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THE FLAMMABILITY OF SKIN AND HAIR IN OXYGEN-ENRICHED ATMOSPHERES

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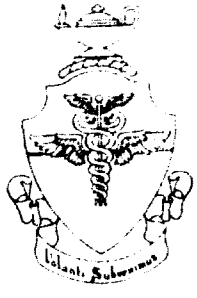

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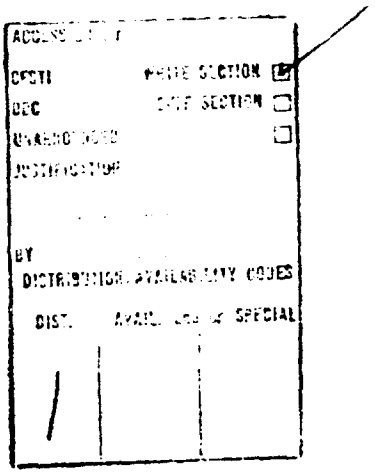

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FOREWORD

The work reported herein was performed by Atlantic Research Corporation, a Division of the Susquehanna Corporation, Alexandria, Va., under contract No. F41609-68-C-0013 and task No. 793002. Inclusive dates of the research were 1 November 1967 to 1 June 1968. The contract monitor was Captain William E. Mabson of the Environmental Physiology Division, USAF School of Aerospace Medicine. The paper was submitted for publication on 1 October 1968.

The appendixes, referred to in this paper, give additional information and are available in the Aeromedical Library, USAF School of Aerospace Medicine, under the title and number of this report. The appendixes have the following titles: appendix I, "Data from Fat, Water, and Hair Analyses of Pigskin and Human Skin Samples"; appendix II, "Test Conditions and Data for Skin and Hair Flammability Program"; appendix III, "Photographs"; and appendix IV, "Data on Human Skin Samples (All Autopsy Specimens)."

The author is indebted to Melvin Crompton and Philip Metz for their technical contribution to the program and to S. Eugene Nelson for his assistance in preparing the report.

This report has been reviewed and is approved.

GEORGE E. SCHAFER
Colonel, USAF, MC
Commander

ABSTRACT

The flammability of hair and skin from white suckling pigs and from humans was studied in atmospheres ranging in oxygen concentration from 20.9% (air) to 100%. Neither pigskin nor human skin would support combustion in pure oxygen at 258 mm. Hg except in the presence of an artifact consisting of exposed subdermal fat and local depletion of heat sink capability. Although pig bristles and human hair burn rapidly in pure oxygen, differences observed in flame spread rates and burning times indicate that skin of suckling pigs is not an adequate simulant for human skin in terms of response to an ignition source in pure oxygen.

Methods of protection against ignition were studied with pigskin samples. The helium concentration necessary to prevent flame spread at 1 atm. total pressure is 75% by volume. Salves and creams are effective against flame spread when the amounts applied are much larger than those normally used.

The values obtained from the present work on unshaved pigskin samples to determine flame spread rate and critical helium concentration (for zero flame spread) are completely consistent with reported values for other types of combustibles.

THE FLAMMABILITY OF SKIN AND HAIR IN OXYGEN-ENRICHED ATMOSPHERES

I. INTRODUCTION

Observations after recent fires involving human subjects in oxygen atmospheres indicate that the humans may have contributed to spread of the fires through combustion of their skin and hair. Since planned space missions will require that human subjects spend considerable time in oxygen-rich atmospheres, both in space and in preparatory studies on the ground, the determination of flammability of human skin and hair and methods of providing protection against such flammability is currently of significance.

The epidermis or outer layer of human skin is a tough covering about 1 mm. thick. The cells of this layer (corneum) no longer possess essential properties of life and are constantly sloughed off and replaced by new cells from living layers below them. The skin surface is modified by a complex surface film consisting of a mixture of materials held together by secretions of the sebaceous and sweat glands plus products of the cornification process. The chemical composition of the cornified cells in the outer skin layer is similar to that of hair. This material, termed keratin, consists of approximately 90% protein, 4% water, and 6% inerts. A sketch of a vertical section of human skin is shown in figure 1. The stratum corneum is the keratin layer.

The surface keratin, the deeper epidermis, and the dermis taken together contain roughly 75% water, 10% protein, 11% fat, and 4% inert material. Since the theoretical heat of combustion of these layers is about 1,400 cal./gm. and the heat required to vaporize the water is approximately 7,350 cal./gm. of skin, it appears likely that a maintained external source of heat will be necessary for the combustion of the entire skin thickness. The stratum corneum and the hair might be expected to burn independently of an external source, however, because the heat of combustion for keratin is approximately 3,400 cal./gm. and very little water is present.

One objective of this program was to determine flammability parameters—including flame spread rate, minimum ignition energy, and total burn time—for the skin and hair of humans and suckling pigs. The pigskin samples were investigated as a possible simulant for human skin. A second objective of the program was to determine the effectiveness of three types of protection against skin and hair flammability, including the use of glass fiber cloth, salves and ointments, and inert gases to dilute the oxygen atmosphere.

II. DEFINITION OF TEST CONDITIONS AND ANALYTICAL METHODS

Sample description

Pigskin samples were strips (5 by 10 cm.) cut from white suckling pigs not older than 8 weeks and weighing 7 kg. or less. Samples were used within 72 hours of slaughter. The pigs were slaughtered and skinned by a local veterinarian who also cut the skins into 5-cm. strips. Upon receipt, these strips were refrigerated prior to sample preparation. The 5-cm. strips were then cut to 10-cm. lengths, and a sufficient sample for analysis (usually about 10 gm.) was removed from between each pair of samples cut from the strips. This analytical sample was used to determine fat, water, and hair content. The thickness of the pigskin samples averaged between 0.5 and 1.0 cm.

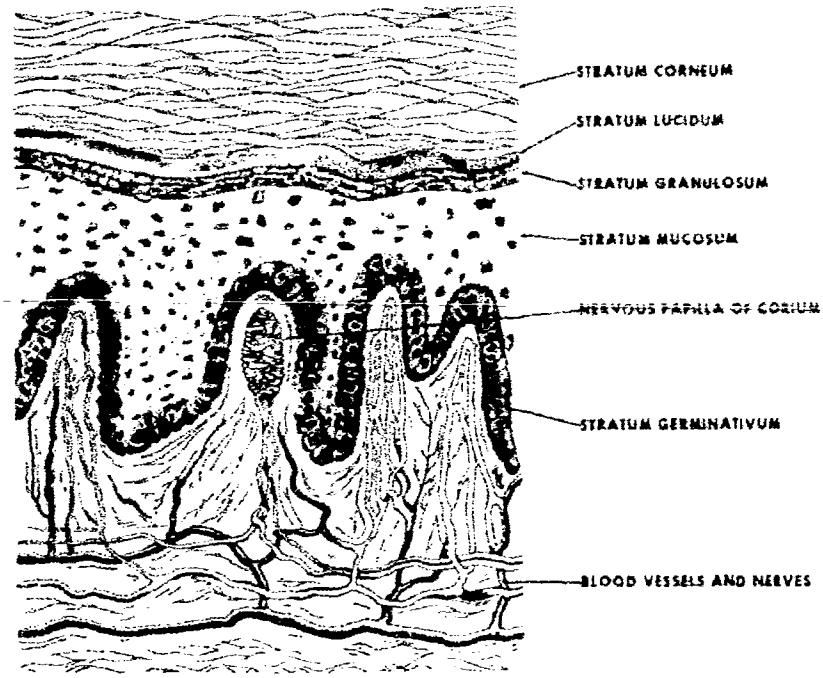

FIGURE 1

Vertical section of human skin.

In most samples significant subcutaneous fat was included, and muscle tissue was included on some.

Human skin samples were obtained from autopsies at local hospitals. Most of the human samples were nearly hairless, while significant hair was present on all of the pigskin samples. Some of the human skin samples used were available only in strips 2.5 cm. wide, but most were about 5 cm. wide. Sample lengths for the human skin specimens were approximately 10 cm. Preparation was similar to that for pigskin, except that a few strips were not large enough to allow fat, hair, and water determinations.

Sample mounting technic

Each sample was mounted in flesh simulant contained in a stainless steel pan (10 by 15 cm.). The skin sample plus simulant was at least 1.25 cm. deep to allow good heat sink simulation. The simulant material slightly overlapped the edges of the samples to prevent edge effects. A typical mounted pigskin sample is shown in figure 2.

The composition of the simulant, approximately that of the major dermal layers, is shown below:

		Percent
Water	—	75.0
Soap (fat simulant)	—	9.0
Hydroxyethyl cellulose gellant (fat simulant)	—	1.9
Gelatin (protein)	—	10.0
Sodium chloride	—	4.0
Bacteriocide and fungicide	—	0.1

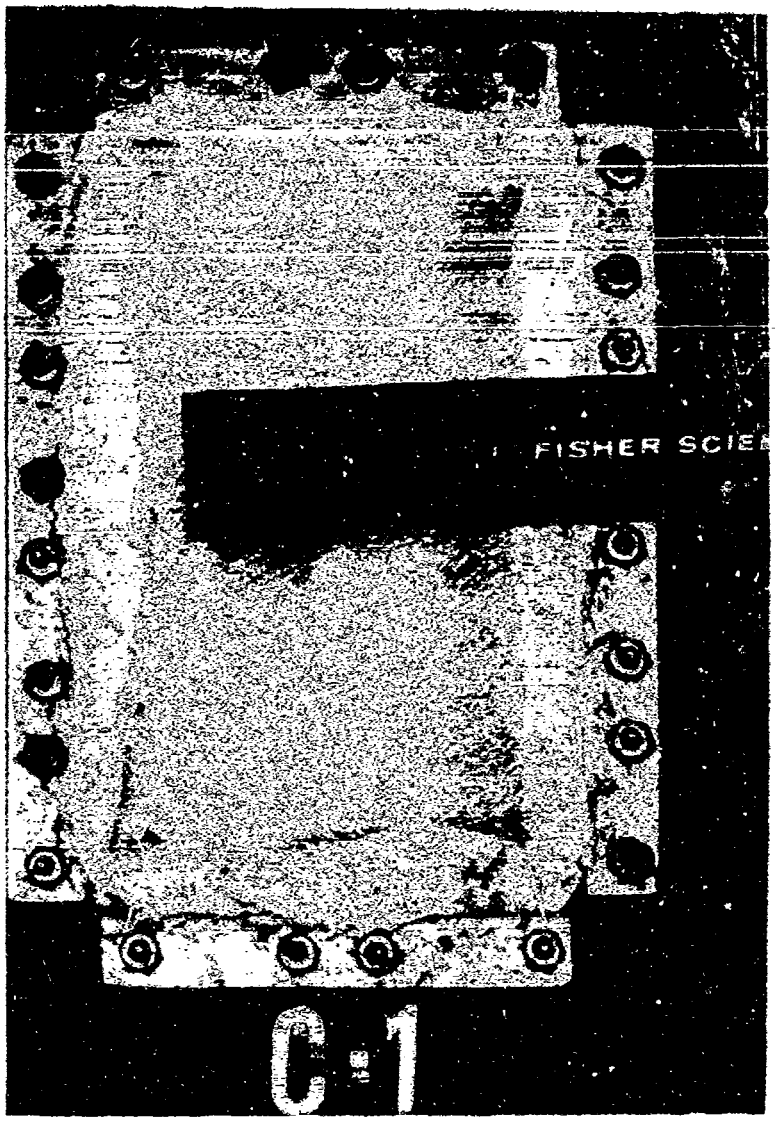

FIGURE 2
Typical pigskin sample mounted in flesh simulant.

The simulant was mixed in a homogenizer (high shear mixer) and was then allowed to set for several hours. After this the simulant could be sliced to the desired geometry for mounting samples. The simulant was not combustible in pure oxygen at 258 mm. Hg pressure.

Each sample used in these tests was mounted at a 45-degree angle as it has been reported (1) that effects of atmospheric composition are more easily observed and are more reproducible with samples at a 45-degree angle than with samples mounted vertically or horizontally.

The first pigskin samples used were fastened to the steel pans with Teflon on glass thread (fig. 2) in order to minimize shrinkage of the skin during exposure to heat. Since it was found that shrinkage did not occur under the conditions used, however, the suturing technic was not used for most of the tests.

General testing procedures and apparatus

The test chamber was a steel shell, 1.635 m. in diameter by 3.28 m. long, which was attached to a large vacuum tunnel for quick evacuation. The vacuum tunnel is exhausted by a high-capacity five-stage steam ejector system. A schematic diagram of the test chamber and accessories is presented as figure 3. Test chamber specifications are listed in table I.

In a normal series of tests five samples were mounted inside the chamber on a 45-degree test board. The arrangement of the steel pans is illustrated in figure 4. The electrical leads in figure 4 were used to bring power to the ignition system, either an electrical arc or a cotton wad ignited by a hot wire. In a number of cases fewer than five mounted samples were available, but most of the test series were performed with five samples. A standard or blank sample which was not ignited was used in most test series for which weight loss due to hair combustion was desired.

In a typical test series five skin samples were weighed, mounted in simulant, and arranged on the test board. The test chamber pressure was reduced to about 200 mm. Hg; then 99.5% pure oxygen was introduced through a drying tube (containing $CaSO_4$) until the pressure was again 760 mm. Hg. This process was performed three times and was followed by a purge with 99.5% oxygen, amounting to at least seven times the chamber volume. After this, the pressure was adjusted to the desired level with or without the addition of diluent gases. On the basis of 99.5% oxygen, the theoretical final atmosphere after the purging steps was about 99.3% oxygen, with nitrogen accounting for the major impurity.

During the tests 16-mm. motion pictures were taken of each sample to determine flame spread rate and total burn time. After completion of the tests the chamber was evacuated and filled with air, and the samples were removed from the simulant for weighing.

The pressure in the chamber was never below about 175 mm. Hg because of water loss from the sample and simulant at lower pressures. Swelling of the simulant due to water vaporization at pressures below 175 mm. Hg presented problems in maintaining a constant arcing distance.

It was observed early in the program that pigskin samples could not be ignited in 258 mm. Hg pure oxygen if they were not allowed to dry somewhat after removal from the refrigerator, because atmospheric condensation onto the cold samples continued to be present after the samples had come to thermal equilibrium with the ambient air. This problem was easily circumvented by exposing the samples to the atmosphere for at least two hours prior to testing. Several pigskin samples were also tested after exposure to the atmosphere without covering for two days. The relative humidity in the preparation room was between 20% and 30% during its period of use in this program.

Atmospheric water content during testing

The removal of water from the gases used in the test atmospheres, plus the large volume of the test chamber, enabled the tests to be performed at an atmospheric water content below that which might be expected to affect the ignition and combustion of hair. From an initial water content of 15.3 gr. of water per pound of dry oxygen, the combustion testing in 180 mm. Hg oxygen of five pigskin samples plus a cotton igniter for each of the samples resulted in a final water content of 25.8 gr. of water per pound of dry oxygen. The dewpoints corresponding to these initial and final conditions are $-22°$ and $-16°$ C., respectively, assuming that the perfect gas law relationships hold over the pressure ranges used in this study.

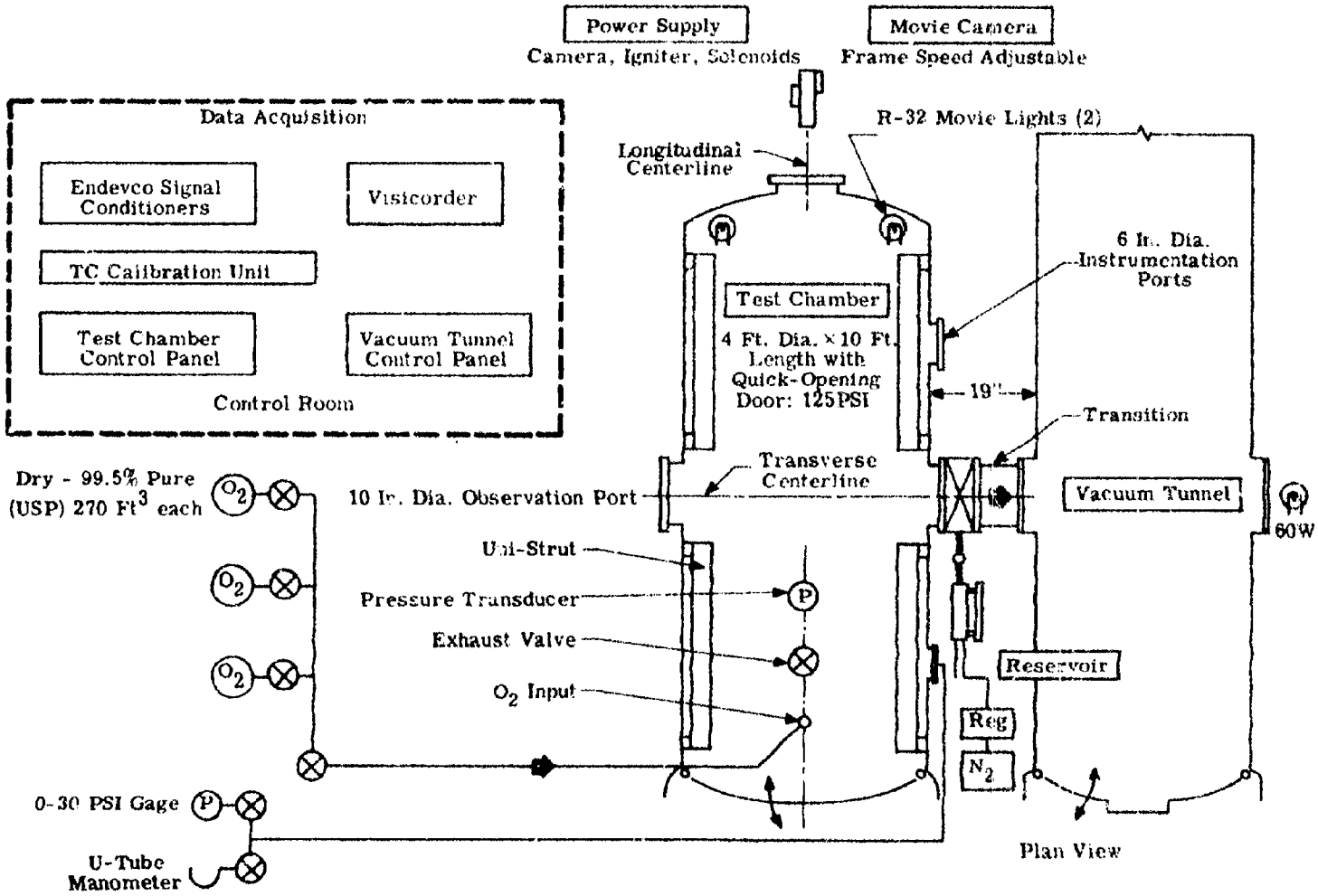

FIGURE 8

Experimental layout.

TABLE I

Test chamber specifications

Shell diameter	1.035 m.
Length	3.28 m., horizontal
Working pressure	5.5 atm. at 232° C. and full vacuum
Construction	ASME code, welded steel shell
Access	Quick opening, hinged head
Head type	Domed
Bottom	Round
Observation ports	Two, 25 cm. in diameter
Instrumentation ports	Two, 15 cm. in diameter
Internal mounting	Uni-Strut channel
Portable	Four nonlocking swivel casters; 910-kg. load rating each; overall height: 19.5 cm.

The method used to obtain these values is as follows: An atmosphere of 760 mm. Hg dried oxygen (~99.3% pure) was prepared according to the procedure outlined above. The water content of this atmosphere was determined to be 15.3 gr. of water per pound of dry oxygen with a water and CO_2 monitoring unit developed for the Air Force by Atlantic Research (2). In this instrument, water is determined amperometrically after absorption on P_2O_5 (formation of H_3PO_4). The instrument is accurate at relative humidities as low as 3% in air.

After the initial determination the pressure in the chamber was reduced to 180 mm. Hg, the tests were conducted, and dried oxygen was added to increase the pressure to 760 mm. Hg. When this pressure was reached, another determination of atmospheric water content was obtained, the value of which was 6.1 gr. of water per pound of dry oxygen. If it is assumed that no water entered with the dried

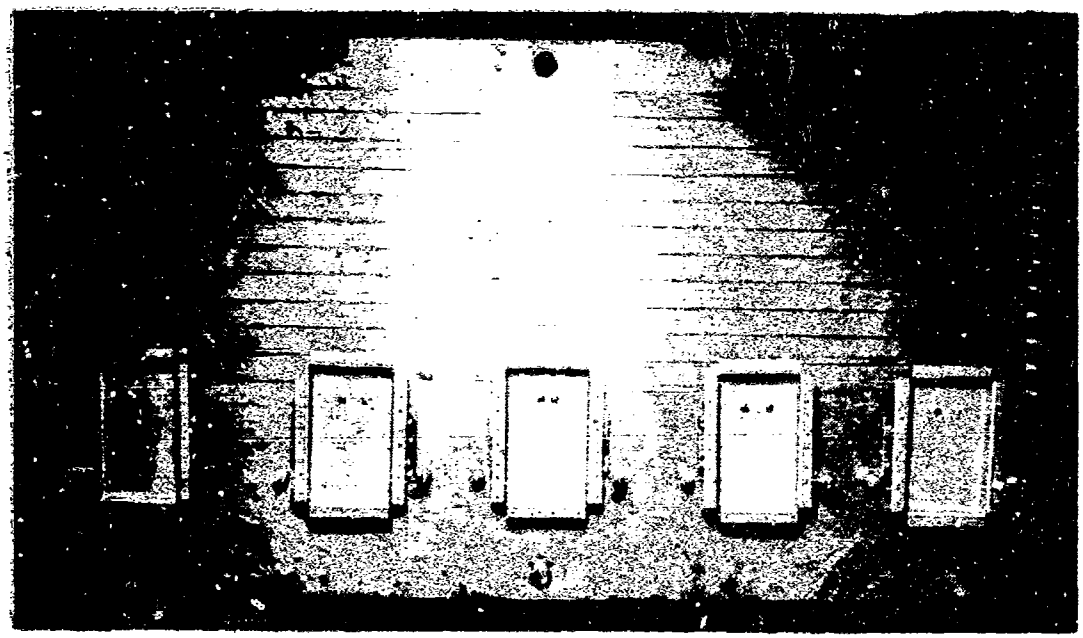

FIGURE 4

Stainless steel pans (sample holders) arranged on test board.

oxygen, then all of the water detected had been contained in the final 180 mm. Hg oxygen atmosphere. Thus, the water content at the conclusion of the test at 180 mm. Hg oxygen could not have been greater than 6.1 × 760/180, or 25.8 gr. per pound.

The measured change in water content of 10.5 gr. per pound of dry oxygen corresponds to a total water weight change of approximately 2 gm., or about 0.4 gm. per sample. This is a reasonable value, since the total weight losses for the samples during preparation and the combustion tests averaged approximately 2 gm. per sample.

Fat, water, and hair analysis

Wherever possible, a portion of each skin sample was analyzed for fat, water, and hair content. Several of the human skin samples were too small to allow removal of a sufficient sample for any of these analyses. The analytical methods used to determine fat and water were taken from reference 3. Each sample was trimmed to a thickness of 0.9 cm. prior to analysis. Air drying at 100° C. under natural convection was used to determine water content. The determination of fat content was performed by extraction with diethyl ether, vaporization of the solvent, and weighing of the (fat) residue. Hair content was determined by weighing the hair shaved from a known area of skin and was recorded in units of milligrams per square centimeter.

Tables of analytical data from these tests are reported in appendix I. The hair content of the pigskin samples ranged from about 1 to 8 mg./sq. cm., whereas most of the human skin samples held very little hair. Average fat content for the pigskin samples ranged from 15% (pig J) to 44% (pigs M and Q). All of the pigskin samples exhibited water content between 35% and 60% with an average of about 50%. The human samples exhibited more variation in fat and water content than did the pigskin samples. Fat content of the human samples ranged from 6% to 69%, and water content varied from 19% to 63%.

Sample ignition

Two methods of sample ignition were used. For most of the tests the igniter consisted of a heated Nichrome wire around which was wrapped approximately 0.25 gm. of cotton. The hot wire plus cotton igniter was believed to represent the general type of source which would be most likely to cause ignition in a space cabin environment. However, the cotton igniter appeared not to be amenable to the measurement of minimum ignition energy for hair.

A method was developed that utilized an electric arc igniter for determining minimum ignition energy. A transformer was used to bring the voltage across a 1.6-mm. gap (between electrode and skin surface) to 3,420 v. (60 cps a.c.). The switching arrangement was designed to allow consecutive ignition of five samples without arcing at the switch contacts. The duration of the arc was set by a timing switch, and the exact duration was determined by an oscillograph trace. The diameter of the electrode used was 3.2 mm.

The energy supplied to a mounted skin sample by an electric arc consists of local heat concentrated at the point of contact and ohmic heating due to current passage through the bulk of the sample. Only the local heating is a source of ignition. For the arc conditions used, it was determined that the local energy input was 1.7 J/sec., and this was the value used to calculate minimum ignition energy in this program.

The method used to determine the energy per unit time of the arc was as follows: Two samples of flesh simulant in aluminum foil cups were balanced against each other on the two pans of a grounded torsion balance. The electrode was placed 1.6 mm. above the surface of one sample, and the arc was struck for the desired time. The weight loss due to local vaporization of water by contact with the arc was immediately measured by rebalancing the samples. The data obtained are shown in figure 5, from which the slope shows that the rate of water vaporization is approximately 0.7×10^{-3} gm./sec. For a latent heat of vaporiza-

tion for water at 21.1° C. of 585 cal./gm., the local heat input rate was 0.41 cal./sec., or about 1.7 J/sec.

The data in figure 5 were collected with ambient air as the atmosphere. Only a very small error is incurred by using ambient air instead of 258 mm. Hg of oxygen, because the conditions for arcing (field strength required) in two different gases with all other conditions the same are related by:

$$\frac{E \text{ air at 1 atm.}}{E \text{ oxygen at 0.34 atm.}} = \frac{\epsilon \text{ oxygen at 0.34 atm.}}{\epsilon \text{ air at 1 atm.}}$$

where E is the field strength and ϵ is the dielectric constant.

Since ϵ air at 1 atm. is 1.00058 and ϵ oxygen at 0.34 atm. is nearer unity, only a negligible difference in the arcing conditions is predicted.

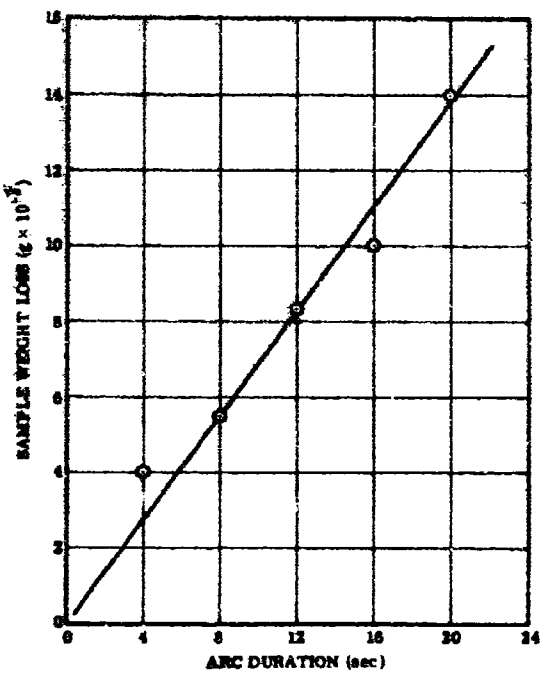

FIGURE 5

Effect of arc duration on weight loss due to electrical arc (3,420 volts, 60 cps, 1.8-mm. gap) striking sample of flesh simulant. Each data point averaged from two or more tests.

III. ANIMAL SKIN TESTS IN PURE OXYGEN

The results of tests in pure oxygen at 24° C., using pigskin samples, are presented and discussed in this section. Test data and representative photographs are presented in appendixes II and III, respectively.

Results of preliminary testing

A series of preliminary tests was performed to ascertain the general nature of skin and hair combustion in 258 mm. Hg of pure oxygen for pigskin samples prepared and mounted as described in section II. A typical sample obtained after testing is shown in figure 6 (compare with figure 2). Most of the hair was consumed, but the exterior layers of the skin were not combusted. However, prolonged exposure of the skin sample to the electric arc resulted in local depletion of heat sink capability, exposure and ignition of subsurface fat, and combustion of the bulk of the sample.

On the basis of these results, it appeared likely that the nap (or surface) burning of the sample could be eliminated through removal of a portion of the hair. One sample was roughly shaved so that the final length of hair was about 2 mm. (approximately 0.125 inch). This sample (A6), prior to testing, is shown in figure 7. The remaining hair on this sample burned similarly to that on sample A3 (fig. 6), as shown in figure 8. The next sample (A7) was then closely shaved (fig. 9). No surface burning resulted from the use of the arc igniter, but prolonged contact resulted in exposure of fat and bulk combustion, as shown in figure 10. The use of a cotton-wad igniter produced results very similar to those obtained with the arc, except that significant fat combustion could be obtained only when a corner of the flesh sample was exposed directly to the burning cotton.

Since the initiation of bulk combustion of a sample was believed to involve an artifact which would not be present with a living human subject, the program evolved into a study of phenomena associated with nap burning, or

FIGURE 6

Sample A3 after test (arc ignition).

hair burning, on pigskin and human skin samples.

Test results with pure oxygen

A summary of the test results with pigskin samples in a pure oxygen atmosphere is presented in table II. Sample standard deviations for the data in table II are presented in table III. The deliberately dried samples were exposed to 20% to 30% relative humidity for two days prior to testing, whereas the normally dried samples were exposed to 20% to 30% relative humidity two to three hours before testing. The flame spread rates and the total burn times were determined from motion pictures of the tests. No spread of combustion was noted when the chamber contained atmospheric air.

According to data in table II, the flame spread rate for hair on pigskin is strongly dependent upon sample conditioning. As noted previously, the presence of condensate on pigskin samples prevented ignition with the arc. The flame spread rate also appears to depend strongly on oxygen pressure and hair weight, but it will be shown later that the flame spread rate of 4.6 cm./sec. at 180 mm. Hg pure oxygen may be somewhat low compared to a flame

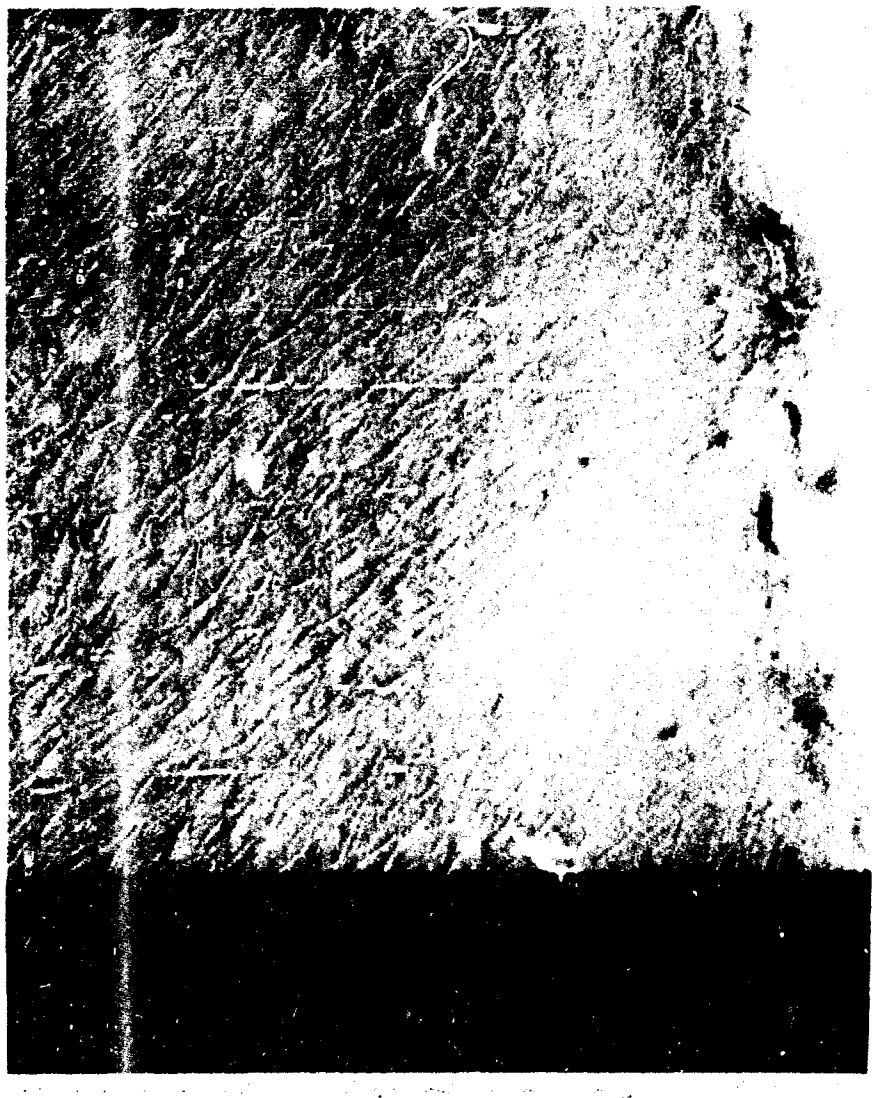

FIGURE 7.

Closeup of sample A6 before test (sample shaved to 8 cm.).

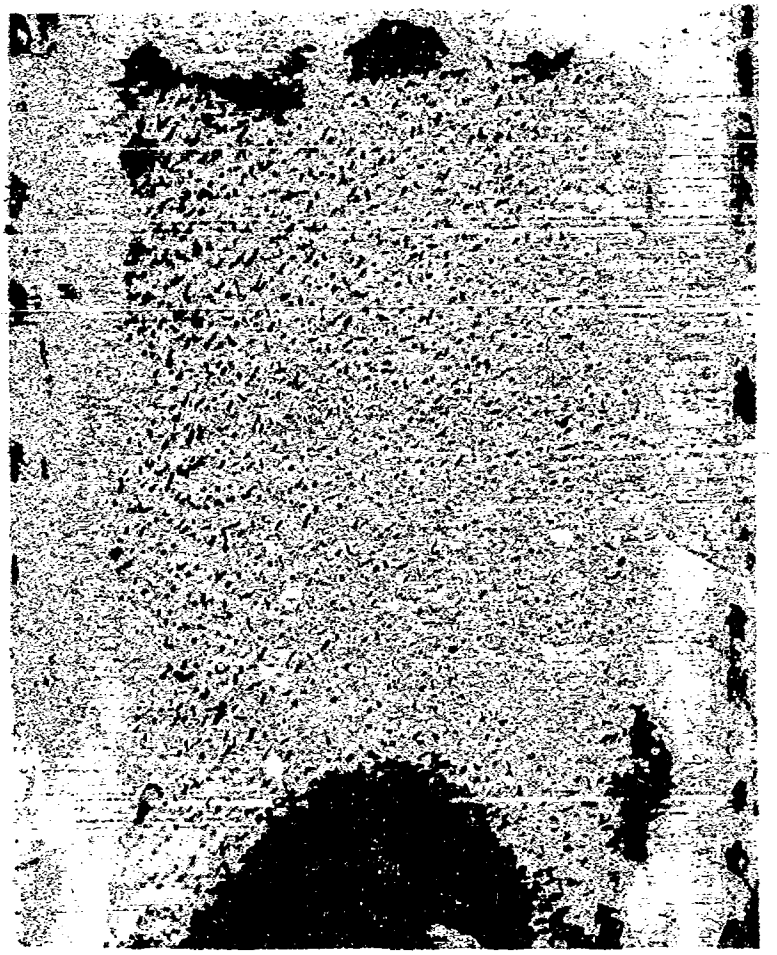

FIGURE 8

Closeup of sample A6 after test (sample shaved to 2 cm.; arc ignition).

spread rate of 9.3 cm./sec. with 180 mm. Hg O_2 and 78 mm. Hg helium obtained later in the program.

The values of weight loss obtained have little merit as indicators of comparative combustion effects because of the small losses in comparison to the reference (unburned) samples. An error of 1 gm. in these weight losses could have easily been due to adherence of simulant onto the tested sample or the reference sample.

Values for total burn time appear to have proceeded through a maximum as flame spread rate was decreased (see table II). This type of behavior was also noted in tests performed with helium-diluted oxygen atmospheres, as will be described later. The data given in table II, however, are regarded as qualitative only, and trends in these data are not explainable on the basis of flame spread rate.

The values for minimum ignition energy for the unshaved samples at 258 mm. Hg oxygen

FIGURE 9

Sample A7 before test (sample closely shaved).

were very reproducible, as reflected in the low standard deviation shown in table III. It appears that a reduction in oxygen pressure and removal of most of the hair cause significant increases in ignition energy, although the magnitude of the minimum ignition energy at 180 mm. Hg seems out of line with the others.

IV. EFFECTS OF DILUENT GASES

The objective of this portion of the program was to determine the partial pressure of helium which, when added to 180 mm. Hg pure oxygen, would prevent flame spread on pigskin samples. The procedures used for these tests were generally the same as those described in section II, except that the desired partial pressures of dried diluent gases were added to the chamber after the final purge with oxygen and the oxygen pressure was reduced to 180 mm. Hg. Ignition of the samples with the electric arc became very difficult when the helium partial pressure was elevated above 278 mm. Hg. In tests calling for diluent pressures higher than 278 mm. Hg, cotton-wad igniters were used. The experimental data for each of these tests are included in appendix II, with representative photographs of samples included in appendix III.

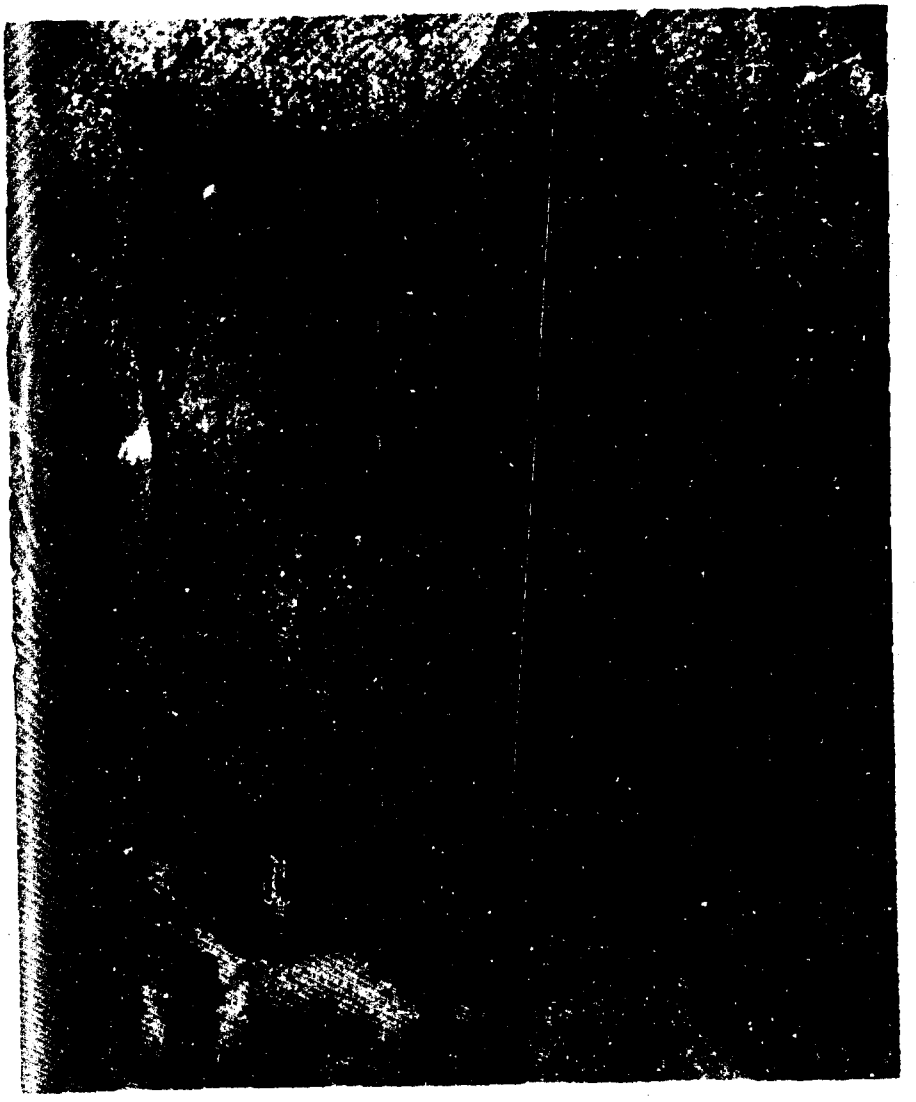

FIGURE 10

Sample A7 after test (sample closely shaved; arc ignition).

TABLE II

Effects of various parameters on flame spread rate, weight loss, total burn time, and minimum ignition energy for pigskin samples in a pure oxygen atmosphere

Conditions of tests	Flame spread rate (cm./sec.)	Weight loss* (gm.)	Total burn time (sec.)	Minimum ignition energy† (J)
258 mm. Hg O_2; deliberately dried samples	36.0 (2)‡	1.2 (1)	2.8 (2)	0.28 (2)
258 mm. Hg O_2; normally dried samples	9.2 (14)	1.1 (10)	9.0 (14)	0.28 (11)
180 mm. Hg O_2; normally dried samples	4.6 (3)	1.2 (2)	4.4 (3)	34 (3)
258 mm. Hg O_2; hair length, 0.125 in.; normally dried samples	3.1 (3)	—	3.0 (3)	4.8 (3)
Atmospheric air: 20.9% O_2–79.1% N_2; normally dried samples	0	0	0	—

*Due to combustion only (related to blank, unburned sample).

†Based on 1.7 J/sec. for the arc conditions used.

‡Number of samples given in parentheses.

TABLE III

*Statistical variability of flame spread rate, total burn time, and minimum ignition energy for pigskin samples in a pure oxygen atmosphere**

Conditions of tests	Sample S.D. of flame spread rate (cm./sec.)	Sample S.D. of total burn time (sec.)	Sample S.D. of minimum ignition energy (J)
258 mm. Hg O_2; deliberately dried samples	4.8	1.8	0.1
258 mm. Hg O_2; normally dried samples	2.6	3.4	0.1
180 mm. Hg O_2; normally dried samples	1.6	1.7	0.0
258 mm. Hg O_2; hair length, 0.125 in.; normally dried samples	2.1	1.4	1.9

*These values of sample S.D. apply to the corresponding data in table II.

The results obtained with normally dried, unshaved pigskin samples tested in diluted oxygen atmospheres are presented in table IV. Values of standard deviation for the flame spread rates and the total burn times are also included in table IV. According to this table, the flame spread rate neared zero as the helium partial pressure was increased to 578 mm. Hg. The presence of the burning cotton influenced the burning of the hair in these tests; thus, the fact that 30% of the sample area burned at 578 mm. Hg helium is believed to be a better indication of the condition of no flame spread than of the flame spread rate. It is estimated that a typical sphere of influence of the cotton igniter was 20% to 30% of the sample area; that is, the combustion of the cotton would have caused combustion of 20% to 30% of the sample area even in atmospheric air. At helium concentrations of 528 and 553 mm. Hg the flame spread occurred only so long as the cotton was burning.

The flame spread rate of 9.3 cm./sec. at 78 mm. Hg helium agrees very well with that of 9.2 cm./sec. for samples in 258 mm. Hg pure oxygen (table II). Thus, the value of 4.6 cm./sec. at 180 mm. Hg pure oxygen does appear somewhat low.

The flame spread rate of 6.2 cm./sec. at 278 mm. Hg helium was strongly influenced by one very high value of flame spread rate (13.2 cm./sec.). If this sample were omitted, the flame spread rate at 278 mm. Hg helium would be 3.8 cm./sec., which would appear in better agreement with the other values obtained.

The values of sample weight loss and ignition energy given in table IV are meaningful only for strictly qualitative purposes. The low values of weight loss assure that no bulk combustion of the samples occurred, and the high values of ignition energy indicate that this parameter is a very strong function of the atmospheric composition.

The test series using 578 mm. Hg nitrogen as the diluent proved to be interesting because the flame spread over more than half of the sample, on the average, as compared to almost no flame spread with the helium diluent at 578 mm. Hg helium. With 578 mm. Hg nitrogen used as a diluent at 180 mm. Hg oxygen, the flame spread rate was only 1.2 cm./sec., as compared with 2.5 to 3.5 cm./sec. for the helium-diluted atmospheres which produced a similar extent of flame coverage of the sample area. This comparison of burning rate is consistent with previously reported results (1, 4, 5), which indicate that for equal mole fractions of helium and nitrogen diluents, flame spread rates are higher with the helium diluent.

If the combustion of hair on a pigskin sample is viewed as depending on multiple ignition of successive hairs from burning hairs, then the lack of flame spread with 578 mm. Hg helium diluent versus over 50% coverage with 578 mm. Hg nitrogen diluent is completely consistent with the hypothesis of Huggett et al. (4). These investigators observed that it was more difficult to ignite solid materials in helium-diluted oxygen than in nitrogen-diluted oxygen. They attributed this to the higher thermal conductivity and diffusivity of helium, which resulted in a decrease in the amount of energy available locally from a given ignition source in helium-diluted atmospheres as compared to nitrogen-diluted atmospheres.

One series of diluent tests was conducted with pigskin samples shaved to a final hair length of about 2 mm. The test conditions and results for this series are presented in table V. Although only one sample was tested at each condition, the data obtained are very consistent with those for unshaved samples (table IV). Flame spread rate and percentage of area covered decreased as the helium partial pressure was increased until the condition of no flame spread for these samples (533 mm. Hg helium diluent) was reached. The values for total burn time given in tables IV and V appear to maximize at a helium partial pressure of 278 mm. Hg, which corresponds to intermediate values of flame spread rate. It is suggested that this result was due to rapid, complete combustion of the hair in pure or slightly diluted oxygen, relatively slow but fairly complete combustion of hair at intermediate partial pressures of helium, and incomplete combustion of the hair at the higher helium concentrations.

TABLE IV

Effects of diluent gases on hair and skin combustion with 180 mm. Hg oxygen pressure*

Diluent	Average flame spread rate (cm./sec.)	Sample S.D. of flame spread rate (cm./sec.)	Average weight loss due to burn (gm.)	Average ignition energy (where applicable) (J)	Average total burn time (sec.)	Sample S.D. of total burn time (sec.)	Approximate percentage of sample area covered by burn
None	4.6	1.6	0.2	84	4.4	1.7	100
78 mm. Hg helium	9.8	6.0	1.0	28	8.6	1.9	100
178 mm. Hg helium	5.2	2.6	0.3	>30	10.2	2.0	100
278 mm. Hg helium	6.2	4.8	0.7	—	10.5	3.4	100
378 mm. Hg helium	2.7	0.2	—	Cotton igniter	9.0	1.3	100
478 mm. Hg helium	2.5	1.2	—	Cotton igniter	8.1	3.3	100
528 mm. Hg helium	3.3†	1.2	—	Cotton igniter	5.5	0.3	70
553 mm. Hg helium	2.6†	1.3	1.3	Cotton igniter	6.7	2.7	80
578 mm. Hg helium	<1†	—	—	Cotton igniter	—	—	30
578 mm. Hg nitrogen	1.2	1.2	—	Cotton igniter	13.9	3.1	70

*At least three pigskin samples were successfully ignited in each of these tests.

†Hair burned only as sustained by burning cotton.

TABLE V

*Effects of diluent helium on hair and skin combustion of pigskin samples with hair length clipped to 0.125 in.**

Diluent	Flame spread rate (cm./sec.)	Weight loss due to burn (gm.)	Burning time (sec.)	Percentage of total area covered by burn
None	7.8	0.1	1.5	100
278 mm. Hg helium	1.3	—	8.2	100
508 mm. Hg helium	0.5	0.5	3.6	30
533 mm. Hg helium	Very slow	0.1	—	< 20

*One sample per condition; oxygen pressure of 180 mm. Hg in all tests.

Plots of the flame spread rates and percentages of total area burned versus helium partial pressures for the diluent tests are presented in figures 11 and 12, respectively. These plots illustrate the finding that no sudden reduction to zero in flame spread rate was found; rather, the rate and extent of flame spread for these samples were a continuous function of helium concentration without a well-defined intercept on the diluent concentration axis.

V. PROTECTIVE COVERINGS AND OINTMENTS

This portion of the program was performed to determine to what degree cloth coverings, salves, and ointments protected against hair combustion in oxygen-rich atmospheres. The tests were performed with unshaved pigskin samples prepared as described in section II. The temperature for these tests was 24° C., and all samples were inclined at a 45-degree angle. Data and photographs from these tests are included in appendixes II and III, respectively.

Protection by salves and ointments

In these tests the ointment to be tested was placed over all but about 2.5 cm. of the 10-cm. sample length. The uncoated portion of the sample was exposed to a burning cotton wad as an ignition source, which provided for initiation of hair combustion on the uncoated portion followed by extinguishment or continuation of combustion when the flame reached the coated area. A typical sample so prepared is shown in figure 13.

Four types of protective ointments were tested: silicone high vacuum grease, Kel-F fluorocarbon grease, a commercial cold cream, and a commercial protective hand lotion. A comparison of the composition of these materials is presented in table VI. Both the cold cream and the hand lotion are used to soften and protect hands from chemical or allergic reactions. Typical application rates in normal use are 0.12 gm./sq. cm. for the hand lotion and 0.20 gm./sq. cm. for cold cream. The hand lotion is typically applied by laboratory technicians in the morning, removed at lunch time, and reapplied after lunch.

The results of these tests are summarized in table VII. The silicone grease proved to be combustible in pure oxygen; so no further testing was performed with this material. The samples coated with Kel-F grease were not ignited under any conditions, but it should be noted that the least amount of coverage used (0.34 gm./sq. cm. or 2.2 gm./sq. in.) was much higher than typical application rates of protective creams and lotions. Samples coated with cold cream or hand lotion did not burn at

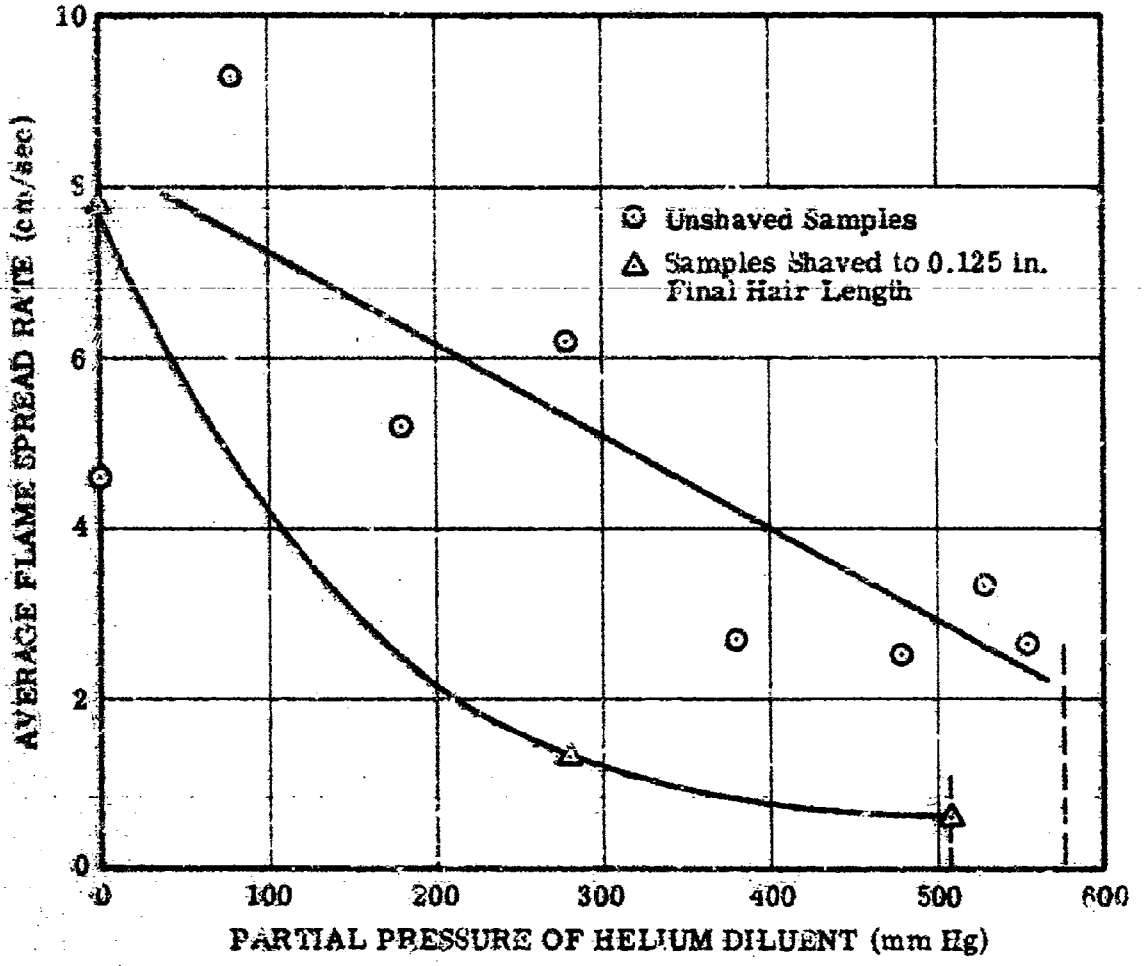

FIGURE 11

Effect of helium dilution (with 180 mm. Hg oxygen) on average flame spread rate for samples of suckling pigskin and hair.

application rates above 0.2 gm./sq. cm. (1.3 gm./sq. in.), but combustion was permitted in some cases at lower coverage rates. Sample M10, after testing, is shown in figure 14.

On the basis of these results, it is considered likely that the amount of coverage (grams/square inch) of these materials required for protection against hair combustion in pure oxygen will be greater than that which is comfortable for the human subjects.

Protection by fire-repellant cloth

Two types of glass fiber cloth were used in these tests: one with a weight of 9 oz./sq. yd., and one with a weight of 6 oz./sq. yd. The heavier cloth is used for garments worn during space missions, and the lighter cloth is used as the outer bedding cover. The two types of tests which were performed with each type of cloth were: (1) garment-fit tests—a study of flame propagation beneath strips of

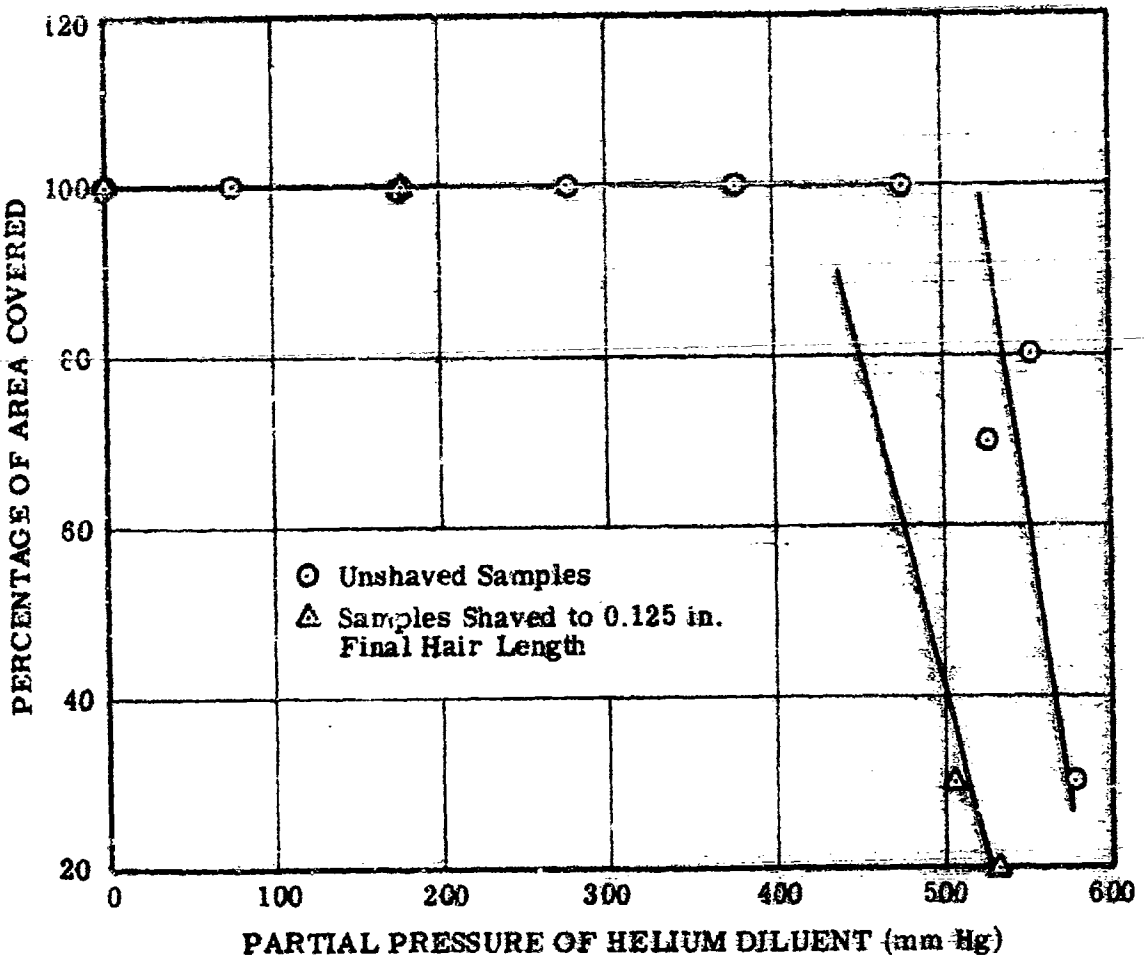

FIGURE 12

Effect of helium dilution (with 180 mm. Hg oxygen) on percentage of pigskin sample area covered by flame.

cloth (2.5 cm. wide) separating two unprotected areas of hair; and (2) thermal-transfer tests—a study of ignition of hair caused by thermal transfer from a burning cotton wad in contact with cloth placed on the sample.

A typical sample mounted for the garment-fit tests is presented in figure 15. Upper and lower exposed portions of skin are separated by the cloth samples. The cotton wad (0.24 gm. each) was placed on the lower exposed portion of skin and ignited. The flesh simulant was made into a mound for these samples so that the weight of the cloth would be borne by the hair and not by the edges of the mounting pans. Weights of zero, 1.8 gm., and 6.4 gm. were placed on each end of the cloth for various test series.. Samples were mounted at a 45-degree angle. Determination of the pressure distribution on the sample as a result of the weights was beyond the scope of this program.

The results of these tests, presented in table VIII, show that combustion did proceed

FIGURE 18

Pigskin sample M10 prepared for test of flame spread with 0.6 gm./sq. in. cold cream.

under the cloth strips at weights of zero or 1.8 gm. on each end. For the conditions of looser fit, the type of cloth made little difference in the probability of ignition of the upper portion of the sample. For prevention of flame spread for these conditions, the weight required on each end of the cloth is between 1.8 and 6.4 gm. A typical sample which did result in combustion of the upper portion of the sample is shown after the test (fig. 16). The heavier cloth was used in this test.

The samples used in the thermal-transfer tests were prepared as shown in figure 17, with the 0.24-gm. cotton-wad igniter placed on the

TABLE VI

Properties of four protective greases and ointments used in flammability tests of pigskin samples

Protective material	Density (gm./cc.)	Approximate composition
Silicone high vacuum grease	1.1	100% silicones
Kel-F grease	2.0	100% $(C_2F_3Cl)_n$
Pond's cold cream	1.1	12.5% sperm oil; 12.0% white wax; 56.0% oil of almond; 0.5% Na_3BO_3; 5.0% rose water; 14.0% water
Cornhusker's lotion	1.1	5.7% ethyl alcohol; 12.3% glycerine and other nonvolatile oils; 82.0% water

TABLE VII

Effects of four creams or salves on skin and hair combustion for pigskin samples (five samples for each test unless otherwise noted)*

Cream or salve	Atmosphere used	Amount of cream or salve applied (gm./sq. in.)	Test results
Silicone vacuum grease	258 mm. Hg O_2	3.0	Silicone grease ignited; samples entirely consumed.
Kel-F grease	258 mm. Hg O_2	2.5	No combustion
Kel-F grease	258 mm. Hg O_2	0.95	No combustion
Kel-F grease	258 mm. Hg O_2	0.44	No combustion
Kel-F grease	70% O_2–30% He; 258 mm. Hg total pressure	0.34	No combustion
Pond's cold cream (8 samples tested)	258 mm. Hg O_2	0.07 to 0.39	The sample at 0.07 gm./sq. in. burned (0.22 cm./sec. spread rate; 35.3 sec. total burn time); the others did not burn—even at coverage of 0.08 gm./sq. in.
Pond's cold cream	70% O_2–30% He; 258 mm. Hg total pressure	0.35	No combustion
Cornhusker's lotion	258 mm. Hg O_2	0.48	No combustion
Cornhusker's lotion (10 samples tested)	70% O_2–30% He; 258 mm. Hg total pressure	0.11 to 0.38†	Two samples burned—one at 0.12 gm./sq. in. (0.49 cm./sec. spread rate; 15.6 sec. total burn time); and one at 0.19 gm./sq. in. (0.92 cm./sec. spread rate; 9.4 sec. total burn time).

*Approximately 1 in. of the sample was left uncovered so that ignition could result for the cotton-wad igniter in all tests.

†Two samples were 0.11 gm./sq. in.; three samples were 0.12 gm./sq. in.; three samples were 0.18 to 0.19 gm./sq. in.; one sample was 0.36 gm./sq. in.; one sample was 0.38 gm./sq. in.

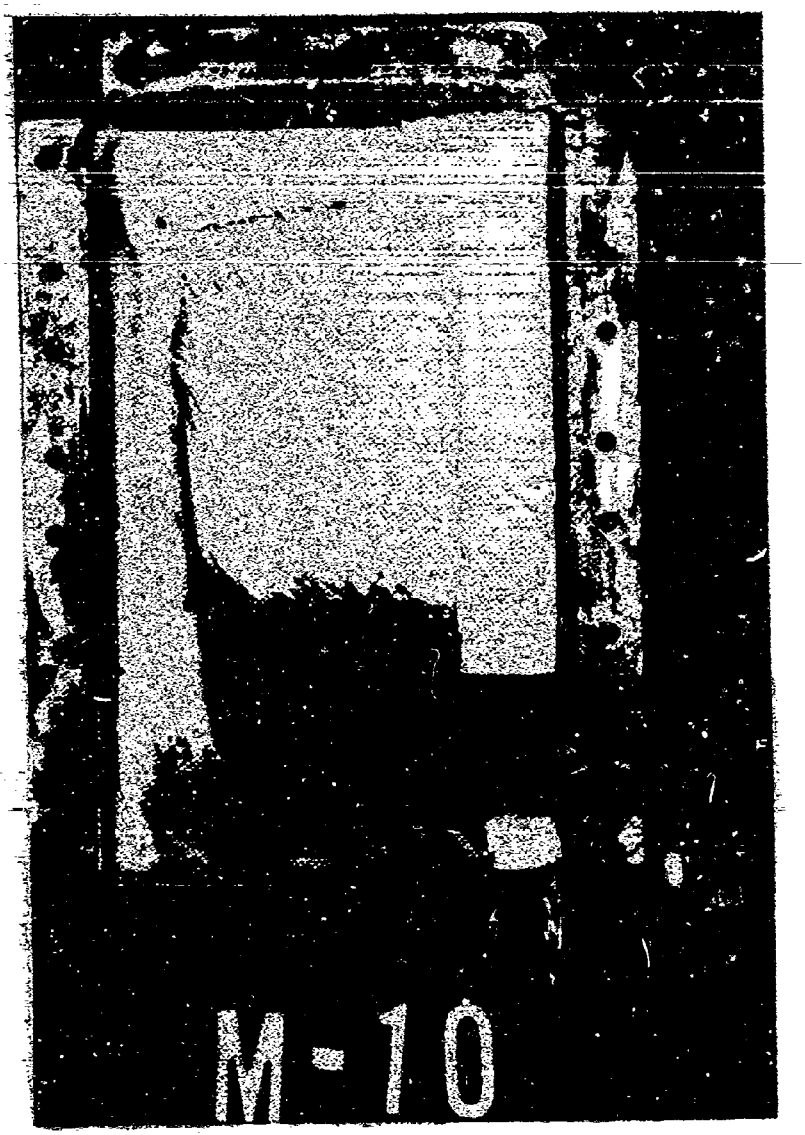

FIGURE 14

Pigskin sample M10 after test of flame spread in 258 mm. Hg oxygen.

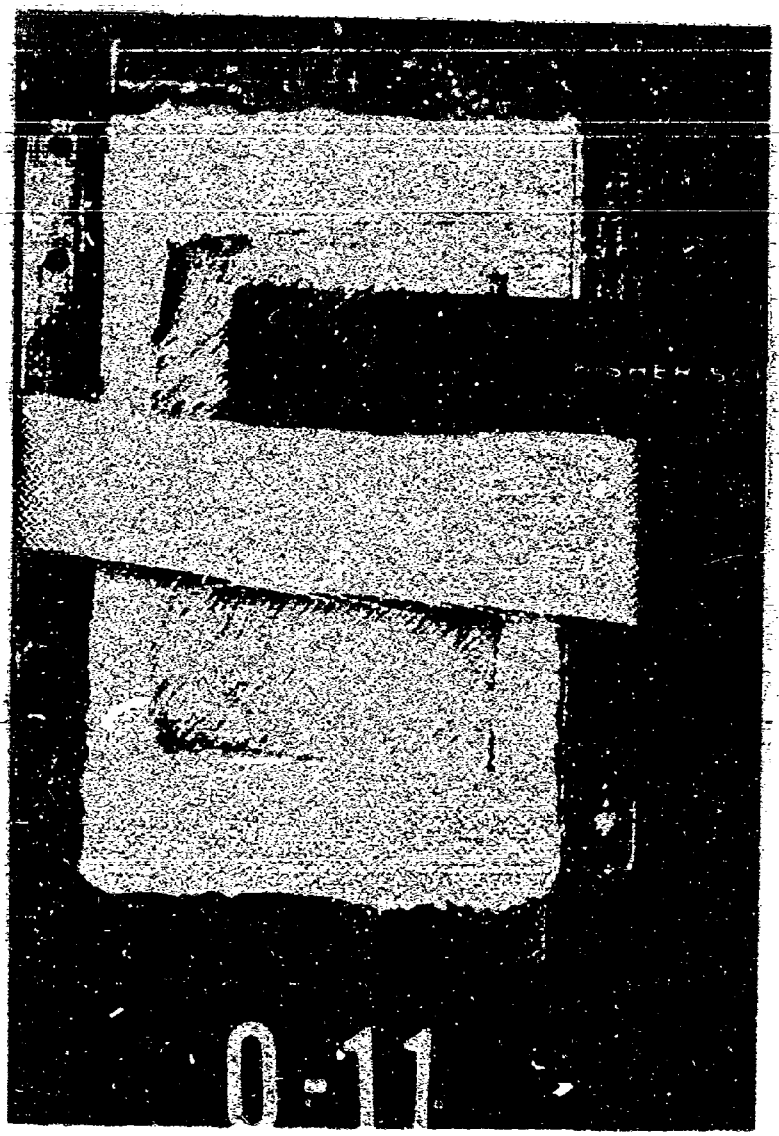

FIGURE 15

Pigskin sample 011 prepared for garment-fit test with heavier cloth (9 oz./sq. yd.). No weight on cloth ends.

TABLE VIII

Effects of cloth protection on ignition of pigskin samples in oxygen-rich atmospheres (five samples per test, unless noted differently)*

Type and conditions of test	Cloth type	Atmosphere	Results
Garment-fit; no weight on cloth	Fyrepel (9 oz./sq. yd.)	258 mm. Hg O_2	Combustion proceeded on two out of five samples
Garment-fit; 1.8 gm. on each end of cloth	Fyrepel (9 oz./sq. yd.)	258 mm. Hg O_2	No combustion of top area of any sample
Garment-fit; 6.4 gm. on each end of cloth	Fyrepel (9 oz./sq. yd.)	258 mm. Hg O_2	No combustion of top area of any sample
Thermal-transfer	Fyrepel (9 oz./sq. yd.)	258 mm. Hg O_2	Sample ignited for four out of five samples. Average delay time between cotton ignition and hair ignition, 11.8 sec.; S.D., 2.0 sec.
Thermal-transfer	Fyrepel (9 oz./sq. yd.)	70% O_2–30% He; 258 mm. Hg total pressure	No samples ignited
Garment-fit; no weight on cloth	Vistaglas (6 oz./sq. yd.)	258 mm. Hg O_2	No combustion of top area (three samples)
Garment-fit; 1.8 gm. on each end of cloth	Vistaglas (6 oz./sq. yd.)	258 mm. Hg O_2	Combustion of top area in one out of four samples
Garment-fit; 6.4 gm. on each end of cloth	Vistaglas (6 oz./sq. yd.)	258 mm. Hg O_2	No combustion of top area
Thermal-transfer	Vistaglas (6 oz./sq. yd.)	258 mm. Hg O_2	All samples ignited. Average delay time between cotton ignition and hair ignition, 3.6 sec.; S.D., 2.2 sec.
Thermal-transfer	Vistaglas (6 oz./sq. yd.)	70% O_2–30% He; 258 mm. Hg total pressure	All samples ignited. Average delay time between cotton ignition and hair ignition, 13.0 sec.; S.D., 1.6 sec.

*In the garment-fit tests a 2.5-cm. strip of the cloth was used to separate two unprotected areas of hair on a rounded sample, and a hot wire-cotton igniter was used to ignite the lower area. In the thermal-transfer tests a sample of cloth was placed over the bottom half of the skin sample, and a cotton wad placed on top of the cloth was ignited.

portion of cloth in contact with the sample. A portion of the cloth was folded to present a barrier against hair ignition resulting directly from the cotton-wad flame. Therefore, if sample ignition occurred, it must have resulted from thermal transfer through the cloth. The results of these tests with the two types of cloth are also included in table VIII.

The heavier cloth seemed to afford much more protection against ignition by thermal transfer than the lighter cloth, not only because of its greater thickness and density but also because some portion of the lighter weight material was consumed by the combustion. Samples after thermal-transfer tests with the heavier and lighter cloths are presented in

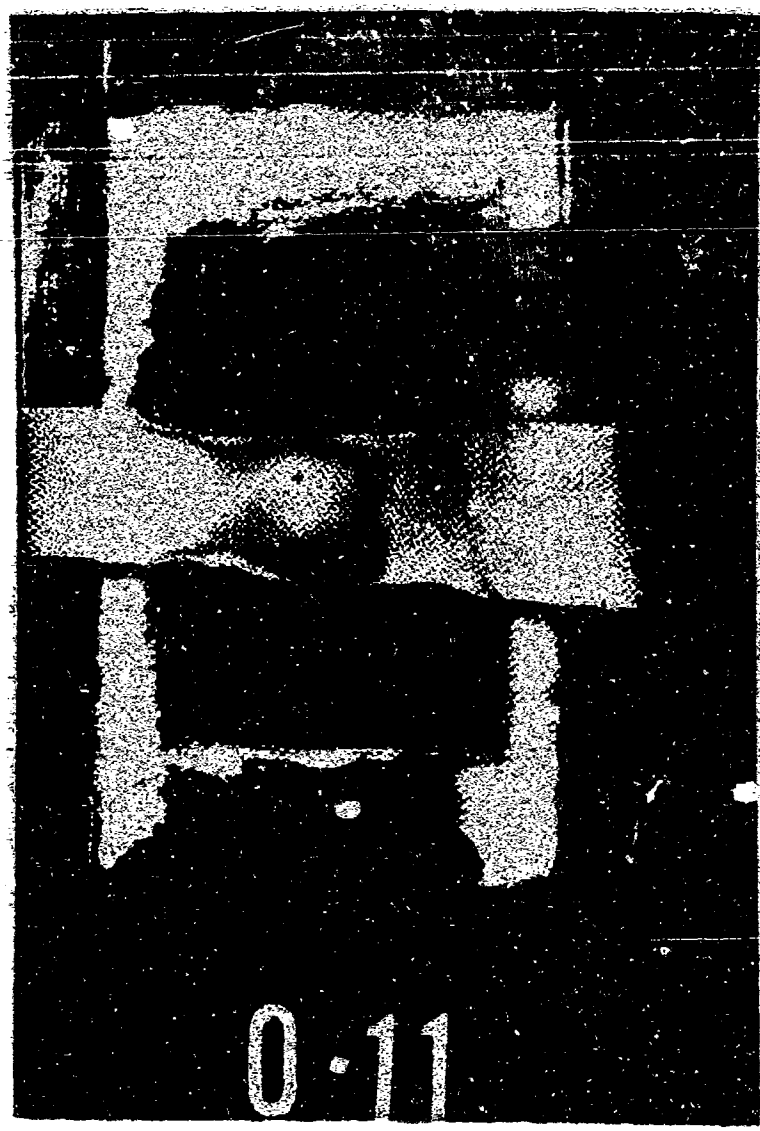

FIGURE 16

Pigskin sample 011 after garment-fit test. A cotton-wool igniter was used in this test.

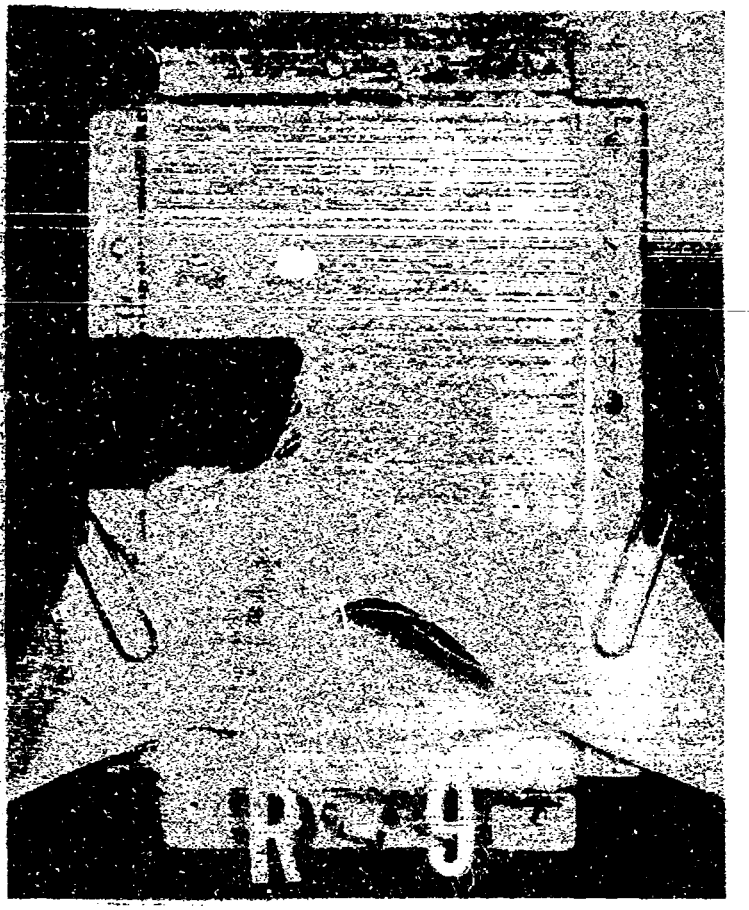

FIGURE 17

Pigskin sample R9 prepared for thermal-transfer test with lighter cloth (6 oz./sq. yd.).

figures 18 and 19, respectively. The lighter cloth (6 oz./sq. yd.) offered less protection to the sample than the heavier cloth (9 oz./sq. yd.), as evidenced by the relative sizes of the burned areas.

VI. COMBUSTION TESTING OF HUMAN SKIN SAMPLES

Analytical data from fat and water analyses of the human skin samples are included in appendix I. Test data and representative photographs are contained in appendixes II and III, respectively. Data concerning the sources of the human skin samples and pertinent information regarding the persons from whom the samples were taken are presented in appendix IV.

General observations

The human skin samples used in the program were obtained from autopsy operations at local hospitals. Initially, amputation samples were obtained, but these were not used because: (1) the amputated flesh had been completely shaved before the surgical procedure; (2) the odor from the amputated flesh

FIGURE 18

Pigskin sample P11 after thermal-transfer test with heavier cloth (9 oz./sq. yd.) in 258 mm. Hg pure oxygen.

made it difficult to handle; and (3) the diseased skin and flesh would likely not provide an adequate simulation of healthy, living skin.

None of the autopsy skin specimens used in the program contained as much hair as the pigskin samples, although many human samples held a few scattered hairs. Most of the first human samples had been locally shaved as a part of the autopsy procedure, but for later samples it was requested that they contain as much hair as possible and that they not be shaved. Even so, only one of the samples used was covered by enough hair for it to ignite and spread over the samples in an atmosphere of 258 mm. Hg pure oxygen.

The human skin was generally thinner and tougher than the pigskin, except for skin from breast areas of women. Some human samples were somewhat wrinkled, probably from age, and these were affected least by the electric arc with which ignition was attempted. For several of the human skin samples, attempts were made to ignite the bulk of the sample by leaving the arc on for up to several minutes.

FIGURE 19

Pigskin sample R9 after thermal-transfer test with lighter cloth (6 oz./sq. yd.) in an atmosphere of 70% oxygen–30% helium at 258 mm. Hg total pressure.

However, no human skin sample could be ignited in bulk as was the pigskin sample shown in figure 10 (a typical result of a long exposure to the arc).

Combustion data for human and pig hair

Table IX presents a comparison of values for various combustion parameters measured in 258 mm. Hg oxygen for samples of unshaved, normally dried pigskin and for one sample of human skin containing body hair. The human skin was prepared in a manner similar to the pigskin samples. Photographs of the human sample (S-7A) before and after the test are presented in figures 20 and 21, respectively.

The data in table IX indicate that the flame spread rate of the human hair in pure oxygen was much greater than the average value obtained for pig bristles. This large difference is believed to be due to the fineness (small diameter) of the human hair as compared with the pig bristles. The fineness of the human hair may also account for the short burning time, although the value of 1.9 seconds is not

TABLE IX

Comparison of human skin and pigskin

	Pigskin samples (average of fourteen)	Human skin sample (one sample)
Hair content	3.5 mg./sq. cm.	< 1 mg./sq. cm.*
Flame spread rate	9.2 cm./sec.	27.5 cm./sec.
Total burn time	9.0 sec.	1.9 sec.
Minimum ignition energy	0.28 J	4.3 J
Weight loss due to combustion	1.1 gm.	0.3 gm.

Only one human skin sample was supplied with sufficient hair to allow a meaningful comparison with the pigskin samples. Both types of samples were dried normally and tested in 258 mm. Hg of pure oxygen.

*Estimated to be about 0.5 mg./sq. cm. This sample was too small to allow removal of a portion sufficient for analysis.

out of line with the average total time of 2.8 seconds for deliberately dried pigskin (table II). The ignition energy required for the human sample would be expected to be high because of the smaller hair concentration compared to the pigskin samples. The value of 4.3 J for the human sample, however, is very similar to the average value of 4.8 J for partially shaved pigskin samples.

The significant differences between values for flame spread rate, ignition energy, and burning time for human hair and suckling pig bristles indicate that pigskin samples do not provide effective simulation of human skin samples in terms of the combustion of the hair present. In addition, the pigskin samples exhibited a greater tendency toward the formation of artifacts (fat exposure) leading to bulk combustion of the samples than did the human skin samples. These differences, plus the extreme variability noted in the texture, thickness, and toughness of human skin from various subjects, indicate that samples of white suckling pigskin do not adequately simulate human skin and its response to ignition sources. It is believed that skin samples from autopsy specimens should offer a more realistic definition of human skin response to ignition sources in oxygen-rich environments than do pigskin samples.

VII. DISCUSSION OF RESULTS

Comparison with previous work

A report of the most extensive experimentation relating to the flammability of skin and hair has been published by the Royal Air Force Institute of Aviation Medicine, Farnborough, Hants, U.K. Denison et al. (6, 7) have described experiments with clothed, dead pigs in oxygen-enriched atmospheres, in which it was found that ignition of the cloth would result in spreading of the flame over the pig, combustion of the hair present, and blistering of the skin, but no bulk combustion of the subdermal fat and flesh. In experiments with depilated human skin from an amputated limb, these investigators (8) found that sections of the human skin would undergo gross combustion even when backed by a substantial heat sink capacity such as a metal base or a thin-walled metal container filled with water.

The results of Denison et al. with pigskin studies are entirely consistent with the results obtained from the work reported herein, but it now appears that their result of bulk burning of human skin was due to localized artifacts caused by exposed fat and depletion of heat sink capability. It is believed that these artifacts were prevented in the present program

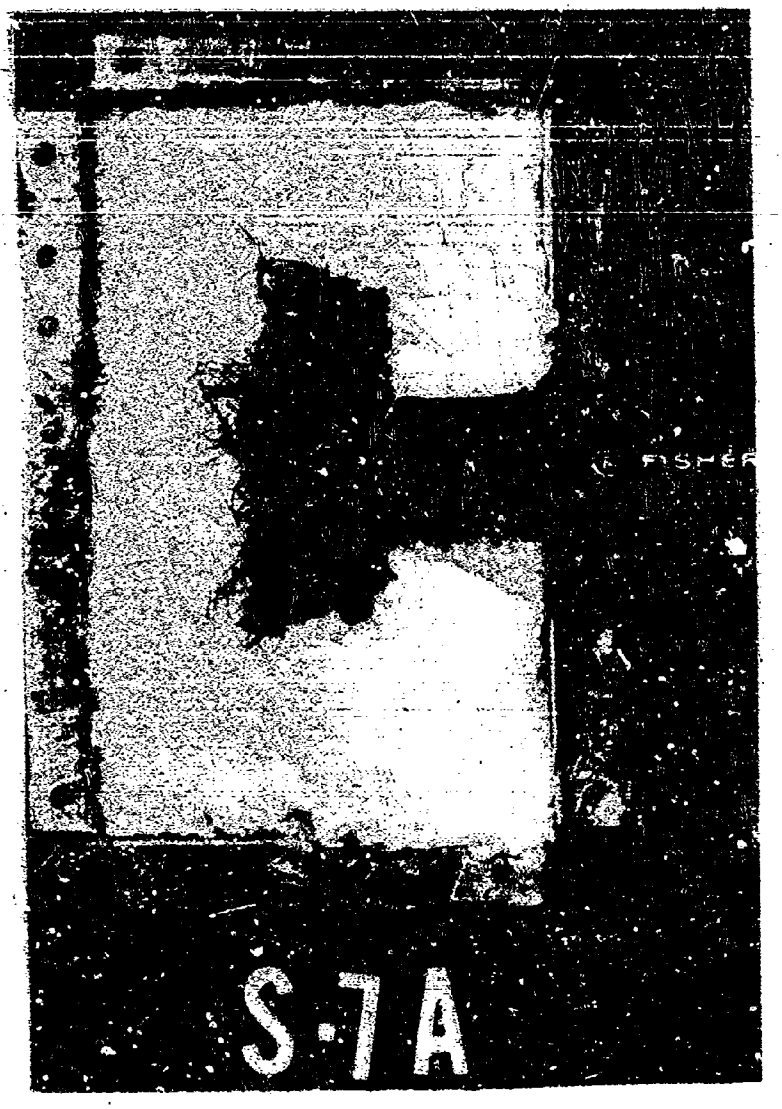

FIGURE 20

Human skin sample S7A prior to combustion testing.

FIGURE 21

Human skin sample S7A after combustion test with arc ignition in 258 mm. Hg pure oxygen.

through mounting of the skin samples in a material (flesh simulant) with heat sink capability similar to that of the skin and by ensuring that edges of the skin samples were in contact with the flesh simulant material.

The use of the flesh simulant material in this manner also eliminated preferential propagation of flame up the edges of the sample. Thus, flame spread rates and relative flame coverage values determined in this program were not influenced by edge effects.

Values obtained in this program for flame spread rate and critical helium concentration (for zero flame spread) are compared to values of these parameters obtained by Huggett et al. (4) for other materials (table X). The values from the present work for unshaved pigskin samples for flame spread rate and critical helium concentration are completely consistent with reported values for other types of combustibles.

Comparison of the minimum ignition energy obtained for pig bristles in 258 mm. Hg pure oxygen with that reported for other materials is very difficult because of the differences in technic. If it is assumed that the electric arc uniformly affected the observed blister area of 0.5 sq. cm., the minimum ignition energy for pigskin would be about 0.2 cal./sq. cm. This value is several orders of magnitude lower than typical values obtained for wood, cotton cloth, etc., using a radiation source (4). It is believed that too little is known about ignition energy requirements, in general, and about arc ignition, in particular, for this comparison to be valid at present.

Correlation with fat, water, and hair content

In no case was a correlation found to exist between flame spread rate, minimum ignition energy, or total burn time and the results of fat, water, and hair analyses. This is not surprising for the data on fat and water content, but one might expect that a variation of 1 to 8 mg./sq. cm. hair content might have some effect on the combustion parameters studied. The only direct correlations observed concerning hair content were the reduction in flame

TABLE X

Values of combustion parameters for unshaved pigskin samples and other materials

Sample material*	Flame spread rate in 258 mm. Hg pure oxygen (cm./sec.)	Critical helium concentration for zero flame spread (mole % He at 760 mm. Hg total pressure)
Pigskin and bristles	9.2	75.2
Wood	0.9	84.8
Paper	2.3	88.4
Cellulose acetate	0.8	80.1
Cotton fabric	8.1	85.4
Foam cushion	33.0	68.0
Plastic wire	2.1	74.0
Painted surface	1.1	80.1

*Data for material other than pigskin were taken from reference 4.

spread rate and the increase in minimum ignition energy due to partial shaving of the pigskin samples (to a final hair length of 2 cm.). The limit of this correlation is provided by the completely shaved pigskin samples and the nearly hairless human samples, for which the flame spread rate was zero and the minimum ignition energy (for bulk combustion) was greater than could be determined by the method used for hair ignition.

One possible explanation for the lack of correlation between combustion parameters and hair content for unshaved pigskin samples is that the variations obtained in the analysis of hair content were on a smaller (area) scale than variations between the samples used; that is, if the entire samples could have been shaved and the hair content determined, the variation would probably have been much less than that observed between 1- by 2-inch samples used for analysis.

Another possible interpretation is that hair length is the most important factor in flame spread rate. On this basis, the higher flame spread rate for the human sample compared to pigskin samples (table IX) would be somewhat expected because of the longer length of the human hair (fig. 19). This relationship between hair length and flame spread rate might be tenable if the amount of oxygen available to the hair combustion process is a function of hair length.

VIII. CONCLUSIONS

The following conclusions have been drawn as a result of the work performed under this program:

1. Two types of combustion can occur when pigskin and hair are exposed to an ignition source in an oxygen-enriched atmosphere. The first type of combustion is nap burning of the hair, and the second is bulk burning of the skin and fat. Bulk combustion of skin and fat is possible only through the presence of an artifact consisting of exposure of fat to the ignition source and depletion of local heat sink capability.

2. The flame spread rate for hair combustion on pigskin samples in 258 mm. Hg pure oxygen is approximately 9 cm./sec. The flame spread rate can be greatly increased by lengthy exposure of the sample to a dry atmosphere and can be decreased through wetting the hair or by reduction of the hair length. Completely shaved samples of pigskin or human skin will not undergo nap burning in 258 mm. Hg oxygen.

3. In atmospheres containing 180 mm. Hg oxygen it is necessary to bring the helium partial pressure to 578 mm. Hg before no flame spread is observed on unshaved pigskin samples.

4. The minimum ignition energy for pig bristles in 258 mm. Hg pure oxygen is approximately 0.3 J. This minimum ignition energy cannot be reduced by drying the sample, but dilution with an inert gas or partial removal of the hair increased the ignition energy requirement.

5. Of the two types of glass fiber cloth tested, the thicker and heavier cloth offered more protection against ignition of hair by thermal transfer through the cloth. The two types of cloth offered essentially equal protection against flame propagation under fire breaks consisting of cloth strips (2.5 cm. wide) held against pigskin samples.

6. Various salves, creams, and lotions were found to prevent flame spread on pigskin samples in 258 mm. Hg pure oxygen, but the extent of application necessary to ensure prevention of ignition appeared to be greater than the amounts of cold cream and hand lotion usually applied.

7. Samples of skin and hair from white suckling pigs do not appear to offer effective simulation of the response of human skin and hair to ignition sources in oxygen-enriched atmospheres. On the basis of the results of this program, the flame spread rate for human hair is greater than for pig bristles, probably because of the smaller diameter of the human hair tested as compared to that of pig bristles.

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13. ABSTRACT

The flammability of hair and skin from white suckling pigs and from humans was studied in atmospheres ranging in oxygen concentration from 20.9% (air) to 100%. Neither pigskin nor human skin would support combustion in pure oxygen at 258 mm. Hg except in the presence of an artifact consisting of exposed subdermal fat and local depletion of heat sink capability. Although pig bristles and human hair burn rapidly in pure oxygen, differences observed in flame spread rates and burning times indicate that skin of suckling pigs is not an adequate simulant for human skin in terms of response to an ignition source in pure oxygen.

Methods of protection against ignition were studied with pigskin samples. The helium concentration necessary to prevent flame spread at 1 atm. total pressure is 75% by volume. Salves and creams are effective against flame spread when the amounts applied are much larger than those normally used.

The values obtained from the present work on unshaved pigskin samples to determine flame spread rate and critical helium concentration (for zero flame spread) are completely consistent with reported values for other types of combustibles.

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