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14. ABSTRACT

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15. SUBJECT TERMS

DYES
WOOL
FIBERS
NYLON
COTTON
FABRICS
TEXTILES
GARMENTS
HEAT FLOW
ENSEMBLES
OUTER LAYER
SKIN(ANATOMY)
HEAT TRANSFER
BLAST INJURIES
FIRE RETARDANT
BURNS(INJURIES)
COTTON TEXTILES
ATOMIC WEAPONS
SYNTHETIC FIBERS
NUCLEAR WEAPONS
THERMAL EFFECTS
THERMAL RADIATION
MILITARY PERSONNEL
OPTICAL PROPERTIES
PHYSICAL PROPERTIES
PROTECTIVE CLOTHING
THERMAL EVALUATION
THERMAL INSULATION
THERMAL PROTECTION
FABRIC EFFECTIVENESS
COTTON WOOL BLENDS
NYLON/COTTON BLENDS
FIRE RESISTANT TEXTILES
SOLAR FURNACE STUDIES
FIRE RESISTANT COATINGS
FIRE PROTECTIVE CLOTHING
PYROLYZED ACRYLONITRILE

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Textile Functional Finishes Laboratory Report No. 192

THE EFFECT OF THERMAL RADIATION ON TEXTILE MATERIALS

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Project Reference:
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ABSTRACT

A description is given of the problem facing the Army in its attempt to provide protection against the thermal effects of atomic weapons. Methods used to simulate thermal effects, equate materials to a common basis, and measure material effectiveness are outlined. Observations noted with typical commercial fibers show that combinations of nylon with cotton can give marked increases in protection in spaced ensembles. It is also shown that research into thermally stable fibers offers a means of significantly reducing the "thermal" protection problem.

Table of Contents

The Effect of Thermal Radiation on Textile Materials

1. Historical Background

In considering the problem of protecting individuals from the effects of atomic weapons, the thermal properties of such weapons are a prime consideration, both in their effect upon the uncovered skin and upon the clothed parts of the body. In Glasstone's handbook[1] on "The Effects of Nuclear Weapons" he has pictorially illustrated how the shape of clothing, its design or fabrication methods, and the properties inherent to the outer layer of clothing may all influence the severity of burn received by an individual exposed to the thermal radiation from an atomic weapon.

The possible significance of the thermal energy resulting from the atomic weapon as compared to immediate nuclear radiation and blast effects can be seen from Figure 1. Here is depicted the area affected by the detonation of a nominal size weapon[2]. In this diagram a sizable area occurs near the center of the blast, shown as a solid area, wherein nuclear radiation hazards are such that protecting against thermal effects would not be of significant value.

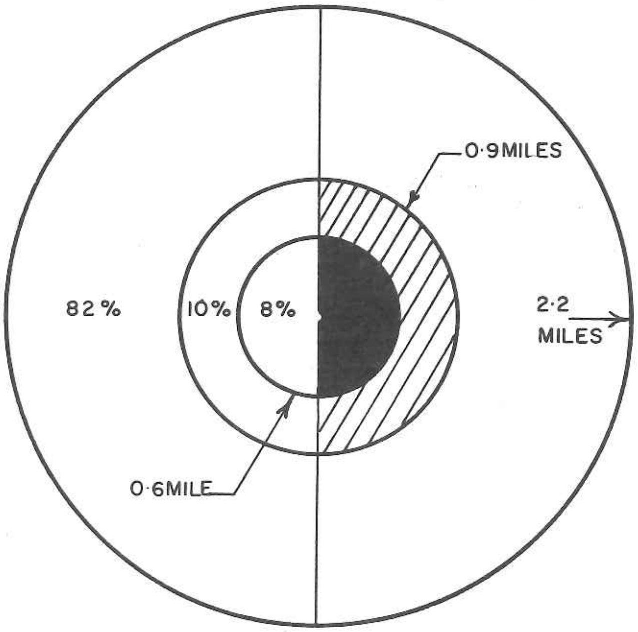
A second zone occurs, shown as a cross hatched area, wherein casualties result from ionizing radiation, thermal radiation and blast effects. The third zone depicted is that area wherein the major effects are thermal and missile wounds. Obviously, a major reduction in casualties can be achieved if the individual can be protected in this third zone.

Providing protection against thermal radiation in this third zone becomes in essence, a problem of rejecting, or negating, an instantaneous dose of thermal radiation. The characteristics of nuclear weapons have been previously described[3], but in general we are dealing with a massive fireball which emits at a black body temperature very nearly equal to that of the sun. The spectral distribution thus includes the range from approximately .3 to 3.0 microns with a very small fraction of the total energy occurring in the near ultra violet, a major fraction in the visible region and a second major fraction in the infrared region.

The casualty producing effects of this radiation has been studied both in our own laboratories[4], by other Government agencies[5], and by investigators at the University of Rochester[6]. The general consensus of these investigations is that approximately 3 to 5 cals/cm^2/sec imposed upon the bare skin will cause serious and probably incapacitating wounds if the area of exposure is extensive. These investigators have similarly found that lightweight clothing in contact with the body provides very little increase in protection over that afforded by bare skin.

The first possible solution that one can evision as a means of protecting against the 3 to 30 cals/cm^2/sec irradiance encountered in the third zone is to provide a highly reflective garment. While this may be a suitable answer for the civilian, it poses many problems for the military. The combat soldier must have on him at all times whatever protective devices can be built into his ensemble. These devices, or

FIG. 1
POPULATION AT RISK FROM A-BOMB



8% – TOTAL DESTRUCTION

10% – SUBLETHAL IONIZING IRRADIATION SICKNESS, BURNS, WOUNDS

82% – THERMAL BURNS, WOUNDS

systems, must be durable, permeable, and compatible with camouflage requirements. Obviously an impermeable mirror-like surface will not meet this requirement.

In addition to the problem of protecting the soldier against burns, it is also of military interest that the environmental protective qualities of the clothing will be maintained after exposure to the weapon so that the problem of resupply will be eliminated. This in itself poses a complex problem since it is necessary to provide a garment that resists destruction as well as providing protection. Since the outer layer of a clothing ensemble will receive the unobstructed rays from a bomb detonation, it is apparent that this layer must serve as the prime deterent to the passage of thermal energy and also resist the destructive effects of such radiation. Thus a primary objective of our studies has been to find or develop materials suitable for clothing which will resist destruction and ignition.

A second objective has been to find materials and/or develop systems that will permit us to isolate this outer layer of clothing from the man's body and thus restrict heat flow. The desirability of isolating the outer layer of the clothing ensemble by an air space was recognized in early studies by investigators at the University of Rochester. Mixter,[7,8] et all, have shown that significant increases in protectivity can be achieved by spacing the outer layer. These laboratory observations were subsequently confirmed in atomic field tests conducted at the Nevada Proving Grounds[9]. While this second objective is in itself of major significance, this presentation will be limited to a description of the materials research program aimed at reaching the first stated objective. As will be discussed, the factor of spacing the outer layer is considered in the techniques used in studying materials for the outer layer.

Early observations of the effectiveness of various ensembles showed that marked increases in protection could be achieved by applying a fire retardant treatment to the cotton fabrics used in a spaced ensemble. However, it was subsequently recognized that the protection afforded by the fire retardant treated cotton would have a definite upper limit and that in order to reach a new plateau other materials would be required. Consequently a program was initiated in our laboratories whereby we would, in essence, "screen" the thermal capabilities of commercially available fibers as well as many of the more exotic fibers under development in the various research laboratories of the country. The present discussion will be limited primarily to a description of some of the effects that we have observed with representative commercial fibers.

2. Methods

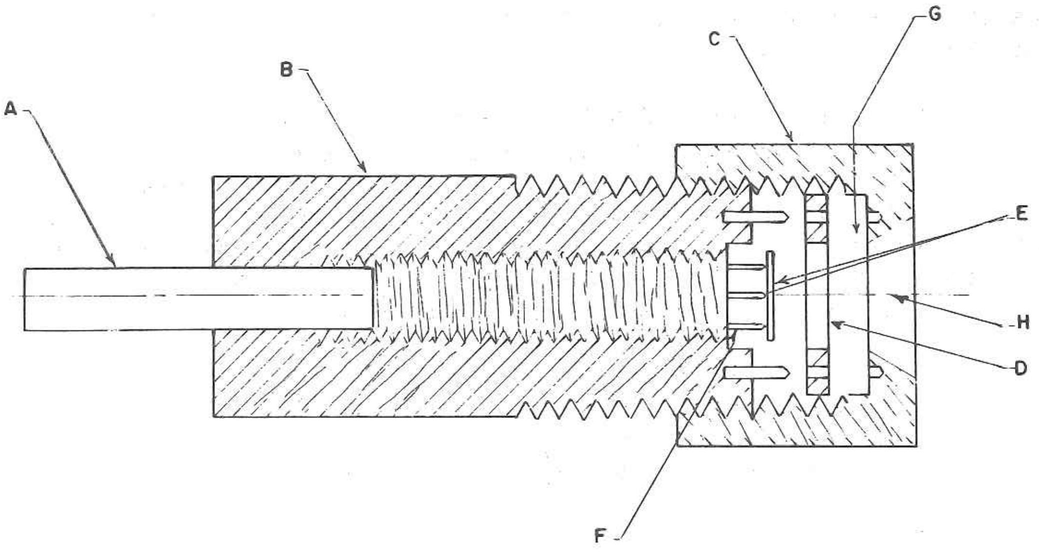
a. Energy Source - In our work to determine the textile fibers best suited for this purpose we have employed the carbon arc apparatus described by McQue[10] and by Davis, et all[11]. In brief, this is a 24" carbon arc searchlight which has been modified to give a converging beam of radiation. The arc is operated at approximately 180 amps and 75 volts with a shutter mechanism mounted at the second focus of the 24" ellipsoidal mirror.

Samples to be irradiated are in turn placed behind the exposure shutters and some measurement of "protectivity" or fabric effectiveness is taken.

b. Measurement of Fabric Effectiveness - There have been two techniques employed to measure the effectiveness of various clothing ensembles and materials. One involves the use of animals wherein the the clothing ensemble is interposed between the animal and the radiant energy source. The second utilizes a skin simulant in lieu of the animal and through temperature measuring devices imbeded therein, the surface temperature rise or temperature profile in depth are determined and related to protectivity.

Both of these techniques require much greater quantities of experimental materials than are generally available in our program. Hence, a technique was developed that enables us to measure the heat flow from rather small samples. This technique has been previously described in detail[12] and is diagrammed in Figure 2. In essence, a high speed calorimeter disc is positioned 0.1" behind the sample and heat flow resulting from a given irradiance imposed on the outer surface is measured. Relative effectiveness of various materials is judged by comparing the heat flow to that observed with some standard material whose behavior with animals is known.

FIG· 2
CROSS-SECTIONAL VIEW OF
CALORIMETER ASSEMBLY



A· THREADED SPINDLE
B· BRASS CYLINDER
C· THREADED CAP
D· BRASS SPACER (0·1")
E· CALORIMETER BUTTON
F· SUPPORTING NEEDLES
G· SAMPLE LOCATION
H· APERTURE

c. Paper Mat Techniques - In order to compare the various fibers it was necessary to utilize a single physical form and a technique for casting fibers into suitable form was developed in cooperation with the Textile Division of E. I. DuPont deNemours Company.[13] The end result of this program was to cast each fiber and fiber combination into a paper mat weighing approximately 5 oz/sq yd (equivalent to summer weight clothing). Both mass and color were rigidly controlled and to date approximately 1000 entities have been produced for study.

d. Destruction Measurements - To evaluate material damage, the circular discs of fiber mat materials used to measure energy transfer are employed. After being subjected to the various irradiances visual measurements are normally made of the degree of destruction sustained from a given exposure. Numerical values are assigned ranging from 0 for no damage to 6 for complete destruction. However, in cases of particular interest, destruction is measured by determining loss in weight.

e. Ignition Measurements - The ignition characteristics of a material are measured using a much larger sample holder than is used in the heat flow studies. In the heat flow measurements a 7/16" diameter aperture is used to insure a fairly even distribution of energy across the target area since with a converging beam of radiation the energy intensity drops off rapidly beyond this central area. While the 7/16" diameter aperture permits a more realistic definition of the energy distribution in heat flow measurements, its geometry does modify the ignition characteristics. Hence, in defining these characteristics auxiliary measurements are made in which comparatively large unrestrained samples are exposed. We find that this technique enables us to measure the irradiance required to produce the sustained combustion typical of that observed when garments are exposed to the larger thermal sources.

3. Observations

a. Typical Fibers

The availability of fibers today for characterization as to their thermal properties is larger than ever before. Some of the more common fibers are listed in Table I. Further, when one considers that many of these fibers types may represent 3 or 4 specific commercial fibers, each one slightly different than the other, this list more than doubles. Finally, if we are to consider many as they are used in two or three component blended fiber fabrics, the number of fibrous entities that could be considered for clothing fabric, the list of possibilities would multiply a hundredfold.

Nearly all of this list has been evaluated in fabric of fiber mat form. Those which have been marked with a single asterisk represent fibers evaluated in the mat form. Others were in fabric form and thus do not lend themselves to some of the comparisons shown later.

TABLE I

Typical Fibers Prepared For Thermal Evaluation

Natural Fibers

- Cotton*
- Wool*
- Silk*
- Asbestos*

Inorganic

- Glass
- Graphite
- Quartz
- Potassium Titanate

Synthetic Fibers

Commercially available

- Cellulosics*
- Modified Cellulosics*
- Polyamides (Nylon)*
- Acrylics*
- Modacrylics*
- Polyester*
- Vinyl chloride*
- Nytrile*

Limited availability

- Fluorocarbon*
- Olefin*
- Pyrolyzed Acrylic*

*Studied as paper mats, usually in blends with other fibers at 10% increments

From work conducted to date with these fibers, individually and in blends, the general conclusions are that we are unable to predict from intrinsic fiber properties what to expect when they are combined with other fibers. Similarly, although fibers such as quartz and graphite are extremely stable they lack the physical properties required to make lightweight garments. Hence the basic fibers and combinations that we have concentrated on are those we expect will give the desirable textile fabric properties.

A typical spectrum of these fibers are shown in Figure 3. Aside from showing that these materials differ from one another with respect to energy transfer for irradiances of one second, several other factors are apparent.

1. Nylon - This data shows that among typical conventional fibers the highest heat flows are normally observed behind the pure synthetic fibers such as nylon. The response of these fibers differ basically from those observed with a fiber such as cotton. The upper limit of effectiveness for the synthetics is governed largely by the irradiance at which initial hole formation occurs. When this occurs a physical collapse results as the initial point of rupture expands throughout the entire exposed area. This is frequently not accompanied by significant destruction of material. Rather, it is a function of the melting point and contraction of the heated material. In contrast, cotton, both untreated and fire retardant treated, undergoes successive degradation stages which leave some residue intact at all but the combustion phase.

Obviously, when fabric collapse occurs with a synthetic such as nylon large fractions of the incident energy are imposed directly upon the calorimeter button, or in a multilayered ensemble, directly upon the sublayers. The irradiance required for the destruction of the synthetics is low and varies with the color or absorptivity of the material. In general, we do not observe sustained combustion occurring with the synthetics but do observe flaring which occurs during the actual thermal pulse.

2. Wool - The response of wool in this lightweight form, 5 oz/sq yd, parallels somewhat that of the synthetics such as nylon. However, as the irradiance increases we observe that melting and fusing occurs in depth rather than the complete collapse typical of the synthetics. The use of heavier and more dense wool constructions will generally improve the performance of this fiber in relation to others.

3. Cotton - The performance of untreated cotton is not shown on this slide, but one may find may reports as to its performance. Generally, it has heat transfer characteristics slightly better than fire retardant cotton up to 8 to 10 calories/cm^2/sec irradiance. In this irradiance range the untreated cotton will ignite and the resulting heat flow is high. Ignition will of course produce total destruction of the cotton and use of darker colors causes flaming to occur at lower irradiances.

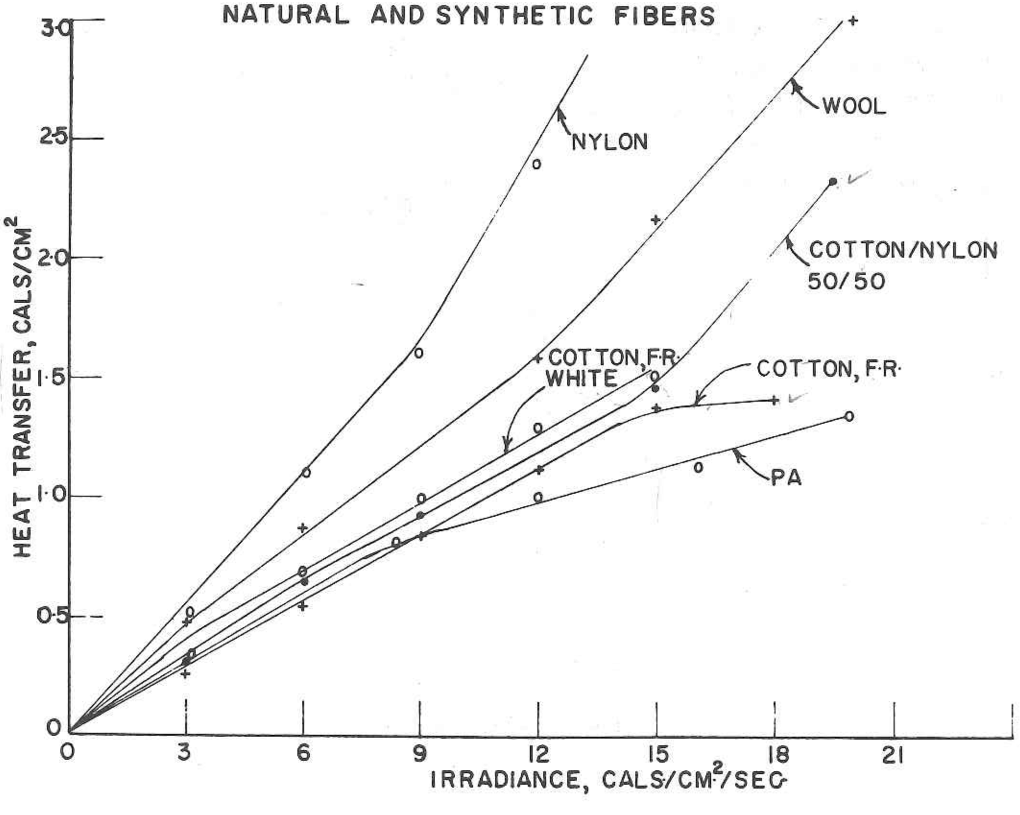
4. Fire Retardant Treated Cotton - The use of a flame retardant on cotton shows reduced heat transfer as compared to either the synthetics or wool. Further, as shown on this slide, its performance is influenced very little by color. The flame retardant eliminates the sustained flaming that occurs with untreated cotton, but the presence of this treatment increases the rate of fiber degradation. Hence relatively low irradiances cause considerable damage to this material, but do produce an opaque charred layer which continues to protect the calorimeter button from the direct rays of the arc. The charred residue weighs approximately 30% of its original weight and is very friable.

5. Cotton/Nylon Blend - Blending of fibers to influence physical comfort and aesthetic properties of fabrics has been generally practiced by the textile industry for many years. It can also effect thermal response, particularly the ignition and destruction characteristics, as is shown by the performance of the 50/50 blend of cotton with nylon. Here its heat transfer properties are similar to those of fire retardant treated cotton, while its resistance to ignition is greatly improved over that of untreated cotton.

The possibility of raising the ignition threshold and at the same time obtaining greater resistance to destruction has caused us to concentrate upon fiber blends in our evaluation of materials. Specifically, as will be shown, it has caused us to be very much interested in the response of cotton/nylon blends since they represent a means of substantially increasing the protective capability of our uniforms. At the same time some of their important physical properties could be realized.

FIG·3

HEAT TRANSFERRED FROM TYPICAL NATURAL AND SYNTHETIC FIBERS



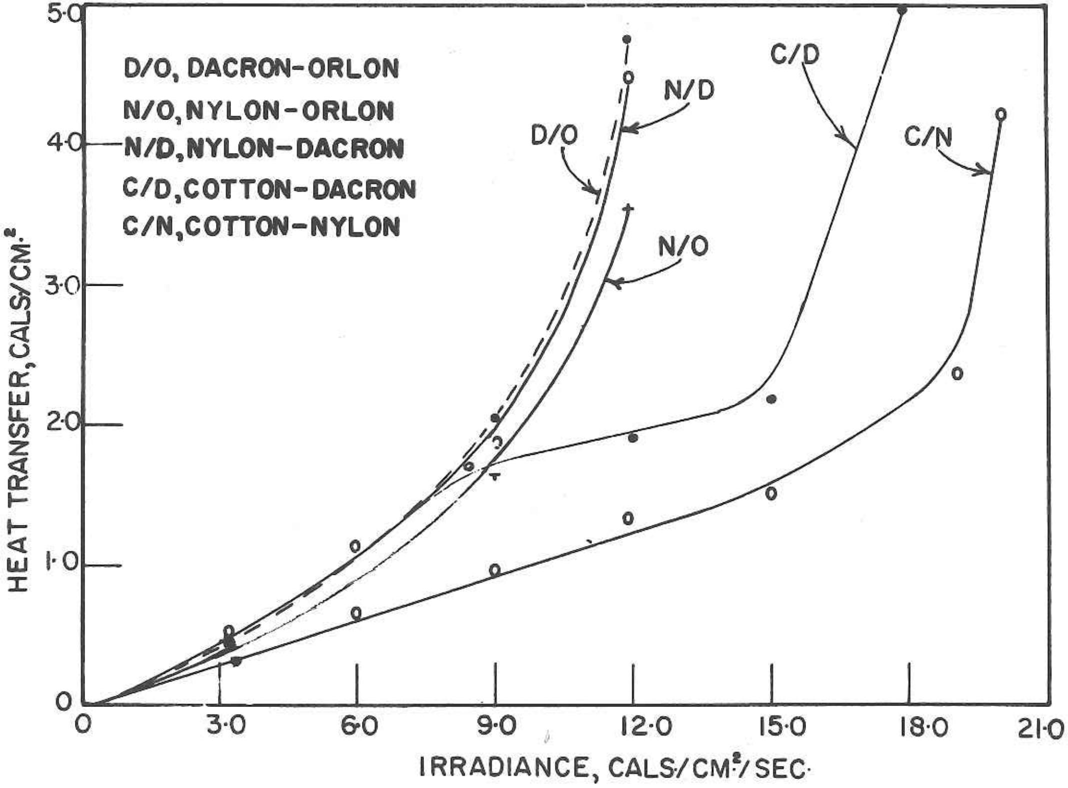
6. Pyrolyzed Acrylonitrile - The bottom curve gives the heat transfer data measured behind pyrolyzed acrilonitrile fibrous materials. It is representative of some of the less conventional fibers that are of interest. Here the natural color of the fiber is black. It is extremely resistant to degradation and does not permit ignition or sustained flaming. However, gases from its decomposition may ignite or flare at high irradiances during the exposure. As shown by Figure 3, it has excellent resistance to heat transfer.

B. Blends of Synthetics - The positive responses that have been observed with some of the cotton/nylon blends are not characteristics of the majority of blends. In general we observe the greatest stability with blends of natural and synthetic fibers and the least stability with blends of synthetics. Relationships for typical 50/50 blends are given in Figure 4 where it is seen that the blends of synthetics such as Polyester with Acrylonitrile, Polyamide (Nylon) with polyester or with acrylonitrile are essentially destroyed at comparatively low irradiances with resultant high heat transfer.

It is similarly interesting to note the marked difference between the response of the cotton/polyester blend and the cotton/nylon blend. The cotton/polyester, although more effective than the combination of synthetics, is much less effective than the cotton/nylon and is actually ignited at a lesser irradiance than required for an equivalent all cotton fabric.

FIG. 4

HEAT FLOW FROM TYPICAL 50/50 BLENDS



C. Behavior of Cotton/Nylon Blends - The consistent superior performance observed with some of the cotton/nylon blends has led to rather extensive studies with these materials and we have observed that their resistance to degradation and ignition is modified by the nylon content, the color of the nylon relative to that of the cotton, and their physical relationship within the fabric. We have found that with all other things being equal, the lowest heat transfer values are observed with nylon contents of 35 to 40%. However, at this nylon content the ignition irradiance is a critical function of the relative colors of the two fibers. This relationship is shown in Figure 5 when ignition irradiance for several cotton/nylon blends is plotted as a function of the ratio of the reflectance of the nylon fiber to the reflective of the cotton fiber.

These curves show that at a low nylon content, i.e., 20% the ignition response is dominated by the cotton fiber and varying the reflectance of the nylon fiber is of little consequence. At 40% nylon content a fabric could be designed wherein the nylon fiber would be slightly more reflectant than the cotton fiber and would possess excellent resistance to ignition. However, at 50% nylon content we are permitted greater flexibility in adjusting the colors of the two fibers and still producing a fabric with high ignition resistance and acceptable heat transfer characteristics. This range of possible selections is extended at the 60% nylon content, but at this level of synthetic content we encounter other problems such as greater thermal destruction. Consequently, we have selected the 50/50 cotton/nylon blend as an optimum solution and are currently developing woven fabrics that will incorporate this effect due to relative color of the fibers.

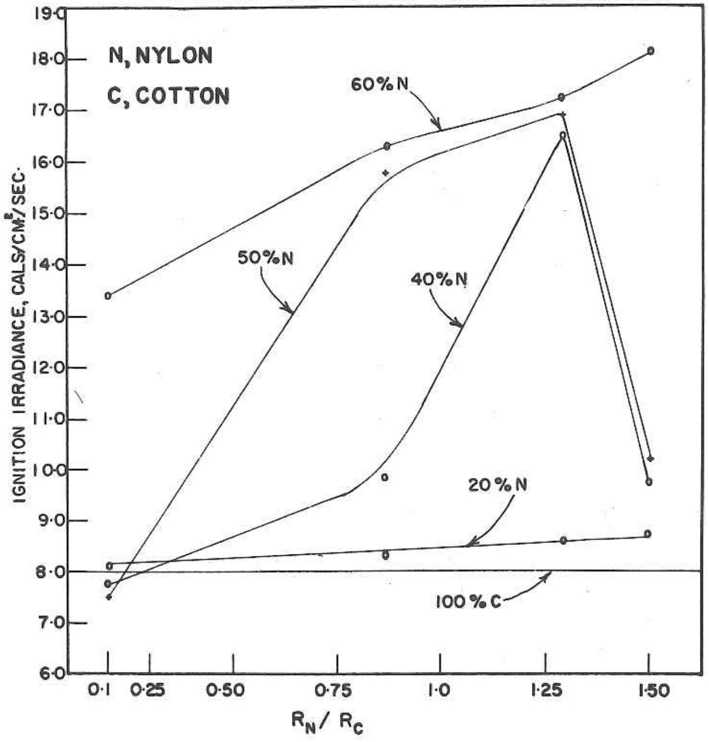
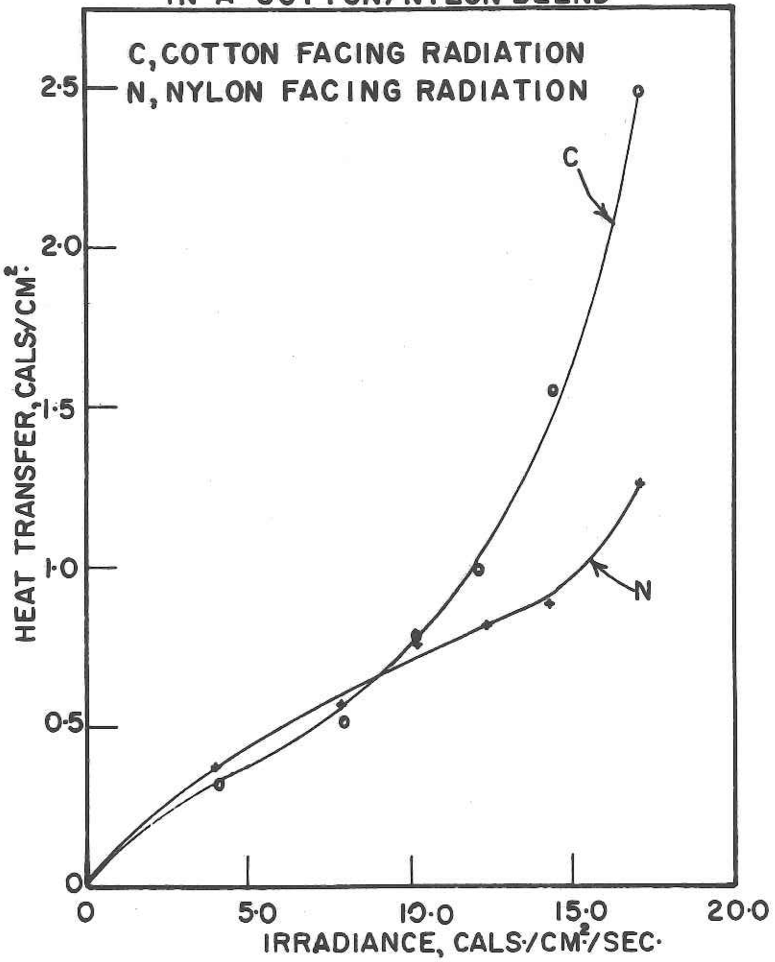


FIG. 5
EFFECT OF RELATIVE COLOR ON THE IGNITION CHARACTERISTICS OF COTTON/NYLON BLENDS

The physical relationship of the two fibers in the fabric similarly effects net response. This is seen from Figure 6 where heat transfer as a function of irradiance is plotted for the two surfaces of a cotton/nylon sateen. This particular fabric was woven so that one surface was composed predominantly of cotton fibers and the other face predominantly of filament nylon fibers. As the curves show, with the cotton face exposed to the radiation we observe relatively high heat transfer and low ignition irradiance. With the nylon face exposed to the radiation, we observe a decrease in heat transfer and a substantial increase in resistance to ignition.

FIG· 6

EFFECT OF FIBER POSITION IN A COTTON/NYLON BLEND



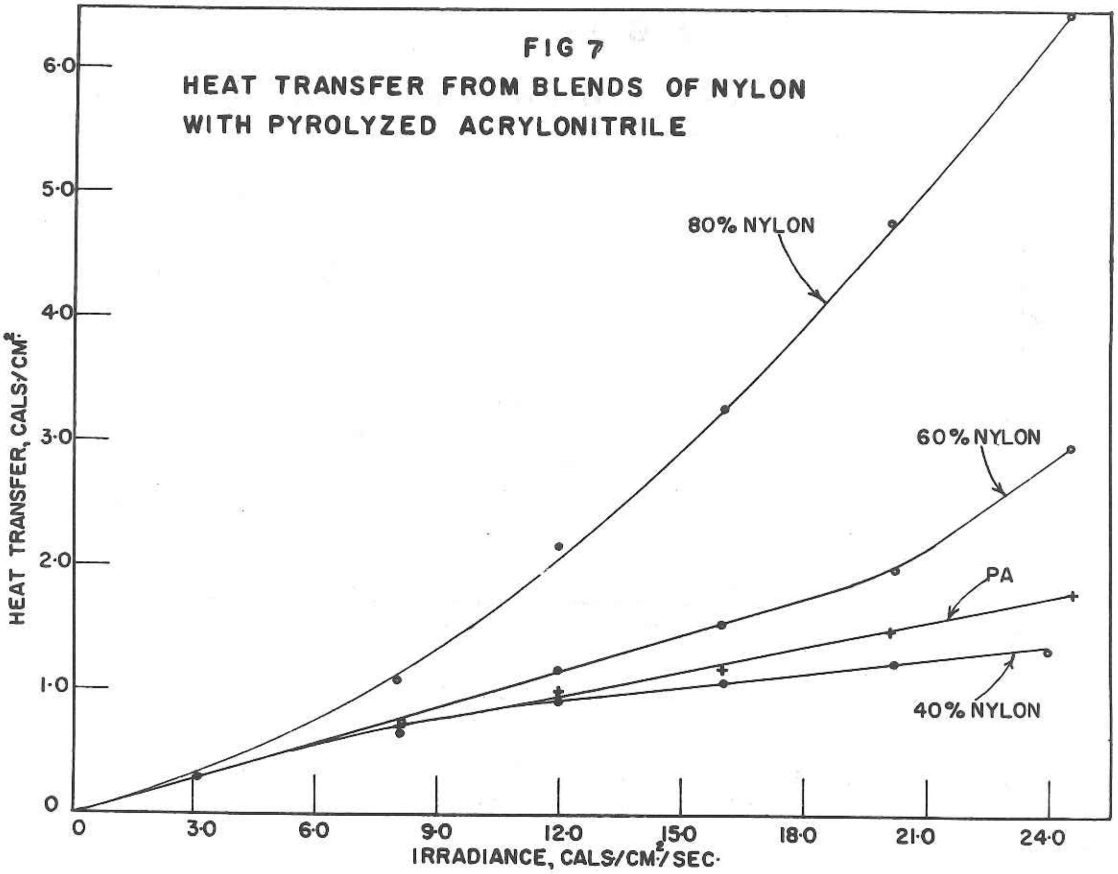
D. <u>Blends of Pyrolyzed Acrylonitrile</u> - In addition to the cotton/nylon blend, the pyrolyzed acrylonitrile fiber has been the subject of considerable study. Here the problem as dictated by fiber physical properties was different. Cotton and nylon, both have the necessary physical properties to allow us to attain strong, lightweight fabrics. Pyrolyzed acrylonitrile does not. While under optimum processing conditions strength approximately equal to wool has been obtained, the fiber lacks the extensibility characteristics of wool and will break under conditions of flex. Thus, with pyrolyzed acrylonitrile, the problem was one of finding other fibers for blending with it which would overcome these physical deficiencies and at the same time retain its thermal protective properties.

Pyrolyzed acrylonitrile, as will be recalled from Figure 3, showed the lowest heat transfer of the fibers considered. Furthermore, in ignition studies there was no tendency for it to ignite at irradiancies up to 25 cals/cm^2/sec. Lastly, it showed little evidence of destruction at this irradiance.

The effect upon energy transfer when blended with other fibers is illustrated in Figure 7 which shows various blends of nylon with pyrolyzed acrylonitrile. From this data it will be noted that as pyrolyzed acrylonitrile is added to nylon in increasing amounts there is improvement in performance over 100% nylon, and it is indicated that with a 50/50 blend performance equivalent to 100% pyrolyzed acrylonitrile might be obtained. With a greater amount of pyrolyzed acrylonitrile, for example, the 40/60 nylon-pyrolyzed acrylonitrile blend, improvement in energy transfer is realized but physical strength is decreased. Not shown is the data for 20/80 nylon-pyrolyzed acrylonitrile which closely follows that for 100% pyrolyzed acrylonitrile.

FIG 7

HEAT TRANSFER FROM BLENDS OF NYLON WITH PYROLYZED ACRYLONITRILE

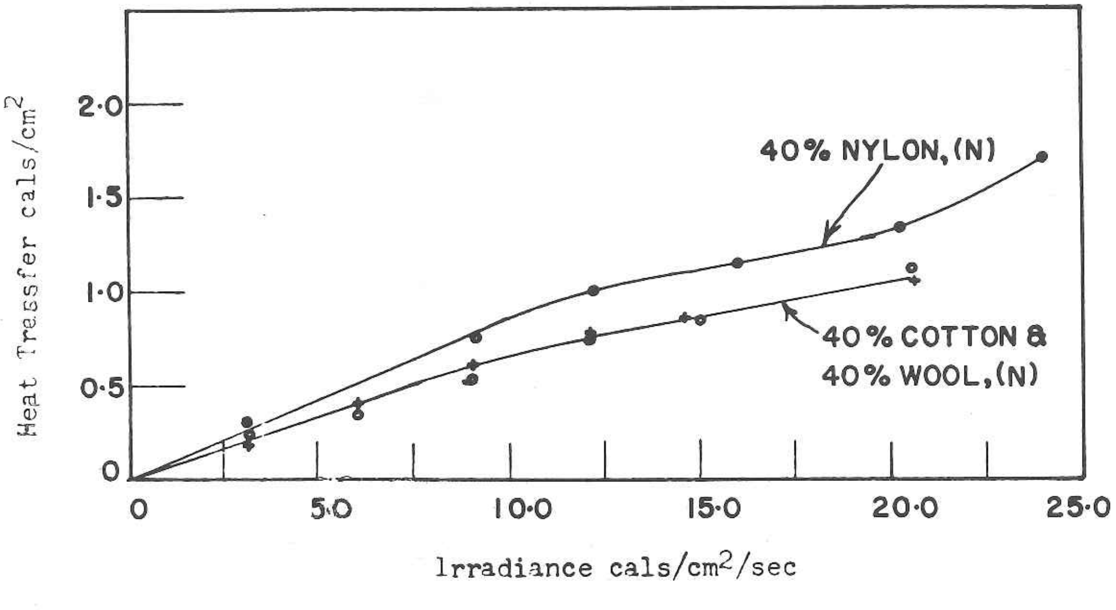


2. Blends of Cotton and Wool - The commonly employed natural fibers, wool and cotton, were also examined in blends with pyrolyzed acrylonitrile and the results in general were parallel to that for nylon. From the data of Figure 8, it will be noted that in 40% cotton or wool fibers with pyrolyzed acrylonitrile, there is a reduction in heat transfer over that obtained with nylon. However, ignition studies showed that at irradiances greater than 21 cals/cm^2/sec sustained combustion was effected and these two blends were destroyed.

It was further noted in this work that the color of the auxiliary fiber influences energy transfer from the pyrolyzed acrylonitrile blend. In Figure 9 data obtained using either grey cotton or grey nylon with pyrolyzed acrylonitrile are presented. Here the reverse is shown with cotton now less effective than nylon. Further, as regards to comparison of colored vs. uncolored auxiliary fiber, darkening the fiber improved the performance of nylon, but effected higher energy transfer in the case of cotton. Further, by this criteria the 60/40 blend of pyrolyzed acrylonitrile with grey colored nylon produced one of the more effective materials found to date.

FIG. 8

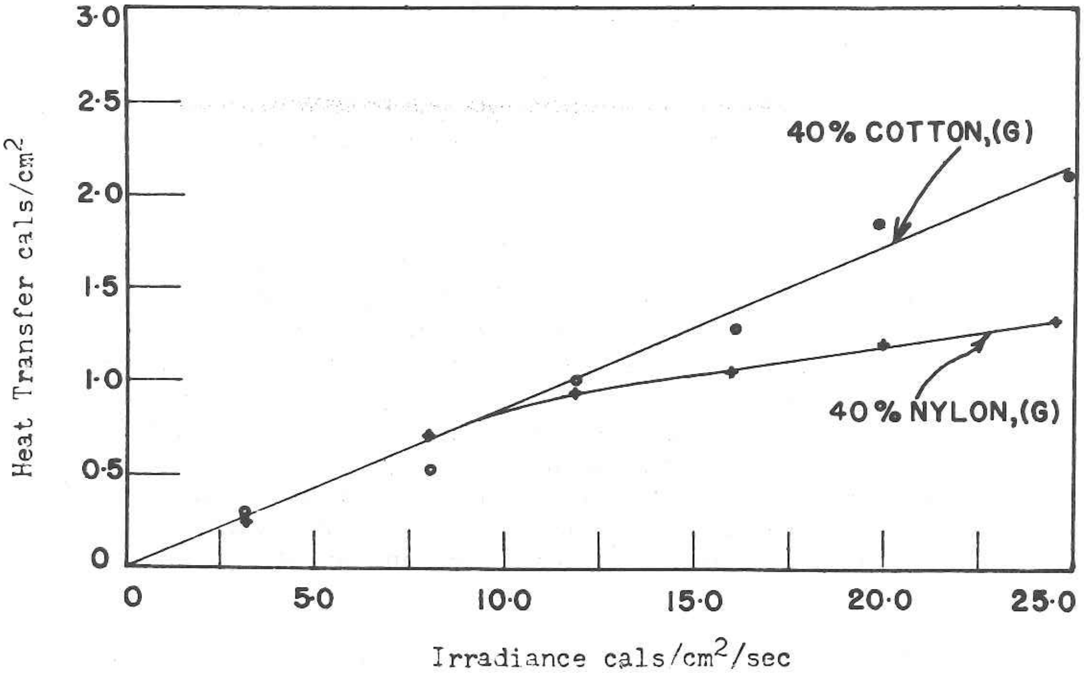
BLENDS OF PA WITH NATURAL COLORED FIBERS



Though inclusion of other fibers with pyrolyzed acrylonitrile produced this beneficial effect in heat transfer, they generally detracted from the good resistance to destruction of that fiber. Combustion and flaming often occurred during exposure and after irradiation the material was extremely friable. Splitting and cracking of the fiber mass occurred, particularly when large areas of 4" diameter were exposed to the solar furnace.

FIG. 9

BLENDS OF PA WITH GREY FIBERS



PA, PYROLYZED ACRYLONITRILE

In summary, though pyrolyzed acrylonitrile blended with other fibers showed promise for inhibiting heat transfer, good performance was not obtained in those blends where its physical deficiencies might be overcome. Further, inclusion of other fibers induced greater decomposition such that a multi-shot capability would not be obtained. Thus, it is no longer a fiber of major attention.

E. <u>Solar Furnace Studies</u> - The work that has been described relates mainly to the laboratory analysis of the many fiber entities and characteristics which of necessity have to be studied in small scale. Actually, the atomic weapon is a large scale device and a much better evaluation of its capability can be obtained with our Solar Furnace.

In this instance we can irradiate areas of 4" diameter and thus include factors of fabric collapse, ignition, and area effects not obtainable with the small area carbon arc. As a consequence any material which survives the analysis of the combined paper mat - carbon arc program is woven into a fabric and reexamined on our solar furnace using animals as indicators of protection.

An illustration of the data obtained in this type of study is shown in Table II. The data listed are the severity of burn measurements observed behind multilayered systems exposed to the cited irradiances with our solar surface. In each case the outer layer was separated from the T-shirt by a 3 dimensional open weave spacer material. The two outer layers considered were a 9 oz/sq yd cotton sateen which had been fire retardant treated and a comparable cotton/nylon sateen which included in its design many of the criteria found in the paper mat studies to be desirable. The burn severity code used is: 1+M for a one plus mild burn, 1+S for a one plus severe burn and 2+I for a 2 plus intermediate burn, etc. In the first column are given the particular outer layer fabrics considered and the irradiances to which the ensembles were exposed.

The data show that this particular fire retardant treatment on cotton offers protection in a limited number of cases at the 10 cals/cm^2/sec level while the untreated cotton/nylon sateen offered protection in all cases. Similarly, as the irradiance was increased, the number and severity of burns observed behind the fire retardant treated cotton increased, while the effectiveness of the cotton/nylon remained essentially constant throughout the irradiance range 13 to 18 cals/cm^2/sec. When one considers that unprotected skin or skin in contact with lightweight clothing will be severely burned in the irradiance range 3 to 5 cals/cm^2/sec, it is obvious that substantial protection can be offered by the careful engineering of fabrics and systems which utilize conventional materials.

It is similarly apparent that further increases in protection are feasible by utilizing some of the experimental fibers which are available today. This can be seen from the data listed for the combination of pyrolyzed acrylonitrile with an experimental fiber. While this particular combination lacks the physical strength required in a combat garment, it illustrates the potential in this type of approach.

TABLE II

Effectiveness of Spaced Ensembles Which Utilize Either Fire Retardant Treated Cotton, a Cotton/Nylon Sateen, or a 50/50 Blend of Pyrolyzed Acrylonitrile With a Modified Polyamide

Sample	Total Number of Exposures	Burn Severity 0	1+M	1+S	2+M	2+T	2+E	3+M	3+S
FR Sateen	9	3		2	4				
Cotton/Nylon @ 10 cals/cm^2/sec	9	9							
FR Sateen	12		1	1	6	2		1	
Cotton/Nylon @ 13 cals/cm^2/sec	12	9			2			1	
FR Sateen	12				5	3		3	1
Cotton/Nylon @ 15 cals/cm^2/sec	12	9			3				
Cotton/Nylon @ 18 cals/cm^2/sec	11	7	1	1	2				
*PA/MP ¢ 16.4 cals/cm^2/sec	8	8							
*PA/MP @ 20.1 cals/cm^2/sec	10	10							
*PA/MP @ 23 cals/cm^2/sec	10	4		1	4		1		

*pyrolyzed acrylonitrile with an experimental fiber

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