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Evaluation of Fire Retardant Fabrics

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EVALUATION OF FIRE RETARDANT FABRICS

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13. ABSTRACT

The validity of current experimental methods of evaluating fire retardant clothing is discussed. Two synthetic materials, Nomex and Polybenzimidazole (PBI) are compared in terms of their physiologic protective capabilities. The data indicates PBI is superior to Nomex in affording slightly longer protection. Several recommendations are made.

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FOREWORD

This technical report was written to provide an objective approach to the evaluation of flame retardant materials and to make recommendations concerning Nomex and Polybenzimidazole (PBI) materials. Lt Colonel James H. Veghte and Dr. Adolf Marko are members of the Aerospace Medical Research Laboratory, Aerospace Medical Division, while Colonel Charles Wilson is a member of the Life Support SPO, Aeronautical Systems Division, Wright-Patterson AFB, Ohio.

This technical report has been reviewed and is approved.

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SECTION I
INTRODUCTION

Aircrew members are frequently subjected to a flame environment in crash landings. During the past 5 years, 210 Air Force aircrew members have sustained burn injuries. This number included 7 injuries classified as minor, 124 as major, 81 fatalities, and involved 4207 days out of service (1). Significantly, more deaths of USAF aircrew and passengers may be attributed to aircraft fires than unsuccessful ejections. For example, during 1966 and 1967, 90 deaths were caused by aircraft fires whereas 50 deaths resulted from unsuccessful ejections (2,3).

USAF personnel have survived brief exposures to burning JP-4 fuel while wearing fire retardant fabrics. One pilot estimates he was directly exposed to a fireball of burning JP-4 fuel for a maximum of 2 seconds while he descended in his parachute. He sustained moderate reversible burns that did not require skin grafting. In another instance, a pilot, fully prepared for rapid egress, survived a roaring JP-4 fire after an exposure of 3 seconds (time estimated by standby fire fighters and ground observers). The person seated in the back seat was exposed to the heat for 6 to 8 seconds. At the time of the fire, he was disconnected from all personal leads. He died of kidney, lung and blood complications secondary to extensive burns. Accurate times of exposure to fire cannot usually be obtained and therefore survival times are based on a subjective time frame. From this very tenuous data, 3 seconds may be realistic in terms of protectiom time. This 3-second exposure time would apply to an uninjured aircrew member who is surrounded by a burning jet fuel fire and, providing he is released from his aircraft equipment, the canopy is already open, holds his breath as long as possible, and runs rapidly through the fire.

These data indicate the necessity for continuing research in developing more flame resistant materials. Research in this area has been conducted for a number of years by the three military services.

The development of new synthetic fibers has now reached a point where a review of their protective properties with respect to the human is necessary. Material testing with heat transmission apparatus or simulated post crash fire exposures are useful but, to be relevant, these results must be related in terms of actual protection of aircrew members.

SECTION II

PROTECTIVE CAPACITY

Table 1 relates the physical properties of Nomex and PBI to predicted time of blistering during actual flame contact. But, it is difficult to make an exact comparison between any two given materials because of the many variables. The time to blister for skin exposed to high radiant loads near a fire provides a comparison of the thermal effects by radiation alone. For example, with a 9 x 9m fire (30' x 30'), the time to blister at a distance of 6.1m/30 ft is 1.3 sec, at 15.2m/50 ft blister time is 4.2 sec, and at 30.4m/100 ft the time is > 12.0 sec (4). These data were obtained from laboratory tests using both skin simulants and animal skin.

LABORATORY TESTING PROCEDURES

Heat Transmission Apparatus

A modified heat transmission apparatus is currently being used in the evaluation of heat transmission through fabrics (5). In essence, the device exposes a test swatch or a fabric covered skin simulant to a metered flame from a Meeker Burner. A shutter coupled with a timer ensures reproducible flame exposure time. The temperature of the material or skin simulant is measured by means of an embedded small gage thermocouple. Reproducibility is reported to be ± 1% over full scale. Rapid recorders graph the temperature-time history.

Animal Burn Studies

Various animals have been used to assess the extent of burn damage (6). Rats or pigs have traditionally been involved in bioassays: rats because of availability and ease of handling; pigs because of their skin's similarity to human skin. Extrapolation from animal burn data to human may be in error but it is thought that this error would be small or negligible. Theoretically, absorbed energy would have identical effects regardless of the type of animal's skin. The amount of absorbed energy would be so large in flame environments that differences in thickness, or vascularity would have a very small effect on resultant burn injury. Therefore, data establishes the fact that, for equal amounts of absorbed energy in rat's skin, the same burn injury occurs regardless of the energy source, flame contact, or thermal radiation (6).

TABLE 1

PREDICTIVE TIME TO BLISTER *

NOMEX						POLYBENZIMIDAZOLE						
Description of Material	Weight (g/m^2)	Weight (oz/yd^2)	Thickness mm	Thickness mils	Time to Blister(Sec) Flame Contact (1200°C)-1.3 cal/cm²	Description of Material	Weight (g/m^2)	Weight (oz/yd^2)	Thickness mm	Thickness mils	Time to Blister(Sec) Flame Contact (1200°C)-1.3 cal/cm²	Difference in Time to Blister(Sec) PBI vs Nomex
Filament, Undyed	168.5	5.00	0.250	9.8	1.9	Filament	168.5	5.00	0.253	9.9	2.1	+0.2
Staple	162.0	4.82	0.510	20.5	3.2	Staple	176.0	5.20	0.538	21.2	3.2	0.0
Staple	138.0	4.10	0.280	11.2	1.9	Staple	140.8	4.15	0.310	12.4	3.0	+1.1
Staple - 2/2 Twill 1.5 DPF	141.6	4.20	0.320	12.7	1.9	Staple - 2/1 Twill 1.5 DPF **	122.0	3.6	0.320	12.7	2.1	+0.2
Staple - 2/2 Twill	205.9	6.10	0.400	16.0	2.4	Staple - 2/1 Twill 1.5 DPF	210.0	6.2	0.390	15.4	2.5	+0.1

*CRITICAL FACTORS IN ORDER OF IMPORTANCE IN HEAT TRANSFER STUDIES

1. Thickness
2. Construction
3. Bulk Density
4. Air Permeability
5. Fiber Type (After Ignition This Factor Becomes the Most Important)

** A 2/2 Twill fiber would provide more protection than the 2/1 Twill because of construction

References: The first three materials were assessed by Stoll at NADC, Johnsville, Pa., the latter two by Stanton at Materials Laboratory, Wright-Patterson AFB, Ohio (14,7).

FIELD TESTING PROCEDURES

Temperature Indicators

Two paper temperature sensitive indicators are currently being used to extrapolate dummy surface temperatures to human skin burn injury. One type of indicator was developed by Loconti and consists of temperature sensitive organic pigments printed on black absorbing paper (11). These pigments have different melting points and, if a pigment melts, at least this temperature was reached in that area. The second type of temperature sensor is vesicle paper. Color changes of the paper are compared to calibrated standards. Recalibration is done periodically.

Simulated Post Crash Fire Facilities

Two fire pit facilities presently exist on military installations (8, 12). One pit is located at Maynard, Massachusetts, and the other pit at the Naval Air Development Center, Johnsville, Pennsylvania. The one at Maynard has been operating for several years while one has existed for a longer time at the Naval Facility. Both pits are located out of doors. At Maynard, a small rectangular pit contains water upon which 25 gallons of fuel, usually JP-4, is poured. Three railroad tracks divide this pool to enhance uniform fuel coverage. In addition, the water surface tension is reduced by a prior additive. The dummy is dressed in the material to be evaluated and the dummy or dummies are run mechanically through the fireball. A cement block wall shields the dummies prior to the fire exposure. On command, two doors swing open, and the dummies are drawn through the fire for 3 seconds at the rate of 3.0m/sec or 10 feet/second. The fire temperature is monitored by a radiometer which measures flame wall temperature at the point of dummy exit. A low, curved metal wall is located about the pit to provide a windshield. The previously mentioned paper temperature indicators (19) have been placed under the clothing on the dummies' surface. A movie record is made of each exposure.

The Navy facility is similar in that a shallow water pool is used to contain the fuel. One difference in construction of the two facilities is that a 15 to 18 foot windshield wall completely encloses the entire pit. Another difference is the manner of exposing the clothed dummy to the flame. A boom swings out from behind a concrete wall and simply swings the dummy in a shallow arc through the fire. The rate of movement (3.0m/sec or 10 feet/second and exposure time - 3 seconds) is identical to the Maynard's regime.

EXPERIMENTAL VARIABLES

Temperature Indicators

The temperature sensors are not ideal for predicting degree of skin burn under clothing. A temperature-time profile should be obtained so that the reliability of flame exposures can be determined. Theoretically, small gage thermocouples could be located at various body sites and this information either recorded by an instrument placed within the dummy or telemetered. This approach is being considered by several groups. Other sources of error with the paper temperature indicators are aging of the organic pigments, and rubbing the indicators with fingers thereby possibly degrading their temperature sensitivity. To assess per cent of potential body burned areas by this means may represent an extrapolation that incorporates a large error. No positive correlation ($P > 0.1$) has been established between effacement of one (105C/221F) thermal sensor and predicting a second or third degree burn. More experimental data must be obtained to verify this extrapolation. The comparison of color of vesicle paper with calibrated standards would reduce this error. But the inherent problem with this technique is that it does not provide a temperature-time profile. This shortcoming can be overcome with the use of thermocouples and heat flux disks to record temperature-time histories during flame exposure.

Field Tests

A number of physical variables affects the flame environment. The amount of energy released by the fire is directly related to the type and quantity of fuel. Other variables involve the direction and velocity of the wind, time of flame contact, measurement of flame temperature actually encountered by the dummy, the number of dummies pulled through at one time may alter the convective pattern for succeeding ones, distance between dummies, and convective fire swirls. Additional sources of error may occur with rerunning dummies, clothing and dummy temperatures at the onset of exposure, location of the movie camera and fuel pooling. Ultimately, subjective assessment based on experience dictates the start of each run.

SECTION III

DISCUSSION

PHYSIOLOGICAL PROTECTION RELATED TO PHYSICAL FACTORS

Clinically, the burned patient often progressively deteriorates. After the initial burn exposure, the person may enter an accelerating cascade of events that could result in death. Depending upon their severity, burns may quickly create widespread havoc to the victim. Thermal injury destroys the ability of capillaries to retain salts, fluids, serum proteins, and red blood cells. Blood vessels may clot, cease to nourish, and dependent tissues weaken and atrophy. Considerable fluid loss from the circulatory system is a paramount and immediate problem. Often replacement fluids, plasma and cells, are poorly retained. Extensive tissue swelling may obstruct air passages and arterial supply to limbs and venous return. The resultant drop in blood pressure and reduced oxygen in the blood leads to poor lung ventilation or presence of lung fluid that creates major kidney damage in 10 per cent of burned patients. Extensive lung damage occurs in 30 per cent of burn deaths. In 75 per cent of the cases, extensive skin areas rapidly become infected with Gram negative and positive bacteria. These organisms frequently produce poisons that further insult blood vessels, kidney and the heart. Bleeding stomach ulcers may occur in 10 per cent of burned patients. Although the initial damage usually occurs to the skin and respiratory tract, the major causes of death result from secondary blood infections, kidney failure, or in some cases hemorrhaging stomach ulcers.

The initial estimation of burn damage is a considerable aid in burn therapy and predicting survivability or disability. Superficial burns are capable of regenerating new skin whereas "deep" burns are not. Skin grafting replacement is then required. Usually the extent of burn injury cannot be determined until 4 to 7 days have elapsed after the thermal shock.

Experiments with burns on human and animal skin have demonstrated two important facts:

- The degree of damage is independent of the mechanisms of heat transfer. Radiated heat causes the same effect as heat transferred by flame contact when equal amounts of emergy are absorbed in the skin (13).

• The rate of damage increases logarithmically with the increase in tissue temperature. At 47.5C the rate of damage is 10 times faster than at 45.0C and also the rate of damage at 50.0C is 10 times faster than at 47.5C (see fig. 1). The combination of these two facts may be employed to establish a relationship between absorbed energy rate in calories per cm^2 per sec and the tolerance time, that is, the time necessary to produce reversible burn injury (called survival) or irreversible destruction of the skin (blister). Unprotected human skin exposed to a heat pulse producing 0.5 $cal/cm^2/sec$ absorbed energy rate will be injured after 2.3 seconds (reversible) and destroyed after 3.4 seconds. At an absorbed energy rate of 0.9 $cal/cm^2/sec$, reversible injury will occur after 1-second exposure and destruction in 1.5 seconds. The tolerance time may be used to measure the relative protective effect of different fabrics. Instead of the previously used absorbed energy technique, the temperature rise of the skin simulant in response to a standardized heat pulse is used because it is directly measured by a thermocouple. For example, a temperature rise of 20C in the skin simulant in 3 seconds would be equivalent to destruction of skin in 3.0 seconds, to reversible injury in 1.9 seconds. The relative protective capacity of different fabrics may be defined in two ways. The first laboratory method is to consider that the minimum protection time from the flames has been assumed to be 3 seconds. Then, the temperature rise in a skin simulant covered with the fabric is measured and compared. Figure 2 shows that at a 3-second exposure time a temperature rise of 15C causes reversible injury (survival) and a 20C rise causes destruction. The second approach is to translate the temperature rise in the skin simulant into tolerance times for reversible and permanent skin damage. Using the first method and comparing Nomex and PBI fabrics of 14 mils thickness, the temperature rise of the skin under Nomex would be 20C while under PBI an 18.5C temperature rise occurs. In the first case, a 20C rise causes destruction of the skin under Nomex. In the second example, the 18.5C rise under PBI is still above the required 15C rise for reversible injury and resulting burns occur. This point is extremely important, and skin simulant temperature rise rates over 20C for 3 seconds results in blister damage and tissue destruction. Survival or reversible skin injury levels should not exceed

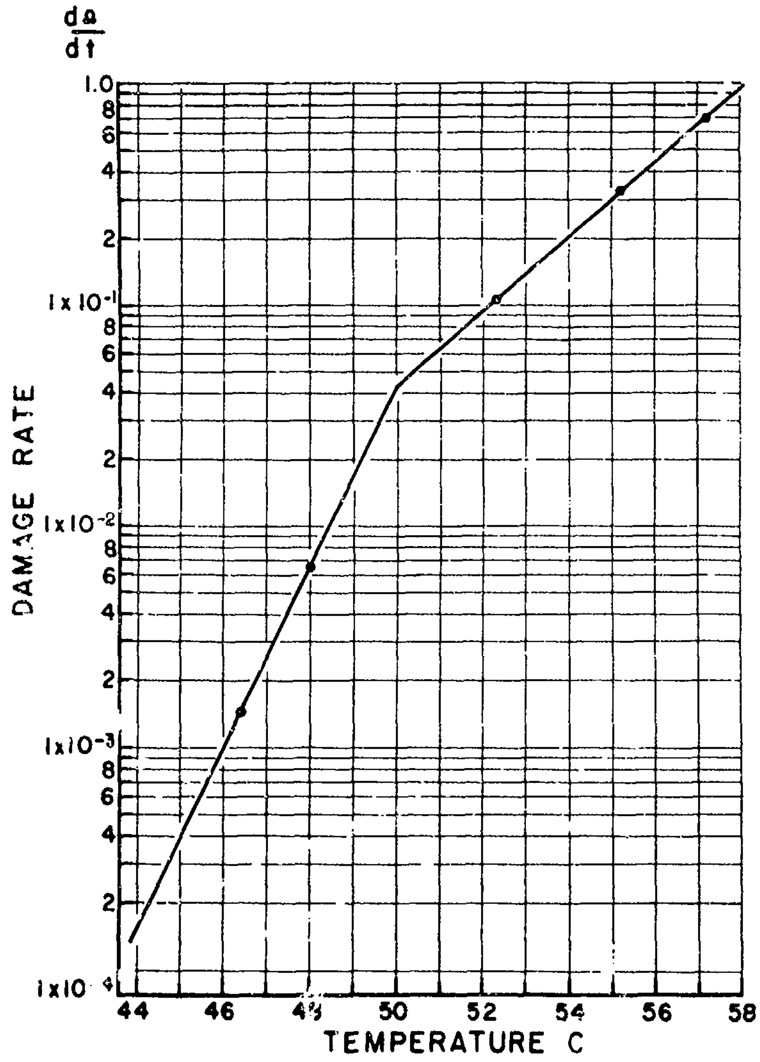

FIGURE 1 TISSUE DAMAGE RATE CHANGE WITH TEMPERATURE INCREASE (REF 14, REPRODUCED WITH PERMISSION OF A. M. STOLL)

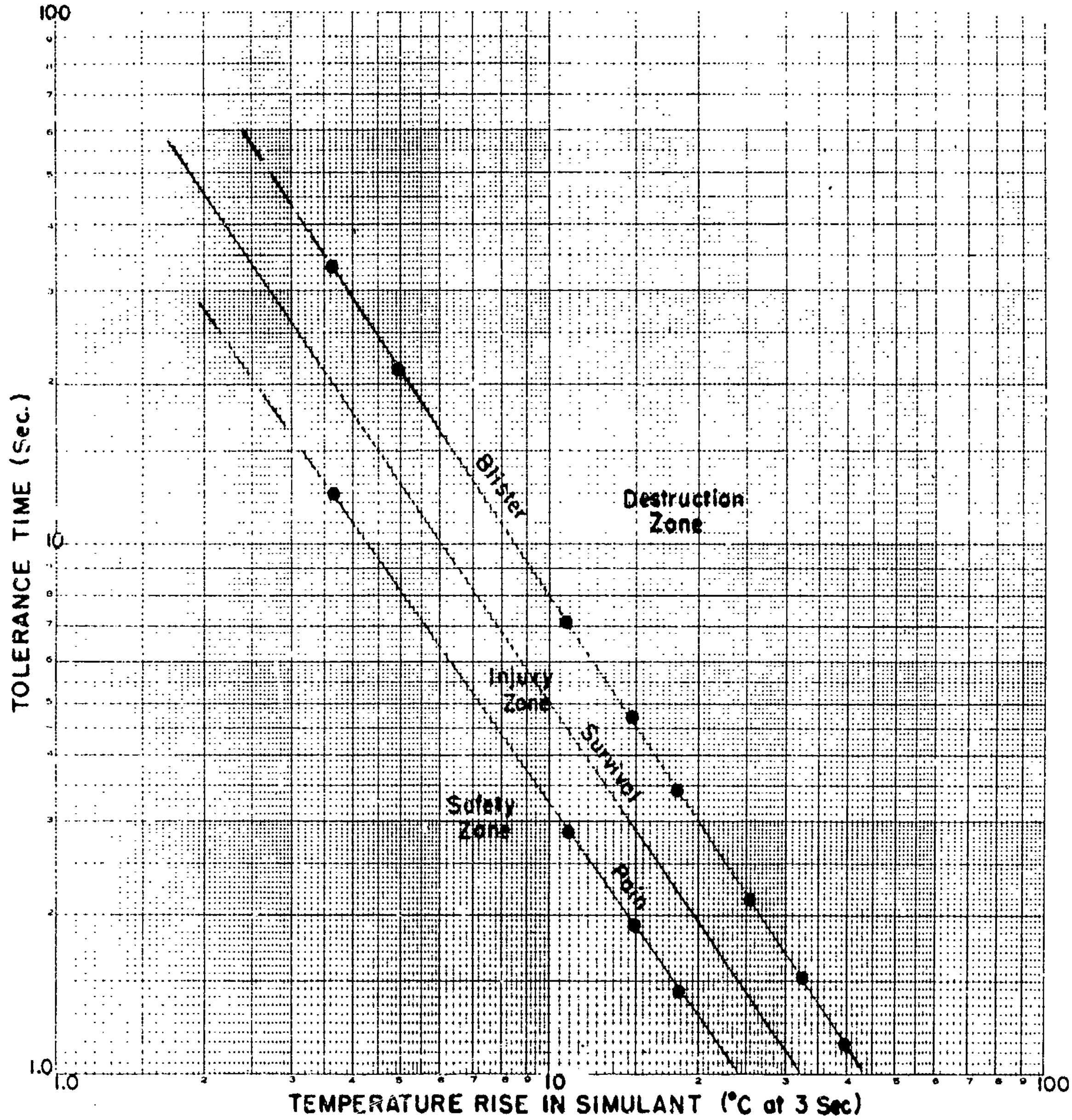

FIGURE 2. HUMAN SKIN TOLERANCE TIME INDICATED BY THE TEMPERATURE RISE MEASURED IN A SKIN SIMULANT AT 3 SECONDS EXPOSURE TO A RECTANGULAR PULSE (REF 14, REPRODUCED WITH PERMISSION OF A. M. STOLL)

15C for 3 seconds. Applying the second method for comparison of the fabrics, Nomex would result in a 3-second protection time and PBI would provide 3.4 seconds. This would mean that the skin would be permanently destroyed. For practical purposes, the protection time related to reversible injury is more important. For the same exposure conditions, reversible injury would occur after 2 seconds under Nomex and after 2.4 seconds under PBI. With increasing thickness of these two materials, the differences in protection time become smaller. Another important medical consideration is the inhalation of smoke or noxious gases that can result in the death of a person in a flame environment regardless of the type of clothing worn.

VALIDITY OF TEST PROCEDURES

Laboratory Tests

The relative protection capacities of materials that have been derived under certain laboratory conditions may not be valid. It was assumed in the comparisons for protective capacities that none of the materials burns away or ignite or cause damage by shrinking or are weakened in tensile strength to a degree of falling off the escaping man. A most crucial point is that the standard Nomex burns during a 3-second fire exposure whereas it doesn't always support combustion in the laboratory tests with simulant skin over the same time period. One reason probably being that the total energy in the Meeker Burner flame compared to the mass of the material and the skin simulant are so much less than the total energy available in large pit fires. Therefore, laboratory test results may be used for comparison of protection capacity, but these data may not be applicable to define the actual protective capacity of the materials in a flame environment. In other words, there are many additional factors to be considered and the sum of these factors may be much more significant than the comparatively small difference in the protection time derived from laboratory measurements.

Field Tests

The underlying philosophy of this type of testing is to expose entire clothing assemblies to potentially survivable flame environments. Testing of this type has been conducted for years and substantial advances in material selection have been derived from these experimental data.

Generalized observations, such as that certain types of Nomex support combustion and pull apart while PBI does not, are valid and justify the expense. But exact quantitative data cannot be obtained without controlling the many physical variables associated with the flame environment. These variables have been previously mentioned. An accurate baseline in which different flame environments could be equated is technically difficult. The surface temperature of the clothing and dummy would have to be measured in many locations to determine the energy flux leaking through the clothing buffer. Temperature-time histories are not now obtained, and instrumentation should be installed within the dummy to provide these data. Until these measurements are obtained, the accuracy of comparative clothing testing in field fire pits cannot be determined. Statistical treatment of the data will require an extremely large number of assembly exposures to obtain even reasonable accuracy because of the large number and magnitude of experimental variables. If it were feasible to control these variables, the number of exposures would be greatly reduced.

Other Selection Criteria

A large number of factors not related to burn protection have to be considered in the final evaluation of a given material. For aircrew acceptance, such factors as comfort, color, weight, and durability may far outweigh the intangible advantage of increased burn protection. Technically, shrinkage rate, moisture regain and cost must all be weighed against the increase in thermal protective capacity of any new material. Physiologically, the increase in survivability of Air Force personnel may hinge not only on advanced, more flame resistant clothing but protective devices to preclude inhalation of noxious fumes and more effective fire equipment in the aircraft;i.e., reflective mylar blankets, foam producers, protective foam buffers sprayed over the clothing, or single point harness releases. Therefore, the final evaluation of new materials that will be worn by aircrew personnel must be based not only on physical test data but on the physiological implications of these data and operational evaluation.

SECTION IV
CONCLUSIONS

Selection of a fire resistant material should be based on the evaluation of all relevant factors and not on heat transmission information alone. These other factors include aircrew acceptability, comfort, durability, moisture regain, color, and cost.

A study of the thermal protective properties of Nomex and PBI has shown that PBI is superior to Nomex for the following reasons:

- PBI does not ignite during a 3-second simulated post crash fire exposure whereas Nomex does. Therefore, it provides a physical buffer between the flame and the skin.
- Laboratory testing with a skin simulant also shows PBI affords better protection over Nomex ranging from 0 to 1.1 seconds.
- The shrinkage of the initial PBI material has been overcome in tests with small laboratory samples.

RECOMMENDATIONS

Research should continue to objectively select the most fire protective material. New materials are now available such as Kynol, Durette, and modified Nomex that should be thoroughly assessed before a final decision is made.

Simulated crash fire exposures combined with laboratory testing are important, but must be placed in proper perspective with all factors, such as physiological implications and practical circumstances, before a decision is reached.

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