The Design and Construction of a Calibrated/Guarded Hot Box Facility

by

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Abstract

A complete Calibrated/Guarded Hot Box test facility was fabricated by Wiss, Janney, Elstner and Associates for the Construction Products Division of W. R. Grace & Co. The facility essentially consists of two environmental chambers, one calibrated chamber, one metering chamber, a control and data acquisition system including a HP9835-A mini-computer, a drying oven, a pre-conditioning chamber, insulated test frames and a pneumatic transport system.

The facility allows specimens to be tested horizontally or vertically, under steady state or dynamic temperature conditions.

Following are some of the design specifications:

Test specimen lateral dimensions:	8' x 8' (2.44m x 2.44m) 6' x 6' (1.83m x 1.83m)
Metering area for the guarded mode:	5' x 5' (1.52m x 1.52m)
Environmental chamber:	
Temperature range:	-30°F to $+160^{\circ}$F (-34.4°C to 71.1°C)
Representative Heating Rate:	35°F/hr. @ 80°F (19.4°C/hr. @ 26.62°C)
Representative Cooling Rate:	20°F/hr. @ 15°F (11.1°C/hr. @ -9.44°C)
Tangential Air Velocities:	1 mph/5 mph (1.61 km/hr./8.05 km/hr.)
Calibrated Chamber:	
Temperature range:	50°F to 120°F (10°C to 48.89°C)
Tangential Air Velocity:	1 mph (1.61 km/hr.)
Pre-conditioning chamber:	
Temperature range:	20°F to 140°F (-6.67°C to 60°C)

INTRODUCTION

The present fuel crisis and the accompanying escalation in the price of fuel has again forced us to re-examine our patterns of fuel consumption and to make concerted efforts to reduce these current consumption levels.

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One of the easiest ways of reducing our present levels of consumption is to properly install adequate amounts of insulation in new and existing structures, both residential and non-residential. However, very little effort has been made to quantify the thermal performance of building systems under actual end use conditions.

To date, virtually all thermal performance evaluations have been performed under dry, steady state conditions. While dry, steady state testing may provide useful comparison of thermal resistance between various insulations and insulation systems, the comparison can not be directly translated into thermal performance under field conditions. As an example, several theoretical studies (1, 2, 3)* and recent experimental work at the Portland Cement Association (4) have shown mass to be a major factor in determining the in-place thermal performance. Therefore, we should examine the adequacy and validity of the concept of thermal performance as defined solely by thermal resistance.

The Grace Guarded/Calibrated Hot Box has been designed and constructed to test large insulation systems under conditions that are closer to actual in-place situations.

For the evaluation of mass effect, for example, some unique features were incorporated into the design of the box. First of all, the cooling and heating systems in the environmental chamber had to be sized sufficiently large to accommodate specified heating and cooling rates. Also the heating/cooling systems needed to be programmable so temperature profiles could be inputed to the system. However, the most unique part of the design is in the metering of the heating and cooling load in the calibrated chamber. Since the calibrated chamber could demand heating and/or cooling during a diurnal temperature cycle in the environmental chamber, it is necessary to have a system that can be precisely metered not only during either heating or cooling but during the transitional periods between heating and cooling without a loss in temperature control.

The design features of this box will also allow us to undertake studies concerning the effects of moisture on the thermal performance of specimens under dynamic temperature conditions.

GENERAL DESCRIPTION OF THE CALIBRATED/GUARDED HOT BOX AND AUXILIARY EQUIPMENT

The equipment was especially designed to fit W. R. Grace's needs. Types of specimens to be tested, the conditions to which test constructions will be exposed in use, and the need to have equipment capable of performing standard tests all entered into the selection process.

The equipment consists of separate calibrated and environmental boxes or chambers. A standard guarded hot box test capability is provided by a 5-ft. square metering box which can be mounted inside the calibrated box. The box permits the equipment to be operated in accordance with ASTM C 236 "Standard Test Method for Thermal Conductance and Transmittance of Built-Up Sections by Means of the Guarded Hot Box". The equipment can be operated as a wall tester, or as a roof-ceiling or floor tester. The calibrated and metering boxes can be either above or below horizontal test speciments. In the calibrated mode, heat flow through the specimen can be either to or from the calibrated box, since the temperatures to which the specimen is exposed can be cycled so that the flow through the specimen changes direction.

The sample sizes accommodated are 8 ft x 8 ft and 6 ft x 6 ft, with specimen thickness up to 1 ft. Specimen thickness can be readily increased using two test frames sandwiched together. The larger, 8 ft x 8 ft, sample size enables the user to check full-height walls and specimens with modest size penetrations, structural members or other variations. The smaller sample size, 6 ft x 6 ft, reduces preparation cost and handling problems when large numbers of variations in design are to be evaluated in systems without pentrations, or other large discontinuities over the test area.

Two environmental boxes are provided. When 8-ft square specimens are tested, the environmental and calibrated boxes are the same size. They have 8-ft square openings (Figure 1). When 6-ft square specimens are tested, both the test frames used and the environmental box have 6-ft square apertures (Figure 2).

*Numbers in parentheses refer to references at the end of the paper.

The equipment can be operated as a steady-state tester, or the temperature on one or both sides of the specimen can be cycled to simulate normally encountered temperatures. When operated with constant temperatures, the heat flow through the walls of the calibrated box can be determined using specimens of known thermal resistance from previous tests in the guarded mode, or measured using Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate, ASTM C 177.

Heating and cooling capacities are provided that enable the equipment to duplicate diurnal roof surface termperature curves. This is accomplished by supplying air sufficiently warmer or cooler than the specimen surface to provide the required rates of heating and cooling. The air velocity is sufficient to provide the needed rate of heat transfer with modest temperature differentials.

The calibrated box, environmental boxes, and test specimens in test frames are moved and positioned with a transporter that has a self-contained electrically powered hydraulic lift system. It moves on air pads. It is capable of handling 8-ft square specimens weighing up to 60 lbs per sq ft and 6-ft square specimens weighing as much as 100 lbs per sq ft. Because of the limited ceiling height in the laboratory, tops of the test frames for 8-ft square wall specimens are removable during transportation. A low profile keeper provides the necessary test frame stability during specimen construction and movement. The laboratory building is air-conditioned so that the ambient air around the equipment can be kept close to the calibrated box temperature during normal operation. This minimizes heat loss or gain through the walls of the calibrated box.

Other equipment includes casting frames for preparation of 6-ft square specimens of roof constructions, racks to hold these specimens during curing and drying, an electric-powered stacker for moving specimens onto and from the racks, and a walk-in horizontal air flow oven into which the racks can be rolled for drying at temperatures up to 160°F.

A preconditioning chamber enables specimens that are to be tested under dynamic conditions to be readied for the test. When such specimens contain moisture, which will move back and forth during diurnal temperature cycles, it may take several cycles before the movement of moisture becomes constant from cycle to cycle. In the pre-conditioning chamber, the specimen is subjected to cycles which duplicate those to be used during testing. Then, when quickly transferred to the tester after conditioning, the actual test can be limited to a few cycles. The preconditioner is designed so that cyclic temperatures can be applied to the top or the bottom of either 6-ft or 8-ft square specimens installed in test frames ready for tests. The side of the specimen not facing the preconditioner is exposed to laboratory air.

GENERAL CONSTRUCTION DETAILS

The calibrated and environmental boxes were constructed with exterior structural frames so that their insulated walls have a minimum of penetrations which act as heat paths. The primary structural members consist of 4-in. x 12-in. cross section tubular steel frames around the outside of the insulation at the open faces of the boxes. Similar frames are used around each test specimen frame. The remainder of each box frame consists of steel tees and angles welded to the tubular frames. Immediately inside the steel frames are the galvanized sheet steel outer skins of the boxes. A 1-ft nominal thickness of polyurethane was foamed in place inside the steel skins. (A 2-ft nominal thickness was used on the sides of the 6-ft square environmental box.) A glass fiber reinforced plastic skin was applied to the interior of the boxes. The test frames are insulated with the same foam, but are faced with 3/4-in. thick plastic coated marine plywood for added strength.

Encased, closed cell, neoprene foam gaskets on the faces of the tubular box frames provide seals between the steel frames around the boxes and test frames. A second seal is provided by a layer of soft polyurethane foam applied to the face of each box. This prevents air currents in the spaces between boxes and test frame. The entire assembly consisting of calibrated box, test frame, and environmental box are clamped together with 1/2-in. coil rods (high tensile strength rods with coarse, 6 per inch, threads). Gaskets are readily compressed by the rods to provide the necessary seal. Stops are added to prevent over-compression of gaskets and insure proper spacing between boxes and specimen frame.

CONSTRUCTION DETAILS OF CALIBRATED BOX

Constant circulation of a water and ethylene glycol mixture through a chiller and re-heat system provides the heating and cooling needed in the calibrated box. The mixture is pumped through a turbine flow meter and a fin tube radiator in the box before being returned to the chiller. A thermopile in the inlet and outlet lines measures the temperature change of the liquid mixture passing through the box. A thermopile consisting of 14 pairs of thermocouples in the back and sides of the calibrated box measure the temperature difference between the inside and outside surfaces of the box. Signals from the turbine flow meter and thermopiles are sent to the data acquisition equipment for processing.

When the metering box is used inside the calibrated box, the signal from a thermopile consisting of 18 pairs of thermocouples across the walls of the metering box is fed to a controller which powers heaters in the metering box that balance the inside temperature to that of the calibrated box. Fans in both boxes provide low velocity air movement adequate to provide relatively uniform air temperature over the entire specimen surface. Fan power in either calibrated or metering box is measured. Air temperatures are measured with bare thermocouples. Connections for 30 thermocouples are provided through the wall of each box.

CONSTRUCTION DETAILS OF ENVIRONMENTAL BOXES

The conditioning of the environmental boxes is accomplished with a 5 HP packaged heating and cooling unit. It is connected to the chamber in use with 6-in. diameter flexible insulated ducts. Fans in the boxes provide a choice of two air speeds over the face of the specimens. One speed is less than 1 mile per hr, and the other over 5 miles per hr. The capacities of the heating/cooling unit are great enough to achieve air and surface temperatures from $-30^{\circ}F$ to $160^{\circ}F$. The surface temperatures of insulated roof specimens can be changed as rapidly as the temperatures of such surfaces change when subjected to daily cycles of solar radiation.

CONSTRUCTION DETAILS OF TEST FRAMES

Test frames are constructed with 3/4-in. thick plastic coated marine plywood on their faces and with 3/4 in. thick exterior plywood on the inside surfaces where test specimens are mounted. All joints in the faces of the frames are thoroughly caulked for air tightness. Thermocouple connections through each test frame provide for up to 48 thermocouples. These will be used for specimen surface and internal temperature measurements.

REFRIGERATION EQUIPMENT

The calibrated and the environmental boxes each require a refrigeration system. A refrigeration system is also required for the preconditioning box. A brief description of each system is given below.

The refrigeration requirements for the calibrated box are $50^{\circ}F$ minimum temperature with a cooling capacity of 2000 BTU's per hour. The cooling demand must also be metered which was an important consideration in the selection process. A portable refrigeration unit, manufactured by Techne was selected for the chiller-heater system.

This equipment incorporates a chiller coil which is located in an insulated receiver tank. A small submersible pump, nominally giving an output of 0.5 GPM, is used to pump the liquid through a turbine flow meter, an electric heating element-to-liquid heat exchanger. The air-to-liquid heat exchanger ultimately controls the temperature in the calibrated chamber. The control temperature is sensed in the calibrated hot box using a Electromax Leeds & Northrup (L&N) IV controller heater system which is described in the instrumentation section. The refrigeration unit has no temperature control circuitry but runs at a constant load during the test and the electric heater unit overrides/supplies additional heat as required by the control system for a specific temperature requirement. The watt hours for cooling and/or heating are measured using the turbine flow meter and the differential temperature transducer which are described in the instrumentation section. Readers should refer to Figure 3 for details.

The environmental boxes also require a cooling system which has a relatively high capability in terms of temperature change and cooling load. The nominal temperature range of these boxes is $-30^{\circ}F$ to $+160^{\circ}F$ with a heating rate of approximately $35^{\circ}F/hr$ at $80^{\circ}F$, and a cooling rate of approximately $20^{\circ}F/hr$ at $15^{\circ}F$. A 5 HP refrigeration unit manufactured by Thermotron Corporation was selected for this system, with a cooling capacity of approximately 6000 BTU/HR at $-20^{\circ}F$. This design uses a remote refrigeration unit with closed forced air cooling to the environmental box via flexible supply and return ducts. Thus, rotation of the box is simplified since the refrigeration system is disconnected during the rotation process and then reconnected for the test setup. The same refrigeration system is used for both the 8 ft and 6 ft environmental boxes. This refrigeration unit also incorporates a remote, air-cooled condensor located outside the laboratory facility.

The preconditioning chamber requires a refrigeration system similar to that required for the environmental boxes. A remote, 2 HP, water cooled unit was selected for this application with a cooling capacity of approximately 8000 BTU/HR at $+20^{\circ}F$. This unit has appreciably less cooling capacity than the 5 HP unit. However, it does provide an adequate rate of exchange over a slightly smaller temperature range ($+20^{\circ}F$ to $+140^{\circ}F$).

INSTRUMENTATION CONSIDERATIONS

Data acquisition and temperature control function for the calibrated box, environmental boxes, and metering box are performed by a mini-computer data acquisition system. The system has the capability of performing 171 Type T thermocouple temperature measurements, 20 measurements dedicated for miscellaneous voltage parameters, and 3 pulse counting measurements related to watt hour and liquid flow parameters. Further, ultimate control of a test for any of the operating configurations is derived from the mini-computer which also acts as primary controller. A computer program is used for performing the necessary calculations related to the heat transfer through the test panel. This program includes all applicable losses and calibration factors.

A Model 3052 Data Acquisition System manufactured by Hewlett Packard (HP) was selected for the calibrated hot box facility. This system includes a Model 9835-A desk top computer, a Model 3455A digital voltmeter, and three Model 3495A scanners which perform the switching functions for all analog input signals. The desk top computer is used for all data acquisition, accumulation, analysis, storage, and primary control functions. It includes a 12 in. CRT with a 24 line display of information which is effective for monitoring the current status of an on-going test. A built-in tape cartridge is used for storing test data. The computer uses a BASIC program language and has an active memory of 49 K-Bytes.

The voltmeter has a sensitivity of one microvolt. This meter also functions as a multimeter and has the ability to measure AC volts, DC volts, and resistance.

Each of the three scanner main frames incorporates four modular units capable of recording twenty channels each of analog data. For Type T thermocouple data, a reference junction temperature is measured by a thermistor (in the form of a resistance value) and recorded on one channel, while the remaining nineteen channels are used to record thermocouple voltage data. All of the data is transferred to the mini-computer via a HP-IB interface cable. An internal software routine is then used to calculate temperature. Thus, the technique of handling temperature data utilizes the mini-computer in place of a linearization prom and external amplifier unit.

The mini-computer also functions as the primary temperature controller of the various boxes in all modes of operation. This is accomplished by using a digital-analog (D/A) interface module to control slave controllers. The slave controllers are conventional 3-mode units (i.e., proportional band, reset, and rate adjustment) which simplify the mini-computer primary control function. The slave controllers can be operated manually or in a remote configuration, where a DC voltage supplied by the D/A module spans the instrument temperature control range. Essentially, the mini-computer establishes a temperature control point. This data is transmitted to the slave controller via the D/A module and the responsibility of the slave controller includes functional on and off cycling or the equivalent.

The D/A modules, as well as pulse counting cards for watt hour data and the liquid-flow data, are interfaced to the mini-computer using a Model HP 6940-B multiprogrammer and a Model HP 59500-A binary converter. The mini-computer "transmits" control point data to the output D/A cards and "reads" data from the pulse counter cards.

The slave controller for the calibrated box consists of a L&N IV Temperature Controller which energizes a heater located in the chiller/heater circuit via a silicon controlled rectifier (SCR). The L&N controller uses a Type T thermocouple located in the plenum of the calibrated box for control. A primary consideration in selecting this controller was its stability characteristics. A $\pm$ 10 percent line voltage variation results in a calibration shift of less than 0.06 percent of the setting. The temperature stability of the controller is also excellent, with less than $\pm$ 0.005 percent shift per degree Celsius. The output signal from the L&N controller controls the heater power via an SCR, which provides a steady power draw to the heater, minimizing temperature changes. A zero firing type SCR was used to minimize watt hour measurement errors (voltage and current). This type of unit also minimizes electrical interference problems normally present with relay circuitry. The L&N controller provides a set point adjustment of approximately $\pm$ 0.2°F.

Temperature control of the environmental boxes is accomplished using a similar technique. A D/A card provides an analog output voltage which is used to control a slave controller incorporated in the remote 5 HP refrigeration unit supplied by Thermotron Corporation. The mini-computer ultimately controls the test but the slave Thermotron controller has the responsibility for the more conventional aspects of temperature control including on and off cycling of heaters and refrigeration equipment.

Instrumentation for the guarded mode includes two control circuits. A thermopile, consisting of 18 pairs of thermocouples located near the inside and outside surfaces of the metering box, generate a differential voltage output which is measured and used to control the air temperature in the metering box with a L&N III differential controller. The output signal from the differential controller is used to control the amount of heat in the metering box via a SCR and one of two heaters (330W or 660W) located in the metering box. The guard space temperature is controlled using the L&N IV controller in conjunction with the chiller-heater system discussed above. Thus, the L&N IV controller sets the control temperature and the L&N III circuit minimizes the temperature difference between the inside and outside surfaces of the metering box.

The cumulative watt hours of electrical energy are measured using equipment supplied by Scientific Columbus. There are two watt hour transducers. One unit is used for measuring fan power in the calibrated box when the system is operated in the calibrated mode and the other unit is idle. When the system is in the guarded mode, both watt hour meters are needed. One is used for measuring the fan power in the metering box, with the second measuring the heater power. Each watt hour meter produces a pulse output proportional to watt hours, with one pulse equal to 0.1 watt hour. Measurement of these parameters is recorded via the pulse counter cards in the multiprogrammer.

Measurement of the cooling and heating load to the calibrated box is accomplished by measuring the liquid flow and the differential temperature across the heat exchanger located in the calibrated box. A turbine flow meter having a range of 0.1 to 2 GPM was selected for the heater/chiller system. This unit produces a pulse output proportional to the flow in the system. The pulse output is measured using the pulse counter cards as described above. Since the system includes a real time clock, calculation of liquid flow (including applicable calibration factors) are easily performed by the mini-computer. Accuracy of flow measurements is better than $\pm$ 1/4 percent. The differential temperature across the air-liquid heat exchanger, located in the calibrated box, is measured using a differential temperature transducer which incorporates ten pairs of thermocouples wired in a thermopile configuration. Liquid supply to the heat exchanger and return to the receiver tank is routed via flexible piping through the differential temperature transducer. This unit amplifies a signal representing differential temperature by approximately one order of magnitude with 1°F equal to 223 microvolts compared to a nominal 22 microvolts for a Type T thermocouple. The sensitivity of the temperature differential measurement is therefore approximately $\pm$ 0.005°F using the voltmeter supplied with the data acquisition system.

There are several other equipments included in the instrumentation system. A high speed printer is used in conjunction with the desk top computer. This unit uses a dot matrix character serial printer and utilizes microprocessor control with a high print speed of 180 characters per second. The calibrated and environmental boxes each incorporate a temperature limit alarm which is independent of the mini-computer primary control function. Temperature above a present limit in either of the test boxes activates an alarm and shuts down all system power. Power for critical instrumentation such as the volt-meter and multiprogrammer is derived from a constant voltage isolation transformer which minimizes line voltage variations to the instrumentation.

CONCLUSION

It is believed that the Guarded/Calibrated Hot Box designed and constructed as presented here can be used to measure the thermal performance of large building systems with a high degree of accuracy.

Even though the thermal performance of systems with high mass under cyclic temperature conditions and in the presence of moisture has yet to be defined, testing in the calibrated hot box will at least give us some answer to the response of the system under such a complex set of conditions.

Test results will be reported periodically to help further the state-of-the-art.

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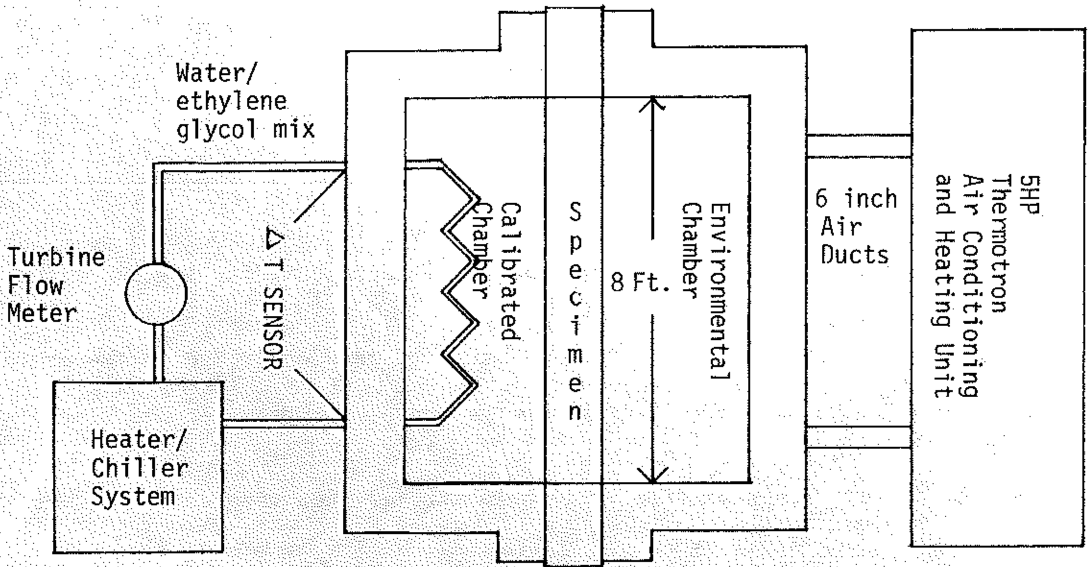

Figure 1 - Boxes 1 and 2

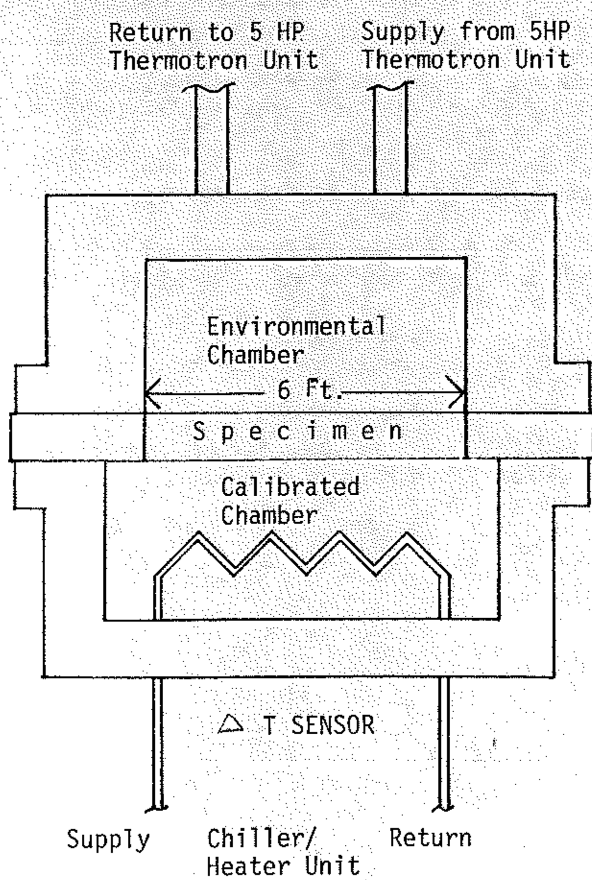

Figure 2 - Boxes 1 and 3

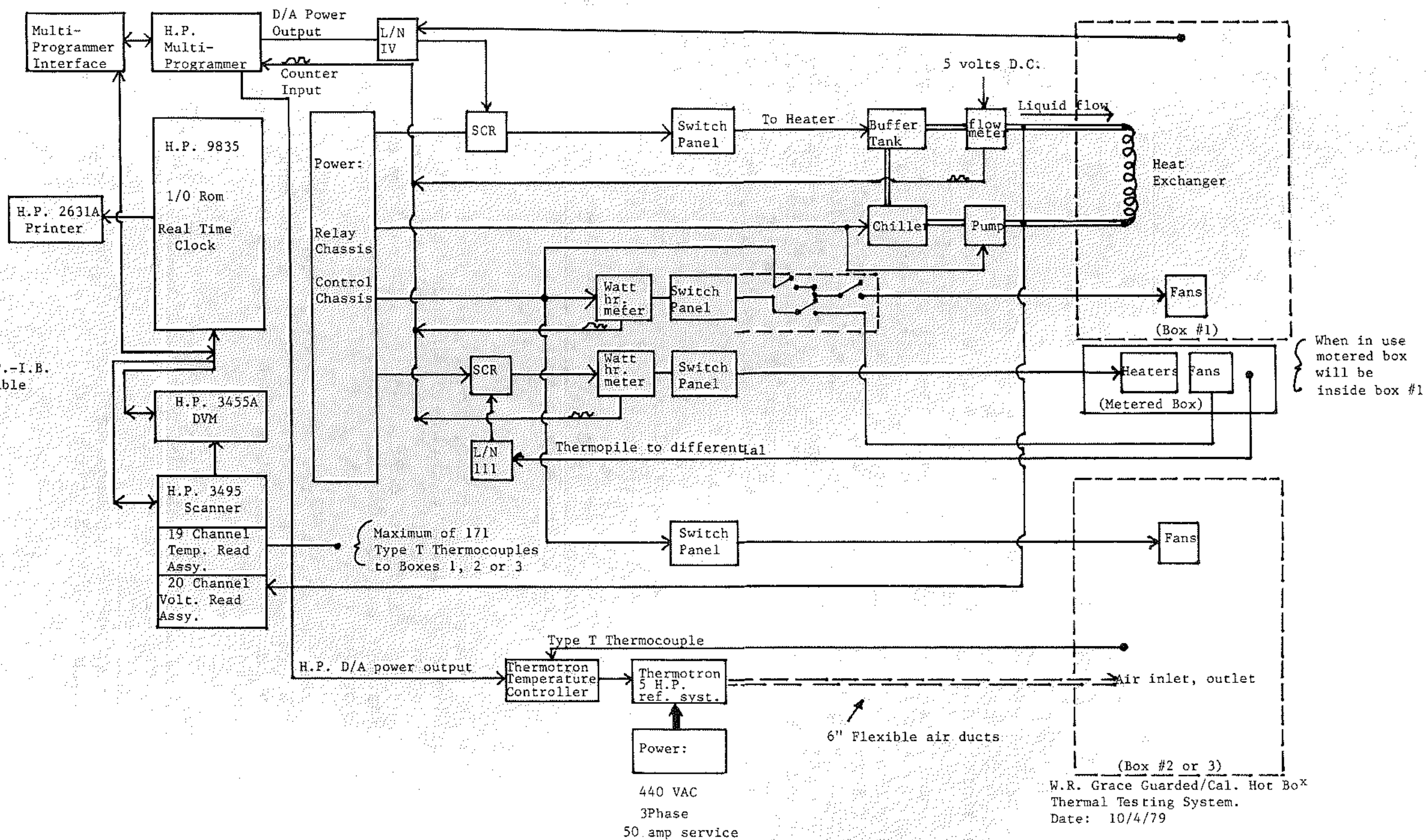
Multi-Programmer Interface
H.P. Multi-Programmer
D/A Power Output
L/N IV
Counter Input
5 volts D.C.
Liquid flow
SCR
Switch Panel
To Heater
Buffer Tank
flow meter
Heat Exchanger
Power:
Relay Chassis
Control Chassis
H.P. 9835
1/0 Rom
Real Time Clock
H.P. 2631A Printer
Chiller
Pump
Watt hr. meter
Switch Panel
Fans
(Box #1)
When in use motered box will be inside box #1
H.P.-I.B. Cable
SCR
Watt hr. meter
Switch Panel
Heaters
Fans
(Metered Box)
H.P. 3455A DVM
L/N 111
Thermopile to differential
H.P. 3495 Scanner
19 Channel Temp. Read Assy.
20 Channel Volt. Read Assy.
Maximum of 171 Type T Thermocouples to Boxes 1, 2 or 3
Switch Panel
Fans
Type T Thermocouple
H.P. D/A power output
Thermotron Temperature Controller
Thermotron 5 H.P. ref. syst.
Air inlet, outlet
6" Flexible air ducts
Power:
440 VAC
3Phase
50 amp service
(Box #2 or 3)
W.R. Grace Guarded/Cal. Hot Box
Thermal Testing System.
Date: 10/4/79

Figure 3