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Olney Medal Address

Some Thoughts and Information On Nonflammable Products

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ABSTRACT

This paper recognizes the need for fabrics that are less flammable and describes criteria normally employed to evaluate flammability characteristics—ease of ignition, rate of burning, ease of extinguishment, types and amounts of smoke and toxic gas generation, thermal shrinkage, thermal insulation ability, and integrity of material at and during the time of heat and fire exposure.

Fire-resisting properties of Nomex, Durette, Fypro, FRL-T-fibers, Kynol and PBI fiber are reviewed, and the performances of some of them exposed in garment form to a burning jet fuel fire are reported. Regular and modified PBI fabrics and the modified aromatic polyamide fabrics are reported to show great promise for use in protective clothing. Their potential for general apparel and home furnishings is also considered.

KEY TERMS

Consumerism
Fire Resistant Fibers
Flammability
Nonflammable Fibers
Organic Polymers
Oxygen Index
Polymers

ON December 14, 1967, President Johnson signed into law a new Flammable Fabrics Act. Its purpose was "to amend the Act to increase the protection afforded consumers against injurious flammable fabrics." The Act became law one year later, and since December 1968 the textile, apparel and home furnishings industries have been in ferment about its significance, particularly with respect to the need for and establishment of new or revised test methods and standards of flammability, and their ability to meet such standards with their present textile products. Moreover, the industry is concerned about its future technical and economic abilities to produce less flammable and thus less hazardous fabrics.

Those of you here today who are active in the textile industry surely need not be reminded of the plethora of technical and trade meetings, symposia, workshops, hearings, papers and policy statements made by people in our industry relative to the Flammable Fabrics Act. In fact, tomorrow at this Golden Jubilee Conference four timely papers on the subject will be presented. Therefore, my initial remarks probably present nothing new to my knowledgeable colleagues regarding the flammability problems that the textile industry has been facing in the past three years.

However, part of my audience today is not necessarily technical, and so I would like to tell them some of my thoughts on the subject and the position that I, as a textile technologist and as a citizen, take concerning this controversial Flammable Fabrics Act.

The first part of my address will deal with the problem, and the actions which I believe our industry properly *should* take, and eventually must take, probably by Government fiat if they do not come voluntarily, in developing safer textiles.

The second part of my talk is more technical and recounts some of the studies in which my associates and I have been engaged in the development of some of the newer protective, fire-resisting materials. Most of this work has been sponsored by the Air Force Materials Laboratory, the NASA Manned Spacecraft Center, and the U.S. Army Natick Laboratories. The objectives of such work are to produce materials which give better fire protection to military personnel and to the astronauts. One by-product of such research, which all of you as taxpayers sponsor, should be the utilization of such information and materials in improved consumer goods to protect all people against unnecessary fire risks.

Greater Consumer Protection

It seems clear to me that both the U.S. Government, and many individual state governments, are rapidly moving in the direction of greater consumer protection. I think we all like the philosophy of consumerism, pro-

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Nonflammable Products

vided it's in somebody else's area and not in ours. All of us are for Truth in Lending, or Truth in Packaging. I don't like to buy a box of tea bags containing 8.8 ounces. As a consumer I want to be protected so that when I buy that television set I have a warranty that is reasonable, equitable and contains no weasel words.

You as a consumer expect the automobile that you buy to be a safe, reliable vehicle, reasonably free from major and minor defects. If it doesn't meet these standards, you want pressure put on, by government if necessary, to get what you believe is coming to you. Perhaps (nay, hopefully) that TV repairman and his wife are just as aggravated at the inept, incompetent, indifferent and expensive service rendered by the automobile dealer who serviced their car as are the auto dealer and his wife who are exasperated at the same kind of unsatisfactory service that they get from the TV repairman.

If you stop to think about it, there's a little bit of solace in this reciprocal retribution. It reminds me of a cartoon in a recent issue of the *New Yorker*. A lady seated in her car is asked by the service manager at the local garage, "Do you want our usual, incompetent, sloppy engine tune-up, or do you want our Ralph Nader Special?"

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Why Not Fire-Safe Textiles?

If we as consumers want other products to be reliable and safe, why not fire-safe textiles?

The case can be made for the need for a proper, reasonable fabric flammability law properly implemented, and intelligently controlled, for here we are not talking about consumerism as it influences only our comfort and pocketbook. Here there is the very vital point of product safety, and this surely transcends most other consumer demands.

Now I know the philosophy and position of many of our perfectly respectable, ethical textile scientists and engineers who feel that the Flammable Fabrics Act, and particularly the new standards that have been promulgated, for example for children's sleepwear, is an unnecessary harrassment to an industry that already has plenty of trouble trying to get along in the United States. The contention is made that many of the proposed new standards are ridiculous, impractical, unnecessary and expensive; that, considering our population, only a relatively few textile fire injuries and fatalities occur each year and therefore there is little need for improvement in the flame-resisting characteristics of clothing and home furnishings, assuming that the most dangerous articles, like those notorious brushed rayon sweaters, are kept off the market.

Unfortunately, most of the textile materials that we use in our everyday activities will burn. From a practical, economic viewpoint we obviously cannot rule out all such materials as being hazardous or dangerous. We all know that most of the apparel and home furnishings that we buy are reasonably safe, but this is because they are rarely exposed to fire. The homemaker by experience, education and intuition knows that her ruffled curtains will burn if exposed to flame, and she sees to it they are not so exposed. In public buildings we all demand, and the law requires, that decorative materials be fire resistant in order to eliminate this kind of public hazard.

Cotton is an example of a widely used apparel fiber which can burn, and yet millions of men wear cotton undershirts and dress shirts every day without any serious concern that they are endangering themselves. On the other hand, none of us now wears shirts made out of nitrate rayon, which once ignited burns rapidly and catastrophically, and which consequently was outlawed in the early 1930's. Our long term goal should be the development of essentially nonflammable apparel and home furnishings, but which have all of the other attributes that we as consumers want: attractive appearance, a wide range of colors, comfort, proper performance, durability and low cost.

10,000 Deaths A Year

U.S. Public Health statistics (*1*) show that in the U.S. there are about 10,000 deaths per year due to burns and thermal injuries. This is at a rate of about 5 deaths per 100,000 population. The frequency of burn injuries has been estimated at about 2 million per year, resulting in the hospitalization of about 100,000 people. Now maybe these are not high rates, and I am not saying that all of these burn accidents resulted directly from the flammability of textiles. Nevertheless, no matter how small the rate and the absolute number of burns and deaths, we must take every means at our disposal to try to reduce or eliminate them.

Concomitant with the passing of the amended Flammable Fabrics Act, an organization was created with which most of my technical colleagues are well acquainted: the Information Council on Fabric Flammability. All persons and organizations interested in reducing the hazards of flammable fabrics are eligible for membership, and most of our textile companies belong to it. Its purpose is: "to work for the reduction of morbidity and mortality from burns caused by flammable fabrics and related materials, by encouraging the exchange and dissemination of all pertinent technical information."

The Cure Is Prevention

Dr. George Crikelair, professor of surgery at Columbia Presbyterian Medical Center, is one of the founders of the council. In an article (*2*) entitled "Medical Aspects of Clothing Burns," he states:

"A burn is a most unpleasant experience. We doctors see too many of them. We cannot get the severely burned patients to survive. We earn good incomes by caring for these patients. We are anxious to lose this business. The greatest advances in medicine have been through *prevention*. Think only about smallpox, diphtheria and poliomyelitis. The cure for massive burns is in prevention.

"The problem strikes us medically because clothing burns most often are severe in extent and depth, and the morbidity and mortality rates are so high. The most common cause of *burns* in children is the scald from hot liquids. The most *lethal* in children of all ages is the clothing burn. It has been customary in rebutting the argument that clothing is the cause of the burn to state that the gas stove or the match that ignites the fabric is really at fault, that the child's running instead of dropping and rolling after the clothing ignites, have all created false factors in the clothing burn, that it is flammable liquid that causes the burn and not the burning clothing."

He goes on to state, "Whatever the ignition cause, doctors agree clothing burns are severe, often fatal, and if the clothing did not burn, the morbidity and mortalities would be largely eliminated. We must recognize that people are people. Children *do* run if their clothing catches fire. They are frightened and hurt. Stoves, matches and flammable fluids are here to stay, and there will be accidents. Despite untold money and time spent on burn research, medically we seem to have reached a plateau on the survival of the severely burned patient. Since so many of these burns are caused by burning clothing, the medical profession votes for prevention of these burns by encouraging the furtherance of flame-retardant clothing."

Scare Tactics

In some of the technical symposia that our textile technology fraternity has held in the last four or five years there has been talk about scare tactics, particularly the presentation by concerned physicians of pictures showing some horrible cases of burned people. And they *are* horrible to look at; one experiences the greatest feeling of compassion for those who have been so afflicted. These are the reasons why we must do everything within our power to prevent such catastrophes. The textile industry and the textile technologist no longer can say, "But burn accidents are so few that we need not pay any attention to them. We need not worry about fibers and fabrics that burn."

I say we do need to pay attention to them. Textile technologists and the textile industry are smart enough to be able to solve these problems and produce clothing and home furnishings that will have proper flame resistance in addition to all of the other attributes that people want.

I am reminded of what Vannevar Bush, the former vice-president of MIT and one of the most famous engineers of our time, said back in the early 30's about the potential for synthetic fibers (*3*). Now remember that the time was 1932 and the only man-made fibers we then had were the regenerated rayons. Bush said, "Will we ever make better fibers than nature in place of what we may call, with due apologies to the hard-working organic chemists, our present weak imitations? Well, there are 100,000 or so known organic compounds, with all sorts of combinations and states of physical aggregation. We have X-rays and polarized light, and ultracentrifuges with which to study them. There are quite a few thousand men in the world capable of constructive thinking. If we cannot beat a silkworm, I am ashamed of the human race."

Precisely at the time Bush made these remarks, Wallace Carruthers was in the midst of his polymer research at Harvard, and then at The Du Pont Co., doing just what Van Bush envisaged. Nylon resulted in 1938. So I say that if man can't come up with fibrous materials that will be less flammable and with all the other requisite properties, we too should be ashamed of our even better-trained scientists.

Evaluating Flammability

Among the criteria normally employed to evaluate the flammability characteristics of materials are: ease of ignition, rate of burning, ease of extinguishment, types and amounts of smoke and toxic gas generation, thermal shrinkage, thermal insulation ability, and integrity of the material at and during the time of heat and fire exposure (*4, 5*).

Ease Of Ignition

Ease of ignition is of major significance, particularly for young children, housewives and older persons, all of whom may be accidentally exposed to direct flame or heat. If materials are difficult or impossible to ignite, or if they immediately self extinguish on removal of the ignition source, then one need not worry about all of the other problems of burning rates, noxious gases or heat transfer properties.

It should be apparent, therefore, that a target objective in the development of fire or flame-resistant materials is their ability to withstand ignition in the first place. Here both the intrinsic characteristics of the fiber or polymer as well as the geometric state of aggregation of fibers, yarns, fabrics and garments are of obvious importance.

Textile materials, because they must be flexible, are necessarily made up of a large number of individual fibers of very small diameter. Thus the fiber surface-to-volume ratio is very high, and the opportunity for easy ignition and rapid combustion is proportionately high.

It is vital that present polymers be modified or new fibers developed which are intrinsically difficult and in the practical sense impossible to ignite. Later on I will show you some data on ignition temperatures and times for several new textile materials.

Rate Of Burning

Until we achieve reasonable success in developing textiles that ignite only with great difficulty or not at all, or are self-extinguishing, we must give serious attention to fabric burning rates. With carbon-base organic fibers, temperatures inevitably can be reached where ignition in air will take place. Then the rate of burning becomes important.

Most people recognize that, once ignited, cellulosic fabrics can burn fairly rapidly unless they are treated with fire-retarding chemicals. In comparison, wool textiles intrinsically have much better flame resistance and a lower burning rate. I'm sure most people who smoke recognize that a burning cigarette or pipe tobacco ember falling on a wool jacket is not considered particularly dangerous. Even where the fabric starts to burn, its rate is so slow that the fire can easily be tamped out.

I cite these two classes of fibers only to demonstrate that most people have a reasonable, logical ability to judge two different degrees of flammability risk. We ought to be able to establish rational maximum burn rates for specific garments and furnishings. The large and comprehensive fabric flammability study being conducted at the National Bureau of Standards should produce quantitative burning rate data. Attempts then should be made to correlate them with minimum acceptable performance levels in garments and home furnishings. Ultimately there must be reasonable subjective judgments made of the maximum burning rate permitted in a dress or sweater or other garment in order that the wearer may be protected against unreasonable fire risk. Government and industry should co-operate in the establishment of such standards.

High Temperature Resisting Fibers

During the Golden Scientific Decade of the 1960's, much research effort and money were expended in developing high temperature and fire resisting flexible fibers. A good part of this work was sponsored by the Department of Defense and NASA. Table I shows a list of high temperature resisting fibers, most of which also have excellent fire resistance.

Fig. 1 shows a plot of strength retention vs. temperature for some of the new materials that have come upon the scene. Using as a benchmark a strength retention of 40 per cent, it can be seen that regular nylon has a temperature capability of about 450F; Nomex, an aromatic polyamide, about 550; polybenzimidazole, a new fiber about which I'll have much to say in a few minutes, about 725; E-glass fiber about 925; carbon fiber about 950; and so on up through the superalloys and refractory metals, which may have thermal durabilities up to about 2000F. For ordinary or even protective clothing, carbon, glass, refractory or superalloy metal fibers are either too heavy or brittle, or both. Therefore, these materials cannot, at the present time, be given serious consideration for use in consumer products even if their costs were low.

Organic Polymers Promising

Some of the organic polymers, however, are most promising. Among these I shall discuss Nomex, Du Pont's aromatic nylon; Durette and Fypro, modified aromatic polyamides produced by Monsanto and Travis Mills, respectively; Kynol, Carborundum's phenolic base fiber; polybenzimidazole (PBI), developed by the Air Force and currently being manufactured by the Celanese Research Co. on a government-owned pilot plant; and certain proprietary modified aromatic polyamides and PBI's developed by my colleagues at Fabric Research Laboratories.

In showing you some of the properties of these new candidate fire-resisting materials, I will also give you counterpart information on untreated cotton and fire-resisting treated cotton for comparison.

The flammability characteristics of textile fabrics are functions of both intrinsic fiber properties and yarn and fabric structure. (Garment design also deserves equal consideration.) Therefore, in our work we attempted to hold all geometric parameters constant, developing and testing, wherever possible, fabrics of the same fiber and yarn size, threads per inch, thickness, weight, weave, etc.

With respect to thermal fire criteria, the following properties were measured: (1) Ignition temperature and time. (2) Burning rate. (3) Thermal shrinkage. (4) Thermal conductivity. (5) Heat transfer characteristics upon flame impingement. (6) Special fire pit testing of mannekins clothed with experimental garments; the tests were conducted at the U.S. Army Natick Laboratories fire pit test facility.

Ignition Temperature And Time

The ignition temperature determination is made by holding a vertically oriented fabric test specimen against a Calrod type heater, to which a thermocouple has been bonded, and then increasing the electrical power and hence the temperature of the heater until the fabric ignites. The temperature of the surface of the heater at the instant of initiation of burning is the approximate fabric fire point. The number of seconds of contact with the Calrod unit to produce ignition is recorded as "time for ignition."

Table II lists air ignition temperatures and times for a rational series of test fabrics. Each block in the table states that ignition did not (No) or did (Yes) occur. The number of seconds of exposure time of the specimen against the Calrod is listed underneath. For example, at 1500F the natural undyed Nomex did not ignite after 40 seconds of exposure; at 1450F the No/Yes indicates that two specimens did not and one did ignite after 40 seconds of exposure; at 1600F the Nomex ignited in one second. Untreated cotton, as a benchmark, ignites immediately at approximately 1000F.

From the table one can see that some of these new exotic materials have remarkably high ignition temperatures. Table III summarizes ignition temperatures where contact times do not exceed 8 seconds. PBI, particularly, shows promise, not only because

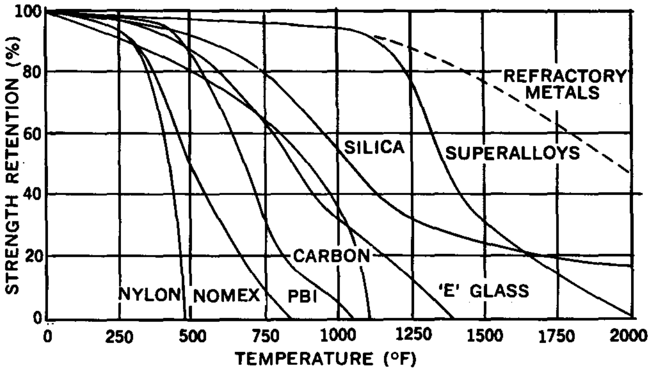

Fig. 1—Strength retention versus temperature.

Table I—Candidate High Temperature-Fire Resisting Fibers

Polymeric
Aromatic Polyamides: Nomex (Du Pont); X-101 (Monsanto)
Polybenzimidazole: (PBI) (Air Force)
Polyoxadiazole
Polyimide: PRD-14 (Du Pont)
Poly dihydro dioxo bis benzimidazo benzo phenanthroline
Phenolic: Kynol (Carborundum)
Modified Polyamides: Durette (Monsanto); Fypro (Travis Mills); Aromatic T (Fabric Research)
Modified Polybenzimidazole: PBI-S (Fabric Research); PBI-T (Fabric Research)

Glass
E-Glass
AF-S994 special glass
Quartz

Carbonaceous Residue
Carbon
Graphite

Metallic
Stainless steel
Superalloy

Refractory-Whiskers
Alumina
Zirconiz

Boron

Table II—Fabric Ignition Temperatures (In Air at 14.7 PSIA)

	Fabric Weight (Oz/Yd²)	Calrod Temperature °F							
		1400	1450	1500	1550	1600	1650	1700	1800
Untreated Cotton	4.5	Ignites Immediately At About 1000F							
FR Treated Cotton	4.5	No 120 Sec	No 90 Sec	Yes 1 Sec					
Dyed Nomex	5.0	No 60 Sec	No/Yes 60 Sec	Yes 5 Sec	Yes 5 Sec	Yes 5 Sec			
Natural Nomex	6.5			No 40 Sec	No/Yes 40 Sec	Yes 1 Sec			
Kynol	7.0	No 60 Sec	Yes 7 Sec	Yes 3 Sec	Yes 2 Sec				
Fypro	4.3			No 60 Sec	No/Yes 60 Sec	Yes 1 Sec			
Durette	4.7					No 30 Sec	Yes 25 Sec		
PBI	5.4						No 300 Sec	Yes 120 Sec	
PBI	4.8					No 300 Sec		Yes 6 Sec	Yes 3 Sec
PBI-S	6.0					No 30 Sec	Yes 2 Sec		

Table III—Fabric Ignition Temperature Ranges (In Air at 14.7 PSIA)

	Weight (Oz/Yd²)	Ignition Temperature (°F)
Untreated Cotton	4.5	—1000
FR Treated Cotton	4.5	1500
Dyed Nomex	5.0	1450-1500
Natural Nomex	6.5	1550-1600
Kynol	7.0	1450
Fypro	4.3	1550-1600
Durette	4.7	1650
PBI	5.4	1700+
PBI	4.8	1700
PBI-S	6.0	1650

Table IV—Limiting Oxygen Index Values for Spun Fabric (From Tesoro and Meiser[7])

Fabric	Weight (Oz/Yd²)	LOI
Acrilan	6.5	18.2
Arnel Triacetate	6.5	18.4
Acetate	6.5	18.6
Polypropylene	6.5	18.6
Vinylon (PVA)	6.5	19.7
Rayon	6.5	19.7
Cotton (Greige)	6.5	20.1
Nylon	6.5	20.1
Polyester	6.5	20.6
Wool (Drycleaned)	7.0	25.2
Dynel	6.5	26.7
Nomex N-4274	4.8	28.2
Phovyl (PVC) 55	6.5	37.1

Table V—Effect of Fabric Weight on LOI Values (From Miller and Meiser[8])

	Weight (Oz/Yd²)	LOI
Cotton Sheeting	4.2	18.2
	8.2	18.5
	12.5	18.8
Wool Felt	2.5	23.0
	5.0	23.3
	7.5	23.7
Polyester Felt (Pressed)	3.0	19.4
	6.0	19.9
	9.0	20.9
Nylon Fabric	6.5	20.1
	8.6	21.2
	14.4	23.5

of its excellent ignition resistance, but because it also appears to have outstanding textile qualities in terms of fabric hand, drape, comfort and physical properties.

Two other methods of ignition were also investigated: (1) a standardized sample of burning facial tissue, with a burning time of 3 seconds; and (2) a propane torch, with a burning time of 10 seconds. The conclusions drawn from these direct flame tests essentially corroborated the Calrod results.

For conventional apparel and home furnishings we probably do not need the ignition resistance of a PBI. I am not sure that we really know what the maximum contact time-minimum temperature relationship should be to achieve fire-safe products. In at least one government standard, the time of contact of the open flame to the test specimen is stipulated to be one second. To me this is not only improper it is absurd.

Fabric Burning Rates

A pertinent related criterion is the tendency of the fabric, once ignited, to continue to burn even after the ignition source is removed. Here another recently developed test method, originally proposed by Fenimore and Martin (*6*), can be employed. This is called the Limiting Oxygen Index (LOI) and is defined as the minimum concentration of oxygen in a slowly rising mixture of oxygen and nitrogen that will just support sustained combustion of the material. Since the percentage of oxygen in air at standard conditions is about 21%, it is apparent that materials which continue to burn freely in air have LOI values less than 21%. Cotton fabrics, for example have LOI's in the range of 17 to 20%. Reduce the level of O_2 below 17% and the cotton will not continue to burn, once the ignition source is removed.

The LOI thus becomes an excellent criterion for evaluating the propensity of a fabric, once ignited by an external source, either to continue to burn or to self extinguish, once the ignition source is removed.

Table IV lists LOI's of commercial fabrics as measured by Tesoro and Meiser (*7*). Using 21% of the line of demarcation, one can easily assess the relative rankings of the various fibers.

Miller and Meiser (*8*) show in Table V that LOI's are almost independent of fabric weight within conventional ranges. There is a slight trend upward with weight increase. The LOI thus appears to be a valid criterion of the intrinsic flammability of the fiber, essentially unaffected by yarn and fabric geometry within conventional fabric weight ranges.

Table VI lists LOI's for our new candidate materials. Their advantages appear obvious.

Assuming that a fabric has a high ignition temperature and a high LOI (the two are obviously interrelated), are these not enough to make the fabric fire safe?

For conventional clothing or home furnishings, the answer is probably "Yes." Assume that such fabrics accidentally come into contact with a direct flame for a relatively short period of time, say 3 to 10 seconds, and then the flame is removed. If the fabrics ignite at all, they will probably immediately self extinguish. This can be the kind of situation that pertains when one accidentally brushes a sleeve against a gas burner or candle, or drops a lighted match on his clothing. If all of us had high ignition temperature-high LOI clothing, much of the fabric flammability hazard would be eliminated.

Table VI—Limiting Oxygen Indices of High Performance Fabrics

Fabric	Weight (Oz/Yd²)	LOI (% O_2)
Untreated Cotton	4.5	16-17
FR Treated Cotton	4.5	31-32
Natural Nomex	6.5	27-28
Dyed Nomex	5.0	25-27
Kynol	7.0	29-30
Fypro	4.3	29-30
Durette	4.7	35-38
PBI	5.4	38-43
PBI-S	6.0	42-49
Nomex-T	6.5	42-52
PBI-T	6.0	65-75

A more serious problem exists, however, when the ignition source is not quickly removed—for example, in a house or factory or aircraft fire where other burning materials are serving as fuel. Here fabrics with high ignition temperatures and high LOI's can be of great advantage in terms of protecting the body, provided that they are thermally stable and do not shrink, and that they maintain their structural integrity and do not become brittle or friable such that body movements will cause them to split apart and fail.

Thermal Shrinkage

Many textile fabrics, when exposed to temperatures approaching their melting or decomposition points, will shrink severely. Such shrinkage can cause the garment to pull tighter over a person's skin surface. The insulating layer of air between the skin and fabric is reduced or eliminated, the heat transfer increases significantly, and a much more severe skin burn can result, even if the fabric doesn't ignite.

Wherever people are exposed to the dangers of direct flame or high heat fluxes, it is important that their garments do not shrink thermally and that fabric integrity is maintained. Where there is sufficient thermal insulation and little or no thermal shrinkage, the protection given the person is greatly increased. Figs. 2 and 3 show two Air Force flight suits that were exposed to a jet fuel fire at the U.S. Army Natick Laboratories fire pit test facility. In Fig. 2 the garment has shrunk, pulling tightly over the mannekin's body. In Fig. 3 the fabric did not shrink significantly, and has essentially retained the same configuration as it had prior to fire exposure. Its advantage is obvious.

Fig. 4 plots fabric shrinkage as a function of exposure temperature. At temperatures above 800F the Nomex fabric was badly charred and curled,

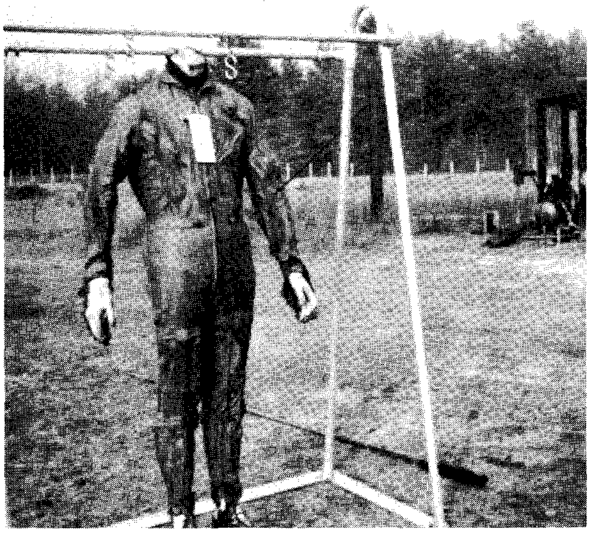

Fig. 2—PBI suit exposed to fire test.

Fig. 3—Stabilized PBI suit exposed to fire test.

making an accurate measurement of shrinkage very difficult. At 900F most of the PBI samples exhibited curling and embrittlement; the Durette fabric was embrittled and slightly shrunken. However, the Fypro fabric, despite its 18% shrinkage, remained relatively soft and flexible after the 900F exposure. PBI fabric exhibits considerably less shrinkage upon exposure to hot air than does Nomex. However, even this thermal shrinkage may be too great for many potential applications. Fypro and Durette exhibit approximately one-half the shrinkage of PBI at temperatures up to 900F. Because of the shrinkage problem, thermal stabilization processes have been developed for PBI. Referring back to Fig. 3, this is a photo of a suit made from stabilized PBI (*9*), and identified in Table II as PBI-S. This work is still under development.

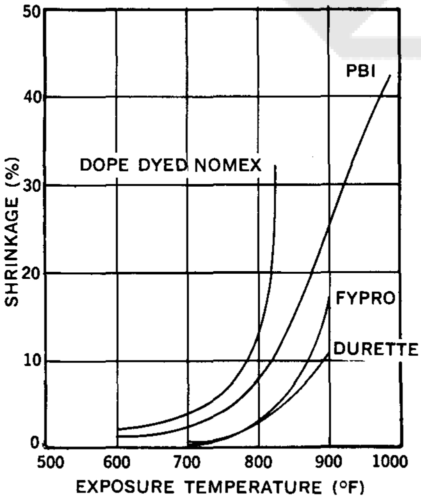

Fig. 4—Shrinkage of dope dyed Nomex, PBI, Fypro and Durette fabrics at elevated temperatures (average of warp and filling).

Thermal Integrity

Another parameter partly related to thermal shrinkage is the ability of clothing to maintain structural integrity upon exposure to heat or fire. If a fabric ignites easily and burns completely, leaving no structural residue, the skin is left exposed and burns can be severe. In contrast, a material which even under high thermal exposure does not burst into flame but only chars and pyrolizes while retaining its structural and dimensional integrity can render significant protection to the individual. Particularly for thick materials, the outer layers can burn. If the burned layers then do not break away and drop off, but rather maintain their shape and retain some strength and flexibility, they then can become a fire-resistant layer, protecting the fabric layers and the person within. This is the kind of ablative mechanism that is employed to protect space vehicles from being burned up by aerodynamic heating on re-entering the earth's atmosphere.

I suggest that, for protective clothing, studies should be made of the thermal insulation and mechanical properties of fabrics during and after their exposure to fire as these properties may pertain to the protection of the wearer. There has been little attention paid to this area of endeavor.

Flame Impingement

The ability of these candidate materials to withstand the impingement of a direct flame has also been studied. The fabrics are directly exposed to a propane gas burner under controlled conditions, and the temperature rise in a plastic skin simulant on the other side of the fabric is measured, via thermocouples, as a function of time.

The skin simulant, developed by the Naval Materials Laboratory, is composed of a resinous compound with thermal and optical properties similar to human skin. The severity of skin burns depends upon the integral of the time temperature profile.

The ability of the skin to withstand increased temperatures over selected time periods can be summarized as follows: A skin temperature *rise* of 21F is the approximate upper limit at which a human subject would feel no pain nor sustain any burn injury even if skin tissue were maintained at this temperature rise for an extended period of time. At a temperature rise of 32F, a human subject would sustain first degree burns after 8 to 9.5 minutes, and second and third degree burns thereafter. At a temperature rise of 50F, a human subject would sustain first degree burns after 2 to 3 seconds, and second and third degree burns thereafter. Thus you can see that the human body cannot withstand large temperature increases for any length of time, and this is why it is so important that protective clothing function as good thermal insulators, as well as being nonflammable.

The heat flux caused by a flame im-

Table VII—Temperature Rise in NML Skin Simulant for 3-Second Flame Exposure

Fabric	Max. Temperature Rise (°C) First Exposure (3-Sec)	After Multiple 3-Sec Exposures
Natural Nomex	27	33
Dope Dyed Nomex	35	39
PBI	24	34
Durette	33	35
Fypro	25	26

Fig. 5—U.S. Army Natick Laboratories' fire pit test facility.

Fig. 6—Clothed mannekin being tested at Natick fire pit.

pinging on the skin simulant was determined by exposing the simulant to a 3-second standard flame exposure. Without a protecting fabric, the temperature rise in the skin simulant was about 61F, equivalent to a heat flux of about 1.7 calories per square per meter per second. Most of the testing was carried out using this 3-second flame exposure, since this was the dwell time of clothed mannekins exposed to the fire pit test.

The average maximum temperature rises within the skin simulant, covered with single layers of various fabrics for 3-second flame exposures, are tabulated in Table VII. Since the PBI fabrics were virtually undamaged by 3-second flame exposures, some samples were deliberately exposed repetitively. Higher temperatures in the skin simulant were recorded during the second and third exposure, with a general leveling off of peak temperature after three, four or more exposures. Presumably this is due to the presence of moisture or other volatile materials in the specimen, which is evaporated during initial flame exposures. This demonstrates that the thermal protection potential of a fabric may depend significantly on its initial moisture content.

Fire Pit Tests

To correlate the laboratory tests with simulated performance tests, the Air Force and the Army conducted a series of tests at the U.S. Army Natick Laboratories fire test facility (Figs. 5 and 6). In the test, fully clothed mannekins are drawn over a 30-foot long pool of burning JP-4 aircraft fuel at a rate of 10 feet per second. Thus the total flame time is 3 seconds. Flame temperatures are in the order of magnitude of 1800 to 2000F.

From observations made by Fabric Research Laboratories personnel, it was apparent that the PBI suits were superior to those fabricated from dope-dyed Nomex, while FR treated cotton suits were poorest. Fig. 7 shows the condition of the three suits, tested in duplicate, after fire exposure. The left suit in each set is PBI, the middle is Nomex, and the right is fire resistant cotton. Portions of both the FR cotton and the Nomex coveralls were burning as the mannekins came out of the flame. The temperature sensors under the suit indicated that burns covering 50 to 60% of the body would have occurred with the Nomex suits, while a maximum of 5% of the body surface was burned with the PBI suits.

The Nomex suit burned in the jet fuel flame because its ignition temperature, 1450-1500F, is lower than the fuel flame temperature of 1800 to 2000F. The ignition temperature of the PBI fabric at 1700F is also lower than the fuel flame temperature. However, as has been previously stated, the PBI must be exposed to high temperatures for longer than 3 seconds before there is any visible sign of ignition. In contrast, the Nomex ignites within seconds.

Both the PBI and the Nomex suits exhibited considerable thermal shrinkage—that of the PBI suit being somewhat less than the Nomex. Shrinkage leads to intimate contact of the fabric with the mannekin, and thereby a

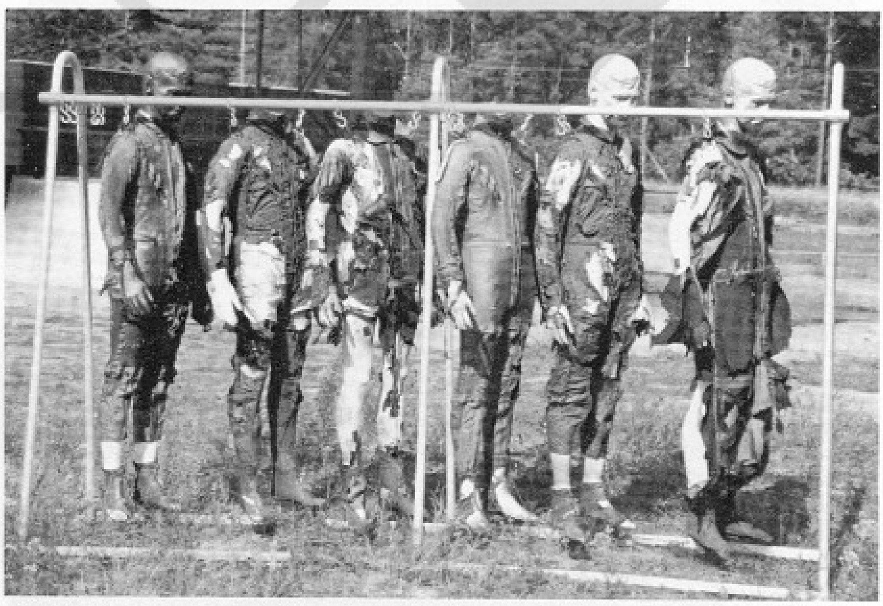

Fig. 7—Candidate suits after exposure to fire pit tests. Left to right: PBI, Nomex, FR cotton, PBI, Nomex, FR cotton.

larger temperature build-up on the mannekin surface. A suit fabricated from thermally stabilized PBI-S fabric (Fig. 3) exhibited no noticeable dimensional changes and no damage after three passes through the fire pit.

Table VIII is from a recent report by the Natick Laboratories entitled "The Behavior of Protective Uniforms in Large Scale Simulated Fires" (*10*). A temperature-area index, based upon the area of the mannekin that has sustained unacceptable temperature increases, is employed to assess the protective capabilities of the various suits. A garment damage rank is also listed. Of the materials tested, including both commercial and experimental polyamides, the PBI appears to have taken first place.

By now you must realize that I am personally extremely enthusiastic about the potential of PBI. I think it is a development which can contribute greatly in the field of protective clothing. At the moment it is being manufactured experimentally only under government sponsorship. As taxpayers you may be interested to learn that until recently the cost was $200 per pound, but is now only $175 per pound. It is my understanding that if the Department of Defense sees fit to proceed with a full-scale plant, the price conceivably could come down to about $5 per pound in quantities of a million pounds.

Some other attributes of PBI are its excellent soft hand, with good strength, toughness and abrasion resistance. It has a moisture regain of about 12%, and this may be a factor in making it a comfortable fabric to wear. Its prime deficiency is that, like Henry Ford's Model T, you can have it in almost any color you want provided it's golden. Dyeing and light fastness problems remain to be solved.

Finally, I must state that I am not here to tell you that the PBIs or Nomexes or other high temperature exotic fibers will solve all of the flammable fabric problems, and that in future years our most popular and widely used fibers—cotton, wool, rayon, nylon, polyester and the acrylics—will no longer be produced. I hope that they will continue to be produced but

Table VIII—Comparison of Rankings of Hot Weather Uniforms (From U.S. Army Natick Labs TR 71-40-CE)

Temperature-Area Index Rank	Uniform System	Garment Damage Rank
1	PBI	1
3	Aromatic Polyamide A	2
2	Army Tankers (CA)*	3
8	PBI/CA*	4
4	Aromatic Polyamide B	5
6	Aromatic Polyamide C	6
7	Army 2-Piece (CA)*	7
5	Modified Aromatic Polyamide	8

* CA = Commercial Aromatic Polyamide

in modified forms so that they will have far better flame resistances.

The point is that for protective clothing we now *do* have materials that will give significantly greater protection to people in hazardous occupations, and we should be thinking about how these fibers can be used for consumer applications.

The point is that we don't need a PBI or a Durette to withstand the everyday hazards that children and old people particularly encounter—the child playing with matches, or the woman brushing her housecoat against a gas stove while she is scrambling the eggs.

The point is that so many clothing fires do stem from relatively short contacts with a flame.

If we can develop materials or treatments that can raise ignition temperatures and times and LOIs, we will have gone a long way towards protecting people from unnecessary fire hazards. Effort leading to the reduction of such hazards must be continued.

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