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Measurement and Analysis of Domestic Hot Water Loads of Three Navy Buildings at Memphis Naval Air Station, Millington, Tennessee: Implications for Decentralized Small Cogeneration

Lance N. McCold
Nyle S. Bishop

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ENERGY DIVISION

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ABSTRACT

Decentralized small cogeneration is the use of cogeneration equipment with electric generating capacities less than 500 kW at individual buildings or building complexes served by a common mechanical equipment room. Cogenerated heat could be used in Navy buildings for space heating, space cooling, or domestic water heating. In most climates, production of domestic hot water is the best use for cogenerated heat because it is needed virtually every day of the year. The Navy initiated this study because information on domestic hot water usage in Navy buildings was either non-existent or of insufficient quality and reliability to confidently design a small cogeneration installation.

Hourly domestic hot water data were measured by a flow meter and temperature sensors and recorded by an electronic data logger. The data were plotted to display their characteristics, and they were analyzed with a simple heat storage model to examine the effects of heat storage on the utilization and proper sizing of a cogeneration system.

EXECUTIVE SUMMARY

Introduction

Decentralized small cogeneration is the use of cogeneration equipment with electric generating capacities less than 500 kW at individual buildings or building complexes served by a common mechanical equipment room. Cogenerated heat could be used by Navy buildings for space heating, space cooling, or domestic water heating. In most climates, production of domestic hot water is the best use for cogenerated heat because it is needed virtually every day of the year. The Navy and ORNL initiated this study because information on domestic hot water usage in Navy buildings was either non-existent or of insufficient quality and reliability to confidently design a small cogeneration installation.

The purpose of this study was to develop and analyze high-quality domestic hot water usage data so that dispersed small cogeneration systems could be designed for three Navy building types: barracks, dining halls, and hospitals.

Approach

Hourly domestic hot water data were measured by a flow meter and temperature sensors and recorded by an electronic data logger. The data were plotted to display their characteristics, and they were analyzed by a simple heat storage model to examine the effects of heat storage on the utilization and proper sizing of a cogeneration system.

Results

The domestic hot water loads of the three buildings are quite distinct, both in magnitude and in the pattern of variability. Several graphical load presentations are given and discussed for each building.

Relationships of the amount of heat supplied by cogeneration, the utilization of the cogeneration unit, and the frequency of on-off cycles to the relative magnitude of heat production rate, hot water use rate, and heat storage rate are presented in graphical form and discussed.

The benefits of heat storage are substantial, but the marginal benefits decline rapidly beyond about 8 hours of storage. The best cogeneration system performance is found where the heat production rate approximately equals the average hot water energy use rate.

Conclusions

With average loads of 350,000 and 1.1 million Btu's per hour, the 600-person barracks and the 8,000 meal per day-days dining hall are large enough to support economical decentralized small cogeneration systems. At 90,000 Btu/h, the hospital's average domestic hot water load is probably too small to support an economical application of presently available small cogeneration systems. The hospital investigated here may or may not be typical of other Navy hospitals.

Cogeneration system performance suffers substantially if the equipment is oversized. Measurement and analysis of the domestic hot water consumption of individual buildings for which the small cogeneration system is being designed can be expected to lead to reduced capital and operating costs and increased operating efficiency.

1. INTRODUCTION

As part of an effort to reduce energy consumption, the Navy is examining new energy conservation technologies, one of which is decentralized small cogeneration — the use of cogeneration equipment with electric generating capacities less than 500 kW at individual buildings or building complexes served by a common mechanical equipment room. A feasibility study found that decentralized small cogeneration is economically feasible under certain conditions at several Navy shore bases.[1] One of these conditions is that a building or complex served by small cogeneration have a use for all the cogenerated heat produced by the cogeneration system.

Cogenerated heat could be used in Navy buildings for space heating, space cooling, or domestic water heating. In most climates, production of domestic hot water (DHW) is the best use for cogenerated heat because it is needed virtually every day of the year. Also, the auxiliary equipment needed to heat domestic water with cogenerated heat is generally less expensive than the equipment needed to heat or cool a building with cogenerated heat.

The Navy initiated this study because the available information on DHW usage in Navy buildings was either non-existent or of insufficient quality and reliability to support the design of a small cogeneration installation. The purpose of this study was the development of high-quality DHW usage data so that dispersed small cogeneration systems could be designed for certain Navy buildings. Several building types have been identified as suitable for small cogeneration applications,[1] the most promising of these being hospitals, barracks complexes, and dining halls.

DHW usage was measured at a hospital, an enlisted personnel dining hall, and a barracks complex at the Memphis Naval Air Station (NAS), Millington, Tennessee. The NAS was selected for this monitoring effort because the facilities' personnel were interested and because it is relatively close to Oak Ridge National Laboratory (ORNL). Since DHW energy usage depends little on climate, the choice of NAS or any other Navy base has little effect on the results.

Section 2 describes the literature review and the experimental and analytical approaches followed in this study. The three buildings are described, and the techniques used to measure the DHW loads are explained, as is the framework within which the data were analyzed.

Section 3 describes the data and results of the analysis. This analysis includes weekly and daily DHW load profiles for the three buildings. The effects of heat storage on mating cogeneration to the buildings are examined. Also, the implications of the loads and heat storage effects on small cogeneration are considered.

Section 4 summarizes the findings of the study and makes recommendations on the relations between building type, size, and use, and cogeneration and heat storage equipment sizes. Uncertainties and topics needing further work are also discussed in this section.

2. APPROACH

2.1 LITERATURE REVIEW

Residential domestic water heating accounts for 3% of the nation's energy consumption and about 14% of the energy consumption of the residential sector.[2,3] In spite of the importance of domestic water heating, not much is known about its use.

The two characteristics of DHW usage, which need to be known for efficient small cogeneration system design, are the variability of DHW usage from day to day and the variability (from hour to hour) of DHW usage within a day. A small cogeneration system that is not operating or that wastes heat while operating because it produces more heat than can be used by the building is either not making money or not making as much money as it could if properly designed. If the variability of DHW usage is known, a cogeneration system can be designed that will operate full-time and seldom produce unneeded heat.

Werden and Spielvogel[4] have published the most extensive data on DHW usage. They reported on dormitories, motels, nursing homes, office buildings, restaurants, apartments, and schools. Their interest was on sizing water heating equipment; in fact, their recommendations have been adopted by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) in their Systems Handbook.[5] Unfortunately, these data are of little help in sizing small cogeneration equipment because minimum hot water loads are needed, not maximum loads. The average DHW loads they present could be used as an upper bound on reasonable cogeneration system size, but one must guess how much less heating capacity a cogeneration system should have than the average DHW load. The data are also insufficient for sizing the heat storage component of a cogeneration system.

Hu et al.[6] measured and analyzed energy usage at several U.S. Army dining halls. They studied three dining halls, Bldgs. 8402, 3701, and 3206, at Fort Lee, Virginia. They reported that electricity was the leading component of energy expenditures and that water heating was the second largest energy expenditure component. They also reported that an average of about 5.5 gal of hot water is used for each meal served at Bldg. 8402. Table 2.1 shows that hot water use in these three dining halls is quite similar when calculated on a per meal basis. It also shows that hot water usage is poorly correlated to dining hall size. If corroborated by other studies, the finding that hot water use is closely related to the number of meals served can be very helpful to the design and sizing of decentralized small cogeneration systems used at dining halls.

A study by the NUS Corporation[7] examined the energy use of Kimborough Army Hospital at Fort Meade, Maryland. The hospital was built in 1958 and has about 195,000 ft^2 of floor area and about 300 beds. The study reports a domestic water heating energy consumption of 100×10^6 Btu/year, or about 27×10^3 Btu/d. This is a factor of about 100 less than estimated by ref. 1. The values presented in both ref. 1

and ref. 7 are estimates, not the result of direct measurement.

Table 2.1. Average hot water usage in three dining halls at Fort Lee, Virginia

Building number	Floor area (ft^2)	Average meals (per day)	Hot water (gal/d)	Hot water use intensity gal / $d\text{-}ft^2$	gal / meal
8402	12,141	1,988	8,671	0.71	5.46
3701	4,700	1,050	4,780	1.02	4.57
3206	9,029	655	3,310	0.37	5.05

Source: ref. 6.

Two studies report on DHW consumption in barracks. Messock[8] measured the steam consumption of Bldg. 3742 at the Naval Air Rework Facility, Cherry Point, North Carolina. Building 3742 reportedly houses 250 people. According to Messock's measurements and assumptions, an average of about 21.6 gal/d/person is used. Messock's measurements were made with an insertion turbine flow meter on the steam side of the water heater. Steam consumption was measured hourly over the course of 7 d. Messock's hourly measurements are reproduced in Table 2.2.

The information presented by Messock is the kind needed for designing small cogeneration systems. There are, however, a number of characteristics of Messock's data which suggest that more such data are needed. The steam flow meter that Messock used is relative insensitive to low steam-flow rates. Substantial under-reporting of low flows could mean that actual daily consumption was as much as 10% larger than

Table 2.2. Domestic water heating steam consumption of a 250-person barracks, Bldg. 3742, at the Naval Air Rework Facility, Bldg. 3742, at Cherry Point, North Carolina average steam consumption (measured in lb/h), June 13-19, 1980[a]

Time	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday
0000	b	0	0	0	b	b	0
0100	b	0	0	0	b	b	b
0200	b	96	0	0	b	b	b
0300	b	550	0	0	b	b	b
0400	b	0	0	0	b	b	b
0500	b	0	0	0	b	b	b
0600	b	0	0	68	b	b	b
0700	b	0	270	960	b	b	b
0800	b	0	369	0	b	0	b
0900	b	28	0	0	b	0	b
1000	0	873	0	0	b	0	b
1100	0	0	0	0	b	0	b
1200	0	0	755	0	0	232	b
1300	0	282	0	0	0	387	b
1400	0	489	0	0	0	74	b
1500	0	0	0	0	0	488	b
1600	0	0	0	898	0	0	b
1700	353	0	457	0	825	430	b
1800	0	0	206	b	0	0	b
1900	121	462	0	b	0	0	b
2000	684	317	0	b	465	0	0b
2100	0	0	0	b	615	0	b
2200	0	0	543	b	0	0	b
2300	0	0	158	b	0	617	b
Daily total	c	3097	2758	c	c	c	c
Average consumption	c	129	115	c	c	c	c

[a]Data are from a study by Messock of the Naval Energy and Enviromental Support Activity.[8]

[b]No data for this hour because of instrumentation problems.

[c]Not applicable.

reported. Messock also assumed that the steam-to-hot-water conversion efficiency was 80%. Because conversion efficiencies could be between 70 and 90%, the actual hot water consumption could be 10% greater or less than estimated. While Bldg. 3742 is reported to be a 250-person barrack, the actual number of occupants at the time of the test was not reported, so a calculated DHW use per person per day is subject to further uncertainty. Finally, only 3 d of uninterrupted data were recorded, and these data include a Saturday, a Sunday, and parts of a Friday and a Monday. These concerns point up the need for further measurements of DHW usage in barracks.

Shelton[9] reports on another study that includes measurement of DHW usage in barracks. Shelton measured water heater run-time in two barracks. Table 2.3 presents hourly summaries of the run-time measurements. Building 841 of Elgin Air Force Base (AFB) had 99 occupants at the time of the test. Building 143 at MacDill AFB had 100 occupants during the measurements. Based on the rated water heating capacities, the measured run times and, apparently, assumed water temperature rises, Shelton calculated hot water consumption of 28 and 30 gal/d/person.

Comparison of Table 2.2 and 2.3 shows quite different hot water use patterns. Table 2.2 shows large peaks of hot water use at 4- to 10-h intervals, while Table 2.3 implies a more steady hot water use rate with fewer large peaks. Some of the difference might be attributed to the different measurement techniques, but the relative lack of large peaks

Table 2.3. Measured water heater run times in barracks at two Air Force bases.
(measured in minutes)

	Elgin AFB Building 841		MacDill AFB Building 143			
Time hour begins	7-28 Mon	7-29 Tues	8-8 Fri	8-9 Sat	8-10 Sun	8-11 Mon
0000		3.5		0	0	8
0100		3.5		8	6	8
0200		0.0		0	0	0
0300		3.5		10	0	10
0400		3.5		0	8	10
0500		8.0		0	0	10
0600		14.0		8	9	11
0700	5.0	4.0		0	0	9
0800	17.5			9	8	0
0900	6.5			0	0	8
1000	3.5		9	10	9	
1100	5.5		0	10	10	
1200	4.0		9	10	9	
1300	7.5		10	9	10	
1400	7.5		0	0	10	
1500	7.0		0	0	10	
1600	4.0		9	9	9	
1700	8.0		9	0	9	
1800	7.0		0	10	9	
1900	7.0		16	9	0	
2000	7.5		8	8	9	
2100	3.5		9	10	9	
2200	7.0		0	0	9	
2300	0.0		9	8	0	

Source: ref. 9.

in Shelton's data suggests that the building's use patterns were quite different.

The existence of some DHW use data for barracks (collected for other purposes) gives designers of decentralized small cogeneration applications a place to start, but the quantity and quality of the data are so limited that the designer must make conservative choices or take substantial risks. For dining halls, the situation is less certain still. However, if one accepts that about 5 gal/meal is used, and if the designer has records of the numbers and time of meals served in a dining hall, he could roughly estimate the appropriate cogeneration module and heat storage capacities. There are virtually no published data to guide the design of a decentralized small cogeneration system for a hospital.

2.2 BUILDING DESCRIPTIONS

DHW consumption was monitored at three buildings on the Memphis NAS and Naval Regional Medical Center (NRMC) located at Millington, Tennessee. The relative locations of the NAS, the NRMC, Millington and Memphis, are illustrated in Fig. 2.1. Memphis has a warm climate, with an average winter temperature of about 51°F and about 3200 annual heating degree days. The domestic water at the NAS and NRMC comes from water wells and a treatment plant located on the NAS, so the domestic water temperature will be fairly constant throughout the year.

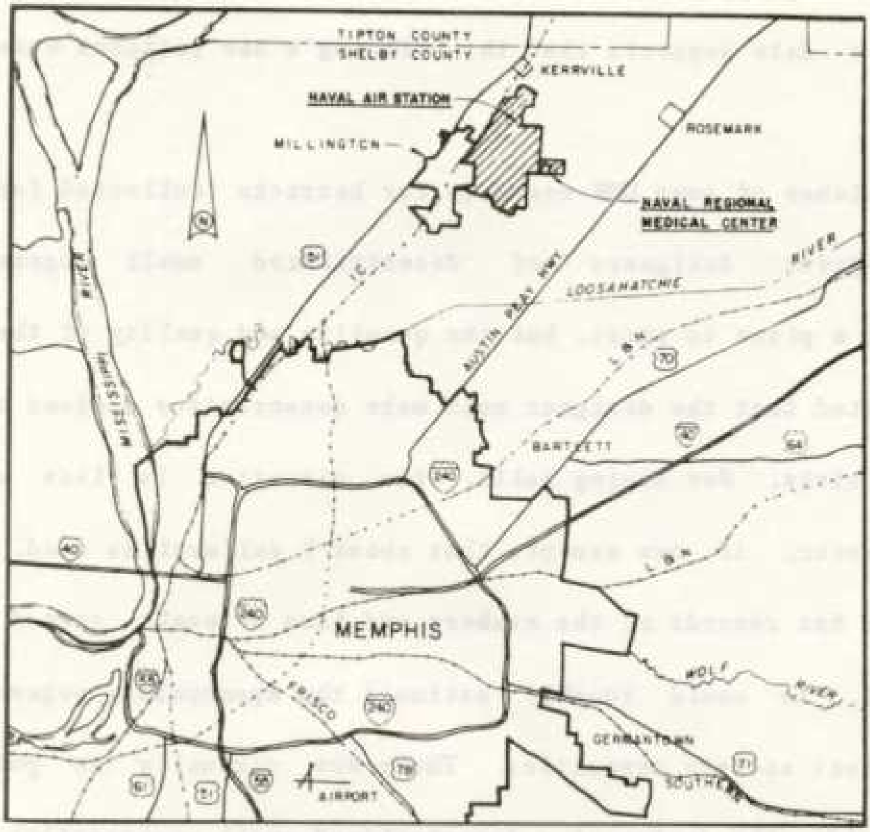


Fig. 2.1. Memphis Naval Air Station area map.

Fig. 2.2. Naval Regional Medical Center Hospital (Bldg. 100).

The three monitored buildings are a hospital (Bldg. 100) at the NRMC, a community/mechanical equipment building (Bldg. 437) that serves a complex of barracks (Bldgs. 435-440), and Ellison Dining Hall (Bldg. 499). Building 499 and building complex 435-440 are located on the NAS. Each building and its use is described in detail below.

Building 100 is a six-story hospital with a floor area of about 220,000 ft^2 (Fig. 2.2). It has a design capacity of 230 beds; however, during the monitoring period, the average number of beds occupied was 62 per night, with a high of 93 and a low of 47 persons per night. In addition, an average of 382 outpatients and 560 staff occupy the building each day. Also, the hospital has a kitchen that prepares meals for patients and staff.

Building 100 has three 10-million-Btu/h natural-gas-fired boilers that provide 90-psig steam for space heating, space cooling, and DHW. There are two DHW systems in use at the hospital. The original DHW system consisted of two 2400-gal tanks, each of which is heated by a 1.6-million-Btu/h steam coil. After completion of the hospital, guidelines established by the Joint Commission on Accreditation of Hospitals limited hot water temperature in patient and treatment rooms to 120°F. Because the kitchen needed 140°F hot water, a separate instantaneous-type water heater capable of raising the temperature of 1920 gal of water 80°F in an hour was installed to serve the kitchen only. Only the original DHW system (which serves everything except the kitchen) was monitored in this study because of project funding constraints.

Building 437 (Fig. 2.3) is a combination community and mechanical equipment building which serves a complex of five three-story barracks, Bldgs. 435, 436, and 438-440. Each barracks building has 21,081 ft^2 of floor area and a design occupancy of 123 persons. During the monitoring period, the occupancy of the five barracks was as shown on Table 2.4. Occupancy above design levels is the usual situation for these barracks.

DHW is produced in two large storage tanks, each of which has a capacity of 430 gal. Each water heater has a steam coil with a rated heating capacity of 1.8 million Btu/h. The steam comes from the NAS's central steam plant. The water supply temperature is usually between 120 and 125°F, but surges up to 140°F have been recorded in the log book in Bldg. 437.

Building 499, Ellison Dining Hall, (Fig. 2.4) has a floor area of 44,200 ft^2. The dining hall serves an average of about 8200 meals/d, with about 9200 meals/d on weekdays and 5100 meals/d during weekends.

Domestic water is heated in two large storage tanks, each of which has a capacity of 1300 gal. Each water heater has a steam coil with a rated heating capacity of 1.63 million Btu/h. Like the barracks, the steam comes from NAS's central steam plant. The hot water supply temperature was observed to be about 145°F. The hot water used by the dishwashers is heated further by a separate system to sanitize the dining utensils.

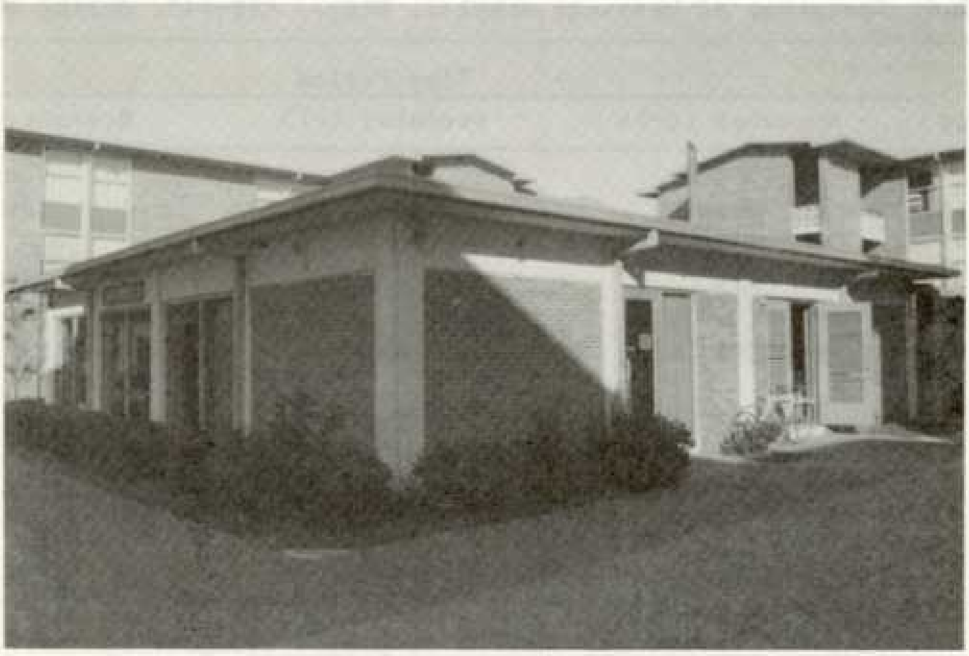


Fig. 2.3. Barracks complex, Mechanical Building (Bldg. 437).

Fig. 2.4. Ellison Dining Hall (Bldg. 499).

Table 2.4. Occupancy of barracks complex, Bldgs. 435-440, during monitoring.

Building	Time Period		
	November 16-30	December 1-15	December 16-31
435	Vacant	196	184
436	172	195	205
438	145	198	132
439	173	205	117
440	205	205	205
Total	695	999	843

Note: These are the numbers of people assigned to these buildings as reported to the author by Mr. Walter Reese, Personnel Supplies Equipment Coordinator, Memphis Naval Air Station, May 31, 1985. Some personnal may not actually reside in their assigned barracks during training exercises. Mr. Reese reported that the Christmas holidays, which find many personnel off the base, began December 19.

2.3 MEASUREMENT OF DOMESTIC HOT WATER LOADS

The DHW monitoring system used in this project measured and recorded the volume (gal) of DHW consumed and the quantity (Btu) of heat imparted to the DHW consumed. This monitoring system consists of three parts. The DHW consumption measurement was performed by a Sonceboz Thermal Energy Metering System (TEMS). The data were logged at hourly intervals by a Campbell Scientific 21X Micrologger at Bldgs. 437 and 499, and by an Autodata Ten/10 at the hospital. At weekly intervals, the logged data were mailed to ORNL, where the data were transferred to a magnetic storage medium.

The Sonceboz TEMS consists of three principal components: a water flow meter, a pair of temperature sensors for hot and cold temperature measurements, and an electronic integrator that measures and displays the volume and the amount of heat added to the water. Figure 2.5 is a schematic of the TEMS and data acquisition system. The flow meter measures the amount of water flowing into the water heater by making a contact closure that is read by the electronic integrator for each 10 gal flowing into the water heater. The temperature sensors measure the temperatures of the water entering the water heater (cold side) and the temperature of the water leaving the water heater (hot side). As the volume is recorded, the temperature difference is also measured by the electronic integrator. The electronic integrator multiplies the volume which has passed by the temperature difference and the heat capacity of water to arrive at the heat imparted to the water. The electronic

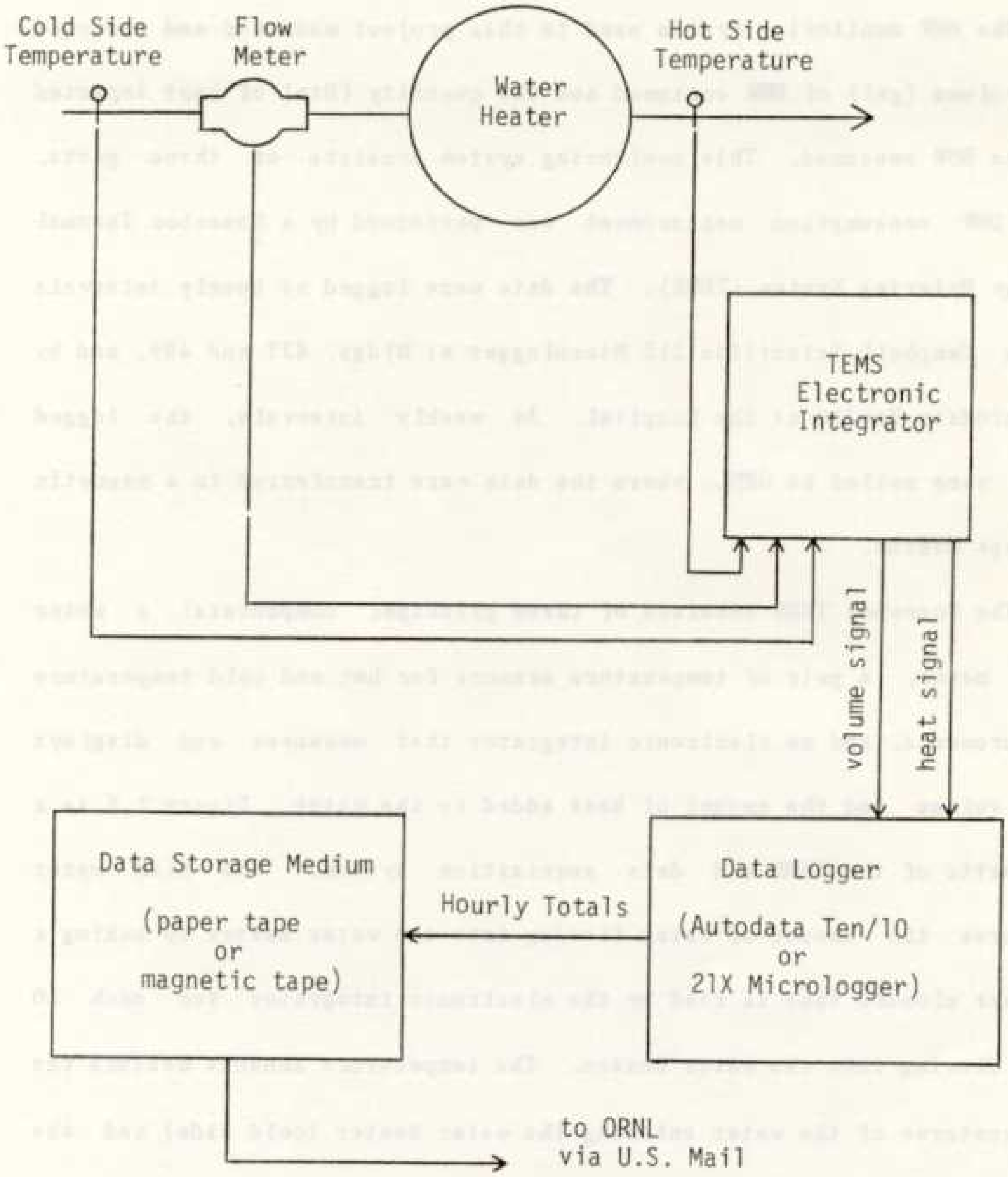


Fig. 2.5. Thermal energy metering system and data acquisition system.

integrator then displays the quantities of volume (U.S. gallons) and energy (10^5 Btu) on odometer-type counters. Tests of the TEMS and their results are described in Appendix A.

The data were recorded on an hourly basis by a data acquisition system (illustrated by Fig. 2.5). The Sonceboz electronic integrator transmits a pulse signal for each unit counted by the electronic integrator's gallon and Btu registers. This signal was read by a datalogger equipped with an internal clock and programmed to receive the Btu and gallon signals and total them each hour. The final data for each hour included the date, time, total volume (gallons) for the hour, and total energy (10^5 Btu) imparted to the water for the hour. The data were recorded on paper tape by an Autodata Ten/10 at the hospital (Bldg. 100) and on magnetic tapes by Campbell Scientific 21X Micrologger systems at the barracks (Bldg. 437) and galley (Bldg. 499). Tests of the data acquisition system and their results are described in Appendix B.

The paper tapes and magnetic tapes were collected and mailed to ORNL to be read and checked weekly. The data, on paper tapes, from the hospital were manually entered onto a personal computer. The data on the cassette tapes were transferred to an IBM personal computer through a Campbell Scientific C20 card. The software that accompanies the C20 card prompts the recorder to transfer the data to the computer.

2.3.1 Hospital Installation

The DHW monitoring system was installed at the NRMC hospital, Bldg. 100, on September 13, 1984. Because the 21X Microloggers had not yet been received from Campbell Scientific, an Autodata Ten/10 datalogger was installed at the hospital. The hospital routinely operates on only one of its two water heaters, switching from one to the other periodically. Water heater 2 was used from the beginning of the data collection period to its end on November 19, 1984. While the hospital's DHW system is equipped with a recirculation system, it is used during only a limited part of the year, and it was not in operation during the monitoring period.

The hot and cold temperature sensors were located as shown in Fig. 2.6. The hot temperature sensor was installed in a thermometer well located at the top of the tank in use. Due to lack of space and excessive heat in the mechanical equipment room, the datalogger and the electronic integrator were located in the basement adjacent to the equipment room.

2.3.2 Dining Hall and Barracks Installations

The dining hall and the barracks monitoring equipment installations were performed November 19 and 20, 1984. These installations were quite similar. They both utilized a lockable utility box housing a TEMS electronic integrator, a Campbell Scientific 21X Micrologger, a Panasonic Model RQ-8300 cassette recorder, and extra cassette tapes.

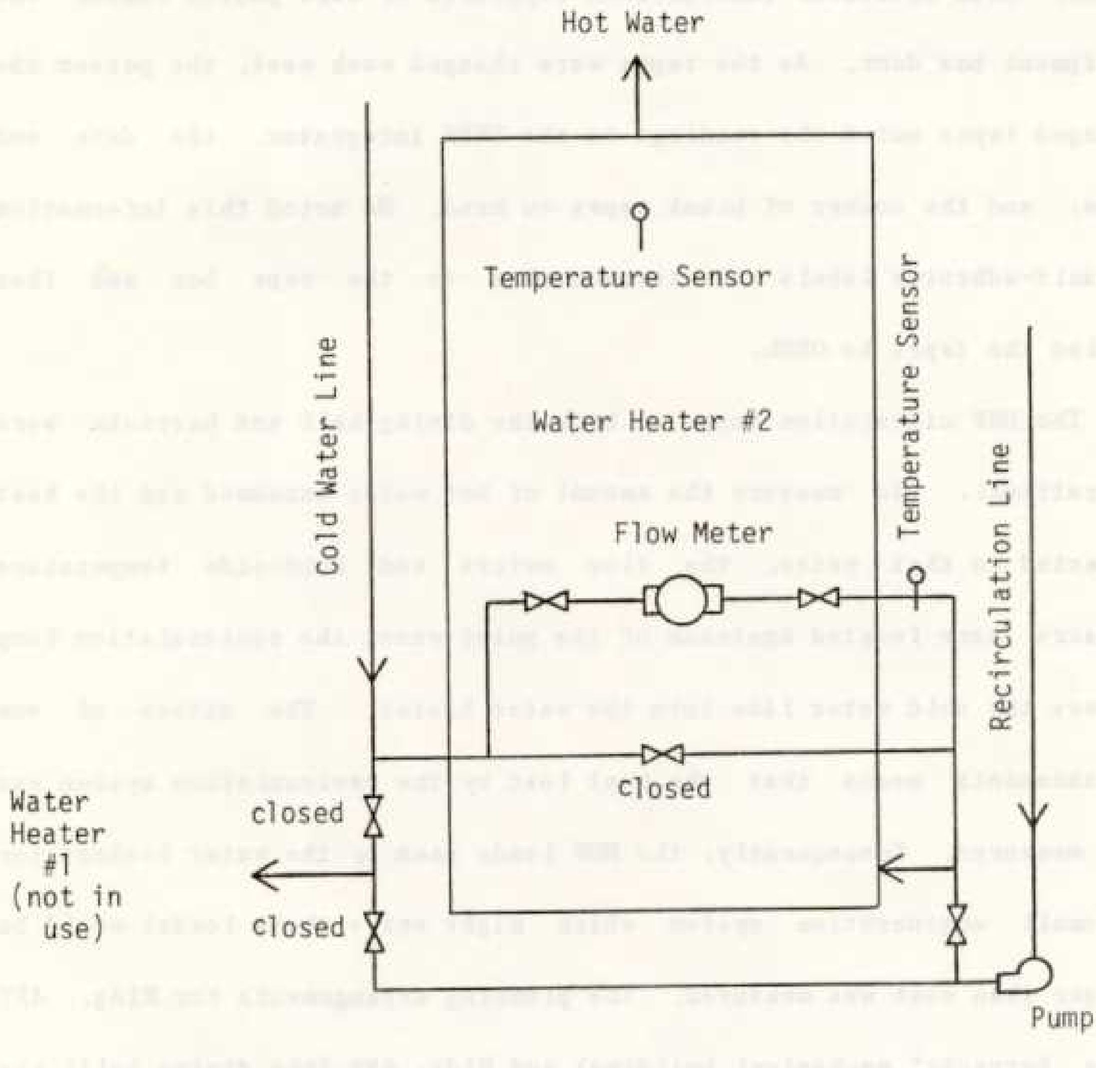


Fig. 2.6. Thermal energy meter plumbing for Bldg. 100.

Figure 2.7 shows the utility box with the instrumentation equipment in place. Data retrieval instructions (Appendix C) were posted inside the equipment box door. As the tapes were changed each week, the person who changed tapes noted the readings on the TEMS integrator, the date and time, and the number of blank tapes on hand. He noted this information on self-adhesive labels and attached them to the tape box and then mailed the tapes to ORNL.

The DHW circulation loops in both the dining hall and barracks were operational. To measure the amount of hot water consumed and the heat imparted to that water, the flow meters and cold-side temperature sensors were located upstream of the point where the recirculation loop enters the cold water line into the water heater. The nature of our measurements means that the heat lost by the recirculation system was not measured. Consequently, the DHW loads seen by the water heaters (or a small cogeneration system which might serve these loads) would be larger than what was measured. The plumbing arrangements for Bldg. 437 (the barracks' mechanical building) and Bldg. 499 (the dining hall) are illustrated in Fig. 2.8. Figure 2.9 is a photograph of the Bldg. 437 installation and Fig. 2.10 is a photograph of the Bldg. 499 installation.

2.4 ANALYSIS

The most cost-effective small cogeneration systems will be those which can run full-time and have all of their thermal and electrical

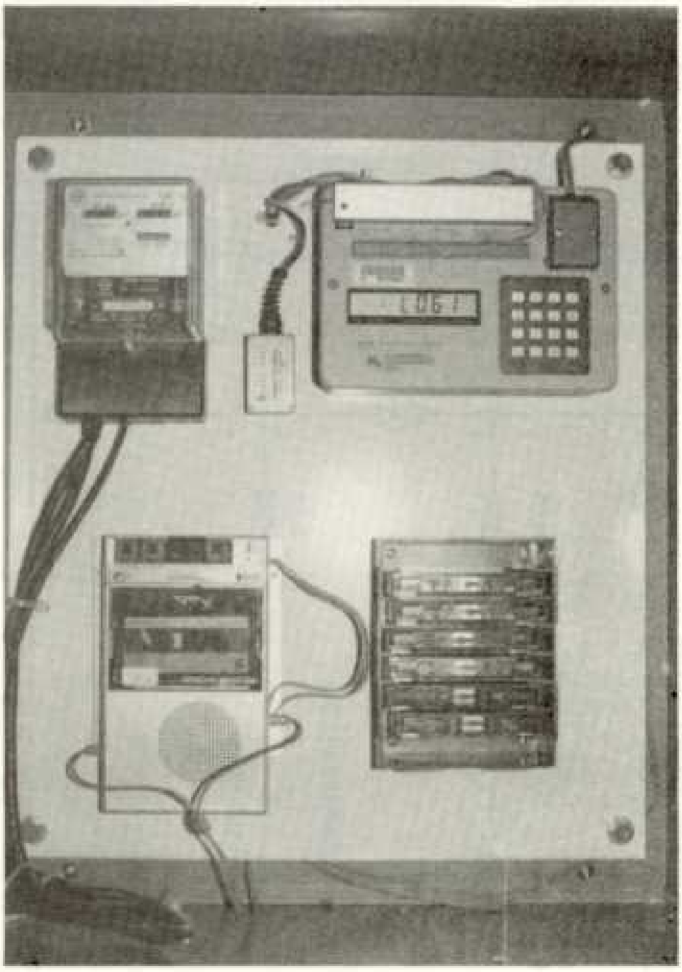


Fig. 2.7. Thermal energy monitoring system integrator and data acquisition system in utility box.

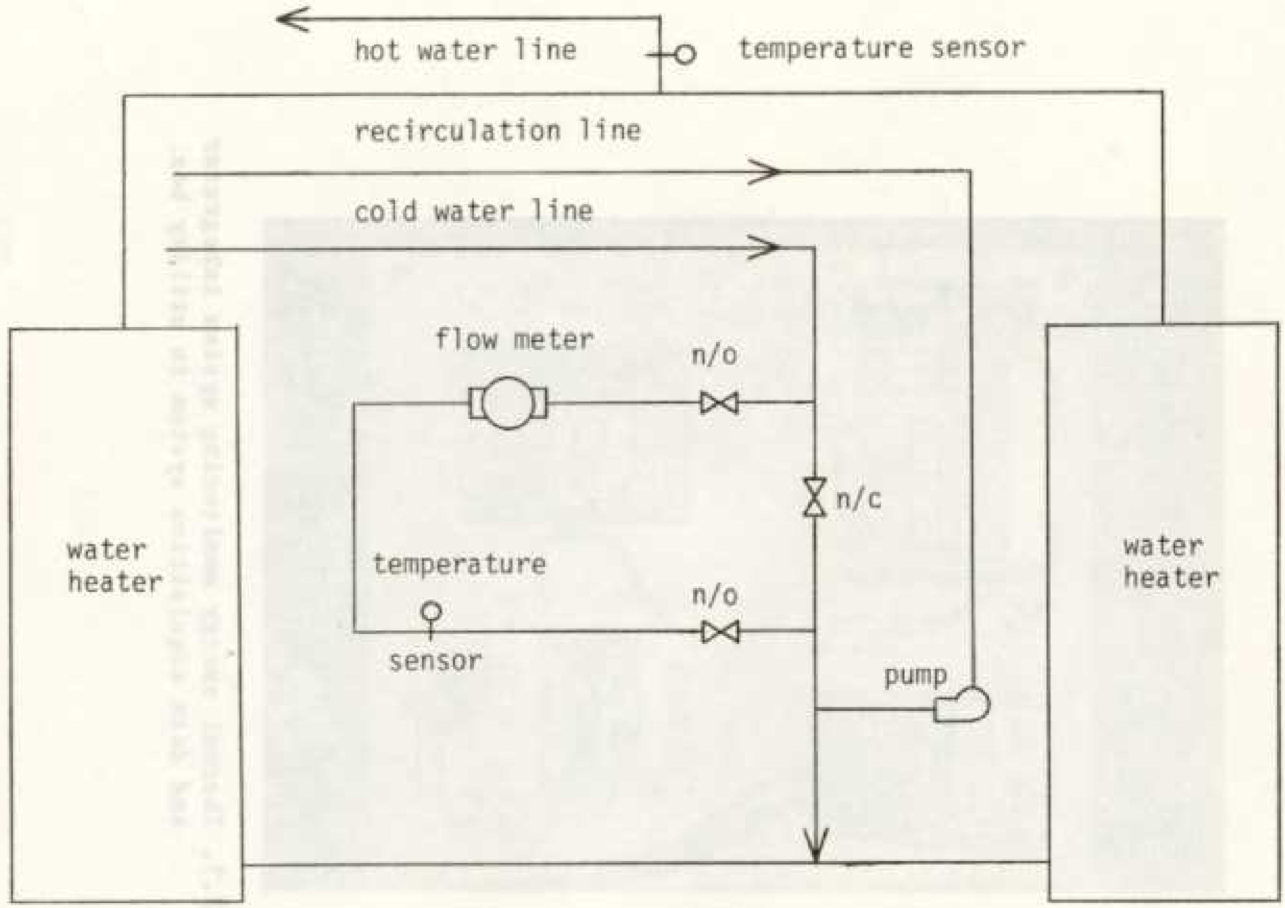


Fig. 2.8. Thermal energy meter plumbing, typical for Bldgs. 437 and 499.

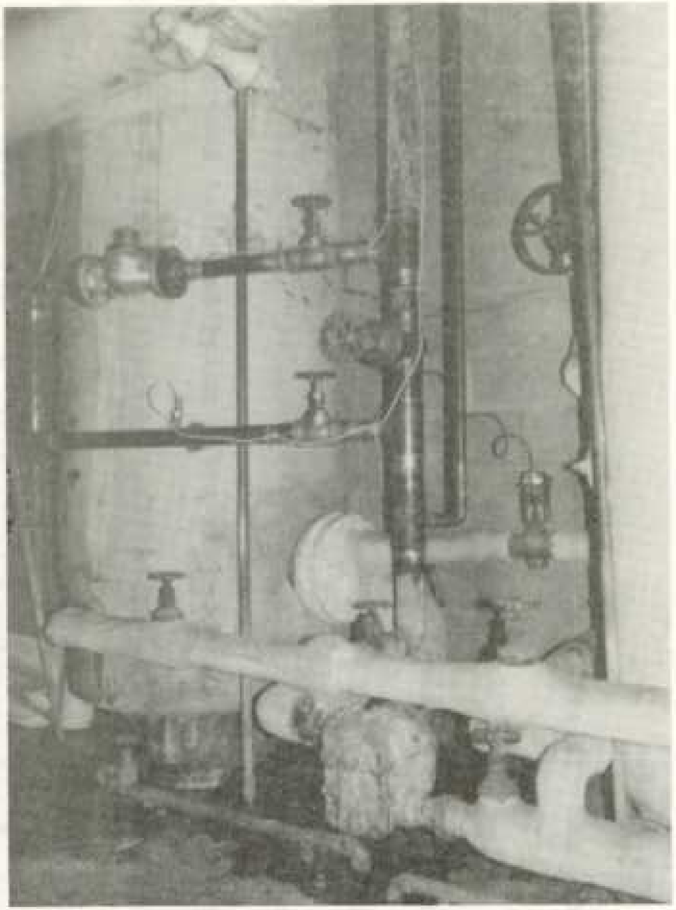


Fig. 2.9. Flow meter, cold-side temperature sensor, and recirculation line as installed in Bldg. 437.

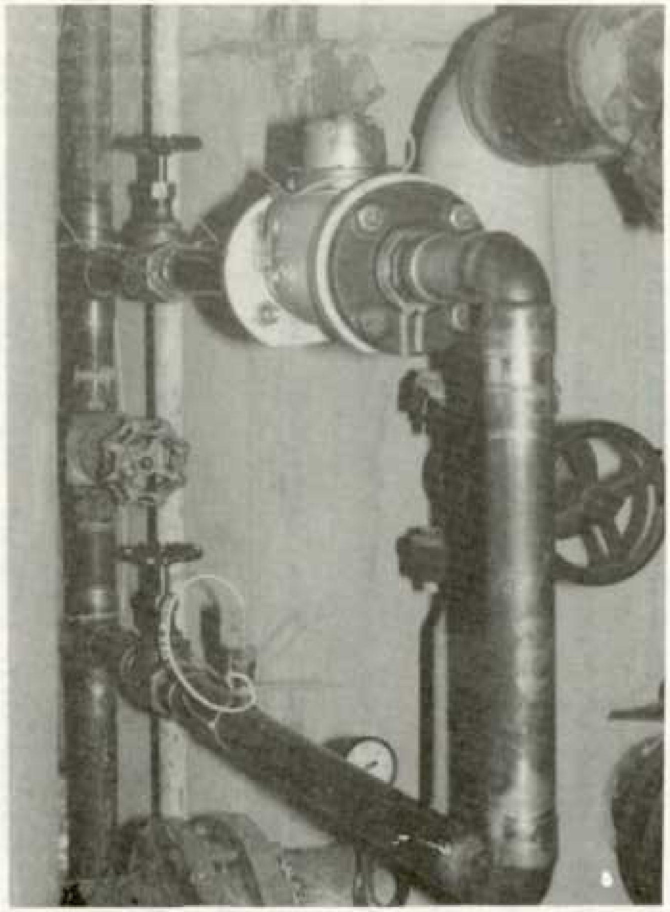


Fig. 2.10. Flow meter and cold-side temperature sensor as installed in Bldg. 499, Ellison Dining Hall.

energy outputs utilized. Previous studies found that domestic water heating was one of the most cost-effective uses of the heat produced by small cogeneration equipment. To properly design a small cogeneration system, two characteristics of the DHW load are needed: the magnitude of the typical daily water heating load and the variability of that load from day to day and from hour to hour. The hourly DHW consumption data collected in this study were designed to determine these characteristics.

An hourly data collection rate was selected because most DHW systems have a storage tank that can approximately meet the hot water demands of an average hour. Consequently, a small cogeneration system will be unaffected by hot water demands lasting much less than an hour. Hourly data can, of course, be totaled to give daily DHW demands or averaged to give long-term averages.

The magnitude and variation of the load served by small cogeneration are important to selecting the most cost-effective combination of cogeneration unit and heat storage system. In order to explore the effects of combinations of cogeneration system heat production rates (referred to as cogeneration system size hereafter) and heat storage system capacity (TES size), a computer model using measured hourly load data was developed to calculate operational characteristics of a variety of cogeneration system and TES size combinations. The program is discussed in Sect. 3 and reproduced in Appendix D. The results of these calculations are presented and disussed in the next section.

As the literature review shows, there is little published information on DHW loads. Graphical summaries of DHW loads are presented in the next section, both to supplement the literature and to help explain the results of the cogeneration system and TES size interactions.

3. RESULTS

The purpose of the study was to learn enough about the DHW loads of selected Navy building types to allow conceptual design of small cogeneration systems for these building types. The two most important characteristics of the loads are the magnitude of the average daily load and the variability of the load from hour to hour and day to day. These two characteristics allow informed selection of a cogeneration module and of the appropriate hot water storage system. This information is presented and discussed in this section.

The data collected for the above purposes may also serve other purposes. For example, the DHW load profiles reported in ref. 5 are used to guide designers in the sizing of conventional DHW systems. Several presentations of the data are included in this section, which may be useful to DHW systems designers, and will help the reader understand the results relating to cogeneration.

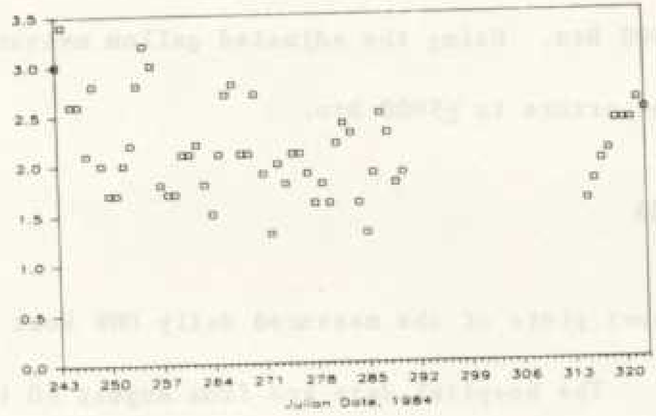
All the results presented here are based on measurements of the volume of water used multiplied by the measured average Btu-to-gallon ratio for the day the data were taken. This method was used because the TEMS flow meter records in units of 10 gal and the integrator records in units of 100,000 Btu. For the temperature rise found on these water heaters, the Btu-to-gallon ratio was between 300 and 500. The resolution of the hourly data was greatly improved by using this method. For example, in an hour in which one Btu unit (100,000 Btu) is recorded, the actual number of Btu consumed could range from less than 5000 to more than 195,000 Btu. Using the adjusted gallon measurements reduces hourly measurement errors to ±5000 Btu.

3.1 LOAD PROFILES

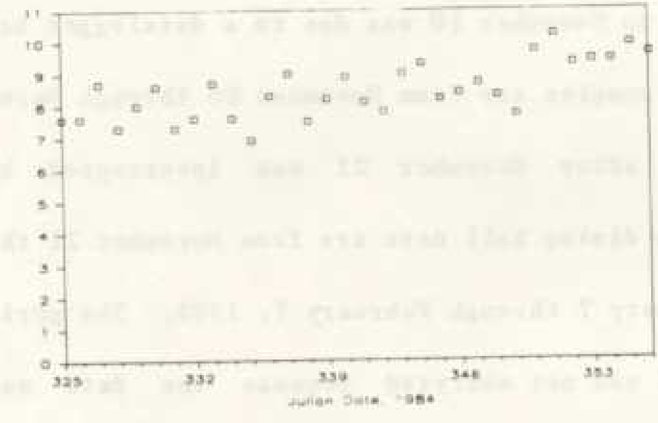
Figure 3.1 shows plots of the measured daily DHW heat loads of the three buildings. The hospital data are from August 30 through October 16, 1984 and November 10 through November 18, 1984. The gap in the data from October 16 to November 10 was due to a datalogger breakdown. Data for the barracks complex are from November 20 through December 21, 1984. Data collection after December 21 was interrupted by a datalogger malfunction. The dining hall data are from November 21 through December 19, 1984 and January 7 through February 7, 1985. The period December 20 through January 6 was not analyzed because the data were considered atypical due to the holidays.

Several other features of the data are apparent from Fig. 3.1. The hospital has, by far, the smallest DHW load, possibly due to this hospital's low occupancy rate and the fact that the hospital's kitchen is served by another water heater. The dining hall's DHW load is the largest. There is no clear trend of loads increasing or decreasing with time. The data suggest that the barracks' DHW load may be increasing over the monitoring period, but further study would be needed to establish whether this is a trend or a random variation.

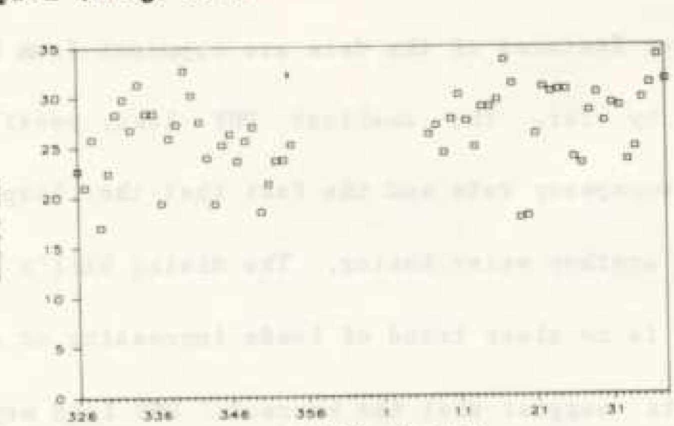
The variability of the barracks' DHW load is much less than that of the other buildings. Most of the barracks' daily loads are within about



(a) Hospital (Bldg. 100)



(b) Barracks complex (Bldg. 437)



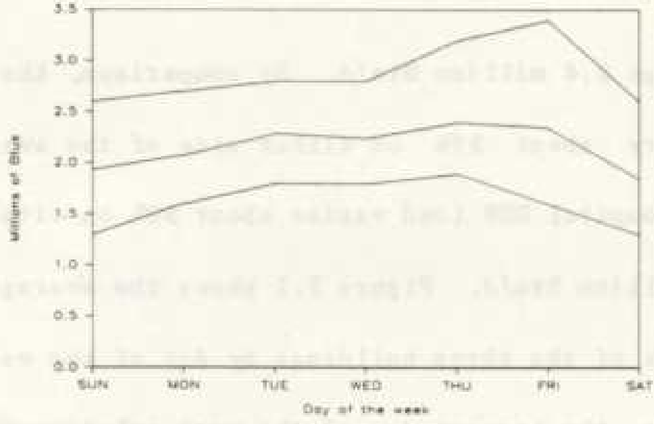
(c) Dining hall (Bldg. 499)

Fig. 3.1. Daily domestic hot water loads.

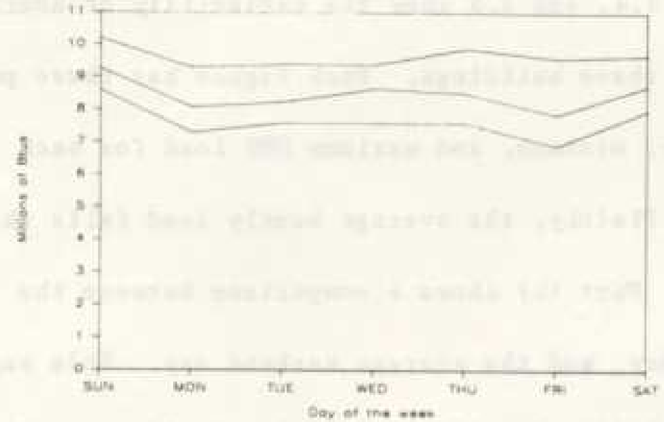
15% of the average 8.4 million Btu/d. By comparison, the dining hall's daily loads vary about 35% on either side of the average 26 million Btu/d, and the hospital DHW load varies about 50% on either side of the average 2.2 million Btu/d. Figure 3.2 shows the average, minimum, and maximum DHW loads of the three buildings by day of the week. The dining hall load shows the largest day of the week relationship. The dining hall's average DHW load is significantly smaller on weekends.

Figures 3.3, 3.4, and 3.5 show the variability of hourly DHW loads for each of the three buildings. Each figure has three parts: Part (a) shows the average, minimum, and maximum DHW load for each hour of the monitored days. Plainly, the average hourly load falls short of telling the whole story. Part (b) shows a comparison between the average day, the average weekday, and the average weekend day. This explains a small part of the variability found in part (a). Weekdays and weekend days are different for all buildings, but only Bldg. 437 [Fig. 3.4(b)] shows a pronounced weekend difference. Part (c) shows the minimum, maximum, and average loads for a single day of the week, Wednesday in this case. Evidently, the hourly variations of DHW loads contribute more to the overall variations of loads than variations from day to day.

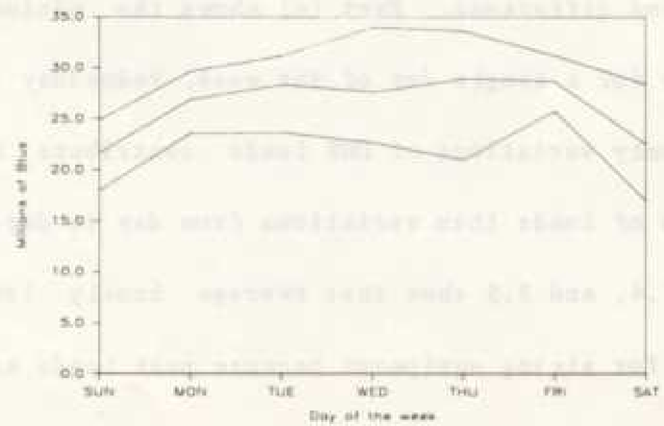
Figures 3.3, 3.4, and 3.5 show that average hourly loads are not really adequate for sizing equipment because peak loads are often much larger than the average loads. On the other hand, Fig. 3.2 shows that average daily loads are likely to give reasonable results, at least for barracks and dining halls.



(a) Hospital (Bldg. 100)

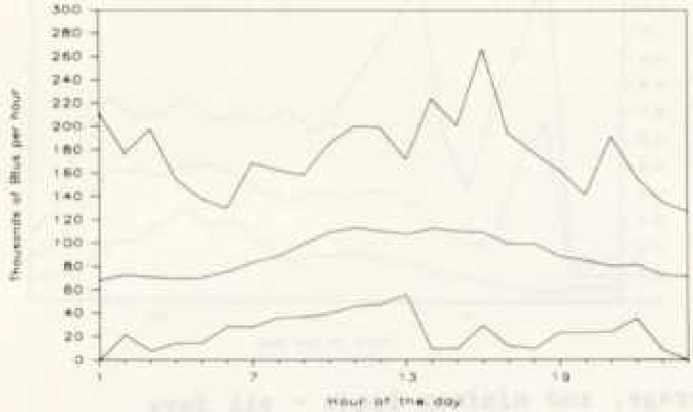


(b) Barracks complex (Bldg. 437)

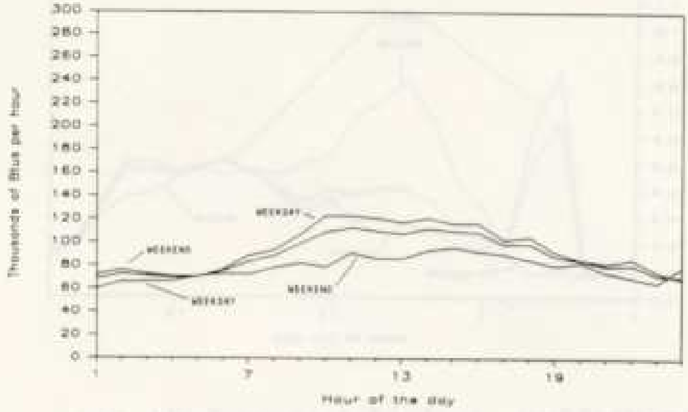


(c) Dining hall (Bldg. 499)

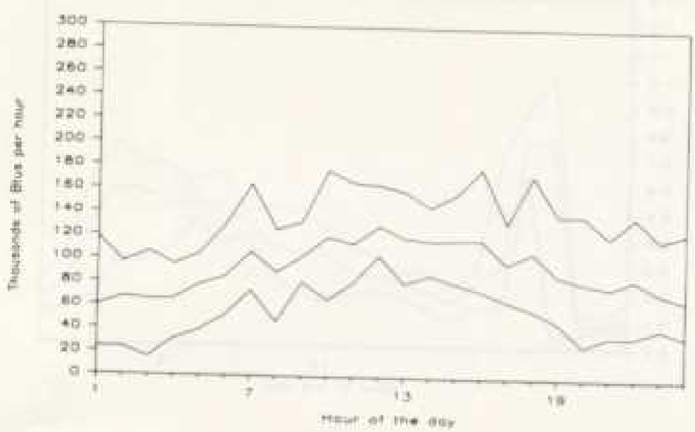
Fig. 3.2. Maximum, average, and minimum daily domestic hot water loads by day of the week.



(a) **Maximum, average, and minimum loads - all days**

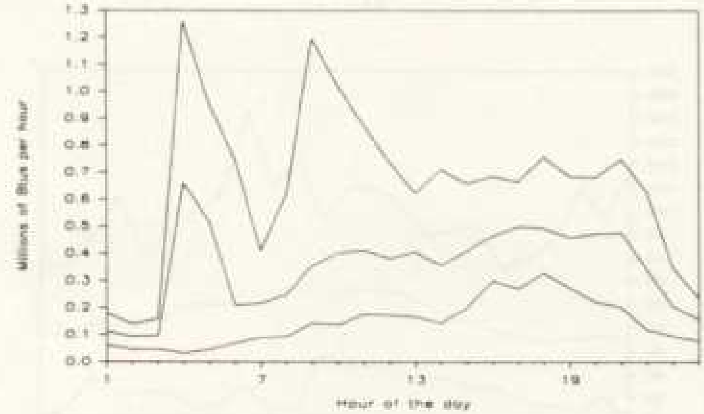


(b) **Average loads - weekdays, weekend days, and all days**

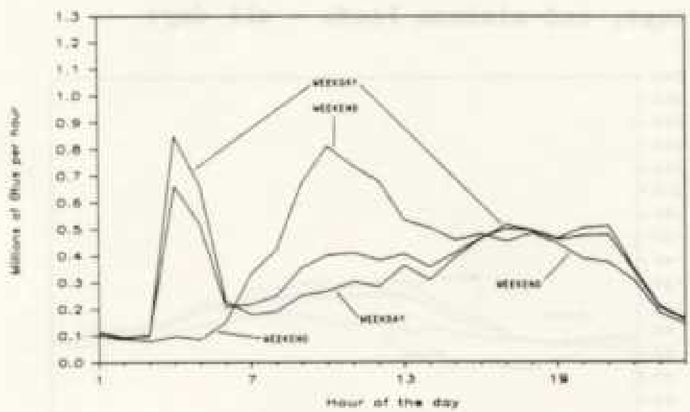


(c) **Maximum, average, and minimum loads, Wednesdays**

Fig. 3.3. Hourly DHW loads, NRMC Hospital (Bldg. 100).



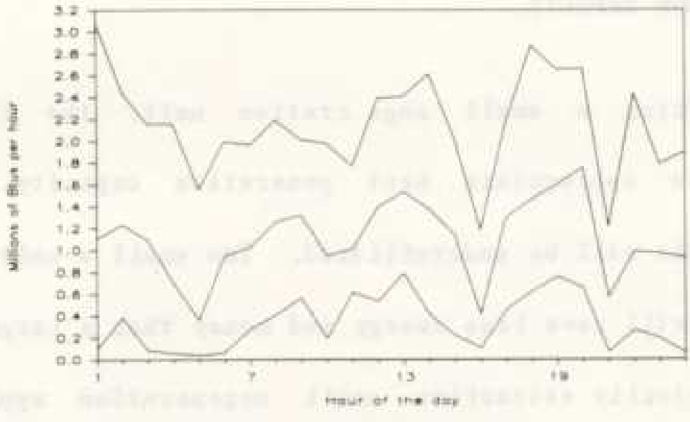
(a) **Maximum, average, and minimum loads - all days**



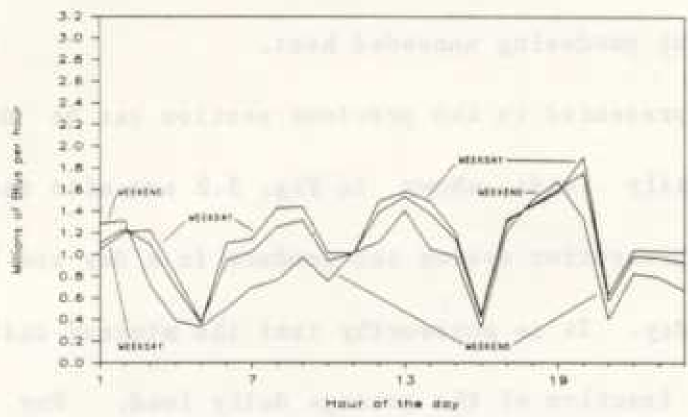
(b) **Average loads - weekdays, weekend days, and all days**

(c) **Maximum, average, and minimum loads, Wednesdays**

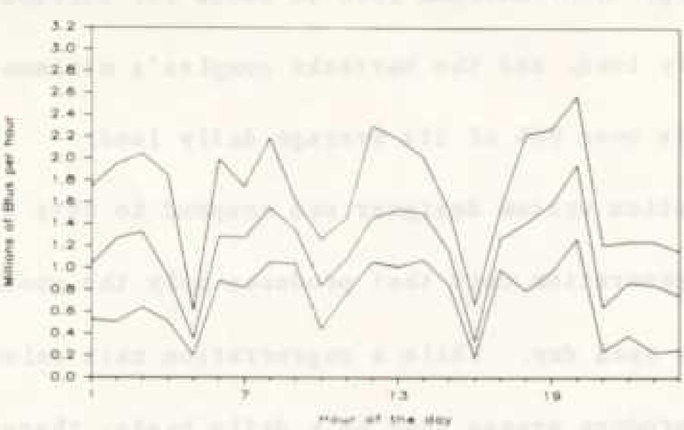
Fig. 3.4. Hourly DHW loads, barracks complex (Bldg. 437).



(a) Maximum, average, and minimum loads - all days



(b) Average loads - weekdays, weekend days, and all days



(c) Maximum, average, and minimum loads, Wednesdays

Fig. 3.5. Hourly DHW loads, Ellison Dining Hall (Bldg. 499).

3.2 HEAT STORAGE EFFECTS

When selecting a small coge eration unit, the first step is determining the appropriate heat generation capacity. Too large a cogeneration unit will be underutilized. Too small a unit will be fully utilized but will save less energy and money than a larger unit would. The most economically attractive small cogeneration applications are those where the cogeneration unit is the largest unit which can operate full-time without producing unneeded heat.

The graphs presented in the previous section can be of some help. The minimum daily loads shown in Fig. 3.2 are also the maximum heat quantities a cogeneration system can produce in a day and be completely utilized every day. It is noteworthy that the minimum daily load is not some consistent fraction of the average daily load. For example, the hospital's (Bldg. 100) minimum load is about 1.1 million Btu/d, 50% of its average daily load, and the barracks complex's minimum daily load, 7 million Btu/d, is over 80% of its average daily load.

The cogeneration system designer can respond to this information by selecting a cogeneration unit that produces only the amount of heat the building can use each day. While a cogeneration unit selected in this way will not produce excess heat on a daily basis, there will be hours when excess heat is produced. Figure 3.6 shows the fraction of the time (hours) during which the DHW loads exceed various values (i.e., the fraction of the time that a cogeneration unit could operate without producing excess heat). For example, a cogeneration unit which produces

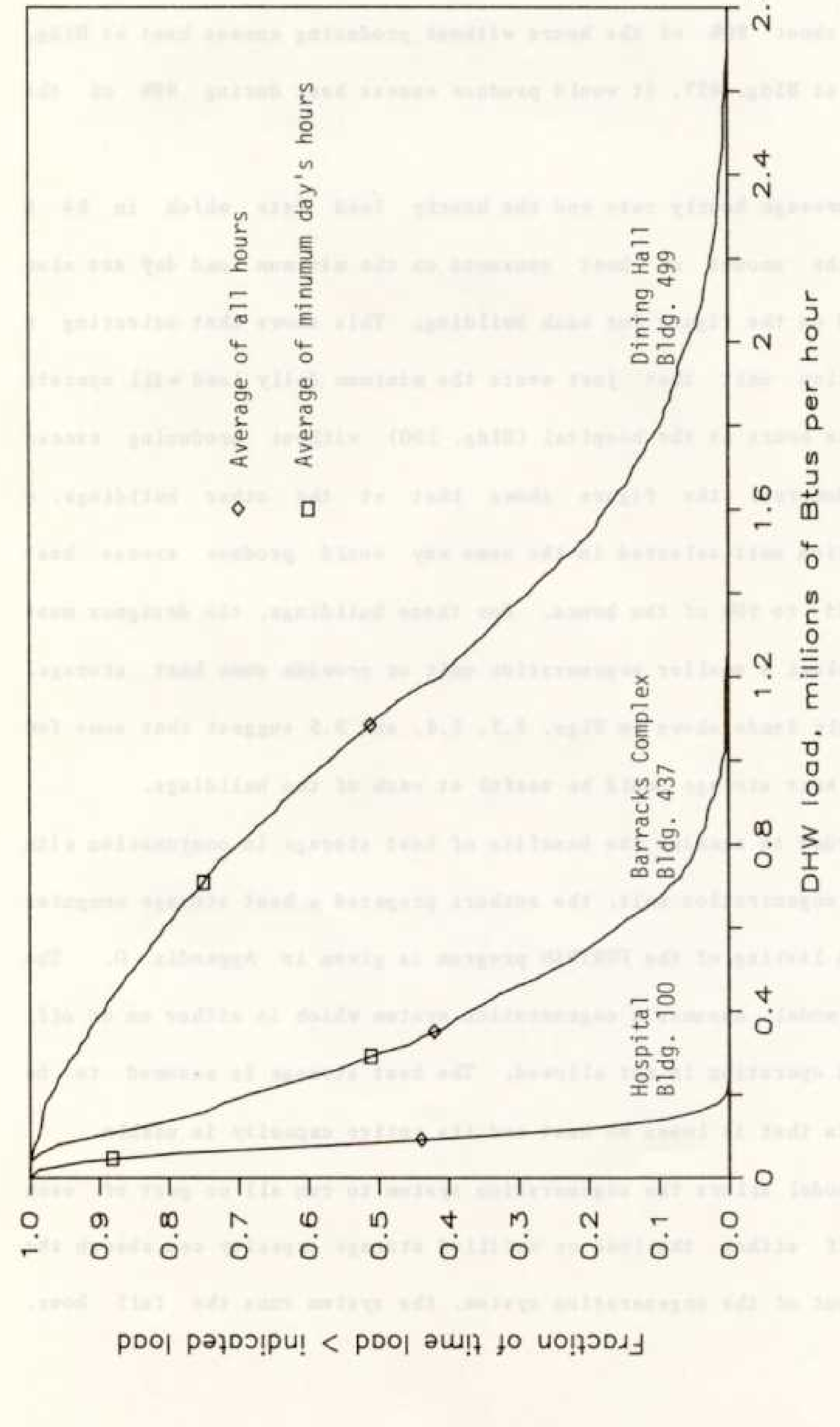


Fig. 3.6. Fraction of the time that hourly DHW load is greater than the indicated value.

600,000 Btu/h would always produce too much heat for Bldg. 100; it would operate about 80% of the hours without producing excess heat at Bldg. 499; and at Bldg. 437, it would produce excess heat during 85% of the hours.

The average hourly rate and the hourly load rate which in 24 h equals the amount of heat consumed on the minimum load day are also indicated on the figure for each building. This shows that selecting a cogeneration unit that just meets the minimum daily load will operate 85% of the hours at the hospital (Bldg. 100) without producing excess heat. However, the figure shows that at the other buildings, a cogeneration unit selected in the same way would produce excess heat during 25 to 50% of the hours. For these buildings, the designer must either select a smaller cogeneration unit or provide some heat storage. The hourly loads shown on Figs. 3.3, 3.4, and 3.5 suggest that some few hours of heat storage could be useful at each of the buildings.

In order to examine the benefits of heat storage in conjunction with a small cogeneration unit, the authors prepared a heat storage computer model. A listing of the FORTRAN program is given in Appendix D. The storage model assumes a cogeneration system which is either on or off; part-load operation is not allowed. The heat storage is assumed to be perfect in that it loses no heat and its entire capacity is usable.

The model allows the cogeneration system to run all or part of each hour. If either the load or unfilled storage capacity can absorb the heat output of the cogeneration system, the system runs the full hour.

When the storage is full and the load is smaller than the output of the system, the system runs part of the hour and turns off. When the load is larger than the system output, the system runs the full hour and the storage meets the remainder of the load. When storage is empty and the load is larger than the system output, the remainder of the load is met by a backup system. In retrofit situations, the backup is the water heater that existed before the retrofit. The number of times the cogeneration system is turned off is recorded because this number may have a bearing on the reliability of the cogeneration system. A diagram of the model's logic is given in Appendix D.

The hourly data collected for this study were used for input to the heat storage model. The model results were normalized by the measured average load (Btu/h) so that the results can be used for larger or smaller buildings with similar usage if the average load is known or can be estimated. For example, another barracks complex with twice as many occupants would have about twice the average hourly DHW load, but the same results would apply.

Figure 3.7 shows graphs of the effect of storage on the fraction of the DHW load supplied by cogeneration for various cogeneration heat production rates and heat storage capacities. (Both these parameters are presented as ratios to the average hourly DHW load.) Figure 3.7 shows that the first 2 h of storage make a significant difference in the effectiveness of the cogeneration system. Subsequent increases in heat storage are less effective. The largest effect is for the case where

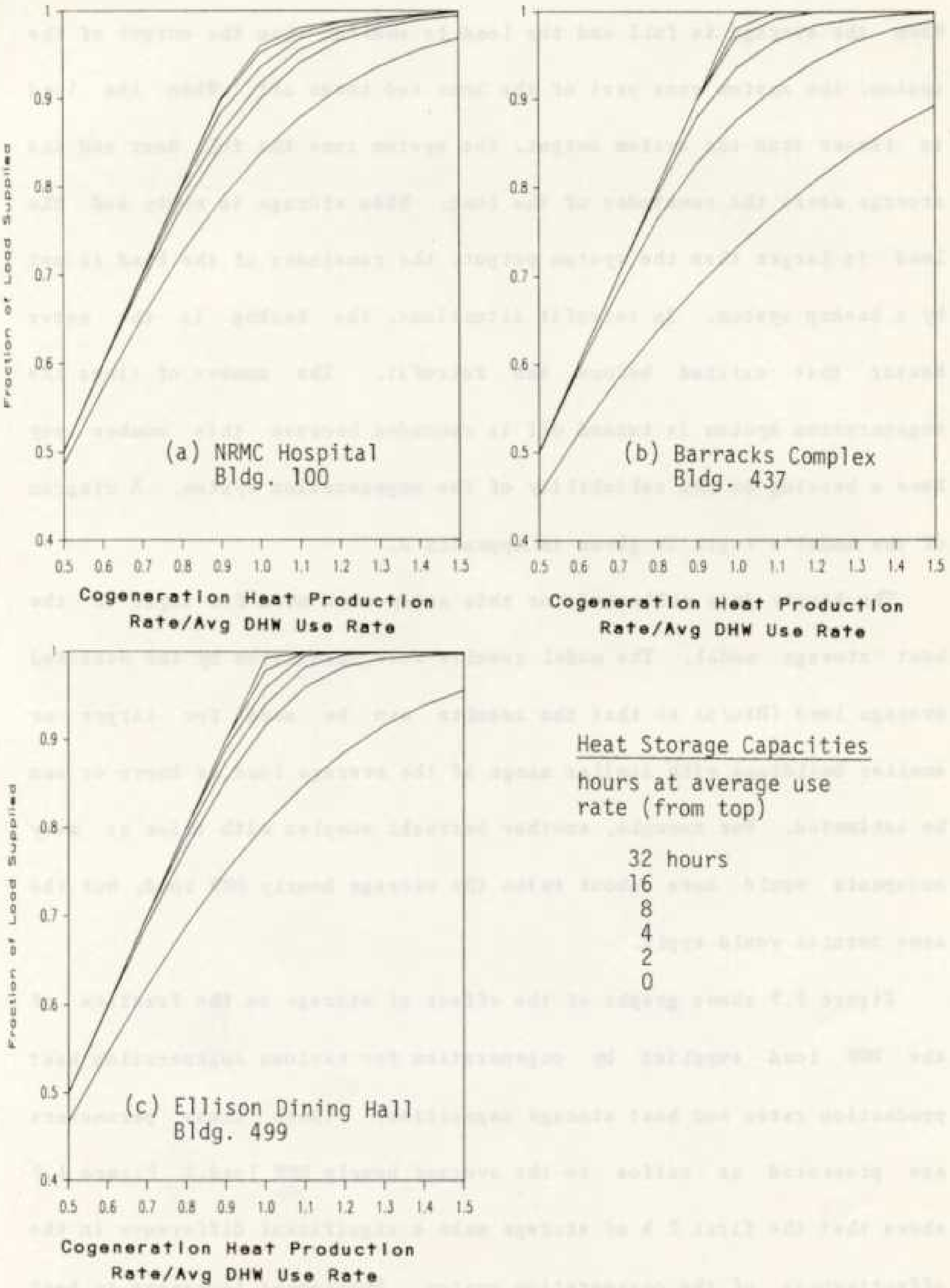


Fig. 3.7. Fraction of domestic hot water load supplied by various cogeneration heat production rates and heat storage capacities.

the cogeneration heat production rate equals the average DHW load. For smaller cogeneration systems, the heat production capacity ultimately limits the fraction of the load supplied by cogeneration. For larger systems, the greater heat production capacity reduces the value of larger quantities of heat storage.

Other things being equal, the cogeneration system that operates the most will give the quickest return on investment. Figure 3.8 shows the fraction of the time the cogeneration system operates (fractional run-time) as a function of system heat production capacity and the quantity of heat storage. The fractional run-time is the total number of hours the cogeneration module operates divided by the number of hours of load data supplied to the program. Figures 3.7 and 3.8 are closely related. Where Fig. 3.7 is useful for estimating the benefits of heat storage, Fig. 3.8 is useful for estimating the fuel and other costs related to system running time.

Many cogeneration system malfunctions are due to electrical and control problems.[10] Some of these are related to the startup, which puts special demands on engines and starting systems. Figure 3.9 shows the effect of heat storage capacity and cogeneration system heat production capacity on the frequency of system startups. Larger heat storage capacity leads to fewer on-off cycles. The number of startups indicated may be underestimated when the number of startups approach 1/h (or 24/d) because the hourly structure of the data allows startups no more frequently than once per hour. Clearly, if starting and stopping

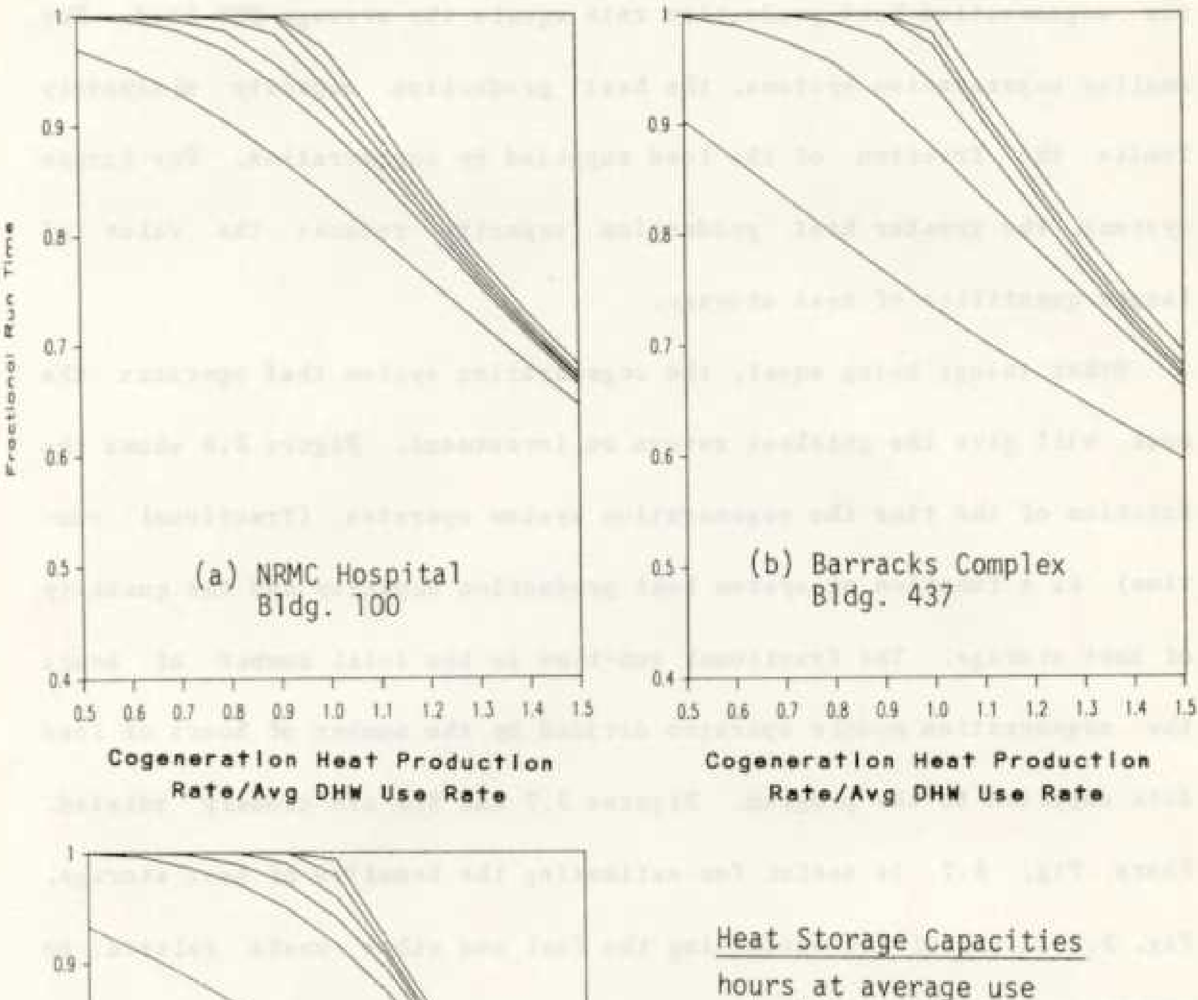


Fig. 3.8. Fraction of the time cogeneration system runs for various cogeneration heat production rates and heat storage capacities.

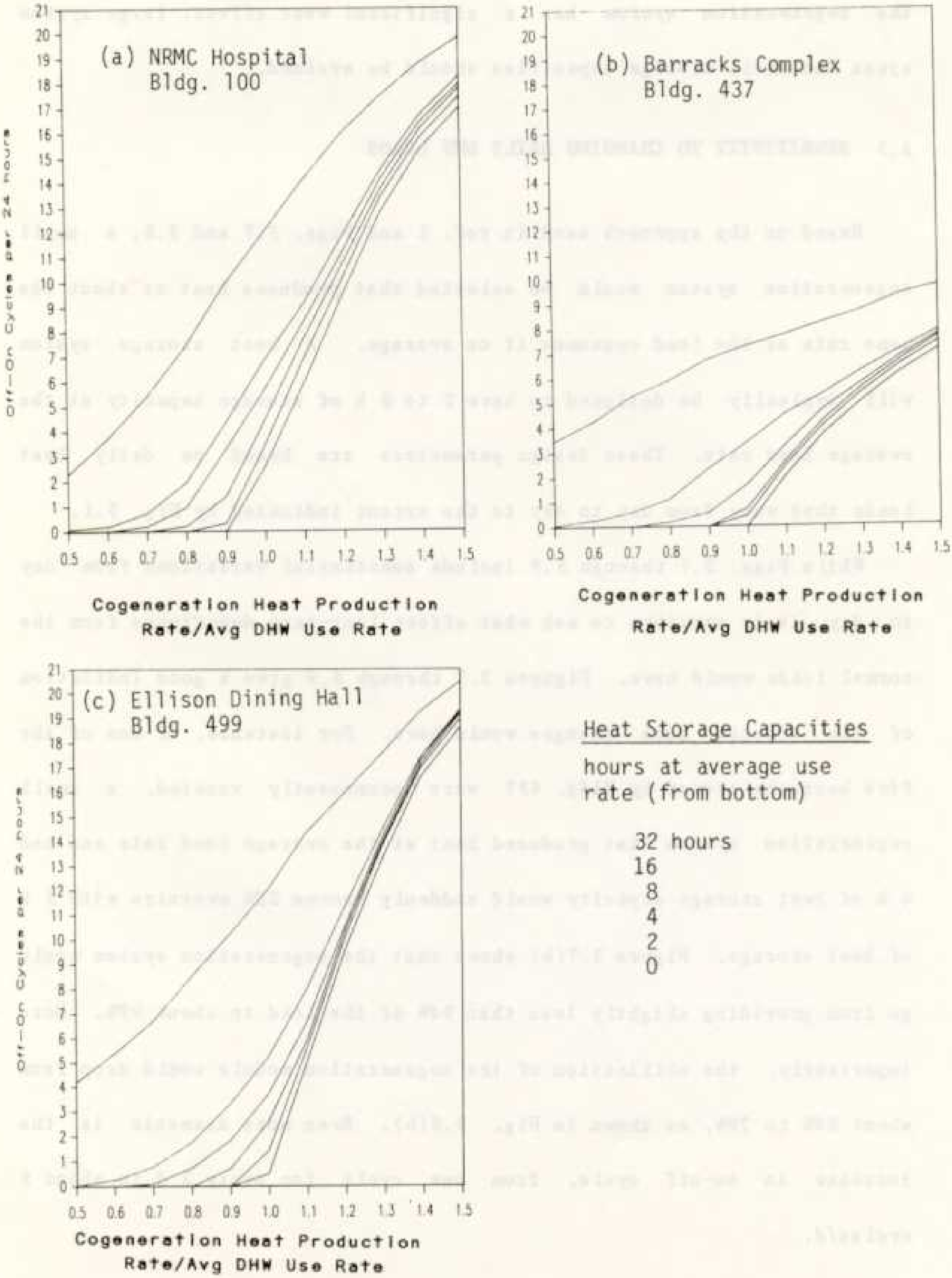


Fig. 3.9. Frequency of on-off cycles for various cogeneration heat production rates and heat storage capacities.

the cogeneration system has a significant wear effect, large system sizes and small storage capacities should be avoided.

3.3 SENSITIVITY TO CHANGING DAILY DHW LOADS

Based on the approach used in ref. 1 and Figs. 3.7 and 3.8, a small cogeneration system would be selected that produces heat at about the same rate as the load consumes it on average. A heat storage system will typically be designed to have 2 to 8 h of storage capacity at the average load rate. These design parameters are based on daily heat loads that vary from day to day to the extent indicated by Fig. 3.1.

While Figs. 3.7 through 3.9 include substantial variations from day to day, it is sensible to ask what effect long-term departures from the normal loads would have. Figures 3.7 through 3.9 give a good indication of the effects such changes would have. For instance, if one of the five barracks served by Bldg. 437 were permanently vacated, a small cogeneration system that produced heat at the average load rate and had 4 h of heat storage capacity would suddenly become 25% oversize with 5 h of heat storage. Figure 3.7(b) shows that the cogeneration system would go from providing slightly less than 94% of the load to about 99%. More importantly, the utilization of the cogeneration module would drop from about 94% to 79%, as shown in Fig. 3.8(b). Even more dramatic is the increase in on-off cycle, from one cycle for every 2 d to about 5 cycles/d.

On the other hand, if the DHW load at Ellison Dining Hall were to increase by 25%, a cogeneration system that had 8 h of heat storage and produced heat at the average load rate would go from meeting about 96% of the load to meeting about 79% [Fig. 3.7(c)]. Utilization of the cogeneration module would go from about 96% to 100% [Fig. 3.8(c)]. In addition, the number of on-off cycles would drop from about 5 every 2 d to none [Fig. 3.9(c)].

The data show no clear evidence in seasonal variations of DHW loads, but seasonal variations are quite possible because in many cases cold water temperatures vary seasonally. Under such circumstances, the small cogeneration system designer must choose to install a system that is oversized part of the year or undersized part of the year, or perhaps both. In light of the data in Figs. 3.8 and 3.9, undersized small cogeneration systems will operate closer to full-time and will cycle off and on less than a larger system.

If, for example, the DHW load of a building is known to vary seasonally by 10%, about the annual average load, then a designer should install a cogeneration system that produces heat at 90% of the annual average load rate. Such a system would operate along the curves shown in Figs. 3.7 through 3.9 between heat production rate to average load rates of 0.8 to 1.0. Selecting a larger cogeneration system would lead to lower utilization and many more on-off cycles.

A similar approach probably should be taken with loads of uncertain magnitude. For instance, if dining halls use about 3000 Btu of DHW heat/meal served, and a particular dining hall serves an average of 5000 meals/d, then the average hourly DHW load will be 625,000 Btu. If no monitoring of DHW consumption had been performed at this hypothetical building, it might be desirable to select a cogeneration system with a heat output rate closer to 500,000 Btu/h than 600,000 Btu/h. On the other hand, a heat flow meter such as we used but without the datalogger can give a good measure of average hot water usage for about $1000, installed.

3.4 FACTORS AFFECTING DHW LOADS

Section 2.1 gives some reasons to expect that DHW loads are related to the use of a building. Table 2.1 shows that the average DHW usage for three quite different dining halls is in the range of 4.5 to 5.5 gal/meal served. Also, residential DHW usage is frequently presented in a per person form. If DHW loads can be related to the usage of the building, then DHW loads might be estimated for other buildings from their use patterns. For example, if Navy dining halls use 5 gal of DHW/meal, then the pattern of meals served might be used to predict the pattern of the DHW load.

To test this idea, we collected the available usage data on the monitored buildings. The number of people going through the cafeteria is recorded each 15 min. We summed the 15-min head counts into hourly totals and compared them to the measured hourly DHW loads. In addition, we received Recapitulation of Meal Record (4601) (NAVSUP FORM 1292) from the dining hall. From this data, we calculated the number of meals served daily. Daily totals from the head counts and from Form 1292 generally agreed within 10%, good enough for our purposes.

Daily totals from Form 1292 are plotted against daily DHW loads on Fig. 3.10. This figure shows little or no relationship between the daily DHW loads and the number of meals served each day. Figure 3.11 shows a plot of the hourly head count data against the measured hourly DHW loads. This figure also shows little relation between DHW load and the number of meals served.

Figure 3.11 was plotted with all hours with no meals served excluded. This was done because there are more hours during which no meals are served than during which meals are served, so the plotter would wear a hole in the paper along with vertical axis plotting the hours with no meals served. The highest and lowest DHW loads occur during hours when no meals are served; evidently, thee is a wide variety of DHW-consuming activities when meals are not being served. The minimum hourly DHW load seems to increase with the number of meals served per hour (see the lower edge of the data scatter in Fig. 3.11). This may reflect the DHW load directly associated with serving meals and cleaning dishes. The higher loads may reflect other dining hall activities that are not directly related to serving the meals but that happen to occur during the meals.

Another attempt to find a relationship between the DHW load and the number of meals served was to plot both meals served and Btus consumed

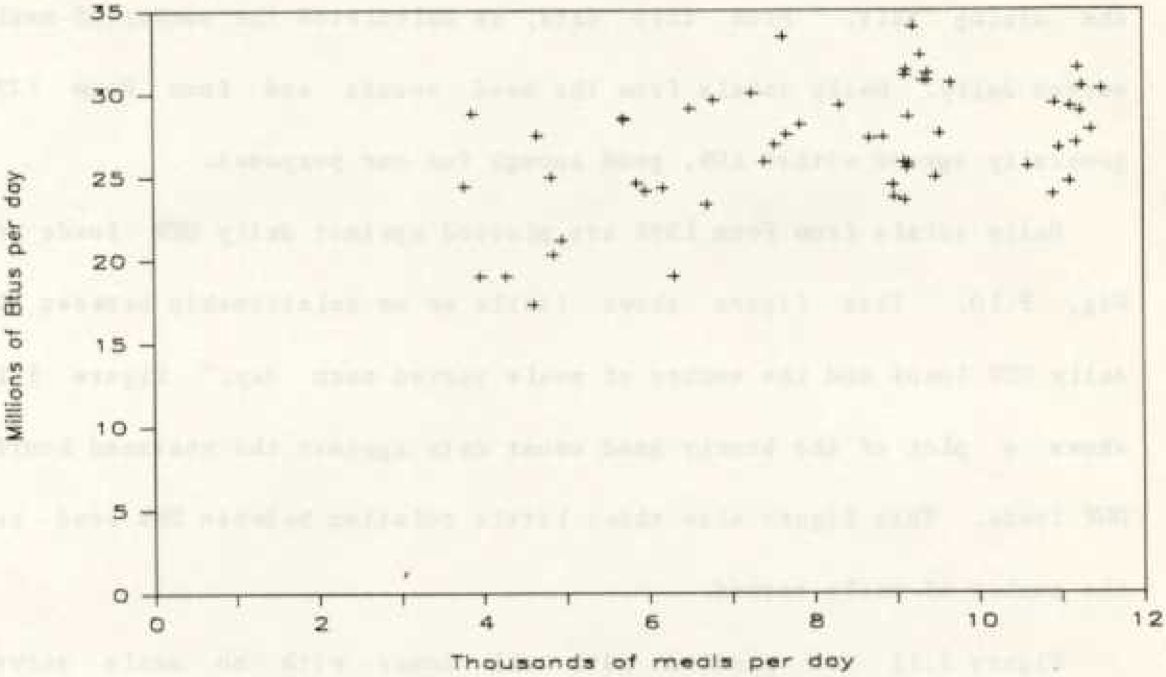


Fig. 3.10. Daily DHW load versus meals served per day.

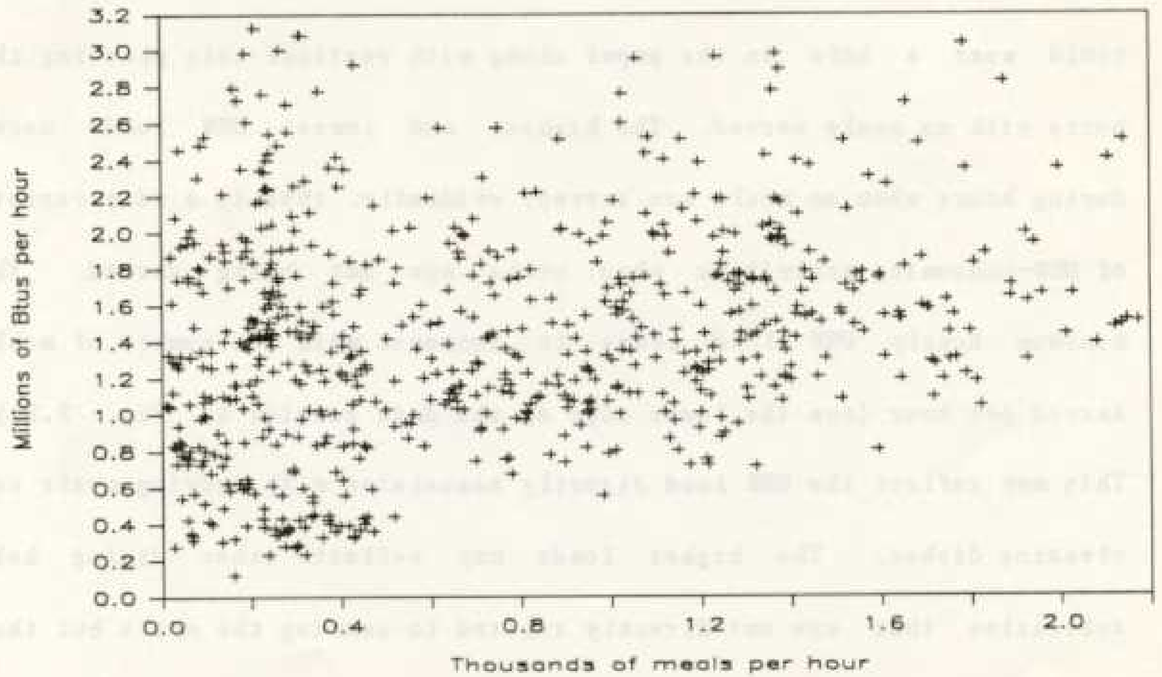


Fig. 3.11. Hourly DHW load versus meals served per hour. (All hours with no meals served have been excluded for graph clarity.)

against time of day on the same sheet. While there appeared to be some relationship between DHW load and meals served, there is a large quantity of DHW that seems unrelated to specific meals but must be general housekeeping. Between the midnight meal and breakfast, there was a large amount of DHW consumption that could hardly be caused by the midnight meal. Also, the DHW load between breakfast and lunch appeared to be too large to be caused entirely by breakfast. Our conclusion is that the number and timing of the meals do not adequately explain the pattern of hourly DHW usage.

Depending on which meal data source we use, the dining hall uses an average of 3100 to 3300 Btu/meal served and 4.4 to 4.7 gal/meal served, but as Figs. 3.10 and 3.11 show, a meal served in a day or hour does not necessarily lead to 3200 Btu of DHW used in that day or hour.

The common practice of reporting residential DHW usage in units of gallons per person per day suggested that a relationship between the occupancy of the barracks complex served by Bldg. 437 and its DHW consumption should be apparent. Comparison of Table 2.4 and Fig. 3.1(b) shows that this expectation is not supported by this data. Why this is so is not clear. We were not able to identify any use of Bldg. 437's DHW, except for domestic purposes by the occupants. One possibility suggested to us is that the actual number of persons occupying the barracks may have little relationship to the reported occupancy (Table 2.4). Clearly, we had no independent measure of the occupancy of the barracks complex.

Using the occupancy from Table 2.4, average DHW consumption for the monitoring period was about 22 gal/person/d. The average DHW heating energy was about 9700 Btu/person/d. Together these values suggest an average water temperature rise of about 59ºF.

4. SUMMARY AND CONCLUSION

The DHW consumptions of three buildings at Memphis NAS were monitored at hourly intervals for periods of 30 to 60 d. The three buildings are the NRMC Hospital (Bldg. 199), a 5-barracks complex (Bldgs. 435-440) at the NAS, Bldg. 437, and Ellison Dining Hall at the NAS (Bldg. 499). During the monitoring period, the average hourly DHW loads of the three buildings were 90, 350, and 1100 thousand Btu/h for Bldgs. 100, 437, and 499, respectively. Hourly DHW loads are strongly related to whether the hour of interest falls on a weekday or weekend. Even accounting for the day of the week there are often substantial variations of loads found on a particular day of the week. These findings suggest that typical load profiles are of limited value for individual buildings. Certainly, optimal cogeneration system design requires knowledge of the actual load variability.

Daily loads also show considerable variability but somewhat less than hourly loads. The barracks' daily load showed the least variability, with most daily DHW loads falling within 15% of the average 8.4 million Btu/d. The hospital showed the most variability, with most of its daily DHW loads falling within 55% of its average 2.2 million Btu/d. The dining hall had variations up to about 40% around its 26 million Btu/d average DHW load.

The DHW loads were measured primarily to determine the best sizes for small cogeneration systems and associated heat storage systems when these are used to meet the DHW loads of buildings of these types.

Figures 3.7, 3.8, and 3.9 present the results concisely. Small cogeneration systems should be selected that produce heat at a rate no greater than the average heat consumption rate. Larger cogeneration systems will operate a smaller part of the time, leading to slower returns on the investment in cogeneration. In addition, larger systems will cycle off and on frequently or will need a radiator or other heat dissipation device to dispose of excess cogenerated heat.

Where the heat load is seasonally variable, an undersized cogeneration system should be selected, except during the seasons when DHW loads are the smallest. Where there is some uncertainty about the size of the average DHW load, a smaller rather than larger cogeneration system is advisable because the economic and operational penalties of oversizing can be substantial.

Heat storage systems can have substantial benefits. Cogeneration systems that are sized to produce 80% to 130% are more fully utilized if they are coupled with a heat storage system. The first 2 h of storage (at the average load rate) are most beneficial. Subsequent increments of heat storage are less and less beneficial. Figure 3.9 shows that heat storage also has profound effect on the cycling of the cogeneration system. Here, again, the first 2 h of storage are very effective, and subsequent increments of storage have less effect.

Reference 1 found that efficient and reasonably priced small cogeneration systems were not available in sizes that produce less than about 200,000 Btu/h. Based on this criterion and the data presented here, it is clear that the DHW load found at the barracks complex and at Ellison Dining Hall is easily large enough to support a commercially available small cogeneration system. Without the kitchen, the hospital's 90,000 Btu/h average DHW load is probably too small to support a cost-effective small cogeneration system. Measurement or estimation of the hospital's kitchen DHW load and learning whether the remainder of the hospital's DHW load (and its low occupancy rate) is typical of military hospitals is the next step in determining whether hospital DHW loads will support small cogeneration. The Gas Research Institute is sponsoring a small cogeneration demonstration at a hospital in Houston, Texas, where the principal loads are space heating and cooling. It may be that the space heating and cooling loads of hospitals are large and steady enough to support small cogeneration systems without large DHW loads.

There are several ways this present work could be extended. Much more data have been collected at Bldgs. 437 and 499 than have been reported on here. These data have been excluded from the present analysis because of time and funding constraints. It would be useful to analyze these data for possible seasonal effects and for holiday periods.

The hospital DHW consumption was much less than expected. It would be useful to know if these DHW use rates are typical of Navy hospitals or hospitals in general. It would also be useful to know what factors determine the size of hospital's DHW load. The kitchen could be a large part of the DHW load. A hospital laundry could consume much DHW. It may also be useful to determine whether the nonkitchen, nonlaundry DHW usage of Bldg. 100 is typical.

The heat storage program (Appendix D) is rather simple. It does not attempt to account for storage losses (it makes calculations at hourly intervals), and it does not account for storage effects of the existing (or backup) domestic water heater. These simplifications were made knowing that they limited the accuracy of the results but recognizing that high accuracy was not necessary at the present level of small cogeneration investigations. Now that good quality DHW data are available, it would be useful to improve the quality of the models of heat storage and small cogeneration systems.

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APPENDIX A

THERMAL ENERGY METERING SYSTEM TEST

APPENDIX A: THERMAL ENERGY METERING SYSTEM TEST

The Sonceboz Model 323 Thermal Energy Metering System (TEMS) was used to measure the volume (gallons) of domestic hot water consumed and the quantity (Btu) of heat imparted to that water by the water heater. The TEMS consists of three components: an electronic integrator, matched temperature hot and cold sensors, and a flow meter.

The Sonceboz TEMS Model 323 records the volume (gallons) of water that is heated and simultaneously determines the amount (Btu) of energy required to heat the measured volume of water. The volume of water is measured by Sonceboz Model 414 flow meters. Each time 10 gal of water pass through a flow meter, an electrical contact is closed. The electronic integrator detects the contact closure and adds one unit (10 gal) to the volume accumulator. Simultaneously, the integrator measures the temperature difference between the hot and cold temperature sensors, calculates the amount of heat implied by that temperature difference and the flow of 10 gal of water, and adds that amount to its memory. When the accumulated amount of heat exceeds 100,000 Btu, the Btu register is advanced one unit and 100,000 Btu is subtracted from the memory.

A performance check was made to ensure accuracy of the Sonceboz TEMS under approximately the same temperature difference (ΔT) and flow conditions the system could experience at the installations. The test setup involved utilizing a pulse generator and a relay switch to create contact closures to imitate the signals from the flow meter. Table A.1 is a list of the test equipment. The ΔT was simulated by inserting the cold temperature sensor in a reference bath and the hot temperature in a controlled variable temperature bath. The ΔT was representative of the actual ΔT of the installations. The reference bath temperature was held constant in an ice-water bath at 32°F, while the variable temperature bath temperature was controlled by adding ice between runs to decrease the value of the ΔT. The variable temperature bath temperature was monitored by a platinum resistance thermometer. The energy (Btu) measured by the electronic integrator was then compared to the Btus calculated with the measured bath temperatures.

Table A.1. Major TEMS test materials.

<u>Thermal energy monitoring system</u>
Sonceboz model 323-20.6 with 7-v DC lithium battery Serial number 84037981
Sonceboz model 323 Pt 100 temperature sensors with standard 6-ft, 4-conductor cables, plus 60-ft extensions
<u>Pulse generator</u>
Wavetek model 175 Serial number B338210
<u>Relay</u>
Teledyne model 640-1 with 2-ft, 2-conductor cables
<u>Secondary standard resistance thermometer</u>
Minco model RTB8078 resistance thermometer bridge Serial number 23890-16
Minco model 57929 platinum resistance thermometer Serial number 1040
<u>Vacuum-insulated glass beakers (2)</u>
4600 ml, 11-in. depth, 6-in. diam

Tests were run with the variable temperature bath at six different temperatures. Each test was run until 10 Btu counts (each equal to 105 Btu) were recorded on the integrator register. The number of gallon counts (each equal to 10 gal) were recorded and combined with the temperature measurements to calculate the amount of heat that should have been recorded by the Btu counter on the integrator.

Table A.2 lists the results. The errors were no larger than 1%, an accuracy that was more than adequate for our purposes.

Table A.2. Thermal energy monitoring system test results.*

Run	Flow counts (10 gal/count)	Variable Temp. both probe resistance (ohms)	Temperature difference from resistance probes (°F)	Calculated heat flow (10^5 Btu)
1	135	119.28	89.07	10.028
2	142	118.23	84.23	9.975
3	156	116.52	76.35	9.933
4	194	113.34	61.70	9.983
5	222	111.60	53.68	9.939
6	300	108.67	40.18	10.053

*Each test was run until 10 Btu counts (10^5 Btu/count) were registered on the integrator. The reference temperature was established by an ice-water bath. The resistance of the resistance thermometer probe in the ice-water bath was 99.95 ohms.

APPENDIX B

DATA ACQUISITION SYSTEM TEST

APPENDIX B: DATA ACQUISITION SYSTEM TEST

The data acquisition system was tested for accuracy. The measurements required to analyze the domestic hot water loads of the three Navy buildings were the total Btus and gallons used per hour. The date, time, and totals were recorded hourly at the building by the dataloggers. For the test, the data were recorded each minute until 10 min was logged by the data acquisition system. The data recorded by the data loggers were then compared to the counts read from the Sonceboz Thermal Energy Metering System (TEMS) integrator registers during the testing period.

The TEMS integrator provides output in the form of negative 7 V DC rectangular pulses for each count recorded by the Btu and gallon register. The data acquisition system counts the pulses from the TEMS integrator. Due to the polarity of these pulses and the characteristics of the dataloggers, a signal isolation technique was required by the data acquisition systems. Photo-optic isolators were installed on the pulse input card of the Accurex Autodata Ten/10 datalogger to accommodate the negative pulses received from the electronic integrator. Campbell Scientific data acquisition systems were used at the barracks and the galley. The 21X micrologger accommodated the negative pulses by connecting a relay that converted the negative pulse into a contact closure. The relay was connected to the Btu lead from the TEMS integrator. The Btu pulse input channel on the 21X micrologger was programmed to read a contact closure. The volume pulse input channel was programmed to read the negative voltage pulses from the electronic integrator.

The data acquisition systems test consisted of four components: two insulated beaker baths used to produce a temperature difference, a simulated flow meter, a TEMS integrator, and the data acquisition system. Figures B.1, B.2, and B.3 illustrate the entire data acquisition system test. The cold temperature sensor was placed in the insulated beaker containing ice and water. The hot temperature sensor was inserted into the insulated beaker filled with hot tap water. The temperatures were not monitored because the test involved the data acquisition systems and not the calibration of the TEMS integrator (discussed in Appendix A).

The flow meter was simulated by a pulse generator with an output of a 1 Hz 5 V square wave pulse. The pulse was converted to a contact closure by the relay shown in Fig. B.1. Thus, each second the TEMS integrator counted one pulse, which represented 10 gal on the gallon register. The dataloggers were programmed to scan and record the Btu total and gallon total each minute. The time interval of 1 min was measured by counting 60 counts registered by the gallons display. At the end of each interval, the number of observed Btu counts registered by the TEMS integrator was recorded (with the time period on Table B.1 for the Autodata Ten/10 and Table B.2 for the CSI 21X micrologger).

The test continued until 10 min of data were collected. The data from the Autodata Ten/10 were read from the paper tape and transferred

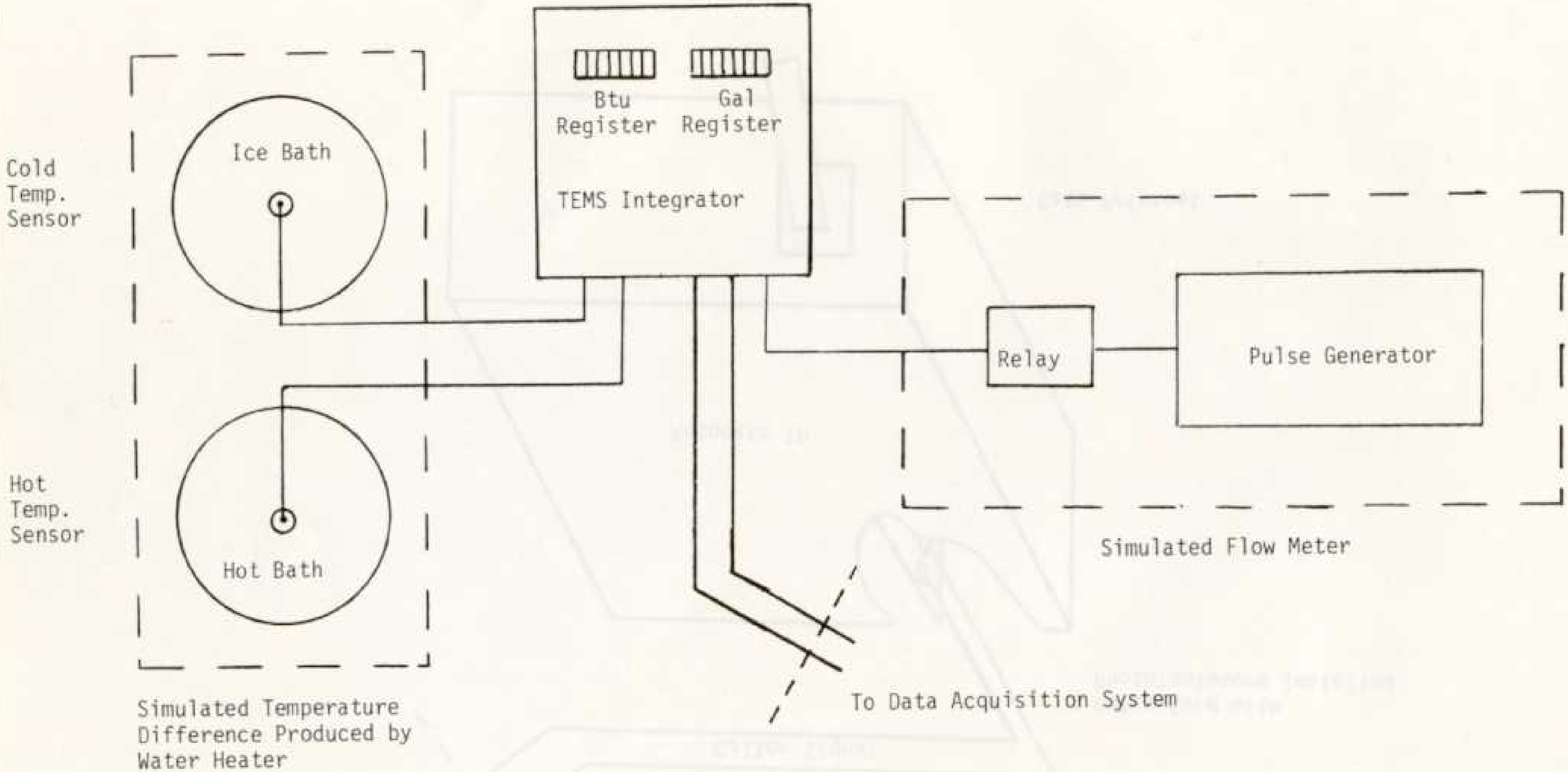

Fig. B.1. TEMS test setup.

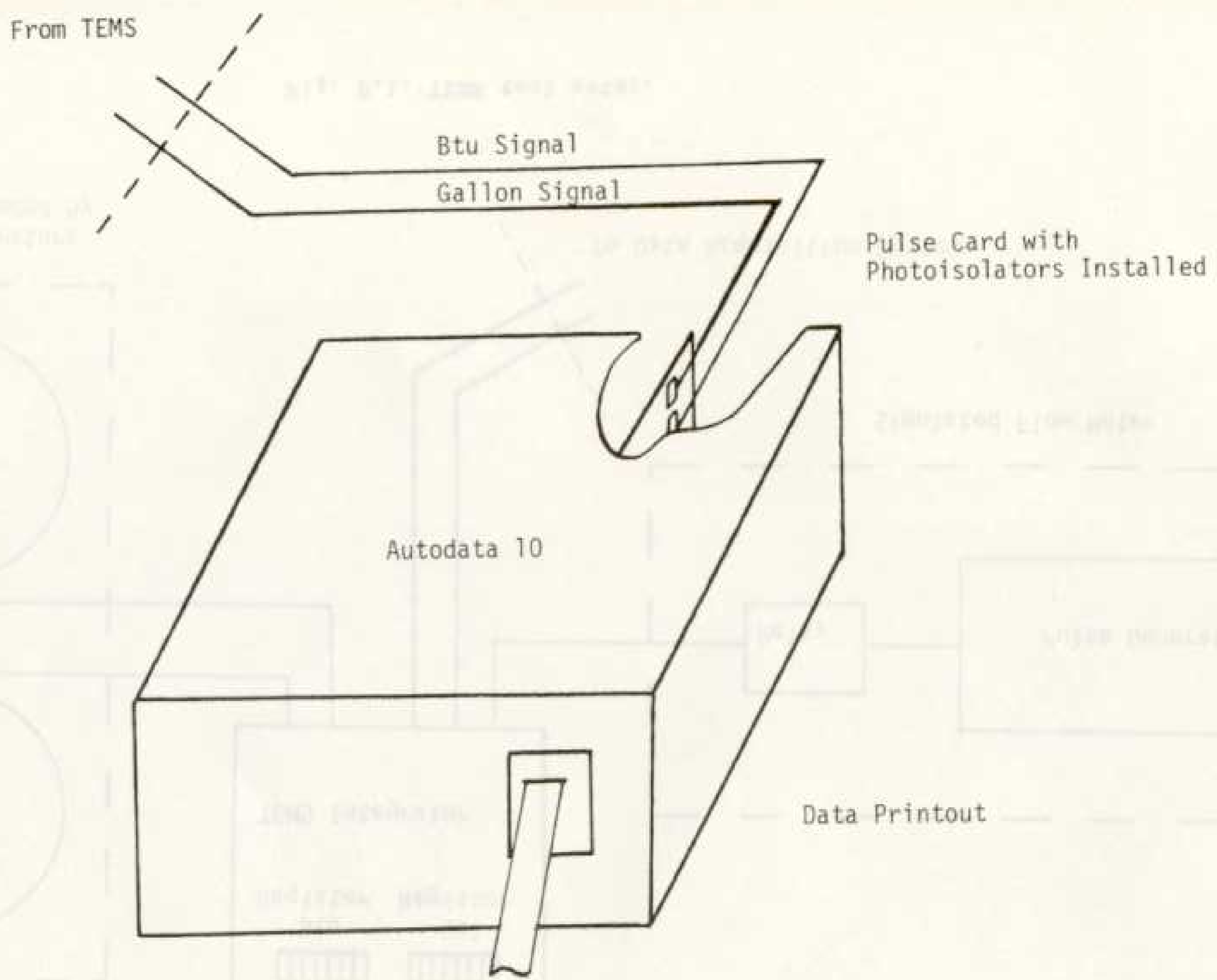

Fig. B.2. Accurex Autodata 10 Datalogger.

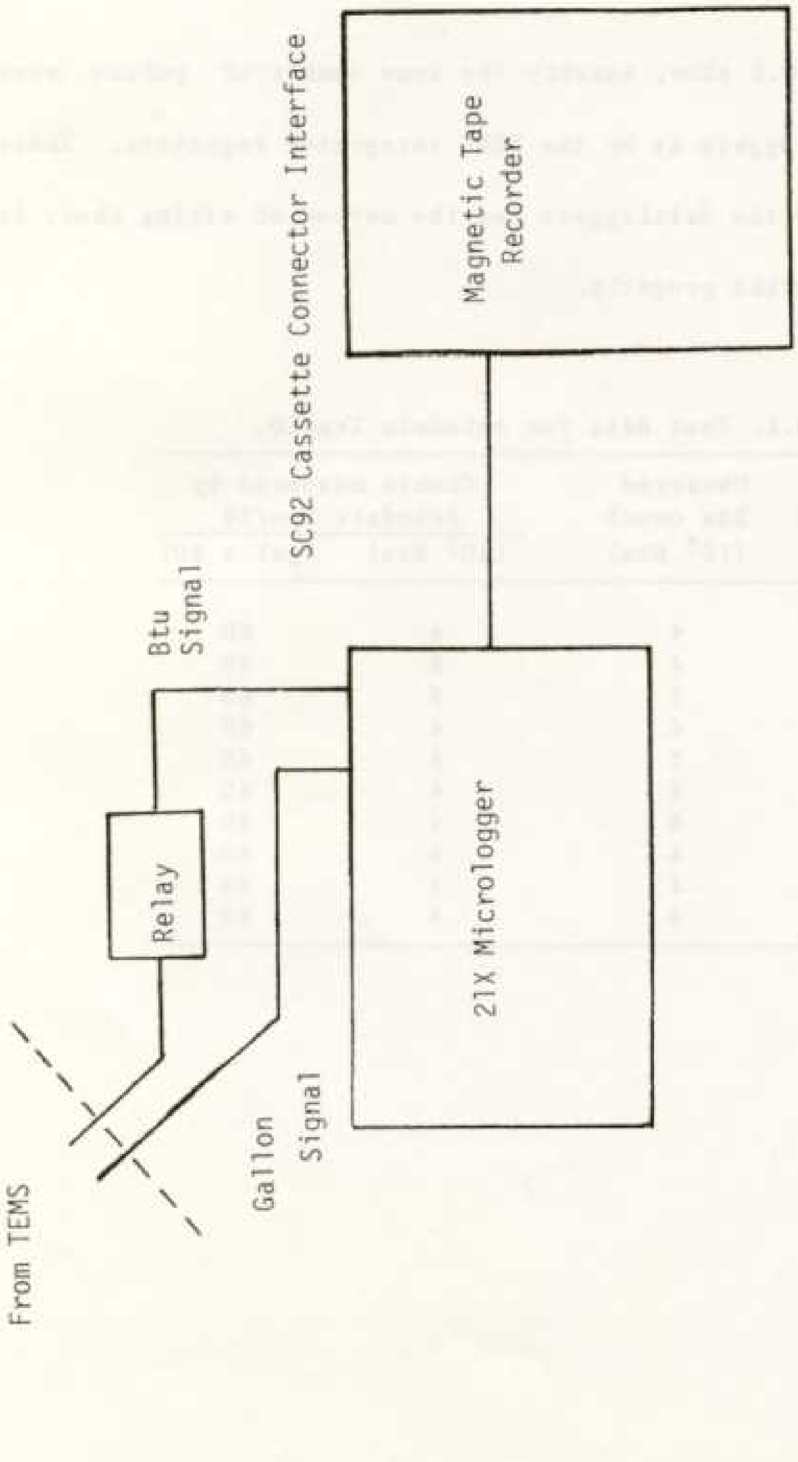

Fig. B.3. Campbell Scientific data acquisition system.

to Table B.1. The data recorded by the 21X micrologger were read by transferring the data to a magnetic tape and downloading the data onto a personal computer. A printout of the data was made and the data were entered into Table B.2.

As tables B.1 and B.2 show, exactly the same number of pulses were recorded by the dataloggers as by the TEMS integrator registers. These tests established that the dataloggers and the method of wiring them to the TEMS integrator worked properly.

Table B.1. Test data for Autodata Ten/10.

Time periods 60-gal pulses 1 min	Observed Btu count (10^5 Btu)	Counts measured by Autodata Ten/10 (10^5 Btu)	Counts measured by Autodata Ten/10 (gal x 10)
1	4	4	60
2	4	5	60
3	5	5	60
4	4	4	60
5	5	5	60
6	4	4	60
7	4	4	60
8	4	4	60
9	4	4	60
10	4	4	60

Table B.2. Test data for CSI 21X micrologger.

Time periods 60-gal pulses 1 min	Observed Btu count (10^5 Btu)	Counts measured by Autodata Ten/10 (10^5 Btu)	(gal x 10)
1	3	3	60
2	3	3	60
3	3	3	60
4	3	3	60
5	2	2	60
6	3	3	60
7	3	3	60
8	2	2	60
9	3	3	60
10	3	3	60

APPENDIX C

DATA RETRIEVAL INSTRUCTIONS POSTED IN THE INSTRUMENT BOXES AT BLDGS. 437 AND 499

DATA RETRIEVAL INSTRUCTIONS

Before changing cassettes, the following procedure must be followed CAREFULLY.

1. Enter: *8 3A 3A

   This action causes the 21X micrologger to dump any residual data to the tape. The recording light (on the tape recorder) will come on. After the light goes off, go on to step 2.

2. Remove the tape with the recorded data by pressing the STOP/EJECT button. Promptly label the tape with the information labels supplied. Example label:

   Millington N.A.S., TN Bldg_____
   Sonceboz Energy Meter Reading
   Btu:_________
   Gal:_________
   Number of Tapes on Hand:________
   Date:__-__-__ Time:__:__

   Initials:_________

3. Load a new cassette in the recorder. Advance the tape forward until the tape leader is past the recording head. Press the FAST FORWARD button, then press STOP button after a few seconds.

4. Simultaneously press the RECORD and PLAY buttons on the recorder to set it for recording. The tape will not move until the micrologger dumps more data onto it.

5. Enter: :0

   The display will read: :LOG1. If this is not entered, there will be no data logged.

   If :LOG1 does not appear, note the error message and call Lance McCold at (615) 574-5216.

   Also, if any other problems occur, please call Lance McCold at the above number.

APPENDIX D

COGENERATION HEAT STORAGE PROGRAM

```
C
C
C      COGENERATION PROGRAM
C
C
C      THIS IS A STORAGE PROGRAM TO EXPLORE THE EFFECTS OF
C      THERMAL ENERGY STORAGE SIZE ON DECENTRALIZED SMALL
C      COGENERATION USED TO MEET A DOMESTIC HOT WATER LOAD.
C
C
C      VARIABLES:
C
C      STRTIM    - STORAGE TIME (Enter even whole number)
C      AVGUSE    - AVERAGE HOURLY BTU LOAD
C      CORANG    - RANGE OF THE AMOUNT OF COGENERATION
C                  PRODUCED, RANGE BEGINS AT 50% AND FOR EACH
C                  VALUE GREATER THAN 1 THE RANGE INCREASES BY
C                  10% I.E. ENTER <3> RANGE = 50% TO 70%
C      COHEAT    - COGENERATED HEAT
C      STORHT(I) - AMOUNT OF STORED HEAT
C      HRLOAD(I) - HOURLY BTU LOAD
C      RUNHRS    - RUN TIME FOR THE COGENERATION UNIT
C      BACKUP    - AMOUNT OF BACKUP HEAT SUPPLIED TO SUPLEMENT
C                  THE COGENERATION HEAT OUTPUT
C      OFFON     - COUNT OF OFF-ON CYCLES FOR THE
C                  COGENERATION UNIT
C      TOTHRS    - TOTAL TIME OF OPERATION
C      OFFTIM    - TOTAL TIME THE COGENERATION UNIT
C                  IS OFF DURING THE TOTAL TIME
C      STOCAP    - AMOUNT OF STORAGE CAPACITY OF THE HEAT
C                  STORAGE VESSEL
C      WASTE     - AMOUNT OF ENERGY DISSIPATE IF EXCESS
C                  HEAT PRODUCED IS RELEASED
C      AVHRLD    - AVERAGE HOURLY LOAD
C      TOTAL     - TOTAL THERMAL LOAD DURING OPERATION
C
C
C
      PROGRAM COGEN
      CHARACTER*10 TITLE*50,FNAME,GRAPH
      REAL AVHRLD,TOTAL,STOCAP,COHEAT,RUNHRS,BACKUP,CAPR,CHTR,
     1 PROR,HRATIO,OFFON,OFFTIM,WASTE,STORHT(2000),CORG,SUM,HRLOAD(2000)
      INTEGER STRTIM,I,J,CORANG,ADD,STOTIM,HRSTOR
C
C   PROMPT USER TO ENTER THERMAL DATA FILE INFORMATION
C
      WRITE(6,111)
      READ(6,211) FNAME
      WRITE(6,311)
      READ(6,211) TITLE
      WRITE(6,411)
      READ(6,511) CORANG
      WRITE(6,611)
```

```
      READ(6,511) STOTIM
      WRITE(6,811)
      READ(6,211) GRAPH
111   FORMAT(5X,'ENTER THE LOAD DATA FILE NAME:')
211   FORMAT(A)
311   FORMAT(5X,'ENTER THE PROJECT LOCATION AND BUILDING I.D.:')
411   FORMAT(5X,'ENTER COGENERATION RANGE: 1=50% EACH ADDITIONAL UNIT
     2EQUALS 10%)
511   FORMAT(I2)
611   FORMAT(5X,'ENTER THE TRIAL STORAGE TIME X HOURS:')
811   FORMAT(5X,'ENTER THE GRAPH DATA FILE NAME π_____.PRNπ:')
C
C   OPEN INPUT AND OUTPUT DATA FILES
C
      OPEN(2,FILE=FNAME,STATUS='OLD')
      OPEN(4,FILE=GRAPH,STATUS='NEW')
C
C   READ THE LOAD DATA
C
      TOTAL = 0.0
      SUM = 0.0
      STRTIM = STOTIM + 2.0
      DO 911 J=1,4300
       READ(2,*,END=99) HRLOAD(J)
       TOTAL = SUM + HRLOAD(J)
       SUM = TOTAL
911   CONTINUE
99    TOTHRS = J - 1.0
      AVHRLD = TOTAL/TOTHRS
      WRITE(4,1211) TITLE
      WRITE(4,1311)
      WRITE(4,1411) STOTIM,CORANG,TOTHRS,TOTAL,AVHRLD
1211  FORMAT(2X,'COGENERATION PROJECT: 'A35/1X)
1311  FORMAT(2X,'STRTIM',6X,'CORANG',5X,'TOTHRS',7X,'TOTAL'
     3 ,5X,'AVHRLD')
1411  FORMAT(3X,I3,9X,I3,7X,F6.0,3X,F10.0,3X,F10.4/1X)
C
C *****  CALCULATE THE AMOUNT OF STORAGE  *****
C
      DO 40 K=1,STRTIM/2.0
        STOCAP = AVHRLD * STRTIM - AVHRLD * (K * 2.0)
        HRSTOR = STRTIM - (K * 2.0)
C
C ***** CALCULATE THE COGENERATED HEAT FOR THE DESIRED *****
C ***** RANGE OF COGENERATION *****
C
      DO 30 L=1,CORANG
        COHEAT = (0.4*AVHRLD) + (0.1*AVHRLD*L)
        STORHT(1) = COHEAT - HRLOAD(1)
        RUNHRS = 1.0
        BACKUP = 0.0
        OFFON  = 0.0
        OFFTIM = 0.0
C
```

```
C ***** CALCULATE THE AMOUNT OF STORED HEAT PER HOUR PRODUCED BY         *****
C ***** COGENERATION , THE TOTAL RUN TIME OF THE COGENERATION MODULE,  *****
C ***** THE AMOUNT OF BACKUP ENERGY REQUIRED, THE TOTAL OFF TIME OF     *****
C ***** THE COGENERATION MODULE, AND THE NUMBER OF TIMES THE MODULE     *****
C ***** STOPPED AND HAD TO BE RESTARTED FOR THE TOTAL OPERATING TIME.   *****
C
      DO 20 M=2,TOTHRS
        M1 = M - 1.
        STORHT(M) = STORHT(M1) + COHEAT - HRLOAD(M)
C
C ***** IF THE STORAGE CAPACITY IS LESS THAN THE  AMOUNT OF COGENERATED *****
C ***** HEAT TURN THE COGENERATION UNIT OFF AND RECORD THE  TIME OFF.    *****
C
        IF(STOCAP.LE.STORHT(M)) GO TO 5
        RUNHRS = RUNHRS+1.
        GO TO 15
5       STORHT(M) = STOCAP
        RUNHRS = RUNHRS +  (STOCAP-STORHT(M1)+HRLOAD(M))/COHEAT
        OFFON = OFFON + 1.0
        OFFTIM = OFFTIM + 1.0-((STOCAP-STORHT(M1)+HRLOAD(M))/COHEAT)
        WASTE  = COHEAT*OFFTIM
15      CONTINUE
        IF(STORHT(M).GE.0.) GO TO 20
C
C ***** IF THE STORED HEAT AND COGENERATION UNIT DOES NOT MEET THE
C ***** REQUIRED LOAD USE THE BACKUP SYSTEM.
C
        BACKUP = BACKUP - STORHT(M)
        STORHT(M) = 0.
20    CONTINUE
      COGR = STOCAP/COHEAT
      CHTR = COHEAT/AVHRLD
      CAPR = STOCAP/AVHRLD
      PROR = (TOTAL-BACKUP)/TOTAL
      HRATIO = RUNHRS/TOTHRS
C
C ***** PRINT THE GRAPH DATA TO THE OUTPUT FILE. *****
C
      WRITE(4,1511)CHTR,HRATIO,PROR,HRSTOR,OFFON
1511  FORMAT(1X,F4.2,1X,F6.4,1X,F6.4,1X,I2,1X,F10.2)
30    CONTINUE
40    CONTINUE
      WRITE(6,1611)
1611  FORMAT(5X,'DONE')
      CLOSE(2)
      STOP
      END
```

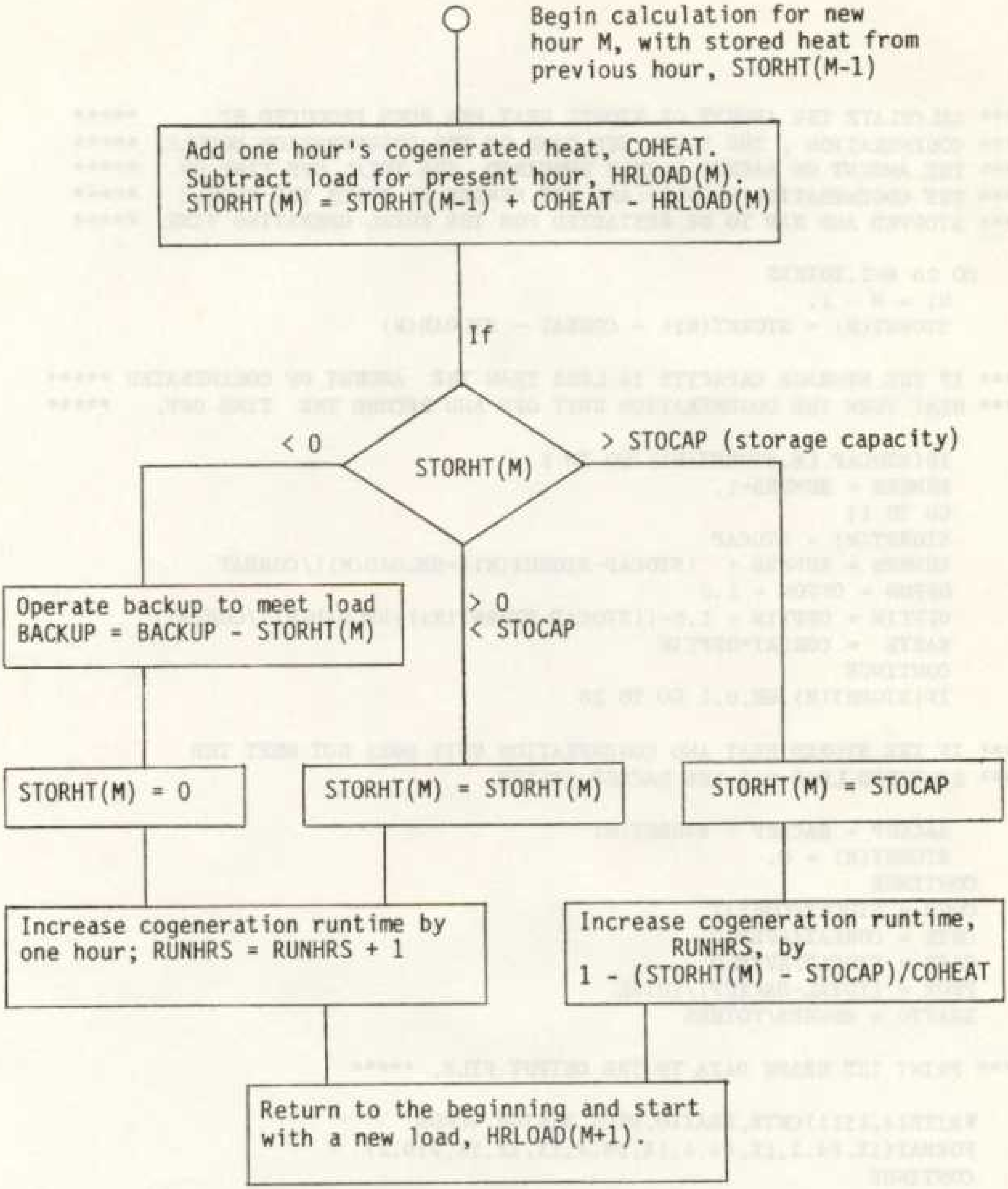

Figure D.1. Storage Program Logic

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