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The Measurement of Fabric Flammability Parameters in Experiments Simulating Human Movement in Burn Accidents

E. A. Zawistowski, J. F. Krasny, E. Braun,
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Final Report

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THE MEASUREMENT OF FABRIC FLAMMABILITY IN EXPERIMENTS SIMULATING HUMAN MOVEMENT IN BURN ACCIDENTS

E. A. Zawistowski[1], J. F. Krasny, E. Braun, R. Peacock and N. Williams[1]

Abstract

This paper describes results of experiments simulating the phenomena occurring during burns of apparel items. Fabrics were burned near a semicylinder which was covered by 54 heat sensors. The areas which received various heat loads (corresponding to various depth of burn injury in real-life flammable garment accidents) were recorded. In most cases, the semicylinder was moved during the burn, so that the burning fabrics made contact with it, simulating movement by the victim during a garment burn. This caused rapid extinguishment in some but not all fabrics. Results are reported for 40 fabrics varying in fiber content, and fabric construction and weight.

Key words: Accident; apparel; burn injury; fabric flammability; fabrics; fire; garments; heat transfer; injury hazard; simulation.

1. INTRODUCTION

The potential of a burning garment to cause burn injury to the wearer, the "potential burn injury hazard," can be considered a complex function of:

1) ease of ignition,

2) flame-spread rate,

3) heat transferred to the wearer, and

4) ease of extinguishment.

[1]At the time this paper was being written, E. A. Zawistowski was a Research Associate for Man-Made Fiber Producers Association at the National Bureau of Standards. His current address is Avtex Fibers, Inc., Front Royal, VA., 22630. N. Williams was working as a Mechanical Engineer for the National Bureau of Standards in the summer of 1975.

Injury severity is determined by:

1) amount of heat transferred to the body, and

2) area over which this heat is distributed.

Ease of ignition and linear (not area) flame spread rate are measured in many flammability tests. Recent studies have, however, suggested a lack of correlation between size of the burn injury suffered by apparel victim fires, and the linear flame spread rate of remainders of garments recovered from accidents [1][2]. Patterns of heat transfer (area and quantitative measurements of the heat received) from burning garments have been studied in mannequin experiments [2-5]. The most sophisticated experiments along this line are still in progress, and results relating potential burn injury to garment configuration, fabric weight, construction and fiber content should become available in due course [6].

Only recently, workers in the field have shown an interest in extinguishability of fabrics. Buchbinder [7] has analyzed the human reactions and attempts at extinguishment in real-life garment fire accidents. She reports that running was the most frequent first reaction, followed by rolling on the ground, wrapping in a rug or beating the flames with the hands, and removal of clothing (the latter seemed to be the most effective reaction in terms of minimizing the burn injuries). Many victims tried more than one of the above methods to extinguish the fire. It is obvious that no single laboratory extinguishment experiment could simulate all these reactions. Below is a list of possible "extinguishment scenarios" and of laboratory research efforts to simulate them:

Running: the University of Maryland is investigating the effect of air speed on heat output and/or extinguishment of fabrics [8].

Extinguishment due to contact of the burning fabrics with surfaces on both fabric sides: this is the extinguishing mode when the victim rolls on the floor, is wrapped in a blanket, or attempts to beat out the fire. Work with a device which clamped burning fabrics on both sides was first undertaken at NBS [9], and was continued at the University of Maryland [8]. The University has also investigated the relative importance of the effects of the vicinity of a heat sink and of oxygen concentration on extinguishment [8]. The Massachusetts Institute of Technology has worked on the

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[2]Numbers in brackets refer to references listed at the end of this paper.

development of a test method based on measurement of the flame spread rate of fabrics near but not touching two surfaces [10].

Extinguishment due to contact of the burning fabrics with one surface: this simulates the contact of burning garments with the victim due to his movement. Experiments in this area are discussed in the present report.

2. THE APPAREL FIRE MODELING APPARATUS (AFMA)

The apparatus used in this work is based on a simplified geometrical arrangement which simulates the salient features of the garment-body system. It consists of a semicylinder, approximately 60 cm (24 in) high and 18 cm (7 in) in diameter, representing the simulated body, e.g., a torso or leg. The simulated body is covered almost in its entirety with heat sensors. It can be moved during a burn to change the garment-fabric distance from several inches to full contact. The apparatus is thus designed to simulate movement of the victim when he becomes aware that his clothing is on fire. Specifically, movement which results in various modes of garment-body contact can be simulated.

Obviously, the manner in which the contact between the body and burning fabric occurs in real life garment fires covers a wide spectrum. AFMA permits investigation of the heat transfer patterns from a burning fabric during the two extreme points of the spectrum: (1) from a burning fabric which at some time during the burn makes excellent contact with the substrate and (2) from a fabric which remains free-hanging during the course of the burn. Results obtained under these two conditions permit comparisons of the burn injury potential of fabrics in a way not previously attempted.

Among the measurements which can be made are heat flux to each of the 54 sensors, with the fabric free hanging at specified distances, or with the fabric brought into contact with the cylinder some time after ignition (fabrics do not generally ignite when in contact with a heat sink). Contact can be established at a predetermined (a) time after ignition, (b) fabric distance burned, or (c) heat flux observed on the semicylinder. The heat distribution patterns before, during and after contact can be studied by means of computer print-out, and should provide information about heat transfer (and thus injury potential) from burning fabrics before and during extinguishment. Other effects to be studied in the future are that of air impinging on the burning fabric, and of covering the burning fabric with, e.g., a blanket. The technical details of the apparatus are given below.

2.1. Description of AFMA

A side-view schematic representation of the semicylindrical apparatus is shown in figure 1. The fabric is mounted on a hinged frame so that it is in the same semicylindrical configuration as the surface of the semicylinder. It maintains a perpendicular alignment with respect to the floor until the instant of contact with the semicylinder. The frame on which the fabric is mounted pivots from the top of the semicylinder. When the fabric is in the free-hanging position, the semicylinder leans forward on a pivot at an approximate angle of 20 degrees from the vertical. When the semicylinder is pulled to the rear the mounted fabric maintains the vertical position and approaches the semicylinder surface. When the semicylinder attains vertical alignment, the fabric makes contact with and conforms to the semicylinder which leans about five degrees to the rear to further enhance fabric-to-surface contact.

Figure 2 illustrates details of the semicylinder construction. The semicylinder surface consists almost entirely of heat flux sensors. "Transite," an asbestos cement sheet, 2.54 cm (1 in) thick, was cut into 10 cm (3.9 in) radius "brake-shoes" which were grooved to accept three copper sensors each. Each sensor is a copper sheet 0.11 cm (43 mil) thick, 7.62 cm (3 in) by 2.54 cm (1 in), bent to a 10.16 cm (4 in) radius. Three chromel-alumel thermocouples are peened into each sensor. The thermocouple wires are threaded through holes in the transite "brake-shoes," then wired in parallel to give an average reading for the sensor surface. The thermocouple wires are brought to a terminal strip which is housed on the inner surface of the semicylinder. Eighteen of these "brake-shoes," are alternately stacked with 0.59 cm (1/16 in) transite spacers and bolted together. The resulting semicylinder is 58.4 cm (22 in) high. The semicylinder surface is blackened by painting with a flat black paint.

Sensors were calibrated in vertical banks of five using a quartz panel which delivered an even heat flux over their area. Calibration was done for three radiant heat flux levels: 0.25 J/cm^{2}s (0.06 cal/cm^{2}s), 0.37 J/cm^{2}s (0.085 cal/cm^{2}s), and 0.44 J/cm^{2}s (0.105 cal/cm^{2}s). The constant thus determined for each sensor was utilized in computer calculations.

2.2. Data Acquisition and Computation

During the experiment, the sensors are scanned every three seconds with a Digital Data Acquisition System (DAS) and data recorded on magnetic tape. Computer programs are used to calculate the heat transferred to the surface in accumulated J/cm^2 for each scan.

One computer program provides the following information[3] in the form of pictorial printouts of the surface with:

1) the cumulative heat received by each sensor after each scan,

2) the maximum heat received by each sensor during the total duration of the burn,

3) the difference between heat received at time of fabric-semicylinder contact and the maximum heat received (see 2) for each sensor, and

4) the difference in heat before and after the instant of contact for each sensor -- this is the heat rise upon contact.

Another computer program[4] was utilized to calculate the percent surface area which could, in the first approximation, be expected to suffer second degree and deeper burns. Occurrence of a second degree burn depends both on the total heat received by the skin and the rate at which it is received [11]. Thus a second degree burn can be expected if heat is delivered to the skin at a rate of 1.05 J/cm^2s over 8 seconds. This represents a total heat input of 8.4 J/cm^2. But, for the same degree of injury the total heat input to the skin can be twice as much, 16.8 J/cm^2, if the heat is delivered at a rate of 0.28 J/cm^2s over 60 seconds. The heat input values in this work were, as described earlier, measured by blackened copper sensors, 0.11 cm thick and backed by asbestos cement. There is no reason to believe that heat sensed in this manner would not be the same heat as sensed by the skin, which is also considered a black body. However, when contact between sensor and burning fabric occurs, it is conceivable that heat may be carried away at a faster rate through the copper than through skin. One could assume that extinguishment of burning fabrics upon

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[3] Data and raw-data are copied into mass storage for reference and subsequently transferred to Tape 1477 on file on the Computer Service Division of NBS for future reference.

[4] Copies of these programs are on file in the Center for Fire Research, Program for Fire Prevention-Products, at NBS.

contact with the AFMA may be somewhat more efficient than upon contact with skin. The magnitude of this difference could not be established without animal experiments designed for this purpose. Extinguishment upon contact with shaved animal skin has been observed by earlier workers, and qualitatively presented a similar phenomenon as the AFMA [3]. The portion of extinguishment which is due to exclusion of oxygen from one fabric side should be the same for skin and copper.

The above values for threshold second degree burns are only approximate because occurrence of injury also depends on the thickness of the skin which varies over the body of any individual and between individuals. For the purpose of the present comparison of the injury potential of fabrics, fire heat levels were recorded: less than 8.4 J/cm^2 (2.0 cal/cm^2), 8.4 to 16.7 J/cm^2 (2.0 to 3.9 cal/cm^2), to represent heat levels at which potential second degree burns would occur; and three levels presenting progressively deeper burns, 16.8 to 41.9, 42 to 83.9 and 84+ J/cm^2 (4.0 to 9.9, 10 to 19.9, and 20+ cal/cm^2). The cumulative summations of area at these levels were printed out by the computer for each scan. The printouts representing the maximum heat flux in any one burn are the basis of most of the discussion in this report. Future reports will analyze other aspects of the heat distribution patterns measured by the sensors during each burn.

2.3. Typical Movement Simulation Procedure

Fabrics. The fabrics used in this work varied widely in fiber content, construction and weight (see fig. 6). They are identified in the figures. Both storage of the fabrics and the experiments were conducted in rooms at approximately 24 °C (75 °F) and 40% r.h.

Specimen Size. Specimens are approximately 63.5 cm (25 in) in the warp or machine direction by 35.6 cm (14 in) in the fill or crosswise direction.

Ignition Source. Experiments are performed utilizing forced ignition. Triangular paper tabs, 3.5 cm by 15 cm by 15 cm, weighing approximately 0.08 g are cut from Whatman No. 2 filter paper and used for fabric ignitions. In general, one paper tab is required to ignite fabrics which weighed up to 204 g/m^2 (6 oz/yd^2), two tabs for 238 to 306 g/m^2 (7 to 9 oz/yd^2) fabrics, and three tabs for 340 g/m^2 (10 oz/yd^2) fabrics and over.

Paper tabs are affixed to the fabric specimen with one staple, so that the base of the triangular paper tab is 15.2 cm (6 in) from the lower edge of the fabric, and centered with its point down.

Specimen Mounting. With the AFMA semicylinder in the non-touching position, the longest specimen direction is held vertically with the intended outside fabric surface facing away from the semicylinder. The fabric is aligned so that the bottom edge of both fabric and semicylinder matched. The fabric is then clamped to the upper portion of the frame, passed between the semicylinder and the vertical members of the frame, and clamped to the side members of the frame in such a way that the fabric conforms as best as possible to the semicylinder surface. Any excess fabric is then trimmed.

The Movement Simulation. With the semicylinder in the non-touching position, the paper tab is ignited and the DAS started. The tilt is initiated at the predetermined point of time or flame travel (see section 3.1) so that fabric specimen - semicylinder contact is established. DAS scanning is continued for an additional 18 seconds after extinguishment.

The semicylinder surface is then carefully scraped clean of char and spot painted when necessary.

The Stationary Experiment. Fabric specimens are mounted and ignited in the usual manner. The semicylinder is held at approximately 10 degrees (see section 3.1.2) forward from the vertical.

General Comments. During the course of the experiment, small tenuous flames, re-ignition, etc. are allowed to continue of their own volition. However, fabric edges burning beyond the mounting frame are extinguished. Replicate tests reproduced injury potential values differing generally by about 10%.

3. RESULTS AND DISCUSSION

3.1. Consideration of Controllable Variables and Their Effect on Observations

3.1.1. Tilt Variables

There are two major variables in the movement simulation experiment: when to move, and how fast to move. A brief consideration of these variables follows.

There are several instances when the tilt can be initiated. The tilt can begin at:

1) a specific time after ignition,

2) specific travel of the flame base, or

3) a specific heat output.

Due to different tendencies of fabrics to burn downwards, as well as sidewards, initiation of tilt at an equal area of involvement was not practical. This work is currently being expanded to include other modes of investigation; among them is starting movement at a given heat transfer to any one of four sensors distributed over the semicylinder surface.

Figure 3 shows the heat transfer patterns for different weights of woven cotton fabrics where the tilt was initiated (a) immediately after ignition of the fabric (when the paper tab was consumed, roughly less than one second after ignition), and (b) when the base of the flame reached 23.2 cm (9 in) above the point of ignition. Increasing shading of the bars in this and subsequent figures indicates increasing amounts of heat received during the total duration of the burn. Thus a bar with a relatively long unshaded portion indicates no or low heat transfer to a relatively large area, and thus a low injury potential of the fabric in the accident situations simulated by the present experiments. It can be seen that the area receiving more than 8.4 J/cm^2 (potential second degree burn) [11] increased with increasing fabric weight for tilts initiated at 23.2 cm burn distance. However when tilt was initiated immediately after ignition of the fabric, area of involvement decreased with fabric weight because of the slower flame spread rate on the heavier cotton fabrics. Tilting when the flame base reached 23.2 cm was used throughout the experiments described in the body of this report.

A few experiments were conducted in which the tilting rate was varied, from 1 to 3 seconds duration of tilt. There was no major effect of this variable on the heat transfer pattern, and a tilt duration of 1.1 seconds was used in all subsequent experiments.

3.1.2. Free-Hanging Burns

Several fabrics were also tested without tilting during the burn, i.e., suspended in the frame but with air supply to both sides of the fabric. In order to choose a standard fixed position for these burns, a cursory examination of the angle of forward inclination (figure 1) of the semicylinder was conducted. Figure 4 shows the percent surface area at various heat levels which were obtained when 65 g/m^2 (1.9 oz/yd^2) and 235 g/m^2 (6.9 oz/yd^2), woven cotton fabrics were allowed to burn at fixed positions of a 10° inclination of the semicylinder and a 20° inclination. Also shown are the results for ignition of the fabric while in contact with the surface (-4° inclination). As expected, ignition did not occur when the fabric was in contact with the surface. It is also interesting that the two fabrics used were not consumed in their entirety, even without tilting. The fixed position of 10° forward was chosen for the "free-hanging," no-tilt experiments.

3.2. Comparison of Free-Hanging Burns and Burns with Contact Due to Tilting

Figure 5 compares heat distribution patterns for free-hanging burns (no tilting) and burns in which as intimate as possible contact between the semicylinder and the burning fabric was established due to tilting. Heat distribution patterns in other situations, such as partial contact, could be assumed to lie between these two extremes.

Tilting greatly reduced the area receiving 8.4 J/cm^2 or more in the case of two woven cotton fabrics and one woven 65/35 polyester/rayon fabric because the flame extinguished soon after contact. However, the effect of tilting was much less in the case of a cotton terry towel fabric. The loops protruding from the fabric apparently prevented intimate contact with the semicylinder, and the fabric continued burning for a considerable time after tilting. Similarly, tilting had relatively little effect on the heat transfer pattern from the acetate satin fabric which tended to curl away from the semicylinder and continued to burn. The acrylic fabric also tended to curl and shrink away from the semicylinder, formed a thick char and continued to burn.

3.3. Total Heat Transfer in Tilting Experiments

The heat transfer patterns of 40 fabrics, some commercial, some experimental were investigated. The tilting mechanism was started when the flame base reached 23.2 cm (9 in) and the fabrics were permitted to burn until they extinguished by themselves. The eight fabrics listed below transferred only insignificant amounts of heat to any of the sensors on the semicylinder surface:

Fabrics with Low Injury Potential

Fiber Content	Weight		Description
	g/m^2	oz/sq yd	
Polyester	72	2.2	woven
	210	6.1	pile
	235	6.9	napped sleep-wear knit
	245	7.2	knit
Nylon	95	2.8	woven
Wool	220	6.5	twill
	310	9.1	knit
Modacrylic	310	9.1	knit

The heat transfer patterns of the other fabrics are shown in figure 6. The bars are arranged in order of decreasing length of the unshaded portion, i.e., in decreasing order of area of the semicylinder receiving less than 8.4 J/cm^2.

The major effect on the size of this area was fiber content of the fabrics. Most fabrics which contained cellulose in some form (cotton or rayon, alone or in blends with polyester) are in the upper portion of the graph, i.e., transferred potentially injurious heat (above 8.4 J/cm^2) to less than half of the available area. Five fabrics containing cellulose transferred more than 8.4 J/cm^2 to a larger area: a polyester/rayon woven fabric, a heavy cotton denim, a heavy rayon knit, and two terry towel fabrics. The other fabrics, with more than half the area receiving more than 8.4 J/cm^2, contained acetate, or acrylic, with the latter generally on the upper end of the scale. The reasons for the relatively high heat transfer from these fabrics became obvious from observation of the burns. The acetate tended to curl away from the semicylinder surface, and continued to burn at the curled edges. The acrylics also puckered and curled away at the edges; in addition they formed rather thick chars which continued to burn even when in contact with the semicylinder.

High heat transfers are indicated by dense shading of the bars. It can be seen that all acrylic fabrics produced more than 168 J/cm^2 over some areas of the semicylinder. Other fabrics which produced such high heat transfer were the cotton denim, the terry toweling, and an acetate satin. The same fabrics also generally produced relatively large areas receiving between 84 and 168 J/cm^2. They could thus be considered to present the highest burn injury potential in the garment burn scenarios represented by the present experiments which, however, do not consider other parameters contributing to garment fire accidents such as ease of ignition.

Among 100% cellulosic fabrics, higher weight generally produced higher heat transfer over larger areas. Exceptions were the two cotton flannels and the two terry towels, i.e., fabrics with a distinct surface texture. They exhibited relatively high heat transfer for their weight. Such fabrics tend to continue to burn even after contact with the semicylinder, the flannel primarily in the nap, the terry towel in both pile and body of the fabric. Apparently the extinguishment effect of heat sink and oxygen exclusion on one side of the fabric is obviated when the fabric-semicylinder contact is poor.

There was no consistent effect of weight in the case of the polyester/cellulosic blend fabrics. One possible explanation is that the polyester melts ahead of the flames, the fabrics become soft, and make good contact with the surface, regardless of weight and thickness, while pure cellulose fabrics form stiff chars and conform less with the semicylinder surface as they increase in weight and thickness.

Two heavy wool fabrics self-extinguished and transferred but little heat to the semicylinder. A light wool fabric transferred heat exceeding 8.4 J/cm^2 to 25% of the semicylinder area. The acetate and acrylic fabrics showed no consistent effects of weight.

The woven acetate fabrics transferred considerably more heat than the knitted ones. The latter were of more open construction, and parts of the fabrics ablated during burning, removing them from the areas scanned by the heat sensors. The only other effect of fabric structure was the above discussed relatively high heat transfer from the cotton flannels and terry towel fabrics which did not extinguish upon contact with the semicylinder as readily as other cotton fabrics.

3.3.1. Heat Transfer Patterns 90 Seconds After Ignition

The previous section discussed the total heat transferred before and after contact with the semicylinder, from ignition to extinction. Only four fabrics had not completed transferring heat in 90 seconds. They are indicated in figure 6 by a second bar below the one indicating total heat transfer, and marked 90 seconds. It can be seen that at 90 seconds after ignition, the two cotton terry cloths had transferred heat to a much smaller area than at the point of extinguishment. The denim, and especially the 175 g/m^2 acetate satin, were much closer to completion of heat transfer at that point. Future investigations will emphasize heat transfer patterns at various times from ignition.

3.4. Effect of Undergarments

The effect of an undergarment on heat transfer patterns was investigated by covering the semicylinder tightly with a cotton underwear jersey, 135 g/m^2 (4.0 oz/sq yd). Three woven outerwear fabrics were ignited as usual, and tilted when the flame base reached 23 cm. Figure 7 compares the results with and without the underwear layer on the semicylinder. In both the cases of the light cotton and polyester/cotton fabrics, the area receiving less than 8.4 J/cm^2 was reduced by the presence of the underwear, presumably because the burning fabric-semicylinder contact was less efficient and the outer fabric may have continued burning for a longer period than when no underwear was present. In the case of the acrylic fabric, the opposite effect of the under layer on the heat transfer pattern was observed. Since this fabric tends to continue burning even while in contact with the bare semicylinder, the underwear fabric apparently had little effect on the burning, but may have provided modest insulation from the heat.

4. CONCLUSIONS

This work has been the first attempt to measure detailed heat transfer patterns from burning fabrics to a simulated body, both in a situation where the body moves and when it is stationary. It has indicated that where burning garments contact the body due to movement, relatively deep burns may occur over a limited area. But the fabrics often extinguish upon contact, and the total area of the body burned may thus be reduced as compared to a case when garments burn at a distance from the body. Whether and how fast such extinguishment occurs, depends on fabric construction and fiber content.

While the present results were obtained with a simulated body differing in thermal characteristics from skin, similar phenomena have been observed in animal experiments [3].

The lowest heat transfer in both modes, free-hanging and upon contact, was found for 100 percent modacrylics, nylon, polyester, and some wool fabrics. Light, open-textured (knit) acetates had a somewhat higher heat transfer, followed roughly in order by cellulosics and cellulosic-containing fabrics, woven acetates, cotton terry and acrylics.

Cotton and polyester/cotton fabrics were found to show a large reduction in injury potential when brought into contact with a simulated body. Heavy-weight acetates and acrylics showed a smaller reduction in injury potential upon contact. Cotton terry showed the least reduction in injury potential.

The degree of reduction in injury potential appears to be related to the ability of the fabric to make contact with the body. This degree of contact in turn is affected by construction and fiber content.

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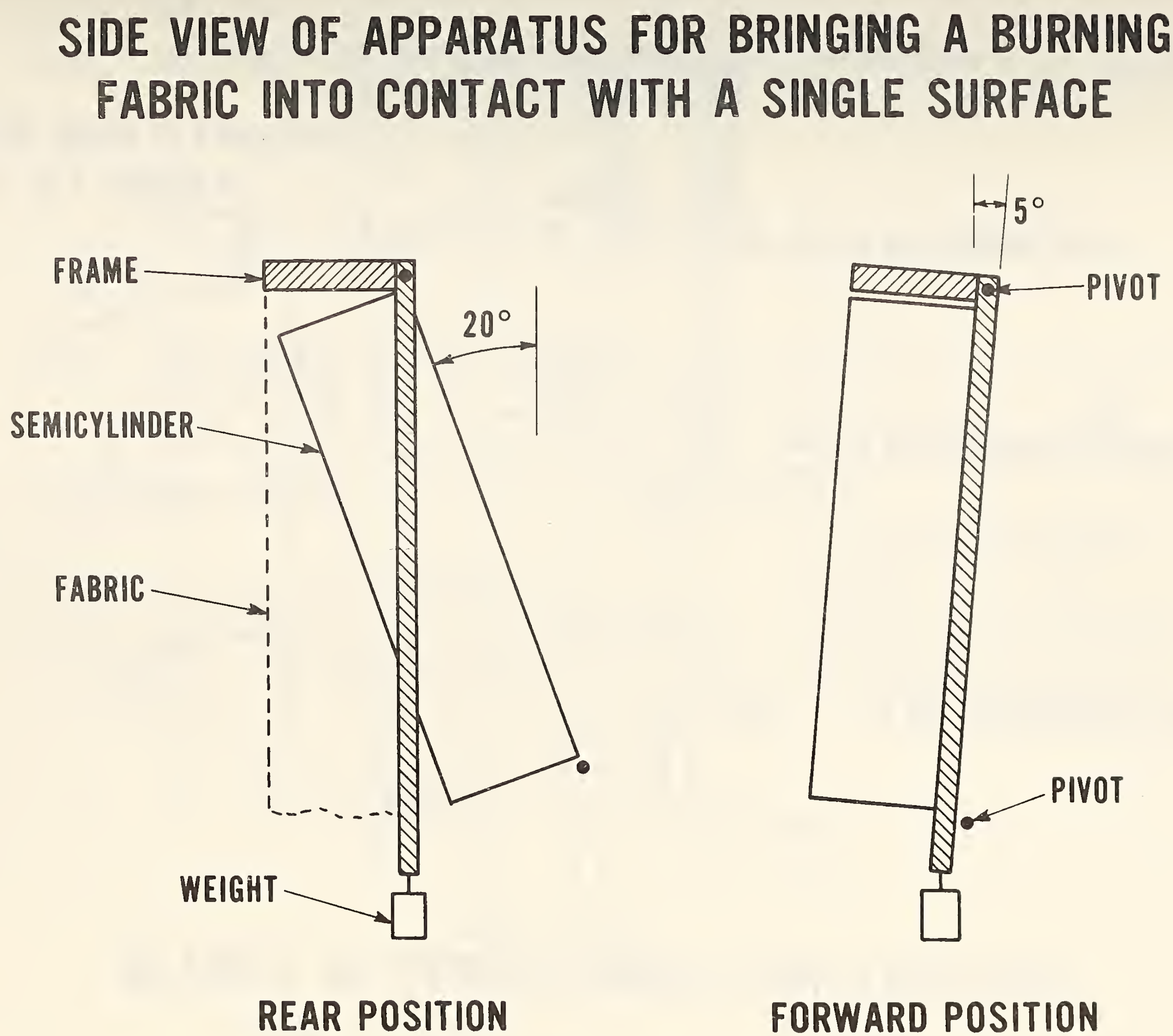

Figure 1. Side View of AFMA

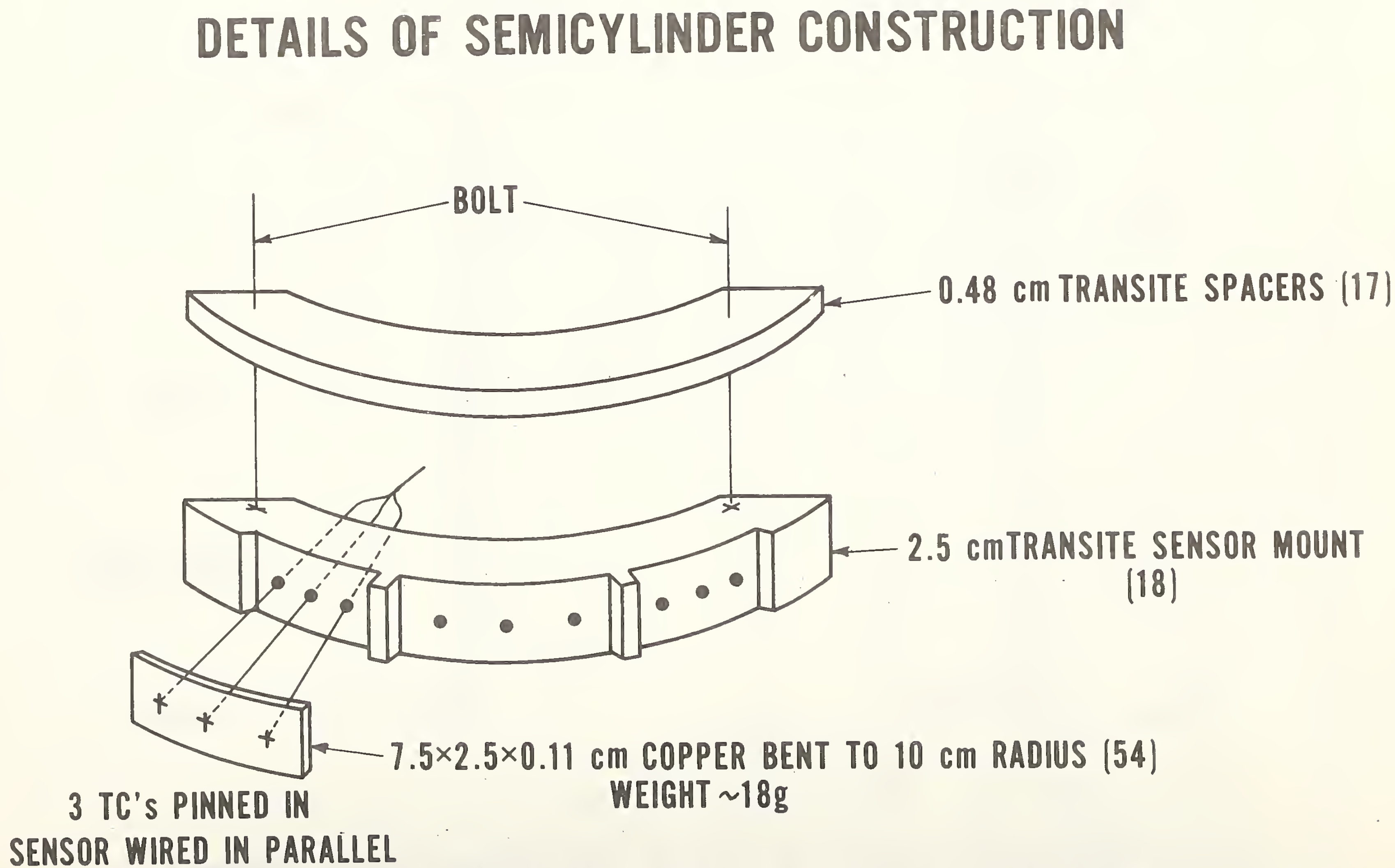

Figure 2. Details of Semicylinder Construction

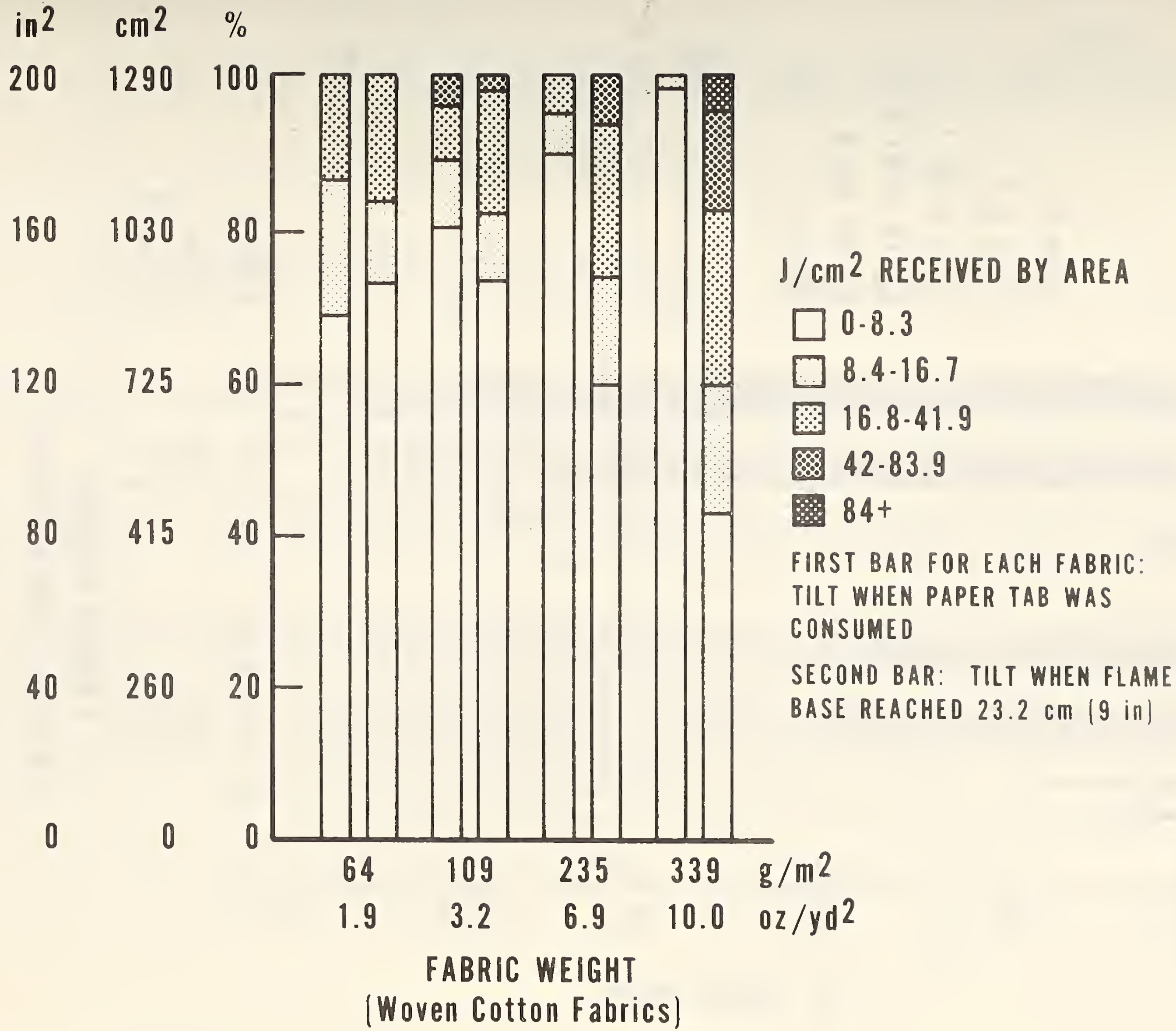

Figure 3. Effect of Timing of Tilt on Heat Distribution Patterns

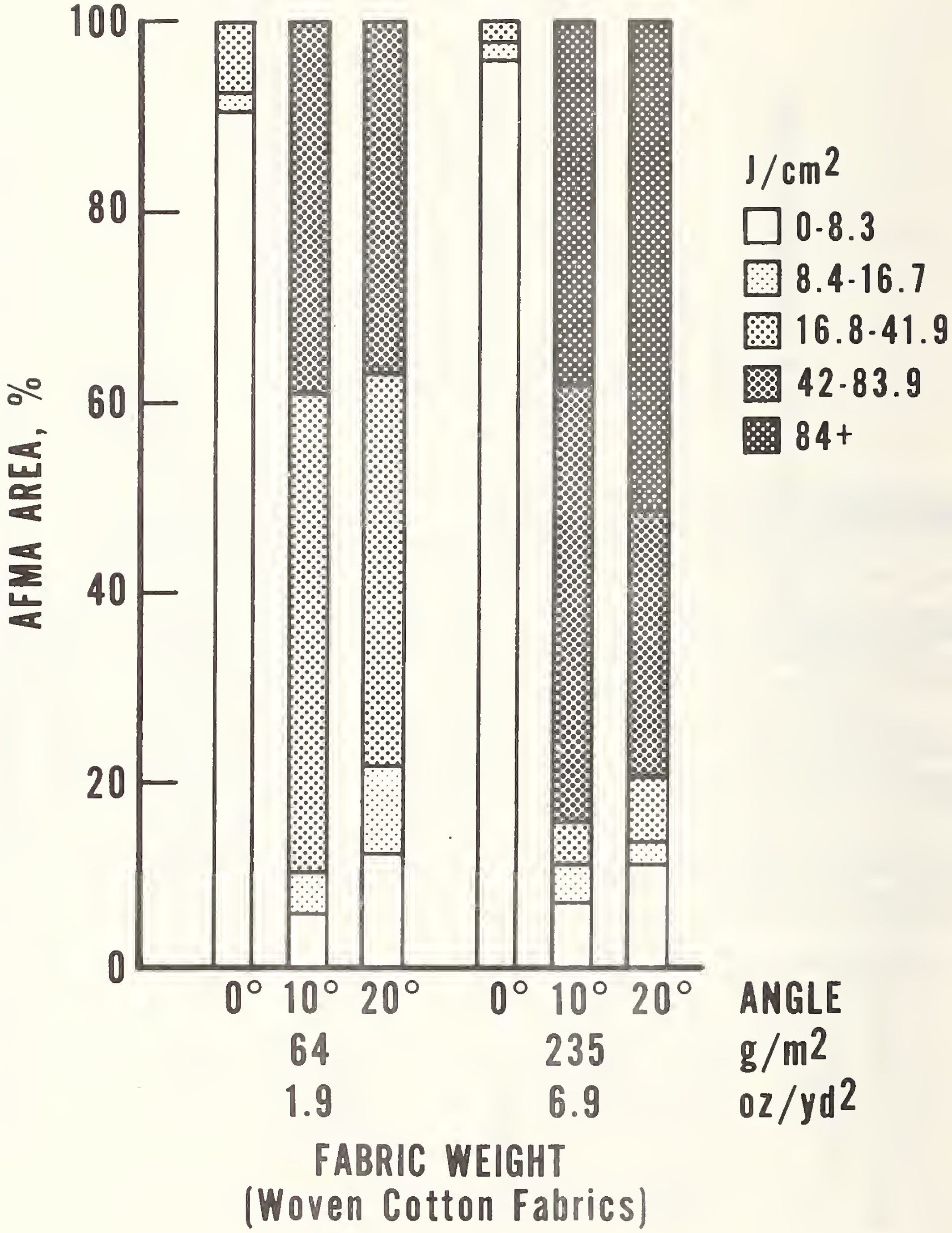

Figure 4. Effect of Angle of Semicylinder on Heat Distribution Patterns (No Tilting)

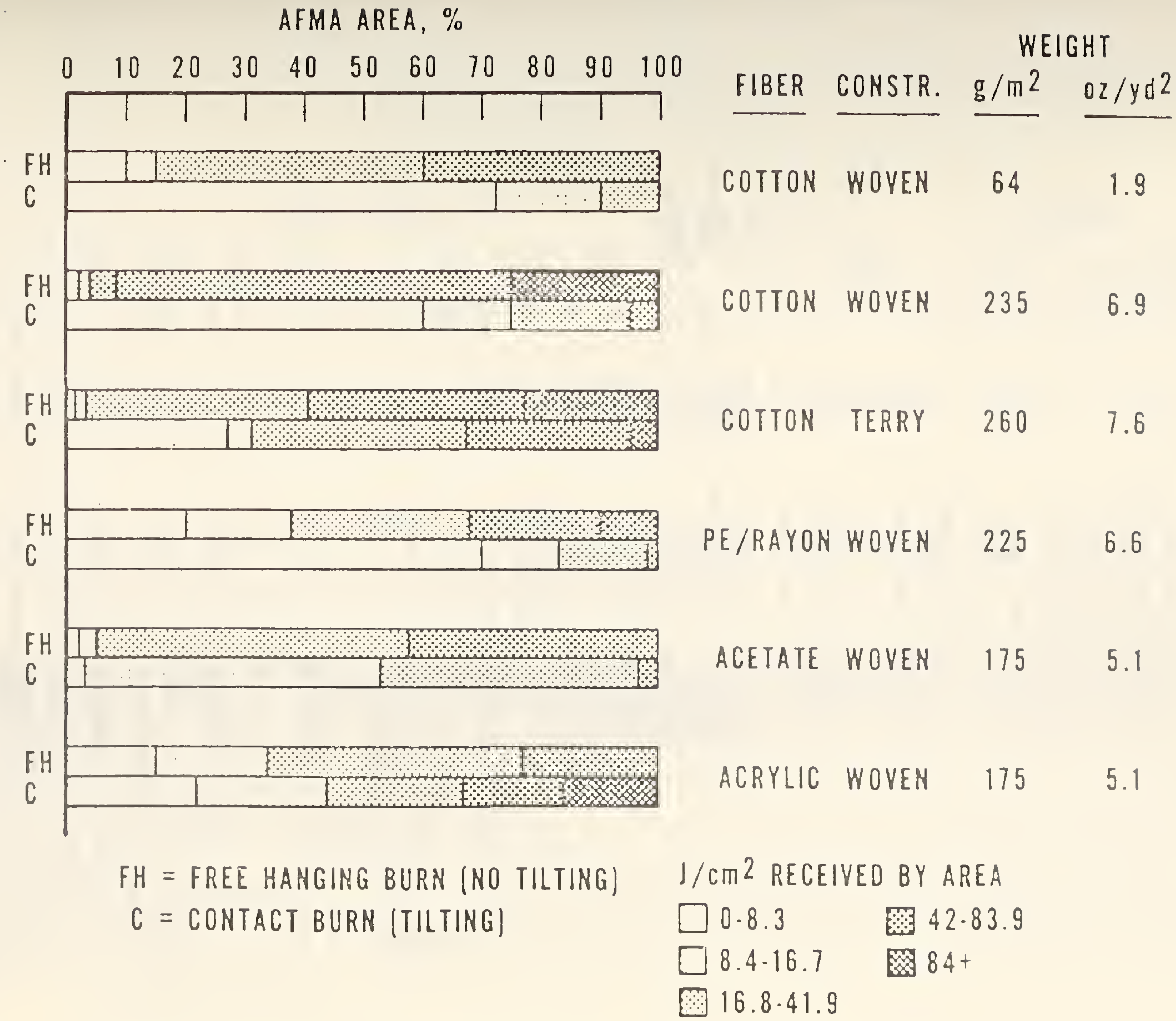

Figure 5. Heat Distribution Patterns Resulting from Free-Hanging Burns and from Burns with Contact Due to Tilting

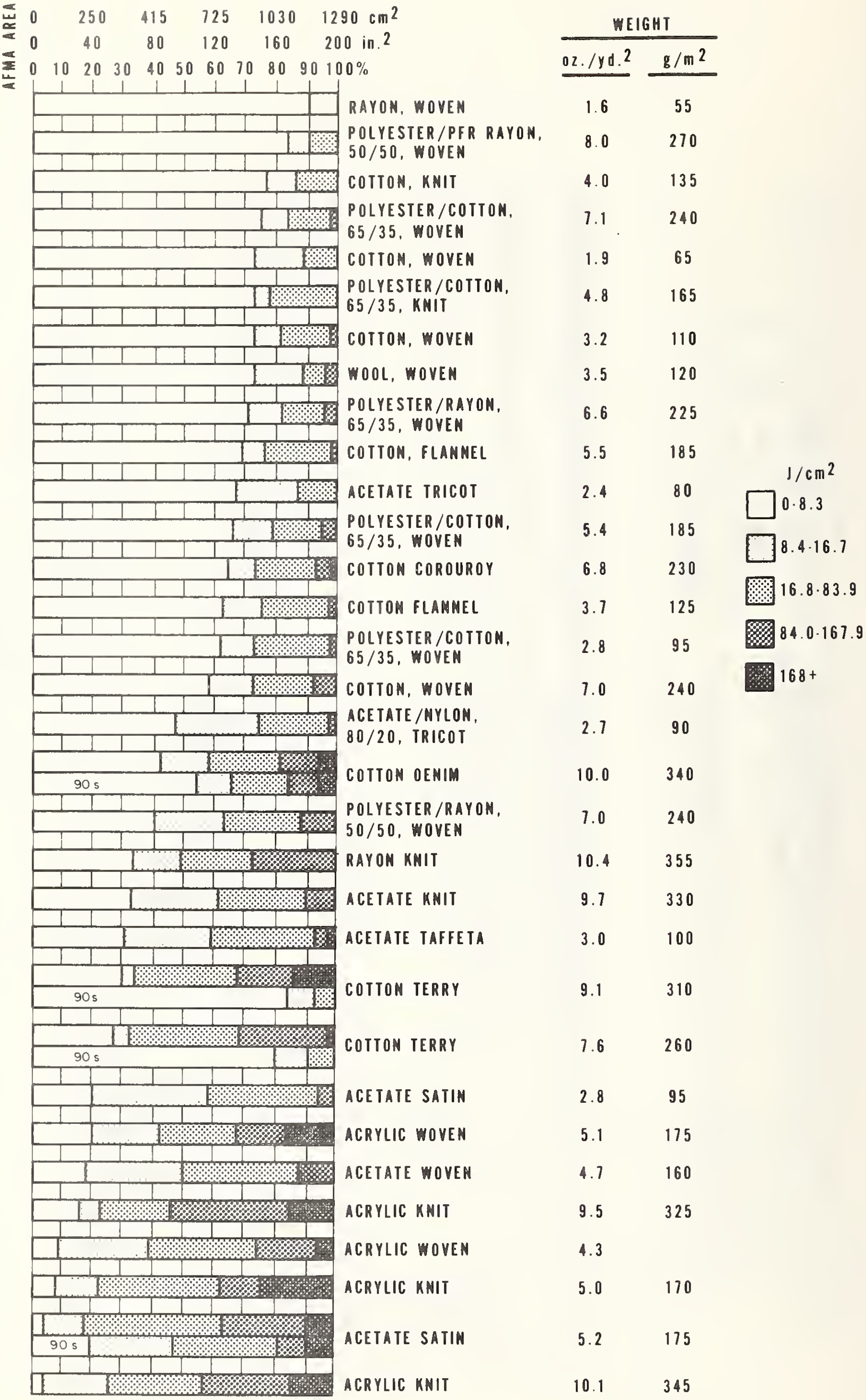

Figure 6. Heat Transfer Patterns of Various Fabrics

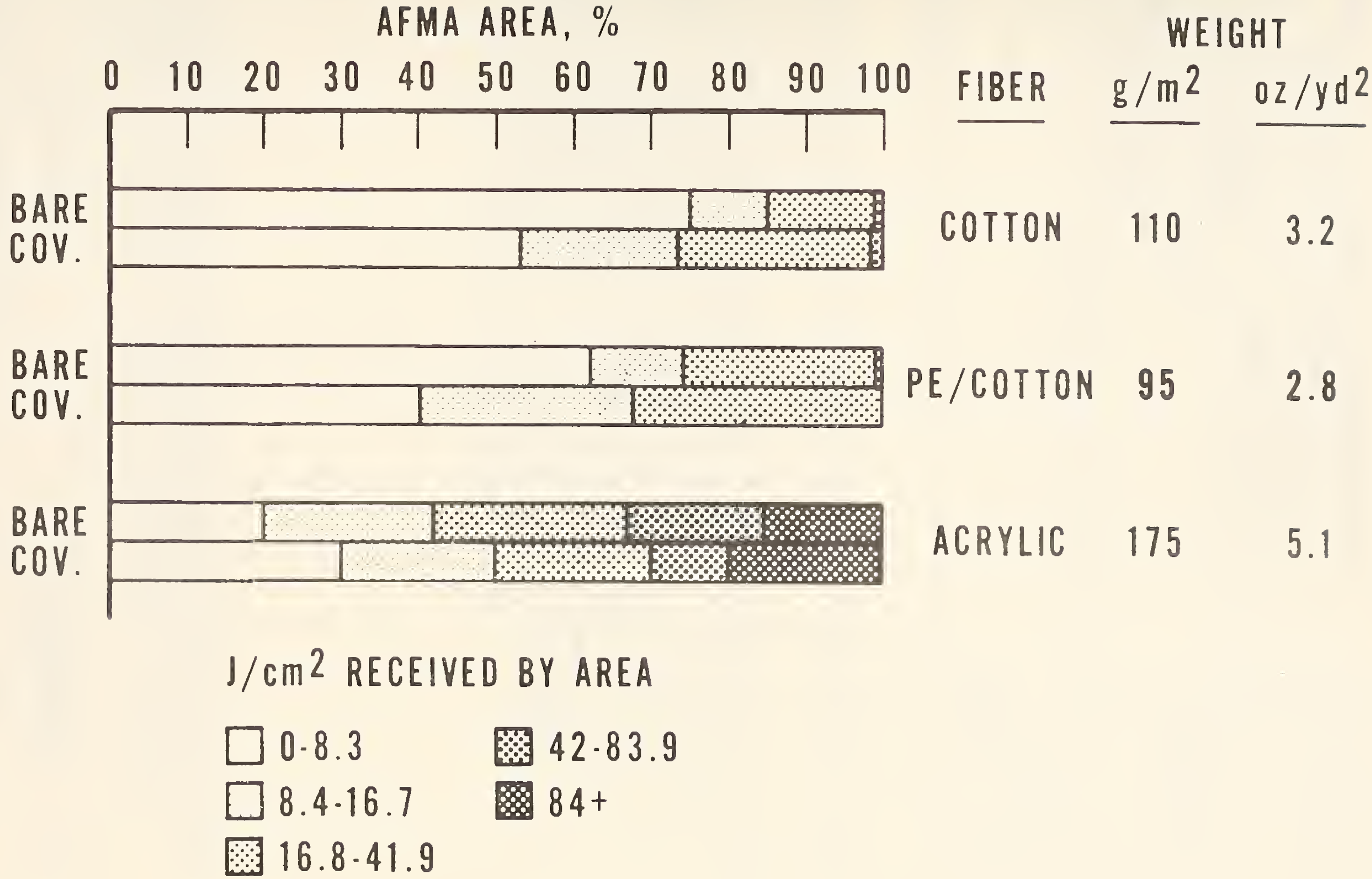

Figure 7. Effect of Underwear Fabrics on Heat Distribution Patterns

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			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This paper describes results of experiments simulating the phenomena occurring during burns of apparel items. Fabrics were burned near a semicylinder which was covered by 54 heat sensors. The areas which received various heat loads (corresponding to various depth of burn injury in real-life flammable garment accidents) were recorded. In most cases, the semicylinder was moved during the burn, so that the burning fabrics made contact with it, simulating movement by the victim during a garment burn. This caused rapid extinguishment in some but not all fabrics. Results are reported for 40 fabrics varying in fiber content, and fabric construction and weight.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Accident; apparel; burn injury; fabric flammability; fabrics; fire; garments; heat transfer; injury hazard; simulation.

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