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An Investigation of the Ignition and Combustion of Loosely Compacted Commercial Steel Wool

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ABSTRACT

The ignition and combustion characteristics of loosely compacted commercial steel wool samples when introduced promptly into low velocity heated air streams and the morphology of the quenched residues were investigated. The effects of the important factors of sample compactness, stream temperature and velocity, and exposure time were established. Comparative tests were also made under similar conditions involving similarly prepared samples of cotton, sheep wool, fiber glass wool, and processed cigarette tobacco.

THE TRANSPORTATION AND STORAGE OF VARIOUS COMPACTED FIBROUS materials are known to constitute a potential fire hazard due to the development of spontaneous ignition. Accordingly, the ignition and combustion characteristics of loosely compacted pure cotton including its fiber degradation morphology were investigated. Effects of sample compactness, defined as the mass per unit of total volume, stream velocity, stream temperature and exposure time on the degradation of the cotton fibers when exposed to a steady heated low velocity stream of air were established. These findings were reported in earlier publications [1,2].

An extension of this earlier work involved a similar study of commercial steel wool. Other important materials (pure sheep wool, fiber glass

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wool and processed cigarette tobacco) were also considered. These materials not only have widely varying origins but also have very wide range of applications and can provide means for comparison with the cotton wool examined earlier. The testing was performed under identical conditions to those of the earlier work. The specimen containers used were of the same size and type to permit a valid comparison.

EXPERIMENTAL

The schematic diagram of the test rig employed is shown in Figure 1. It consists mainly of an air heating electric furnace of 24 ceramic heating elements connected to a three phase power supply circuit. Air supply to the electric furnace is regulated by a pressure control valve. The size of the test section is 50 mm × 50 mm × 70 mm. A quartz viewing window is provided for visualization purposes. The operating range of the air stream velocity and temperature employed in the test section is 0.1–5.0 m/s and 300–780 K, respectively.

The desired test section temperature was achieved by connecting the required number of heating elements to the power supply and fine temperature adjustment was made using a variac. The air stream temperature in the test section was continuously monitored using three Chromel-Alumel thermocouples connected to a multipoint temperature

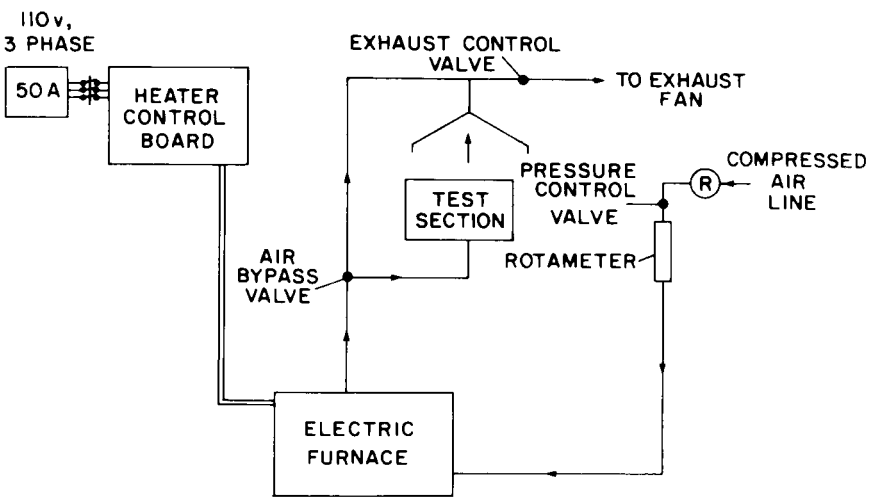


Figure 1. Schematic diagram of main test rig

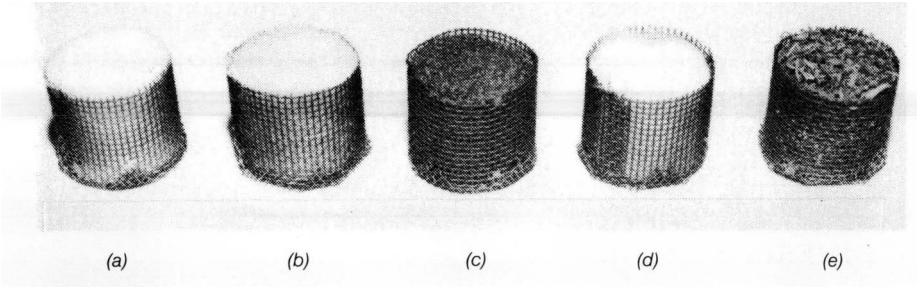


Figure 2. All wire mesh specimens. Compactness = 84.88 kg/m³. (a) cotton; (b) sheep wool; (c) steel wool; (d) fiber glass wool; (e) tobacco.

readout/recording system. The air stream velocity in the test section was controlled precisely by an air bypass valve.

To minimize the environmental effects, all the materials were stored in air-tight polyethylene bags which were stored at room temperature. All samples were prepared according to ASTM Standard [3] for cotton. Each material was first carded using carders and then weighed accurately using an analytical balance which could read to within 0.1 mg. The weighed material was then compacted uniformly into a standard stainless steel wire mesh (mesh #16) cylindrical container of 30 mm diameter, 25 mm height and open at the top. The samples were placed vertically in the test section and axially aligned to the air flow. Figure 2 shows the samples of the materials under investigation.

The air stream temperature and velocity within the test section were set at the desired values and the specimen, which was in equilibrium with ambient conditions, was introduced promptly into the test section. The specimen was then removed from the test section after the elapse of a certain time and to quench the reaction, suspended in an atmosphere of nitrogen vapour, as it boiled off a pool of liquid nitrogen. Later on, in addition to the examination of the sample under optical microscope, a small portion of the quenched specimen was mounted on a metal stub and was sputter-coated with gold. A scanning electron microscope was used to examine its morphology and to obtain scanning electron micrographs. Each test was repeated at least five times, so as to provide consistently typical results. The same procedure was followed while studying the effects of sample compactness, air stream velocity, and air stream temperature.

Table 1. Average steel wool fiber widths corresponding to their commercial grades.

Commercial Grade	Average Fiber Width, μm
0	61
00	43
000	31
0000	20

COMMERCIAL STEEL WOOL

Steel wool specimens of four different commercial grades, namely '0', '00', '000', and '0000' were tested. The steel wool which was reportedly manufactured by drawing rectangular steel bars under serrated knives, had a reported average carbon content of 0.13%. Due to the limitations in the preparation of uniformly compacted samples of compactness lower than 84 kg/m^3, the range of the sample compactness employed was confined to from 84 kg/m^3 to 285 kg/m^3. The average steel wool fiber widths corresponding to their commercial grades were measured and are listed in Table 1. Figure 3 shows a representative scanning electron micrograph of the steel wool fibers.

The steel wool was soaked and washed in methanol to remove any oil or other residues. The wool was then exposed to the room environment for five hours to dry. Specimens were prepared from the clean dry wool as per the procedure described earlier.

General Observations

A change in color of the steel wool samples from steel gray to metallic blue was noted after samples were introduced into the heated oxidizing stream of air having a temperature above 600 K. Auto ignition was observed to take place in the core of the specimens. The distance between the ignition centre and the base of the specimen was observed to be dependent on the sample compactness, sample grade (fineness), and the air stream velocity. The auto ignition started with a very bright glow, accompanied by sparks. After the ignition, combustion was very intense and without a flame. The combustion front propagated very rapidly with a bright yellow glow and sparks. Figure 4 shows photographs of various stages of the steel wool combustion. It was further observed that in all these tests, the top portion of the samples was partially oxidized showing that the combustion extin-

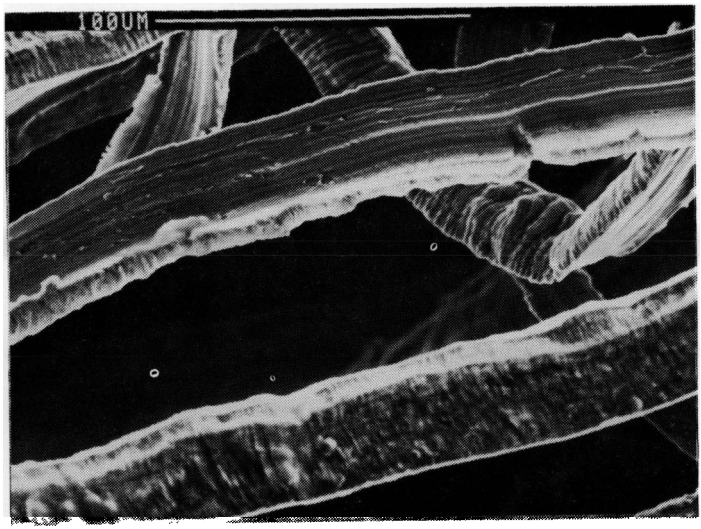


Figure 3. Scanning electron micrographs of steel wool fibers

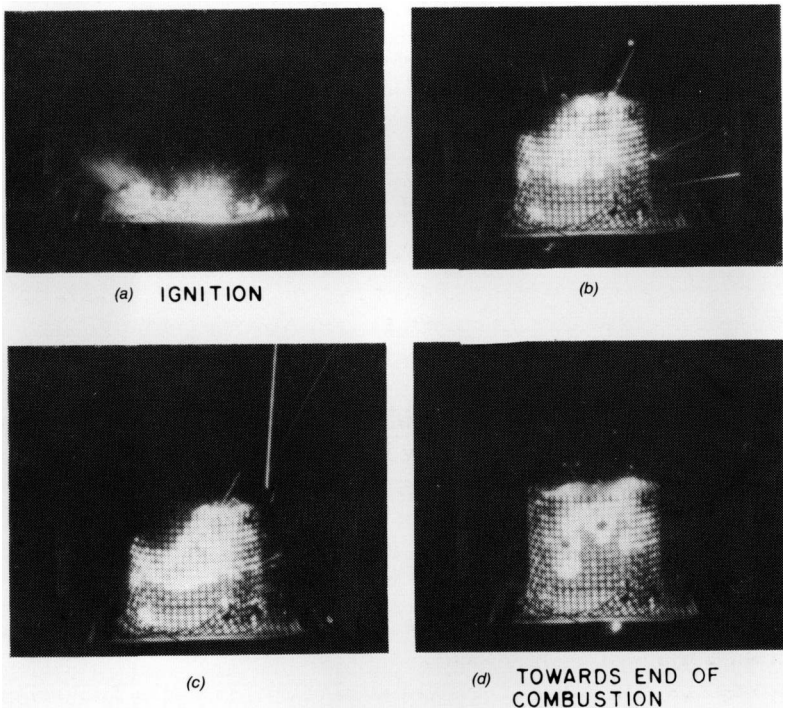


Figure 4 Various stages of steel wool combustion (T = 693 K, V = 2 1 m/s, ρ = 84 88 kg/m³ grade '00', specimen container all wire mesh)

Table 2. Specimen container: all wire mesh; sample compactness: 285 kg/m³; air stream velocity: 4.0 m/s.

Commercial Grade	Average Fiber Width, μm	Minimum Auto Ignition Air Stream Temperature, K
0	61	690
00	43	682
000	31	662
0000	20	650

guished before the entire sample was oxidized. A significant amount of weight gain due to the oxidation of the material of the sample was observed.

The auto ignition stream temperature for "all wire mesh" specimens of 285 kg/m³ compactness prepared from grade '0000' steel wool was found to be as low as 650 K at the air stream velocity of 4.0 m/s. Under identical conditions, the ignition delay times and the total burning times were longer for the "bottom wire mesh" specimens compared to the "all wire mesh" specimens. Table 2 displays the minimum auto ignition temperatures for the four commercial grades of the steel wool.

Residue and its Morphology

Steel is known to oxidize into the two oxides: Fe_2O_3 and Fe_3O_4 when it undergoes intense combustion in oxygen rich environment. If a steel sample is entirely oxidized to the non-magnetic Fe_2O_3, the weight gain would be 43%, while the corresponding gain in weight would be 38.2% when the steel is oxidized entirely to form the magnetic Fe_3O_4.

The presence of carbon in the steel wool was evident from microscopic examination of the steel wool sample (Figure 5). It was observed that the color of the residue was glossy black and magnetic, indicating that the oxide in the residue was mainly Fe_3O_4. The actual weight gain was found to be from 31% to 36%, corresponding to the sample compactness range of 85 kg/m³ to 285 kg/m³. The difference in the weight observed between the actual weight gains and that expected from complete oxidation to the lower oxide Fe_3O_4 (38.2%) could be attributed to:

a. Loss of a small amount of the residue into the air stream and through the formation of sparks
b. Incomplete oxidation of the steel wool resulting in the formation of FeO, the degree of which was observed to increase with a decrease in the sample compactness

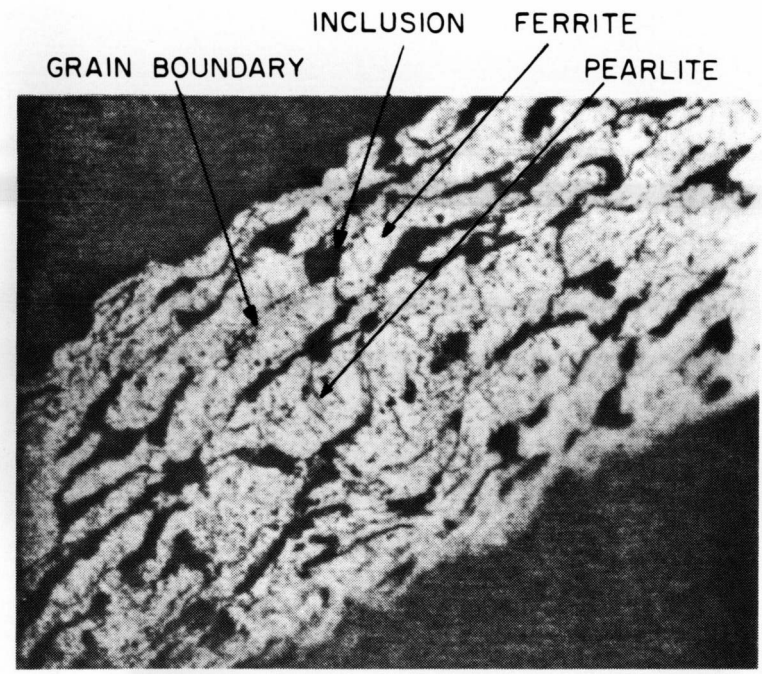


Figure 5. Optical micrograph of steel wool fiber (polished 0 5 μm, etching agent nital (10 sec))

c. Possible formation of other lighter oxides due to the presence of very small amounts of C, Mn, Si, etc. in the steel wool

The loss of residue into the stream increased with a decrease in the sample compactness since the resistance to flow increases with compactness.

A morphological examination of the residue was carried out. It can be observed from the scanning electron micrographs (Figures 6 and 7) that the residue consists of oxidized and flaked fibers having widths greater than that of the original steel wool fibers. Also, the fiber ends are fused in the form of hollow spheres and some of the fibers are fused together forming large, hollow, oxide lumps. These lumps have attached to them a large number of hollow oxide spheres. The diameters of these spheres are approximately as large as the width of the original fibers. Figure 8 shows a typical view of the hollow oxide sphere. The crystalline appearance of the sphere surface is typical.

It is suggested that the formation of the spheres can be explained by

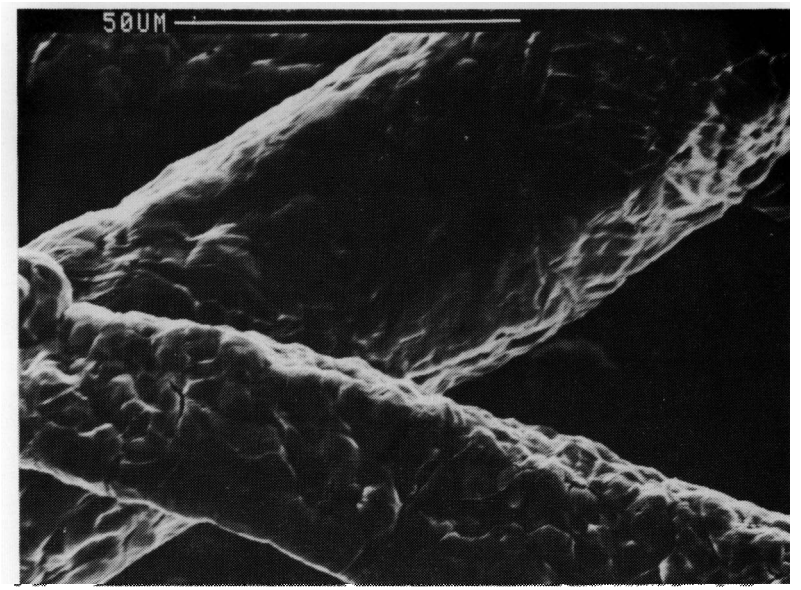


Figure 6. Scanning electron micrograph of residue showing oxidized flaked fibers (grade '00')

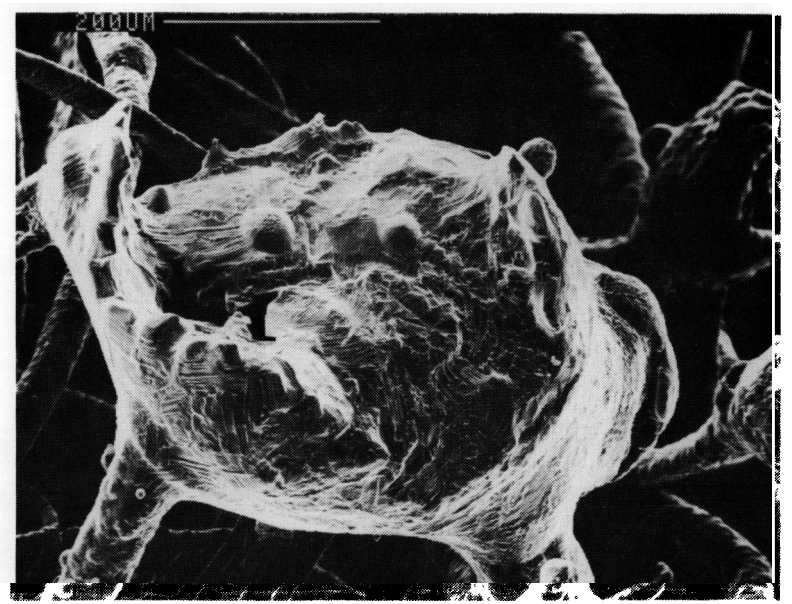


Figure 7. Scanning electron micrograph of residue showing a typical steel wool oxide 'lump' (grade '00')

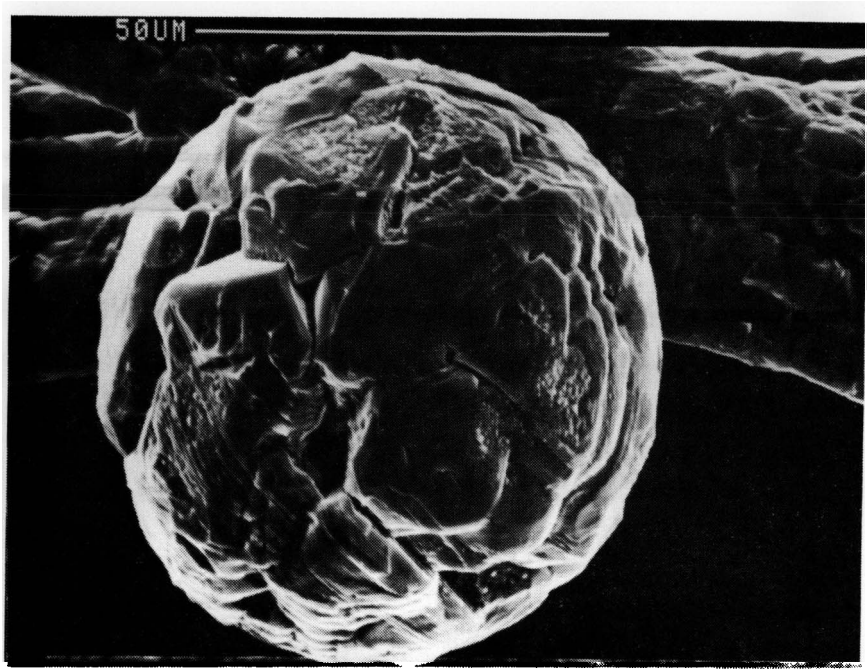


Figure 8. Scanning electron micrograph of residue showing a typical crystalline oxide sphere with an oxidized flake fiber in the background.

the following mechanism. When the steel wool is exposed to the hot moving stream of air, surface oxidation of the fibers begins. Due to the different thermal properties of the hot outer oxidized layer and the unoxidized core of the fibers, the oxidized layer starts to crack, allowing oxygen to penetrate. This oxygen also reacts with the small amount of carbon already present in the steel, eventually forming carbon dioxide. At the same time, oxygen reacts with the steel. Due to the pressure rise between the two oxide layers caused partly by carbon oxides generation, a hollow oxide sphere is ultimately formed. Moreover, the steel wool fibers contain normally some surface and internal defects. The pressure rise in the internal cavities caused by CO_2 generation, after the surface oxidation, also contributes to the formation of the hollow oxide spheres. The crystalline sphere surface shows the cracked oxide layer. It has been reported that hollow spheres are common in coal ash and ash from volcanoes [4]. The formation mechanism of these spheres, probably, has some similarity to that for the steel wool residue spheres, as both the materials contain carbon.

Comparison with Cotton

Despite the very obvious difference in origin and properties between commercial steel wool and cotton wool, the effects of some of the fundamental physical parameters such as sample compactness, air stream temperature, and air stream velocity on auto ignition and combustion characteristics were similar in general. It should be noted that the minimum ignition temperature for cotton was 600 K (specimen container: All Wire Mesh; air stream velocity: 4.0 m/s; sample compactness: 85 kg/m^3).

The presence of the hollow tar spheres in the cotton char and the hollow oxide spheres in the steel wool residue, evidently indicates similarity between the formation mechanisms of the tar spheres and the steel oxide spheres. In both cases, the pressure rise within the fiber structure due to gas expansion caused by its exposure to high temperature, results in the expansion of the fiber shell, which ultimately forms the sphere. A comparison on the basis of fiber fineness was not possible within the scope of this work, as the study was restricted to one variety of cotton [1].

Comparison with Sheep Wool

Uniformly compacted specimens, prepared from raw as well as scoured (washed and combed) white Scottish Blackface ewe wool of 33 μm average fiber diameter, were tested. The selected range of the sample compactness was 20–285 kg/m^3. The exposure time of 15 minutes for each specimen was kept constant throughout.

No significant changes were observed when raw wool samples were exposed to the air stream having temperatures lower than 450 K. However, the raw wool samples started smoldering, a few seconds after the introduction of the specimen into the 473 K air stream. The smoldering diminished after about three minutes. A change in the color of the wool from flat white to light brown was observed when the specimen was removed from the test section after 15 minutes exposure to the heated air stream. Also, the fibers were coated with a thin brittle layer of decomposed lanolin.

For the stream temperatures above 500 K however, severe smoldering with significant sample expansion, change in the color from flat white to flat black, and fiber melting were observed. It was further observed that after about 11 minutes of exposure, the smoldering and the boiling gradually diminished. The sample, after its removal from the test sec-

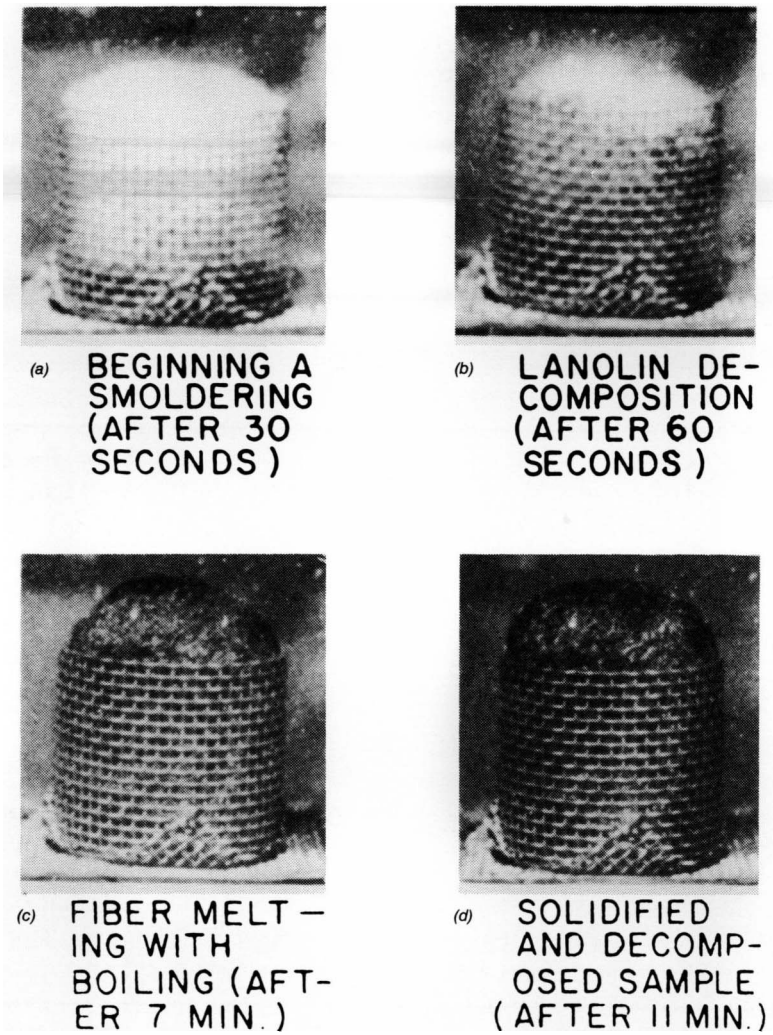


Figure 9. Four stages of raw sheep wool decomposition. (T = 750 K, V = 2.1 m/s, C = 169.77 Kg/m³, specimen container: all wire mesh).

tion, was hard and brittle. Figure 9 shows four stages of the wool decomposition.

When scoured wool samples were tested, no apparent change in the color or properties of the wool was observed upon exposure of the sample for 15 minutes to the 473 K stream. A behaviour similar to that of the raw wool, was observed when the scoured wool specimens were ex-

posed to a stream having a temperature above 500 K. The decomposition of the wool took place without ignition.

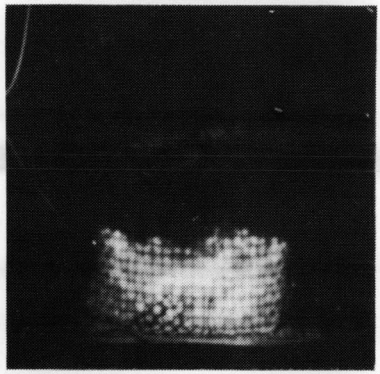
In this testing, it was confirmed that the sheep wool has excellent resistance to fire spread. Moreover, it was observed that the scoured wool samples had better resistance to decomposition compared to the raw wool samples, when subjected to the hot oxidizing air stream. This could be attributed to the presence of combustible lanolin and other oily substances in the raw wool.

It has been reported by Walker et al. [5,6,7] that bales of raw wool burst into flames when opened after about 60 days. They suggested that slow decomposition of raw wool by bacterial activity produces flammable pyrolytic products. The decomposition is exothermic and since wool is a poor conductor of heat, raises the core temperature of the bales. This in turn increases the rate of decomposition in the core. The rate of diffusion of air (oxygen) is very small as the bales are tightly compacted. Hence, upon exposure to the oxygen when the bales are opened, the core, which is at a high temperature, undergoes auto ignition. It is therefore suggested that the potential fire hazard posed by the decomposition of raw wool during transportation and storage could be substantially reduced by washing the wool prior to baling.

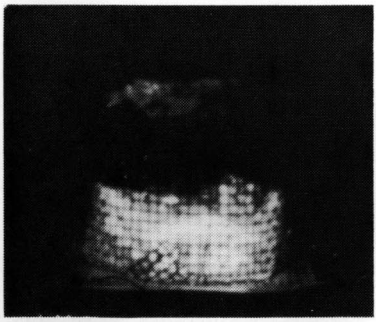
Comparison with Tobacco

Similar tests were performed on commercial regular blend cigarette tobacco. The average length and width of the tobacco fibers were 12 mm and 1 mm, respectively. The range of sample compactness and the stream velocity were restricted to 170–285 kg/m^3 and 0.1–1.0 m/s respectively, because of the noncohesive nature of tobacco. The air stream temperature range was from 473 K to 673 K.

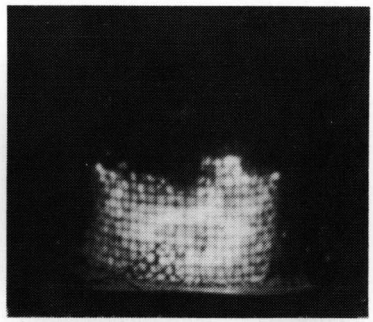
Instantaneous smoldering with heavy smoke began when the tobacco specimens were introduced into the test section. The recorded auto ignition stream temperature was as low as 483 K. The auto ignition and combustion were similar to that of the cotton except, after the ignition at the bottom, the top surface of the specimen also ignited. The combustion front propagation, however, was slower than that of the cotton. The effects of the three parameters on the auto ignition and the combustion characteristics were also similar to that of the cotton. The combustion of the samples was observed to be complete. The residue was in the form of white ash and it was found to be consistently around 10% of the original sample weight, irrespective of sample compactness and stream velocity. The microstructure of tobacco ash was found to be similar to



(a) COMBUSTION FRONT (AFTER 1 MINUTE) WITH SPARKS



(b) COMBUSTION FRONT WITH THE IGNITION AT THE TOP (AFTER 2.5 MIN.)



(c) COMBUSTION FRONT WITH THE ASH AT THE TOP (AFTER 5 MIN.)

Figure 10. Various stages of tobacco combustion (T = 500 K V = 2.1 m/s, C = 200 kg/m³, specimen container all wire mesh)

that of white cotton ash. Figure 10 displays various stages of tobacco combustion.

Comparison with Fiber Glass Wool

Comparative tests were also performed to check the resistance of commercial Pyrex fiber glass wool to the high temperature streams.

Specimens prepared from fiber glass wool were tested under identical conditions to those employed for the other materials. The average diameter and length of the fiber glass wool fibers were 3 μm and 300 mm, respectively. The ranges of the sample compactness, stream velocity, and stream temperature were 55–285 kg/m^3, 0.1–4.0 m/s, and 400–773 K, respectively. The exposure time of 15 minutes was also kept constant throughout.

Virtually no apparent change in the fiber glass wool over the test conditions employed was observed except for a slight expansion of the sample when it was exposed to air streams having temperatures and velocities of up to 773 K and 4.0 m/s, respectively. It is thus evident from these tests that fiber glass wool has excellent resistance to moderately high temperature streams. However, the exposure times used were relatively short and commercial fiber glass wool insulation normally contains combustible binder material.

ACKNOWLEDGEMENT

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