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Instrumentation System for the Los Alamos National Security and Resources Study Center

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LOS ALAMOS SCIENTIFIC LABORATORY

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Instrumentation System for the Los Alamos National Security and Resources Study Center

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INSTRUMENTATION SYSTEM FOR THE LOS ALAMOS
NATIONAL SECURITY AND RESOURCES STUDY CENTER

by

H. S. Murray and M. A. Trump

Abstract

The National Security and Resources Study Center, a modern, three-level building containing 5574 m^2 of temperature-controlled space and an integral solar energy heating and cooling system, is in operation at Los Alamos, New Mexico. This report describes the instrumentation system used to measure the energy production (solar energy system), consumption [heating, ventilating, and air conditioning system (HVAC)], and losses (building shell) in all the building's operating modes. Included are descriptions of the sensors (temperature, mass flow, power, etc.), the data-acquisition system, and the data-reduction programs.

I. INTRODUCTION

The National Security and Resources Study Center (NSRSC) located at Los Alamos, New Mexico, has been heavily instrumented as part of a research program on the use of solar energy for heating and cooling large commercial and public buildings. The NSRSC is a three-level building containing approximately 5574 m^2 of temperature-controlled space. The solar energy system, designed to supply the major portion of the building's heating and cooling requirements, is an integral part of the building. Other energy-saving features include extensive use of insulation, heat recovery from the ventilation exhaust, and the use of both evaporative and mechanical cooling. The energy storage system is designed so that it may be split between hot, pressurized water and chilled, low-pressure water during the cooling season. Additional information concerning the building and its energy system is contained in a paper presented at the 1977 ISES meeting.[1] For the purpose of instrumentation, the NSRSC may be considered as four interconnected systems. These are the solar energy system; the heating, ventilating, and air conditioning (HVAC) system; the control system; and the building shell. In this report, the instrumentation of each will be described in detail.

II. INSTRUMENTATION

A. Solar Energy System

Figure 1 is a simplified mechanical schematic of the system. Instrument locations are marked by type (i.e., Temp., Flow, Power, etc.). Appendix A summarizes this instrumentation, which is the minimum required to yield energy balances for the basic system components. Thus the energy input from the solar collector to the primary heat exchanger, H1, is determined by temperature measurements at its inlet and outlet, and by a mass flow measurement in the collector coolant loop. The other system components are instrumented in a similar manner.

With the exception of the solar collector manifold temperatures, all temperature measurements are made with 100-Ω platinum resistance probes (RTDs). With RTD probes in LASL-designed bridge completion networks, temperatures are read with a resolution of 0.025°C to an accuracy of 0.12°C. The collector manifold temperatures are measured with copper-constantan (type-T) thermocouple probes referenced to 65.5°C. Resolution and accuracy are 0.1 and 0.25°C. Critical flow measurements are made by turbine flow meters (TFMs) and equal-area pressure-drop (Annubar*) probes. The TFMs are used on 1.25-cm (1/2-in.), 3.2-cm (1-1/4-in.), and 7.6-cm (3-in.)-diameter pipes, and the Annubar probes are used on the 10-cm (4-in.) and 15-cm (6-in.)-diameter lines. The TFMs and Annubar probes are typically 1% devices. Each TFM is provided with a pulse

*Ellison Instrument Div., Dieterich Std. Corp., Boulder, Colorado.

rate to dc converter, which transmits a 4- to 20-mA signal (0-100%) to the data-acquisition system. The Annubar differential pressure signals are translated by means of individual differential pressure transducers, which send 4- to 20-mA signals to the data-acquisition system.

Auxiliary energy is supplied to the building in the form of steam at 689 kPa. When this auxiliary energy is required for heating or cooling, the pressure is reduced to 103 kPa and the steam is allowed to flow through two small heat exchangers and the condensate is returned to the central power plant. For the purpose of energy determination, the steam pressure and temperature and the condensate flow and temperature are measured. The pressure and flow measurements produce 4- to 20-mA signals.

The electrical power consumed by the major pumps in the solar energy system is measured by three-phase watt transducers whose 4- to 20-mA outputs are sent to the data-acquisition system. The watt transducers are 480-V delta connected and each reads the current in two legs of the three-phase line. Accuracy is better than 1%.

Weather data in the form of ambient temperature, wind speed, and wind direction is gathered from a small weather station located on the roof. In addition, the solar flux is measured in both the horizontal and collector planes by two pyranometers designed for this purpose.

The solar energy system instrumentation occupies 68 analog channels in the data-acquisition system and permits the determination of energy balances, efficiencies, and overall system performance.

B. Heating, Ventilating, and Air Conditioning Systems

Figure 2 is a simplified HVAC system schematic in which typical instrumentation locations are shown. Appendix B summarizes this instrumentation. Two types of air temperature measurements are made. Copper-constantan (type-T) thermocouples are used in all air supply and return ducts as well as in the fan discharges. The accuracy of these measurements is within 0.5 °C with a resolution of 0.1 °C. The thermocouple reference system is shared with the solar energy system instrumentation. Where air temperature measurements must be made in ducts of large cross section, an averaging temperature probe is used. These applications include the air washers, cooling coils, and heat recovery unit. The probe consists of a 1000-Ω Balco resistance thermometer with an active length of 6.6 m, which is suspended across the duct so that it responds to the average air temperature. Excitation and read-out of the probe is accomplished through a conventional bridge network. The accuracy and resolution of the measurement are similar to the thermocouple measurement described above.

Air flow measurements within the supply and return ducts are made by precision propeller anemometers precalibrated to provide an output of 1 V at an air speed of 180 m/s. As a means of checking the in-place calibration of the anemometers, each is provided with a duct air monitor device (DAMD)* permanently mounted in the duct, upstream of the anemometer. Each DAMD consists of a honeycomb air-straightener section followed by an array of static and total pressure sensors interconnected in an averaging configuration. The output lines (static and total pressure) from each DAMD are routed to a central jack panel, where the differential pressure and average air velocity in each duct may be displayed. A sensitive capacitance manometer (0- to 133-Pa full-scale) with a 0- to 10-V output is connected to one of the analog data channels. The differential manometer inputs may be connected to any one of the 13 DAMDs through the central jack panel. A program running in the data-acquisition computer is used to read the signals from the selected propeller anemometer and DAMD and compute an in-place calibration factor for the anemometer. By repeating this procedure at several flow rates, a set of calibration curves may be generated for the individual anemometers.

Dew point temperature measurements are made in the return air ducts and at selected locations in the air handling equipment. The device used is a DewProbe**, an electrically heated, self-regulating, lithium chloride dew-point hygrometer. The DewProbe temperature is sensed by a 500-Ω nickel resistance thermometer. A conventional bridge network is used for excitation and read-out of the resistance thermometer. The actual dew point temperature is related to the measured temperature by a nearly linear function.

Air flow in the HVAC system is controlled by variable position dampers that respond to pneumatic outputs from the control system. The relative positions (0 to 100%) of 14 of these dampers are measured by potentiometers coupled

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*Air Monitor Corp., Santa Rosa, California.

**Honeywell, Minneapolis, Minnesota.

to the actuator shafts. The potentiometers are excited with 5 V dc and the voltage at the arm of each potentiometer is read by the data-acquisition system as a measure of the damper position.

Electrical power to the two supply and two return fans, the cooling tower, the two water chillers, and the auxiliary domestic hot water heater is measured by three-phase delta-connected watt transducers that provide 4- to 20-mA signals to the data-acquisition system. In a similar manner, the building lighting loads are measured by three additional watt transducers. The total electrical load of the building is measured by a cam-driven contact installed in the main kilowatt-hour meter. This contact, which provides one transition per kilowatt-hour, is used to generate interrupts in the data-acquisition program; these interrupts are integrated to provide a measurement of the electrical energy consumed in the building.

C. Control System

The controls for the solar energy system and the HVAC system are based on conventional pneumatic proportional control systems. The solar energy system has two heating modes (normal and auxiliary) and three cooling modes (normal, auxiliary, and nighttime evaporative). Operation of the system in any one of these modes results in the closure of a contact associated with a pressure to electric transducer. The contact closures are wired to a digital interrupt module in the data-acquisition system, which senses the state of the control system and then makes any necessary changes in the data-acquisition and display tasks.

D. Building Shell

Instrumentation of the building shell has been restricted to one small conference room in the northeast corner of the upper level (Room 232). Because this room has a separate air supply and reheat box, it is possible to measure the energy delivered to it by the HVAC system. Instrumentation is also provided to measure electrical energy input; energy losses through the walls, roof, and floor; and the temperature profile within the room. Instrumentation to accomplish these tasks has been installed but no provision has yet been made to record or process information from it. Appendix C summarizes this instrumentation.

1. Energy Input. Two 100-Ω platinum resistance thermometers are used to measure the temperature of the reheat water entering and leaving the box. Reheat water flow is measured by a 1/2-in.-diam TFM. The supply air temperature gain across the reheat box is measured by two 1000-Ω Balco resistance thermometers and the air flows by a propeller anemometer-DAMD combination. The TFM and anemometer both provide voltage signals (0-5 V and 0-1 V full scale), whereas the temperature probes are used with bridge completion networks.

Electrical power supplied to the overhead lights is measured by a single-phase watt transducer that supplies a 0.1 V full-scale signal. Temperature measurements (1000-Ω Balco probes) are made at the ceiling air-diffuser, at the six fluorescent light fixtures, at four ceiling tiles, and at six locations on the room walls.

2. Energy Losses. The temperature and dew point of the air in the return plenum are measured with an averaging probe and a dew-point hygrometer (DewProbe). Both are resistance thermometer probes used with bridge completion networks. The energy flows through the walls, roof, and floor are measured by heat-flux sensors (thermopiles), which provide a direct millivolt output. Twenty-three of these sensors are used in the following locations: six in both the north and east walls, four in the roof, one in the floor, and four in both the north and west walls of the adjoining room (Room 215). The last eight sensors are used because of differing wall constructions between the two rooms, both constructions being typical of various parts of the building. Wherever a heat-flux sensor is used, it is backed up with two temperature measurements - one on the inside of the wall board and the other on the outside of the building. In this way the "U" value of the wall section in question may be determined because both the heat flow and the temperature across the wall are measured. The surface temperature measurements are made by thin, foil-type resistance elements (100-Ω copper). These are used with conventional bridge completion networks.

3. Controls. The variable air damper position is read with a potentiometer coupled to the actuator shaft. This potentiometer is used to provide a

0- to 5-V (p to 100%) signal. The control pressure signal from the room thermostat is measured by a pressure to electric transducer that provides a 2.5- to 12.5-V signal over a range of 0 to 15 psi.

III. DATA ACQUISITION

A. Requirements

Early in the project it was realized that the complexity of the system and the number of measurements needed to characterize it made it imperative that some form of on-line data reduction and display of system behavior be provided. A simple data logging scheme would result in the generation of large quantities of data, which would be useless until further processing. Therefore, specifications were written for a minicomputer-based data-acquisition system with the capability for simultaneous data acquisition, reduction, display, and program development. The specifications also provided for system expansion, both in the number of data-acquisition channels and in the capability for analog and digital outputs, because a projected expansion of the research program will require development and implementation of programs for energy management and control for the building energy systems.

B. Configuration

The system selected and ultimately delivered consists of a PDP-11/34* central processor with 32K of parity core memory, 7.5 megabytes of mass storage (disk pack), a console terminal, a CRT terminal with both alphameric and graphics capability, and a fully integrated local process input/output (I/O) subsystem. A communications interface and autoanswer modem are also included to permit access from remote terminals. The local process I/O is presently configured with 2 A/D converters connected to 160 analog channels and a single 16-channel digital interrupt module. All but five analog and six digital channels are presently in use.

The system software, RSX-11M,* is a real-time, multiuser, multitask operating system. All program development is done in FORTRAN IV. The system

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*Digital Equipment Corp., Maynard, Massachusetts.

permits task scheduling as a function of time and specific events, which results in the system's operating around the clock with a minimum of operator intervention.

C. Capabilities

Each A/D converter is capable of sampling analog channels at the rate of 200/s. By using the two converters in parallel, an effective sampling rate of 400/s is achieved. The full-scale range of each analog channel is programmable between ±10 mV and ±10 V in a 2,2,5 sequence with 12-bit resolution. The gain programming and channel selection are accomplished by FORTRAN subroutine calls to the process I/O. At present, the system samples all the channels once every 15 s and converts the readings to appropriate engineering units (°F, gal/min, etc.) and stores these values in a common block accessible to other programs. A second program, running at the same interval, then calculates the energy balances appropriate to the building's operating mode (heating, cooling, etc.) and updates a disk file with the current and integrated values for these balances. Every half-hour during the day (hourly at night) a summary of these balances is written in a disk file. In addition, mode changes sensed by the digital interrupt module will force summaries to be recorded. Once each day, at midnight, a disk file located on the removable disk pack is updated with the day's summaries, a copy of the day's energy summaries is printed on the system console, and all integrations are reset to zero. This disk pack holds up to one month's summary data and serves as long-term archival storage. During the day additional summaries and information regarding the individual channels may be requested without interrupting the system operation.

D. Expansion

As it now stands, the system may easily be expanded by up to 64 analog or digital channels by plugging in additional cards in the process I/O chassis. Further expansion will require an additional process I/O. A planned expansion is to add a remote process I/O to handle information from the building shell instrumentation. This will require that a single interface card be added to the central processor and the remote process I/O installed near the small conference room. All data communications between the two will be sent over a single coaxial cable, which is already in place. From a programming standpoint, the two process I/Os have identical characteristics. The other contemplated expansion is a dedicated graphics display to be used for public viewing of system performance parameters.

REFERENCE

1. H. S. Murray, M. A. Trump, and J. C. Hedstrom, "Solar Heating and Cooling System Performance Experiments in the Los Alamos National Security and Resources Study Center," Proc. 1977 Ann. Mtg., Amer. Sec. ISES, Orlando, Florida, Vol. 1, pp. 9-1 through 9-5.

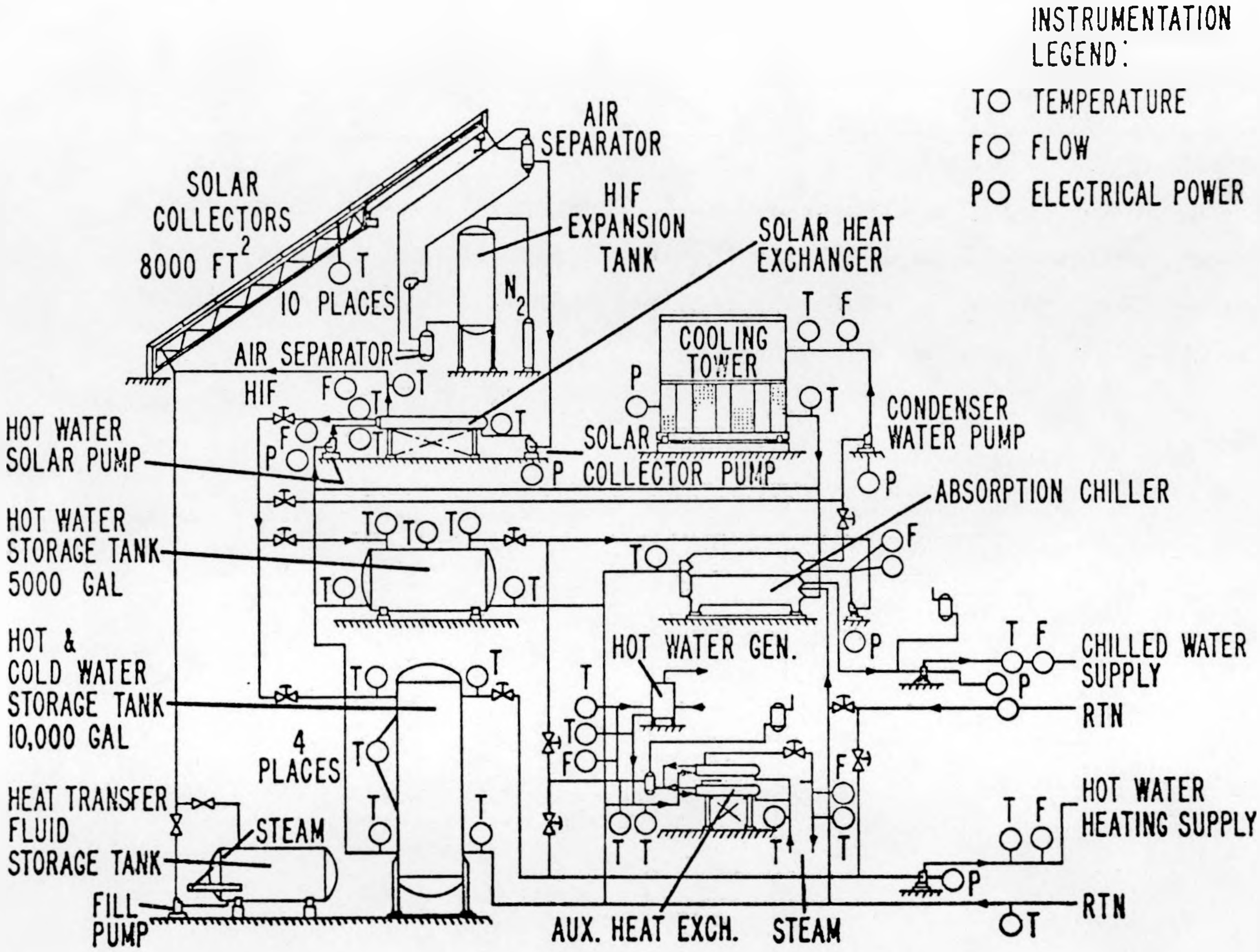

Fig. 1. NSRSC Mechanical Schematic

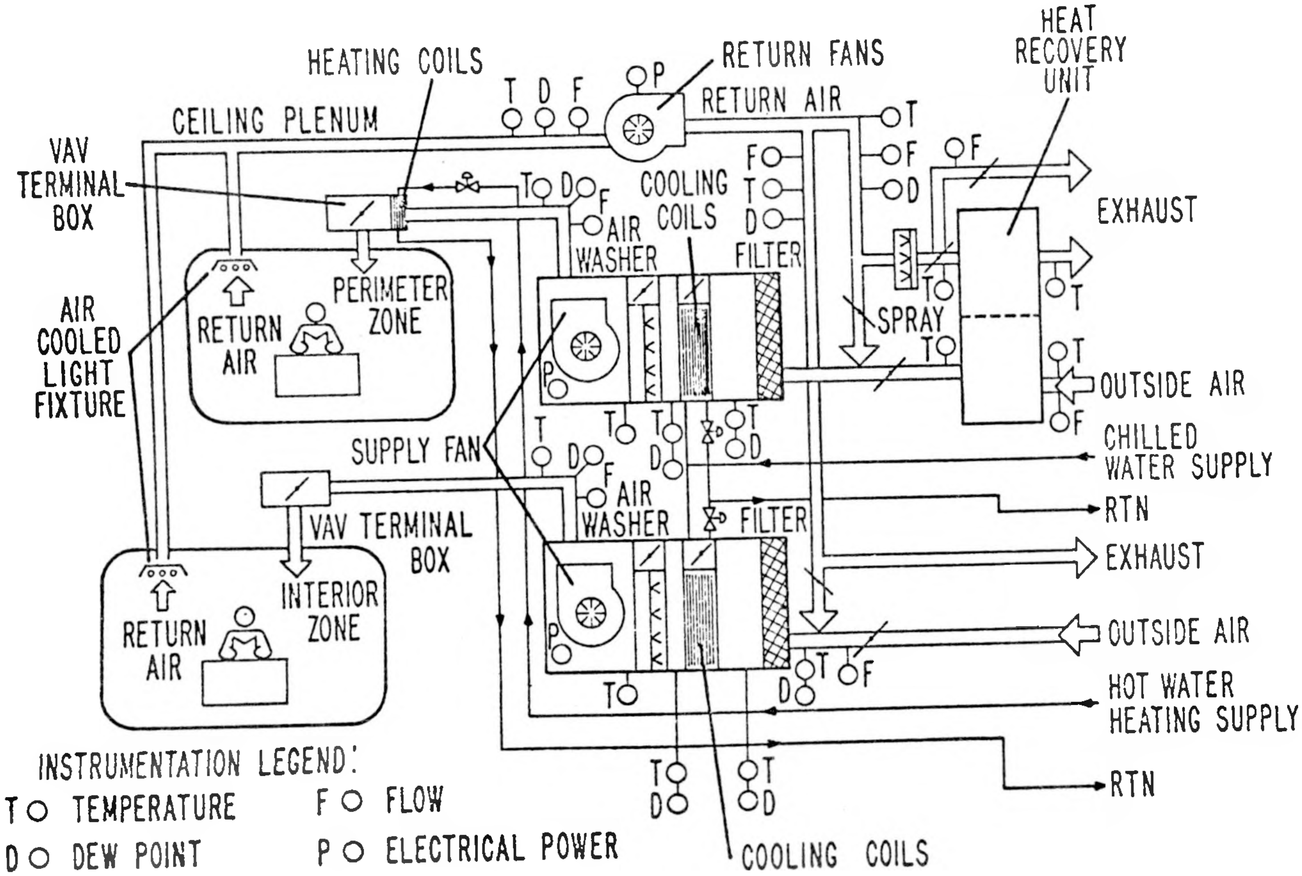

Fig. 2. NSRSC HVAC System Schematic

APPENDIX A

SOLAR ENERGY INSTRUMENTATION SUMMARY

Location	Transducer Type	Range	Sensitivity
Chiller, Hot Water Return	RTD	-12°C to +143°C	1·3 mV/°C
Chiller, Hot Water Supply	"	"	"
Chiller, Cold Water Return	"	"	"
Chiller, Cold Water Supply	"	"	"
Perimeter Cooling Coil Return	"	"	"
Perimeter Cooling Coil Supply	"	"	"
Interior Cooling Coil Return	"	"	"
Interior Cooling Coil Supply	"	"	"
Cooling Tower Return	"	"	"
Cooling Tower Supply	"	"	"
Storage Tank 2 Return 1	"	"	"
Storage Tank 2 Supply 1	"	"	"
Storage Tank 2 Return 2	"	"	"
Storage Tank 2 Supply 2	"	"	"
Solar Heat Exchanger Oil Return	"	"	"
Solar Heat Exchanger Oil Supply	"	"	"
Solar Heat Exchanger Water Return	"	"	"
Solar Heat Exchanger Water Supply	"	"	"
Storage Tank 1 Return 1	"	"	"
Storage Tank 1 Supply 1	"	"	"
Storage Tank 1 Return 2	"	"	"
Storage Tank 1 Supply 2	"	"	"
Auxiliary Heat Exchanger Water Return	"	"	"
Auxiliary Heat Exchanger Water Supply	"	"	"
Domestic Hot Water Return	"	"	"
Domestic Hot Water Supply	"	"	"
Reheat Water Return	"	"	"
Reheat Water Supply	"	"	"

Appendix A (cont)

Location	Transducer Type	Range	Sensitivity
Storage Tank 1	RTD	-12°C to +143°C	1·3 mV/°C
Storage Tank 1	"	"	"
Storage Tank 1	"	"	"
Storage Tank 1	"	"	"
Storage Tank 2	"	"	"
Auxiliary Heat Exchanger Condensate	"	"	"
Auxiliary Heat Exchanger Steam	"	"	"
Solar Collector H.T.M. Top Through Bottom; 10 Probes	TC	-270°C to +262°C	44·1μV
Collector Coolant Loop	Annubar-D.P. Cell	$42{\cdot}9 \times 10^{-3}\ m^3/s$	$37{\cdot}3\ V/m^3s^{-1}$
Cooling Tower Loop	Annubar-D.P. Cell	$42{\cdot}9 \times 10^{-3}\ m^3/s$	$37{\cdot}3\ V/m^3s^{-1}$
Chilled Water Loop	Annubar-D.P. Cell	$0\text{-}18{\cdot}3 \times 10^{-3}\ m^3/s$	$87{\cdot}4\ V/m^3s^{-1}$
Chiller Hot Water Loop	Annubar-D.P. Cell	$0\text{-}29{\cdot}0 \times 10^{-3}\ m^3/s$	$55{\cdot}2\ V/m^3s^{-1}$
Solar Heat Exchanger Water Loop	Annubar-D.P. Cell	$0\text{-}29{\cdot}0 \times 10^{-3}\ m^3/s$	$55{\cdot}2\ V/m^3s^{-1}$
Perimeter Cooling Coil Loop	Turbine Flow Meter	$0\text{-}12{\cdot}6 \times 10^{-3}\ m^3/s$	$127\ V/m^3s^{-1}$
Interior Cooling Coil Loop	Turbine Flow Meter	$0\text{-}12{\cdot}6 \times 10^{-3}\ m^3/s$	$127\ V/m^3s^{-1}$
Reheat Water Loop	"	$0\text{-}12{\cdot}6 \times 10^{-3}\ m^3/s$	$127\ V/m^3s^{-1}$
Domestic Hot Water Loop	"	$0\text{-}1{\cdot}9 \times 10^{-3}\ m^3/s$	$842\ V/m^3s^{-1}$
Condensate Return	"	$0\text{-}0.32 \times 10^{-3}\ m^3/s$	$5000\ V/m^3s^{-1}$
Low Pressure Steam	Gauge Pressure Cell	$0\text{-}3{\cdot}45 \times 10^5$ Pa	4·6 μV/Pa
Collector Coolant Pump (P1)	Watt Transducer	0-20 kW	8 mV/kW

Appendix A (cont)

Location	Transducer Type	Range	Sensitivity
Solar Heat Exchanger Water Pump (P2)	Watt Transducer	0-8 kW	20 mV/kW
Reheat Water Pump (P3 or P4)	"	0-6 kW	26·7 mV/kW
Chiller Hot Water Pump (P5)	"	0-20 kW	8 mV/kW
Chilled Water Pump (P6)	"	0-6 kW	26·7 mV/kW
Condenser Water Pump (P7)	"	0-20 kW	8 mV/kW
Solar Flux (Horizontal Plane)	Pyranometer	0-1000 W/m^2	$10{\cdot}67 \times 10^{-6}$ $V/W{\cdot}m^{-2}$
Solar Flux (Collector Plane)	"	0-1000 W/m^2	$9{\cdot}66 \times 10^{-6}$ $V/W{\cdot}m^{-2}$
Ambient Temperature	Thermistor	-73°C to +38°C	1·8 mV/°C
Wind Speed	Drag Cup Anemometer	0-44·7 m/s	22·4 mV/m/s
Wind Direction	Weather Vane Potentiometer	0-360°	13·9 mV/°C

APPENDIX B

HVAC INSTRUMENTATION SUMMARY

Location	Transducer Type	Range	Sensitivity
Perimeter Cooling Coil Inlet	Average Temperature Probe	-11°C to 53°C	1·56 mV/°C
Perimeter Cooling Coil Discharge	"	"	"
Perimeter Air Washer Discharge	"	"	"
Interior Cooling Coil Inlet	"	"	"
Interior Cooling Coil Discharge	"	"	"
Interior Air Washer Discharge	"	"	"
Heat Recovery Exhaust Inlet	"	"	"
Heat Recovery Exhaust Discharge	"	"	"
Heat Recovery Intake Inlet	"	"	"
Heat Recovery Intake Discharge	"	"	"
Perimeter Cooling Coil Inlet	Dew Probe	-28°C to 44°C	1·39 mV/°C
Perimeter Air Washer Inlet	"	"	"
Perimeter Supply Fan Discharge	"	"	"
Perimeter Return Duct, Upper Level	"	"	"
Perimeter Return Duct, Middle Level	"	"	"
Perimeter Return Duct, Lower Level	"	"	"
Perimeter Return Fan Discharge	"	"	"
Interior Cooling Coil Inlet	"	"	"
Interior Air Washer Inlet	"	"	"
Interior Supply Fan Discharge	"	"	"
Interior Return Duct, Upper Level	"	"	"
Interior Return Duct, Middle Level	"	"	"
Interior Return Duct, Lower Level	"	"	"

Appendix B (cont.)

Location	Transducer Type	Range	Sensitivity
Interior Return Fan Discharge	DewProbe	-28°C to 44°C	1·39 mV/°C
Perimeter Supply Fan Discharge	Thermocouple Probe (Cu-const)	-270°C to +262°C	44·1 μV/°C
Perimeter Supply Duct, Upper Level	"	"	"
Perimeter Supply Duct, Middle Level	"	"	"
Perimeter Supply Duct, Lower Level	"	"	"
Perimeter Return Duct, Upper Level	"	"	"
Perimeter Return Duct, Middle Level	"	"	"
Perimeter Return Duct, Lower Level	"	"	"
Perimeter Return Fan Discharge	"	"	"
Interior Supply Fan Discharge	"	"	"
Interior Supply Duct, Upper Level	"	"	"
Interior Supply Duct, Middle Level	"	"	"
Interior Supply Duct, Lower Level	"	"	"
Interior Return Duct, Upper Level	"	"	"
Interior Return Duct, Middle Level	"	"	"
Interior Return Duct, Lower Level	"	"	"
Interior Return Fan Discharge	"	"	"
Minimum Outside Air Duct	"	"	"
Supply Fan (S1)	Watt Transducer	0 to 40 kW	4 mV/kW
Interior Supply Fan (S2)	"	0 to 20 kW	8 mV/kW
Perimeter Return Fan (R1)	"	0 to 20 kW	8 mV/kW
Interior Return Fan (R2)	"	0 to 8 kW	20 mV/kW
Cooling Tower Fan	"	0 to 30 kW	5·3 mV/kW

Appendix B (cont)

Location	Transducer Type	Range	Sensitivity
Middle Level Lighting (PP1A)	Watt Transducer	0 to 120 kW	1·3 mV/kW
Upper Level Lighting (PP2A)	"	0 to 120 kW	1·3 mV/kW
Main kWh Meter	Contact Closure		1 Closure /kWh
Perimeter Supply Duct, Upper Level	Propeller Anemometer	0 to 180 m/s	5·6 mV/ms^{-1}
Perimeter Supply Duct, Middle Level	"	"	"
Perimeter Supply Duct, Lower Level	"	"	"
Perimeter Return Duct, Upper Level	"	"	"
Perimeter Return Duct, Middle Level	"	"	"
Perimeter Return Duct, Lower Level	"	"	"
Perimeter Return Fan Discharge	"	"	"
Heat Recovery Bypass	"	"	"
Heat Recovery Intake	"	"	"
Interior Supply Duct, Upper Level	"	"	"
Interior Supply Duct, Middle Level	"	"	"
Interior Supply Duct, Lower Level	"	"	"
Interior Return Duct, Upper Level	"	"	"
Interior Return Duct, Middle Level	"	"	"
Interior Return Duct, Lower Level	"	"	"
Interior Return Fan Discharge	"	"	"
Interior Supply Fan Inlet	"	"	"
Minimum Outside Air Duct	"	"	"
Perimeter Return Fan Vortex Damper	Position Potientiometer	0 to 100%	50 mV/%
Perimeter Bypass Damper	"	"	"

Appendix B (cont)

Location	Transducer Type	Range	Sensitivity
LiBr Absorption Chiller Pumps	Watt Transducer	0-15 kW	10·7 mV/kW
Rankine Cycle Chiller Pumps	"	0-7.5 kW	21·3 mV/kW
Auxiliary Hot Water Heater	"	0-5 kW	32 mV/kW
Lower Level Lighting (PPA & 13)	"	0 to 120 kW	1·3 mV/kW
Perimeter Air Intake Damper	Position Potientiometer	0 to 100%	50 mV/%
Heat Recovery Bypass Damper	"	"	"
Perimeter Min. Outside Air Damper	"	"	"
Interior Return Fan Vortex Damper	"	"	"
Interior Bypass Damper	"	"	"
Interior Exhaust Damper	"	"	"
Interior Air Intake Damper	"	"	"
Interior Min. Outside Air Damper	"	"	"
Perimeter Cooling Coil Face Damper	"	"	"
Interior Cooling Coil Face Damper	"	"	"
Perimeter Air Washer Face Damper	"	"	"
Interior Air Washer Face Damper	"	"	"
Nighttime Heating Mode	Contact Closure		
Perimeter Air Washer Pump	"		
Normal Cooling (Mode 3)	"		
Auxiliary Coolign (Mode 4)	"		
Nighttime Evaporative Cooling (Mode 6)	"		
Heat Recovery Air Washer	"		
Auxiliary Heating (Mode 2)	"		
Interior Air Washer Pump	"		

APPENDIX C

BUILDING SHELL INSTRUMENTATION

Location	Transducer Type	Range	Sensitivity
Rm. 232, East Wall, Outside, 6 Places	Surface Resistance Thermometer	-18°C to 67°C	0·36 Ω/°C
Rm. 232, East Wall, Inside, 6 Places	"	4°C to 38°C	"
Rm. 232, North Wall, Outside, 6 Places	"	-18°C to 67°C	"
Rm. 232, North Wall, Inside, 6 Places	"	4°C to 38°C	"
Rm. 215, North Wall, Outside, 4 Places	"	-18°C to 67°C	"
Rm. 215, North Wall, Inside, 4 Places	"	4°C to 38°C	"
Rm. 215, West Wall, Outside, 4 Places	"	-18°C to 67°C	"
Rm. 215, West Wall, Inside, 4 Places	"	4°C to 38°C	"
Rm. 232, Roof, Outside, 4 Places	"	-18°C to 67°C	"
Rm. 232, Roof, Inside, 4 Places	"	4°C to 38°C	"
Rm. 232, Floor, Inside, 1 Place	"	4°C to 38°C	"
Rm. 232, East Wall, Inside, 6 Places	Heat Flow Sensor	$\pm 4{\cdot}73 \times 10^{6}$ W/m	$6{\cdot}35 \times 10^{-8}$ W/m
Rm. 232, North Wall, Inside, 6 Places	"	"	"
Rm. 215, North Wall, Inside, 4 Places	"	"	"
Rm. 215, West Wall, Inside, 4 Places	"	"	"
Rm. 232, Roof, Inside, 4 Places	"	"	"
Rm. 232, Floor, Inside, 1 Place	"	"	"
Rm. 232, Reheat Coil, Air Supply	1000-Ω Balco Probe	14°C to 38°C	3·96 Ω/°C
Rm. 232, Reheat Coil, Air Discharge	"	"	"
Rm. 232, Ceiling Air Diffuser	"	"	"
Rm. 232, Fluorescent Light Fixtures, 6 Places	"	"	"

Appendix C (cont)

Location	Transducer Type	Range	Sensitivity
Rm. 232, Room Air Temp, 6 Places	1000-Ω Balco Probe	14°C to 38°C	3·96 Ω/°C
Rm. 232, Return Air Plenum	"	"	"
Rm. 232, Return Water, Inlet	1000 RTD	38°C to 93°C	0·396 Ω/°C
Rm. 232, Reheat Water, Outlet	"	"	"
Rm. 232, Return Air Plenum	500-Ω DewProbe	-28°C to 44°C	0·72 Ω/°C
Rm. 232, Reheat Water Loop	TFM	0 to $6 \cdot 3 \times 10^{-5}$ m^3/s	$79 \cdot 4 \times 10^6$ V/m^3s^{-1}
Rm. 232, Supply Air Duct	Propeller Anemometer	0 to 180 m/s	5·6 mV/ms^{-1}
Rm. 232, Control Pressure	P-E Transducer	0 to $1 \cdot 03 \times 10^5$ Pa	96·7 μV/Pa
Rm. 232, Room Lights	Watt Transducer	0 to 1000 W	1 mA/kW

APPENDIX D

Three types of resistance temperature sensors are used in the NSRSC instrumentation system. Because the precise measurement of fluid temperatures is crucial to the successful determination of energy balances, and because the accuracy of any resistance temperature sensor is dependent on the bridge circuit and excitation used, a discussion of our approach to resistance thermometer is in order.

I. PLATINUM RESISTANCE THERMOMETERS

Platinum resistance thermometers (RTDs) were chosen for temperature measurements in the NSRSC solar energy systems primarily because of their stability and accuracy as compared to thermocouples. In several cases it is necessary to measure a temperature difference of 5.6°C (10°F), which is extremely difficult to do with thermocouples but is well within the capabilities of platinum resistance thermometers. Ideally, the RTD should be excited by a current source as shown schematically in Fig. D-1. This technique provides the maximum sensitivity and is completely immune to the efforts of lead resistance. However, it requires the use of two multiplexer channels for each RTD and sufficient resolution in the data system to read the entire RTD signal with the precision required for the relatively small temperature difference involved. The costs of the extra multiplexer channels and the increased data system resolution requirements caused us to reject this approach. If the RTD is incorporated into a resistive bridge network that is balanced in the middle of the temperature range of interest, the resolution requirements of the data system are considerably reduced. For example, in the NSRSC solar energy system, the fluid temperatures range from approximately 10°C (50°F) to approximately 121°C (250°F). This produces a resistance change of 43.55 Ω (103.92 Ω to 147.47 Ω) in a 100-Ω RTD. In order to achieve a resolution of 0.056°C (0.1°F), the four-wire, current-excited system would need a resolution of approximately 1 part in 7000, whereas the bridge system operated over the same temperature range would require a resolution of approximately 1 part in 2000. The effects of sensor lead resistance may be compensated for by the use of a three-wire RTD. The bridge circuit and three-wire RTD used at the NSRSC are shown schematically in Fig. D-2. The RTD resistance contains three terms. R_o is the actual sensor resistance at the chosen bridge balance point, nominally 65.5°C (150°F). The temperature-dependent term (T-To) is controlled by the probe temperature coefficient of resistance, which is 0.3916 Ω/°C. R_p is a residual lead resistance between the probe connector and the sensing element. It is typically between 0.1 Ω and 0.5 Ω for the 5-1/2-in. probes and 2.5 Ω for the 23-in. probes. R_L is the lead resistance, which varies between 0.2 Ω and 1.6 Ω, depending on the distance between the probe and the bridge network. If the right-hand side of the bridge network is adjusted for $V_z = V/2$, then the bridge output voltage $(V_B - V_Z)$ may be expressed by the following equation.

$$V_O = V_B - V_Z = V \frac{[\alpha(T - To) + R_o + R_L]}{[\alpha(T - T_o) + R_o + R_L] + (R_o + R_L + 2R_p)} - \frac{1}{2} \quad , \qquad (1)$$

where

V = the bridge excitation voltage, typically 1.5 V,
α = the temperature coefficient of resistance, 0.3916 Ω/°C,
T_o = the bridge balance temperature, 65.56°C (150°F),
T = the probe temperature,
R_o = the probe sensor resistance at T_o, typically 125 Ω,
R_p = the probe residual resistance, typically 0.20 Ω, and
R_L = the lead resistance, typically 1.00 Ω.

From Eq. (1) it can be seen that for $R_p = 0$ and $T = T_o$ (bridge balanced), $V_o = 0$, independent of R_L. For $T = T_o$ (bridge unbalanced), V_o is slightly dependent on R_L (and R_p) provided R_L and $R_P << R_o$. Equation (1) may be solved for T and written as Eq. (2).

$$T = \frac{4V_o\left(R_o + R_P + R_L\right) + 2VR_P}{\alpha\left(V - 2V_o\right)} + T_o \quad . \qquad (2)$$

In characterizing the individual probes it is convenient to add R_o and R_p together as R_o', which is the measured (two-terminal) value of the probe at $T = T_o$. The resulting relationship (Eq. 3) is used in the computer data-acquisition programs to extract temperatures from the bridge voltage measurements.

$$T = \frac{4V_o\left(R_o' + R_L\right) + 2VR_p}{\alpha\left(V - 2V_o\right)} + T_o \quad . \tag{3}$$

Two measurements are made on each probe to determine R_o and R_p. The lead resistance, R_L, is determined from a single measurement made on the wiring plant with the probe in place.

The individual bridge networks are adjusted for $V_Z = V/2$ and R_o' is matched to the probe value within 0.1 Ω. The values of R_o', R_P, and R_L for each probe are retained in the data-acquisition program for use in the temperature conversion routine, which is based on Eq. (3). The above process has resulted in temperature deviations between probes of no more than 0.1°C (0.18°F) over the operating temperature range (10°C to 121°C).

II. TEMPERATURE AVERAGING PROBES

The NSRSC HVAC system supply fan inlet ducts are approximately 2.1 m by 2.7 m in cross section. Air temperature measurements within these ducts are made to determine the temperature drops across the air washers and cooling coils. Because of the duct dimensions and possible airflow variations, temperature measurements made at a point within the duct by a single probe are not particularly useful. The temperature averaging probe is a 1000-Ω resistance thermometer whose active element is 2.7 m (22 ft) long and is flexible enough to be suspended within the duct across the face of the air washers or cooling coils. The sensor is exposed to moving air in all parts of the duct, which accounts for its averaging behavior. Because of the probe's relatively high resistance (1000-Ω at 21°C) a two-wire connection from the probe to the bridge network is used. This is shown schematically in Fig. D-3. The equation relating temperature to the voltage output of the bridge circuit is similar to Eq. (2) with R_o and R_L equal to zero, where

V = the bridge excitation voltage, typically 1.5 V
α = the temperature coefficient of resistance, 3.956 Ω/°C
T_o = the bridge balance temperature, 21.1°C
T = the probe temperature
R_o = the probe resistance at T_o, 1000 Ω
V_o = the bridge output voltage.

All probes are assumed to have the same nominal resistance and temperature coefficient of resistance.

III. DEW POINT PROBES

The Dewprobe temperature is sensed by a 500-Ω nickel resistance thermometer. The resistance element is included in a bridge network similar to the one used for the average temperature probe described above. However, the bridge balance point is 66.8°C (5.64 Ω) and the temperature coefficient of resistance is 2.741 Ω/°C. The dew point temperature is related to the probe temperature by Eq. (4).

$$DPT = -34.304 + 0.67955T + 2.1421 \times 10^{-4}T^2 , \qquad (4)$$

where

DPT = Dew point temperature in °F
T = The probe temperature in °F.

Each probe is supplied with 120-V ac power, which is stepped down 24 V ac by an internal transformer. This power is used to heat the lithium chloride saturated wick that surrounds the temperature sensor.

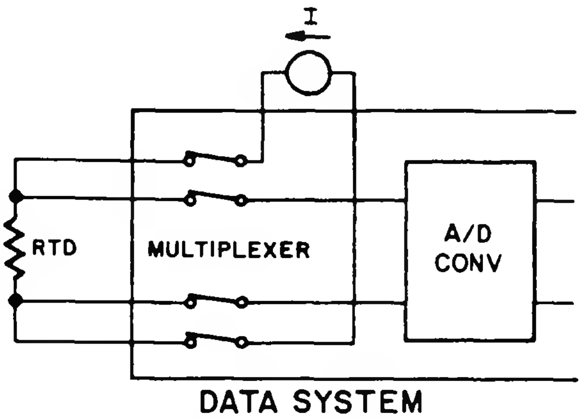

Fig. D-1. RTD current excitation.

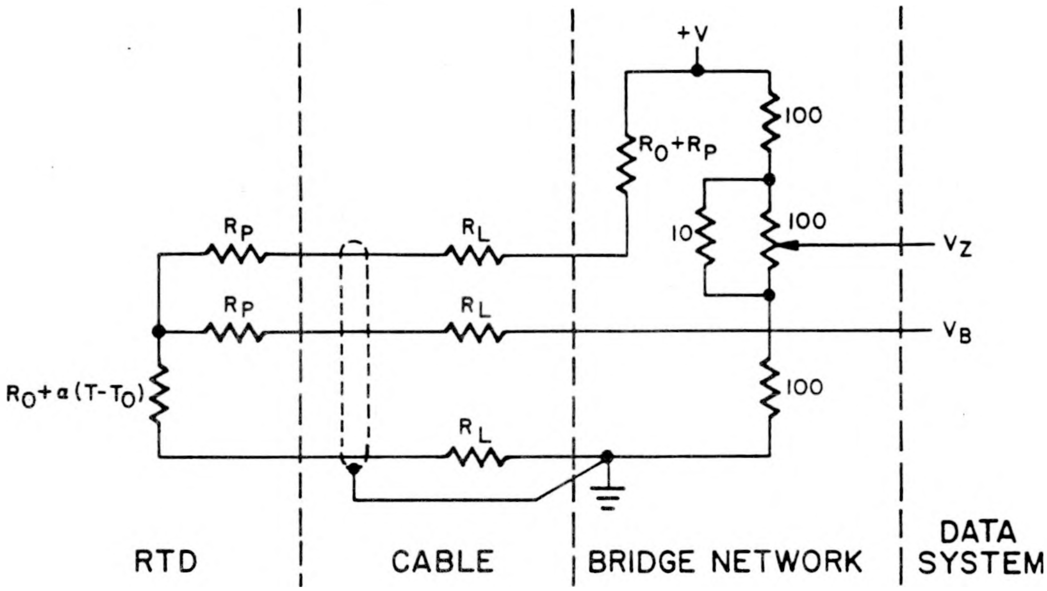

Fig. D-2. Three-wire RTD bridge circuit.

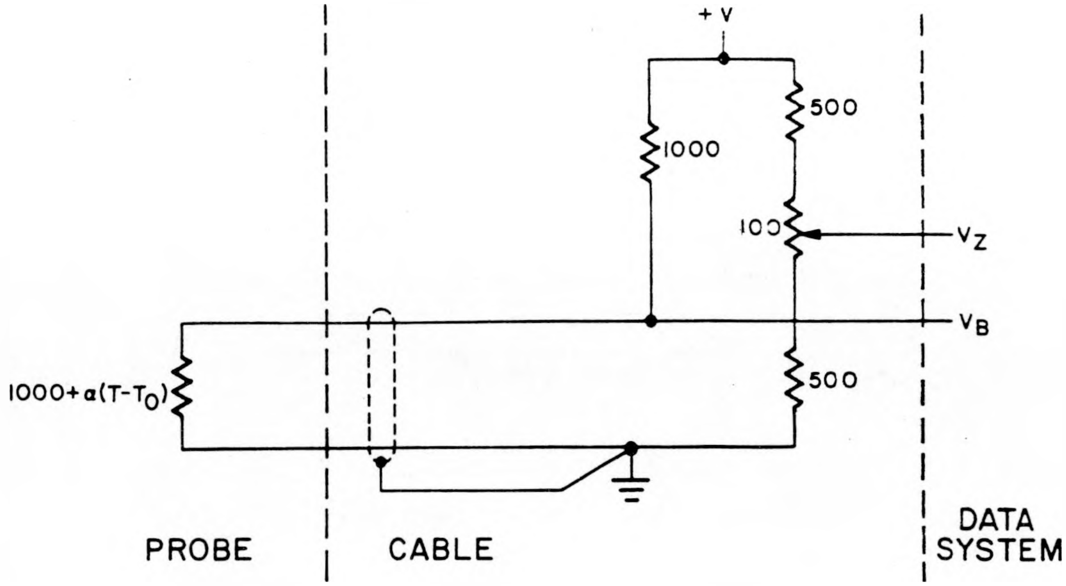

Fig. D-3. Two-wire RTD bridge circuit.