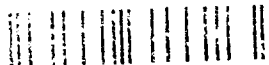


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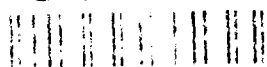
THERMAL ENERGY TEST APPARATUS



NAVY CLOTHING & TEXTILE
RESEARCH FACILITY
NATICK, MASSACHUSETTS

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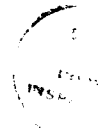
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13. ABSTRACT (Maximum 200 words) The Navy Clothing and Textile Research Facility (NCTRF) designed and fabricated a thermal energy test apparatus to permit evaluation of the heat protection provided by crash crew firefighter's proximity clothing materials against radiant and convective heat loads, similar to those found outside the flame zone of aircraft fuel fires. The apparatus employs electrically operated quartz lamp radiant heaters and a hot air convective heater assembly to produce the heat load conditions the materials are to be subjected to, and is equipped with heat flux sensors of different sensitivities to measure the incident heat flux on the sample material as well as the heat flux transmitted by the sample. Tests of the apparatus have shown that it can produce radiant heat flux levels equivalent to those estimated to be possible in close proximity to large aircraft fuel fires, and can produce convective heat fluxes equivalent to those measured in close proximity to aircraft fuel fires at upwind and sidewind locations. Work was performed in 1974.				
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TABLE OF CONTENTS

	<u>Page</u>
List of Illustrations	iv
List of Tables	v
Introduction.	1
Design Rationale	1
Description of Thermal Energy Test Apparatus	5
Operation of Apparatus.	14
Performance Characteristics of Apparatus	15
Evaluation of Crash Crew Firefighter's Clothing Materials.	20
Conclusions	27
References	A-1



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LIST OF ILLUSTRATIONS

Figure		Page
1	Integrated Normal Radiation Intensity Over Wavelength Spectrum for Various Radiant Sources	4
2	Overall View of Thermal Energy Test Apparatus and Accessory Units	6
3	Chassis Mounted Thermal Energy Test Apparatus	7
4	Window Opening in S-S-S Assembly	9
5	Heat Flux Sensor Assembly	10
6	Voltage Control Unit	13
7	Radiant Heater Irradiance Versus Variac Output Voltage at a Distance of 3 in. from the Heaters	18
8	Radiant Heater Irradiance at 3 in from the Heater Versus Heater Color Temperature	19
9	Normalized Irradiance at Different Target Distances for the Radiant Heater Assemblies for a Fixed Variac Output Voltage of 100 V	30
10	Convective Heater Output Temperature and Heat Flux 2 in. away from Heater as a Function of Variac Output Voltage	32
11	Normalized Absorbed Heat Flux at Different Target Distances from the Convective Heater Assembly Operating at a Fixed Voltage of 120 V and an Output Temperature of 860°F	33

LIST OF TABLES

Table		Page
I	Radiant Heat Tests of Crash Crew Firefighters' Clothing Materials	22-23
II	Convective Heat Tests of Crash Crew Firefighters' Clothing Materials	24-25

INTRODUCTION

The Navy Clothing and Textile Research Facility (NCTRF) designed and fabricated a thermal energy test apparatus for the purpose of evaluating the thermal transmission characteristics of materials subjected to radiant and convective heat loads from fuel fires. The materials evaluated were those used in firefighters crash crew proximity clothing.

An infrared quartz lamp radiant heat test apparatus had been previously developed by NCTRF (1) for use in specification testing of the heat resistance characteristics of metallized fabrics for crash crew firefighters clothing, but because it was designed as a quality control, pass-fail type device, it did not have the versatility of the apparatus described herein. It employed a visual subjective method to determine the heat resistance of the fabrics evaluated, used a fixed distance between sample and radiant heat source at a specific operating voltage to control the incident radiant flux level, and inferred repeatability of incident radiant flux levels from optical pyrometer color temperature measurements.

The thermal energy test apparatus is intended to provide an objective evaluation of the heat transmission through the materials to determine their protective characteristics and to assess their thermal resistance properties and thus expands upon the qualities of the previous device. The thermal energy test apparatus utilizes heat flux transducers to directly measure the heat flux incident on, and transmitted through, the sample materials. In addition, the apparatus has: moveable heaters so that the distance of the heat source from the sample can be changed to vary the level of energy incident on the sample for a specific operating voltage; a voltage control unit which permits changing the incident energy level by controlling the electrical energy input to the heat source; and both radiant and convective heat sources which can be operated individually or in combination to create one or both types of heat loads on the sample material.

This report discusses the reasons why the particular heating devices selected for use in the apparatus were chosen, describes in detail the features of the apparatus, provides data on the performance characteristics of the apparatus, and shows the ability of the apparatus to discern the strengths and weaknesses of materials used in firefighters crash crew proximity clothing.

DESIGN RATIONALE

In selecting a particular heater type for this application, consideration must be given to the real environment to which the materials to be evaluated will be subjected. For the materials of interest, which are those used in firefighters crash crew proximity clothing, protection against heat loads caused by fires from burning aircraft fuels outside the flame zone is of utmost importance.

A study by Graves (2) assessed the various thermal characteristics of a fuel fire environment to which firefighters may be exposed. The following information has been taken from this study.

a. Upwind from the fires the heat load experienced by firefighters is primarily due to radiant heat. The maximum radiative heat flux for large JP-4 fuel fires was estimated to be $1.9 \text{ gcal/cm}^2/\text{sec}$ at the fire edge, decreasing to 1.5 and $1.2 \text{ gcal/cm}^2/\text{sec}$ at distances of 10 and 20 feet from the fire edge, respectively. The maximum measured levels, however, at 10 and 20 feet from the largest test fire (18 feet, 8 inches in diameter) were only 0.38 and $0.23 \text{ gcal/cm}^2/\text{sec}$, respectively.

b. From the experimental results of spectral radiometric measurements, 1600°K was the minimum flame temperature that could account for the radiative intensity values measured in certain wavelength bands.

c. The spectral energy distribution of the thermal radiation emitted in the aircraft fuel test fires was not the same as would have been obtained from a blackbody¹ at the 1600°K radiant temperature expressed by Graves. The spectral energy distribution was approximately 84% at wavelengths from 0 to 4 microns, whereas a blackbody source having a temperature of 1600°K radiates about 77% of its energy below 4 microns.

d. Convective heating effects may be ignored for materials to be used outside the flame zone, because high convective heat loads do not extend much beyond the flame zone except toward positions directly downwind. For a 12-foot-diameter test fire and a 14-to-18 MPH wind, maximum heat flux levels of $2.8 \text{ gcal/cm}^2/\text{sec}$ were measured directly downwind 10 feet from the fire edge but the levels at this distance were only 0.4 and $0.23 \text{ gcal/cm}^2/\text{sec}$ at the sidewind and upwind locations at this distance. Downwind at 20 feet from the fire edge the maximum heat flux level measured was $0.9 \text{ gcal/cm}^2/\text{sec}$, a three fold drop from the level measured at 10 feet.

From Graves' information we can discern that heat loads from fires outside the flame zone are primarily due to radiant energy except for downwind locations and that the bulk of the radiant energy is emitted at wavelengths up to 4 microns (86%). It should also be noted that the flux levels stated previously are maximum values, and that heat levels associated with a fire have a temporal nature and can be reduced substantially and quickly by good fire suppression techniques. The duration of these maximum flux levels would be brief; exposure to these levels would probably be less than 60 seconds.

¹A blackbody absorbs all radiation incident upon it and reflects or transmits none, or emits at any specified temperature the maximum amount of thermal radiation at all wavelengths.

Figure 1 shows the integrated, normalized, radiant emission as a function of wavelength for three blackbody source temperatures and that estimated by Graves for large fuel fires. It can be seen from the curves that the spectral emission for a large fuel fire falls within the spectral band of a 1600°K and 2000°K blackbody radiant source up to 4 microns, where 86 percent of the radiant energy of a fuel fire is emitted. A radiant heat source with a similar temperature range would function as a suitable simulator for the wavelength spectrum associated with a large fuel fire.

A thermal energy apparatus that approximates the heat effects of a fire environment outside the flame zone must be designed to include a radiant heater, which can create the heat flux levels stated previously, and whose spectral energy distribution is similar to that determined by Graves for aircraft fuel fires. Moreover, this radiant heater must be able to maintain these levels for the time periods likely for these exposures. Besides the radiant heat source, the apparatus should also be able to produce convective heat flux loads on the material specimens. Based upon Graves' information, however, this capability is of secondary importance.

In developing the thermal energy test apparatus, principal interest was given to equipping it with a radiant source that could produce the heat flux levels measured and estimated by Graves, and provided repeatability and an easy means of control. After various types of electric and gas-operated sources, (quartz lamp, silicon carbide rod, refractory gas fired burners, etc.) were considered, a quartz lamp radiant heater was selected.

A quartz lamp radiant source has many desirable features. It radiates as a greybody² (same spectral energy distribution as a blackbody) because the quartz enclosure: has essentially a flat transmission curve out to 3.5 microns (3); produces this type of radiation over a range of operating temperatures; has a high-intensity uniform radiation field (4); is easily controllable; and provides repeatable performance. Other types of electrically operated radiant sources were not selected because they did not have all the combined advantages of a quartz lamp device. They either had very low operating temperatures, less radiation efficiency, or were surface radiators which produce a larger proportion of their energy as convective energy rather than radiant energy when compared with a source enclosed in a transparent housing (quartz lamp) operating at the same temperature (3). Gas-fired radiant burners were eliminated because of: The amount of support equipment required for safety purposes and proper operation; some questions as to their repeatability; possible incident energy control problems; and the constant presence of an appreciable amount of convective heat for any particular heat flux level created.

² A greybody maintains a constant ratio of monochromatic emissive power to the monochromatic emissive power of a blackbody at the same temperature and wavelength over the entire wavelength spectrum.

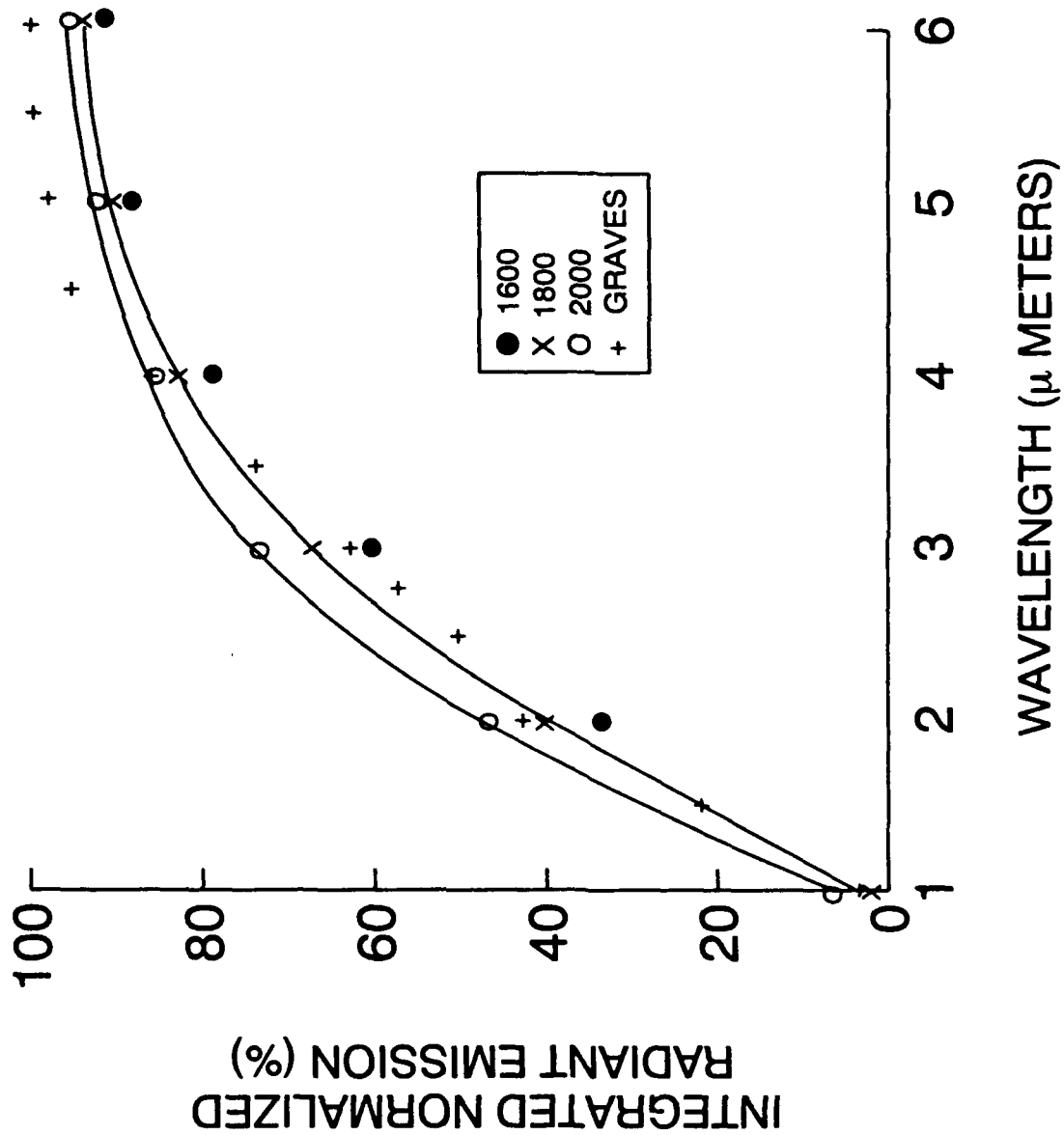


Fig. 1 Integrated normalized radiant heat emission (%)
vs. wave length (μ meters)

Because of the selection of an electric-type radiant heat source, a convective heater using the same type of energy source was considered desirable. Consequently an electrically operated heater-blower unit was selected as the convective heater. We realized that the maximum air temperature achievable with this type of unit would be around 1000°F, which is considerably below the flame temperatures measured by Graves for fuel fires (2020°F for JP-5). Since proximity fire-fighters' clothing is worn outside the flame zone, however, the air temperatures outside the flame zone are well below 1000°F except for downwind locations near the edge of the fire.

In a study conducted by Veghte (5), an average maximum air temperature of 480°F was measured at the clothing surface for firefighters standing within 6 to 10 feet of the flame edge. The highest temperature measured was approximately 750°F.

DESCRIPTION OF THERMAL ENERGY TEST APPARATUS

The thermal energy test apparatus consists of a material sample holder, manual shutter, and heat shield (S-S-S) assembly; heat flux sensor assembly; two radiant heater assemblies; a convective heater assembly; and a switch control and temperature monitoring (S-T) assembly all mounted and contained on a common chassis. Three accessory components are used with the apparatus: a voltage control unit (VCU), electric timer, and a two-channel millivolt recorder. Figure 2 shows the apparatus with the three accessory components, and Figure 3, the apparatus itself.

Figure 3 depicts the relationship of the various apparatus component assemblies. At the left in Figure 3 is the S-S-S assembly. Directed at the S-S-S assembly are the two radiant heater assemblies, each oriented at 45 degrees to the normal axis of the S-S-S assembly, and the convective heater assembly, which is located on the normal axis of the S-S-S assembly. The radiant and convective heater assemblies are on sliding bases for easy repositioning with respect to their distance from the material sample holder. In the right background of Figure 3 is the S-T assembly.

The apparatus utilizes: electric power, which is controlled through the VCU, for operation of the heater assemblies; an electric timer for monitoring heater preheat times and overall test duration; a millivolt recorder which provides a continuous readout of the heat-flux sensor output; and a water supply for cooling the infrared heaters, the heat shield, and the heat flux sensor. The water and electrical connections are all secured into the base of the chassis with all routing tubing and wiring located below the surface of the chassis.

Sample Holder, Manual Shutter, Heat Shield (S-S-S) Assembly

This assembly is designed so that a material sample geometry 2 inches wide by 4 inches high can be exposed to a selected heat load when the manual shutter is moved from its closed position to its open position.



Figure 2 Overall view of thermal energy test apparatus and accessory units showing chassis mounted sample holder, manual shutter, radiant and convective heaters, and switch control and temperature monitoring assemblies; electric timer; two channel MV recorder; and voltage control unit



Figure 3 Chassis mounted thermal energy test apparatus showing material sample holder, manual shutter, and heat shield assembly; two radiant heater assemblies; convective heater assembly; and switch control and temperature monitoring assembly

The sample holder located to the rear of this assembly (Fig. 2) accepts a 5.5-inch-diameter sample material up to 1.5 inches thick. The 2-inch by 4-inch sample-exposure opening is located on the heater side of the sample holder (Fig. 4). The material sample is retained in the holder by backup ring spacers and the heat flux sensor assembly (Fig. 5). The sensor housing is secured to the sample holder by pivoting two hinged screws over the two wing attachments on the sensor housing and finger tightening two knurl nuts.

The manual shutter has a 2.5-inch by 4-inch center opening and slides in a guide space between the sample holder and heat shield. It exposes the sample material when it is pushed against the side supports of the assembly and closes off the opening when pulled out. Figure 2 and 3 show the shutter in the closed position.

The heat shield, which is located to the heater side of this assembly (Fig. 3 and 4), is a water cooled, welded, stainless-steel jacket with a 2.5-inch by 4-inch center opening. The shield reduces the amount of heat which could penetrate the structure of the sample holder. This allows almost continuous testing of materials without a lengthy cool-down period between tests. The shield is connected to the water supply by quick disconnect ball lock fittings located on the base of the chassis to the rear of the S-S-S assembly.

Heat Flux Sensor Assembly

The apparatus is equipped with four sensor housings and a range of heat flux sensors for proper sensor sensitivity selection. Figure 5 shows one of the sensor assemblies. The sensors, manufactured by Medtherm Corp., are water cooled, and have full scale ranges of 0.1, 0.5, 1.5, and 2.5 gcal/cm²/sec. The response time for the transducers is 1500 milliseconds for the 0.1 and 0.5 gcal/cm²/sec units and 290 milliseconds for the 1.5 and 2.5 gcal/cm²/sec units. The sensors are connected to the millivolt recorder by an electrical connector and to the water supply with two poppet-type, quick-disconnect, ball-lock fittings which connect to mating fittings in the base of the chassis. The sensors are mounted in a transite insulator which is secured in a stainless steel housing. The steel housing has a rear opening for passage of the sensor wiring and water tubing connections and two wing attachments for securing it to the sample holder (Figs. 2 and 5).



Figure 4 Window opening in S-S-S assembly. The heat flux sensor can be seen in the center of the opening. The heat shield jacket face can also be seen.

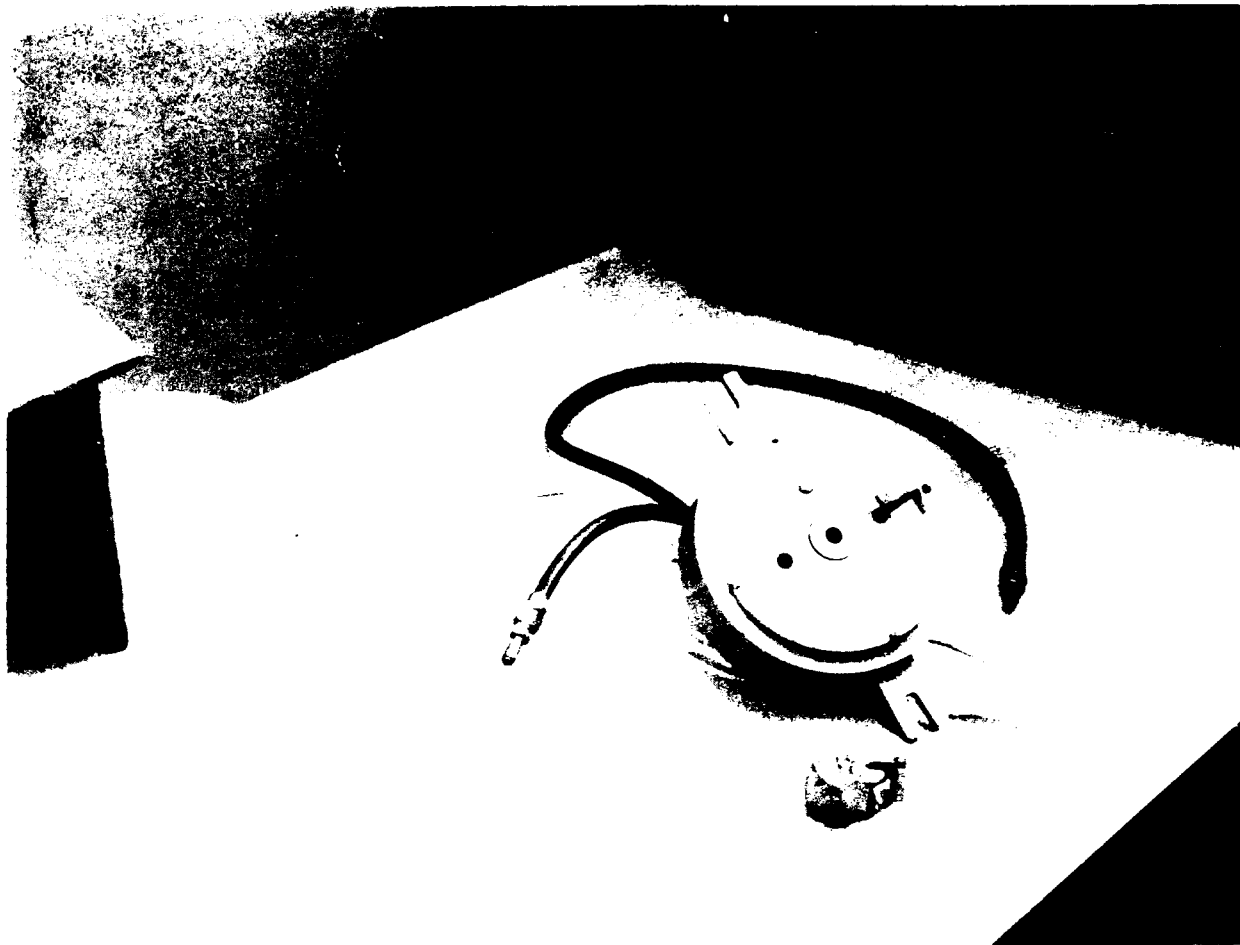


Figure 5 Heat flux sensor assembly showing water cooling tubes and electrical connector

Radiant Heater Assemblies

Each of the two radiant heater assemblies are composed of two Research Inc. Model 5305-5A parallel-ray infrared strip heaters. These assemblies can be seen in Fig. 3. Each strip heater is equipped with a GE 1200T3/C1 tungsten filament tubular clear quartz lamp and a parabolic shaped specular aluminum reflector which produces a narrow highly directional radiant heating pattern. Each quartz lamp has a 6-inch lighted length, a rated voltage of 144 volts, and a power consumption of 1.2 KW at rated voltage. Each strip heater unit has a rated radiant heat output of 140 watts per linear inch of lamp length at rated voltage or 200 gcal/sec.

The strip heater units of the radiant heater assembly are electrically connected in parallel through a terminal box mounted on the top of the assembly. The terminal box connections are routed to the power switches on the S-T assembly through a flexible electrical conduit attached to the chassis surface and the terminal box. Each strip heater of the assembly is water cooled. The strip heaters are connected to the water supply through quick-disconnect ball-lock fittings located on the base of the chassis. Each assembly also has a base arrangement which permits the assembly to move back and forth with respect to the sample location. The base is secured to the chassis by two slides mounted below the chassis surface which have four screws that project up through slot openings in the chassis surface and holes in the base of the heater assembly. The screws are attached to spring-tensioned knurl nuts for tightening of the base to the chassis surface. The radiant heater assembly can be moved in and out along the slots in the chassis surface after the tension on the knurl nuts has been reduced.

The voltage input to each radiant heater assembly is controlled separately by individual variacs located in the VCU and by separate power switches on the S-T assembly.

Convective Heater Assembly

The convective heater assembly is composed of: a Master AHD-751 heater-blower with a special resistance heater winding rated to produce air temperatures of 900°F to 1100°F at 1 inch from the heater outlet at rated voltage (120 V) depending upon the position of the air intake orifice of the blower. The heater-blower has a sliding base and a transition piece located at the outlet of the blower. The assembly can be seen in Fig. 3.

Besides the special heater winding, the heater was further modified so that the voltage to the heater winding could be controlled separately from the blower-motor voltage input, permitting the selection of a range of operating temperatures below the values mentioned previously. The voltage level to the heater is controlled by a third variac located in the VCU. This variac can be activated only after the blower motor is turned on, thus protecting the heater element from overheating and burning out. Electrical connections to the heater-blower from power switches on the S-T assembly are made through a flexible conduit attached to the base of the apparatus chassis and the heater housing. The sliding base of the convective heater assembly is attached to the chassis in the same manner as the bases of the radiant heater assemblies.

The transition piece on the heater outlet, which reduces the dispersion of the hot air emanating from the heater barrel, is equipped with a chromel-alumel thermocouple unit located at the center of the transition piece to monitor the heater outlet air temperature. Thermocouple extension wire is brought out from the thermocouple unit at the bottom of the transition piece, passed through a slot in the base of the chassis, and connected to an Omega millivolt meter in the S-T assembly. The meter is equipped with a direct-reading temperature scale.

Switch Control and Temperature Monitoring (S-T) Assembly

The S-T assembly is equipped with four power switches, which control the electrical energy input to the two radiant heater assemblies and the convective heater assembly, and an Omega millivolt meter with a direct reading temperature scale. The assembly can be seen in Fig. 3.

Two of the four power switches control the electrical input to the convective heater. They are shown at the top left and right of this assembly in Figure 3. The switch at the top left controls the electrical input to the blower motor of the convective heater and the input voltage to the control variac located in the VCU that provides power to the resistant heater element of the convective heater. After the control variac for the convective heater is energized by turning on the switch at the top left, the switch at the top right is turned on to supply the electrical output of this variac to the resistance heater element of the convective heater. This operational sequence allows control of the voltage to the resistance element and insures the availability of full power at the blower motor before the heater is energized, thus preventing overheating and burnout of the heater element.

The two power switches at the bottom left and right of the assembly (Fig. 3) each power a radiant heater assembly by connecting the outputs of two of the control variac components of the VCU to the inputs of their respective radiant heater assemblies.

The Omega millivolt meter in the center of the assembly has a full-scale range of 0 to 1500⁰F and is calibrated to give a direct temperature readout for a chromel-alumel thermocouple input.

Accessory Components

Voltage Control Unit (VCU). This unit, assembled for NCTRF by General Radio Corp., consists of three separate variac control units installed in a common cabinet which is mounted on casters. Figure 6 depicts the VCU. The output voltage of each variac is controlled by a handwheel located on the face of the cabinet. Installed alongside each variac handwheel is a voltmeter which measures the output voltage of the variac. The variac at the top of the VCU controls the voltage input to the heater element of the convective heater. It has an output voltage range of 0 to 150 V, for an input voltage of 120 V, and has a maximum current rating of 50 amps. The other two variac components are identical and are used to control the input voltage to the two radiant heater assemblies. These variacs have an output voltage range of 0 to 280 V, for an input voltage of 240 V, and have a maximum current rating of 65 amp. The electrical output of each variac component of the VCU is fed into the back end of the S-T assembly of the apparatus and connected to the proper control switch.

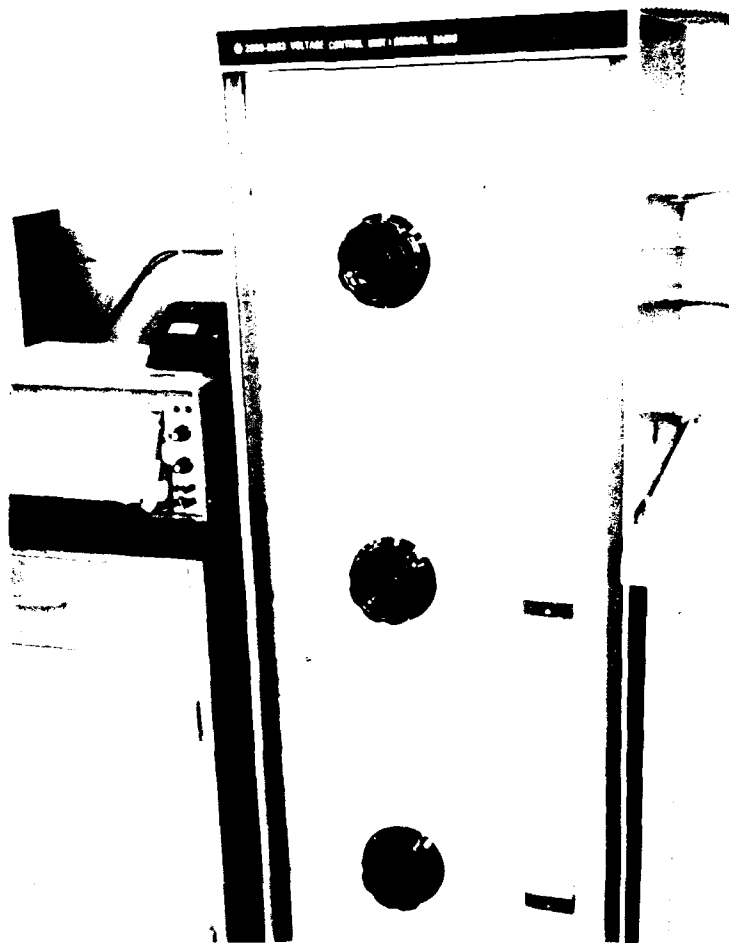


Figure 6 Voltage control unit showing hand wheel controls for the three variac components and their corresponding voltmeters

Electric Timer. A manually actuated electric timer, capable of measuring time intervals of 0.1 sec., is used with the apparatus for monitoring both heater preheat time intervals and the duration of the tests.

Millivolt Recorder. A Honeywell Electronik 19 two-channel millivolt recorder is used with the thermal energy test apparatus to measure the output of the heat flux sensors. The recorder is equipped with two separate preamplifier units. Each preamplifier unit provides zero pen control and span sensitivity selection for the channel it controls. The recorder is also equipped with a 10-speed chart drive which permits chart speed selections from 1 second per inch to 10 minutes per inch. In normal operation only one channel is used. The other channel is available as an additional input for either thermocouple elements or for outputs from signal conditioning elements, such as an integrator which could be used to totalize the output of the heat flux sensor.

OPERATION OF APPARATUS

A calibration and material evaluation sequence are conducted to use the apparatus. For calibration a heat flux transducer assembly of suitable range for the incident heat flux level of interest is installed in the sample holder and connected to the water supply and millivolt recorder. The manual shutter is closed. The proper recorder range is then selected and the recorder chart turned on at a suitable recording speed. The heater(s) to be used is then turned on and the shutter opened. The heater(s) output can then be adjusted by changing its input voltage or by changing the heater(s) distance with respect to the sensor as well as the heater(s) input voltage. The heater(s) voltage is changed by rotating the hand wheel on the variac in the VCU to which it is connected. The heater(s) is moved by sliding the heater(s) assembly along the base of the chassis in the slots provided. For each change made in heater(s) input voltage, sufficient time must be allowed for the heater(s) output to stabilize. This occurs when the heat flux sensor output becomes constant. Once the proper incident flux level has been obtained, the output voltage of the variac is noted, the shutter is closed, and the heater(s), recorder, and water supply turned off. The variac handwheel position and the heater(s) location are not disturbed. This completes the calibration. The heat flux sensor assembly is then disconnected and removed from the sample holder.

For evaluation of a sample material, the material is located in the sample holder and a heat flux sensor assembly of sufficient sensitivity is then installed behind the material sample. The distance between the sample and sensor is selectable by use of a range of available spacer rings. The sensor is then connected to the water supply and recorder, and the water

supply and heater(s) turned on. A preheating period is then allowed to insure that the heater output has stabilized (60 seconds for radiant heaters, up to 5 minutes for the convective heater). The preheat period is monitored by activating the electric timer. After the preheat period is over the recorder chart speed drive is turned on to a suitable speed value and the shutter opened. The heat flux transmission through the sample material is then continuously recorded as a function of time for either a selected period of time or until some destruction of the material is observed. The shutter is then closed; the heater(s), recorder chart speed, electric timer, and water supply are turned off; the heat flux sensor is disconnected and removed; and the sample is removed. The maximum transmitted heat flux, test time, and material sample condition are then noted as well as the incident heat flux level established during the calibration procedure. The transmitted heat flux curve from the recorder chart can also be integrated to obtain the total energy transmitted during the test period if this information is also required.

The apparatus has sufficient flexibility so that the radiant heater assemblies and the convective heater assembly can be operated simultaneously or separately. When operated together, each heater can be started in sequence during the calibration phase to determine the contribution of each to the total heat flux load being established. Whenever the convective heater is used, its output air temperature, which is indicated by the Omega Millivolt Meter in the S-T assembly, is also noted.

PERFORMANCE CHARACTERISTICS OF THE APPARATUS

A series of tests were conducted on the apparatus to determine performance characteristics.

1. Radiant Heater Assemblies.

(a) Preheat Time

(b) Irradiance levels at the heat flux sensor location for a fixed target distance when the assemblies were operated at different control variac output voltages.

(c) Color temperatures produced at different variac output voltages.

(d) Normalized irradiance values at the heat flux sensor location for different distances from the sensor target when the assemblies were operated at a fixed control variac output voltage.

2. Convective Heater assembly.

(a) Preheat time.

(b) Absorbed heat flux levels at the heat flux sensor location and the heater output air temperature when the assembly was operated at different control variac output voltages.

(c) Normalized absorbed heat flux levels at the heat flux sensor location for different distances from the sensor target when the assembly was operated at a fixed-control variac output voltage.

3. Effects of Combined Radiant and Convective Heater Operation.

All heat flux, voltage, and air-temperature measurements were made with the heat flux sensors, voltmeters, and the Omega MV meter that are part of the apparatus or its accessory components. The color temperature measurements for the radiant heater assemblies were made with a dual range optical pyrometer manufactured by Pyrometer Instrument Company. The ranges were 1000 to 1500°K and 1250 to 2150°K.

The following gives the results of these measurements:

1. Radiant Heater Assemblies.

(a) The preheat times to insure a constant irradiance pulse was 60 seconds. It was found that the irradiance level reached 96 percent of its final value within 60 seconds.

(b) The irradiance level at a 3-inch distance from the target surface produced by these assemblies ranged from 0 to 1.88 gcal/cm²/sec for a change in control variac output voltage of 0 to 110 V (Figure 7).

(c) For an irradiance range of 0.46 to 1.66 gcal/cm²/sec at a target distance of 3 inches, the color temperature of the heater assemblies spanned from 1615 to 1965°K (Figure 8). This represented a voltage change at the output of the control variac of 50 to 100 V.

(d) The normalized irradiance level for a fixed control variac output voltage was reduced 60% by changing the target distance from 3.0 to 7.5 inches (Figure 9).

2. Convective Heater Assembly.

(a) The preheat time for the convective heater to insure a constant heat flux output was found to be 5 minutes. This preheat period is particularly required at the higher output temperatures to insure that the heater output temperature has stabilized.

(b) For control variac output voltages ranging from 40 to 130 V this assembly produced heat flux levels of .054 to .76 gcal/cm²/sec at a target surface 2 inches away. For this same voltage range the heater output temperature increased from 150 to 960°F (Figure 10).

(c) For a fixed control variac output voltage, the normalized heat flux output varied by approximately 70% when the distance from the sensor target to the heater was changed from 2 to 9 inches. The flux range produced for a 120 V control variac output voltage and a heater output temperature of 850°F went from 0.63 down to 0.19 gcal/cm²/sec (Figure 11).

3. Combined Operation of Radiant and Convective Heater Assemblies.

A test was conducted using both the radiant and convective heater assemblies to determine how they functioned together. The convective heater was operated at a control variac output voltage of 120 V and was located 4 inches from the target. The radiant heater assemblies were operated at a control variac output voltage of 80 V and were located 3 inches from the target. This combination produced an output temperature from the convective heater of 850°F, a color temperature for the radiant heater assemblies of 1835°K, and an absorbed heat flux level at the target surface of 1.29 gcal/cm²/sec. The individual measurements of the heat flux outputs for both the convective and radiant heat assemblies were 0.38 and 1.06 gcal/cm²/sec, respectively. The sum of the individual flux values was 1.44 gcal/cm²/sec whereas the combined measured flux value was only 1.29 gcal/cm²/sec, indicating there was some interaction between the individual heater performances.

It was surmised that the air movement and the air temperature produced by the convective heater at the surface of the heat flux transducer moderated the radiant heater flux, causing the lower combined flux level. This interaction between the two types of heater assemblies shows the necessity of making a measurement of the combined heater outputs during calibration rather than estimating the total incident flux by simply adding the individual heater flux outputs obtained during individual heater calibrations.

Relationship of the Performance Characteristics of the Heater Assemblies to the Fire Environment.

1. Radiant Heater Assemblies.

Figure 7 shows that these assemblies can create irradiance levels equal to the maximum values estimated by Graves (1) for large aircraft fuel fires (from 1.9 gcal/cm²/sec at the edge of the flames to 1.2 gcal/cm²/sec at 20 feet from the flame edge.) These radiant heater assemblies produced an irradiance of 1.88 gcal/cm²/sec at a control variac output voltage of 110V and 1.2 gcal/cm²/sec at about 82 V.

Based upon the color temperature measurements, the spectral characteristics of fires as determined by Graves are approximated by the apparatus for control variac output voltage of 50 to 100 volts. Over this voltage range the color temperatures of the assemblies rose from 1615 to 1965°K. As discussed previously in the "Design Rationale" Section, the integrated, normalized, radiant emission of a large fire is recreated to a reasonable degree for radiant source color temperatures of 1600 to 2000°K. Within the color temperature range of 1615 to 1965°K and a 3-inch target distance, the measured irradiance levels ranged from 0.46 to 1.66 gcal/cm²/sec (Figure 8). The 1.66 gcal/cm²/sec level is equal to that estimated by Graves at 6 feet from the flame edge of large fires.

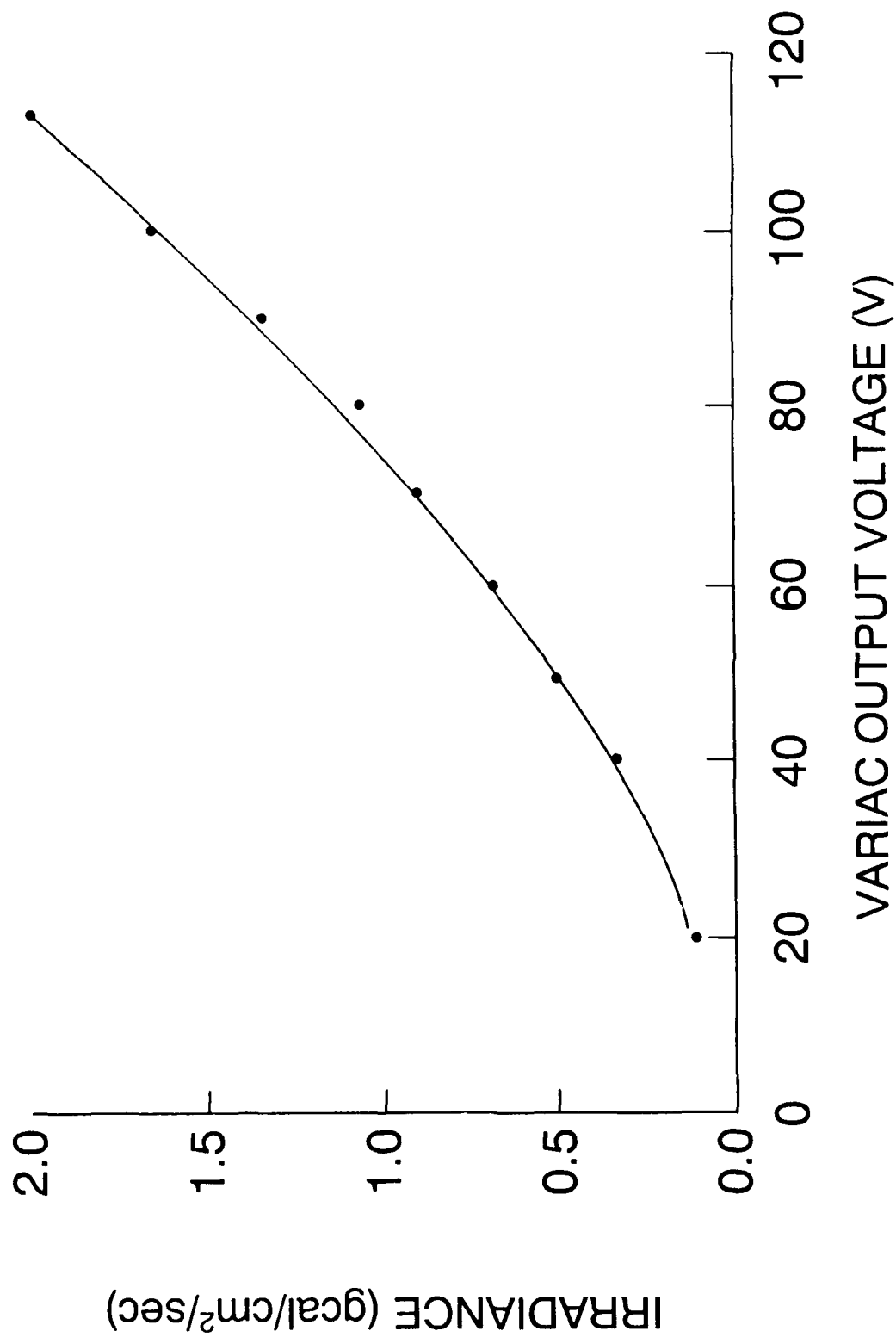


Fig. 7 Radiant heater irradiance at 3 in. from heaters
versus variac output voltage

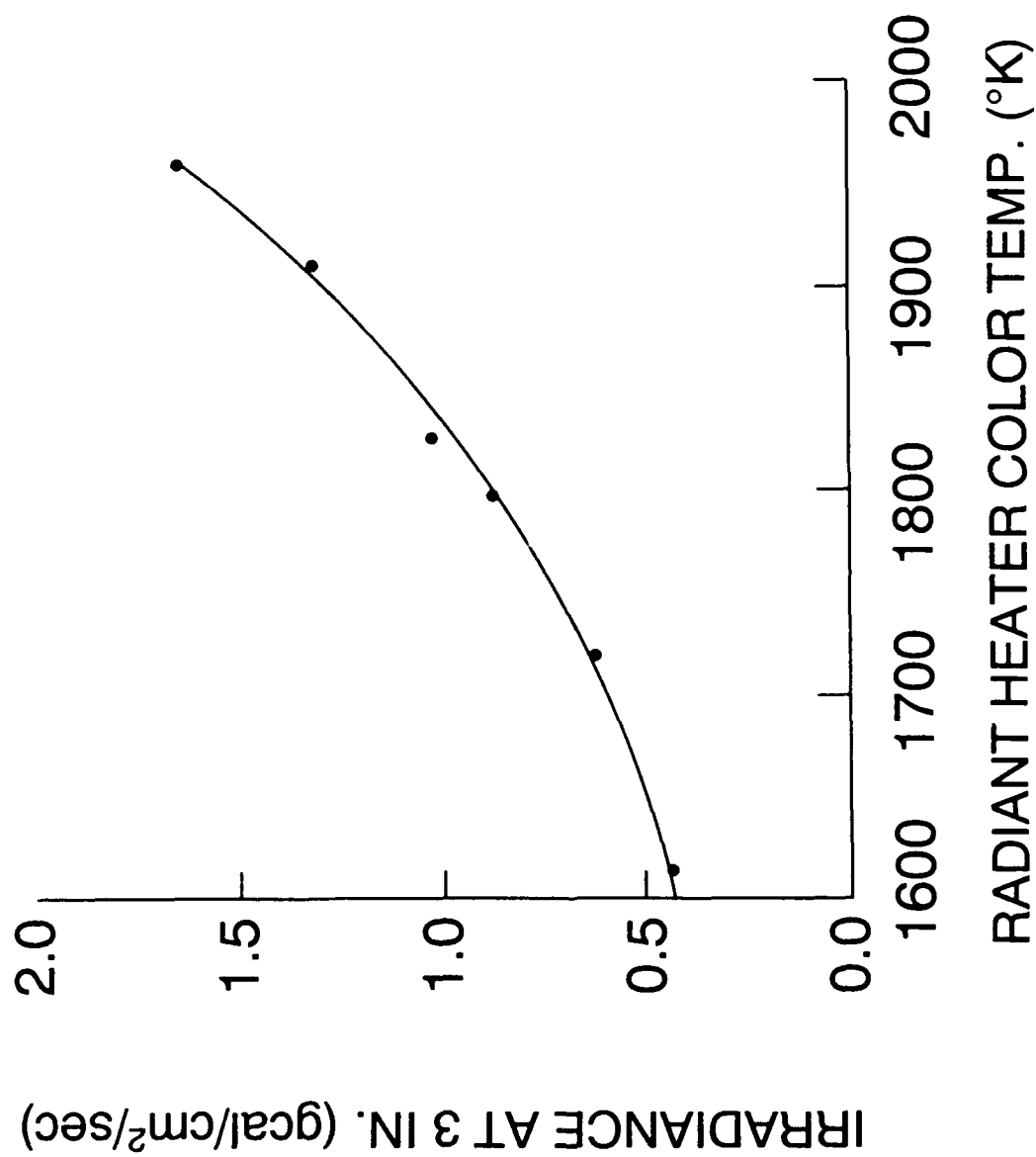


Fig. 8 Radiant heater irradiance at 3 in. from heaters
versus heater color temp.

To produce a wide range of flux values at a particular operating voltage or color temperature, the target distance can be changed. For instance, by operating at 100 V (color temperature 1965°K), the irradiance can be varied from 1.66 down to 0.62 gcal/cm²/sec. Irradiance values of 1.5 to 1.2 gcal/cm²/sec which are covered in this range are equivalent to the levels estimated by Graves at 10 and 20 feet from large fuel fires. From these comparisons it appears that the radiant assemblies of the apparatus should simulate, to a reasonable degree, the radiant intensity and spectral energy distribution created by a large fuel fire.

2. Convective Heater Assembly.

The maximum heat flux levels produced by this heater encompass the range of flux values measured by Graves at a 10-foot distance from the edge of fuel fires for either the upwind or sidewind directions. The Graves test fires ranged in size from 3 feet to 18 feet, 8 inches in diameter with wind velocities of 0 to 18 MPH. These fires produced a maximum heat flux of approximately 0.45 gcal/cm²/sec at 10 feet upwind or sidewind to the fire as compared to the 0.76 gcal/cm²/sec level possible with the convective heater. The 0.76 gcal/cm²/sec flux level is equivalent to the highest downwind value at 25 feet from the flame edge, extrapolated from the Graves data.

The maximum output air temperature possible with the heater exceeded the peak maximum value measured by Veghte 6 to 10 feet from 600-gal JP-5 fires. The heater can produce an output air temperature of 960°F, whereas the maximum peak value measured by Veghte in his fire tests was 750°F, and the average maximum temperatures were less than 500°F.

Based upon the test fire results of Graves and Veghte, the convective heater can produce air temperatures and flux levels comparable to the fire test levels in close proximity to the fire for upwind and sidewind measurements. Downwind flux levels are produced only for distances of 25 feet or more from the fire edge.

EVALUATION OF CRASH CREW FIREFIGHTER'S CLOTHING MATERIALS

Some standard and experimental crash-crew firefighters' clothing materials were evaluated with both the radiant and convective heater assemblies to demonstrate the suitability of the apparatus for determining the thermal transmission and resistance characteristics of these materials.

The materials were 1/8-inch-thick, polycarbonate, plastic sheet stock; 7-mil, gold-coated, polyester film coupled with the 1/8-inch-thick, polycarbonate sheet; cattlehide leather coupled with a wool fleece batting; and aluminum-coated asbestos³ cloth coupled with a wool fleece batting. The polycarbonate sheet is a non-standard material being considered for the facepiece support component of the firefighters' visor system. The 7-mil,

³Asbestos materials were eliminated in 1975.

gold-coated, polyester film was representative of the facepiece material used in the current firefighters' visor system and, when coupled with the polycarbonate sheet, represents an experimental visor assembly. The cattlehide leather, the wool fleece batting and the aluminum-coated asbestos-cloth materials were all equivalent to materials previously used in the crash-crew firefighters' glove (6). The coupling of the leather with the wool fleece batting and the aluminum-coated asbestos with the wool fleece batting represents the materials assemblies previously used in the firefighters' glove for the palm and back surface of the hand, respectively.

When these materials were tested, the heat flux sensor used to measure the heat transmission through the materials was placed 0.2 inch away from the back surface of the polycarbonate sheet when testing both the polycarbonate sheet alone and when it was evaluated with the gold coated polyester film. In tests of the cattlehide leather and aluminum asbestos cloth with the wool fleece battings, the sensor was in direct contact with the back surface of these combinations. This change in sensor placement was done because the face of a firefighter is not in direct contact with the visor system, whereas there is direct contact between the glove surfaces and the hand. Thus the transmitted heat flux levels measured in this manner would have some correspondence with those actually encountered by an individual wearing these assemblies.

When tests of the leather and aluminum asbestos cloth with the wool battings were conducted, the assemblies were compressed so that their thickness was approximately 1/8 inch. Tables I and II give the test results for these materials when evaluated with the radiant and convective heater assemblies, respectively. From the data the following comments can be made with respect to these materials:

A. Radiant Heat Tests (Table I)

1. The polycarbonate sheet provides very little protection (30% transmission to incident radiant heat ratio) and poor heat resistance (thermally distorts within 70 seconds) to moderate incident radiant heat flux levels ($0.48 \text{ gcal/cm}^2/\text{sec}$).

2. The gold-coated polyester-film polycarbonate-sheet combination provides excellent protection (low transmission 5%) and good heat resistance (minor distortion) to high incident radiant heat ($1.63 \text{ gcal/cm}^2/\text{sec}$) for up to 300 seconds when the gold coating acts as the front surface reflector of the polyester film with respect to the heat source. When the gold coating is on the back surface of the polyester film with respect to the heat source, moderate heat transmission (10%) and poor heat resistance occurs (distortion of polyester film) after 100 seconds exposure to an incident flux of $0.48 \text{ gcal/cm}^2/\text{sec}$. The benefit of using the gold coating at the front surface is readily seen.

3. The leather-wool fleece batting combination showed poor heat resistance to low incident radiant flux levels ($0.48 \text{ gcal/cm}^2/\text{sec}$) and high heat transmission (18%) within 70 seconds.

TABLE I Radiant Heat Tests of Crash Crew Firefighter's Clothing Materials

Sample	Incident Radiant Heat Heat Flux (gcal/cm ² /sec)	Maximum Transmitted Heat Flux (gcal/cm ² /sec)	Ratio of Maximum Transmitted To Incident Radiant Heat Flux	Test Duration (sec)	Remarks
1/8 inch polycarbonate	.48	.145	.300	69	Polycarbonate Distorts
Gold Coated Polyester Film with 1/8 inch Polycarbonate Sheet					
A. Gold Coating on Polyester Film oriented to function as rear surface reflector of Polyester film with respect to the source	.48	.046	.096	100	Polycarbonate and Polyester Distort
B. Gold Coating on Polyester Film oriented to function as front surface reflector with respect to heat source	1.12	.050	.045	300	Very slight distortion to Polycarbonate
	1.63	.071	.044	300	Polycarbonate Distorts. Some distortion of polyester film but gold coating not affected

TABLE I Radiant Heat Tests of Crash Crew Firefighter's Clothing Materials (Cont'd)

Sample	Incident Radiant Heat Heat Flux ($\text{gcal}/\text{cm}^2/\text{sec}$)	Maximum Transmitted Heat Flux ($\text{gcal}/\text{cm}^2/\text{sec}$)	Ratio of Maximum Transmitted To Incident	Test Dura- tion (sec)	Remarks
Cattlehide Leather with Wool Fleece Batting	.48	.038	.079	30	Smoking
	.48	.084	.180	70	Leather Shrunk and Scorched and Wool Fleece Front Surface Yellowed
Aluminum Coated Asbestos Cloth with Wool Fleece Batting	.48	.011	.023	300	No degradation
	1.12	.022	.020	300	No degradation
	1.34	.031	.023	180	Smoke at 100 Sec. Slight Yellowing of Back of Asbestos
	1.63	.037	.023	80	Smoke at 55 Sec. Yellowing of Back of Asbestos.

4. The aluminum-coated asbestos cloth-wool fleece batting combination showed low heat transmission (2%) and good thermal resistance (300 seconds test duration) at incident fluxes up to $1.12 \text{ gcal/cm}^2/\text{sec}$. At the higher test flux levels (1.34 and $1.63 \text{ gcal/cm}^2/\text{sec}$), smoking and discoloration of the back surface of the asbestos was noted for exposure times of 180 and 80 seconds, respectively.

B. Convective Heat Tests (Table II)

1. The polycarbonate sheet showed moderate to high heat transmission (9 to 14%) for all test temperatures and demonstrated poor heat resistance at the lowest test temperature (510°F) and was badly blistered at the highest test temperature (920°F) within 50 seconds.

2. The gold-coated polyester-film, polycarbonate-sheet combination showed moderate heat transmission (7.5 to 8.5%) and poor heat resistance (thermal degradation within 60 seconds) at test temperatures of 510 and 610°F . The polyester film melted within 20 seconds at the 920°F test temperature.

3. The leather, wool-fleece batting combination showed moderate heat transmission (9 to 11%) for all test temperatures and showed increasing levels of thermal degradation as test temperatures increased from 510 to 920°F . At 920°F this combination showed extreme thermal degradation within 40 seconds.

4. The aluminum coated asbestos cloth wool batting combination showed relatively high heat transmission (12 to 13%) at test temperatures up to 610°F and displayed maximum transmission (18%) at 920°F . This combination showed some thermal degradation within 60 seconds at test temperatures of 610°F and higher.

From this data one can surmise that the tested materials, when assembled properly (gold coating of facepiece used as front surface when combined with supporting transparent plastic sheet, for example), provide excellent protection against high radiant-heat-flux levels except for the leather, wool-fleece combination. The metallized surfaces (gold and aluminum coatings) reduced the heat transmission below 5% for all the incident-radiant-heat-flux test levels. After only 70 seconds at an incident radiant flux of $0.48 \text{ gcal/cm}^2/\text{sec}$, the leather, wool-fleece combination transmitted 18% of the incident radiant flux level. All of the metallized assemblies started to show some thermal degradation (distortion, smoking, discoloration) at incident radiant fluxes of $1.12 \text{ gcal/cm}^2/\text{sec}$ after 300 seconds. The leather, wool-fleece combination began to smoke after 30 seconds at an incident-radiant-flux level of $0.48 \text{ gcal/cm}^2/\text{sec}$.

It is also apparent from the data that none of the material combinations can withstand a high convective heat flux without undergoing some form of thermal degradation. It appears that air temperatures above 500°F with corresponding flux levels greater than $0.32 \text{ gcal/cm}^2/\text{sec}$ and exposure times of less than 60 seconds must be avoided for the materials to remain unaffected.

TABLE II Convective Heat Tests of Crashcrew Firefighter's Clothing Materials

Sample	Heater Outlet Air Temp. (°F)	Incident Convective Heat Flux (gcal/cm ² /sec)	Maximum Transmitted Heat Flux (gcal/cm ² /sec)	Ratio Maximum Transmitted To Incident Heat Flux	Test Dura- tion (sec)	Remarks
1/8 inch Polycarbonate Sheet	510	.32	.029	.091	60	Polycarbonate Distorted
	510	.32	.044	.138	120	Polycarbonate Badly Distorted
	920	.76	.091	.120	50	Polycarbonate Blistered. Cannot see through blistered area.
Gold Coated Polyester Film with 1/8 inch Polycarbonate Sheet with Gold Coating on Front surface facing heat source	510	.32	.027	.085	60	Polycarbonate Distorted
	610	.41	.031	.076	55	Hole in Polyester; Polycarbonate Blistered
	920	.76	.023	.030	20	Hole in Polyester

TABLE II Convective Heat Tests of Crashcrew Firefighter's Clothing Materials (Cont'd)

Sample	Heater Outlet Air Temp. (°F)	Incident Convective Heat Flux (gcal/cm ² /sec)	Maximum Transmitted Heat Flux (gcal/cm ² /sec)	Ratio Maximum Transmitted To Incident Heat Flux	Test Dura- tion (sec)	Remarks
Cattlehide Leather 510 with Wool Fleece Batting		.32	.031	.097	60	Slight Discoloration of Leather Surface
	510	.32	.034	.106	120	Leather Surface Scorched
	610	.41	.038	.093	60	Leather Surface Scorched
	920	.76	.082	.108	39	Leather Shrunk and both surfaces blackened Wool Batt: front surface brown
Aluminum Coated Asbestos Cloth with Wool Fleece Batting		.32	.041	.128	22	No material degradation
	510					
	610	.41	.049	.120	60	Aluminum Asbestos back Surface Black and Front Surface of Wool Batt Brown
	920	.76	.136	.179	28	Aluminum Asbestos back Surface Black and Front Surface of Wool Batt Scorched Black

These tests of crash-crew firefighters' materials with this apparatus have shown that the thermal transmission characteristics of these materials to radiant and convective heat loads can be measured in a precise manner. The results highlight the excellent radiant heat protection the metallized fabrics provide as well as their poor convective heat protection characteristics when compared to radiant heat performance. The non-metallized (leather, wool-fleece) material combination gave poor protection against both heating methods. These data show that the metallized materials will provide good protection to radiant heat intensities levels that could be encountered outside the flame zone of a large fuel fire. Care must be taken however, to insure that downwind operation near the edge of the fire be avoided because of the relatively poor convective heat protection provided by these materials.

CONCLUSIONS

1. Incident radiant fluxes at levels which can occur within close proximity to large fuel fires can be simulated by the thermal energy test apparatus. The spectral distribution of the energy based upon color temperature measurements are similar to that determined for fuel fires.
2. Incident convective heat fluxes at air temperatures found in close proximity to fuel test fires at upwind and sidewind locations can be produced by the apparatus. Downwind convective fluxes similar to those measured close to the edge of fuel fires cannot be achieved, but downwind flux levels equivalent to that extrapolated for a distance of 25 feet from the edge of fuel fires can be produced.
3. Tests of conventional crash-crew firefighters' clothing materials have shown that the apparatus can pinpoint the protection levels offered by these materials against both radiant and convective heat loads by direct, precise measurements.
4. The tests conducted demonstrated that the apparatus is a practical fire simulator for evaluating conventional and experimental crash-crew firefighters' proximity clothing materials in the laboratory against heat loads similar to those produced outside the flame zone of fuel fires.

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