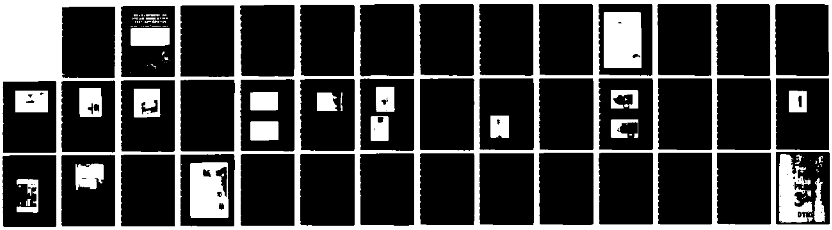
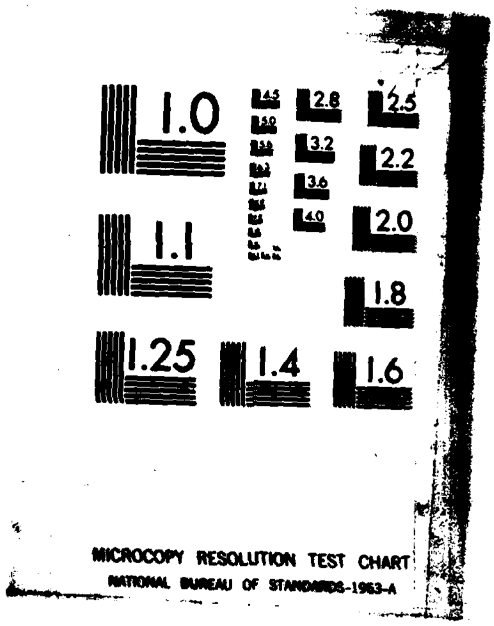
AD-A137 663 DEVELOPMENT OF STEAM SIMULATION TEST APPARATUS PHASE I 1/1
FORMAL TECHNICAL REPORT(U) FOSTER-MILLER INC WALTHAM MA
J F HEALEY ET AL. OCT 83 NAV-8303 NCTRF-152
UNCLASSIFIED N00140-83-C-RA13 F/G 11/5 NL





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DEVELOPMENT OF STEAM SIMULATION TEST APPARATUS

Phase I - Formal Technical Report

NAVY CLOTHING AND TEXTILE
RESEARCH FACILITY
NATICK, MASSACHUSETTS

Technical Report No. 152

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
NAV-RA13-FM8303-6/NCTRF-152	AD-A137663	

4. TITLE (and Subtitle)
Development of Steam Simulation Test Apparatus - Phase I - Formal Technical Report

5. TYPE OF REPORT & PERIOD COVERED
Phase I - Formal Technical Report; January-October 1983

6. PERFORMING ORG. REPORT NUMBER
NAV-8303

7. AUTHOR(s)
John F. Healey and John F. McCoy

8. CONTRACT OR GRANT NUMBER(s)
N00140-83-C-RA13

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Foster-Miller, Inc.
350 Second Avenue
Waltham, MA

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
22801

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Regional Contracting Center
Detachment, Building 11
Newport, RI 02840

12. REPORT DATE
October 1983

13. NUMBER OF PAGES
37

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Navy Clothing and Textile Research Facility (NCTRF)
21 Strathmore Road
Natick, MA 01760

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same as 16.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

heat flux measurement, water vapor transmission, atmospheric steam generation, textile testing, skin burn protection

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development of an apparatus designed to measure heat flux and water vapor transmission through various fabrics/fabric assemblies when exposed to simulated conditions of water vapor saturated air at 140, 160, and 180°F, saturated steam at 212°F, and superheated steam at 300 and 500°F, all at atmospheric pressure. (U)

The report discusses system design, operation and validation testing. It was concluded that the test apparatus operates as expected and that persons experienced in operating general lab equipment may be expected to operate this apparatus. (U)

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1. INTRODUCTION

This document is the Phase I final technical report prepared by Foster-Miller, Inc., for U.S. Navy Contract No. N00140-83-C-RA13, "Study on the Determination of Steam Burn Protective Materials for Possible Use in Shipboard Garments," summarizing the results of the Phase I efforts in the design, fabrication and testing of the steam simulation test apparatus. Work done under this contract is monitored by the Navy Clothing and Textile Research Facility (NCTRF), Natick, MA.

1.1 Background

On those occasions when Navy personnel are exposed or may be exposed to the hazards of live steam, it becomes necessary to provide them with clothing which will offer maximum steam burn protection. The Navy has recognized the need to evaluate the degree of steam burn protection provided by fabrics and fabric assemblies which are or may be used in shipboard garments.

Foster-Miller, Inc. was contracted to design a test apparatus and to conduct a study for determining the effectiveness of various fabrics and fabric assemblies in providing protection against steam burns.

1.2 Program Objectives

The broad objective of this program are to provide the data necessary to perform a comparative evaluation of the steam burn protection offered by various fabric/fabric assemblies when exposed to simulated steam rupture conditions and to define the parameters and physical requirements needed to design steam burn protective clothing.

Specific program objectives are:

- Design a steam simulation test apparatus
- Fabricate the apparatus and perform system validation tests
- Conduct tests on fabric/fabric assemblies provided by the Navy
- Analyze test results
- Deliver steam simulation test apparatus to the Navy.

1.3 Scope of Effort

The program is to be completed in two phases:

- Phase I - Development of Steam Simulation Test Apparatus
- Phase II - Thermal Transmission and Water Vapor Measurements.

This report summarizes Phase I efforts. During Phase II, fabric/fabric assemblies supplied by the Navy will be evaluated for their steam burn protection with the steam simulation test apparatus developed in Phase I. The Phase II effort will be presented in a separate report.

2. SYSTEM DESCRIPTION

Figure 1 presents the apparatus designed to simulate steam exposures and monitor the thermal protection offered by candidate fabrics and fabric assemblies. The apparatus is compact and easy to use by technicians with minimal specific training. Selection of oversize heat sources ensures achievement of selected operating conditions and stability of conditions at the selected level. The apparatus is designed to provide repeatable results independent of the operator. The selection of a fast acting electronic balance ensures that the sample weighing process can keep pace with other system functions, ensuring high production rates.

Technical features of the system are presented in Table 1. Details of the system design are presented in the following subsections.

Subsection 2.1 presents an overview of the entire test apparatus. Subsection 2.2 through 2.6 describe, in detail, the components of the subsystems.

2.1 System Overview

Figure 2 presents schematically the test apparatus. It is designed to operate in three basic modes, all at atmospheric pressure:

- Superheated steam at 300°F and 500°F
- Saturated steam at 212°F
- Water vapor saturated air at 140°, 160° and 180°F.

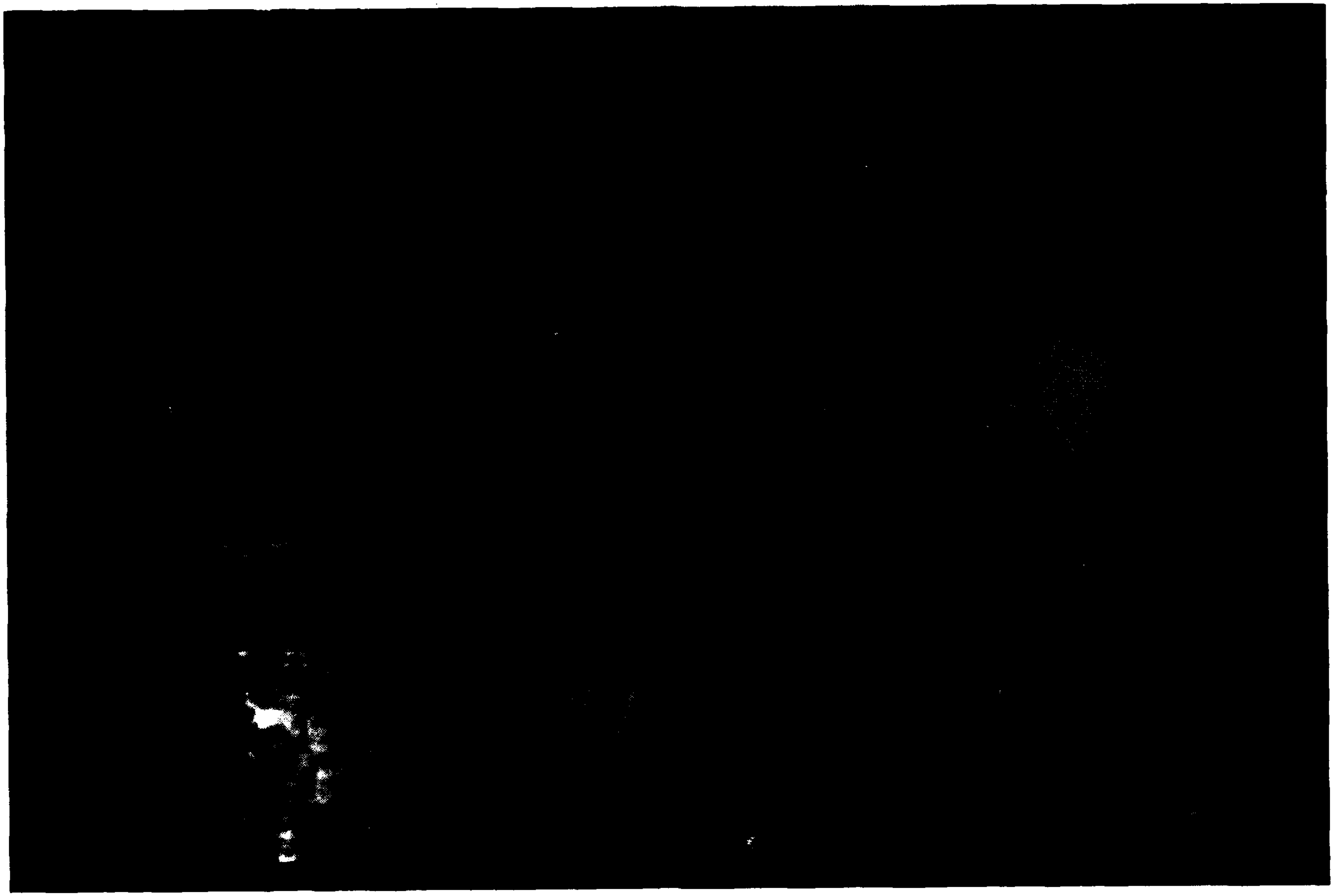

Figure 1. Steam Burn Test Apparatus
(Boiler Guard Removed for Clarity)

Table 1. Features of Steam Simulation Test Apparatus

Features
Exposure conditions - steam at 500°, 300°, 212°F; saturated air at 180°, 160°, 140°F
Exposure conditions can be maintained continuously and automatically for 120 sec (adjustable)
Square wave exposure of sample
Sample isolated prior to square wave exposure
Sample area - 2 in. diam
Sample thickness - to 1 in.
Separation between transducer and sample to 1/2 in.
Vertical sample orientation
Commercially available heat flux transducer capable of broad range (International Thermal Instruments)
Heat flux with/without fabric sample in place
Transducer output compatible with laboratory recording instruments
Controlled transducer/sample spacing and pressure
Measures absorbed and transmitted vapor gravimetrically
Self-contained, benchtop design
Requires electrical power service only
Rapid, secure sample clamping

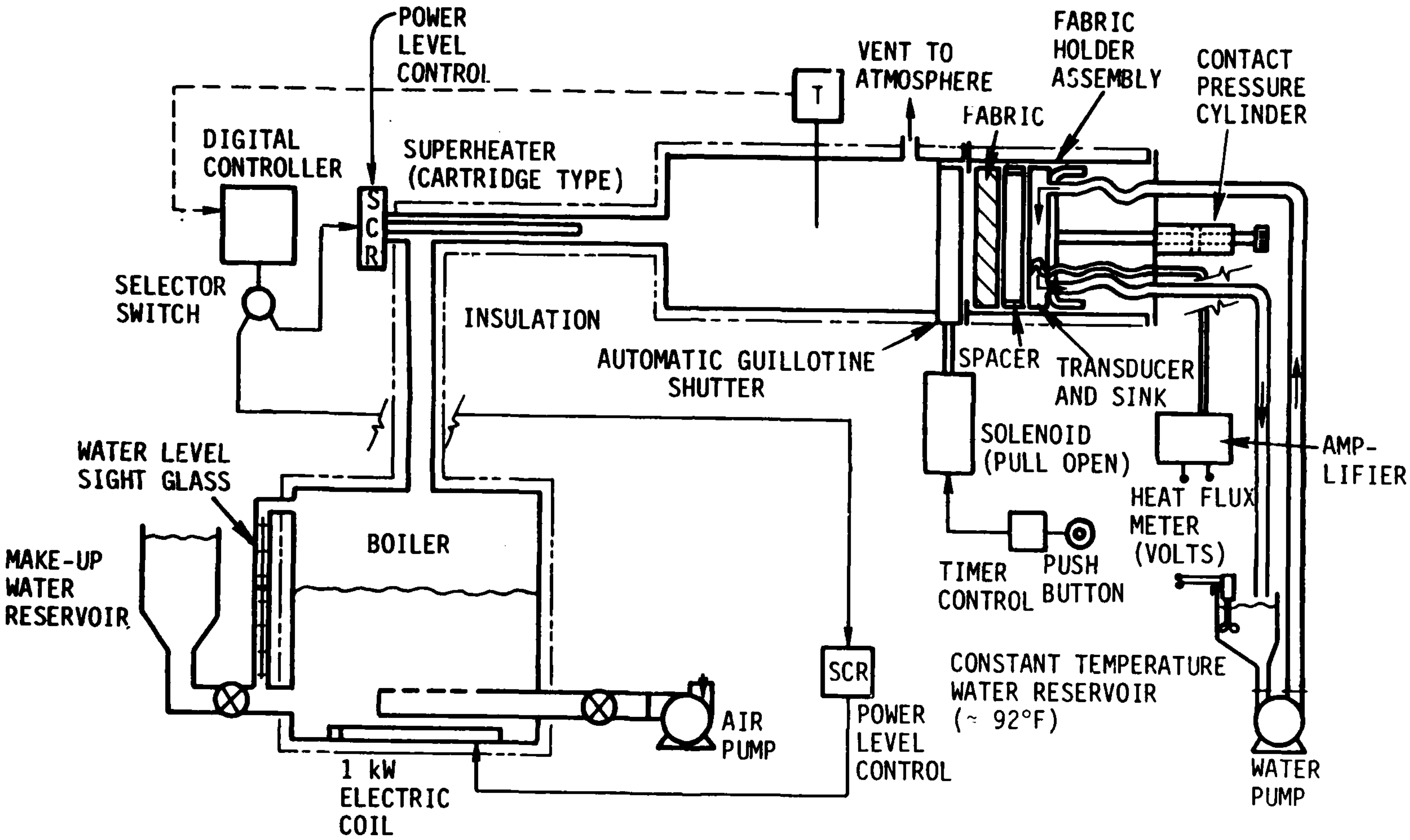

Figure 2. Test Apparatus Schematic

The subsystems can be described by reference to five specific functions performed:

- Steam/water vapor generation
- Fabric sample mounting
- Fabric sample exposure
- Heat flux measurement
- Vapor transmission measurement.

2.2 Steam/Water Vapor Generation

Required test conditions include superheated and saturated steam as well as water vapor saturated air.

The steam/water vapor generation subsystem consists of the following five major components:

- Boiler
- Superheater
- Steam chest
- Digital temperature controller
- Selector switch.

The selector switch is a three-position, center "off" switch. The remaining two-switch positions set the mode of operation of the steam/water vapor generation subsystem. The modes of operation are:

- Superheated steam
- Saturated steam or air.

The boiler, shown in Figure 3, is fabricated from stainless steel pipe and plate, and is designed to operate at atmospheric pressure. A number of 1/2 NPT ports provide for attachment of the make-up water, sight glass, condensate return and boiler drain lines. A single port on the top of the boiler provides for attachment of a 1-1/4 in. stainless steel pipe which directs

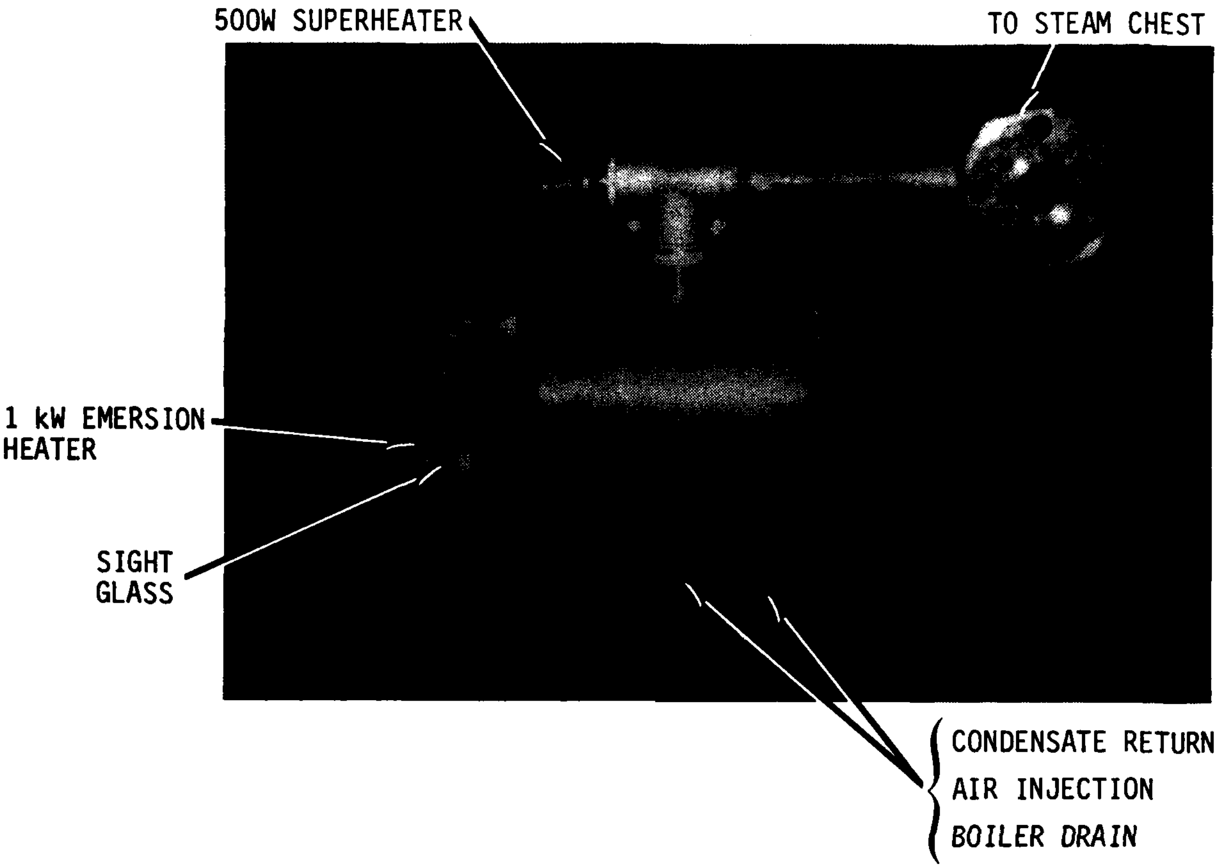

Figure 3. Boiler with Superheater

the flow of steam or air to the steam chest and which also houses a 115Vac, 500W superheater element.

A single 1 in. NPT port near the bottom of the boiler accepts an 115Vac, 1000W immersion heater.

The steam chest, shown in Figure 4, is fabricated from Teflon® tubing and plate. Like the boiler, it is designed to maintain and operate at atmospheric pressure.

A Teflon® plate is bolted to either end of a Teflon® tube and sealed to the tube by an "O-ring." A 1/2 in. thick Teflon® plate at one end of the steam chest provides attachment for the pipe carrying steam or saturated air from the boiler.

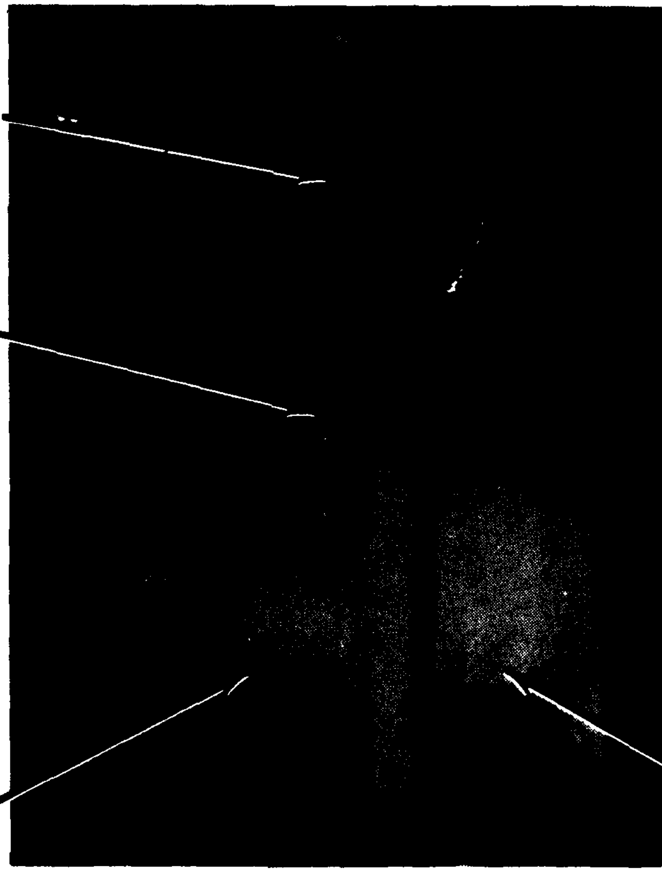

Figure 4. Steam Chest

A 1-1/2 in. thick Teflon® plate at the opposite end and an additional 1/2 in. thick cap-plate are machined to house and guide a water-cooled shutter. Attached to these plates are the shutter actuator and fabric sample holder.

Ports in the steam chest provide for attachment of a condensate return-to-boiler-line and a system vent and for insertion of a thermocouple probe.

An "Omega" Model D921, 115Vac digital temperature controller, shown in Figure 5, is used in conjunction with a copper/constantan thermocouple probe located within the steam chest to monitor and control the steam chest conditions.

Figure 5. Model D921 Digital Temperature Controller

In the superheated steam mode, the 1 kW electric emersion heater operates at full power and heats water in the boiler. Steam from the boiler is heated to either 300° or 500°F in a superheater section by a 500W cartridge heater. The superheated steam is stored in the steam chest where temperature is monitored by a thermocouple probe connected to the digital controller. The controller activates the 500W cartridge heater to maintain the desired superheated steam temperature.

In the saturated steam mode (212°F), steam temperature is monitored by the thermocouple probe in the steam chest, and the digital controller activates the 1 kW electric emersion heater in the boiler. The superheater is not used since it was deactivated by the selector switch.

In the saturated air mode, an air pump sparges air through the water in the boiler. The 1 kW electric emersion heater is controlled as it was during the saturated steam mode, except in this case, air saturated with water vapor at 140°, 160°, or 180°F is maintained in the steam chest. The superheater is not used.

An SCR power level controller is connected in series between the 1 kW electric emersion heater and the digital temperature controller and is used to adjust the power level to the heater, if necessary.

2.3 Fabric Sample Mounting

Fabric samples are cut to a 2-3/4 in. diameter and placed in a stepped cylinder. A step on the cylinder inner diameter acts as a "stop" for the sample. A retaining ring placed behind the fabric holds it firmly against the "stop." The inner diameter of the retaining ring maintains a 2 in. diameter sample exposure.

Figure 6 shows the two pieces of a typical sample holder. Figure 7 shows the holder and a fabric sample assembled. The sample holder shown is for holding fabric/fabric assemblies up to 1/4 in. thick. Sample holders are chosen depending on sample thickness and are capable of holding fabric/fabric assemblies up to 1 in. thick. Sample holder parts are machined from Teflon®.

Figure 8 shows the sample and holder mounted in its housing. The sample housing is attached to the shutter-end of the steam chest and is hinged horizontally, allowing it to be swung away from the steam chest for insertion and removal of the sample.

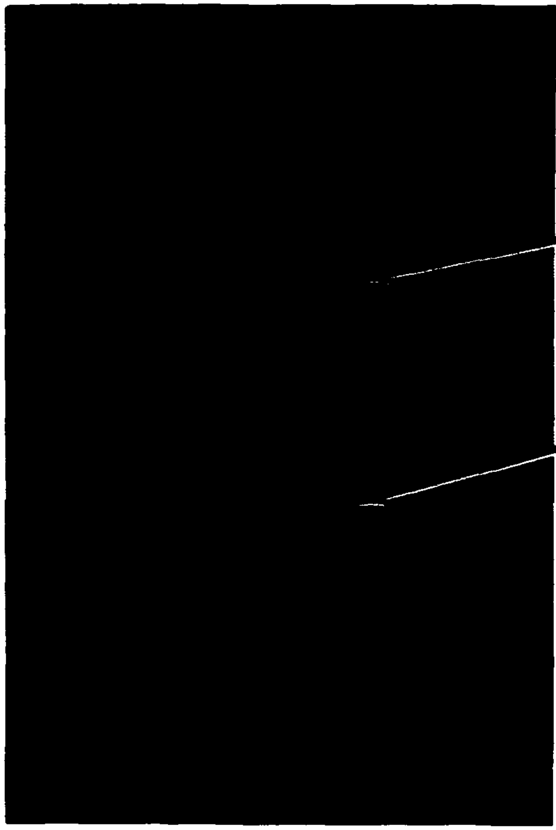

Figure 6. Sample Holder Parts

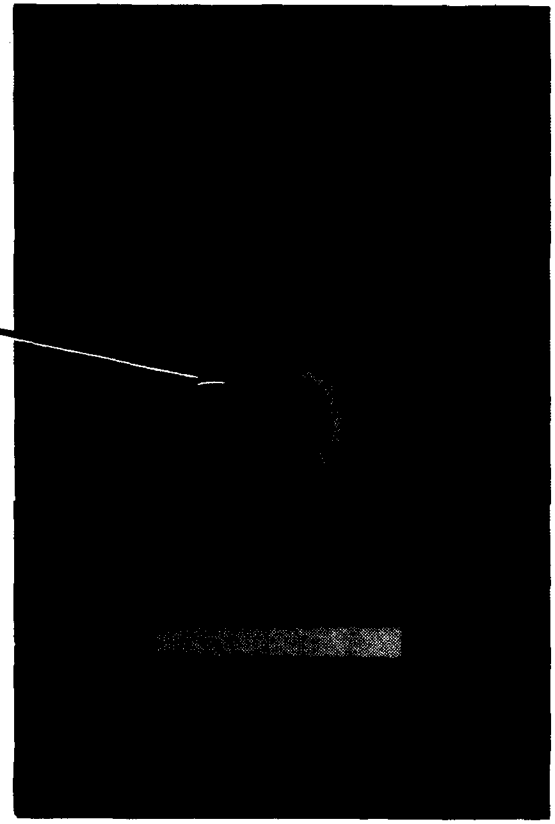

Figure 7. Assembled Sample Holder

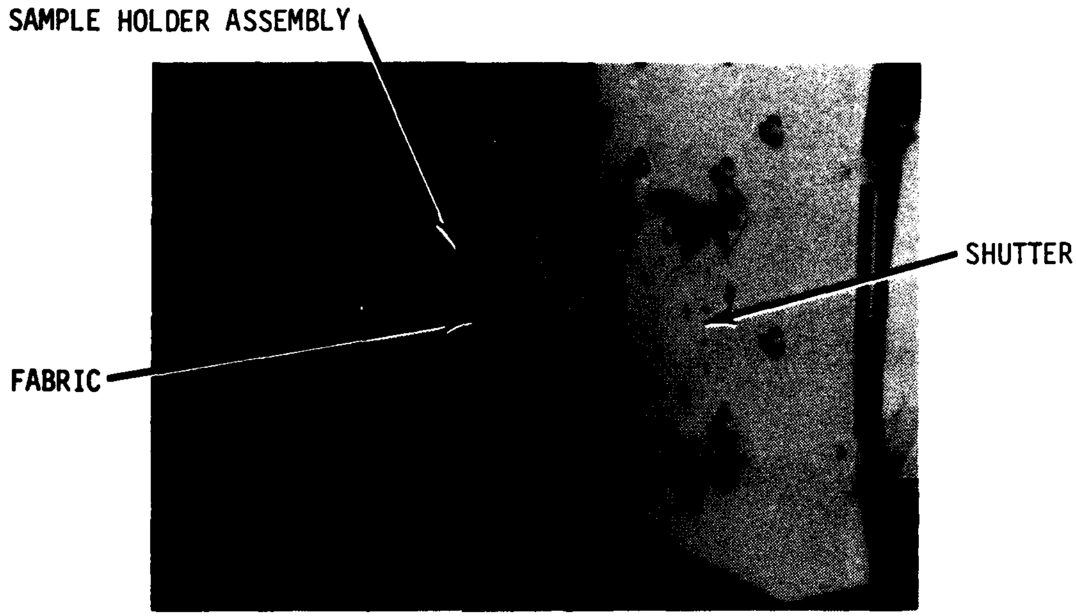

Figure 8. Sample Holder with Fabric Sample Mounted in Housing

When in position for testing, as shown in Figure 9, four toggle clamps secure the sample housing to the steam chest.

The sample housing also contains the heat flux measuring device. Shown removed from the sample housing in Figure 10, is the heat flux transducer, water-cooled transducer piston, and contact pressure cylinder.

The double-ended contact pressure cylinder allows external positioning of the transducer within the sample holder housing. When the heat flux transducer is positioned in contact with the test sample, a hand-operated air pump is used to pressurize the pneumatic cylinder holding the transducer in positive contact with the sample. A pressure gage provides a reference for repeatable contact pressures.

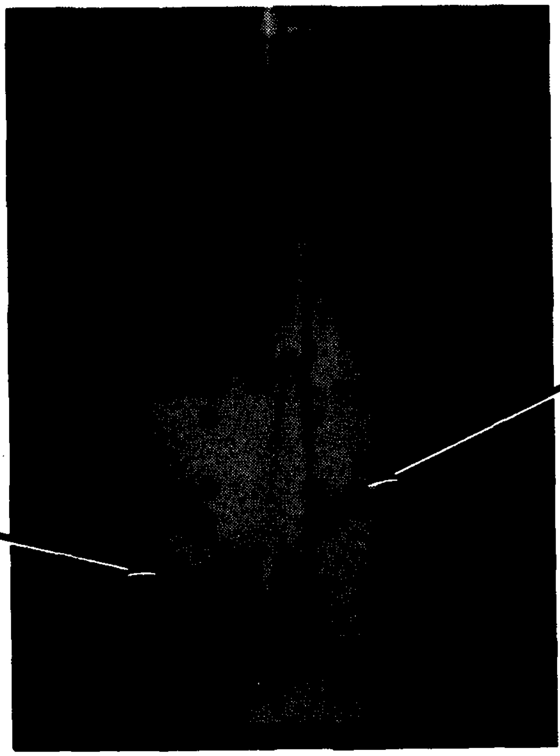

Figure 9. Sample Holder Housing Clamped to Steam Chest

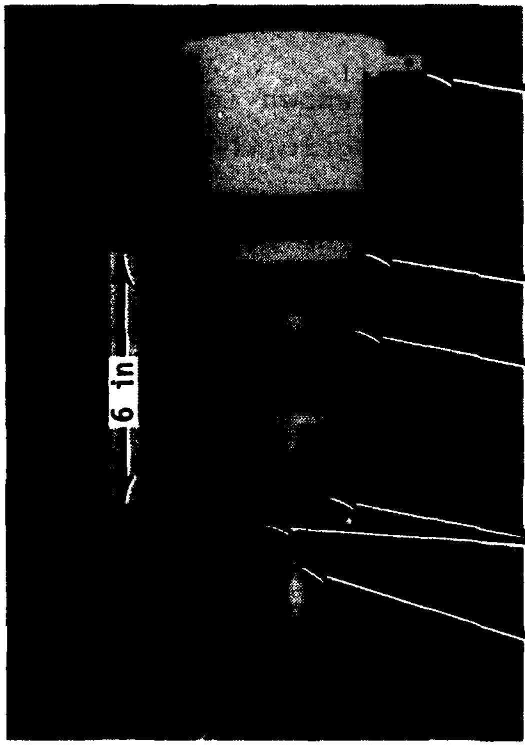

Figure 10. Disassembled Sample Holder Housing

When tests require a 1/2 in. space between the sample and heat flux transducer, a Teflon® spacer, or "stand-off", is positioned between the transducer and the sample. The contact pressure cylinder is pressurized to ensure that the space between the transducer and sample is maintained.

The transducer piston is a water-cooled two-part assembly constructed of copper and stainless steel. It acts as a heat sink for the heat flux transducer. The copper section is basically a 1/4 in. thick disc, counter-bored from either surface, leaving a 0.020 in. thick section between the heat flux transducer and the heat sink water. One counter-bore accepts the 0.055 in. thick, 2 in. diam heat flux transducer which is held in place by a high-temperature adhesive. The other counter-bore acts as a well for circulating cooling water. Thermal contact between the heat flux transducer and highly conductive copper web is ensured by application of a high-temperature, thermally conductive paste.

The stainless steel section of the transducer piston, when attached to the copper section, serves as a cap for the cooling water well and provides inlet and outlet water ports for the well. A machined "boss" on the stainless steel section is threaded and allows the transducer piston to be screwed onto the rod of the double-ended contact pressure cylinder.

Cooling water circulating through the transducer provides an adjustable, but constant, reference temperature for one surface of the heat flux transducer (the heat sink). The highly conductive copper web and thermal paste ensure efficient heat transfer between the cooling water and transducer.

Cooling water is supplied by a Haake Model D1 constant temperature immersion circulator shown in Figure 11. The cooling water is pumped by the circulator from its reservoir through a series network first to the transducer piston, then through the water-cooled shutter, back through a copper cooling coil to the reservoir. This provides a constant temperature heat sink for the heat flux transducer.

Flexible water and electrical lines from the transducer piston and heat flux transducer exit the sample housing through holes in an aluminum disc which supports the contact pressure cylinder and transducer assembly and attaches it to the sample housing.

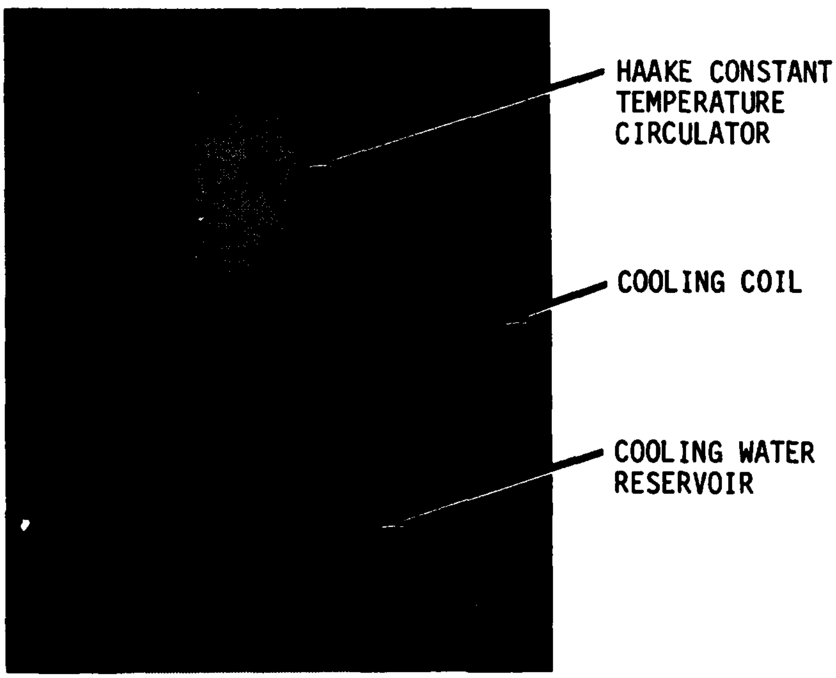

Figure 11. Haake Constant Temperature Circulator

2.4 Fabric Sample Exposure

Timed exposure of the test sample to the simulated conditions of steam or water saturated air is accomplished through the use of a double acting pneumatic cylinder, a water-cooled shutter, a solenoid operated four-way pneumatic valve, a time delay relay and a momentary contact reset switch. A 1/12 hp, 115Vac air compressor, used also to supply air to the boiler for the saturated air tests, acts as a source of compressed air power for opening and closing the shutter. A pneumatic accumulator provides ample volume of compressed air to ensure fast, consistent shutter actuation. Shutter control is shown schematically in Figure 12. Figure 13 and 14 show the shutter in its closed and open positions, respectively.

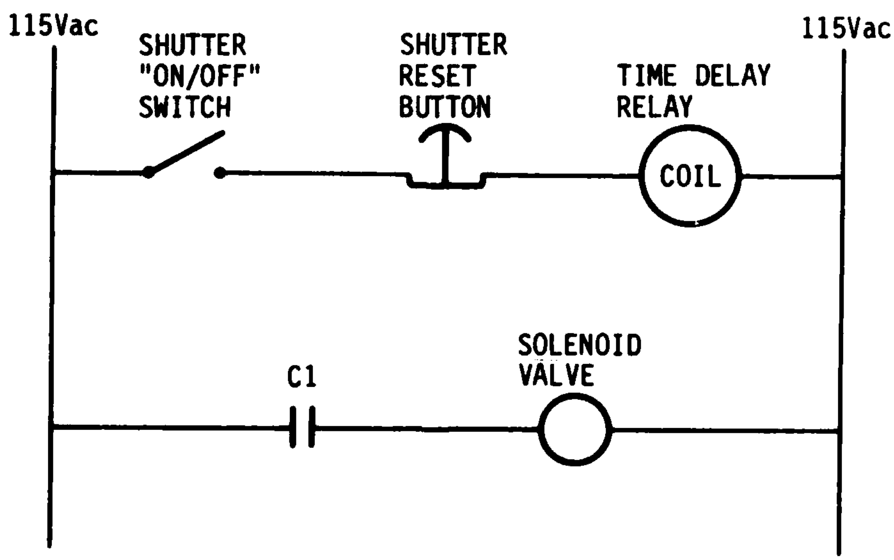

Figure 12. Schematic of Shutter Control Circuit

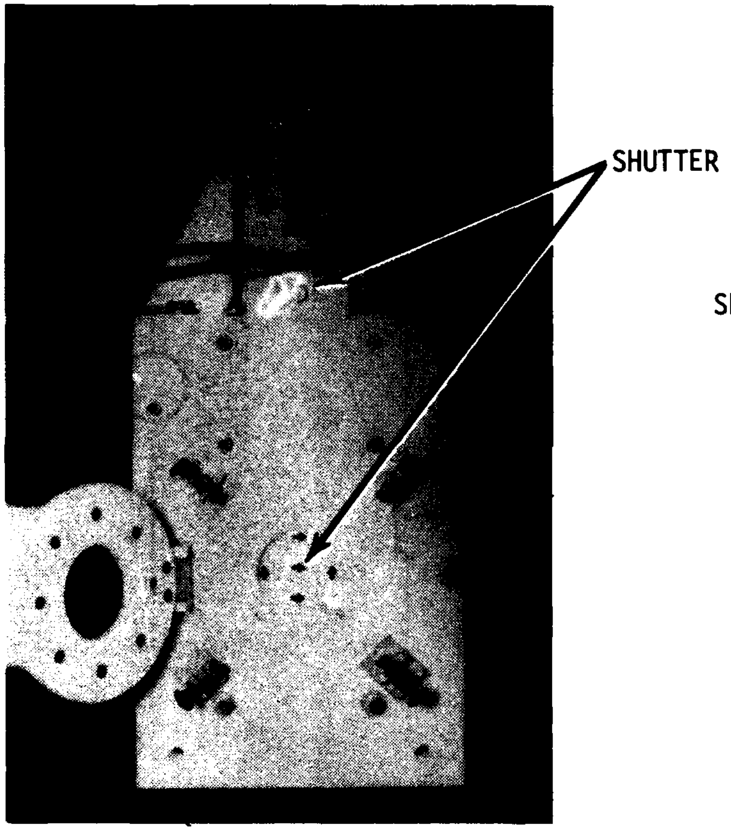

Figure 13. Shutter Closed

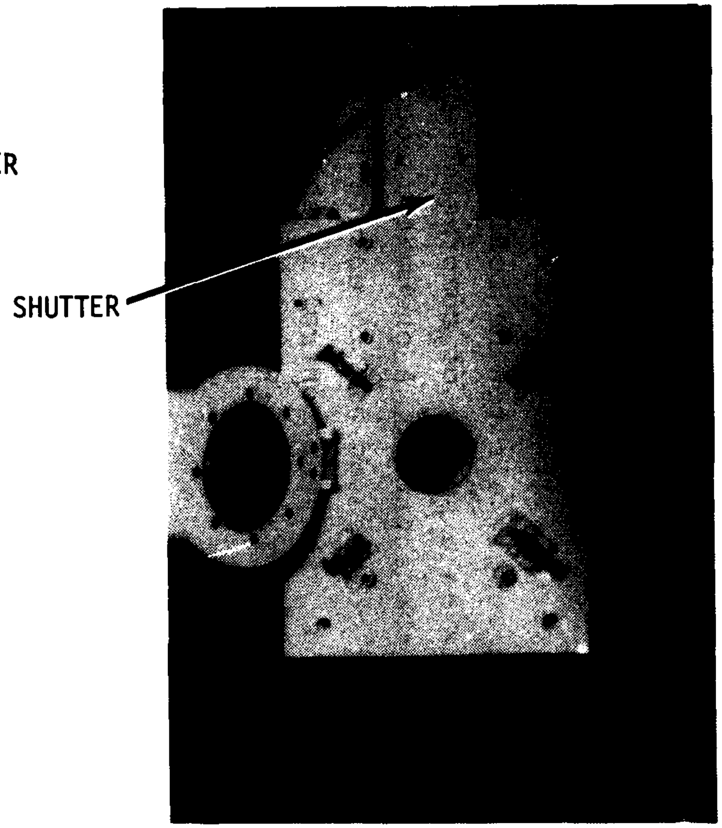

Figure 14. Shutter Open

With the shutter in its normally closed position, air pressure is supplied through the electrically de-energized solenoid valve to one side of the double acting air cylinder, thereby holding the shutter closed. The other side of the air cylinder is vented to atmosphere through the solenoid valve.

A momentary reset switch interrupts 115Vac line voltage to the coil of the externally adjustable time delay relay. Interruption of the coil line voltage resets the relay timer and at the same time closes a set of relay contacts which supply 115Vac line voltages to the solenoid valve.

The energized solenoid valve reverses the pneumatic signal on the double acting air cylinder, opening the shutter and exposing the sample to the preset steam chest conditions.

At the end of a 120 sec interval, the solenoid valve is de-energized by the time-delay relay. The pneumatic signal to the shutter air cylinder is again reversed and the shutter closes.

With air pressure maintained at 30 psi, shutter actuation occurs in 300 msec or less, providing a square wave sample exposure.

As mentioned in subsection 2.3, cooling water is supplied to the shutter by a Haake constant temperature immersion circulator. This eliminates virtually all heat flux through the transducer until the shutter is opened. Cooling water passes through the shutter and back to the circulator reservoir after it has first passed through the transducer piston. The shutter is machined from Teflon® plate and measures 2-1/2 in. wide, 8-1/4 in. long and 19/32 in. thick. A pattern of 1/4 in. diameter drilled holes directs the flow of cooling water to the area of the shutter which is exposed to steam chest conditions when in the closed position. The pattern of cooling water flow through the shutter is shown in Figure 15.

2.5 Heat Flux Measurement

The transducer for the measurement of heat flux through the fabric/fabric assemblies is an International Thermal Instruments Model B heat flux water. The flux meter is 2 in. in diameter, 0.055 in. thick and has a thermal conductivity of about 0.08 Btu/hr·ft·°F.

During testing one surface of the meter is generally maintained at 93°F, to simulate normal average skin temperature. When the opposite surface is exposed to the higher temperatures of the steam chest, a thermopile arrangement within the flux meter senses the temperature difference between the two surfaces and generates a dc millivolt signal. The signal is proportional to the heat flux through the meter and is easily converted to heat flow in

$$\frac{\text{gram-cal}}{\text{sec}\cdot\text{cm}^2} \text{ or } \frac{\text{Btu}}{\text{hr.ft}^2}$$

with a meter constant supplied by the manufacturer.

The flux meter dc millivolt signal is fed to a Rustrak Model 288 chart recorder and to a Simpson Model 2865 digital voltmeter. The Rustrak recorder produces a hard copy of the heat flux data while the Simpson voltmeter provides instantaneous readings during testing.

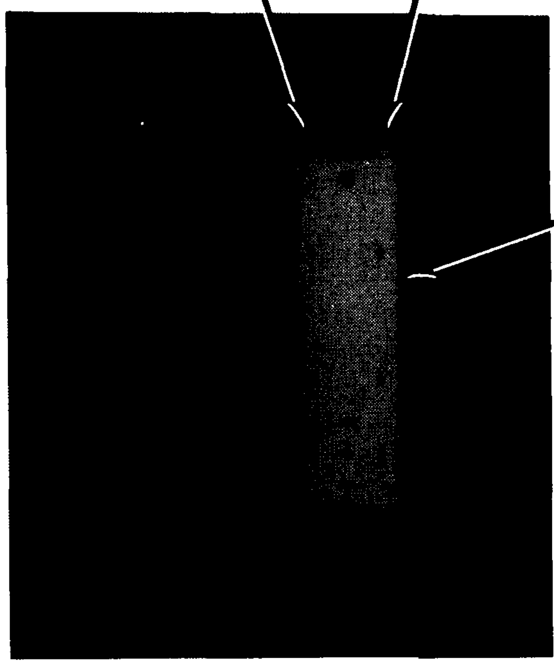

Figure 15. Shutter With Cooling Water Flow-Path Shown

Figure 16 shows the Rustrak recorder and Simpson voltmeter mounted in the apparatus control box. The control box which houses most of the system electrical equipment also contains an Omni Amp II millivolt amplifier shown in Figure 17. With the Omni Amp II, the flux meter signal can be either fed directly to the chart recorder and voltmeter or can be amplified. The Omni Amp II provides signal amplifications of 1, 2, 5, 10, 25, 50, and 100.

2.6 Vapor Transmission Measurements

Vapor transmission measurements are made by accurately weighing the fabric/fabric assembly before and after a test. A swab is used to remove condensation moisture from inside the

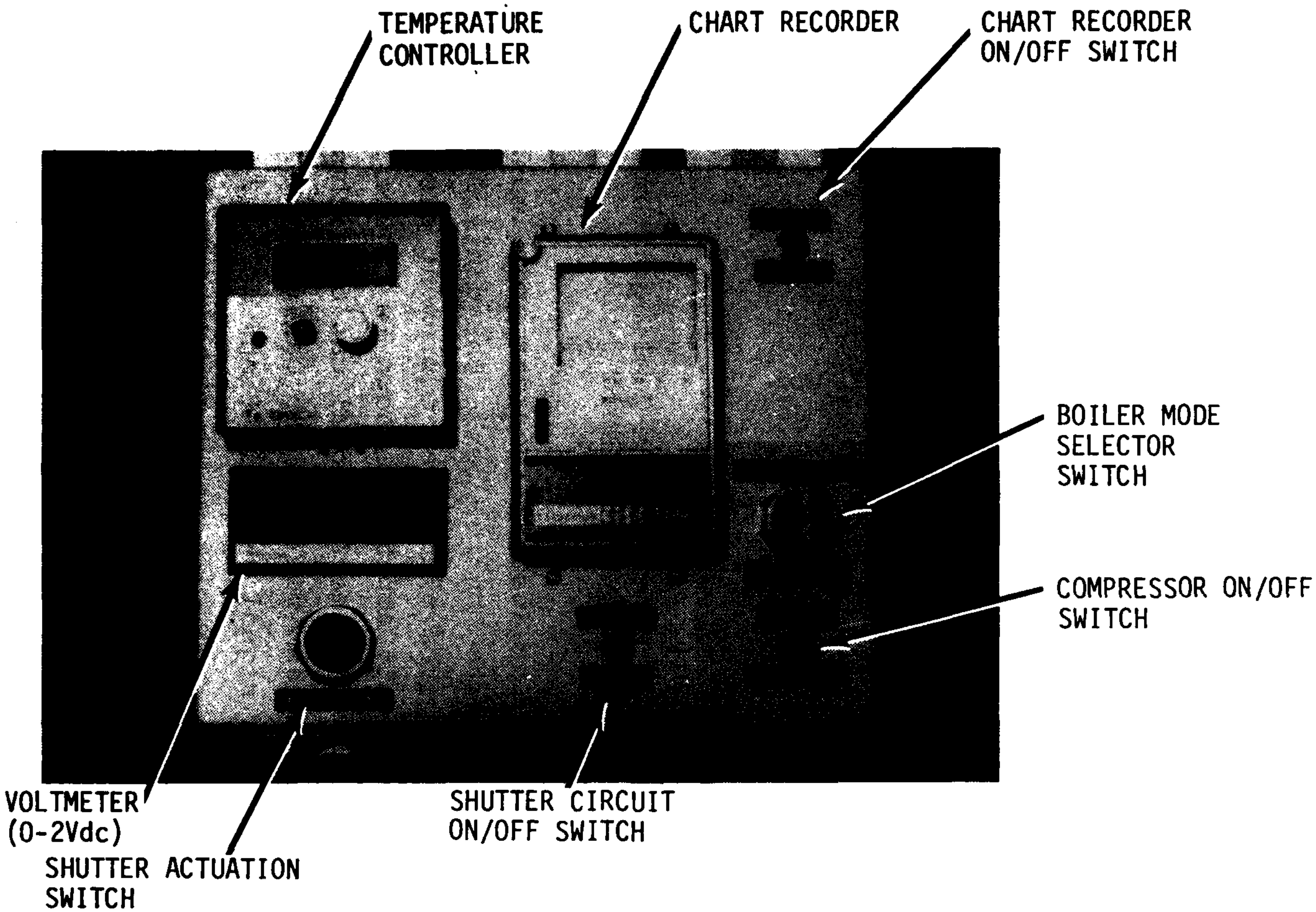

Figure 16. Instrument Control Box

Figure 17. Control Box Open Showing Omni Amp II

sample holder housing. Condensation mass is determined by weight increase.

A Fisher/Ainsworth Model MX-200 balance is used to determine before and after test weights of the fabric/fabric assembly and moisture swab. The difference in the fabric/fabric assembly weight determines the moisture absorbed by the assembly. The difference in the swab weight determines the amount of water vapor transmitted through the fabric/fabric assembly.

3. SYSTEM OPERATION

The test apparatus as shown in Figure 18 requires only 115 Vac power for operation. A power cord attached to the apparatus control box plugs into any standard 15 amp, 115 Vac outlet.

Boiler make-up water is supplied by a self-contained 5 gallon tank. Cooling water for the Haake constant temperature circulator is maintained in a cooling water reservoir.

The following subsection outlines the system start-up and operation. A detailed operations manual will be supplied in the Phase II Final Report.

3.1 System Start-Up

- Fill boiler make-up water tank.
- From make-up water tank, fill boiler until boiler water level is at maximum height in boiler sight gage.
- Fill cooling water reservoir.
- Load chart recorder paper.
- Turn amplifier "ON" (Omni Amp II).
- With all switches in the "OFF" position, connect apparatus to 115 Vac line voltage.
- Turn air compressor "ON" and adjust system pressure to 30 psi.

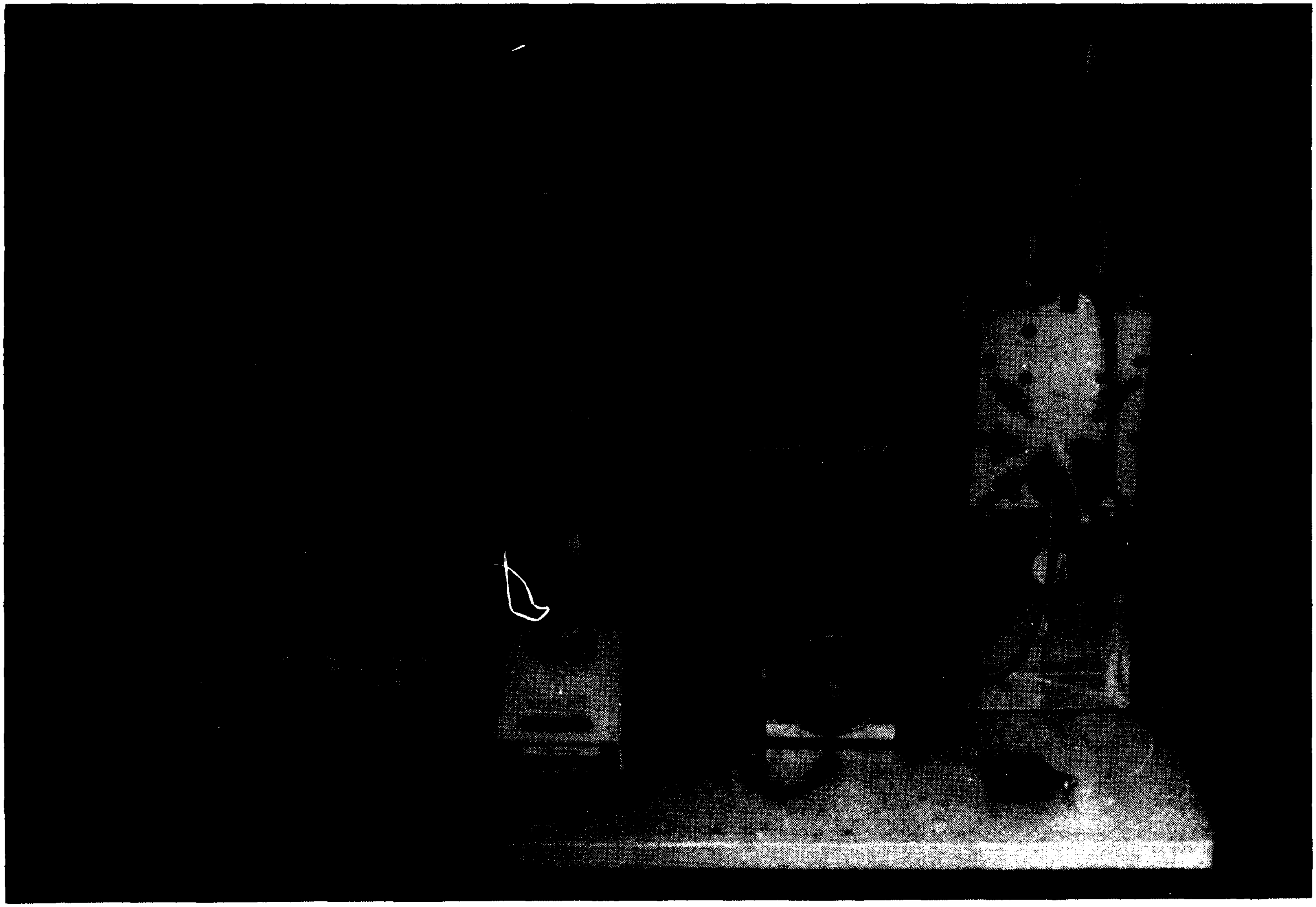

Figure 18. Steam Burn Apparatus
(Boiler Guard Removed for Clarity)

- Turn shutter control circuit "ON" and check shutter for proper cycle time.

- Turn Haake circulator "ON" and set cooling water temperature to the desired level (33°C normally).

- Check that heat flux transducer output is zeroed on Simpson dc voltmeter.

- Momentarily turn on chart recorder to check that it is zeroed and operating properly.

- Check the display of the Omega temperature controller for a temperature reading equal to that of the ambient temperature.

- Check that the Ainsworth balance is operating and zeroed.

- Set temperature controller to the steam chest temperature desired.

- Using the "Boiler Mode" switch, set to the boiler mode corresponding to the preset temperature condition:

Set Temperature	Boiler Mode
140°, 160°, 180°, 212°F	Saturated air/steam
300°, 500°F	Superheated steam

- When testing in the saturated air mode (140°, 160°, 180°F), adjust boiler sparging valve to the desired flow.

3.2 System Operation

Figure 19 shows a typical sample data sheet on which all necessary data are recorded. All necessary data except post-test sample and swab weights are recorded prior to sample response to the test conditions. The following sequence describes the test operations:

- Place sample in holder and load assembly into sample housing
- Swing sample housing into place against steam chest and clamp in place
- Using the contact pressure cylinder, manually position transducer piston against sample holder or spacer (if used)
- Pressurize contact pressure cylinder using hand pump
- Turn chart recorder "ON"
- Open the shutter by depressing "shutter reset" button
- When the shutter closes at the end of about 120 sec, release pressure in contact pressure cylinder, unclamp sample housing and swing it away from steam chest
- Remove the sample from its holder; weigh the sample and record its weight on the data sheet

INDICATE TEST NUMBER ON CHART PAPER AND ATTACH HERE	DATE ___/___/___ OPERATOR ______ SAMPLE NO. ______ TEST NO. ______ FABRIC TYPE ______ FABRIC ORIENTATION ______ FABRIC THICKNESS ______ in. CHEST TEMPERATURE ______ °F COOLING WATER TEMPERATURE ______ °F SAMPLE SPACING ______ in. EXPOSURE TIME ______ sec PRETEST SAMPLE WEIGHT ______ g POST-TEST SAMPLE WEIGHT ______ g PRETEST SWAB WEIGHT ______ g POST-TEST SWAB WEIGHT ______ g NOTES: ______

Figure 19. Data Sheet for Test Sample

- Using the preweighted swab, dry the inner surfaces of the sample housing as well as the transducer; weigh the swab and record its weight on the data sheet

- Turn off the chart recorder, remove the test strip, record the test number on it and attach it to the data sheet.

4. VALIDATION TESTING OF THE APPARATUS

After completion of construction, a series of operational tests was made to verify that the apparatus performed satisfactorily. These tests included:

- Operation at specified temperature points
- Transducer calibration
- Preliminary fabric tests.

The following discusses each of these points.

4.1 Operation at Temperature

The apparatus was operated at each of the temperature points specified in the scope of work, namely:

- 140°F saturated air
- 160°F saturated air
- 180°F saturated air
- 212°F steam at 1 atmosphere
- 300°F steam at 1 atmosphere
- 500°F steam at 1 atmosphere.

Each temperature condition was achieved automatically in the steam chest when the appropriate conditions were set on the controls. The temperature controller has a ±1°F dead band around the setpoint. However, because of superheater, thermal inertia, 300° and 500°F steam temperatures within the chest vary from -5° to +±10°F from the setpoint. This range is acceptable. Other temperature conditions are held to within much tighter limits.

Exposure of a sample of the heat flux transducer does not noticeably affect the temperature within the steam chest. The steam capacity of the system is considerably greater than the losses through the sample or transducer. This produces the necessary temperature stability when the shutter is opened.

4.2 Transducer Calibration

Our initial approach to checking heat flux transducer calibration was to insert various test materials of known thermal conductance in place of the fabric samples. However, all suitable materials of known thermal conductivity in thicknesses that will maintain one-dimensional heat flow are metals. For these materials, the conductance is much larger than the conductance of the gas film on the steam side. This resulted in unacceptably small changes of heat flux as the various test materials were changed.

As the direct approach was not feasible, the manufacturer of the heat flux transducer was contacted and questioned on its testing for accuracy. We have been assured in several conversations with International Thermal Instruments, supplier of the heat flux meter, that the meter output is accurate, producing absolute values within ±3 percent and that transducers of the type used in the steam burn apparatus are commonly used as an industry standard in the calibration of heat sources. Further attempts to verify the accuracy of the measured heat flux values were not made. Although there may be small ($\sim$3 percent) unconfirmed absolute errors in the measured heat flux values, the apparatus will provide accurate relative comparisons of fabric heat transmission.

4.3 Preliminary Fabric Tests

Tests were run with and without fabric samples to assess the capability of the apparatus. Test samples of denim and aluminized fabric were used.

Figures 20, 21 and 22 show the three different responses for 122 sec exposures to 500°F steam. The highest heat flux is into the transducer without a sample. Also the heat flux is higher through denim than through aluminized fabric during the testing time. These results appear reasonable, because denim allows penetration of steam, whereas the aluminized fabric prevents steam transport to the detector.

For both the bare transducer and the denim tests, a large initial transient exists. This is believed to be due to non-steady-state heat flow in the transducer or transducer/fabric combination. It takes some time for steady-state heat flow to be established. It is not believed that changes are due to a decrease in temperature of steam within the steam chest, as no indication of temperature change was observed from the thermocouple measurement within the steam chest.

The steady-state heat flux through the bare transducer is consistent with that expected. Condensing atmospheric steam has a temperature of 212°F. Since steam is condensing on the front of the transducer, this temperature is assumed. The heat sink on the rear side of the detector was held at 32°C (89.6°F). This provided a 122.4°F temperature difference across the 0.055 in. transducer. For the 2540 Btu/hr-ft^2 heat flux, a thermal conductivity of 0.09 Btu/hr-ft-°F is implied. This is consistent with a typical value of 0.08 Btu/hr-ft-°F reported for the polymide-glass material of the transducer. Variations in materials and properties of the heat flux transducer lead to variations in thermal conductivity which are consistent with our observation.

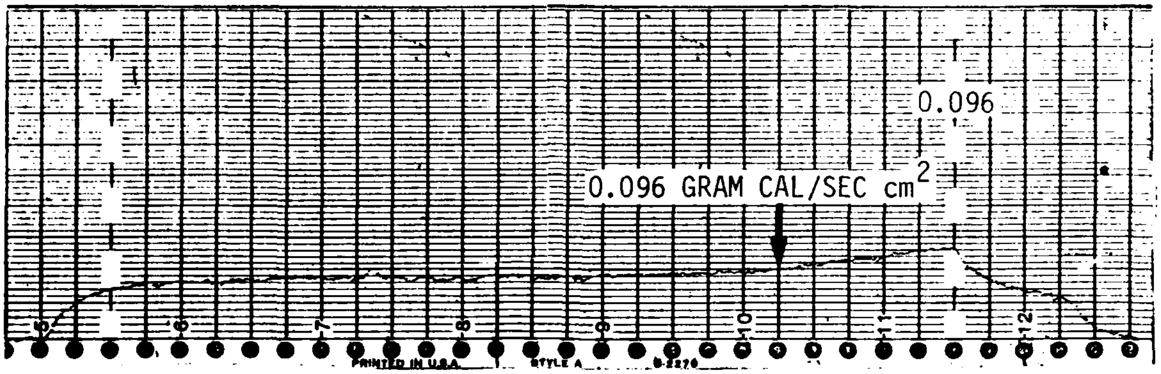

Figure 20.   Heat Flux through Aluminized Fabric, Aluminum Side Exposed to the Steam

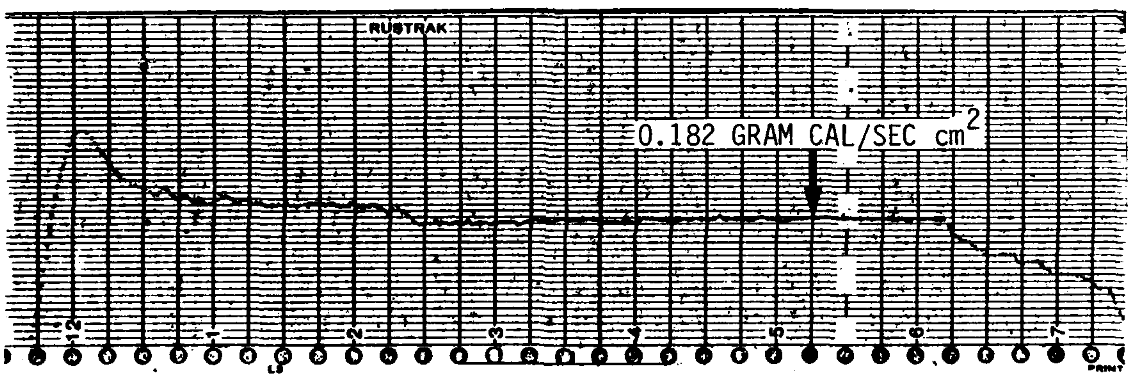

Figure 21.   Heat Flux through Denim

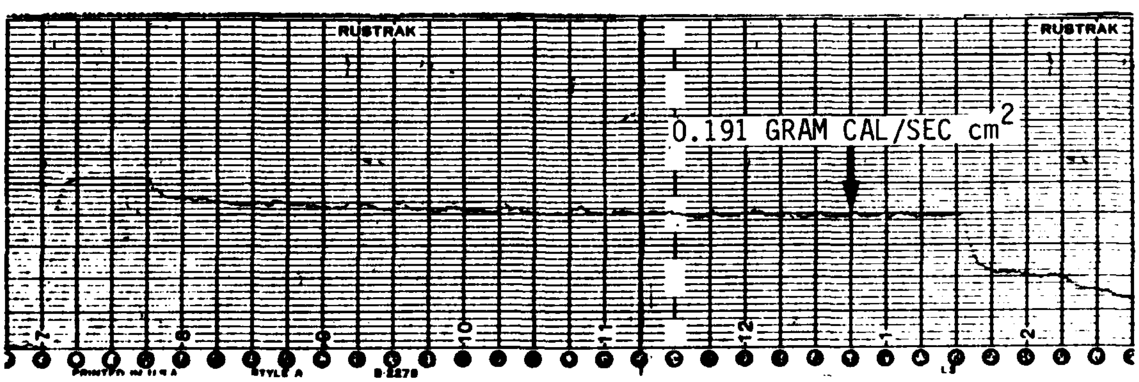

Figure 22.   Heat Flux into Transducer without Sample

5. CONCLUSION

The test apparatus operates as expected. Preliminary testing results are consistent with general expectations. No special skills for operating the device are required. Persons experienced in operating general laboratory equipment may be expected to operate this apparatus for determining heat flux through various fabrics/fabric assemblies.