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Evaluation of the Flammability of Cotton Bales

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Bales of cotton were classified by the International Maritime Organization (IMO) code regulations as a flammable solid (Class 4.1), which required hazardous goods papers to accompany waterborne shipments. Various scientific investigations were conducted to evaluate the flammability hazard of bales of cotton to determine if this hazardous designation was valid. Cigarette (NFPA 261/ ASTM E1352), match (NFPA 705) and open flame (CA TB 129) tests were conducted; the potential for self-heating and spontaneous combustion was evaluated; and the potential of cotton bales sustaining smouldering combustion in their interiors at various compression densities was studied. These studies showed that bales of cotton should not be required to have the hazardous designation, 'flammable solid', and led to the IMO and the US Department of Transportation (DOT) removing the designation for baled cotton [compressed to a density of 360 kg/m^3 (22.4 lb/ft^3) or greater; meets ISO 8115], with effect from 1 January 1999. Published in 2002 by John Wiley & Sons, Ltd.

INTRODUCTION

The US Department of Transportation (DOT) regulates the movement of products on US highways, railroads and waterways. Prior to 1999, the US Coast Guard, as DOT's enforcement arm for vessel shipments, required cotton shippers to prepare dangerous goods declarations for cotton exports. Cotton shippers were required to follow International Maritime Organization (IMO), International Maritime Dangerous Goods (IMDG) Code Regulations that classified cotton as Class 4.1 (flammable solid; see appendix). Cotton also was listed as Class 9 (a miscellaneous hazardous material; see appendix) by DOT for domestic waterborne shipment which required hazardous goods papers to accompany a shipment.

Research was conducted to evaluate the flammability hazard of bales of cotton, which was used to support a petition to the DOT and IMO to exempt certain categories of baled cotton from these regulations. This paper describes some of this research.

BACKGROUND

Research test results, along with the industry's experience with containerized shipment, were submitted in a petition to DOT on 6 June 1996.[1] The petition[1] argued that cotton compressed to universal density should not be regulated as a class 4.1 flammable solid under IMO regulations for vessel shipment or as a class 9 hazardous substance under DOT regulations for domestic waterborne shipment. Data submitted to DOT in the petition to get baled cotton deregulated were used by DOT to prepare a proposal, which was submitted to the IMO November 1997[2] to have baled cotton deregulated. At the IMO meeting in February 1998, amendment 29 to the IMDG code was approved,[3] which removes baled cotton [compressed to a density of about 360 kg/m^3 (22.4 lb/ft^3) or greater; meets ISO 8115[6]] from Class 4.1 (flammable solid), effective 1 January 1999. Because of the IMO decision to deregulate baled cotton, DOT published a standard,[4] making the IMDG code amendments with effect from 1 January 1999 in the USA. The DOT also finalized[5] a rule removing baled cotton as a class 9 hazardous substance and, therefore, from the Hazardous Materials Regulations (HMR). This aligns the US HMR with international air, sea and land transport requirements, which became effective 1 January 1999.

This, in addition to removing the hazardous cargo requirements and their associated costs so the bale can shipped as ordinary cargo, has helped lower insurance rates for storage of cotton bales in US gin, merchant and textile mill warehouses.

Baled cotton/packaging

After seed cotton is removed from the field, it is transported to the ginning facility where the cotton fibre is removed from the cottonseed and compressed in bales of about 227 kg (500 lb). The most significant factor affecting fire risk is bale density. Bale density is directly related to the amount of airspace inside the bale and the diffusion of air into and out of the bale, which is necessary to support smouldering combustion (see appendix).

Cotton fires can occur during the ginning process. The ignition source can be heat from friction or sparks from metal to metal contact of the ginning machinery. Once ignited and burning, common belief has long maintained that these smouldering wads of cotton fibre can be introduced into the centre of a cotton bale to smoulder unnoticed for long periods of time. This is referred to as

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a 'fire packed' bale. Cotton bale fires in cotton warehouses or during shipping have been blamed on internal bale fires that finally broke to the surface weeks or even months later as well as on spontaneous combustion. Millions of dollars per year have been spent on insurance premiums to guard against financial loss from cotton bale fires.

Worldwide, bales of cotton vary considerably in dimensions and weigh from about 85 kg (187 lb) to over 227 kg (500 lb). The International Organization for Standardization (ISO 8115)[6] specifies that bale dimensions should be of length 139.7 cm (55 in), width 53.3 cm (21 in), height 70 to 90 cm (27.6 to 35.4 in) and density of 360 to 450 kg/m^3 (22.4 to 28 lb/ft^3). Bales of cotton produced in the USA meet these dimensional standards and are of two types. Now almost 100% of US cotton bales are produced at the gin to what is termed 'Universal Density' (UD). UD bales have a target weight of 218 kg (480 lb). Typical UD bale dimensions are consistent with the ISO specifications. The remaining less than 1% of the crop consists of bales (called compressed universal density bales) that are compressed to universal density in a two-stage process. First, the bale at the gin is compressed to approximately 225 kg/m^3 (14 lb/ft^3; referred to as 'flat or modified flat density') and is then taken to a warehouse facility for compression to its final export density of 450 kg/m^3 (28 lb/ft^3). Anecdotal historic evidence gathered by the authors, concerning delayed cotton bale fires in gin or cotton warehouse storage facilities, implicated the lighter density bales ('flat or modified flat bales') much more strongly in fire incidence than the modern UD bale. Lighter density bales have had some propensity for delayed fire breakout due to internal smouldering but the UD bales did not. All cotton bales are subject to fire or fire damage from external causes.

Cotton bales in the USA are packaged in compliance with US Department of Agriculture (USDA) regulations that include detailed specifications for packaging materials and bale ties. The more recent improvement in bale packaging materials gives a higher level of protection to the cotton lint inside the bale wrap. When the amount of exposed cotton is coupled with lower bale density [<225 kg/m^3 (<14 lb/ft^3)] the risk of loss due to fire is greater. Today, bales are wrapped in products that are stronger, more closely woven and, in some cases, constructed from an impervious film, and provide complete protection to the bale's six sides. Virtually all bales are now packaged with the bale ties placed inside the bale cover. The placement of the bale ties inside the bagging eliminates as a source of ignition the hypothesis that 'fire in baled cotton is caused by bursting of bands contacting other ferrous metal and creating sparks' (unpublished report, *Investigation of Causes and Remedies for the Occurrence of Fires in Railroad Shipment of Cotton Bales*, SRI Project C-1029, July 14, 1955).

EXPERIMENTAL

Fire-packed bales

Evaluation of smouldering combustion in a UD bale. The anecdotal evidence for UD bale fires, caused by the delayed breakout of internal smouldering fire, pointed to the need to establish the risk of smouldering fire occurring within UD bales. To test the hypothesis that smouldering combustion, once started in the interior of the bale, could be contained within a UD bale for long periods of time, a full size test UD bale of upland cotton weighing 205 kg (452 lb) [density approximately 387.3 kg/m^3 (24.1 lb/ft^3)] was produced. During ginning, thermocouples were placed at predetermined locations in the bale's interior. On one end of the bale a smouldering wad of cotton was placed in the bale's geometric centre. On the other end, also in the geometric centre, a small electric heater was placed. Electric current was passed through the heater, within the pressed and tied experimental bale, to initiate a fire within the bale. The temperatures indicated by the interior thermocouples were monitored for several days.

Further tests were conducted to see if combustion initiated nearer to the bale surface would result in the smouldering combustion being continued. The test bale was repacked with two more electric heaters, one 13.3 cm (5.25 in) and one 6.35 cm (2.5 in) from the outside. Again, thermocouples were placed in strategic positions to monitor temperatures. After tying the bale, both heaters were powered until the cotton around the heater, as indicated by a closely placed thermocouple, reached at least 400°C (750°F). In a separate test, by direct measurement, it was determined that loose cotton smoulders at a temperature of around 345° to 400°C (650° to 750°F) measured at a small distance from the ignition source. The thermocouples used to monitor heating temperature were a short distance away from the heating elements and were separated from the heater by a thin mat of cotton. Since cotton is an insulator, the actual temperature at the heater was unknown. However, the temperature was at least high enough to melt the glass core of the heater, which should occur around 595°C (1.100°F). Both of the heating site temperatures, 6.35 cm (2.5 in) and 13.3 cm (5.25 in) from the bale outside edge, were monitored for several days.

Calculation of available oxygen in a bale of cotton. Sustained internal smouldering combustion of a cotton bale depends either on available oxygen contained within the bale or on oxygen that diffused in from outside the bale. Using the assumptions: (1) cotton fibre is essentially pure cellulose; density of cellulose = 1.44 g/cm^3; (2) UD bale dimensions = 139.7 cm (55 in) × 53.3 cm (21 in) × 71.1 cm (28 in); and (3) actual test bale weight = 205 kg (452 lb), a calculation was made to determine if enough oxygen could be present within the test bale to sustain smouldering combustion.

The volume of the UD test bale based on the defined dimensions was 529 411 cm^3, which yielded a bale density for the test bale of: (205 kg)(1000 g/kg)(529 411 cm^3) = 0.387 g/cm^3. The ratio of cotton fibre density to pure cellulose would be (0.387 g/cm^3)(1.44 g/cm^3) = 0.27. This ratio says that the test bale is about 73% open space filled with air. The volume of air contained in the total bale volume would be 529 411 cm^3 or 0.53 m^3 multiplied by 0.73 = 0.39 m^3. The theoretical amount of air required to oxidize the carbon, hydrogen and sulphur in a fuel can be calculated from the following Eqn. (7)

$$106.8(C/12 + H_2/4 - O_2/32 + S/32) = m^3\ air/kg\ fuel$$

where C, H_2, O_2 and S are the decimal weights of carbon, hydrogen, oxygen and sulphur, respectively, in 1 kg of fuel.

Cotton is cellulose, a polysaccharide that is a 1 → 4-linked linear polymer of β-D-glucopyranose. Assuming the chemical formula for cotton cellulose is the glucopyranose monomer repeat unit $C_6H_{10}O_5$, then the above equation becomes:

$$106.8(0.444/12 + 0.062/4 - 0.494/32) = m^3\ air/kg\ fuel$$

where the values of the numerators are determined by dividing the total molecular weight of the cellulose monomer (repeat unit), which is 162 into the molecular weights of the carbon, hydrogen, and oxygen present (assuming no sulphur), which are 72, 10 and 80, respectively. To determine the amount of fuel (cotton) that can be burned by the amount of air present in the bale, the equation becomes:

$$106.8(0.037 + 0.0155 - 0.0154) = m^3\ air/kg\ fuel$$

This equation yields 3.96 m^3 air/kg fuel (cotton). There is about 0.39 m^3 of air in a UD bale. This amount of air, if totally utilized, could combust cotton according to the following ratio:

$$(0.39\ m^3\ air)(3.96\ m^3\ air/kg\ cotton) = 0.0985\ kg\ cotton.$$

This calculation shows that if all the air contained in the UD bale were used for combustion, no more than approximately 100 g of cotton would be consumed. Any sustained smouldering combustion within a UD bale would have to depend on air diffusing into the site of combustion and combustion products diffusing out. Test results with the full size UD bale indicated that air diffusion into and out of the bale is not sufficient to sustain combustion.

Oxygen diffusion/packing density studies. It was not feasible to use full size UD bales to replicate a range of bale densities. In order to determine the packing density where sufficient oxygen will diffuse into a cotton bale to sustain internal smouldering combustion, miniature bales approximately 6.35 cm (2.5 in) × 13.01 cm (5.125 in) × 8.89 cm (3.5 in) (total volume of 734.4 cm^3 [0.0259 ft^3]) were used. Bale densities could be adjusted easily by packing various weights of ginned cotton into the constant volume of the miniature bales. Small heating elements were constructed using 24 gauge, Chromal A wire with an electrical resistance of 5.28 ohm/m. 2.54 cm (1 in) lengths of the heating wire were attached to copper lead wires. These small heating elements were bent into a 'U' shape to take up a minimum of room inside the small bales. The heaters were powered with a 12-volt transformer delivering a current of 7.5 amp for 30 s. This current would cause the chromal heater wire to glow a bright orange.

A low density of 192.9 kg/m^3 (12 lb/ft^3) was used first and increased from there. Each heater was placed in the geometric centre of the miniature test bales. After each miniature bale was heated, it was set under a fume hood for 4 h. If no smouldering fire broke through to the outside of the bale during the waiting period, the bale was then opened and the internal heated area was observed. If fire did break through during the waiting period, the bale was extinguished by sealing in a metal container and then evaluated after cooling.

Evaluation of spontaneous combustion of cotton bales

Self heating. To determine if standard cotton fibre could be considered self-heating, raw cotton was subjected to a self-heating test in accordance with the DOT self-heating test for materials as specified in 49 CFR 173, Appendix E.[8] The test was conducted by Stresau Laboratory, Inc., an independent laboratory specializing in hazardous materials evaluation. A 53.2 g sample of raw cotton was loosely filled into a 10 cm^3 fine mesh, wire basket which was placed in an oven set at 140°C (285°F). The temperature was recorded over a 24 h time period. A material is classified as Division 4.2 (liable to spontaneous combustion) if spontaneous ignition occurs or the temperature of the sample exceeds 200°C during the 24 h testing time.

Testing of cotton bales to evaluate open flame and smoulder flammability

Flammability studies were performed to evaluate the flammability characteristics and the hazard potential of wrapped gin UD bales of cotton. The bales were compressed to a density of about 385 to 450 kg/m^3 (24–28 lb/ft^3), weighed about 450 kg (480 lb), and were wrapped in woven polypropylene or burlap (jute). Studies were done using a cigarette test similar to NFPA 261/ASTM E1352;[9,10] a match test similar to NFPA 705;[9] and an open flame test similar to CA TB 129[11] at Omega Point Testing Laboratory in Elmendorf, TX. CA TB 129 is a test used to determine the burning behaviour (for arson-like fires) of mattresses used in public occupancies. Since these test methods were not designed for bales of cotton, the test used was adapted to cotton bales.

Cigarette and match tests. The cigarette and match tests were performed on the tops and bottoms of the bale to evaluate potential ignition problems if cigarettes and/or matches were carelessly thrown on the bales. For the cigarette test, four cigarettes were lighted and placed 20.3 cm (8 in) apart on the tops of the bales. The cigarettes were covered with sheeting according to the tests and allowed to burn completely. After 1 h the char lengths were measured. For the match test, four wooden matches were lighted and placed about 20.3 cm (8 in) apart. The matches were allowed to burn completely and the time for complete burning recorded. Both the cigarette and match tests were allowed to continue for 1 h to make certain that no further flaming or smouldering ignition would occur after the cigarette or match had burned completely.

Open flame tests. Open flame tests were performed on both rounded and flat sides of the bales. The open flame calorimetry tests utilized the oxygen consumption principle[12] to measure heat release and to assess potential hazard. A T-burner [205 mm (about 8 in)] with a 17.8 kW flux [propane gas (net heat of combustion of

2050 ± 50 kJ/mol) flow was a constant 12 l/min; approximate ratio of heat release rate output to gas flow rate is 1.485 kW] for 180 s is the flaming, high flux, ignition source used for CA TB129.[11] The maximum flame temperatures on the flat sides of the bales were 631°–1100°C (1096°–2012°F) and on the round sides 908°F (457°C). A product fails the TB 129 test procedure if any of the following criteria are exceeded. (1) Weight loss due to combustion of $\geqslant$1.36 kg (3 lb) in the first 10 min of the test. (2) A maximum rate of heat release of $\geqslant$100 kW. (3) A total heat release of $\geqslant$25 MJ in the first 10 min of the test.

The bales were placed on a load cell under the open calorimeter so the weight loss could be monitored continuously. For the test the ignition source was placed 15.24 cm (6 in) from the bottom of the bale in the centre of the face being tested (flat face/side or rounded face side) and 2.54 cm (1 in) from the surface of the bale. To measure the penetration of the heat during ignition and subsequent smouldering ignition, thermocouples were placed inside the bales at a distance of 15.24 cm (6 in) from the location on the surface where the T-burner ignition source was placed. To measure the temperature on the surface created by the ignition source, thermocouples were placed on the surface of the cotton bale directly under the burner.

RESULTS AND DISCUSSION

Fire-packed bales

Evaluation of smouldering combustion in a UD bale. In the initial test on the full UD cotton bale, the thermocouples, near both the initial smouldering wad of cotton and the electric heater, went from showing an elevated temperature down to the temperature of the rest of the bale [approximately 17.2°C (63°F)]. The test bale was then opened for inspection. The burning wad of cotton had not continued to smoulder for very long after being planted in the bale (only small additional amount of fibre consumed). The electric heater had initiated combustion, as indicated by the charred fibre around it, but this fire had also gone out in a very short time. It appears the packing density of the UD test bale was such that air diffusion into the bale was not sufficient to sustain combustion. The shortest distance from the outside of the bale to the point of combustion was approximately 26.7 cm (10.5 in).

In further tests where the heaters were placed 13.3 and 6.35 cm (5.25 and 2.5 in) from the exterior of the bale, the falling temperatures at the thermocouples showed that both fires had initiated but had quickly extinguished. Air diffusion into the bale, even at 6.35 cm (2 .5 in) from the surface, was not enough to sustain combustion. The odour of burning cotton could be detected several feet away from the outside of the bale during the heating of the element that was 6.35 cm (2.5 in) from the exterior surface of the cotton bale. This indicated that there was some gas exchange but not enough to sustain combustion.

Oxygen diffusion/packing density studies. A summary of the results of the tests run to determine the packing density where diffusion of air was insufficient to sustain smouldering combustion is in Table 1. If the bale density was $\geqslant$225 kg/m^3 ($\geqslant$14 lb/ft^3) smouldering combustion was not sustained unless it was within 1.27 cm (0.5 in) of the outside edge.

Spontaneous combustion

Self heating. In the test for self-heating [49 CFR 173, Appendix E[8]], the sample reached oven temperature, 140°C (285°F), in 2 h and remained at this temperature (140°C) for the remainder of the 24 h test period. The sample experienced a loss of 2.2 g (0.078 oz). There was no visible change to the sample. Based on the criteria defined in the Experimental section above (no spontaneous ignition and no increase in temperature to 200°C) cotton is not a self-heating substance.

Testing of cotton bales to evaluate open flame and smoulder flammability

Results of the cigarette and match tests showed no tendency to ignite or sustain ignition (i.e. all bales of cotton passed the match and cigarette ignitions tests). Data from these tests show that neither woven polypropylene or burlap (jute) covered bales would be ignited if cigarettes or matches were thrown on the bales.

UD bales exposed to the open flame (CA TB129) passed according to the criteria defined in the experimental section above (weight loss in the first 10 min was $<$1.36 kg (3 lb), the maximum rate of heat release was $<$100 kW, and the total heat release was $<$25 MJ in the first 10 min). The open flame tests produced some superficial flaming ignition, but all flaming ignition ceased during the first few minutes after the flame source was removed, and none of the bales re-ignited to flaming ignition. Therefore, all of the criteria for California TB129,[11] a severe test to evaluate mattresses for arson-like fires, were passed by all bales tested.

Table 1. Results of oxygen diffusion/packing density studies

Bale density, kg/m^3 (lb/ft^3)	Results[a]
192.9 (12)	75% of the bales sustained smouldering combustion such that it broke to the outside during the waiting period
208.9 (13)	25% sustained smouldering and broke out during waiting period
225.0 (14)	Zero bales sustained combustion with heaters in centre. Combustion was only sustained if heater was within approximately 1.27 cm (0.5 in) of outside edge
>225.0 (>14)	Smouldering combustion was not sustained

[a] If smouldering combustion did not break out during the waiting period, in all cases it had self-extinguished and was not still smouldering within the bale when inspected at 4 h.

Fire packed bales

Results of the tests of the full size UD bale indicated that cotton bales with densities $> 387.3\ \mathrm{kg/m^3}$ (24.1 lb/ft^3) would not sustain internal smouldering combustion. In fact, any initiated combustion was extinguished almost immediately within the bale. A simple calculation of available oxygen in a bale of cotton compressed to UD and ISO densities also indicated that, for sustained combustion, the air would have to diffuse from the outside of the bale. Analysis of packing densities using small bales showed that bales with packing densities $<225\ \mathrm{kg/m^3}$ ($<14\ \mathrm{lb/ft^3}$) could sustain smouldering combustion but for packing densities $> 225\ \mathrm{kg/m^3}$ ($> 14\ \mathrm{lb/ft^3}$), smouldering combustion was not sustainable within the interior of the cotton bale.

These results are also in keeping with the anecdotal evidence on cotton bale warehouse fires originally gathered by the authors. Up until the last decade, the US cotton ginning industry commonly produced cotton bales known as ‘flat’ or ‘modified flat’ bales. These bales were packaged with packing densities somewhere in the range of 160.7–225 kg/m^3 (10–14 lb/ft^3). This is the same range that was found to sustain internal smouldering combustion in the model cotton bales. It is probable that these older style cotton bale packages were prone to internal smouldering combustion that would eventually result in an external fire. It was a common gin practice, that if a cotton bale was suspected of being exposed to fire during the ginning process, to set those bales by themselves on the gin yard for several days to see if they would eventually start smouldering on the outside. It was not uncommon to see one or two smoking bales set aside in a gin yard during the ginning season. With the advent of the UD bale, except for smouldering fire that was already external to the bale during the pressing process, this sight is much less common. In summary, all evidence supports the conclusion that UD cotton bales will not support internal smouldering combustion. Unless there is evidence of external combustion already present at the time of baling, and this is readily detectable by smell and sight, UD bales are not a fire hazard from smouldering combustion.

Spontaneous combustion

Historical anecdotal information suggests that bales of raw cotton can spontaneously combust. However, the science indicates this is incorrect unless there is some type of self-heating reaction (e.g. oxidation) taking place that generates enough heat to ignite the cotton. Horrocks *et al.*[13] suggest that self-heating reactions could be associated with the presence of waxy or oily deposits on raw cotton, which could raise internal temperatures great enough to cause ignition. They showed that pure cotton fabric contaminated with 5% (w/w) vegetable oil can ignite at temperatures below 200°C (392°F). In their study, thermal analysis showed that the source of internal exothermic activity is oxygen dependent.

Cotton fibre, not contaminated with oil, does not melt but does start to decompose around 260°–270°C (500°–518°F) and its combustion temperature is about 360° to 400°C (680° to 752°F).[14] The typical wax content of cotton is about 0.4% to 1% of the fibre dry weight.[14] The wax chemically is a mixture of high molecular weight, long-chain, mainly saturated fatty acids and alcohols (with even numbers of carbon atoms, C_{28-34}), saturated and unsaturated hydrocarbons, and sterol[14] that are not readily oxidizable, self-heating drying oils. Therefore, it is not likely that the wax naturally on cotton fibre would undergo a self-heating reaction that would lead to spontaneous combustion. Also bales of cotton with packing densities $> 225\ \mathrm{kg/m^3}$ (14 lb/ft^3) do not sustain smouldering combustion within the interior of the cotton bale as discussed above.

In this paper self-heating of cotton and microbial action of wet cotton were explored to determine if baled cotton can spontaneously combust. Based upon the results of the self-heating test [49 CFR 173, Appendix E[8]] required by US DOT regulations for suspected self-heating substances, cotton is not a ‘self heating substance’, because it did not spontaneously ignite or increase in temperature to 200°C. Also, microbial activity could not cause self-ignition since the highest temperature that may be reached during microbiological breakdown of plant material during composting, for example, is 80°–90°C (175°–195°F) (Parnell, personal communication). This is well below the ignition temperature of cotton [about 360° to 400°C (680° to 752°F)[14]] and the temperature [$<$200°C (392°F)] that Horrocks *et al.*[13] found for cotton fabric contaminated with 5% vegetable oil.

It could be postulated that microbiological degradation of cotton fibres has the potential to evolve methane and/or oxygen that in vapour phase could lead to spontaneous combustion. Theoretically it is highly implausible for enough methane gas and/or oxygen to be evolved by microbial degradation of cotton to cause combustion. A mechanism through which significant quantities of oxygen might be generated during microbial degradation of cotton fibre is not known. Biological formation of methane occurs in anaerobic environments in which organic matter undergoes decomposition. However, the microbes that decompose cellulose do not produce methane. Also, the predominant microbial community associated with cotton fibre is associated with the fibre during cultivation and is primarily aerobic not anaerobic (Cotty, personal communication).[15]

Raw, mature, unspun cotton fibre, that has been ginned and mechanically cleaned is typically about 6–7% moisture and its dry composition is about 95% highly crystalline cellulose [the non-cellulosic constituents making up the other 5% of the fibre dry weight are typically: protein (1.3%), pectic substances (1.2%), ash/minerals (1.2%), wax (0.6%), total sugar (0.3%) and other constituents (0.4%)[14]]. The ability to degrade the highly crystalline cotton cellulose is relatively rare among microbes and not very rapid (Cotty, personal communication).[15] The non-cellulosic constituents, particularly pectins, which are more likely to support methane generation if anaerobicity and the proper microflora occurs, are in too low a quantity. Bacteria also degrade methane when released into the aerobic environment (Cotty, personal communication).[15]

Chun,[16] at the request of the authors, undertook a study to determine actual methane production from wet cotton, to determine if the amount of methane evolved would be sufficient to cause and support combustion. Cotton samples were placed in air tight vials, and different amounts of water were added to each vial. The vials were stored for up to 4 weeks at 27°C (80.6°F) and the air spaces above the cotton were sampled. In the experiments with wet cotton by Chun,[16] if all of the gases generated were assumed to be methane, the quantity of methane evolved even after 4 weeks was considerably below the limit to cause and support combustion. Therefore, by actual measurement as well as theoretically, it is not plausible for enough methane to be evolved by microbial degradation of cotton to cause combustion.

Flammability (smoulder and open flame ignition)

To determine the smoulder and open flame ignition propensity of a UD bale of cotton, various tests were run, including a test that employed a severe flame exposure (17.8 kW for 3 min). All bales tested passed all of the criteria for CA TB129,[11] a severe test to evaluate mattresses for arson-like fires. When compared with a much lower mass, typical building furnishings and contents, the peak rate of heat release of the cotton bales was much lower. The conclusion reached from the evaluation of flammability characteristics and hazard potential, using severe tests as well as cigarette and match tests, is that bales of cotton as presently packaged [> 225 kg/m^3 (> 14 lb/ft^3)] should not be considered 'flammable solids'.

SUMMARY/CONCLUSION

Tests performed on UD bales and small cotton bales of varying densities indicate that an internal smouldering fire (fire-packed bale) does not spread but self extinguishes in a very short time. This is true even when the fire source is within 1.27 cm (0.5 in) of the surface of the miniature bales if the bale density is > 225 kg/m^3 (> 14 lb/ft^3). Actual tests, as well as other technical information, indicate that cotton does not self-ignite (spontaneous combustion) unless it is contaminated with significant amounts of an oxidizable/self-heating oil; also wet bales cannot self-ignite. Severe flammability tests conducted on full-size bales generated data verifying the minimal risk of cotton when packaged in universal density [UD; compacted to 353.6 kg/m^3 (22 lb/ft^3) or greater] bales. Using the results of this research it was concluded by the IMO and the DOT that bales of cotton packaged in accordance with ISO 8115[6] and as presently packaged in the USA should not be considered a flammable solid.[3,17]

Appendix

Applicable definitions

Class 4.1 Flammable solids. [18,19] Solids which, under conditions encountered in transport, are readily combustible or may cause or contribute to fire through friction: self-reactive and related substances which are liable to undergo a strongly exothermic reaction.

Class 4.2 Substances liable to spontaneous combustion.[18,20] Substances which are liable to spontaneous heating under normal conditions encountered in transport, or to heating up in contact with air, and being liable to catch fire.

Class 9 Miscellaneous hazardous materials.[21] Means a material that presents a hazard during transportation but does not meet the definition of any other hazard class (this includes elevated temperature materials).

Combustion. Flammability is a relative rather than an absolute matter and there are different types of combustion. Cotton is cellulose, which is an organic polymer that is not volatile, but when heated may decompose into volatile flammable fragments, solid carbonaceous char, or both.[14,22] Cotton, a char former, is not inherently ignition resistant and when compressed to > 225 kg/m^3 (14 lb/ft^3) is like a block of wood and difficult to ignite. Types of combustion include the following.

Smouldering combustion (e.g. as caused by cigarettes) is the direct oxidation of either the polymer or its char.[22] The primary factors affecting it are diffusion of oxygen to the combustion site and heat release—both rate of heat release and amount of heat released. When the oxygen or combustible materials are exhausted, the heat release becomes insufficient for self-propagating oxidation and the smouldering is extinguished.

Flaming combustion (that which results in an open flame) is a gas phase reaction and occurs when heat causes degradation of the polymer (cellulose) releasing volatile products (flammable gases) that undergo rapid oxidation in air. In the initial stages of burning, heat is supplied to the non-volatile polymer initiating an endothermic degradation reaction (predominately pyrolytic in nature).[22] The flammable gaseous products of this polymer pyrolysis diffuse to the surface, are released to the atmosphere directly above the substrate and mix with the oxygen of the air so that combustion takes place. This is an exothermic process and the heat generated is partially transferred back to the substrate to continue the polymer pyrolysis. The heat flux (should be related to total heat liberated) at the surface of the solid phase is a critical factor in determining whether the material will self-extinguish.

Spontaneous combustion is self-ignition of combustible materials through chemical action (usually oxidation), which results in the evolution of heat.[23] If the temperature of the material reaches its ignition temperature [for cotton cellulose this is about 360° to 400°C[14]], spontaneous ignition occurs. For example, vegetable oil soaked cotton is susceptible to spontaneous ignition,[13] because the reaction of oxygen and vegetable oil is fairly rapid and evolves considerable heat. Spontaneous combustion is prevented if the amount of oxygen reaching the cotton is restricted or the heat is quickly dissipated.

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