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HVAC Modifications and Computerized Energy Analysis for the Operations Support Building at the Mars Deep Space Station at Goldstone

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are described.

~~This article describes~~ the key heating, ventilation, and air-conditioning (HVAC) modifications implemented at the Mars Deep Space Station's Operation Support Building at Jet Propulsion Laboratories (JPL) in order to reduce energy consumption and decrease operating costs. An energy analysis comparison between the computer-simulated model for the building and the actual meter data was presented. The measurement performance data showed that the cumulative energy savings was about 21% for the period 1979-1981. The deviation from simulated data to measurement performance data was only about 3%.

I. Introduction

This article describes the HVAC modifications implemented and the energy and cost analysis provided by the computer simulation for the Operations Support Building (G-86), one of the major energy consumers of the Deep Space Complex, located at the Mars Deep Space Station (DSS-14) at Goldstone, California.

Reduction of energy consumption, as well as operation costs, at all NASA-JPL Deep Space Network Facilities has been a NASA directive since 1974. Under an intensive energy conservation program, the goal was to reduce by the end of FY85 both the fossil fuel consumption and purchased energy by 50%. Consumption levels at FY73 were to be considered the "baseline."

To that effect, a two-approach method was followed. The first approach was to implement a technical program of energy consumption surveys (audits) to identify and analyze the areas of major consumption. A computer program called Energy Consumption Program (ECP) was developed in-house. It provided a model of the building by simulating the hourly, daily, monthly, and yearly behavior of the heating and cooling loads. Simulation comparisons of both existing and modified conditions resulted in the net energy savings and net energy cost savings.

Two consulting engineering companies were contracted to assist in the studies. In 1975, Keller and Gannon Consulting Engineers used a commercial computer program (E^3) developed by the Southern California Gas Co. The Keller and Gannon Study determined the energy profile and the possible energy savings due to a set of HVAC modifications. In 1976, Burns and Roe, Consulting Engineers, provided another energy study, which included additional proposed modifications.

The second approach was for personnel awareness and motivation under the Energy Conservation Awareness and Recognition Program (ECARP). This program was initiated for the purpose of motivating energy conservation actions within the organization. Energy Conservation Representatives (ECR) for each building were appointed to monitor the initial conservation actions implemented at that time, especially in the area of lighting level reduction, thermostat settings, etc.

The energy conservation program instituted at the Deep Space Communication Complex at Goldstone, California, has been successful. In FY84, one year before the deadline, the goals to reduce 50% of the fossil fuel consumption and purchased energy were accomplished.

II. Building and Original HVAC Equipment Configuration

The Operations Support Building is a two-story structure which houses all remote servo controls and data acquisition equipment for the entire Mars station. Figures 1 and 2 illustrate the floor plan for each story.

The building was originally divided into seven air-conditioned zones (Table 1). Figure 3 provides a schematic diagram of the original HVAC configuration air side. Figure 4 provides a schematic diagram of the original cooling and heating equipment configuration.

The building was originally air-conditioned by three active Air Handling Units (AH1, AH2, and AH4) and one standby unit (AH3); AH1 is a multi-zone blow-thru unit, and the other three are single-zone draw-thru units. Unit AH1 supplied conditioned air to Zones Z1 to Z6, satisfying the temperature of the zones by mixing hot and cold airstreams. If the offices at Zone Z5 and the women's restrooms were too cold, Electric Duct Heaters EH4 and EH3 were energized by thermostats located in the respective areas.

Unit AH2 (and/or standby unit AH3) supplied conditioned air to the control and communication plenums (Zone Z1) by providing air at 50°F, modulated to 55°F using EH1 (or standby EH2) to satisfy the requirements of 70°F at 50% RH at the control and communication rooms located on the second floor. Unit AH4 supplied conditioned air to the hydrogen maser room (Zone Z7) by drawing air from the plenum (Zone Z1), and returning it back to Unit AH4, or relieving it to Zone Z1.

On the refrigerant side, direct expansion cooling coils (DX) at Units AH1, AH2 (and/or AH3 standby), and AH4 cooled the air to the required temperatures. Unit AH1 was served by two compressors (C1 and C2) and one standby Compressor (C3). Compressors C1, C2, and C3 are connected to two Air-Cooled Condenser Units (ACCU1 and ACCU2). Unit AH2 was served by Compressor C4, connected to Air-Cooled Condenser Unit ACCU3. Unit AH3 was served by Compressor C5 (standby), connected to the Air-Cooled Condenser Unit ACCU4. Unit AH4 is served by Compressor C6, a part of Air-Cooled Condensing Unit CU1. On the heating side, Electric Boiler B1 provides heating hot water through a heat exchanger for the heating coil at Unit AH1, and steam for the steam injector at the same unit (Humidifier HU1).

In 1977, loads and capacities were simulated with the JPL-ECP program on the basis of a new energy consumption survey (Ref. 1). In 1979, some electronic and lighting loads had changed. Therefore, this analysis is divided into two phases: Phase I, describing the original building loads in the period 1979-1981, and Phase II, describing the modified building loads that were caused by the Network Consolidation Program (NCP) Mark IVA changes.

III. Phase I of HVAC Modifications

Phase I consisted of a simulation of the original building as of 1979, and all modifications using ECP, with an updated electronic load of 85.5 kW.

The 7 air-conditioned zones of Table 1 were modeled by ECP into 6 macro-zones. Table 2, Mod-0, gives the results of the original equipment configuration without any HVAC modifications. Figure 5 reflects the original HVAC configuration as modeled by ECP. Table 2, Mod-0, provides the monthly and yearly energy consumption and energy cost. The energy cost was based on a fixed energy rate of 0.05 dollars/kWh(e).

All HVAC modifications were examined in light of initial conservation measures and new energy costs, and the selected list for Phase I is as follows:

Mod-1 – Change the inside design temperature: from 72°F (22°C) all year to 68°F (20°C) in winter and 78°F (25°C) in summer. Install "dead band" thermostat controls.

Mod-2 – Provide variable air-volume (VAV) control at Zone Z3 only. Install a by-pass air flow at Unit AH1 (Table 3).

Mod-3 – Arrange HVAC system components and change the cooling system from DX to chilled water. In this modification, Compressor C2 is disconnected and Compressor C1, with the addition of a liquid cooler (LC1), will provide chilled water to Units AH1, AH2, and AH3. AH4 (maser unit) will continue to be served by Compressor C3. Modified cooling and heating equipment configuration is shown in Fig. 6.

Mod-4 – Add outside air (OSA) economizers and automatic temperature reset setpoints to Units AH2 and AH3. This modification required that Units AH2 and AH3 were operating with the economizer. In this case, Unit AH1 supplies 0 CFM to Zone Z2, and it is operating in low speed (minimum CFM). If the *economizer is not operating* due to outside weather conditions, Unit AH3 becomes a standby unit and AH-1 supplies 20,000 CFM (9,440 l/s) to Zone Z2, operating in high speed.

Mod-5 – Add chilled water storage tank to provide: (1) reduction of partial load losses, (2) leveling of cooling loads, and (3) uniform supply chilled water temperatures. Based on the calculated loads generated by Mod-4, Table 3 provides the energy consumption and energy cost *without storage tank, with storage tank* option and the total annual savings.

The results of the computer simulation are presented in Tables 2 and 3. A summary of all modifications, based on the original building conditions, is provided in Table 4.

IV. New HVAC Configuration — Phase II

In 1983, the total electronic loads at the operation support building were increased from an original load of 85.5 kW to an ultimate load of 255 kW. This proposed increase was due to the JPL Network Consolidation Program Mark IVA, and it is the basis for the computer simulation under Phase II.

The building configuration changed slightly from the one shown in Figs. 1 and 2. The new configuration is shown in Figs. 7 and 8. Figure 9 is the new view of the actual Control Room 201. The zones remain the same as shown in Table 1, except for changes in the Zone air flow which are shown in Table 6. Table 5 also provides the updated ECP zone identification.

Table 6 provides the results of Mod-6 for the basic DX design, with additional units AH5 and AH6, and the required C4 and C5 compressors to accommodate the increased load of 255 kW.

The three HVAC modifications for Phase II were based on Mod-6 data and are listed below.

Mod-7 – Change the inside design temperature: from 72°F (22°C) all year to 68°F (20°C) in winter and 78°F (25°C) in summer. Install "dead band" thermostats. Change the DX system to a chilled water system. Add setpoints to units AH5 and AH6.

Mod-8 – Add OSA economizers and automatic reset setpoints for Units AH5 and AH6.

Mod-9 – For existing chilled water storage tank, and based on the new calculated loads generated by Mod-8, Table 8 provided energy consumption and energy cost *without storage tank, with storage tank* option and the total annual savings.

The actual HVAC configuration, which includes Units AH5 and AH6 and Chiller CH2, is reflected in Fig. 10.

The results of the computer simulation are presented in Tables 6 and 7.

A summary of all Phase II modifications, based on Mod-6, is given in Table 8.

V. HVAC System Design Controls and Operation

The original HVAC design used American Society of Heating, Refrigeration and Air-Conditioning Engineering (ASHRAE) standard air discharge temperature setpoints compatible with the operating parameters of the installed refrigeration and heating equipment. Temperature control was achieved by reheating the air to the desired setpoint in the zone. Capacity control was performed manually and was limited to adjusting the mechanical unloaders in the refrigeration compressors. The design of the system was constrained in such a way that a reduction in the cooling load below 50% of the original design capacity would damage the refrigeration equipment. This problem was avoided by maintaining a sufficiently high artificial load to prevent a drop below the 50% point.

A. Design Criteria

The data obtained from the analysis of the original building operation and the proposed modifications were the basis for the selection of the mechanical design. The new control design was to meet stringent requirements for unattended HVAC system operation and easy maintainability.

In addition, the new system configuration was to permit an expansion in load capacity up to 300% of its base design, as well as to accommodate load changes from 20% to 100% of the base capacity with only minor adjustments.

B. HVAC Design Modifications

The existing air distribution network was revised and the required air flow capacity increased. The function of each air handler was defined and allocated to meet the imposed demand at maximum obtainable efficiency. The new HVAC functional block diagram is shown in Fig. 11.

To best utilize the existing refrigeration equipment, and to consolidate it with the added cooling capacity, a load decoupled chilled water system with thermal storage was selected as the prime mechanical cooling system. Sections of the existing DX systems were modified and retained for redundancy and backup.

The existing manual controls were removed and replaced with fully automated temperature and humidity controls, which are able to select the most economical mode of operation available to meet the demand. The required equipment can start and stop without operator assistance, and the status of each major component is displayed on the HVAC status panel.

C. HVAC Operation Logic

Since the electronic equipment installed is the major load, all HVAC parameters were adjusted to provide, with the least amount of energy expenditure, both an optimum inlet temperature to the electronic racks and a rack discharge temperature most suitable for human comfort. The new HVAC achieves this by operating and controlling the equipment as outlined below.

1. **Plenum Air Distribution**. Four air handlers, with a total supply of 82,000 CFM (38,695 l/s), hold the air pressure differential between the main plenum and the control room at 0.04 in H_2O ± 0.01 in H_2O (1 mm H_2O + 0.25 mm H_2O) and maintain an airflow of 475 CFM (225 l/s) per kW of installed electronic load. With the mass of air flowing through an equipment rack adjusted to 475 CFM ±20 CFM (225 l/s ± 9.5 l/s) per kW of heat to be dissipated, a rise of 8°F (4.5°C) in the air temperature is produced. And with the plenum (rack inlet) temperature maintained at 64°F (18°C), the air will exit from the racks at an average temperature of 72°F (22.2°C). All other loads such as lights, roof, etc., are added to the airstream after it leaves the control room. This load changes the return air temperature from 72°F (22.2°C) to 75°F (24°C) before it is cooled again. If the enthalpy of the outside air (OSA) is less than the enthalpy of the return air (RA), the enthalpy controller will release the economizer lockout and the system will operate with 100% outside air. The chilled water cools the air until the temperature drops below the plenum setpoint. With the OSA temperature below the plenum setpoint (64°F/17.8°C), the controls close the chilled water valves and limit the amount of OSA to the level needed to maintain the plenum setpoint.

2. **Comfort and Plenum Backup Air Distribution**. One two-speed air handler (Unit AH1) supplies the comfort load via a double duct system. At low speed, the unit delivers 11,000 CFM (5,190 l/s) of either heating or cooling air to the system. Zone control is achieved by mixing either heating or cooling air with return air.

If one of the plenum supply units fails, the unit switches to high speed, delivering 27,000 CFM (12740 l/s) and diverts 20,000 CFM (9440 l/s) to the main plenum (Fig. 12).

3. **Chilled Water System**. The chilled water system is a load decoupled system which consists of four closed loop flow circuits: two constant flow charge circuits of 180 GPM (11.4 l/s) each, and two variable flow demand circuits of 0-160 GPM (0-10 l/s) each. All circuits are connected to a 10,000 gallon (37,854 l) storage tank which acts as a pressure differential equalizer, a load buffer, and a thermal mass storage. The cooling capacity for Charge Circuit No. 1 is provided by Chiller No. 1, a 60 ton (211 kW) split system with two compressors; and for Charge Circuit No. 2 by Chiller No. 2, a 90 ton (316 kW) package unit with four compressors. Figure 13 shows the Chilled Water Functional Block Diagram, and Fig. 14 shows the liquid cooler LC1, Pumps P3, P3A, P4, and P4A assembly.

The mode of operation depends on the demand. The controls select the appropriate lead-lag and start-stop sequence for each of the four circuits. On a rise in demand, the chilled water control valves open and the demand pumps start. The pumps draw chilled water from the thermal storage tank until the temperature of the water entering the supply headers connecting the demand pumps and the storage tank rises to the "High" setpoint. The signal that the stored cooling capacity is used up starts the charge pumps and initiates the chiller start sequence. Once operating, the chillers adjust their cooling capacity to maintain a preset temperature in the supply header.

During a period of low demand, with the control valves only partially open, the excess cooling capacity of the charge circuit is supplied to the thermal storage tank and displaces the warm water until the temperature of the water leaving the tank drops to the "Low" setpoint. This signal that the storage is fully charged stops the charge pumps and initiates the chillers pump down and stop sequence.

As the demand increases, more water is diverted into the demand circuits and less goes into the storage tank. This increases the amount of time the charge circuits have to operate until a new equilibrium is reached. When the demand approaches the charging capacity, all circuits operate continuously. On a drop in demand, the control valves begin to throttle the flow through the demand circuits again. This increases the back pressure at the inlet to the demand pumps, and more water from the charge circuits is diverted back to the storage until the storage is charged again and the cycle is repeated.

4. Control Groups. The control system selected is hierarchical in nature and has three levels of control function arranged in three control groups as follows:

(1) Primary Controls: The primary control group encompasses all sensors, switches, and protective devices which allow an operator to control the system manually.

(2) Secondary Controls: The secondary control group encompasses all sensors (temperature, humidity, power, etc.), amplifiers, logic functions, and indicating displays needed to automatically control the mechanical equipment. The controls continuously monitor the operation of the primary controls and the HVAC system performance, and display the current status on the HVAC status panel. If a component failure is detected, the controls will select and start a backup, give an alarm and indicate the type of failure and the equipment affected. If a power failure occurs, the controls reset all systems to "off," and restart the equipment in a preselected sequence once power is restored.

(3) Technical Facility Controller (TFC): The secondary controls also act as an interface for the remote commands from the third level of controls: the Technical Facilities Controller. The remote commands are accepted and evaluated, and if they are within the selected safety limits of performance, they will be passed on to the primary controls. The new status is then displayed on the HVAC status panel and sent back to the Facilities Controller for evaluation. If the commands of the Facilities Controller violate the safety limits, or if no commands are generated, the secondary controls automatically revert back to autonomous operation (Fig. 15). The actual HVAC status panel is shown in Fig. 16.

VI. Verification of Computer Simulation vs Measurement Performance

A. Phase I

This study provided the computer simulation for the original HVAC system as shown in Table 2. The following two outputs are important for energy consumption verification:

(1) Total electrical consumption for one year,

(2) Total electronic equipment load for one year.

In Table 2, the original HVAC equipment simulation gave the total electric consumption as 1,856,944 kWh(e)/yr, and the total electronic equipment load as 749,000 kWh(e)/yr.

The actual electric meters data were used for verification. The meters' locations are shown in Fig. 17. The Mod-0 computer simulation was based on survey data for the year 1979, and the corresponding actual electric meter readings (Meter No. 42 and Meter No. 43) for that year were as follows:

Meter No. 42: 2,360,000 kWh(e)/yr (Building Meter)

Meter No. 43: 953,600 kWh(e)/yr
(Electronic Equipment Load Meter)

By comparing the actual meter data vs the simulation from Table 2, we observe that the meter readings seem to exceed the computer simulation results by 21%. In order to obtain the realistic difference, the following points are noted:

(1) The electronic equipment load at the actual meter reading is 953,600 kWh(e)/yr, which is equivalent to 109 kW(e). This is compared against the electronic equipment load provided for the computer simulation of 749,000 kWh(e)/yr, or its equivalent 85.5 kW(e). This difference represents a 204,600 kWh(e)/yr (953,600 − 749,000) that should be accounted for in the ECP input.

This load reduction, or its equivalent, was purposely done in 1979 because of expected ongoing consolidation of electronic equipment at the time of the study. In fact, in 1984 the electronic load was 794,200 kW(e)/yr, which is equivalent to 91 kW(e), i.e., close to the electronic equipment computer-simulated load of 85.5 kW(e).

(2) Excluding the additional loads for Building G-84, UPS and MDU panels (as shown in Fig. 17), which is approximately equal to:

30 kW(e) or 262,800 kWh(e)/yr

(3) The total unaccounted loads in Items 1 and 2 above is 467,400 kWh(e)/yr (204,600 + 262,800).

Deducting that amount from the building electric meter gives:

1,892,600 kWh(e)/yr (2,360,000 - 467,400).

The true deviation between the meter reading and the computer simulation would be:

(1,892,600 - 1,856,944) / 1,892,600 = 2%

which is below the allowed margin (±10%) in this computer simulation.

The energy consumption for Meter No. 42 for the year 1981, after all the modifications of Phase I were completed, read 1,591,200 kWh(e)/yr. Beginning in 1980, Building G-84 was out of commission, and the deduction for UPS and MDU panel was about 12 kW(e) or 105,100 kWh(e)/yr. Deducting this amount from the meter reading gives 1,486,100 kWh(e)/yr, which, if compared with the computer simulation output of 1,524,400 kWh(e)/yr, gives a 2% deviation of the simulated load.

Actual electronic loads have not decreased as much as originally scheduled, but lighting and other accessory loads have decreased. The net effect was that the total building energy consumption in 1981 showed a net decrease of

(1,892,600 - 1,486,100) / 1,892,600 = 21%

as compared to the 1979 level.

The net decrease in energy costs in 1981 (relative to 1979) was about

(1,892,600 - 1,486,100) X 0.0633 or $25,731.

The 0.0633 dollars/kWh was the actual cost of prorated utility (Southern California Edison) purchased and JPL generated electricity for 1981.

The simulated values in Table 5 give the cumulative energy savings (Mod-1 through Mod-5) as 18%, which, if compared with the 21% figure, indicates that the computer simulation and the meter performance data are in good agreement.

B. Phase II

The actual electric meter readings were found to be below the computer simulated results listed in Table 8. Note that the electronic equipment load in 1985 has gone up slightly to 97 kW(e), and the computer simulation input was for 255 kW. The control room was only partially loaded.

Another verification made for the computer simulation inputs was to compare it against the Test Performance Data. These tests were performed in June 1985 and are given in Table 9. The ECP input data and test performance data values verify their agreement.

Another parameter to be verified is the chilled water storage tank discharge capacity, which is shown as Mod-5 in the computer simulation. The input data for Mod-5 was a 10°F differential for the chilled water, giving a charging capacity of 69.4 tons of refrigeration (or 244 kW). The temperature difference between discharge cycle start and finish was found to have a 9°F differential temperature, giving the tank discharge capacity as 62.55 tons (220 kW), which is within the conditions imposed to the storage tank charging/discharging cycle.

Under Phase II, the actual HVAC system is partially loaded. And according to Table 8, the projected energy savings will be (4,610–3,935)/4,610 = 15%, and the projected cost-savings $47,305.

VII. Summary

Several HVAC modifications were implemented to the Operations Support Building (G-86) at the Mars Deep Space Station DSS-14 to reduce the required peak-load capacity, and decrease energy and costs. The introduction of the chilled water storage tank provided the sink for the excess cooling capacity available during nighttime operation and allowed a controlled shift of that capacity to the peak demand time. In addition, the chilled water storage acted as a margin of safety for unexpected changes in load or cooling equipment failure.

Automatic controls were optimally designed to operate with the optimum combination of mechanical equipment required to meet the HVAC demand, and provided the basis for the lowest operating and maintenance cost obtainable.

Computer simulations were performed using the ECP program and the simulation results were compared against the actual meter reading. The results agreed to within 3%.

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List of Symbols

ACCU	Air-cooling condenser unit
AH	Air handler
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineering
B	Boiler
BD	Barometric or backdraft damper
Btu	British thermal units
C	Compressor
°C	Degree centigrade
CFM	Cubic feet per minute
CH	Chiller
CU	Air-cooled condensing unit
E_C	Economizer
ECARP	Energy Conservation Awareness and Recognition Program
ECP	Energy Consumption Program
ECR	Energy Conservation Representative
EH	Electric duct heater
°F	Degrees fahrenheit
FY	Fiscal year
GPM	Gallons per minute
HP	Horsepower
HVAC	Heating, ventilating and air-conditioning
HU	Humidifier or steam injector
in H_2O	Inches of water
kW	Kilowatt
kW(e)	Kilowatt (electrical)
kWh(e)	Kilowatt-hour (electrical)
kWh(t)	Kilowatt-hour (thermal)
kWh(e)/yr	Kilowatt-hour (electrical) per year
l	Liter
LC	Liquid cooler
l/s	Liters per second
MD	Motorized damper
MDU	Main distribution–utility
mm H_2O	Millimeters of water
Mod	Modification
MWh(3)	Megawatt-hour (electrical)
MWh(t)	Megawatt-hour (thermal)
NCP	Network Consolidation Program
OSA	Outside air
P	Pump
RA	Return air
RH	Relative humidity
SCE	Southern California Edison
ST	Storage tank
TFC	Technical facilities controller
ton	Ton of refrigeration
UPS	Uninterrupted power supply
VAV	Variable air volume
Z	Zone

Table 1. Original configuration and ECP zone identification (Phase I)

Zone No.	Room No.	Room Name	Floor	Zone Air Flow CFM (l/s)	ECP Zone No.
1	101 102	Control room, plenum Communications room, plenum	1	40,000 (18,000)	2
2	201	Control room comfort	2	4,480 (2,115)	3
3	202	Communication room comfort	2	2,000 (945)	3
4	206, 207 208, 209	Offices	2	2,350 (1,100)	1
	202	Corridor			
5	210, 211	Offices	2	400 (190)	4
6	105	Frequency Standard Control Room (Hydrogen maser room)	1	2,000 (945)	6
7	205	Women's rest room	2	125 (60)	5

Table 2. Yearly energy consumption and costs – Mod-0, Mod-1, Mod-2, Mod-3, and Mod-4

Mod	Accessories		Lights			Equipment		Thermal Meter kWh(t)	Electric Meter kWh(e)	Cost, Dollars
	Thermal Btu	Electrical 10^6 kWh(e)	Incandescent 10^3kWh(e)	Fluorescent 10^6kWh(e)	Electric 10^6kWh(e)	Mechanical kWh(e)	Thermal tons			
Mod–0	0	0.438	0.365	0.211	0.749	0	0	0	1,856,944	92,847
Mod–1	0	0.438	0.365	0.211	0.749	0	0	0	1,851,731	92,587
Mod–2	0	0.438	0.365	0.211	0.749	0	0	0	1,849,902	92,495
Mod–3	0	0.370	0.365	0.211	0.749	0	0	0	1,757,267	87,863
Mod–4	0	0.402	0.365	0.211	0.749	0	0	0	1,558,538	77,927

Table 3. Chilled water storage tank energy consumption and costs – Mod-5

Parameter	Without Storage Tank	With Storage Tank	Annual Savings
Yearly energy consumption, kWh(e)	206,950	172,810	34,137
Yearly energy costs, dollars	14,893	12,469	2,423

Table 4. Summary of all modifications (Phase I)

Mod No.	Description	Annual Energy Consumption		Estimated Construction Costs, Dollars	Annual Costs, Dollars	Annual Costs Saving, Dollars	Payback Period, Years
		Thermal MWh(t)	Electrical MWh(e)				
Mod–0	Original condition	0	1,856.9	–	92,847[a] 130,914[b]	–	–
Mod–1	Addition of dead controls	0	1,851.7	2,000	92,587[a] 130,548[b]	260[a] 366[b]	5.46
Mod–2	Addition of VAV control to Zone Z-3	0	1,849.9	1,500	92,495[a] 130,418[b]	92[a] 130[b]	11.54
Mod–3	Rearranging HVAC system addition of CHW system	0	1,757.3	80,000	87,863[a] 123,887[b]	4,632[a] 6,531[b]	12.25
Mod–4	Addition of HVAC status panel and econ. and auto reset for AH2 and AH3	0	1,558.5	90,000	77,927 109,877	9,936[a] 4,010[b]	6.42
Mod–5	Addition of chilled water storage tank (10,000 gal.)	0	1,525.4	25,000	76,029[a] 10,754[b]	1,718[a] 2,423[c]	10.30
Total All Mods		0	1,524.4	198.500	76,209[a] 107,454[b]	16,638[a] 23,460[b]	8.46

[a]Annual cost and annual cost savings on a fixed rate of 0.05 dollars/kWh(e).
[b]Annual cost and annual cost savings adjusted for variable rate (0.07/0.05).
[c]Annual cost savings was calculated on a variable rate.

Table 5. ECP zone identification (Phase II)

Zone No.	Room No.	Room Name	Zone Air Flow CFM, l/s	ECP Zone No.
1	101 102	Control room, plenum	82,000 (38,695)	2
2	200 201	Control room, comfort	3,800 (1,795)	3
3	206 207	Lounge room New monitor room	2,850 (1,345)	1
4	208	New communications room	2,200 (1,040)	4
5	204	Women's rest room	150 (70)	5
6	105	Frequency Standard Control Room (Hydrogen maser room)	5,000 (2,360)	6
–	–	–	2,000 (945)	7*

*Bypass air flow at Unit AH-1.

Table 6. Yearly energy consumption and costs – Mod-6, Mod-7 and Mod-8

Mod	Accessories		Lights			Equipment		Thermal Meter kWh(t)	Electric Meter kWh(e)	Cost, Dollars
	Thermal Btu	Electrical 10^7 kWh(e)	Incandescent 10^3kWh(e)	Fluorescent 10^6kWh(e)	Electric 10^6kWh(e)	Mechanical kWh(e)	Thermal tons			
Mod–6	0	0.1363	0.365	0.255	0.2234	0	0	0	4,610,038	322,703
Mod–7	0	0.1111	0.365	0.255	0.2234	0	0	0	4,132,582	289,281
Mod–8	0	0.1111	0.365	0.255	0.2234	0	0	0	3,991,366	279,396

Table 7. Chilled water storage tank energy consumption and costs – Mod-9

Parameter	Without Storage Tank	With Storage Tank	Annual Savings
Yearly energy consumption, kWh(e)	495,680	439,350	56,332
Yearly energy costs, dollars	35,321	31,223	4,098

Table 8. Summary of all modifications (Phase II)

Mod No.	Description	Annual Energy Consumption		Estimated Construction Costs, Dollars[b]	Annual Costs, Dollars[c]	Annual Costs Saving, Dollars	Payback Period, Years
		Thermal MWh(t)	Electrical MWh(e)				
Mod–6	Original condition and addition of AH5 and AH6[a]	0	4,610		322,703	–	
Mod–7	Addition of dead band controls	0	4,133	26,000	289,281	33,422	0.8
	Addition of Chilled Water System No. 2						
Mod–8	Addition of HVAC status panel. Economizer and automatic reset for AH5 and AH6	0	3,991	40,000	279,396	9,785	4.1
Mod–9	Connection of Chilled Water System No. 2 to existing chilled water storage	0	3,935	4,000	275,298	4,098	1.0
Total All Mods		0	3,935	70,000	275,298	47,305	1.5

[a]The hypothetical Mod–6 is based on the original air handling and DX systems, in addition to Units AH5 and AH6 with their corresponding DX systems.
[b]Estimated construction costs shown are the additional costs for the chilled water system, economizer, and automatic controls, above the cost required for a DX system of identical capacity.
[c]All annual costs were calculated on a fixed rate of 0.07 dollars/kWh(e), except Mod–9, which was calculated on a variable rate.

Table 9. ECP input data and test performance data

Location	Input Data	Test Data
Plenum	64°F	63°F @ 50% RH 64°F @ 80% RH
Control room	72°F	72°F – 73°F @ 50% RH 71°F – 75°F @ 80% RH

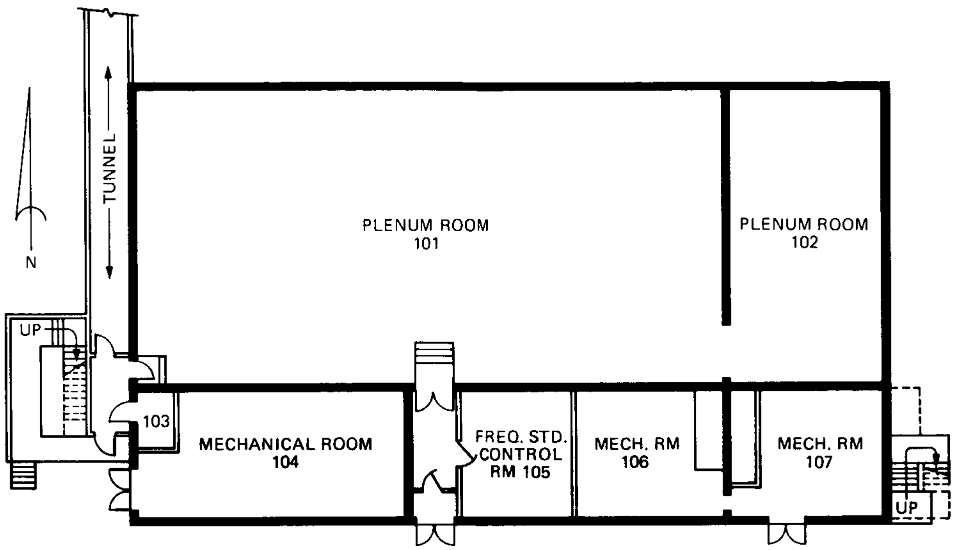


Fig. 1. Operations Support Building, first floor plan

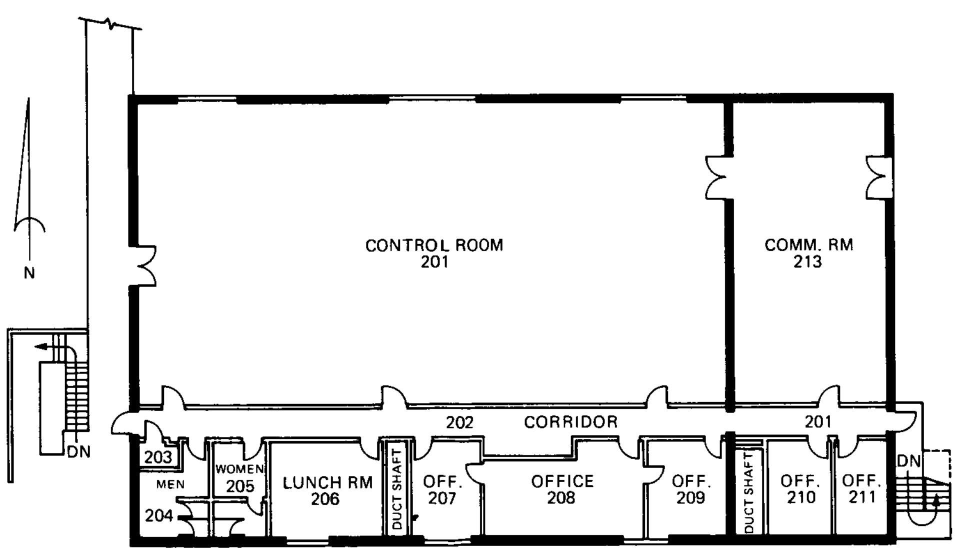


Fig. 2. Operations Support Building, second floor plan

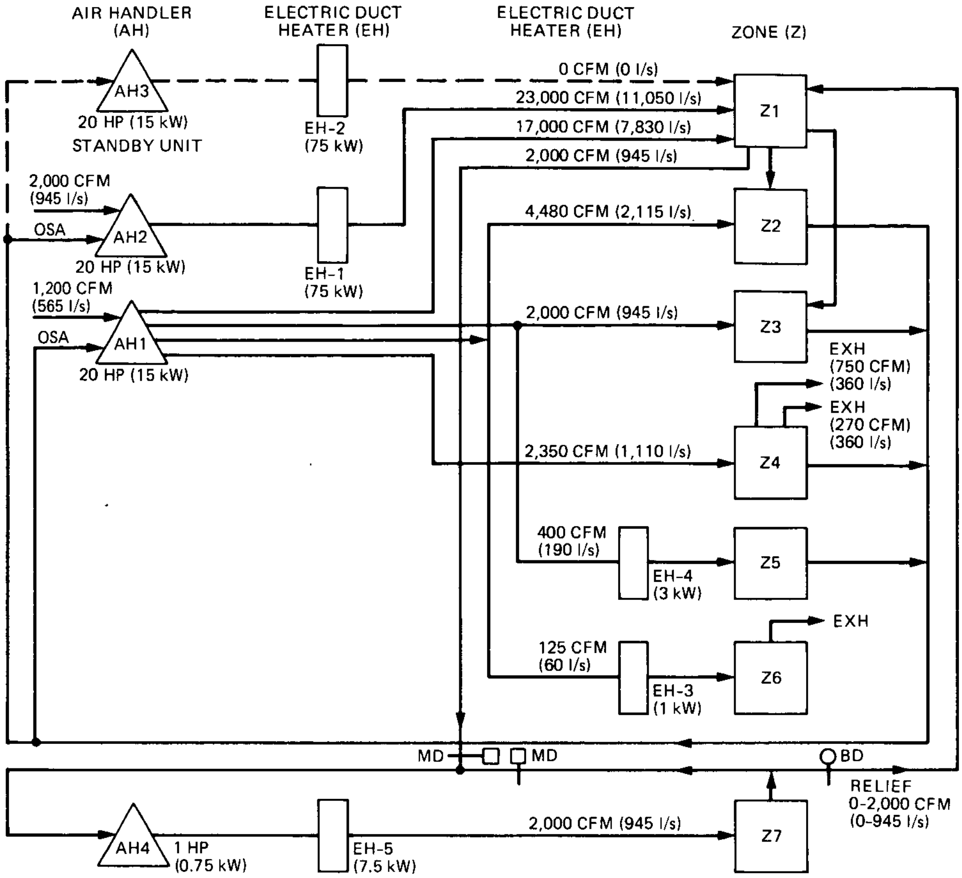


Fig. 3. Original HVAC zoning and air flow configuration

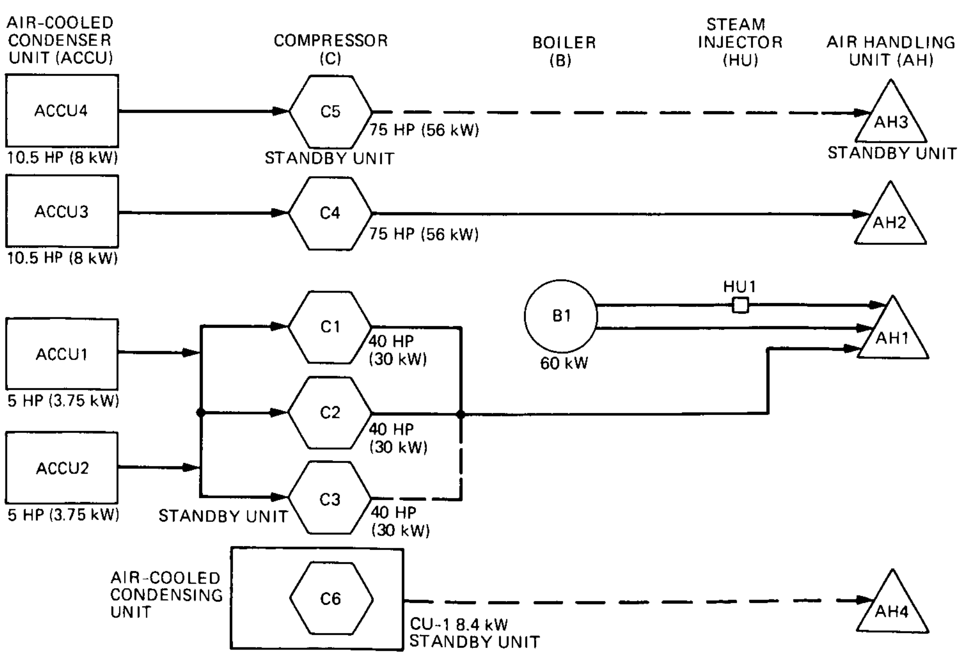
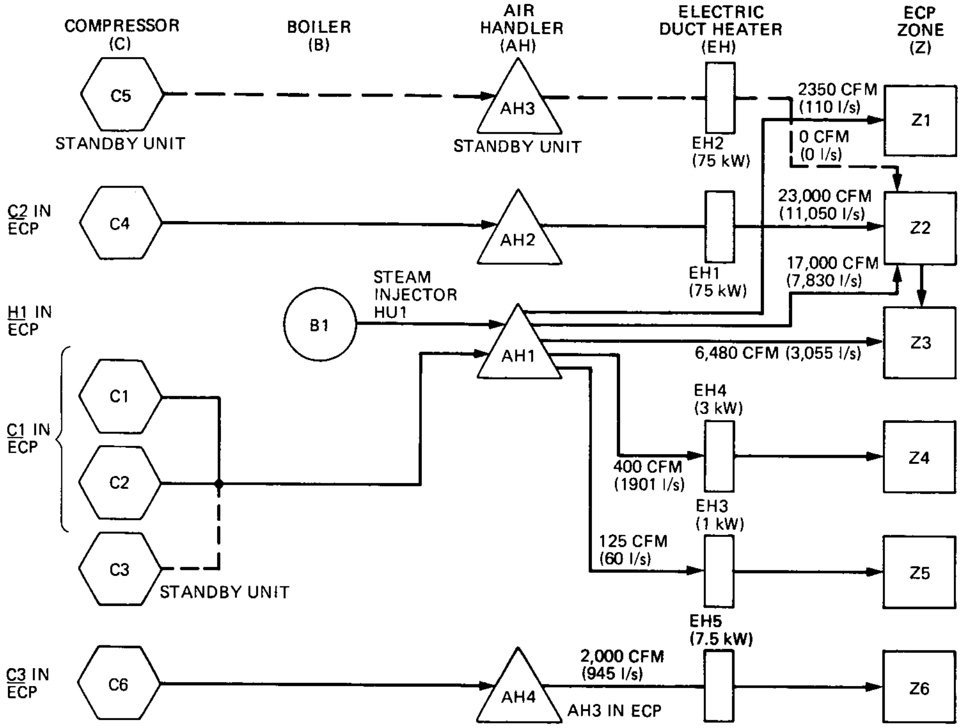


Fig. 4. Original cooling and heating equipment configuration



NOTES: 1. ALL STANDBY UNITS ARE NOT MODELED BY ECP.
2. ELECTRIC DUCT HEATERS EH1, EH2, EH3, EH4 AND EH5 ARE NOT ECP MODELED.
3. RETURN/RELIEF/EXHAUST FROM ZONES ARE NOT SHOWN FOR CLARITY.

Fig. 5. Original HVAC configuration (ECP modeling)

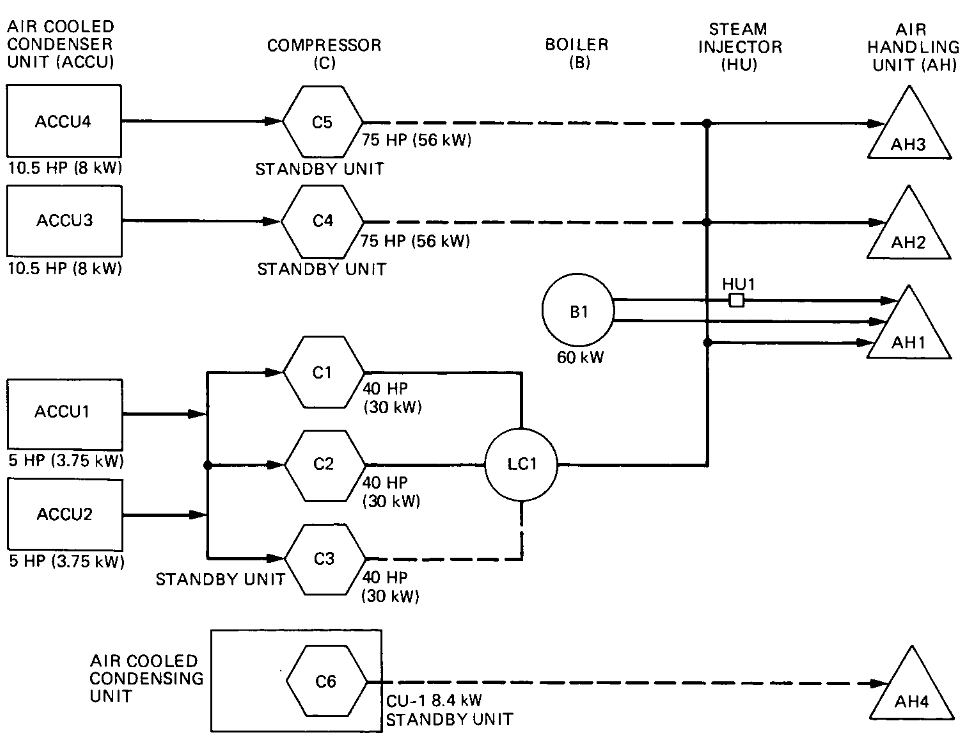


Fig. 6. Modified cooling and heating equipment configuration

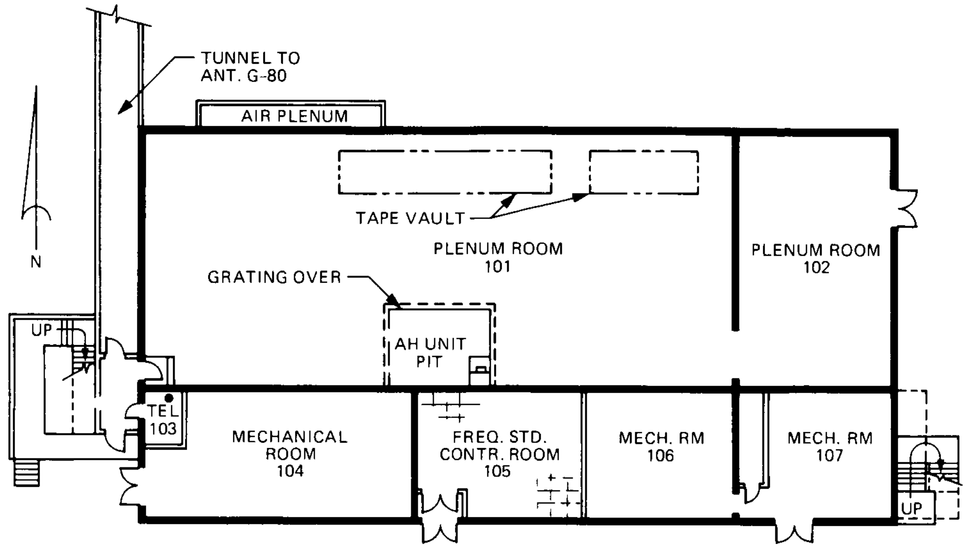


Fig. 7. Operations Support Building, first floor plan, modified

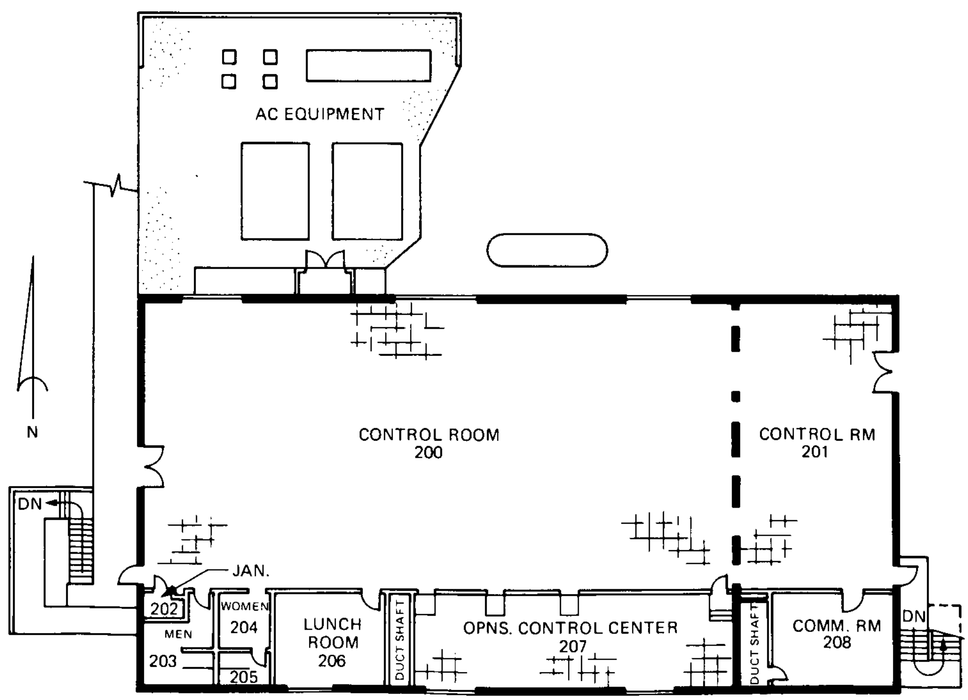


Fig. 8. Operations Support Building, second floor plan, modified

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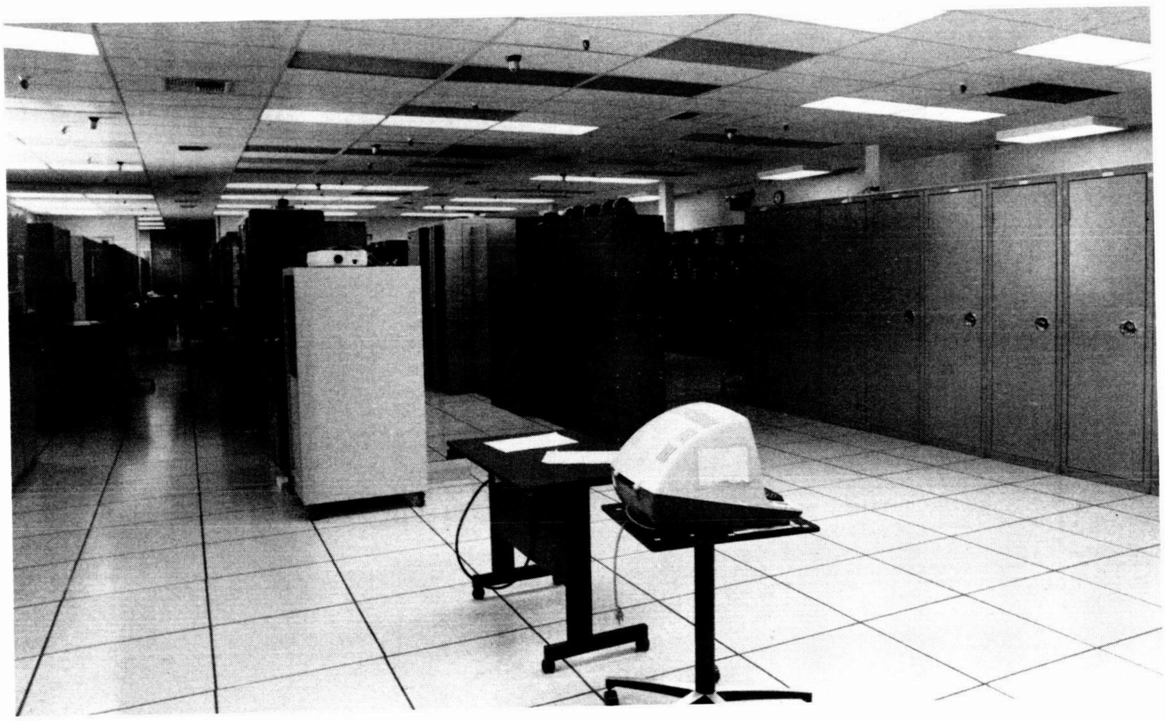
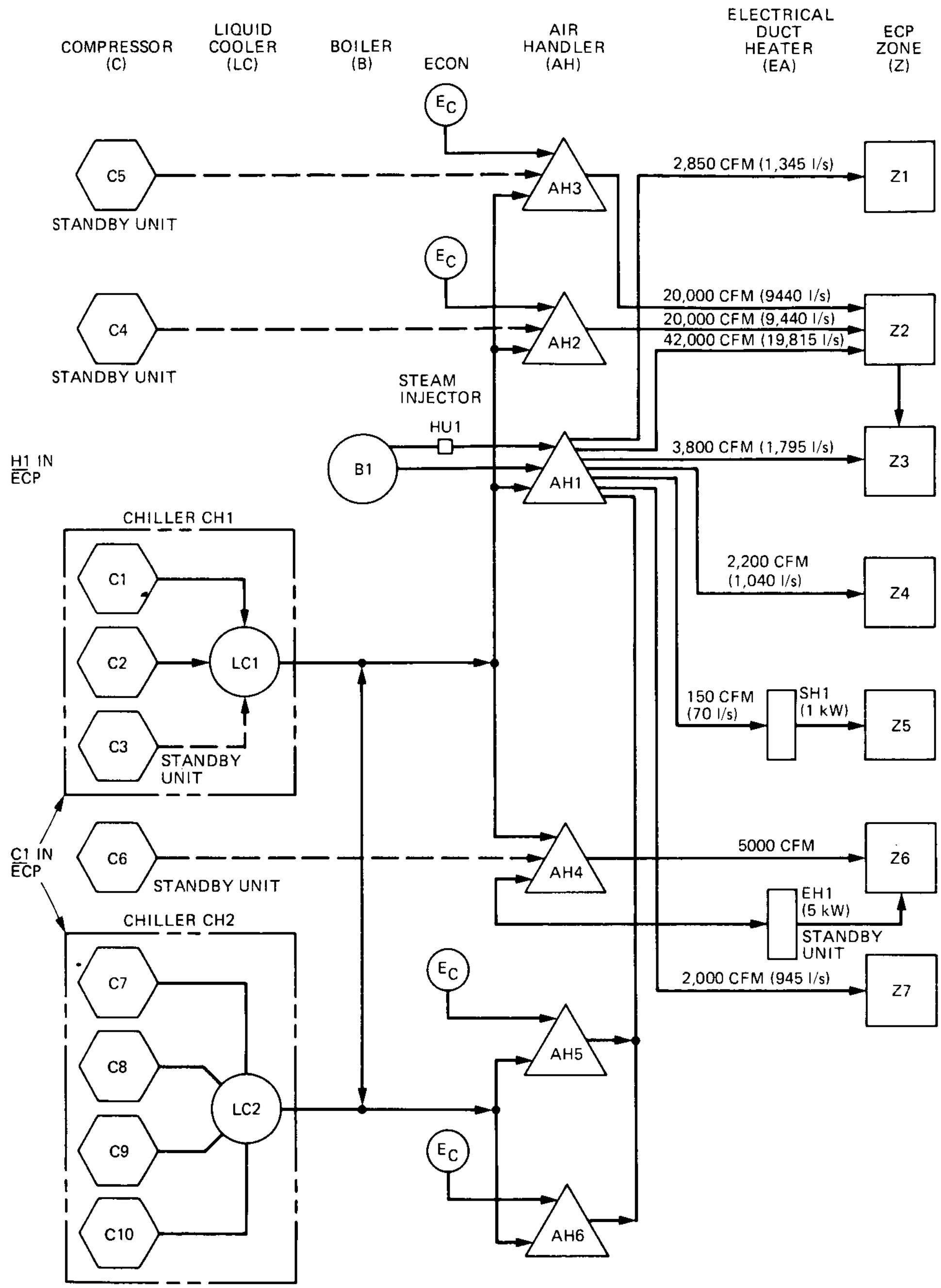


Fig. 9. View of actual control room (201)



NOTES: 1. ZONE 7 (NO LOAD) IS INTRODUCED IN THE COMPUTER MODEL AS A REQUIREMENT FOR UNIT AH1 TO OPERATE IN THE STABLE PART OF THE FAN CURVE (11,000 CFM/5,190 l/s MIN.).
2. ELECTRIC DUCT HEATER EH3 FROM PHASE I IS NOW RENAMED SH1.
3. ALL STANDBY UNITS ARE NOT ECP MODELED.
4. RETURN/RELIEF/EXHAUST FROM ZONES ARE NOT SHOWN FOR CLARITY.

Fig. 10. Actual HVAC configuration

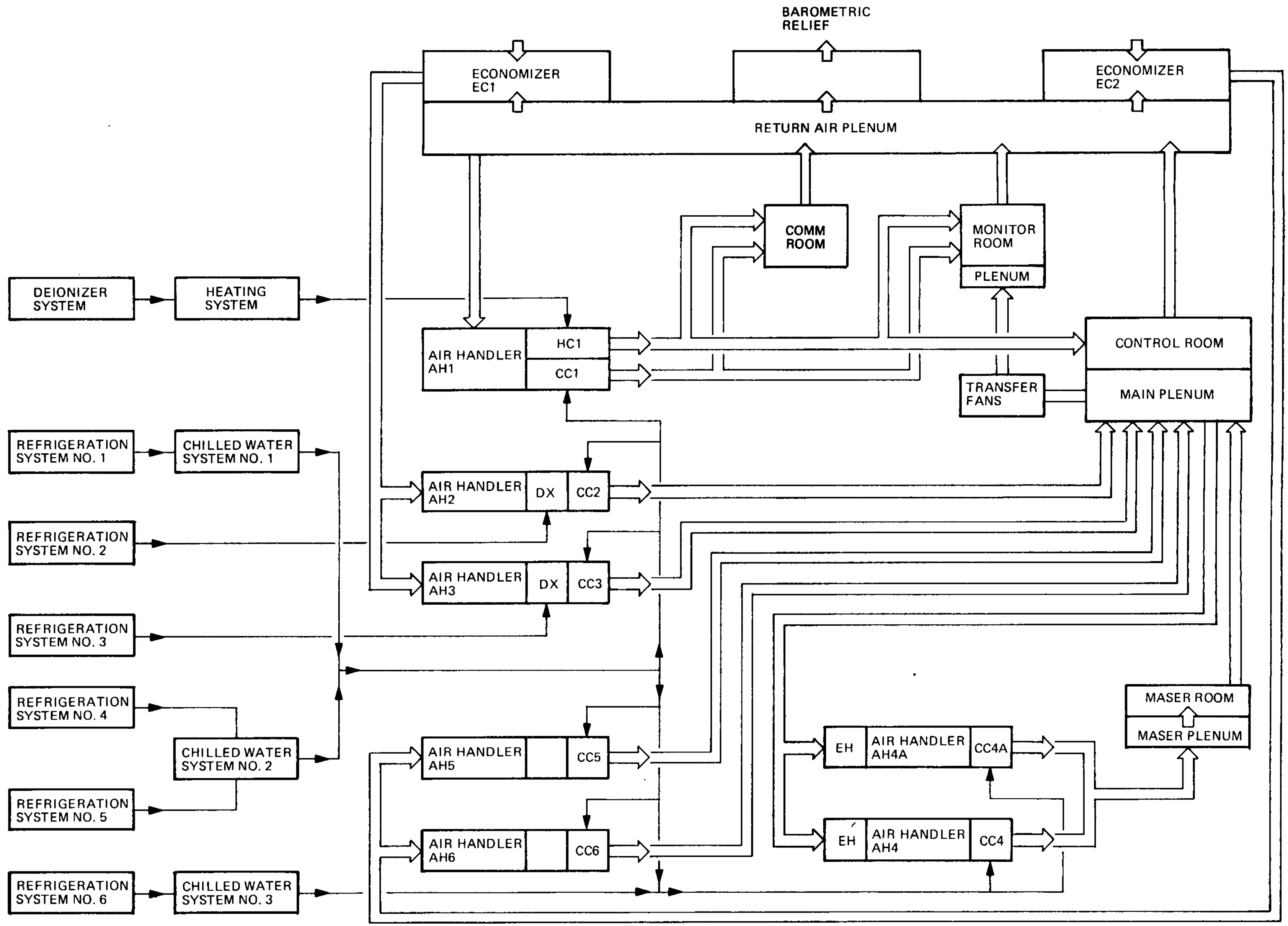


Fig. 11. HVAC, functional block diagram

C-3

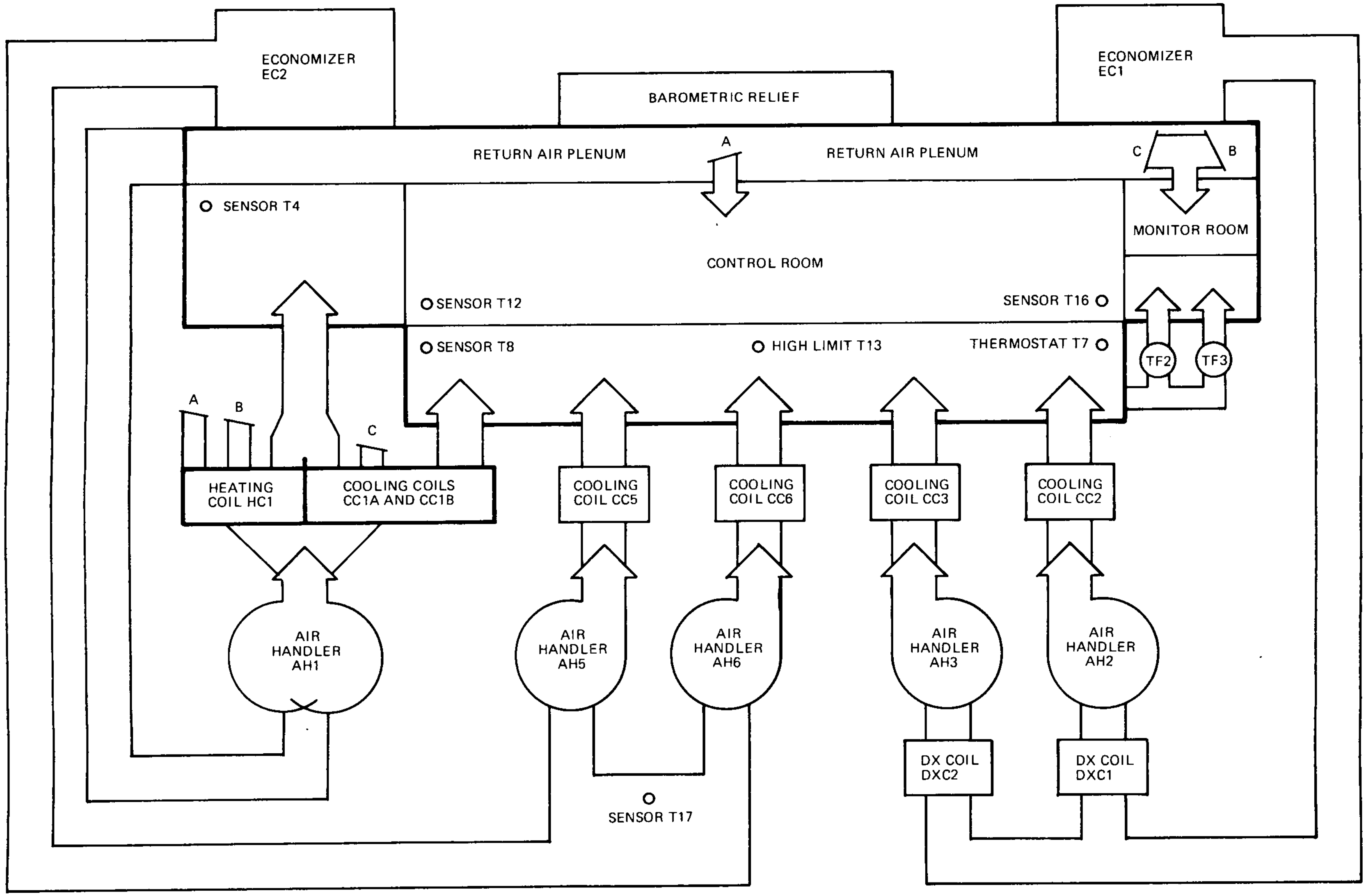


Fig. 12. Air distribution, functional block diagram

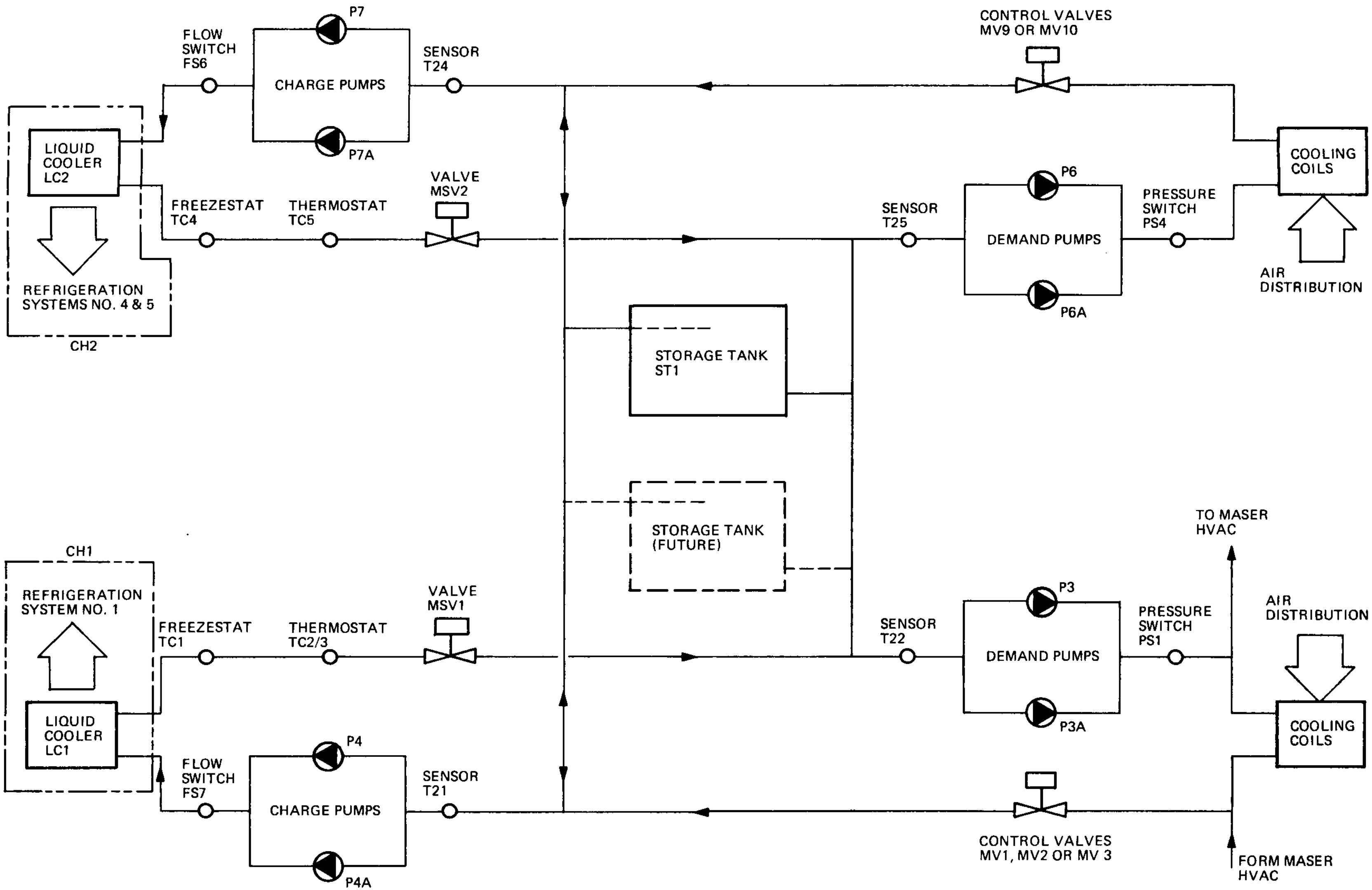


Fig. 13. Chilled water, functional block diagram

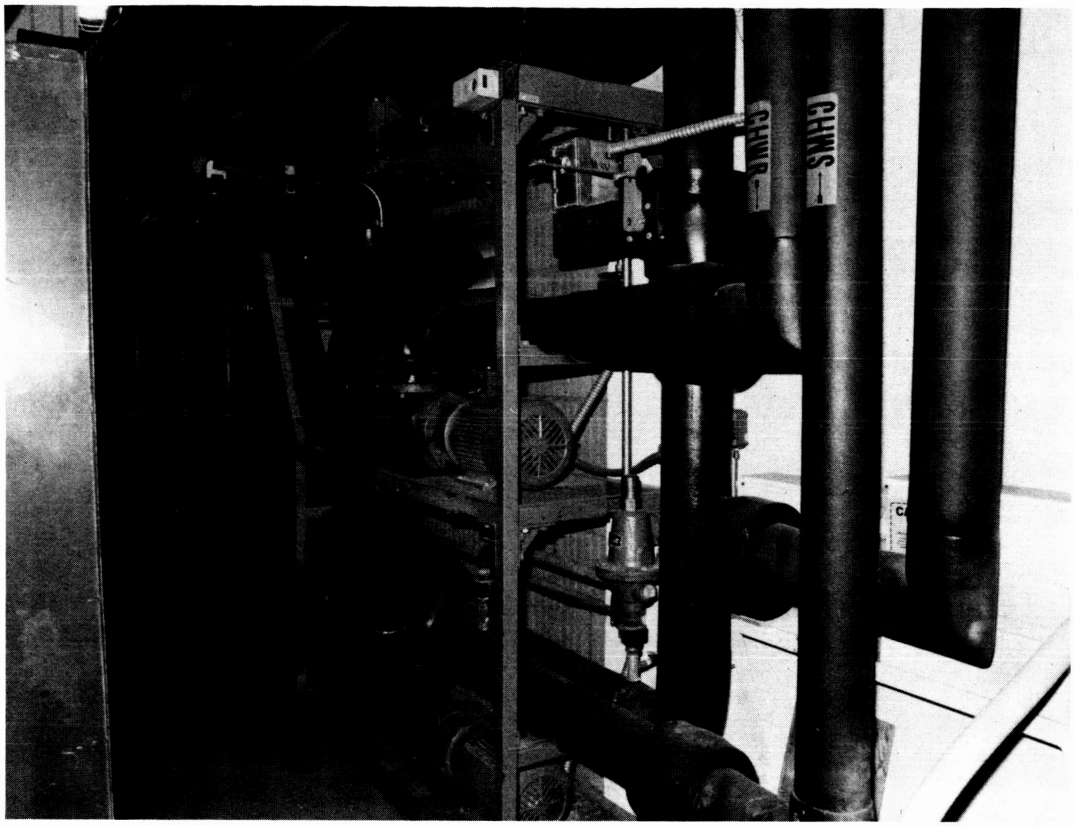


Fig. 14. Liquid Cooler LC1, Pumps P3, P3A, P4 and P4A assembly

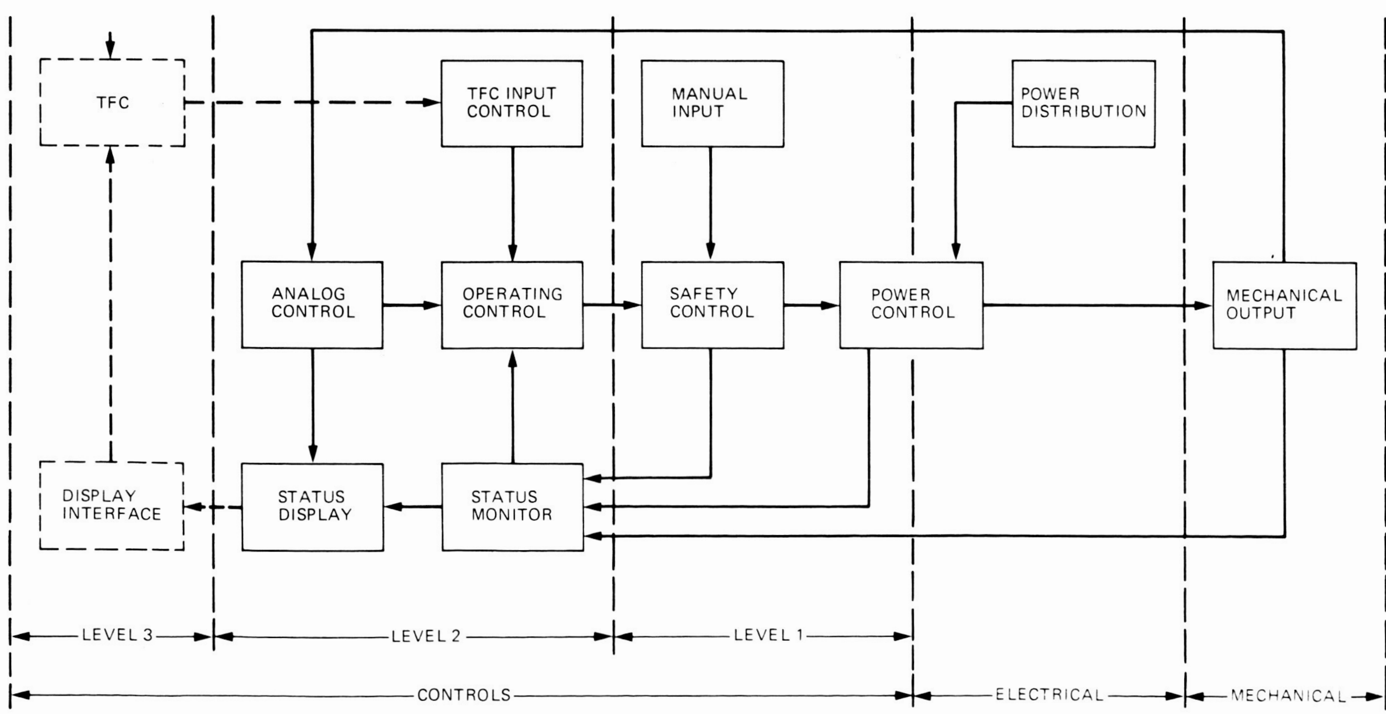


Fig. 15. HVAC controls, functional block diagram

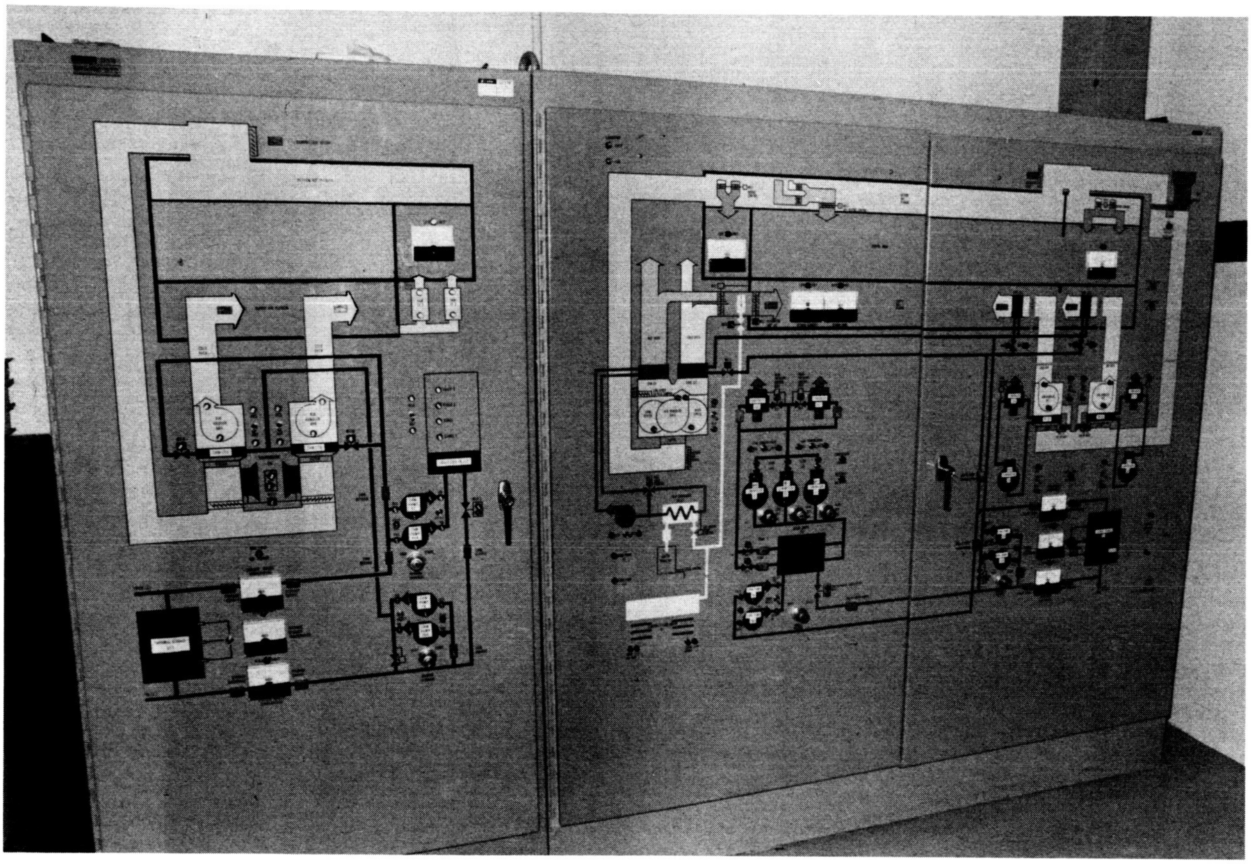


Fig. 16. HVAC status panel

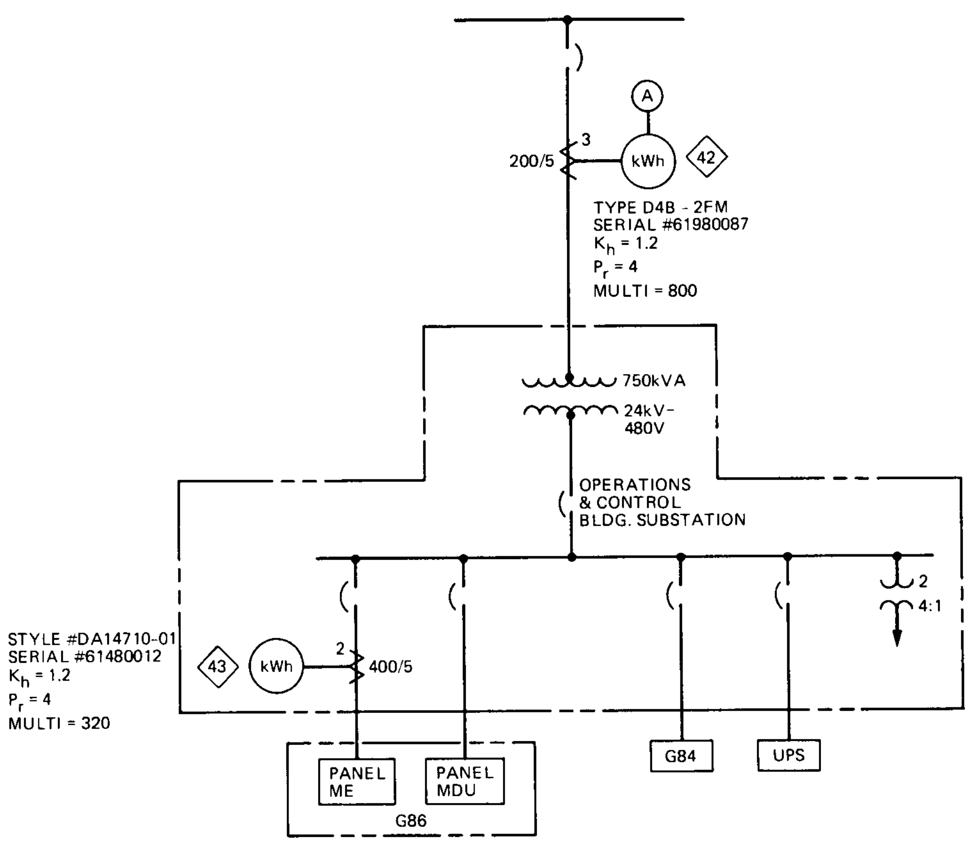


Fig. 17. Electric meters for Operations and Control Substation and for Building G-86