Vol. 1, Chapter 1), then reviewing ongoing practices (Vol. 2, Chapter 2) and technical procedures (Vol. 2, Chapter 1), and finally reading the suggestions in Vol. 2, Chapter 3. Staff members of small utilities should also read Vol. 1, Chapter 3, which may help them set up a small load research program to comply with PURPA requirements. The more experienced practitioner may prefer to use this manual as a guidebook, using the extensive cross referencing of chapters provided. Utilities

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*Part 290 is titled "Collection of Cost of Service Information under Section 133 of PURPA 1978." The regulations contained in Part 290 were issued by the Federal Energy Regulatory Commission as Order 48 (docket RM 79-6), originally issued September 28, 1979, and revised January 4, 1980.

that intend to incorporate new power generation technologies will find Vol. 3 useful. This manual attempts to discuss important issues, describe likely problems, and suggest useful guidelines. However, the procedures of the manual should not be unquestioningly adhered to, and load researchers should attempt to incorporate additional advice from utilities, other reports, and professional organizations.

This manual discusses present utility load research practices and problems. New load research techniques and equipment will of course evolve. Therefore, some discussions herein will inevitably become outdated and should be read with caution in future years.

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LOAD RESEARCH MANUAL

Volume 3: Load Research for Advanced Technologies

ABSTRACT

This three-volume manual presents technical guidelines for electric utility load research. Special attention is given to issues raised by the load data reporting requirements of the Public Utility Regulatory Policies Act of 1978 and to problems faced by smaller utilities that are initiating load research programs. In Volumes 1 and 2, procedures are suggested for determining data requirements for load research, establishing the size and customer composition of a load survey sample, selecting and using equipment to record customer electricity usage, processing data tapes from the recording equipment, and analyzing the data. Statistical techniques used in customer sampling are discussed in detail. The costs of load research also are estimated, and ongoing load research programs at three utilities are described. The manual includes guides to load research literature and glossaries of load research and statistical terms. In Volume 3, special load research procedures are presented for solar, wind, and cogeneration technologies.

1 INTRODUCTION

1.1 OBJECTIVE

This volume describes the special load research requirements of advanced technologies, mainly solar energy, wind, and cogeneration systems, and presents plans for gathering data on the load characteristics of these systems. The problems of sample design, instrumentation, data acquisition, and interpretation that are common to load research on conventional electrical systems are treated in Vols. 1 and 2 of this manual. Therefore, the discussion of these subjects will not be repeated except when necessary to avoid confusion.

1.2 DEFINITION OF SOLAR, WIND, AND COGENERATION TECHNOLOGIES

Solar, wind, and cogeneration technologies range from systems still in the developmental stage to those already commercially available. Only the latter are of concern here, because only those systems being commercially introduced now will be of practical concern to electric utilities in the next 10-15 years. To allow a treatment of this subject in sufficient depth, the discussion is limited to:

- Solar - active space and water heating systems
- Wind - wind power plants for individual residential and small multi-unit residential or commercial buildings

- Cogeneration - internal combustion engine, steam turbine, and combustion gas turbine systems, including total energy plants

With this limitation, systems such as absorption or Rankine-cycle solar cooling, photovoltaic systems, and Stirling engines as drivers for generators are excluded from consideration. However, mention will be made of constraints that apply to these more advanced technologies. Most of the discussion is applicable to these systems as well. Where applicable, thermal storage will be considered in conjunction with solar heating systems.

1.3 SPECIAL LOAD RESEARCH PROBLEMS

Undertaking a load research project on solar, wind, and cogeneration systems on the customer's premises may present special problems because of:

- The evolving nature of these technologies, as manifested by the great heterogeneity in system configuration, operating and control characteristics, back-up schemes, and storage systems
- The lack of enough installations of any one kind of system in any one location to permit statistically adequate sampling for extrapolation purposes or even the instrumentation of enough replicate installations to verify the precision of measurements
- General unfamiliarity of utility personnel with the methods of design and performance analysis applicable to these systems

The general objectives of undertaking load research on conventional technologies -- to provide data for load forecasting, system planning, cost-of-service analysis for rate design, and new technology cost-benefit and feasibility analysis -- apply to solar, wind, and cogeneration systems as well. These objectives are discussed in the previous volumes of this manual. As utilities are required by law (PL 95-617) to offer reasonable rates to customers using solar and other renewable-resource and energy-conserving technologies, data acquisition for cost-of-service analysis is likely to be one of the most important immediate objectives of load research on these technologies.

In the past, the approach to electrical load research has been largely empirical. The usual experimental plan has been to:[1]

- Design a plan for the simple or stratified random sampling of the customer population, to adequately represent in the sample all types of users that contribute to demand and to spread the sampling error more or less evenly across all classes

- Install demand survey instruments on sample customers' equipment and collect 15-, 30-, or 60-min integrated demand data over a sufficiently long period of time, frequently more than a year
- Simultaneously monitor appropriate environmental variables (e.g., outdoor temperature for residential total service loads)
- Collect related information on customer characteristics (e.g., type of structure, design heating or cooling load, floor area of building, indoor temperature set point)
- Compute a number of statistical demand parameters (e.g., coincidence and load factors, maximum diversified demand per customer, etc.) for monthly, seasonal, and annual intervals and compile demand profiles and other data for peak and average demand days, weeks, etc.
- Correlate demand data with selected independent variables measured simultaneously (e.g., daily maximum diversified demand versus daily outdoor temperature)

For the technologies under consideration here, the approach outlined above may not be feasible. The heterogeneity of the system concepts, configurations, operating and control modes, and other characteristics may make statistical sampling impractical. Moreover, there can be no question of statistical sampling and metering if there are only a few "one-of-a-kind" installations, or none at all, in the utility territory. Unfortunately, there is no thoroughly proven method that is applicable to this situation. However, one possible approach is as follows: (1) select one or more existing installations or construct and thoroughly instrument a "typical" installation, (2) develop a mathematical demand simulation model and verify it on the basis of the experimental data, and (3) generalize or extrapolate the simulation model results by use of an appropriate Monte Carlo or other averaging scheme to represent the behavior of a sufficiently large class of customers equipped with the systems. This method is still developmental, but initial results indicate that it may have some promise.

Experimental load research may be divided into two basic types: controlled or "laboratory-type" experiments and uncontrolled or "field" observations. In the former (which need not be confined to an actual laboratory in the strict sense of the term), a device or system is constructed or installed and instrumented for the purpose of taking experimental observations under conditions where all independent variables and parameters judged to significantly affect the dependent variable or variables (usually the demand) are measured or controlled.* Barring systematic instrument biases and human errors, errors in well-designed laboratory experiments are mainly the result

*These independent variables and parameters are usually identified on the basis of a theoretical analysis, albeit simplified or idealized, of the physical phenomena underlying the operation of the equipment and the environmental or demographic factors that affect its use.

of limitations of instrument resolution and calibration drift.* The results of a well-designed and accurate laboratory experiment generally yield engineering information about equipment or system performance under controlled conditions. Even life-style effects can be imposed on the system to some extent by clever experimental design. In one case, an experimental solar water heater was tested in the laboratory by being operated simultaneously with a conventional water heater in a residence. When hot water was used by the residence, a signal caused a similar quantity of water to be drawn from the experimental unit. This represented water heater operation with real random "forcing."

Field observations, on the other hand, usually involve instrumenting existing installations and measuring their response to the major environmental and operator variables that affect them under expected operating conditions. In this case, the observer may be able to exercise little if any control over some of the factors influencing the dependent variable and, in the extreme but all-too-frequent situation, not even have sufficiently precise information on some of these factors. The critical difference between a field and a laboratory experiment frequently lies in the interpretation of the results. A laboratory experiment is run to determine experimentally the equipment efficiency, jacket losses, transient response to changes in use, etc. A load research field experiment is usually conducted to yield data on customer class demand. This demand may be as much due to random life-style effects as to the technical characteristics of the environment and may not be easily relatable to the environmental variables or customer characteristics measured. In the extreme case, the particular technology in question may actually be irrelevant as long as the load under study is, for example, the space heating load of single-family residential customers. The present state of knowledge, however, does not yet permit such total "decoupling" of customer behavior and end-use/generation system technology.

Utility load research usually falls into the "field study" category. For example, in studying the demand characteristics of residential electric water heaters under field conditions, the experimenter generally exercises no control over the pattern of hot water use by the inhabitants of the installation being monitored. Usually a large enough number of installations must be monitored to constitute an adequate statistical sample of the class of loads being measured. A laboratory experiment on water heaters, on the other hand, may vary hot water withdrawals under known and controlled conditions if its purpose is to study the water heater peak demand, capacity, or efficiency, or to verify a predictive or correlative mathematical model of the system, or both. In this case only a minimum number of replicates (sometimes only one) of the water heaters need to be measured to assure validity of the data. However, a number of replicate measurements under all test conditions are usually taken to assure sufficient precision of the results.

Due to the complex nature of most solar energy, wind, and cogeneration systems and their insignificant market penetration, most utility load research projects will probably have to combine the features of both laboratory and

*Probably a more important source of error is the failure to identify and control all of the significant independent variables, but that is as much a problem of present theoretical understanding of the physical phenomena as a problem of experimental design.

field experiments. Laboratory-type experiments under controlled conditions may have to be carried out to understand the system's operating principles and to obtain data on its efficiency and reliability before undertaking field testing on customers' premises. Regardless of the type of project being planned or conducted, however, it is important to identify and properly measure all independent variables and parameters that are believed to have a significant effect on the demand being studied. Unless this is properly done, interpretation and generalization of the data obtained may be difficult or even impossible. Identification of the appropriate independent variables and parameters usually requires some theoretical understanding of the physical principles and customer life-style factors influencing system operation. Idealized models may be helpful also, even if a given system is too complex to analyze rigorously.

2 LOAD RESEARCH METHODOLOGY

2.1 PLANNING THE LOAD RESEARCH PROJECT

Perhaps the first question to be asked in designing a load experiment is: How will the data be used? If load data are to be acquired for load forecasting and capacity planning, generalization and extrapolation of the sample results to the entire utility system usually are required. In this case, the extrapolation method needs to be determined at the outset of the project so that all pertinent variables will be measured. Cost-of-service analysis in support of rate design imposes a requirement that the data base be truly representative of the customer class demand and energy use. This may mean 100% sampling of some customers with new technologies.

A cost-benefit or technical feasibility study of new as compared to conventional technology, on the other hand, may be conducted by comparing one or more of the new solar, wind, or cogeneration systems to a conventional system. In this case an extensive program of random statistical sampling of many field installations may not be necessary. Instead, the emphasis may be placed on obtaining the maximum amount of engineering data for assessment of system performance under a variety of environmental and use conditions. Nevertheless, some generalization to the utility system as a whole is still desirable.

Once the project objectives have been defined, the next task is to determine whether enough installations of the appropriate system exist in the utility service area. For solar water and space heating, there may be enough installations in some areas. This is less likely to be true for wind energy and cogeneration systems, unless 100% sampling is contemplated.

2.1.1 Research Approach if Random Sampling of Existing Installations Is Possible

If enough installations of the specific load to be tested are available, the well-established methods of simple or stratified random sampling apply (see Vol. 2, Chapter 1). To summarize this approach, the sample size is determined by requiring that the sample average energy use be within a preset tolerance limit of the time-averaged energy use of the population (or subpopulation) with a probability of at least a preselected (usually high) value.

If the objective of the contemplated load survey is to obtain data on existing solar water or space heating installations, wind plants, or cogeneration systems, these systems may be taken to constitute distinct strata or subclasses and the required sample size determined. The results could be considered representative of the technology and configuration mix in the sample and perhaps even could be extrapolated to higher saturations with the assumption that the mix will not change. This method should work for customers with flat-plate collector solar water heating systems, small propeller-type wind plants, and even small diesel generators. Solar space heating systems and large cogeneration installations using steam or gas turbines may not be as homogeneous in their demand and energy use characteristics and thus less amenable to this method.

The typical sequence of tasks in a random customer sample metering scheme is depicted in Figure 1. There is, of course, no typical utility; nor is it possible to devise a study plan applicable to all cases. The outlined sequence is, therefore, a purely hypothetical one. For more information on load research methods, consult Refs. 2, 3, and 4 and the bibliography in Vol. 2 of this manual.

2.1.2 Research Approach if Random Sampling of Existing Installations Is Not Possible

In many cases statistical random sampling and test metering of advanced electricity end-use or generation technologies will not be feasible because of an insufficient number of similar installations in a utility service area. In this situation, the following alternatives remain:

- Obtain data from a recent or current experiment by another (preferably similar) utility, calibrate (if possible) by constructing or instrumenting one or more test installations in own territory, and extend results to own system.
- Construct and instrument new or suitable existing test installation(s) and generalize data to system as a whole.

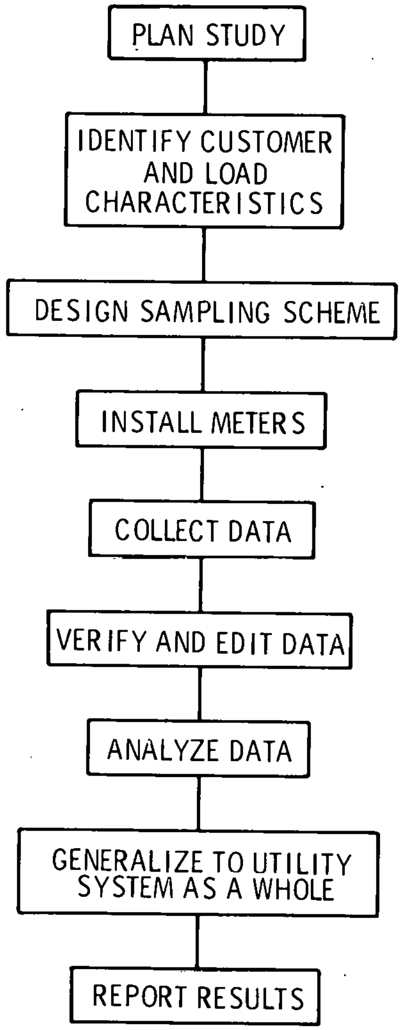

Fig. 1 Principal Tasks in Typical Load Research Study (source: based on Ref. 1)

The major difference between the two approaches narrows down to the question of how to account for expected demand diversity with large numbers of customers equipped with the system under study. One method used when conventional electric heat pumps were still "new" technology was to assume that the single-family residential heating load class coincidence factors were essentially independent of the particular heating, ventilating, and air conditioning (HVAC) technology involved and depended more on the demographic and structural characteristics of the customer class. This was the approach adopted by Bary[5] of the Philadelphia Electric Company in analyzing results of experiments on load characteristics of electric heat pumps. To estimate the cost of service of the residential electric heat pump load, Bary assumed that the intraclass coincidence factor of this load would be the same as that of the company's residential gas heating customers. Sporn and Ambrose[6] also interpreted the results of demand measurements on single heat pump units using literature data on electric resistance and gas heating coincidence factors.

Work by Gordian Associates, however, indicates that the approach is a questionable one, principally because data on coincidence factors of specific loads are rather unreliable.*

An alternative and still developmental method would be to use some random selection procedure to establish a "sample" of pertinent customer characteristics and then use a computer model to simulate transient demand profiles for the customer loads in the sample. This approach is clearly predicated on the availability of a reliable and efficient (and experimentally validated) simulation model of the solar, wind, or cogeneration system to be studied. More will be said about this approach in Sec. 2.3.2 of this volume. Sometimes, however, a more limited load experiment may be adequate. Such an experiment could compare the solar energy, wind, or cogeneration system with electrical back-up or net generation to a conventional system using utility power, in a technical feasibility analysis. It is clearly desirable to "control" the exogenous variables that may affect the comparison. Three methods have been used in the past:

- Install the experimental system and the conventional system in parallel in the same structure or facility and operate both at frequent intervals.
- Install the control system in a given structure and take data over a period of time (e.g., one or two months, one complete heating and cooling season), then replace it with the experimental unit and repeat the data acquisition for approximately the same length of time.
- Install the experimental system and the control system in two structures that are as similar as possible (e.g., neighboring houses in a development, apartments located in the same building) and gather data on both systems simultaneously.

The last is the least preferred but perhaps the simplest method. It is least preferred because customers' occupancy schedules and electrical appliance or equipment usage habits or schedules play so large a role in determining demand and energy usage that it is impossible to duplicate exactly conditions of the experimental and the control systems. It is far more preferable to test the systems in the same installation, if this is possible, but even then a method must be devised for equalizing the random variations of weather, occupancy, production rate, or other factors from one measurement period to another. This usually requires some theoretical understanding of the concept and operation of the system and the installation site. For example, daily degree-hours have been used to correct heating load variations from one day to another in a recent study of residential electric heat pump demand characteristics.[7] However, in the analogous cooling case, use of dry bulb cooling degree-hours may not work as well because the cooling load also

*For example, the monthly coincidence factor based on 30-min integrated demand for residential electric heating and air conditioning systems appears to vary with monthly heating and cooling degree-days or other environmental variables, but this variation is difficult to quantify because of the considerable scatter in the data (e.g., the range is 60-90% for central air conditioners).

depends on humidity and insolation. Therefore, to ensure that the experiment will yield the data necessary for the proposed method of analysis, that method should be determined and perhaps even tested before any instruments are installed or metering is begun.

2.2 DATA ACQUISITION

2.2.1 Instrumentation and Measurements

Much utility load research has involved the measurement of electrical power, energy use, temperature, and, sometimes, the rainfall and hours of daylight (see Vol. 2, Chapter 1). Solar heating, wind energy conversion, and cogeneration load research requires at least the determination of insolation, wind speed (and direction), and steam or hot water flow rates if the results are to be interpreted properly. More-recent research (see, for example, Refs. 8 and 9) has increasingly recognized the value of "getting the most mileage" out of the data by more-extensive instrumentation of the test customers. This may mean multipoint temperature measurements as well as measurement of humidity, diffuse and total solar irradiation, surface temperature, torque, rotational speed, and other variables. There are many sources of information on measuring instruments and their operating principles. Some of the more comprehensive sources are:

- ASHRAE Handbook and Product Directory - 1977 Fundamentals,[10] Chapter 13, has extensive references to the literature, and the product directory section lists manufacturers of instruments.
- Mark's Standard Handbook for Mechanical Engineers,[11] Chapter 15.
- Manufacturers' catalogs. Some publish extensive data on methods of temperature, flow, and other physical measurements and give equipment specifications and ordering information.
- Specific monographs on the measurement of power, temperature, flow, etc.

This section will not attempt to discuss the specific instrumentation available for measuring and recording load data but will focus, instead, on some general principles and sources of metering error.

The extent of instrumentation needed for a solar, wind, or cogeneration system depends on the:

- Specific data acquisition objectives
- Size of the sample
- Metering equipment the utility already has available
- Funds available for purchasing new metering instruments and related equipment

Clearly, a project that measures the demand of solar water heaters belonging to a comparatively large sample of customers requires a different approach than a more limited comparison of an office building with a diesel cogeneration system to one using utility power. A project having as its objective end-use system efficiency analysis imposes different instrumentation requirements than one where only the usual statistical demand parameters (e.g., maximum diversified demand, load factors based on diversified demand, etc.) are to be measured. Although it is impossible to establish all-encompassing rules for test-site instrumentation for solar, wind, or cogeneration systems, the following five points should be considered by load researchers selecting an instrumentation plan.

First, considerations of cost and use of equipment already available will probably always enter into instrumentation planning. However, it makes no sense to monitor a dependent variable such as demand and not the independent variables that influence it. For space heating, this means measuring the actual space-average indoor temperature as well as outdoor temperature; for water heating, cold water inlet and hot water supply temperature must be measured as well as flow rate.

Second, a poor measurement is worse than none at all, as it may mislead the analyst and introduce greater uncertainty into the data. For example, since building conduction and sensible infiltration heat loss and gain are, to a first approximation, functions of the indoor-outdoor temperature difference, it is the true space-average indoor temperature that must be measured to allow proper interpretation of experimental results. Location of the sensor in the return air duct, unless its reading there has previously been correlated experimentally with the space temperature, is useless and misleading. As another example, wind speed and direction for evaluation of infiltration should be measured at the experimental site and under circumstances that the structure is exposed to, not at a distant airport.

Third, equipment cycling should be taken into account in designing the data acquisition scheme. If 15- or 30-min averaging is used, it should be recognized that temperature sensors located in air ducts passing through attics or basements or in cold or hot water pipes will give erroneous readings if the blower or pump stops during the integration interval and the temperature of the stagnant fluid begins to drift toward the ambient temperature. Recording of blower and water pump on and off times may be used to sort out valid temperature data in these situations.

Fourth, instrument breakdowns or sensor failures should always be anticipated and some back-up system or independent checks provided. One obvious example is the importance of checking the monthly energy consumption data recorded on a magnetic tape survey meter installed at a test site against the reading of the watt-hour meter, if the meter reader notes the exact time of the meter reading.[1] A more subtle example of an internal check is measuring water tank temperature rise as a check on collector heat absorption calculated from fluid inlet and outlet temperature and flow rate readings. These checks are only possible if some redundancy in instrumentation is provided.

Fifth, complicated multipoint data logging systems will always require an inordinate amount of time to "debug." Consistent failures of one or more key components of the scheme frequently will bring the experiment to a halt until more-permanent repairs are made or a replacement found. This may mean the loss of several months or an entire season of experimentation and should be anticipated in the plan. In instrumenting a few installations with a sophisticated data-gathering scheme, the drain on the time of technicians and engineers should be recognized. In the end, only persistence in systematic trouble-shooting and checking by someone intimately familiar with the instrumentation scheme will pay off.

2.2.2 Data Sampling versus Averaging

Sampling of a physical variable at preset intervals means measuring the instantaneous value of the variable. Averaging or totaling the variable at preset intervals means that the quantity recorded is the time-integrated value over the recording interval. The two are obviously not the same. Both methods are used in load research, but 15-, 30-, or 60-min averaging is the usual approach. This and the data recording interval have important consequences in the interpretation of the results.

Recording equipment is available for automatic acquisition of physical data at intervals ranging from a few seconds to the standard 5-, 15-, or 30-min averaging intervals of load survey magnetic tape recorders.* Analog data recording of continuous signals is limited essentially only by the response time of the sensor-transducer system; digital system sampling rates can be as high as 1000 data per second. Nevertheless, traditional utility load survey practice has been to acquire 15- or 30-min integrated demand data that, for analytical purposes, are often converted to hourly data. The choice of the interval has been dictated in part by standardized time pulse frequencies of survey equipment commercially available and in part by the large quantities of data typically acquired in a load survey.

Since residential HVAC and water heating equipment, the major residential electric loads, and many commercial loads cycle at intervals much shorter than 15 min, the effect of time averaging on the results should be clearly understood by the researcher. Although a rigorous analysis is beyond the scope of this discussion, some intuitive arguments are possible.

If the data are averaged over intervals of Δt, no information is obtained on time-varying phenomena with cycling frequencies higher than $1/\Delta t$. This usually means that even 15-min integrated data cannot be used to validate a model of thermostat or HVAC equipment cycling.

The magnitude of some demand statistical parameters used to characterize the results may depend on the averaging period. For example, if the 15-min noncoincident maximum demand of a house with solar heating supplemented by electric resistance heating is 13 kW and the connected load is 19 kW, the instantaneous demand during the peak period may have reached any value from 13 kW to 19 kW. Indeed, studies have indicated that maximum 15-min average heating demand is generally as much as 20% greater than 30-min average demand which, in turn, may be 20% greater than 60-min average demand.[2] Consider,

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*If low disk-revolution to pulse ratios are used, data resolution into shorter averaging periods is possible.

then, what might happen to the coincidence and load factors as the averaging period is increased. If many customer loads are being monitored, it is probable that the maximum diversified demand of the group on a per-customer basis will grow only slightly as the averaging time is decreased whereas the likelihood of encountering a higher value of individual (noncoincident) peak demand will increase significantly. This means that measures of intraclass diversity such as the coincidence factor will decrease as the integration interval is decreased and will reach a minimum value when demands are measured instantaneously. Energy use, of course, remains constant regardless of the data averaging period.

Data sampling (without averaging) at equal intervals of t also may be misleading if the phenomena under observation have cycles with a period less than $2\Delta t$.* Figure 2 illustrates the effect of sampling frequency on the shape of the resulting function. In summary, when engineering data on system performance are required, the sampling interval should be at least half and preferably one-fifth the shortest time constant of the system.

2.2.3 Data Recording

Two- or four-channel magnetic tape survey cassette recorders have become the usual method of automatically recording load survey data on conventional electricity end-use systems. Obviously, this method should be considered first for load studies of solar, wind, and cogeneration systems as well, especially if the utility uses tape meters for customer billing or even has a translator in-house. A major advantage of this method is the cost

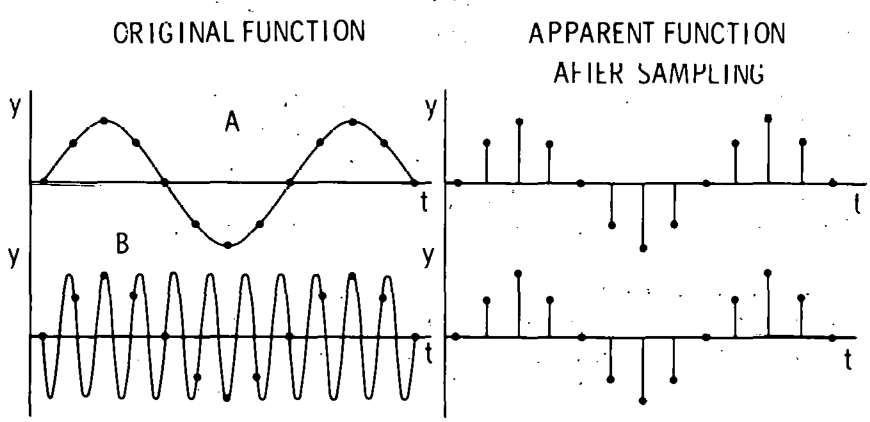

Fig. 2 Effect of Sampling Interval on Information Obtained about a Function (source: D.M. Himmelblau and John Wiley & Sons, Inc., by permission)

*If the function is aperiodic, this statement applies to the harmonics obtained as a result of Fourier analysis of the function.

relative to that of more-sophisticated schemes. However, a four-channel recorder has only three channels and a two-channel recorder only one channel available for data entry, one channel being required for the time tick. Therefore, multiple recorders per test site may be required if, as is desirable, several independent variables as well as demand are measured. For example, a typical solar water heating experiment may require as many as five recorders if all of the important variables required to establish transient energy and mass flow balances around the solar collectors, thermal storage, and water heating systems are monitored. Clearly, some trade-offs are required in the instrumentation plan and multichannel data logging equipment may be more cost-effective at some point. In considering these trade-offs, it is better to err on the side of redundancy because the ability to establish energy and mass flow balances around the system and its major components would enable the calculation of a missing or questionable measurement in the event of a signal failure or other malfunction.

For acquisition of engineering data as part of a cost-benefit or technical performance study, the best procedure usually is to thoroughly instrument one or more sites. In this case, the use of more-sophisticated multichannel analog or digital data logging equipment should be investigated. However, even with the two- or four-channel recorders, data from several channels may be "multiplexed" onto one channel if recorder resolution is high enough. Equipment for doing this is available commercially.

2.3 ANALYSIS AND GENERALIZATION OF LOAD DATA

2.3.1 Empirical Methods

A more-or-less standard format has evolved over the years for analysis and presentation of load research data.[2] The analysis has usually consisted of:

- Computation of statistical demand parameters: load factors, demands, and energy usage per unit such as heated space floor area or design heating load
- Regression analyses of demand and energy use versus each other, versus independent variables such as outdoor temperature, and versus discrete customer characteristics such as family size or appliance saturation

This empirical or regression approach is probably the simplest one. If thermal "memory" effects are neglected, the demand $P_j(t)$ of a customer j at an instant (or in a time interval centered on) t may be represented by a function that is the sum of two deterministic parts and one random part:

$$P_j = E_j(T_o, T_i, I_t, V, W, \ldots) + S_j(t) + \varepsilon(t)$$

where:

E_j = environmental-variable-dependent demand (deterministic),

T_o, T_i = outdoor and indoor dry bulb temperature,

I_t = total insolation,

V = wind speed,

W = humidity ratio,

S_j = operating-schedule-dependent demand (deterministic),

t = time, and

ε = random fluctuations.

The diversified demand imposed on the utility system by a class or group of n customers is given by:

$$P = \Sigma P_j \; (j = 1, \ldots, n)$$

Its maximum over some well-defined time interval $(t_2 - t_1)$ is:

$$P_m = \max P(t) = \max \Sigma P_j(t)$$

As already mentioned, correlating P or P_j with independent variables measured at the same instant neglects the thermal memory of the system. To account for it, the demand at time t may be correlated with environmental variables measured at time $t - \tau$, where τ is determined by repeated analyses of the data and chosen as that value of the time lag giving the highest coefficient of determination (R^2) in the regression analysis.* Most load studies have used only the ambient dry bulb temperature, T_o, the temperature deficiency, $65 - T_o$ or $T_o - 65$ (i.e., number of heating or cooling degree-hours during the period under consideration), or other averages as the regression variable, since almost all loads appear to be temperature-sensitive to a certain extent. Morever, the lack of sufficient precision in even the most carefully obtained field observations usually makes the unique determination of regression coefficients for the other variables very difficult. Nevertheless, it is the failure to determine the other environmental variables, equipment use schedules, and life-style effects that contributes a considerable amount of scatter to the regression data (over and above the errors or data scatter due to sensor errors).

Regression of a demand statistic against environmental variables assumes that a solar heating or other system is either under thermostatic control or otherwise responsive to the environment. Exceptions to this are, of course, obvious. For example, while the amount of solar energy collected and stored is a function of the outdoor temperature and insolation, the rate and frequency of hot water withdrawal by the occupants usually is not. In a process facility hot water use may follow a certain fixed schedule. In this case the environmental dependence, E, may be negligible in comparison to the schedule effects, S, or it may constitute part of the random fluctuation.

This method of data analysis is valid if random sampling of customers is used and data on the current customer load are desired. The method does not go far enough, however, to permit extrapolation to new technologies or changes in customer usage habits. Nor is it applicable if only a few test

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*R^2 is a measure of the agreement of the regression analysis with data. The value of R^2 lies between 0 and 1, with 0 indicating no agreement and 1 indicating perfect agreement.

sites are instrumented and monitored. That is, although correlation of HVAC demand and ambient temperature is still possible for an individual test site, computation of load class statistics clearly is not. This brings up the question of how to generalize and extrapolate the data.

2.3.2 Engineering Simulation

Use of a computerized engineering simulation model is recommended if technical performance data for cost-benefit assessment are required. The approach may be described as follows:

- Develop or otherwise acquire a generalized engineering simulation model of the specific load (e.g., solar water heaters) in question.
- Verify the model and calibrate it, if necessary, using experimental observations.
- Extend the results to other environmental conditions, other manufacturers' equipment, and other control schemes by simulation of the systems not tested.

This is the usual engineering analysis approach. Given a good simulation model, comparison of new and conventional technology should give sufficiently accurate results for estimation of differences in noncoincident peak demand, energy use, and costs of ownership and operation. For example, the solar collector area and thermal storage tank volume per square foot of house area can be optimized in this manner.

In any case, simulation of selected test sites in parallel with load data acquisition is highly desirable. Simulation yields a running analysis of test results and may enable the observer to detect errors or inconsistencies in the data as well as gain a better understanding of the factors that affect customer demand. Since most solar water and space heating, wind turbine, and cogeneration systems are complex and the thermal or electrical demands these systems meet are usually time-varying, time-domain simulation is better able to bring out the "flywheel" effects and other aspects of system operation that quasi-steady-state or "bin"* methods of heating demand (or wind energy supply) analysis ignore. A number of simulation models have been developed and are available either through computer time-sharing networks or for direct purchase, sometimes for the cost of reproducing the documentation only.** These should be investigated if extensive experimentation is planned.

Turning to the problem of extrapolation and generalization of the results to the utility system at large, the engineering simulation approach

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*See Ref. 14 for an explanation of bin methods.

**No recommendations or listings of these models are appropriate here. However, information on HVAC system models is available from the <u>ASHRAE Bibliography on Available Computer Programs</u>,[12] from the American Consulting Engineers Council, and from other professional and industry organizations. For a recent listing see Ref. 13, p. 420.

fails to take into account the usual diversity of customer demographic and structural characteristics encountered in any utility territory and the reduction in peak demand per customer imposed on the system as the result of that diversity. There is no simple solution to this problem, as has been discussed. However, a Monte Carlo simulation method under development by Gordian Associates under Electric Power Research Institute sponsorship may have some merit. It is summarized in the following section.

2.3.3 Monte Carlo Diversified Demand Modeling

Monte Carlo diversified demand modeling attempts to duplicate theoretically what a load survey would accomplish in practice. The method is predicated on the availability of a reliable and efficient computer simulation model that can calculate the time-varying demand profile of an individual customer. The basic steps in the procedure are as follows:

- Characterize, on the basis of theoretical or empirical data, the independent variables and parameters affecting the load and obtain information on the distribution of these characteristics among the appropriate utility classes.
- Set up a matrix containing the customer load characteristics identified above and their probability distributions.
- Set sample size.
- Draw a sample of combinations of the above characteristics using the Monte Carlo method.
- Simulate the above hypothetical customer load profiles using the verified simulation model.
- Add the simulated demand curves and analyze as required.

A schematic diagram of this procedure is given in Figure 3. The application of the method to heat pump demand is discussed in Ref. 15. It should be noted that the Monte Carlo demand simulation method is still under development and has not been thoroughly tested.

2.3.4 Validation of Simulation Models

To insure the scientific validity of the results, all theoretical models used in load research should be validated against measurements from carefully designed and controlled experiments. Although a thorough discussion of simulation model validation is beyond the scope of this manual, the analyst should keep in mind that all mathematical models of physical phenomena involve some assumptions and idealizations. Generally, the more complex the phenomenon in question, the more idealizations are required to make the problem mathematically tractable, even with computers. Therefore, regardless of the specific history of scientific acceptance of any particular algorithm, no credence should be placed in the output of the simulation until the combined effect of the idealizations and modeling procedure is tested. Model validation can be conducted at two basic levels of aggregation:

- Individual algorithms and submodels of the major physical phenomena or energy-exchange mechanisms can be tested in isolation from the overall model by measuring under controlled conditions the phenomena or mechanisms in question.
- The overall simulation model can be validated as a "black box," with its results compared to data on the customer load as a whole.

As an example of the first method, consider a residential solar water heating system consisting of solar collectors, thermal storage, and a water preheating tank. If the system is sufficiently instrumented, it should be possible to validate the collector, storage, and preheating system submodels individually by comparing their output to measured data on the flow rate, temperature, etc. of fluid flowing into and out of each component. When the validity of the submodels is established over the range of temperatures, flows, or stagnation conditions the system is expected to encounter in actual use, the performance of the overall model integrating these algorithms also should be satisfactory. The converse, however, is not true.

It also is possible to validate the overall system model by comparing model output (e.g., system electrical demand) to measured values, given measured values of the inputs to the system: insolation, cold water temperature, etc. Although simpler, this method of model validation yields no information on the accuracy of the individual algorithms used in the model. Even though the overall predicted and measured demands may agree satisfactorily, it should not be assumed that the individual algorithms themselves are valid since there may have been compensating errors. The likelihood of these compensating errors confounding the result may be diminished by increasing the number of test cases; however, at some point the most critical algorithms should be validated if extensive use of the model is contemplated.

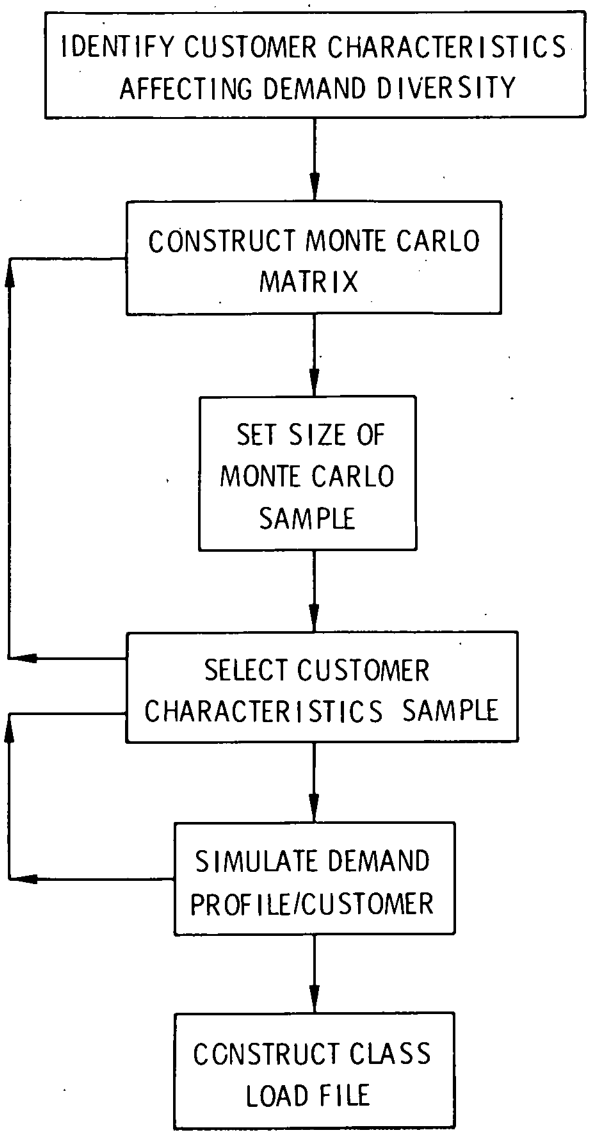


Fig. 3 Monte Carlo Simulation Method for Diversified Demand Estimation

The above statements apply, of course, to engineering simulation models. Models that seek to incorporate life-style or customer usage effects require additional validation against measured data on carefully characterized customers, using statistical sampling and analysis procedures. Considerable ingenuity may be required in devising suitable experimental tests for such models, tests that should examine not only the overall predictive capability of the model but some of the underlying assumptions as well.

As a practical matter, few operating utilities can likely afford the staff time and cost of extensive model validation. Therefore, they should strive to learn which of the models available to them have been sufficiently tested and modify them for their own use, if possible. Industry and professional organizations such as EPRI and ASHRAE are sponsoring programs to survey and test available simulation models. The appropriate publications of these organizations should be consulted for more information.

3 SOLAR WATER AND SPACE HEATING SYSTEMS

This chapter examines typical configurations and example instrumentation schemes for solar water heating and space heating systems. Solar Rankine or absorption cycle cooling is not considered. However, the methods discussed should be applicable, in principle, to those systems as well as to interruptible air conditioning and cool storage.

A review of utility solar energy activities was published in the December 1979 Electric Power Research Institute (EPRI) Journal. EPRI also has published a considerable number of reports about experimental solar projects in progress at various utilities. These should be consulted for details about specific studies. The illustrations in Secs. 3.1 and 3.2 demonstrate that solar water and space heating systems run the gamut from relatively simple residential systems to exceedingly complex multi-unit residential or nonresidential systems. Literature on energy research for solar heated buildings is extensive, and includes the journal Solar Energy, published monthly for the International Solar Energy Society by Pergamon Press, and the journal, transactions, special monographs, and the Handbook and Product Directory - 1978 Applications[16] of ASHRAE. Valuable information on solar water and space heating system design and performance analysis also may be found in Refs. 17-19.

3.1 SOLAR WATER HEATING SYSTEM CONFIGURATIONS

Solar water heating systems can have either natural or forced circulation. In natural-circulation systems, such as the thermosyphon system shown in Figure 4, the fluid circulates due to the density differences that arise when a part of the fluid is heated. The fluid in forced-circulation systems is moved by a pump in the collector loop.

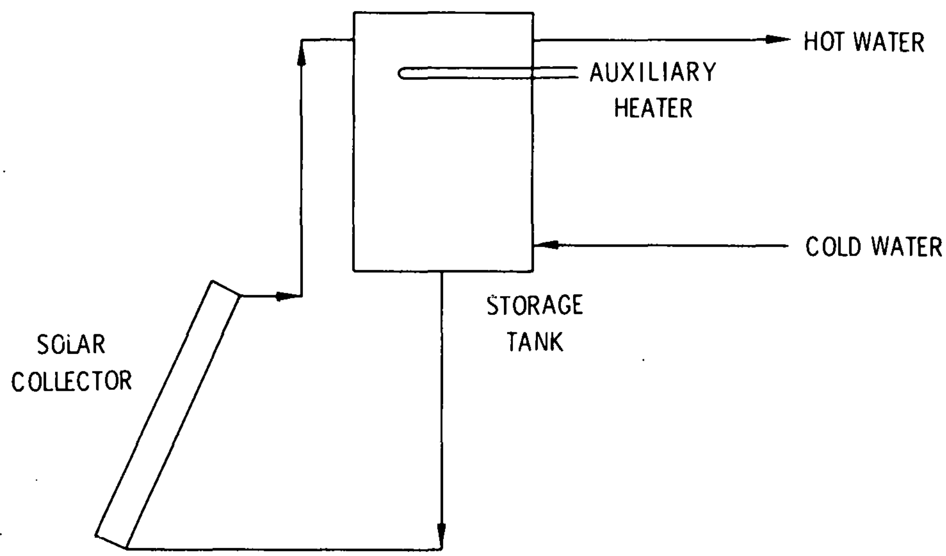


Fig. 4 Natural-Circulation (thermosyphon) Solar Water Heating System

Additional differences in configuration depend on whether the system is a draining or nondraining system. A draining system uses water (with corrosion inhibitors) as the collector and storage fluid and must be drained when the air temperature is expected to fall below freezing. Figures 5 and 6 are examples of one- and two-tank draining systems. One-tank systems use potable water as the collector and storage fluid; two-tank systems use a storage tank to preheat water.

Nondraining systems use a water-glycol mixture or other heat transfer fluid that does not freeze. Again, both one- and two-tank configurations are possible, as shown in Figures 7 and 8.

The water heating systems described above employ circulating liquid collectors. Water also can be heated with an air collector system, which will be discussed in conjunction with solar air space heating systems. (See Ref. 19 for more information.)

3.2 SOLAR SPACE HEATING SYSTEM CONFIGURATIONS

As with solar water heating, a number of solar space heating system configurations are possible. In passive residential heating systems with electric back-up, the back-up systems function in the same way as conventional electric heating systems, but the house demand characteristics may be markedly different from those of a conventional all-electric house due to enhanced absorption and storage of solar heat by the walls. Electric servomotors required to move insulation or drapes, blow beads (in bead walls), etc. in passive structures also can impose their own peculiar load shapes on the total house load. As the architecture of passive solar structures is frequently rather unusual, space limitations do not permit a more detailed description of these systems here.

Active solar space heating systems employ either liquid or air collectors and water tank, rock bed, or, somewhat less commonly, phase-change thermal storage. Figures 9 and 10 illustrate solar liquid and air systems, respectively, for residential and small commercial buildings. Figure 11 shows a large multisource building heating and cooling system employing solar collectors, underground water tank storage, and water-to-water heat pumps. These systems are commercially available and have been installed in existing buildings.

3.3 SOLAR RADIATION CHARACTERISTICS

3.3.1 Insolation

Insolation is the radiant energy of the sun incident on any given surface per unit area per unit time. Insolation is composed of a direct (beam or specular) component and a sky diffuse component, as shown by the equation:

$$I_t = I_{DN} \cos \theta + I_d$$

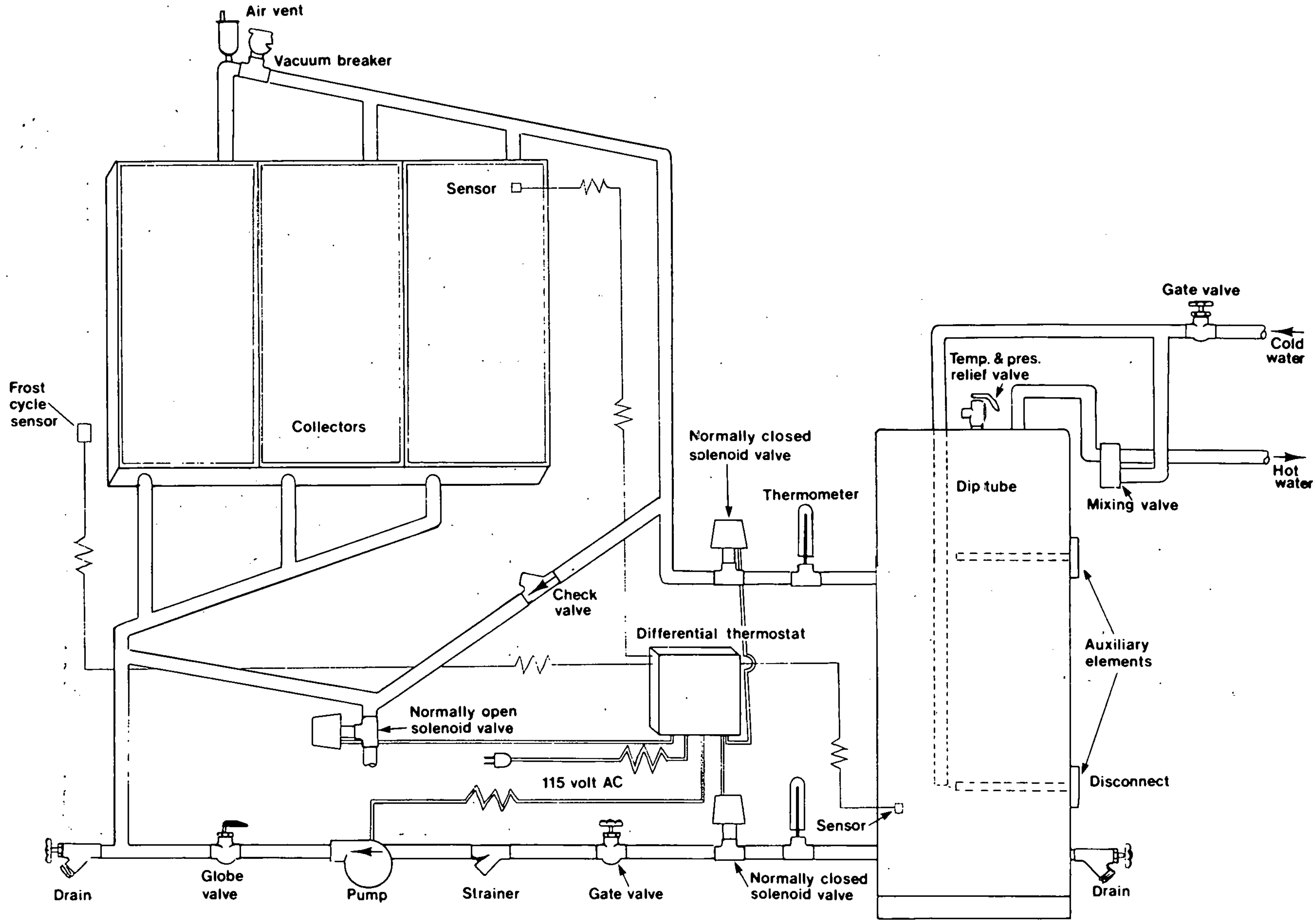


Fig. 5 Forced-Circulation Draining Solar Water Heating System: One Tank (source: Ref. 19)

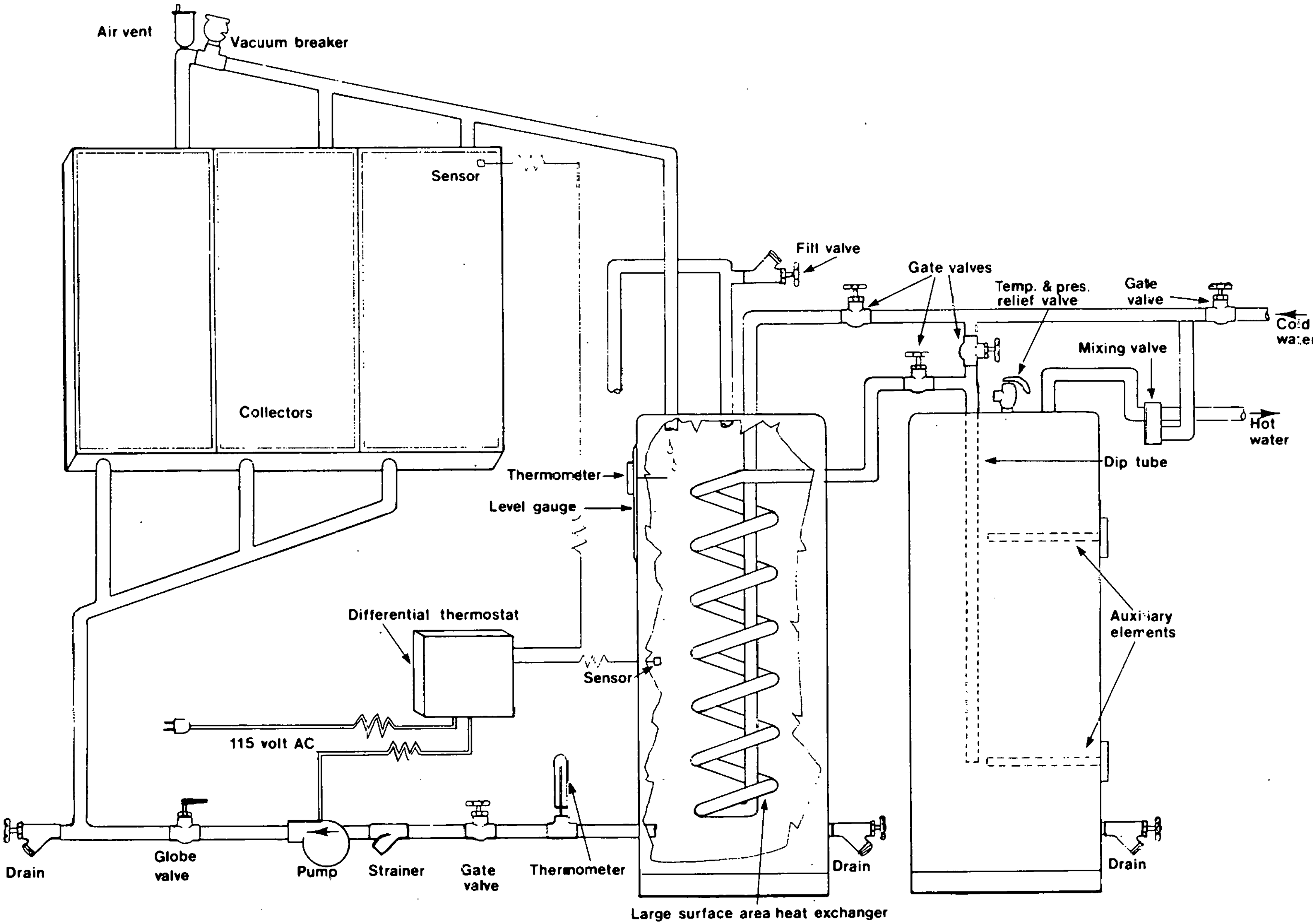


Fig. 6 Forced-Circulation Draining Solar Water Heating System: Two Tanks (source: Ref. 19)

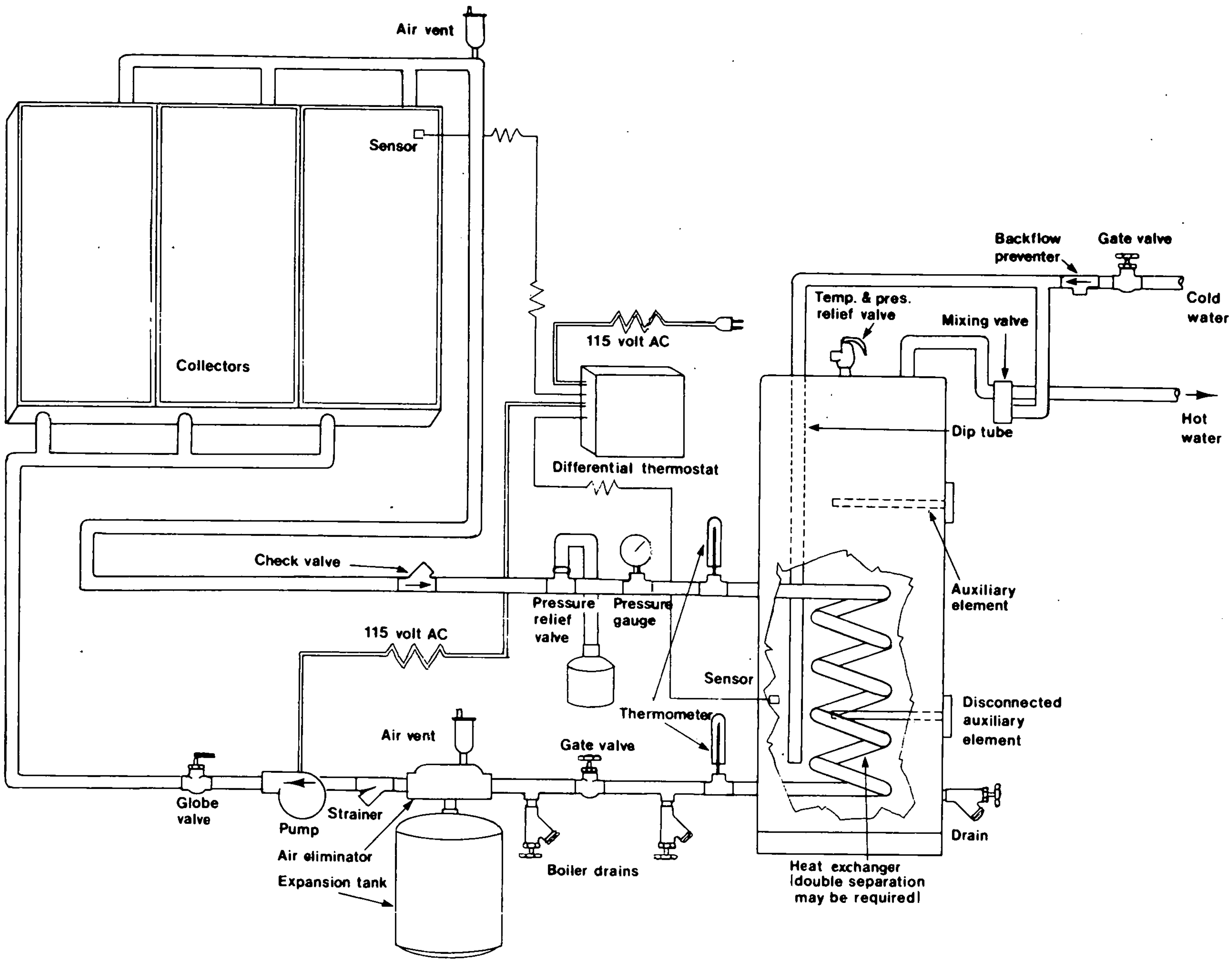


Fig. 7 Forced-Circulation Nondraining Solar Water Heating System: One Tank (source: Ref. 19)

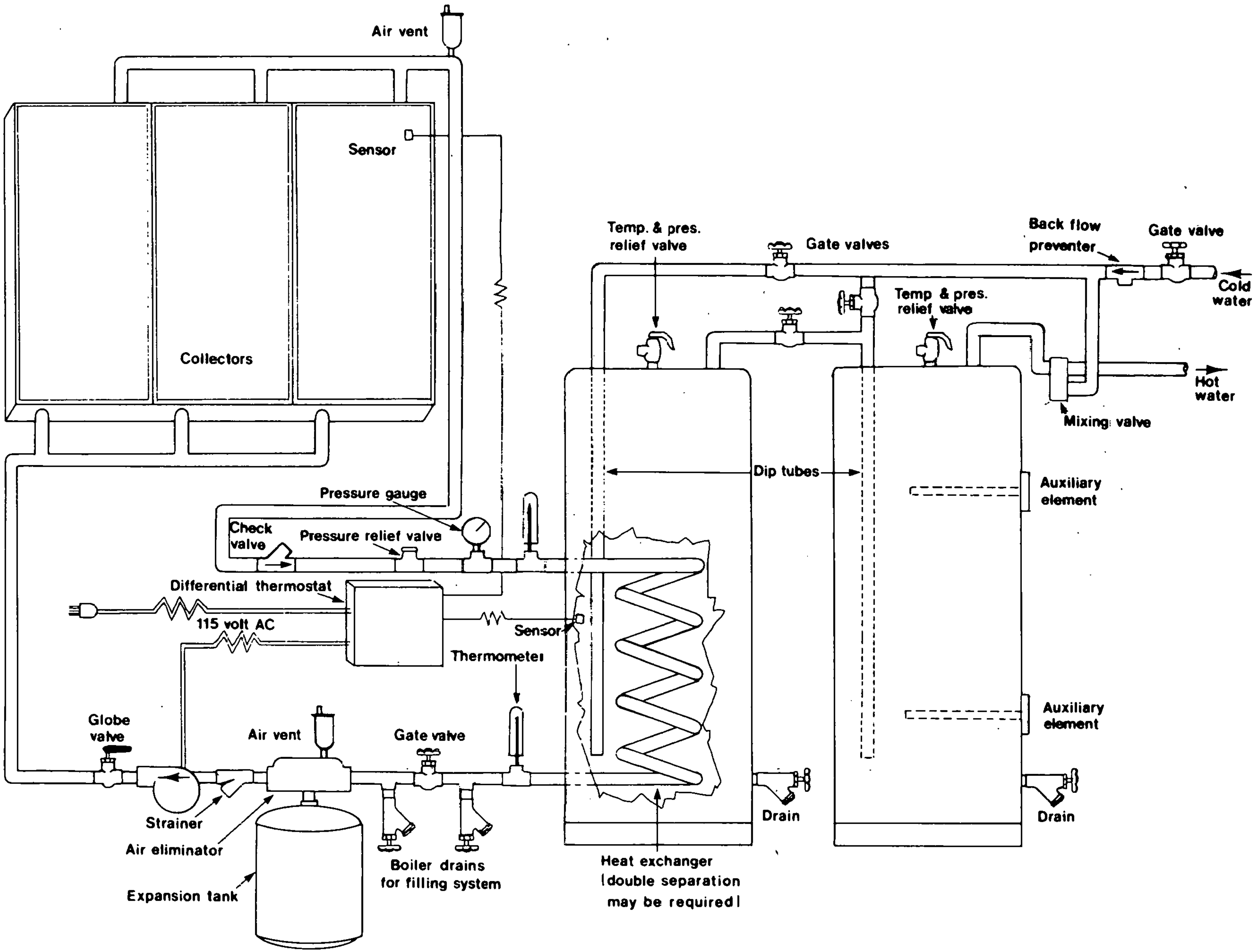


Fig. 8 Forced-Circulation Nondraining Solar Water Heating System: Two Tanks (source: Ref. 19)

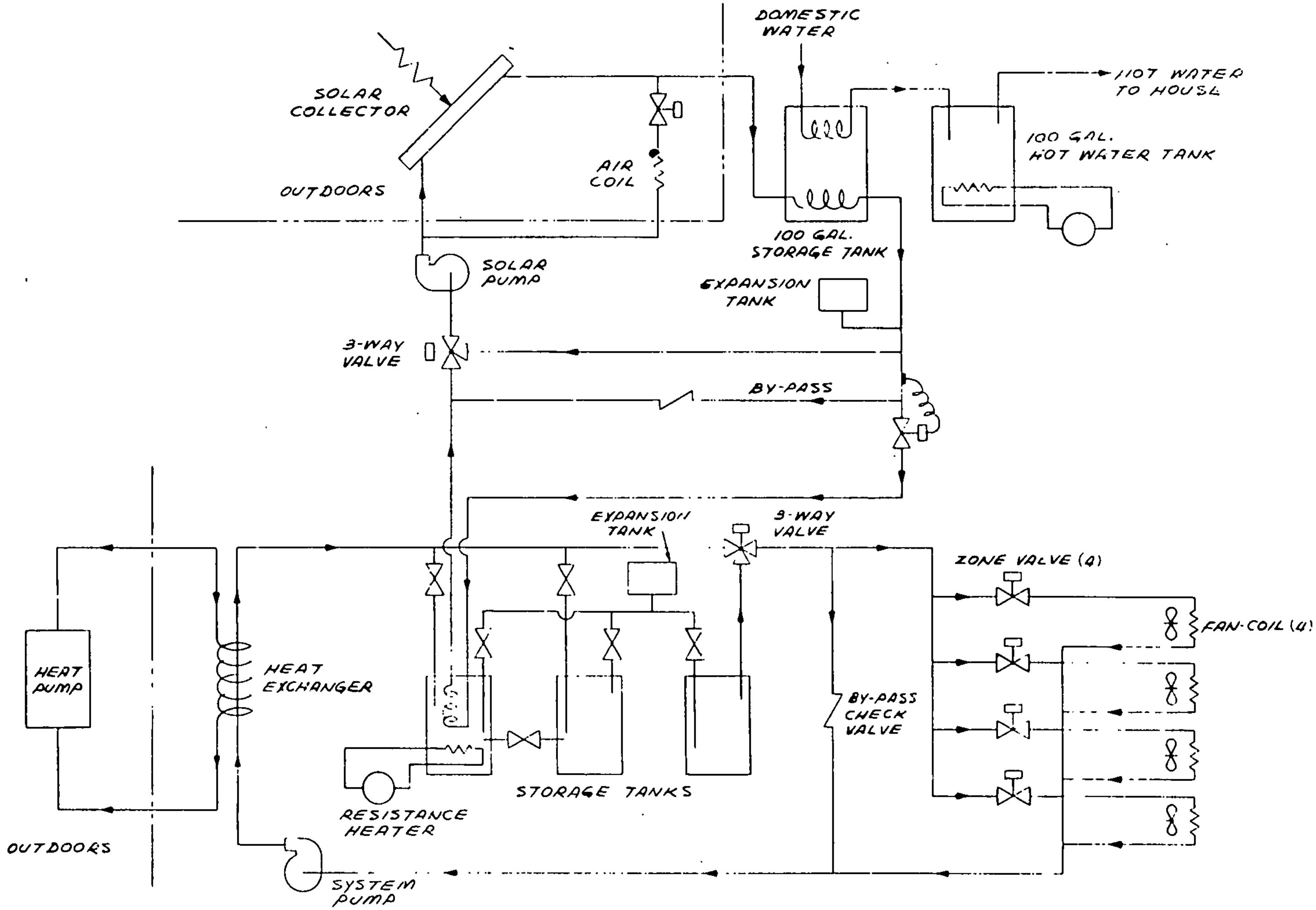


Fig. 9 Potomac Electric Power Company Solar Home with Heat Pump System (source: Electric Power Research Institute[8])

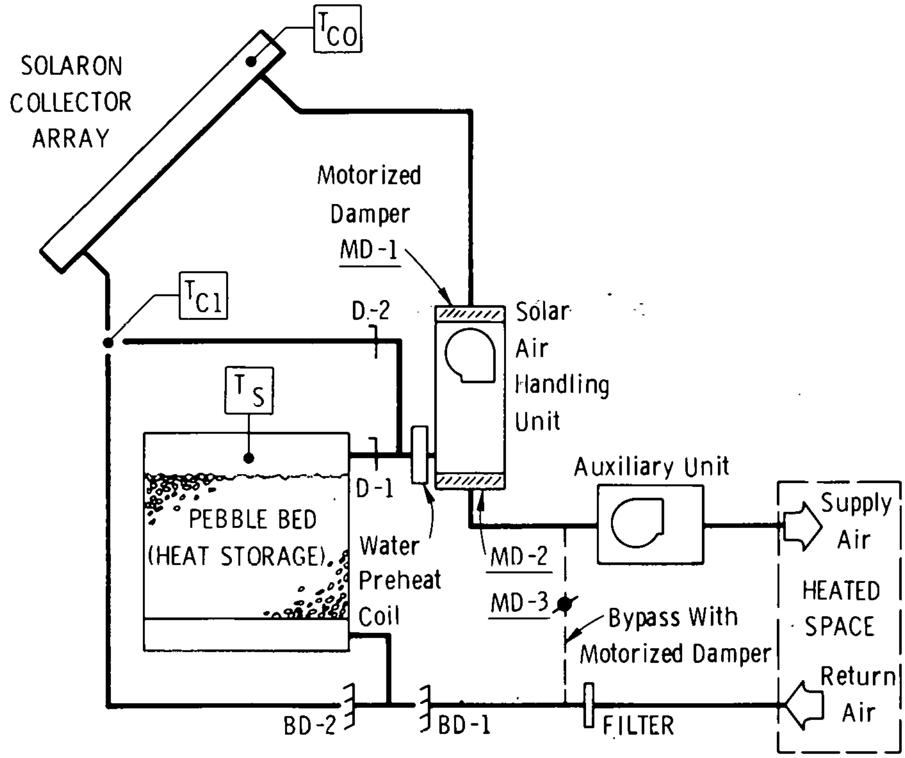


Fig. 10 Solar Space Heating System with Air Collectors and Pebble Bed Storage (source: Solaron Corp., by permission)

where:

I_t = total solar irradiation in Btu/(h-ft^2),

I_{DN} = direct normal irradiation in Btu/(h-ft^2),

θ = angle of incidence between the direct solar beam and the normal to the surface in degrees or radians, and

I_d = diffuse sky radiation in Btu/(h-ft^2)

Total insolation may be measured by a pyranometer. When fitted with a shadow band that blocks the direct rays of the sun, the pyranometer may also be used to measure diffuse insolation. Direct radiation is then determined as the difference between total and diffuse insolation. Normal direct radiation also may be measured directly by a beam-collimated pyranometer, called a pyrheliometer. (For a detailed discussion of solar radiometry see Chapter III of Ref. 17.) Solar radiation is measured regularly at many stations in the United States and throughout the world. Most of the domestic stations measure total horizontal insolation, defined as:

$$I_{tH} = I_{DN} \sin\beta + I_{dH}$$

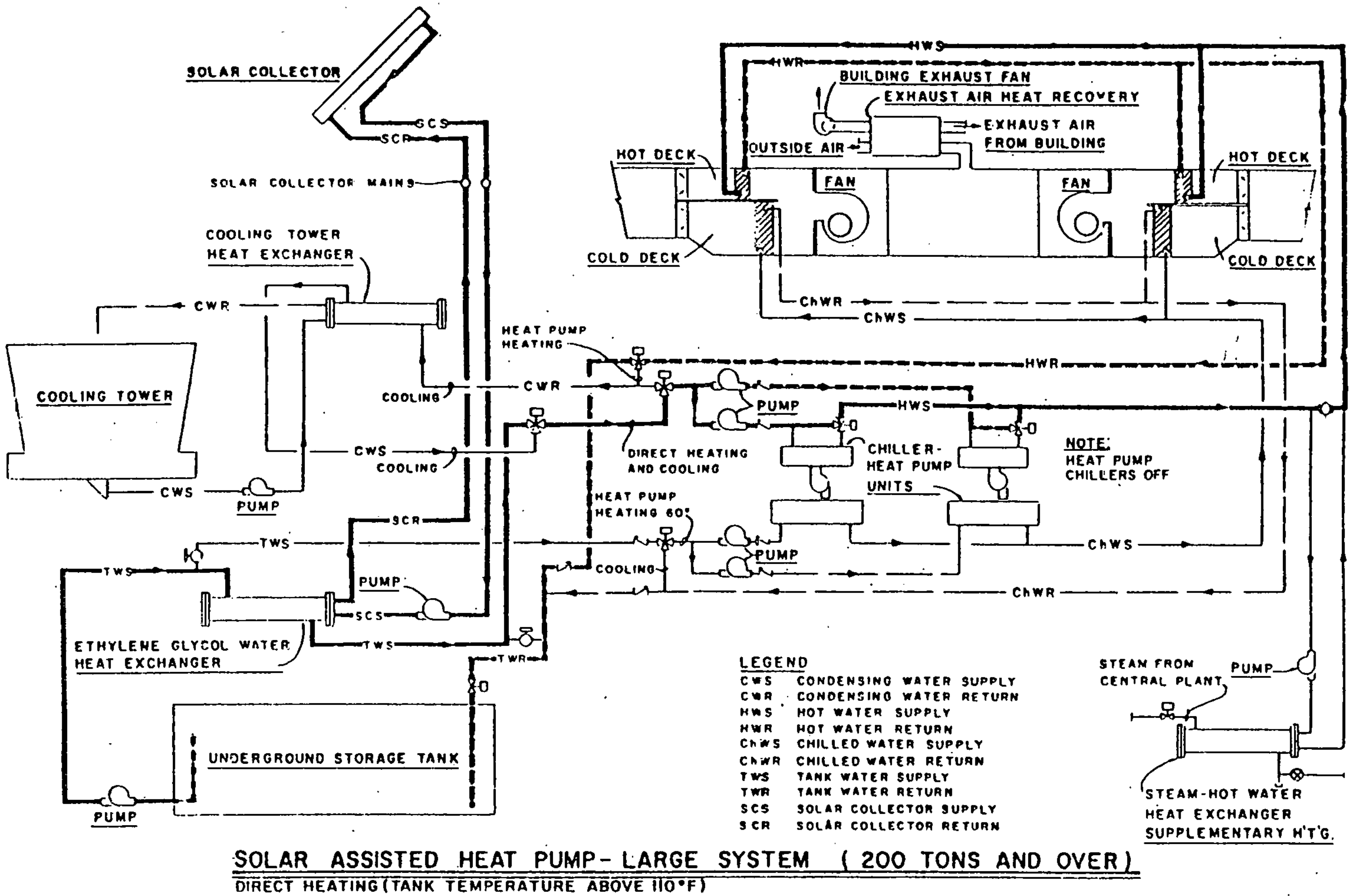


Fig. 11 Denver Community College Solar-Assisted Heat Pump System (source: Bridgers and Paxton Consulting Engineers, by permission)

where:

I_{tH} = total horizontal insolation in Btu/(h-ft^2),

β = solar altitude in degrees or radians, and

I_{dH} = diffuse horizontal insolation in Btu/(h-ft^2).

A comparatively small number of stations measure direct normal irradiation. Sunshine duration in total minutes per day also is measured. Information concerning available insolation data may be obtained from the National Oceanographic and Atmospheric Administration (NOAA).*

3.3.2 Insolation Incident on an Arbitrary Surface

Data on horizontal solar radiation may be used to calculate the insolation incident on a surface at an angle other than horizontal by the formula:

$$\cos\theta = \cos\beta \cos\Upsilon \sin\Sigma + \sin\beta \cos\Sigma$$

where:

θ = angle of incidence between the direct solar beam and the normal to the surface,

β = solar altitude,

Υ = solar azimuth angle of the surface, i.e., the difference between the solar azimuth and the surface azimuth angles, and

Σ = surface tilt angle from the horizontal.

All these angles are measured in degrees or radians and are illustrated in Figure 12. If the pyranometer is mounted in the plane of the solar collector, insolation incident on the surface is obtained directly.

If the local measurements are not available, clear-day insolation may be calculated from knowledge of the yearly and daily variation of the sun's position. The data required for the calculation are local standard time and the latitude and longitude of the location. The procedure for this calculation may be found in Ref. 10 (pp. 58.3-58.6). Calculated values should be reduced by local atmospheric clearness numbers (and corrections for an industrial atmosphere, if necessary), also given in Ref. 10.

3.4 SOLAR ENERGY COLLECTION AND STORAGE

The actual amount of useful solar energy collected by a nontracking flat plate collector (the only kind considered here) is a function of the

*NOAA Environmental Data Service, National Climatic Center, Asheville, North Carolina 28801.

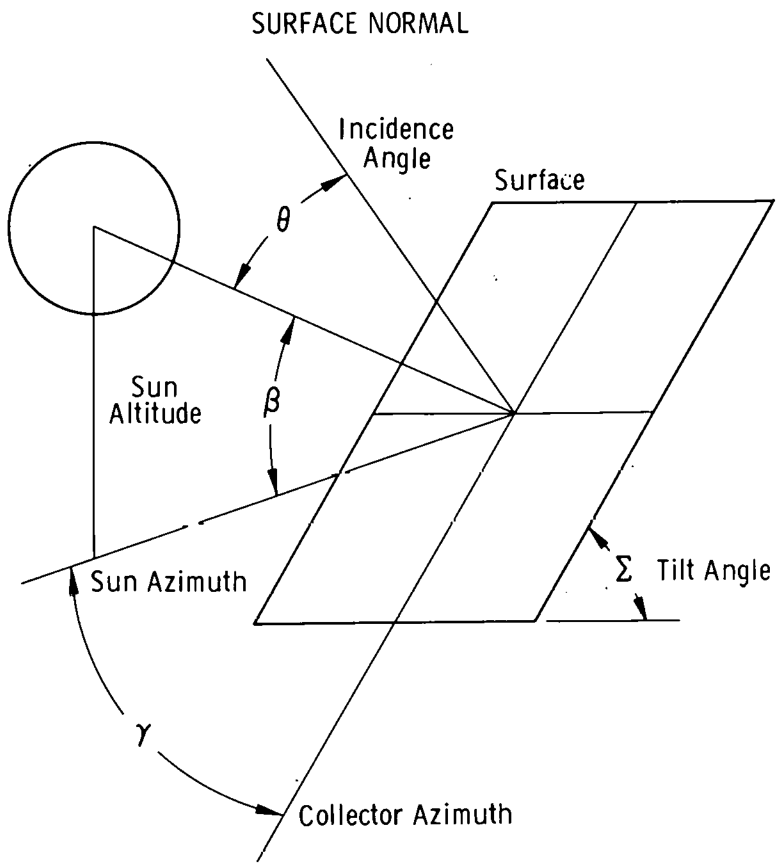


Fig. 12 Solar Incidence Angle

incident total insolation, the collector efficiency, and the temperature of the circulating fluid and ambient air. The design equations of the major energy system components are summarized below. These equations enable identification of the environmental and structure- or system-specific physical variables that affect system performance. For a more detailed description of collector and thermal storage system analysis methods, see Refs. 16, 17, 18, and 20.

3.4.1 Flat Plate Solar Collectors

The useful heat obtained from a flat plate solar collector is described by the Hottel, Whillier, and Bliss formula:[17,18]

$$q = \dot{m}c_p(T_o - T_i) = F_R A_n[I_t\overline{\tau\alpha} - U(T_i - T_a)]$$

where:

q = instantaneous useful heat flow in Btu/h,

$\dot{m}$ = mass flow rate of circulating fluid in lb/h,

c_p = specific heat of circulating fluid in Btu/(lb-°F),

T_o = outlet temperature of fluid in °F,

T_i = inlet temperature of fluid in °F,

F_R = heat removal factor (dimensionless),

A_n = net collector area in ft^2,

I_t = total insolation normal to plane of collector in Btu/(h-ft^2),

$\overline{\tau\alpha}$ = average transmittance-absorptance product of cover glass and absorber plate (dimensionless),

U = overall heat transfer coefficient between ambient air and the collector fluid in Btu/(h-ft^2-°F), and

T_a = ambient temperature in °F.

The collector heat removal factor is given by:

$$F_R = (\dot{m}c_p/A_nU)[1 - \exp(-A_nU/\dot{m}c_p)]$$

Technical literature from solar collector manufacturers usually presents collector performance data in the form of the efficiency versus temperature difference/insolation ratio:

$$F' \propto f\ [(T_iT_a)/I_t]$$

where F' = collector efficiency. A typical collector efficiency curve is shown in Figure 13.

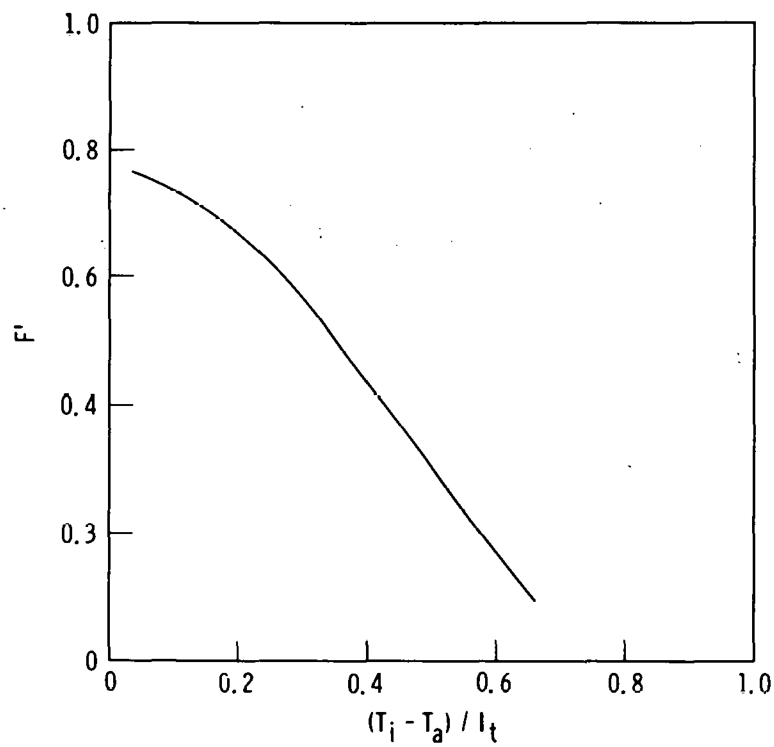


Fig. 13 Solar Collector Efficiency

3.4.2 Water Tank Thermal Storage Systems

A simple model of the transient behavior of a water tank thermal storage or water preheating system may be written as follows:

$$\rho c_p V dT/dt = \dot{m} c_p (T_1 - T_2) + q - UA_s(T - T_a) + q_r$$

where:

ρ = density of water in lb/ft^3,

c_p = specific heat of water in Btu/(lb-°F),

V = volume of water in tank in ft^3,

T = average temperature of water in tank in °F,

t = time in h,

$\dot{m}$ = mass flow rate of water withdrawn from tank in lb/h,

T_1 = cold water supply temperature in °F,

T_2 = stored hot water return temperature in °F,

q = heat supplied by solar collectors, $\dot{m} c_p (T_o - T_i)$, in Btu/h,

U = overall heat transfer coefficient in Btu/(h-ft^2-°F),

A_s = tank surface area in ft^2,

T_a = space temperature in °F, and

q_r = heat supplied by auxiliary resistance heaters in Btu/h.

This first-order ordinary differential equation may be integrated numerically for arbitrary time-varying values of the heat inputs, q and q_r, and the water withdrawal rate, $\dot{m}$, if it is assumed that there is no thermal stratification in the tank and the water is well-mixed at all times. In that case, $T = T_2$. While this is a reasonable first approximation, it is not necessarily a good one as most water heater tanks are built to enhance stratification by introducing the cold water at the top of the tank. In the latter case, linear stratification, or $T = (T_1 + T_2)/2$, may be assumed or a more complex mathematical treatment of the problem, resulting in a system of differential equations, may be attempted. More rigorous analyses of thermally stratified water tanks have been published.[18,21]

3.4.3 Rock or Pebble Bed Thermal Storage Systems

Thermal stratification is much more pronounced in rock or pebble beds, especially if the long dimension is vertical and thermal charging occurs from the top down. A transient model for one-dimensional heat transfer in a cross-sectionally uniform rock or pebble bed storage system is given by the differential equations:

$$\dot{m} c_p dT/dx = hS(T_s - T)/L$$

$$m_s c_{ps} dT_s/dt = hS(T - T_s)$$

where:

$\dot{m}$ = mass flow rate of fluid (air) in lb/h,

c_p = specific heat of fluid in Btu/(lb-°F),

T = local instantaneous fluid temperature in °F,

x = displacement from bed inlet in ft,

h = film heat transfer coefficient in Btu/(h-ft^2-°F),

S = bed heat transfer surface in ft^2,

T_s = local instantaneous solid temperature in °F,

L = bed length in ft,

m_s = mass of rock bed in lb, and

c_{ps} = specific heat of rock bed in Btu/(lb-°F).

These equations may be integrated analytically[22,23] or numerically.[18] Solutions that have been published for simple sinusoidal and other time-varying inlet fluid temperatures are useful for design purposes. For more realistic temperature functions, numerical integration is usually necessary. However, bed heat transfer (charging and discharging) efficiency expressed as an average heat conductance hS may be estimated from experimental measurements of T_1 and T_2 (inlet and outlet fluid temperature) and $\dot{m}$ (mass flow rate of fluid) if this simple model is assumed and integrated for the actual operating conditions encountered. (T_1 = T at x = 0; T_2 = T at x = L.)

3.4.4 Phase-Change Thermal Storage Systems

A simple model of heat transfer and melting of a phase-change thermal storage material, where the liquid and solid phase are in contact, may be obtained by assuming that the temperature profile in the liquid phase in contact with the heat transfer surface is linear, a good assumption if the liquid-phase thermal diffusivity is high. The position of the liquid-solid interface after time t from the start of melting is given by the formula:

$$X = [2k(T_o - T_f)t/(\rho_s \lambda_f)]^{\frac{1}{2}}$$

where:

X = thickness of liquid layer in ft,

k = thermal conductivity of liquid in Btu/(h-ft-°F),

T_o = constant surface temperature in °F,

T_f = melting point temperature in °F,

t = time from start of melting in h,

ρ_s = density of solid in lb/ft^3, and

λ_f = heat of fusion in Btu/lb.

The quantity of heat, H, stored in the melted fluid after time t has elapsed is:

$$H = [2\rho_s \lambda_f k(T_o - T_f)t]^{\frac{1}{2}} A$$

where:

H = heat absorbed (stored) in Btu, and

A = heat transfer surface area in ft^2.

For a more detailed explanation of this solution see Ref. 24. A more sophisticated mathematical model of phase-change materials has been published as well[25] (also see Ref. 18).

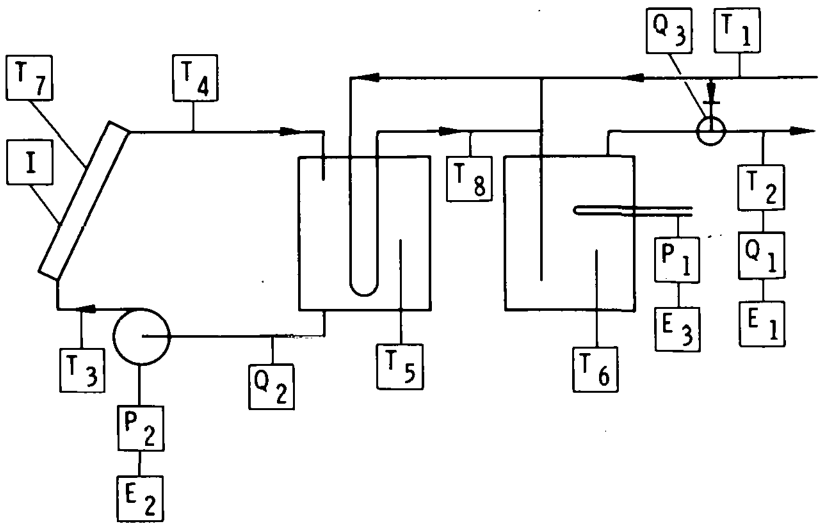
3.5 INSTRUMENTATION PLANS AND COSTS

As already stated, the extent to which a test site or facility should be instrumented depends on the size and complexity of the site and the systems to be tested and, of course, on the objective of the project. Because of the variety of solar water and space heating system configurations, development of a generalized instrumentation plan applicable to all buildings and solar heating systems is clearly impossible. Instead, the plans given in the following section represent recommendations only.

3.5.1 Solar Water Heating

Instrumentation plans for two-tank draining and nondraining water heating systems are shown in Figures 14 and 15. Both systems have 18 measurement points (1 total insolation, 8 fluid temperature, 1 surface temperature, 3 flow rate, 3 electrical power, and 3 event recorders). A similar nondraining two-tank system using basically the same points, except for the tank temperature sensors and event recorders, is being used in a solar hot water load experiment by Public Service Electric and Gas Company in Newark, N.J.[26] The total cost of the instrumentation and data recording system was reported as $7,000 in 1979, but some of the data logging equipment was modified from components available in-house.

The water heater instrumentation plans shown are designed for obtaining reasonably detailed engineering data on system performance. In a load research project involving a fairly large sample of solar water heaters, obtaining this amount of engineering data on each member of the sample would be unnecessary. It would suffice to monitor the time-dependent water flow rate, hot water temperatures, and resistance heater and solar fluid pump power for most of the houses in the sample for information about life-style dependent effects. In the system shown in Figure 14, these quantities could be monitored at sensors Q_1 (hot water flow), T_2 (hot water temperature), and P_1 and P_2 (resistance heater and solar fluid pump). This assumes that the cold water supply temperature does not vary significantly in the survey area. One four-channel tape recorder per water heater would suffice. It would be important to characterize the water heater completely, by recording tank volume, size of heating elements, collector area, pump rating, and the schedule of house occupancy.

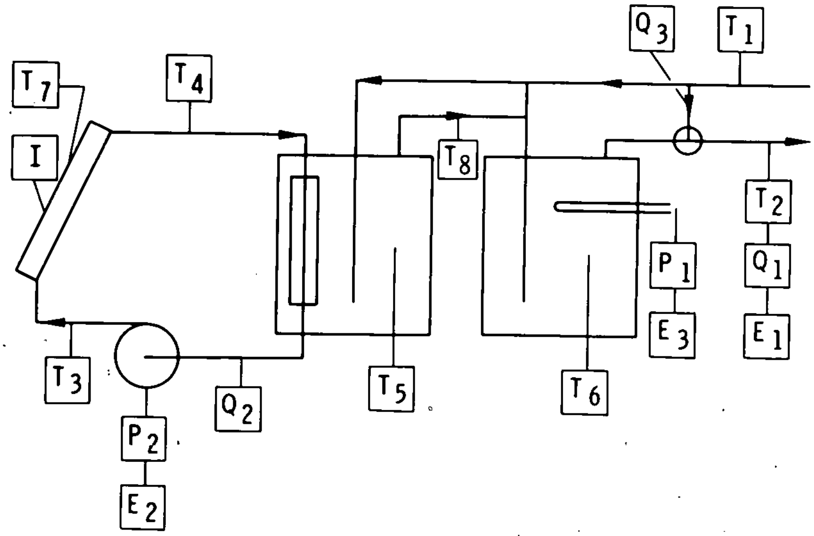


SENSOR	DESCRIPTION
I	TOTAL INSOLATION INCIDENT ON COLLECTOR
T_1	COLD WATER SUPPLY TEMPERATURE
T_2	HOT WATER TEMPERATURE
T_3	COLLECTOR INLET TEMPERATURE
T_4	COLLECTOR OUTLET TEMPERATURE
T_5	TANK TEMPERATURE
T_6	TANK TEMPERATURE
T_7	COLLECTOR PLATE TEMPERATURE
T_8	PREHEATED WATER TEMPERATURE
T_9	AMBIENT TEMPERATURE (SENSOR NOT SHOWN)
Q_1	HOT WATER FLOW
Q_2	COLLECTOR LOOP FLOW
Q_3	TEMPERING WATER FLOW
P_1	RESISTANCE HEATER POWER
P_2	PUMP POWER
E_1	EVENT RECORDER FOR HOT WATER FLOW
E_2	EVENT RECORDER FOR PUMP
E_3	EVENT RECORDER FOR RESISTANCE HEATER

Fig. 14 Instrumentation Plan for Two-Tank Draining Solar Water Heating System

3.5.2 Solar Space Heating

Figure 9 displays the instrumentation plan for the Potomac Electric Power Company's solar-assisted heat pump system.[8] Table 1 lists the data requirements for the system. This experiment is very extensively instrumented and involves multipoint measurement of the solar array and event recording of pump and valve operation. The sensor list includes measurement points for the



SENSOR	DESCRIPTION
I	TOTAL INSOLATION INCIDENT ON COLLECTOR
T_1	COLD WATER SUPPLY TEMPERATURE
T_2	HOT WATER TEMPERATURE
T_3	COLLECTOR INLET TEMPERATURE
T_4	COLLECTOR OUTLET TEMPERATURE
T_5	TANK TEMPERATURE
T_6	TANK TEMPERATURE
T_7	COLLECTOR PLATE TEMPERATURE
T_8	PREHEATED WATER TEMPERATURE
T_9	AMBIENT TEMPERATURE (SENSOR NOT SHOWN)
Q_1	HOT WATER FLOW
Q_2	COLLECTOR LOOP FLOW
Q_3	TEMPERING WATER FLOW
P_1	RESISTANCE HEATER POWER
P_2	PUMP POWER
E_1	EVENT RECORDER FOR HOT WATER FLOW
E_2	EVENT RECORDER FOR PUMP
E_3	EVENT RECORDER FOR RESISTANCE HEATER

Fig. 15 Instrumentation Plan for Two-Tank Non-draining Solar Water Heating System

heat pump. Table 2 presents the cost of the instrumentation and data logging equipment for this system as reported by Westinghouse. A breakdown of the meteorological station costs is given in Table 3.

Figure 16 shows a system flow and instrumentation diagram for a multi-unit, solar-augmented water-source heat pump system. This scheme is being used in a load research experiment by the Southern California Edison

Table 1 Data Requirements for a Solar Space Heating Experiment (see Figure 9)

Temperature

Inlet and outlet fluid temperatures to solar array
Individual inlet and outlet fluid temperatures in each group of collectors
Fluid inlet and outlet temperatures to hot water preheat heat exchanger (from solar collectors)
Fluid inlet and outlet temperatures to storage tank heat exchanger
Hot water preheat storage tank temperature
Inlet and outlet water temperatures to hot water tank
Storage water inlet and outlet temperature to the heat pump heat exchanger
Storage tank temperatures
Inlet and outlet water temperatures to fan-coil units
Space temperature in each zone
Outside ambient temperature

Flow rate

Domestic hot water
Solar heat-transfer fluid
Water through heat pump heat exchanger

Event recording

Solar coolant circulator pump
Primary water circulator pump
Each fan-coil unit
Storage system three-way valve
Operating mode
Defrost mode
Solar system three-way valve
Heat pump

Power

Heat pump compressor
Solar coolant pump
Primary water circulator pump
Aggregate of fan-coil blowers
Storage resistance heaters
Domestic hot water tank resistance heater
All house electrical uses

Environmental measurements

Outdoor temperature
Insolation
Wind speed and direction
Relative humidity

Source: Electric Power Research Institute[8]

Table 2 Major Instrumentation System and Component Costs for a Solar Space Heating Experiment (see Figure 9)

Component	Cost (1979 $)
Doric data logger and tape deck	11,729
Demand recorder	540
Watt-hour meters (3)	102
Flow transducers (3)	1,310
Range extenders (3)	675
Freq. to DC converters (3)	450
Watt meters (3)	450
Thermocouples (36)	1,074
Visual flow meters (3)	105
Dial thermometers (3)	104
Weather station	3,930
Total	20,469

Source: Electric Power Research Institute[8]

Table 3 Cost of Weather Station Components for a Solar Space Heating Experiment (see Figure 9)

Component	Cost (1979 $)
Modular meteorological system, consisting of aspirated temperature and relative humidity shield	350
Temperature sensor	55
Relative humidity sensor	475
Eppley black and white pyranometer	590
Wind speed sensor	325
Wind direction sensor	325
Crossarm	50
Mainframe	250
Power supply	250
Wind speed and direction translator	425
Calibration oscillator for wind speed and direction translator	50
Temperature translator	225
Relative humidity translator	225
Solar radiation translator	225
Meteorological tower - 14 ft, hinged (7 ft mast std.)	85
Extra sensor cable (100 ft at $0.25/ft)	25
Total	3,930

Source: Electric Power Research Institute[8]

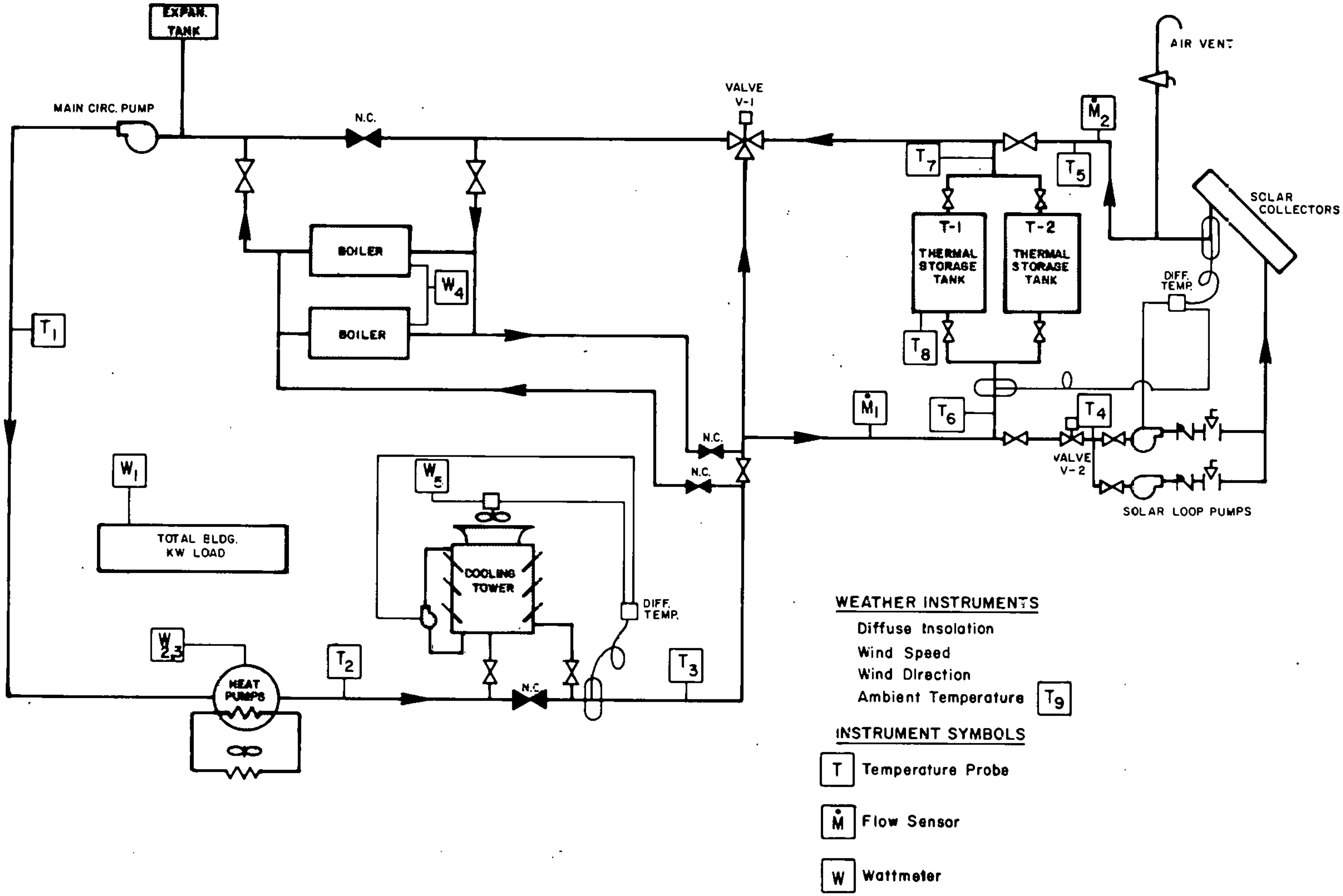


Fig. 16 Instrumentation Scheme of Solar-Augmented Multi-Unit Water-Source Heat Pump Research Project (source: Southern California Edison Company and Electric Power Research Institute[9])

Company.[9] Table 4 lists the instrument tolerance and measurement range specifications.

If many solar heated homes are to be monitored, measurement of the collector-plane insolation, outdoor and indoor (space average) temperature, back-up system demand, and pump power may suffice. This would require two four-channel tape meters with one channel available for determination of an additional variable, such as total service demand.

Table 4 Measurement Range and Sensor Tolerance Specifications

Variable	Range	Max. Sensor Tolerance
Temperature	°F	°F
Heat pump inlet	40-120	± 0.5
Heat pump outlet	40-120	± 0.5
Boiler inlet	40-120	± 0.5
Solar collector inlet	40-160	± 0.1
Solar collector outlet	40-160	± 0.1
Tank inlet	40-160	± 0.1
Tank outlet	40-160	± 0.1
Tank interior	40-160	± 0.5
Ambient	40-120	± 1.0
Power	kW	%
Total adm. bldg. load	0-250	1
Heat pump panel D	0-100	1
Heat pump panel E	0-100	1
Boiler input power	0-100	1
Cooling tower	0-10	1
Flow	gpm	%
Bypass loop	0-50	1
Solar collector loop flow	0-50	1
Ambient Conditions		
Diffuse insolation	0-200 Btu/ft^2-hr	5%
Wind speed	0-100 mph	5%
Wind direction	0-360°	5°
Time	day - hr - min	5 min

Source: Southern California Edison and Electric Power Research Institute[9]

4 WIND ENERGY CONVERSION SYSTEMS

The wind energy conversion systems considered here are two- or three-blade propeller systems and vertical-axis Darrieus machines with up to 4100 W net electrical generating capacity. These are designed to be installed and operated on the customer's premises, for customers such as a single-family residence, small community, or industrial facility. However, several much larger windmills designed to operate as part of a utility generating plant are being developed and tested by the U.S. Department of Energy. These wind plants range in generating capacity from 100 kW to 2000 kW.[27]

The wind turbines of concern interface directly with the utility grid, thus becoming net producers of power when generation exceeds demand. Most of the wind turbines now commercially available are of the two- or three-blade, horizontal-axis propeller type. But some vertical-axis machines are also being offered on the market. The systems designed to interface with the grid are either variable-speed-constant-frequency (VSCF) or constant-speed-constant-frequency (CSCF) systems, producing 50 or 60 Hz of AC power at 110 V or 220 V. Both AC synchronous and induction generators are used, with rectifiers and inverters used with VSCF machines as appropriate.

4.1 WIND TURBINE TAXONOMY

Wind turbines are either wind-axis or cross-wind-axis machines. A similar classification divides wind turbines into horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). Horizontal-axis or propeller-type machines, such as those shown in Figure 17, are self-starting but have the disadvantage of requiring a mechanism to keep the rotor oriented in the wind direction. Furthermore, the relatively heavy generator has to be mounted on a tower or, if the generator is on the ground, the power of the propeller has to be transmitted to the generator via a long mechanical or hydraulic linkage.

Vertical-axis machines are usually of the Darrieus rotor type, also shown in Figure 17. Vertical-axis machines do not require orientation into the wind, and the generator and speed controls can be on the ground. The Darrieus is not self-starting; one or more Savonius rotors mounted on the central shaft or a reversible induction motor-generator must be used to start the machine. In the latter case, the motor is used to bring the rotor up to the speed at which it begins to put power into the line or deliver it to the load. The Pinson machine is also a vertical-axis machine (but not a Darrieus rotor type) and is self-starting.

4.2 WIND CHARACTERISTICS

The instantaneous wind speed usually is expressed in terms of a steady-state or mean value and a fluctuating part:

$$v = V + v'$$

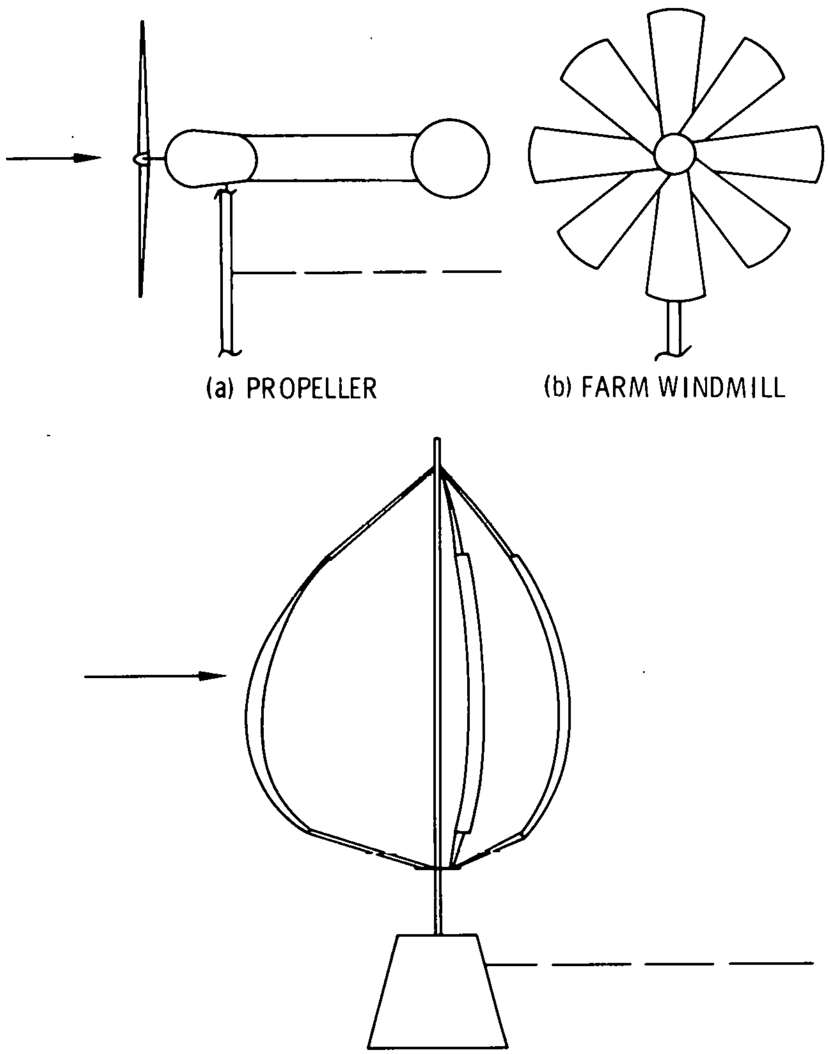


Fig. 17 Horizontal- and Vertical-Axis Wind Turbines

where:

v = instantaneous wind velocity in m/s,

V = mean wind velocity in m/s, and

v' = velocity fluctuation in m/s.

The mean wind velocity V is defined as:

$$V = \int v(t)dt/(t_2 - t_1)$$

where the integral is taken over any specified time interval $(t_2 - t_1)$. The following relationships hold for the velocity fluctuation:

$$\int v'(t)dt = 0$$

$$\int v'^2(t)dt = \bar{v}'^2 \geq 0$$

where $\overline{v}'$ = average velocity fluctuation in m/s. In practical measurements and calculations, only the mean wind velocity, V, is of concern.

4.2.1 Averaging Time

Depending on the source of the wind data, averaging times may range from a few minutes to several hours. Wind data from weather tapes may be obtained from the National Oceanographic and Atmospheric Administration (NOAA)*. NOAA data record one-hour average wind speeds for years before 1965 and three-hour average wind speeds for 1965 and subsequent years. However, since the power density of the wind stream varies as the cube of the wind velocity, shorter averaging periods, such as 5-15 min, are more desirable for accurate calculations of power density.

4.2.2 Horizontal Wind

Atmospheric air motion is, of course, three dimensional. However, in the planetary boundary layer, where the wind is influenced by the contours of the terrain and the roughness of the ground surface, the horizontal component of the wind velocity is of principal interest. That component is measured with a cup or propeller-type anemometer that is free to rotate in a horizontal plane. In the following discussion, the term wind should be taken to mean the horizontal wind velocity.

4.2.3 Logarithmic Wind Profile

Except in periods of extreme calm or stability, atmospheric air flow is almost always turbulent. The wind in the earth's boundary layer (up to an altitude of several hundred meters) exhibits vertical shear that may be expressed mathematically by a logarithmic wind profile formula that can be derived from turbulence theory:

$$V(z) = V_o(z/z_o)^b$$

where:

- $V(z)$ = wind velocity at altitude z in m/s,
- z = altitude in m,
- V_o = wind velocity at the top of the roughness layer in m/s,
- z_o = height of the roughness layer in m, and
- b = exponent.

The exponent b depends on the relative roughness of the terrain. Typical values are given in Table 5. The logarithmic profile for any given location

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*NOAA Environmental Data Service, National Climatic Center, Asheville, North Carolina 28801.

Table 5 Typical Values of b and the Roughness Height in the Logarithmic Wind Profile Formula

Location	b	z_o (m)
Open water, open plain	0.1-0.16	0.01-0.1
Trees, houses	0.28	0.1-0.5
Tall buildings	0.4	0.5-1.2

Source: Refs. 28 and 29.

may be determined from long-term simultaneous measurements of the velocity at two elevations (anemometers usually are located at 10 m and 30 m). This gives the value of the exponent b as:

$$b = \ln(V_2/V_1)/\ln(z_2/z_1)$$

where:

V_2, V_1 = wind velocity at elevations z_2 and z_1 in m/s, and

z_2, z_1 = elevations on the same vertical axis in m.

NOAA wind data are given in knots or nautical miles per hour. One knot = 1.1516 statute miles per hour, or 0.5144 meters per second (1 mph = 0.4470 m/s).

4.2.4 Velocity-Duration Curve

The annual frequency of horizontal winds may be expressed as a velocity-duration curve, shown in Figure 18. This curve is a plot of the wind speed versus the number of hours per year that the corresponding wind speed is exceeded, or:

$$H = H(V)$$

where H = number of hours per year that the wind speed exceeds V. The velocity-duration curve may be easily converted into a velocity-frequency distribution by taking the derivative of the velocity duration curve:

$$h(V) = dH(V)/dV \approx \Delta H/\Delta V$$

where h(V) = velocity frequency distribution in h/(m/s). In practice, the velocity-frequency curve may be obtained by sorting velocity data into bins of, for example, 0.5-m/s width.

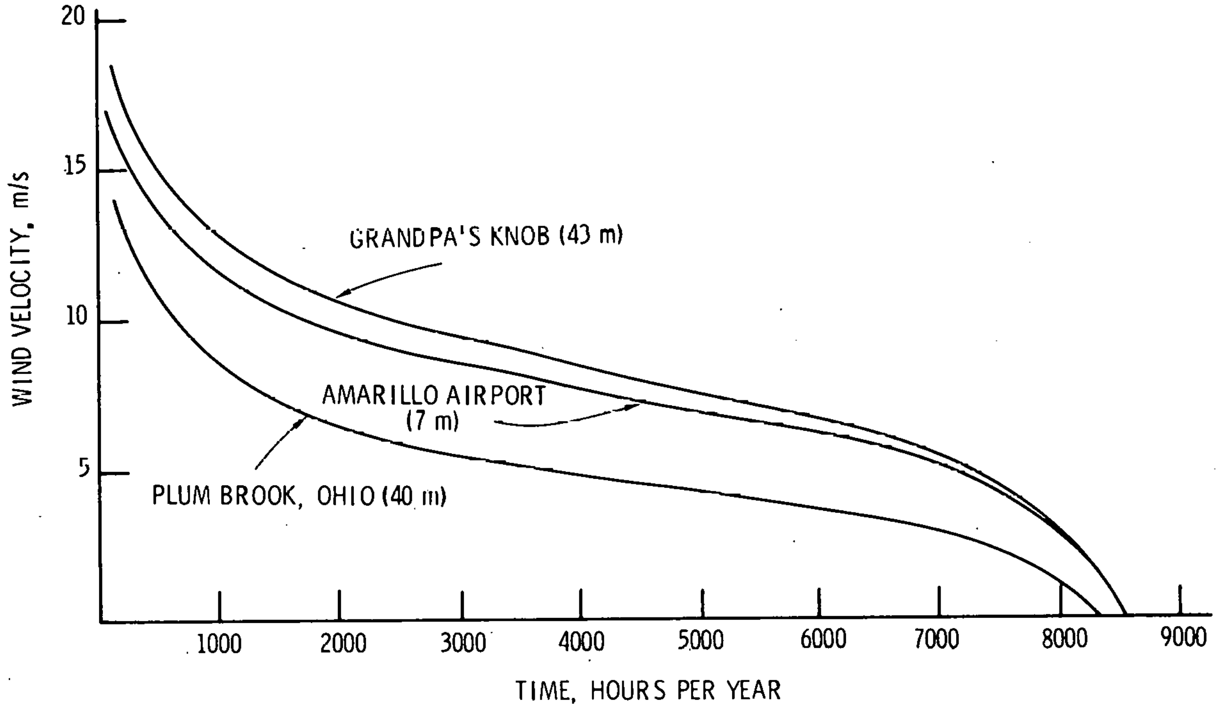


Fig. 18 Velocity-Duration Curves (source: Ref. 29)

4.2.5 Power in a Windstream

The theoretical power in a windstream is the product of the volumetric flow rate of the wind through an arbitrary swept area, A_s, and the kinetic energy of the windstream per unit volume:

$$P_{th} = \rho V^3 A_s/2$$

where:

P_{th} = theoretical power in kW,
ρ = mass density of air in kg/m^3,
V = wind velocity in m/s, and
A_s = swept area in m^2.

Wind power density is the theoretical wind power per unit swept area:

$$e = P_{th}/A_s = \rho V^3/2$$

where e = theoretical power density in W/m^2.

Air density may be calculated from its dry bulb temperature, barometric pressure, and humidity ratio by the following formula:

$$v_H = (1/M_a + W/M_w)R_g T/p$$

where:

v_H = humid volume of air in m^3/kg dry air,

M_a = molecular weight of air in kg/kmol,

M_w = molecular weight of water in kg/kmol,

W = humidity ratio (kg water vapor/kg dry air),

R_g = universal gas constant in kPa-m^3/(kmol-K),

T = absolute temperature in K, and

p = barometric pressure in kPa.

The density and humid volume are related through:

$$\rho = v_H/(1 + W).$$

where ρ = density of air in kg/m^3. Constants for use in the above equations are given in Table 6.

4.3 WIND TURBINE PERFORMANCE

4.3.1 Power Coefficient

The power per unit swept area that a wind turbine may extract from a windstream at mean free-stream velocity V is:

$$P/A_s = C_p P_{th}/A_s = C_p \rho V^3/2$$

where:

P = actual power extracted from wind stream in kW, and

C_p = power coefficient.

Table 6 Constants and Conversion Factors for Air Density Calculation

Symbol	Engineering Unit	SI Unit
p	1 atm = 14.696 psia	101.33 kPa
M_a	28.96 lb/lbmol	28.96 kg/kmol
M_w	18.02 lb/lbmol	18.02 kg/kmol
R_g	10.73 psia-ft^3/(lbmol-R)	8.314 kPa-m^3/(kmol-k)
T	(°F + 459.7)R	(°C + 273.15)K

The power coefficient depends on the turbine blade tip-to-wind speed ratio:

$$X = RN/V$$

where:

X = tip-to-wind speed ratio.

R = wind turbine radius or radius of VAWT equator in m, and

N = angular velocity in Hz.

The theoretical maximum value of the power coefficient for propeller-type machines is $C_p = 0.593$, a value called the Betz coefficient. Figure 19 shows C_p as a function of the tip-to-wind speed ratio, X, for common horizontal - and vertical-axis machines.

4.3.2 Power Duration Curve

The velocity-frequency and power coefficient relationships for a given wind turbine may be used to define an annual power duration curve:

$$G = G(P)$$

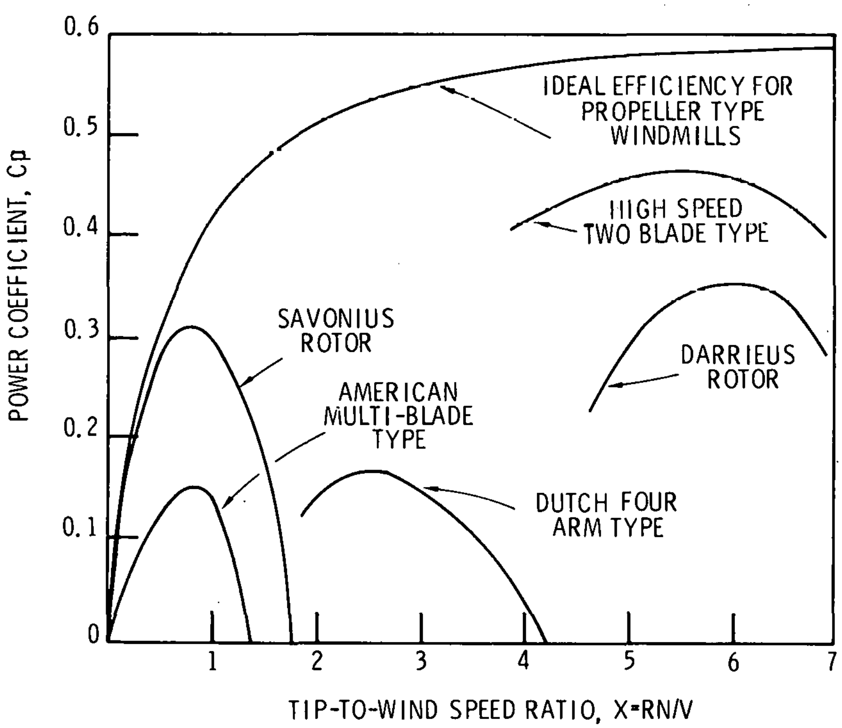


Fig. 19 Power Cofficient for Various Wind Turbines (source: Ref. 29)

where G = number of hours per year that the power exceeds a value P. For a given value of $P = C_p \rho V^3 A_s/2$, the corresponding value of G is:

$$G = \int_{V}^{\infty} \frac{C_p \rho V^3 A_s h(V)}{2} dV$$

The calculation is conveniently carried out in a tabular form by approximating the integral as a sum of finite increments dV of velocity.

4.4 GENERATION METHODS

Wind turbines operate as either constant-speed-constant-frequency (CSCF) or variable-speed-constant-frequency (VSCF) systems, assuming, of course, that the wind plant is connected to the utility grid and generates 60-Hz AC power. Some of the more common generation schemes for both types of wind plants are described below. Generation methods in use or under consideration and their relative merits are reviewed in Refs. 30 and 31. The operation of both the CSCF and VSCF schemes is illustrated by means of power-duration curves in Figure 20.

4.4.1 Constant-Speed-Constant-Frequency Systems

Constant-speed-constant-frequency wind plants employ turbine blade pitch control schemes to maintain the turbine rotational frequency at the rated value required to produce 60-Hz power. Two common generation schemes are used: AC synchronous generator with DC field excitation and AC induction generator. In either case, once the turbine cut-in speed is reached, hydraulic or electrical servomechanisms are used to maintain rotational frequency up to the cut-out speed, at which point the blades are fully feathered and the brake applied. In some cases, where the generator is grid-connected, the induction generator is operated in reverse as an electric motor to bring the blades up to the speed at which the turbine begins generating extra power, which is then put into the line.

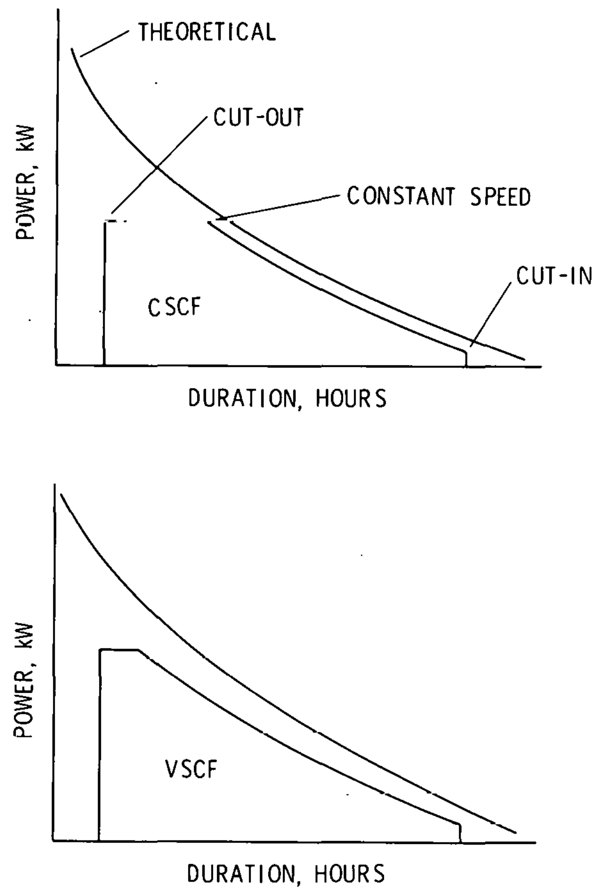


Fig. 20 Schematic Diagrams of Power-Duration Curves for CSCF and VSCF Systems

4.4.2 Variable-Speed-Constant-Frequency Systems

In variable-speed-constant-frequency systems, the rotor speed varies according to the wind velocity and load on the generator. Among the generation schemes used are AC-DC-AC conversion and field modulation-demodulation. In the first case, alternating current of variable frequency is rectified to DC and then inverted to AC. The other scheme involves use of AC generation with AC field modulation.

4.5 INSTRUMENTATION PLANS AND COSTS

As with solar heating systems, the extent to which a wind-turbine-generator installation should be instrumented depends on the objectives of the load research. If the purpose of the project is only to determine the system load characteristics of wind generators, measurement of the following variables at 15- or 30-min intervals may suffice: active power generated, reactive power generated, line power consumed, and wind velocity at turbine rotor hub or equatorial plane.

To determine ambient air density, it would be desirable to also obtain local measurements of ambient dry bulb and wet bulb temperatures and barometric pressure. If wet bulb temperature and pressure measurements are available from the local NOAA station and only the ambient dry bulb temperature is measured on-site, two four-channel magnetic tape survey recorders would suffice.

The above instrumentation scheme would permit load researchers to measure the net power generated by the wind plant and calculate its overall efficiency. However, it would not be possible to determine the wind shear, and use of the data to estimate wind plant performance at other elevations would be difficult. Wind direction measurements are, of course, also desirable if the experiment is to yield data useful for wind plant siting purposes. If the mechanical efficiency and bearing and gear losses are to be determined as well, shaft torque and rotational speed should be measured.

Figure 21 and Table 7 illustrate the instrumentation points for determining load characteristics and wind plant efficiency (the cost of a typical weather station is given in Table 3). While many additional measurements are usually taken on developmental wind machines,[32] these are not of concern here.

4.5.1 Line Power and Generated Power

If a customer's wind plant is connected to the customer load and the utility grid, the customer at any given time may be a net consumer or generator of power, depending on the match (or mismatch) of the available wind energy and the customer's load. If the usual electro-dynamometer watt-hour meter is connected to the point of utility power entry to the customer's premises, it will run backward if the wind plant is putting power back into the grid. Therefore, it is important to measure generated power and line power using two separate meters equipped with ratchet switches that allow discrimination between the two sources of power to meet the customer's load.

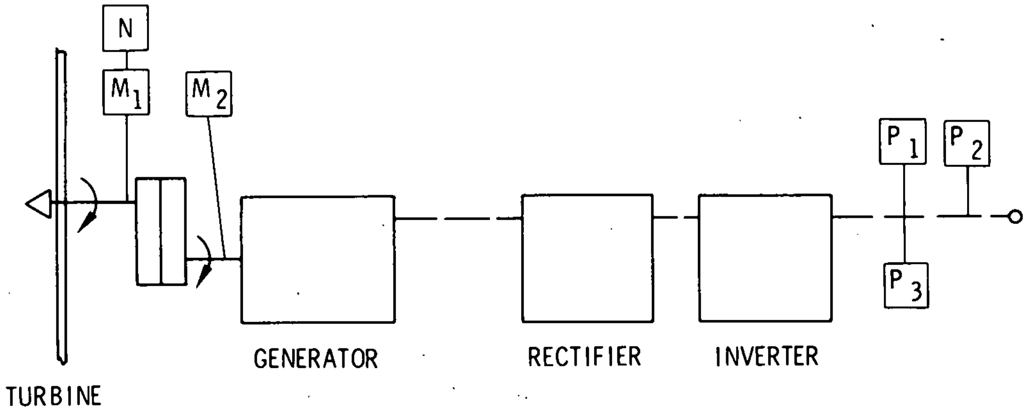


Fig. 21 Wind Energy Conversion System with Utility Grid Interface

Table 7 Data Requirements for Wind Energy Conversion Load Research

Measurement	Sensor Point in Fig. 21
Environmental	
Wind velocity[a]	
Wind direction[a]	
Ambient temperature	
Barometric pressure	
Relative humidity	
Wind rotor	
Rotor speed (angular velocity)	N
Rotor shaft torque	M_1
Generator shaft torque	M_2
Generator active power	P_1
Generator reactive power	P_2
Line power	P_3

[a]HAWT at elevation of rotor axis; WAWT at elevation of equatorial plane.

4.5.2 Reactive Power

Use of wind turbine generators connected to the utility grid calls for the measurement of reactive power. Reactive power may be measured with instrumentation similar to that used to measure active power. Apparent, active, and reactive power are related through the equation:

$$P_{app} = \sqrt{P^2 + Q^2}$$

where:

P_{app} = apparent power in kVA

P = active power in kW, and

Q = reactive power in kVA.

Manufacturers of watt-hour meters also make "Q-hour" meters that accept currents from 30° leading to 60° lagging. The cost of this meter is about the same as that of a watt-hour meter; about $25 per meter (in 1980) for single-phase, two- or three-wire service, when purchased in quantity. Instrument packages for measuring and recording apparent power, active power, reactive power, power factor, and energy also are available commercially. Typical prices are given in Table 8.

Table 8 Cost of Instrument Package for Wind Power, Power Factor, and Energy Measurement

Component	Cost (1980 $)
Prewired watt-hour and Q-hour meters, two pulse initiators, magnetic tape recorder, steel panel, test switch, weather-proof outdoor enclosure	
Single-phase, energy registers only	1200
Polyphase, energy and demand registers	1500-2000
Ni-Cd battery, trickle charger with 8-hour carryover	100

Source: Westinghouse Electric Company, personal communication (Jan. 1980).

5 COGENERATION

A cogeneration plant produces electrical or mechanical power as well as useful thermal products such as steam, high-temperature hot water, or chilled water. This rather broad definition includes, for example, diesel engines, gas and steam turbine-driven generators with exhaust and coolant heat recovery, systems for power recovery from industrial process streams, utilization of nuclear plant waste heat, and fuel cells. Cogeneration systems may be divided into systems with utility back-up and stand-alone systems. Total energy plants are designed to produce all of the electricity, heating, air conditioning, and water heating needs of the customers served. This discussion, however, will be limited to plants at the customer's site connected to the utility grid and thus capable of either drawing or supplying power on a continuous or intermittent basis. Prime movers to be considered will be diesel engines, combustion gas turbines, and steam turbines. Stirling-cycle machines and fuel cells will not be discussed as these are still under development.

5.1 COGENERATION SYSTEM CONFIGURATIONS

Cogeneration systems are generally quite complex. A plant may produce a number of energy "products" and use one or more sources of purchased energy for back-up or capacity augmentation. Cogeneration plants also may vary in electricity generating capacity from a few kilowatts to several hundred megawatts, consist of one or more prime movers of the same or different kinds (i.e., combined gas and steam turbine plants), and involve auxiliary fossil-fuel-fired boilers. Since cogeneration systems supply electricity, thermal energy, and, sometimes, mechanical energy, (for example for direct-drive chillers), their design and control schemes fall into two broad categories:

- Plants designed to meet peak electrical demands and supply steam or hot water from available rejected heat from the prime mover (total energy plant)
- Plants designed to meet a balance of electrical and thermal demands (cogeneration)

In the former case, auxiliary boilers must be used to meet the thermal demand if that is greater than the waste heat available. If the thermal requirements are less than the electrical requirements, peak efficiency cannot be achieved because some of the rejected heat from the prime mover cannot be utilized. In the cogeneration case, on-site generation may be limited (ideally) to optimize the availability of rejected heat from the prime mover and the purchased electricity from the grid, or excess electricity may be sold to the grid if a suitable rate is negotiated with the utility. The second case is of special interest here. A brief summary of cogeneration systems, classified according to the type of prime mover, is given below. For more details, consult Ref. 11.

Diesel Engine Systems. Diesel engine cogeneration plants may be fired by gas or distillate oil. The usual practice is to recover heat from the engine coolant and exhaust gases in a waste heat boiler, but the engine itself can be operated under ebullient cooling conditions. Stationary diesel engines are available in sizes from a few to 48,000 horsepower in a single unit. Figure 22 is a schematic diagram of a Diesel engine cogeneration system. Diesel engine-generator sets used by hospitals and other institutions as emergency stand-by power sources are not considered true cogeneration plants, since these are operated only periodically during operation and maintenance checks. However, some hospitals are considering operation of their stand-by diesel generators for peak shaving, and these systems may thus become objects of load research in the near future.

Gas Turbine Systems. Industrial gas turbines may be used as prime movers for generators with exhaust waste heat recovery. A typical commercially available system generates 500 kW and produces 3000 lb/h steam with an overall efficiency of up to 70%. Gas turbines come in simple or regenerative configurations and with single- or multiple-axle turbines and compressors. Some of these systems are illustrated in Figure 23. The rated generating capacity of turbine plants may range up to several hundred megawatts. Gas turbines have, of course, an advantage over diesel engines, in that essentially all of the turbine waste heat is in the form of a high-temperature exhaust gas suitable for recuperation and steam generation.

Steam Turbine Systems. Industrial steam turbines used in this country are generally of the axial flow type, although small radial flow (Pelton wheel type) machines also are used. Radial flow machines, while used in Europe, are not common in this country.[11] Steam turbines may be classified in a number of ways, but the characteristics of interest with respect to their use as prime movers in cogeneration systems are the pressure of the exhaust steam and

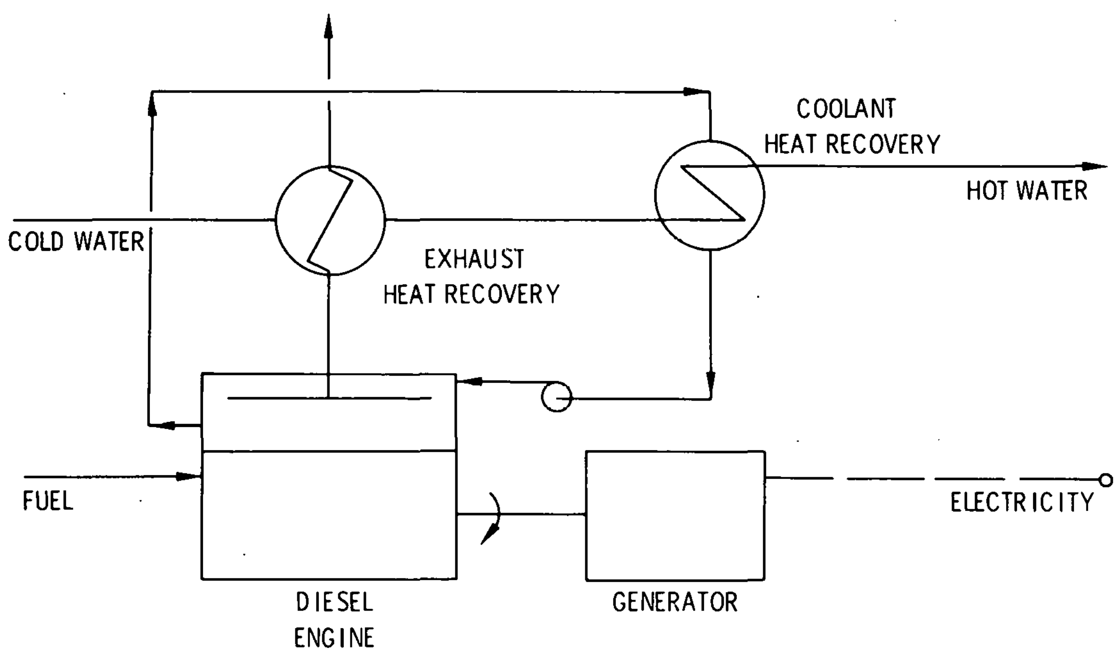
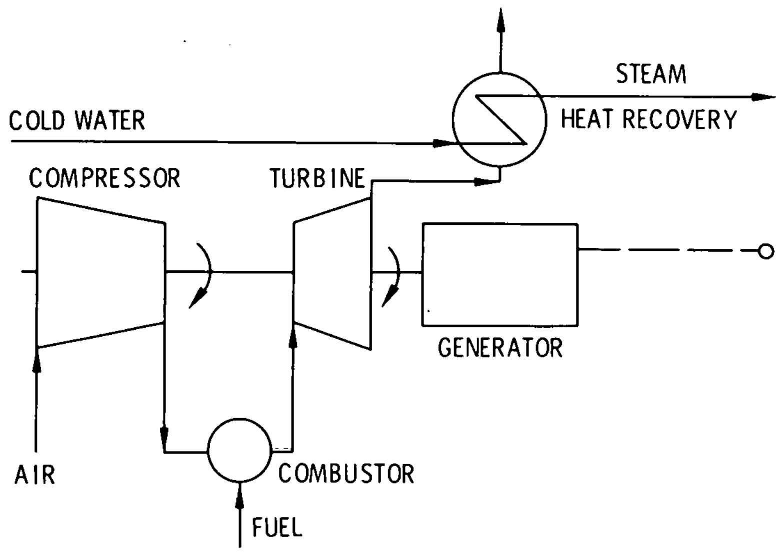
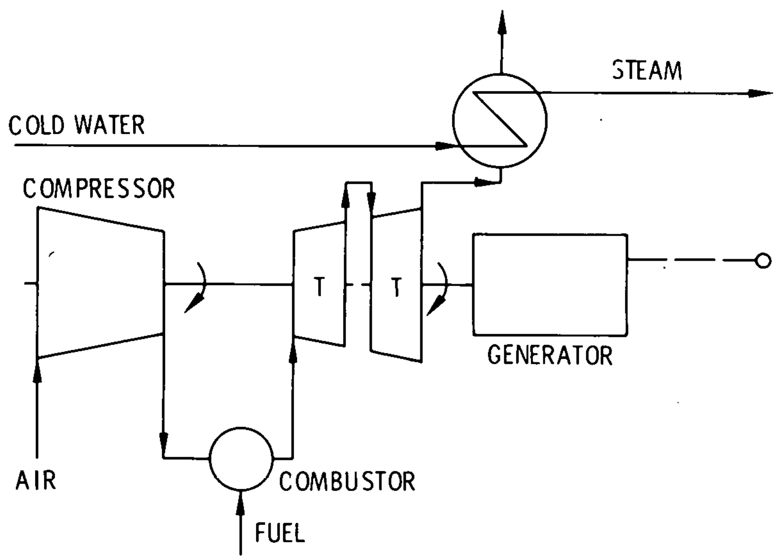


Fig. 22 Diesel Engine Cogeneration System



(a) Simple System



(b) Twin-Axle System

Fig. 23 Gas Turbine Cogeneration Systems

whether extraction or reheat is employed. A turbine that exhausts steam at a pressure above saturation conditions is a noncondensing or back-pressure turbine. One in which the exhaust steam is below saturation pressure is a condensing turbine. In an extracting turbine, part of the steam is withdrawn at a pressure between supply and exhaust (see Figure 24).

Combined-Cycle Systems. Combined-cycle cogeneration systems may be classified as either topping or bottoming systems. A topping system is one in

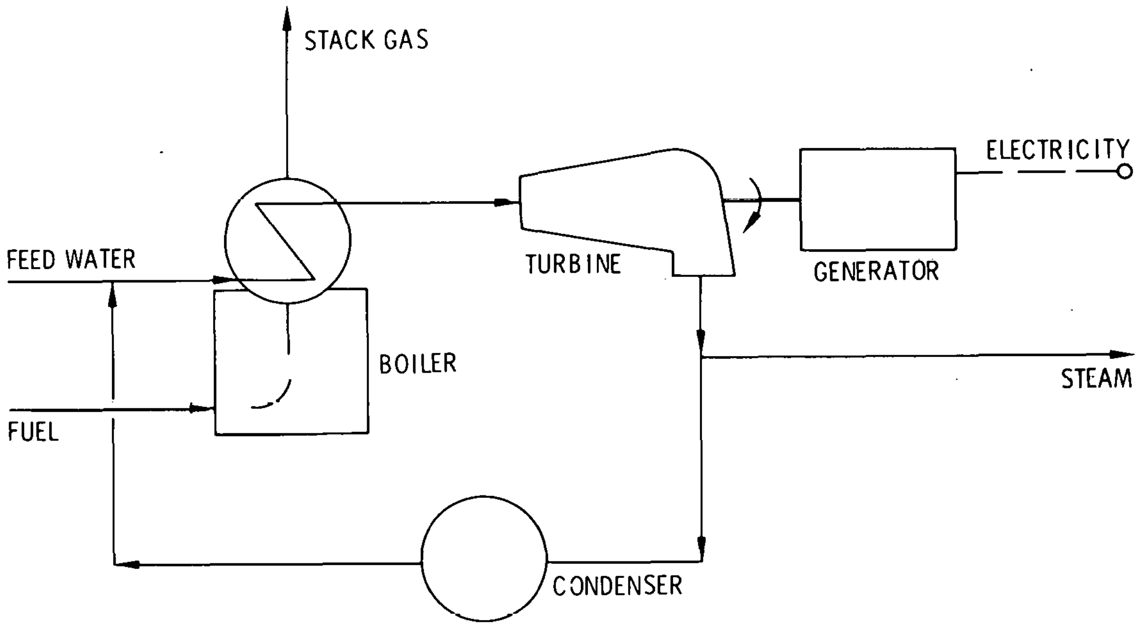


Fig. 24 Steam Turbine Cogeneration System

which power generation occurs "upstream" of steam production or direct heat recovery. Figures 25 and 26 illustrate two combined topping cycle cogeneration systems proposed for a community college and a new housing project.[33] Both systems use topping gas turbines, steam turbines, and auxiliary boilers. The community college scheme utilizes electric-motor-driven chillers, the housing project direct-drive chillers.

Power Recovery Systems. Power recovery from both gaseous and liquid process streams is sometimes practical. If the process stream is relatively clean and noncorrosive, direct power recovery using turboexpanders (gases) or reversible pump-turbines (liquids) may be feasible. If indirect power recovery is necessary, steam or organic Rankine-cycle bottoming turbines are used. The basic difference between these turbines and the topping systems discussed in the previous section is, of course, that in a bottoming system, thermal products are generated upstream of the power recovery step.

5.2 ENERGY PRODUCT DISTRIBUTION

Since cogeneration plants, by definition, produce more than one energy product, it is necessary to consider the:

- Time-varying absolute and relative production rates of electric power, steam, high-temperature hot water, and chilled water under full- and part-load operating conditions
- Time-varying demands for electricity and thermal products of the customers supplied by the plant

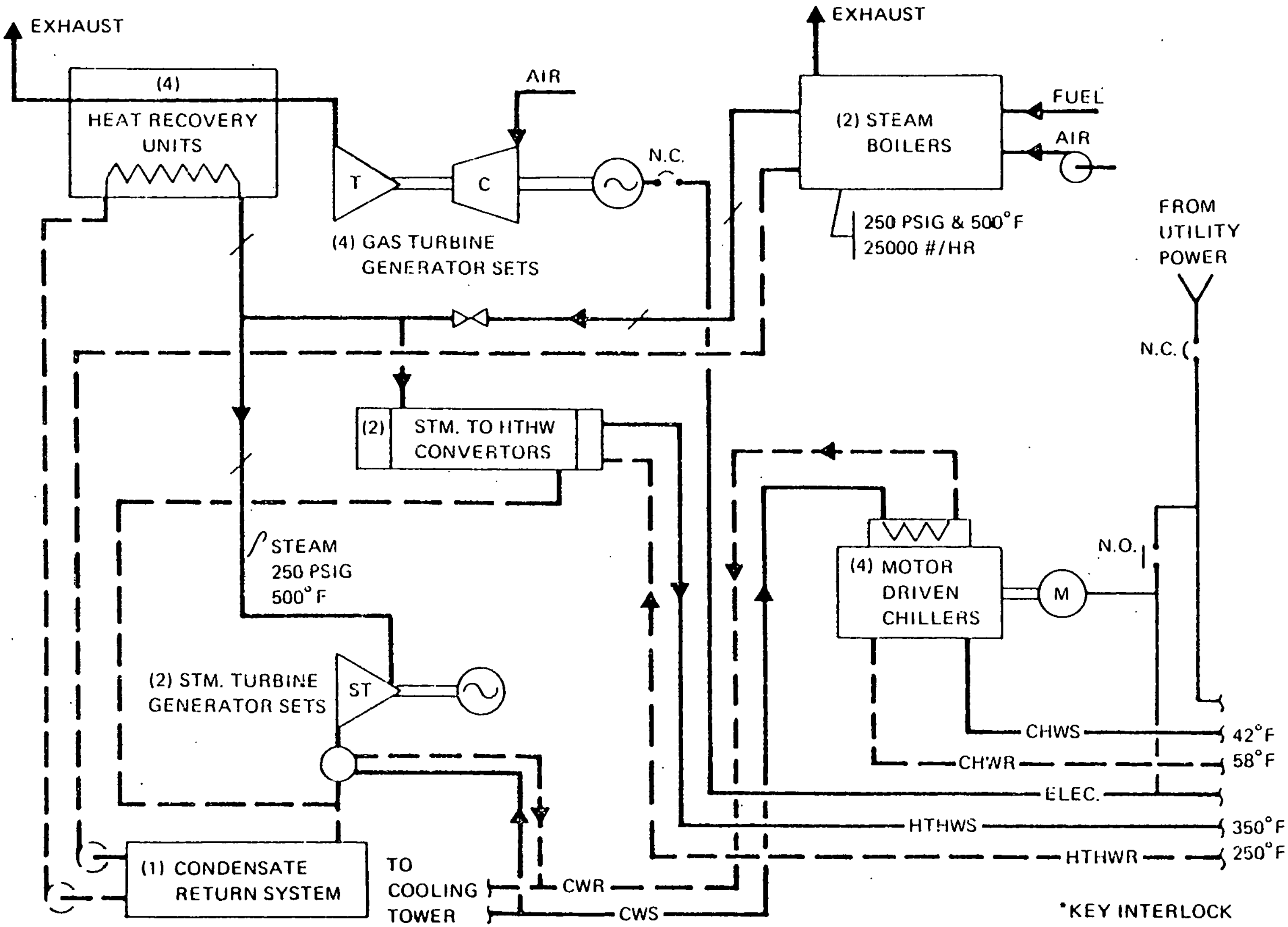


Fig. 25 Combined-Cycle Cogeneration Plant Using Gas and Steam Turbines, Proposed for Bronx Community College (source: Michael Baker Jr. of New York, Inc., by permission)

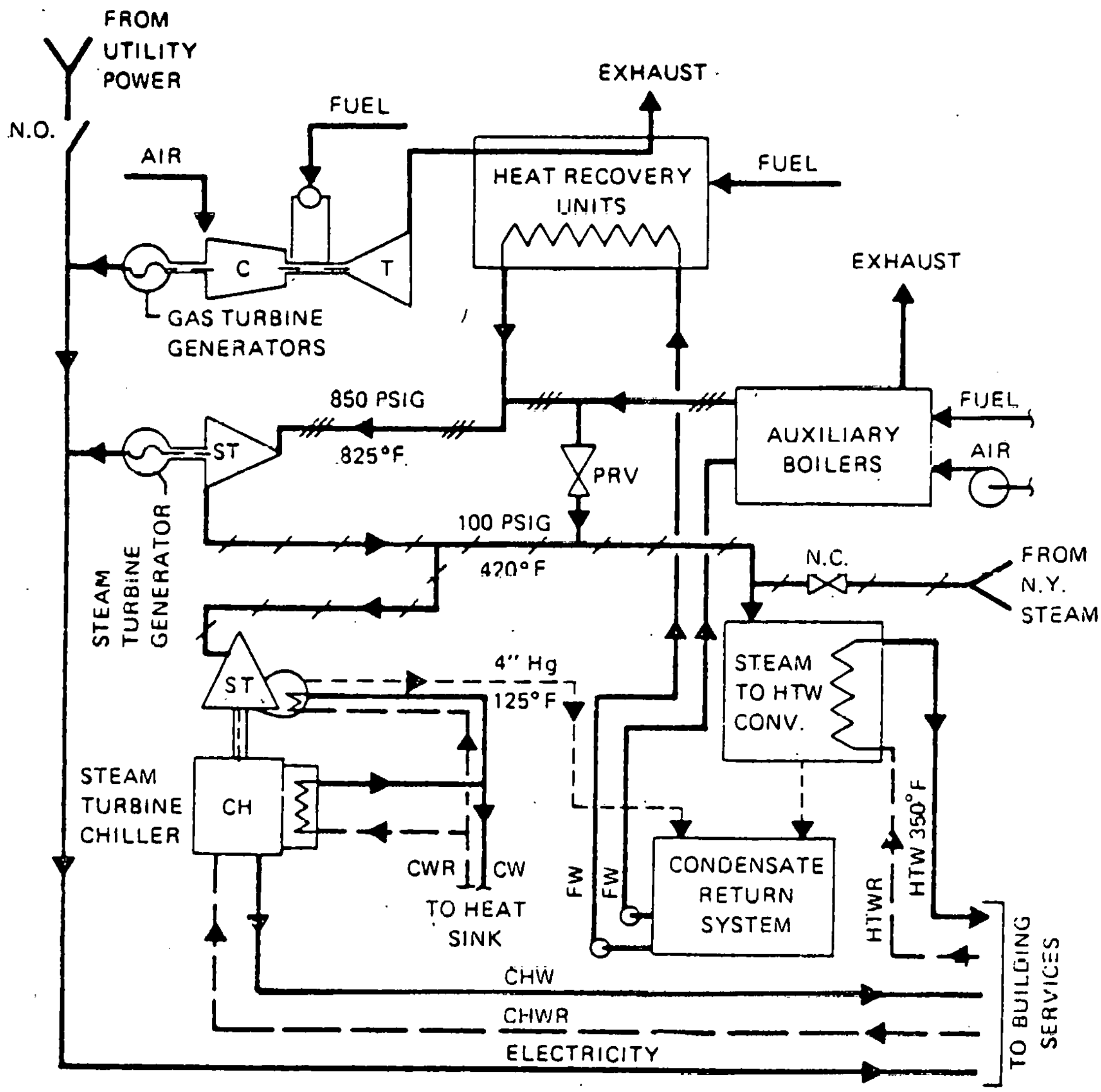


Fig. 26 Combined-Cycle Cogeneration Plant Using Gas and Steam Turbines, Proposed for Lower Manhattan Landing Project (source: Michael Baker Jr. of New York, Inc., by permission)

The amount of waste exhaust and cooling water heat is limited by the thermal efficiency of the system:

$$q_w = (1 - \eta_{th})H_{nc}\dot{m}_f$$

where:

q_w = theoretically recoverable quantity of waste heat available in Btu/h,

η_{th} = thermal efficiency of power generation (dimensionless),

H_{nc} = net heat of combustion of the fuel in Btu/lb, Btu/ft^3, or Btu/gal, and

$\dot{m}_f$ = rate of fuel consumption in lb/h, ft^3/h, or gal/h.

Because of this limitation, the higher the generation efficiency the lower the amount of theoretically recoverable waste heat. The fraction of this heat that can be recovered feasibly depends on the temperature of the waste streams. It is obvious, however, that prime movers whose waste heat is a high-temperature exhaust are to be preferred to those that reject part of the waste heat in the cooling water.

The relative electrical and thermal demands on the plant are of concern. In plant design and operation, some companies will give priority to electrical demand while others will give priority to thermal demand. As already stated, a cogeneration plant is designed to meet the demand for steam, hot water, or chilled water to the optimum degree and the electrical generation shortfall, if any, is made up by purchased power from the utility grid.

In summary, then, in cogeneration systems the two major aspects of operation to consider are the ratio of electrical to thermal product generation and the corresponding demands for these products.

5.3 INSTRUMENTATION PLANS AND COSTS

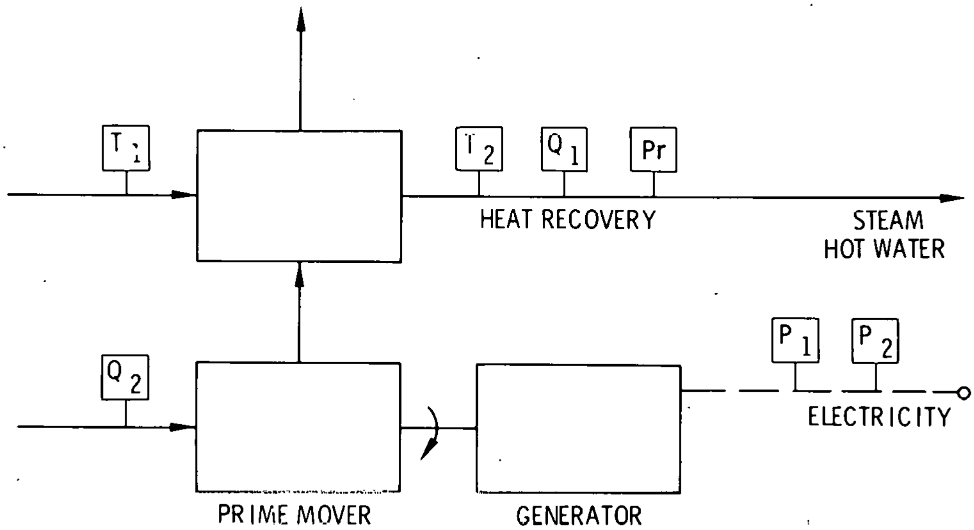
Because of the complexity and great variety of system configurations possible for cogeneration plants, recommendation of a generally applicable load research instrumentation scheme is not practical. As a minimum, however, power generation and demand and steam and hot water generation and demand should be monitored as well as the fuel consumption rate (for determination of overall system efficiency). Instrumentation of a cogeneration plant involves measuring the rate of consumption and generation of electricity and thermal products. The variables to be measured are listed in Table 9. Figure 27 is an example of an instrumentation scheme for a plant that produces power and steam.

It should be noted that the usual cogeneration scheme is much more complex than the simple diagram shown in Figure 27. If more than one prime mover, generator, or thermal product is involved, each appropriate input (e.g., fuel consumption rate, feedwater flow rate) and output (e.g., power generated, steam rate) must be measured if the thermal efficiency of each unit is to be computed. Line power when demand exceeds generation also should be determined. If the fuel consumed is pipeline gas or fuel oil, its thermal energy content (i.e., higher heating value) usually is stated by the supplying utility or vendor. However, it should be noted that fluctuations in fuel heating value can occur, especially if synthetic gas from a gasifier is used directly.

Instrumentation costs also may be estimated on the basis of a cost of $400-800 per point for enthalpy or "Btu" meters and $450-530 per point for power metering and recording (also see the cost estimates for polyphase watt-hour and Q-hour metering packages in Sec. 4.5 of this volume).

Table 9 Data Requirements for Cogeneration System Load Research

Measurement	Sensor Point in Fig. 27
Boiler feedwater temperature	T_1
Steam or hot water temperature	T_2
Steam pressure	Pr
Steam or hot water flow rate	Q_1
Fuel flow rate	Q_2
Active power generated	P_1
Reactive power generated	P_2



SENSOR	DESCRIPTION
T_1	FEEDWATER TEMPERATURE
T_2	STEAM SUPPLY TEMPERATURE
Pr	STEAM PRESSURE
Q_1	STEAM FLOW RATE
Q_2	FUEL FLOW RATE
P_1	ACTIVE POWER
P_2	REACTIVE POWER

Fig. 27 Instrumentation Plan for a Cogeneration System

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