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The *Hindenburg* Fire: Hydrogen or Incendiary Paint?

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ABSTRACT

A theory of the *Hindenburg* fire that has gained popular acceptance proposes that an incendiary paint covered the outer surface of the airship. Further, according to this theory, the paint was both the point of ignition and the sole cause of the rapid spread of the fire. The hydrogen within the airship is held blameless for both the start of the fire and its subsequent advance. We have examined this theory experimentally and quantitatively. We find that the basic ideas underlying this theory are wrong. The composition of the paint is documented, and its flammability rating shows that it is safe. Indeed, we have confirmed in our own experiments that the *Hindenburg* paint barely burns. The burn rates we obtained are consistent with both testing-laboratory documentation and with our analysis of the burn rate of an actual piece of *Hindenburg* fabric that survived the 1937 fire. The burn rate of the paint is thousands of times too slow for the painted fabric to have been the driving force for the *Hindenburg* fire. Even if the paint were a form of solid rocket propellant (which it is not), the burn speed would still be too slow. For example, if the *Hindenburg* had been painted with exactly the propellant used in the Space Shuttle Solid Rocket Boosters, it would take about 12 hours for the airship to burn from end to end. For the aluminum-powder paint used on the *Hindenburg*, the burn time would be approximately 40 hours. The *Hindenburg* was consumed by flame in 34 seconds. Further, the incendiary-paint theory involves igniting the paint by means of an electrical spark. It has been shown that spark ignition is physically implausible if a natural spark is employed. Experiment and theory are in accord, and they make clear that the incendiary-paint theory is without merit.

1. INTRODUCTION

The motivation for this paper is to examine experimentally and quantitatively some of the hypotheses that underlie a popular, novel theory of the fire that ended the life of the airship *Hindenburg*. This theory, which we will call the **incendiary-paint theory** (referred to herein as the **IPT**), was developed by Addison Bain[1] and made public with the assistance of Richard Van Treuren[2]. In this theory, they claim that the paint on the outer fabric cover of the *Hindenburg* was both the point of ignition and the prime mover for the spread of the fire, not the hydrogen that lifted the airship. The most recent publication of this theory is a book by Van Treuren with one chapter written by Bain[3]. In these publications, they assert that the paint[4] is either a form of solid rocket propellant or perhaps thermite, and this paint burned with explosive swiftness. In these writings, the hydrogen lifting gas within the ship is held blameless for both starting the fire and its subsequent rapid propagation – the paint bears the entire burden. The IPT is most clearly explained in their earlier papers[1,2]. The book by Van Treuren[3] is not as detailed on how the fire started and how it spread. Although they are presented in the book with less detail, none of the primary hypotheses from the earlier publications are changed.

The exact sequence of all of the events in the *Hindenburg* fire and their causes cannot be fully known; hence, there has been room for theories. The incendiary-paint theory is the most recent, and arguably the most novel. Each theory is supported by available evidence and logical inference. None of the theories is perfect — all suffer uncertainties. The most significant uncertainties are contained in one or more premises or hypotheses, whether they are explicitly identified or not. Hypotheses are important because they are foundations upon which a theory is built. Unfortunately, hypotheses can be flawed. A hypothesis that is shown to violate a basic scientific principle, or to disagree with careful experiment, is said to be fatally flawed. When a fatally flawed hypothesis is uncovered, the related theory is generally regarded as invalid. Although it is unrealistic to expect agreement that any one of the theories uniquely explains the *Hindenburg* fire, it may be easier to reach a consensus that the incendiary-paint theory is not a defensible candidate.

In this paper, we focus on the burn rate of the painted *Hindenburg* outer cover and demonstrate that it cannot be the cause of the rapid spread of the fire. There is also the question of how the fire started. The IPT proposes that an electrostatic spark ignited the painted fabric. This idea has been investigated at length in a separate paper by Dessler[5]. In this paper, he shows that a brief electrostatic spark, or even a bolt of lightning, cannot ignite the paint. In distinct contrast, hydrogen is easily ignited by even a weak spark. The interested reader is referred to the web site[5] for details on why a spark could not have set the *Hindenburg* paint on fire.

2. ANALYSIS

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[1] Bain, A., Colorless, nonradiant, blameless: A *Hindenburg* disaster study, *Gasbag Journal/Aerostation* (39: March), 9-15 Aerostation Section, 1999.

[2] Van Treuren, R.G., New study of LZ-129 fire completed, *Gasbag Journal/Aerostation* (31: March), 2, 1997. Van Treuren, R. G. and A. Bain, "The *Hindenburg* fire at sixty, Part One: Flammable containers of hydrogen"; "Part Two: Did a hydrogen explosion destroy the LZ 129?", and "Part Three: What really happened the night of May 6, 1937?" *Buoyant Flight 44*(March-April) 2-7, (May-June) 2-6, and (July-Aug.) 2-6, 8, 1997.

[3] Van Treuren, R. G., *Hindenburg: The Wrong Paint Hydrogen: The Right Fuel*, 266 pp., Atlantis Productions, Edgewater, 2001.

[4] The proper term is "dope", not "paint". However, for the purpose of examination of the Incendiary-Paint Theory, we follow Bain's and Van Treuren's usage.

[5] The *Hindenburg* Hydrogen Fire: Fatal Flaws in the Addison Bain Incendiary-Paint Theory. Available at: http://spot.colorado.edu/%7Edziadeck/zf/LZ129fire.htm

2.1 The Incendiary-Paint Theory

A hypothesis within the IPT that rests heavily on inference is that, early in the fire, only the painted outer cover and not hydrogen was burning. The reason for this hypothesis is that "it did not look like a hydrogen fire[6]." Bain advanced this hypothesis because hydrogen burns with an almost invisible, pale blue flame, and the fire was quite visible. However, a hypothesis must be tested before it can be accepted. For example, it does not look like the Earth is moving. Instead, it looks like the Sun, Moon, planets, and stars are revolving about the Earth, so, one might hypothesize that the Earth is the center of the universe.

A critical response, of course, is that both hydrogen and outer cover were burning, with the hydrogen burning first and being unnoticed until it set the fabric on fire. Then the fabric would emit light because it was burning. There would also be bright, visible light produced because fabric, gas cells, wires, and girders within the fire act as a mantle. (In a gas lantern, pale burning gas is made to produce a bright light by placing a mantle in the flame. It would be the same for a hydrogen flame.) The material surrounding the burning hydrogen both burned with a visible flame and acted as a mantle making visible the burning hydrogen[7]. Anyone interested in performing an experiment to check this can do the following. In a darkened room light a gas stove burner. There will be a pale blue flame (if the gas/air mixture is correct). Then place a small piece of cotton cloth in the flame. [Warning: Use 100% cotton fabric, not a blend containing plastic-based fabric such as polyester or nylon. Plastic-based fabrics can give off dangerous fumes, and they can melt and make a mess on your stovetop.] The cloth will burn with a bright yellow flame, and the ash that remains, as long as it is in the gas flame, will continue to give off a yellow light.

The idea that a hydrogen fire is virtually invisible is not new. In the original Accident Report of the German investigators, this point was made specifically, "As a hydrogen-air mixture burns nearly without color, under the given circumstances the first ignition could have happened on the upper part of the vertical stabilizing fin and could have quickly spread to the leading edge of the fin on the ship's body[8]." Or from the American report (p. 14), "The range of activity of combustion will be from the lower limit of 4.5% [hydrogen], at which there will probably be an invisible union without evidence of flame." Further, (p. 63) "...such a discharge likely would have ignited any adequately rich stream of leaking hydrogen that reached it; and that from the point of ignition the flame would have shot back to the leak, there quickly would have burned a larger opening and set going a conflagration of great violence and rapidity." Most who have carefully examined the films of the *Hindenburg* fire agree that the ship seems to be burning from the inside out.

Eyewitness reports of the *Hindenburg* fire are much like those of fires of other hydrogen filled airships, e.g., the German airships shot down in flames in WWI[9]. None looked like

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[6] Unless specifically noted, this and following quotations are from Bain's paper referenced in Footnote 1.

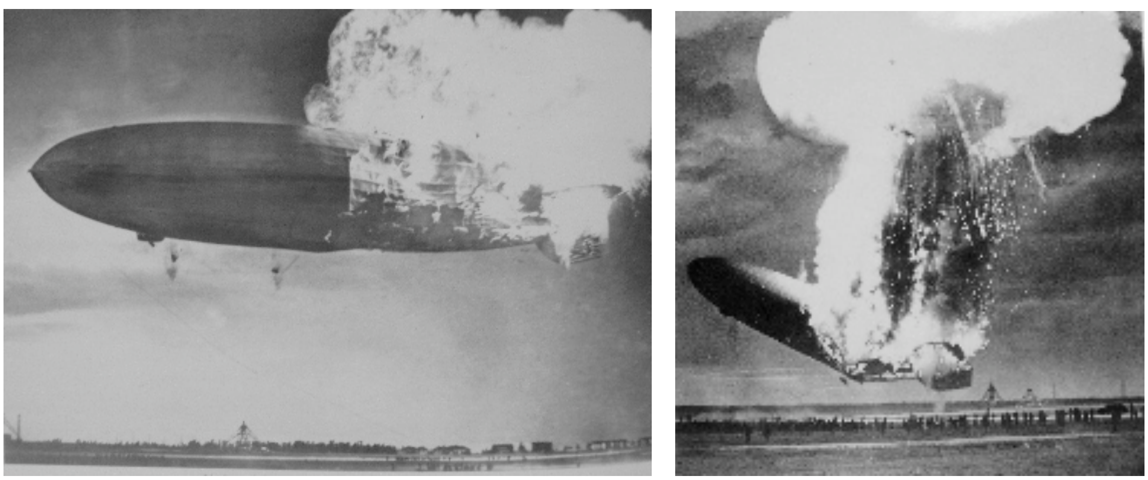
[7] Commercial gas lanterns, such as the Coleman lantern, use a durable mantle over a propane gas flame to create a bright light. Without the mantle, the flame produces little visible light.

[8] Eckener et al., p. 16, Report of the German investigation commission about the accident of the airship "*Hindenburg*" on May 6, 1937 at Lakehurst, U.S.A. (English Translation), in *The Hindenburg Accident*, edited by R.W. Knight, 7 C's Press, Riverside, 1977. (This is a reprint of the original 1938 report.)

[9] Robinson, D.H., *The Zeppelin in Combat*, 410 pp., Schiffer, Atglen, 1944.

a hydrogen fire. All of these airships burned with bright flames that were visible for miles even though the upper third of the fabric covers of the earliest WWI ships were unpainted and the lower two-thirds were coated (but without added aluminum or iron oxide powders). Later WWI German airships had black paint on their undersides to foil searchlights. Further, flames engulfed all of these hydrogen-filled airships in less than a minute – irrespective of the cover material or paint. There are two reasons *all* burning hydrogen-filled airships blazed with a bright, visible flame: (1) the burning hydrogen starts the gas cells, fabric, etc. burning, and these burn with a highly visible flame, (2) although the hydrogen flame is faint, the material surrounding the burning hydrogen acts as does the glowing mantle in a gas lantern.

On the matter of when the hydrogen in the gas cells burned, Bain argues that, because the tail stayed level even though the fire had already involved the aft section of the airship (Fig. 1a and b), the hydrogen gas cells were still intact. A critical response is that, although the hydrogen in the rearmost gas cells has burned, the tail is momentarily kept from falling both by inertia and by an updraft created by the firestorm above the tail. The fireball propagates upward at nearly 100 m/sec, which could easily create an updraft of about 25 m/sec. Such an updraft is all that is needed to keep the tail from falling[10]. There is evidence that the updraft was even faster. One sees in Fig. 1b the airframe buckling as the tail, which surely has no remaining hydrogen for lift, is pushed upward by the updraft. We have all seen the effects of a fire-generated updraft when a burning piece of paper is lifted by the updraft created by its own fire.



(a) (b)

>Fig. 1a. Why isn't the tail falling, and why is the flame visible? According to the IPT, the rear gas cells are still intact, and the hydrogen they contain (still unburned) is lifting the tail. An alternative explanation is that the cells burned open some time ago, and nearly invisible flaming hydrogen is incinerating the fabric cover and internal gas cell material, which burn brightly. The tail is held aloft by both the inertia of the airship and the updraft created by the fire. Also note the flame-front near amidships displays an unnaturally straight vertical line. The line is near the demarcation between gas cell 8 (which is burning), and gas cell 9 (which has not yet started to burn). We can see two more fire voids further aft; each marks a structural ring that separates gas cells. If the fire were being spread by the paint, none of these vertical features would be present.

[10] Alan Sherwood, Personal communication.

>Fig. 1b. Why is the tail still level? Surely, by now the hydrogen in the rear cells has burned. This shows that a level tail is not sufficient to conclude that the gas cells are intact and hydrogen is not burning.

Appealing as these criticisms of the IPT may be, they do not have the force of experiments and quantitative analysis; they do not demonstrate that the IPT violates basic physical laws. On the matter of the updraft holding the tail level, the updraft force could, in principal, be calculated quantitatively, but the calculation would suffer significant uncertainties. In contrast, the following investigation of the burn rate of the painted *Hindenburg* fabric is in a different class. It is simple, it utilizes neither eyewitness accounts nor qualitative inferences, and the results have precision.

2.2 *Hindenburg* Paint Does Not Burn like Solid Rocket Propellant

Solid rocket propellant contains an oxidizer and a fuel. The solid propellant segments (called grains) in the Space Shuttle Solid Rocket Boosters (SRBs) contain ammonium perchlorate, the oxidizer, mixed with the fuel, aluminum powder in a rubbery binder. The ammonium perchlorate breaks down when heated to produce free oxygen. This allows the rocket propellant to burn without air. In contrast, cellulose acetate butyrate produces no free oxygen, so it cannot burn without air. If ignited inside a rocket case, where no air is available, combustion products smother the flame, and the burning stops. The primary constituent in the *Hindenburg* paint (to which aluminum and iron oxide was added) is cellulose acetate butyrate. A fabric painted with the cellulose acetate butyrate simply does not burn well, which explains why so many unburned pieces of fabric were found on the ground after the fire. Once carried away from the flaming hydrogen by the fire-induced updraft, the damp, painted fabric scraps self-extinguished, i.e., stopped burning. If the paint burned as well as does solid rocket propellant, no pieces of the painted outer cover would have survived.

Assumptions that are basic to the IPT are (1) the paint burns as does solid rocket propellant, and (2) solid rocket propellant burns rapidly. Both of these assumptions are wrong. The composition of the *Hindenburg* paint is documented. For example, Bain (Footnote 3, p. 162) reports on correspondence "between the Zeppelin works and suppliers of the doping compound, commonly referred to as 'Cellon'." Bain continues, "Of note, in a June 30, 1937 letter, is that the lacquers produced by the Worwag and Atlas-Ago companies are processed of cellulose acetobutyrate." The burning properties of cellulose acetobutyrate, or cellulose acetate butyrate, and other cellulose acetates, are well known, and they have been rated for flammability[11].

A material is rated HB if: 1. In a horizontal orientation, the burn requires more than one minute for a 3-inch length, or 2. The sample stops burning before a 5-inch length is reached. Furthermore, HB rated materials are considered "self extinguishing". Cellulose acetate butyrate is listed as UL 94 HB. This designates the material as "combustible but nonflammable", which means it will burn if held in a fire, or if attached to a flammable material, such as cotton fabric, but by itself, either it will burn slowly or it will not sustain a fire. Some suppliers use the NFPA scale of 0 to 4. Materials that will not burn have a NFPA rating of 0, while materials that will burn readily are rated 4. Cellulose acetate butyrate is rated NFPA 1, which means it will burn if placed in a flame. The painted *Hindenburg* fabric burned because it was in a hydrogen fire.

[11] For example, see, www.azom.com

Published data indicate that the paint on the *Hindenburg* is not flammable, and its burn speed when coated on cotton fabric ought to be slow. Following the scientific method, we performed an experiment to test this hypothesis. We made some replica samples of the *Hindenburg* outer cover and experimentally measured their burn speeds. For the composition of the paint and the amounts of aluminum powder and iron oxide powder additives, we used the formula reported by Bain (Footnote 3, p. 169, also his Fig. K9 on p. 156), cotton fabric 100 gm/m^2, iron oxide powder 4.6 gm/m^2, and 6 gm/m^2 aluminum powder. We also burned plain cotton fabric and then the fabric painted with various combinations of aluminum powder or iron-oxide powder added to the cellulose acetate butyrate. Details of the preparation of the samples and the burn tests are from Appleby[12]. His data that are relevant to the present discussion are presented in Tables 1 and 2[13].

Between 4 and 6 samples of each of the four treatments were burned to test for consistency of the burn times. Appleby's paper contains an additional sample treatment. The columns in Tables 1 and 2 list the makeup of the samples, the mean time (in seconds) for the various samples to burn along a measured 10 cm length, and the extrapolated time (in hours) to burn the 200-meter (656 ft) length from near the front of the upper fin to the nose of the *Hindenburg*. The samples in all the burn tests were oriented horizontal to the ground (as was the *Hindenburg*). The standard deviations for the burn times for samples 1 - 4 in both Tables 1 and 2 is typically less than 10%

Table 1. Burn Tests of Cellulose Acetate Butyrate (Cellon) Doped Cotton Fabric

Description of Sample Coats refer to cellulose acetate butyrate	Mean Time to Burn 10 cm	Extrapolated Time to Burn the *Hindenburg*
1. Plain cotton fabric, no coating	29.4 seconds	16.3 hours
2. Cotton with 4 coats, no additives	62.2 seconds	34.6 hours
3. Four coats, top 3 coats contained aluminum powder (replicating the lower half of the *Hindenburg*)	55.7 seconds	30.9 hours
4. Four coats, 1st coat with iron oxide, next 3 coats contained aluminum powder (replicating the upper half of the *Hindenburg*}	68.3 seconds	37.9 hours

Note particularly, (1) the burn time for Sample 4,which is the formulation that replicates the topside *Hindenburg* outer cover. It is the slowest burning of the three painted samples, indicating that nearly 40 hours would be required to consume the airship, and (2) the plain cotton fabric (Sample 1) burned faster than any of the painted samples, further demonstrating that the paint was not responsible for the rapid spread of the *Hindenburg* fire.

In arguing for the IPT, the paint on the *Hindenburg* fabric cover is likened to solid rocket propellant. Particular attention is drawn to the propellant in the Space Shuttle Solid Rocket Boosters (SRBs). We have already shown in this section that the *Hindenburg*

[12] W. H. Appleby, Airship *Hindenburg*: Experimental study of the involvement of the outer covering paint (dope) in the disastrous final fire, *The Citizen Scientist*, 17 Dec. 2004. www.sas.org/tcs/weeklyIssues/2004-12-17/project1/index.html

[13] These samples are not difficult to reproduce. Anyone wishing to perform their own burn-rate experiments can obtain certified dope materials from Aircraft Spruce and Specialty Company www.aircraftspruce.com, red iron oxide from Elementis www.elementis.com, and aluminum flake powder from Toyal America www.fitzchem.com/mfg_Toyal.shtml

paint is **not** a form of any sold rocket propellant. Further, we show in Section 2.3 below, that solid rocket propellant does not burn rapidly, particularly at atmospheric pressure. We also show that even if the paint had been a flammable SRB type of propellant, the burn time would still be a thousand times too slow to explain the *Hindenburg* fire.

Cellulose nitrate was available to paint the *Hindenburg*. Cellulose nitrate is less expensive, but it was known to be flammable, so **it was not used**. Cellulose nitrate, in flaked or filamentary form, is called gun cotton, and, in various formulations, is used in artillery and firearms instead of black powder. With aluminum powder added, cellulose nitrate does indeed make a solid rocket propellant. Although nonflammable Cellon was used on the *Hindenburg*, we nevertheless proceeded to measure the burn speed of cellulose-nitrate/aluminum-powder paint, because it represents a best case for the IPT. The results of the tests are shown in Table 2. All measurement procedures were the same as for Table 1, except we replaced the nonflammable cellulose acetate butyrate with flammable cellulose nitrate. Although the burn rates were higher, (and this time faster than the plain unpainted fabric) our measurements imply a time of more than 11 hours to burn the *Hindenburg*. This extreme test illustrates that, even if this highly flammable material had been used on the *Hindenburg* — and remember, it was not — it would fail to account for the 34-second incineration of the airship.

Table 2. Burn Tests of Cellulose Nitrate Doped Cotton Fabric

Description of Sample Coats refer to cellulose nitrate	Mean Time to Burn 10 cm	Extrapolated Time to Burn the *Hindenburg*
1. Plain cotton fabric, no coating	33.5 seconds	18.6 hours
2. Cotton with 4 coats, no additives	16.2 seconds	9.0 hours
3. Four coats, top 3 coats contained aluminum powder	20.4 seconds	11.3 hours
4. Four coats, 1st coat contained iron oxide, next 3 contained aluminum powder	20.8 seconds	11.6 hours

To further confirm these slow burn rates, we also measured burn rates of 35 mm camera film with its emulsion removed. Older film was made of cellulose nitrate, and is rated as highly flammable[14]. Modern film is made of cellulose acetate butyrate and called “safety film”. The burn rates we obtained in burning sample of both kinds of film are consistent with the burn rates of Tables 1 and 2. These additional experiments demonstrate that, in both direction and speed, the spread of the *Hindenburg* fire was not driven by properties of the ship’s cover.

The IPT proponents also imply that helium filled airships burn the same as a hydrogen-filled airship. For example, they cite the burning of the USS Macon and a helium-filled U.S. Navy blimp. The Macon was not destroyed by fire but settled into the Pacific, only to have, late in the ditching operation, some gasoline on the water surface be ignited by flares in the control car. The Macon fire was small and late; it was merely a footnote to the event. The Navy blimp fire was initiated by a lightning strike that started a gasoline fire while the ship was moored. The gasoline fire engulfed the center of the ship from the bottom up. The fire burned slowly. A photo of the fire shows fire fighters putting out the fire with the nose still intact and attached to the mooring mast. The nose contained an

[14] Guidelines for Care & Identification of Film-Base Photographic Materials, Monique C. Fischer, Andrew Robb, Art Conservation Program, University of Delaware, Winterthur Museum, 1993, http://palimpsest.stanford.edu/byauth/fischer/fischer1.html

appreciable bubble of helium. Had the ship been inflated with hydrogen, you would not see fire fighters working around the intact nose. It would not have been there.

In support of the above analysis of the blimp fire, we performed burn tests on samples of genuine ZPG-3W envelope (cotton-based) fabric. First, a circular sample with a small hole in the center was oriented parallel to the ground; attempts to ignite it at the center hole were unsuccessful. The flames self-extinguished before any burn rate could be established. Then a small specimen of the blimp fabric was ignited at its top edge while held vertically. The flame quickly self-extinguished, showing that the blimp cover would not burn downward. Another rectangular specimen, 3″ x 4″ (7.6 x 10.2 cm), was hung with its long dimension vertical. The bottom edge ignited reluctantly. A sheet of gaseous flame covered both sides of the specimen. The bottom edge of the flame reached the top of the sample in 30.8 seconds, which yields a burn rate roughly the same as the samples in Tables 1 and 2. The blimp cover material is combustible, but not flammable. Flaming gasoline drove the burning of the blimp – for the *Hindenburg*, it was flaming hydrogen.

We have also taken advantage of a recorded burning of a sample of actual *Hindenburg* outer-cover material[15] in a TV documentary, Addison Bain sacrificed a piece of *Hindenburg* painted fabric. His sample showed some red iron oxide bleed-through on the unpainted side of the cloth, so the sample was from the upper half of the *Hindenburg*. We recorded this demonstration and played it back frame by frame to obtain data on time vs. burn distance. Using Bain's fingers as a standard of measure, we estimate the size of the specimen to be about 3/4″ x 2 ½″(1.9 cm X 6.3 cm). Timing the burn as recorded on the TV segment, we estimate that the sample burned to half its width, 3/8 inch (1 cm) in 7 seconds. This corresponds to a time of 40 hours to burn the 200 meters (660 ft) from near the front of the upper fin of the *Hindenburg* to its nose. This data agrees with the burn time for the replica of the topside cover of the *Hindenburg* (Sample 4 in Table 1).

If this sample of original *Hindenburg* outer cover burned at the speed of the *Hindenburg* fire, the entire sample would have burned in a flash lasting only 0.002 seconds, i.e., **2 milliseconds!** It is also significant that about 2/3 of the specimen did not burn. Anyone viewing this TV sequence will see that the remaining portion of the specimen was unscathed, exhibiting its original silver appearance. The simple fact is that the burn rate of the *Hindenburg* cover is painfully slow.

2.3 Solid Rocket Propellants Burn Slowly

The roaring, dazzling flames exiting the nozzles of the Solid Rocket Boosters on the Space Shuttle might well lead one to assume that solid-rocket propellants burn rapidly and that they burn equally rapidly when outside the rocket motor. Neither of these assumptions is true. Again, taking the Space Shuttle SRB propellant as our example, the burn speed is surprisingly slow. The burn rate for SRB propellant is only 0.37 inch/sec (1.0 cm/sec) at 625 psi[16]. It is even slower if the propellant is outside the rocket case because the burn rate is pressure dependent. At atmospheric pressure the burn-rate slows to about 0.2 inch/sec (0.5 cm/sec, or 1 foot per min). We already know that a slow burn rate at high pressure makes sense because the SRB burns for about two minutes (124 sec to be precise). The burn starts from the surface of a hole running the length of the rocket. The burn proceeds to the outer edge of the propellant grain. This distance is just over 4

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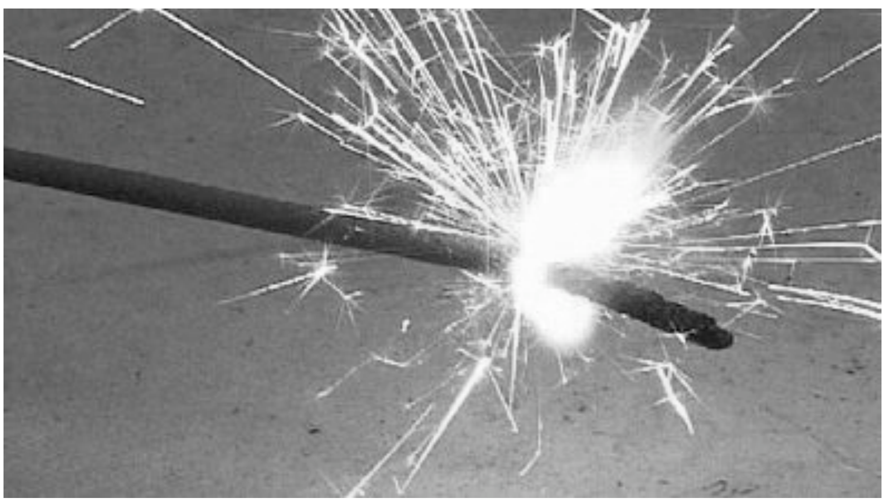
[15] TV documentary, *Secrets of the Dead, What Happened to the Hindenburg?* British television *Twenty -Twenty,* 1999.

[16] Letter from David Ricks, NASA/MSFC, 3 Nov. 2000.

feet. So, inside the Space Shuttle SRBs, the rocket propellant burns 4 ft in 2 minutes. If the pressure were reduced to atmospheric pressure, the burn time would roughly double. In comparison, to account for the speed of the *Hindenburg* fire, if it is to burn nearly the length of the *Hindenburg* in 34 seconds, the burn rate must be about 6 m/sec, 20 ft/sec, or 1,300 ft/min. A burn rate this high is unlike a rocket propellant, but it is what one expects for a hydrogen fire.

The relationship between burn rate and pressure for rocket-type propellant was discovered over 100 years ago, and the physical chemistry of the rocket-propellant burning process has been textbook material for at least half a century[17]. Most find it surprising to learn that a chunk of solid rocket propellant, if tossed into a burning fire, would burn about as slowly as would a fuse or a sparkler (see Fig. 2). The composition of a sparkler is much the same as solid rocket propellant: an oxidizer, such as ammonium perchlorate or cellulose nitrate, and aluminum or magnesium powder mixed in a binder, sometimes with a small amount of iron powder to add to the sparkles. SRB propellant consists of[18] 69.6% ammonium perchlorate for the oxygen source, 16% aluminum for propellant, 12% rubber binder plus 2% curing agent, and 0.4% iron oxide, which acts as a catalyst that speeds the generation of oxygen from the perchlorate. There is no thermite reaction in the burning SRBs. Sparklers, as one should expect, burn at about the same speed as solid rocket propellant.



>Fig. 2. Sparklers are a form of solid rocket propellants in composition and they burn at about the same rate as Space Shuttle Solid Rocket Booster propellant, i.e., less than about 0.2 inches per second at atmospheric pressure. A sparkler takes about a minute to burn from one end to the other. If it burned at the speed of the *Hindenburg* fire, a sparkler would burn in a flash lasting only about 0.04 seconds.

Another hypothesis within the IPT is that there was a thermite reaction in the burning paint because one coat of paint on the upper half of the *Hindenburg* contained iron oxide. The thermite hypothesis rests entirely on the simple fact that thermite is a mixture of iron

[17] Seifert, H.S., M.M. Mills, and M. Summerfield, The physics of rockets, *American Jour. of Physics*, *15*, 1-21, 1947. Zaehringer, A.J., Combustion, in *Solid Rocket Technology*, edited by M. Shorr and A.J. Zaehringer, pp. 129-146, John Wiley, New York, 1967.
[18] Shuttle Flight Operations Manual, Vol. 8B, NASA Document JSC-12770.

oxide and aluminum powder. Nothing else was offered to support the idea. Our analysis shows that a thermite reaction on the surface of the *Hindenburg* is, at most, unimportant, and it probably does not occur at all.

In the thermite reaction, iron oxide supplies oxygen to burn aluminum. The reaction is $2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$. The reaction is hot (~3000 C), and the reaction products are molten iron and molten aluminum oxide. However, in the *Hindenburg* paint, the ratio of iron oxide and aluminum powders are wrong for thermite. According to numbers supplied by Bain [Footnote 3, p. 169], for the application to the *Hindenburg* cover, the ratios by weight are 20% iron oxide and 80% aluminum, which is not the required ratio for thermite. To obtain a thermite reaction, a mixture of 75% iron oxide and 25% aluminum powders (a 3 to 1 ratio by weight, with iron oxide being the principal constituent) must be thoroughly mixed. The coats of paint on the upper half of the *Hindenburg* contained, by weight, less than 10% of the required iron oxide. If the reactants are in different proportions or not well mixed, the burning reaction is adversely affected because only some of the material burns and the remaining material acts to cool the fire, perhaps preventing sustained burning.

The fact that the constituents are in a paint binder is also a problem for the thermite hypothesis because the paint gets in the way of chemical union of the iron oxide and the aluminum by acting to keep the particles apart. If, somehow, all of the iron oxide were consumed in a thermite reaction, less than about 10% of the aluminum powder would be involved. The volume of potential thermite reactants is such a minor part of the total volume of the paint that a thermite reaction could not proceed because the reactants are too dilute. The effect of dilution is as if we mixed small amounts of hydrogen and oxygen gases into a large volume of helium. If an ignition source were introduced, there would be either a weak fire, or none at all because few hydrogen molecules could quickly find an oxygen molecule among all the helium atoms. Finally, iron oxide paint was applied on only the topside of the *Hindenburg*. A thermite fire would have produced a noticeable demarcation line between the burning of the upper half (which had the iron oxide) and the lower half (which had none). There was no such horizontal demarcation line (e.g., see Fig. 1 a, b).

3. DISCUSSION AND CONCLUSIONS

The incendiary-paint theory of Addison Bain is subject to many criticisms. By restricting ourselves to a thorough examination of selected hypotheses that underlie the theory, we have, for these hypotheses, obtained analyses that are uncomplicated and the results are quantitative and definitive. The results do not depend on eyewitness accounts (known to be unreliable), flawed logic (e.g., the color of the flame is yellow-orange, therefore the hydrogen is not burning), or unsupported inferences based on what is happening (e.g., the tail is not falling, therefore the hydrogen has not burned). Rather, our arguments focus on experiments and application of basic physical principles.

One fundamental hypothesis of the IPT is how the paint was ignited without the aid of burning hydrogen. The hypothesis is that there was “panel-to-panel arcing” and that “the discharge traveled parallel to and along the covering surface, not perpendicular to, but through the grain”. This hypothesis has been shown to be wrong. Not even a lightning bolt (the *Hindenburg* was struck several times by lightning) could set the painted fabric ablaze. Each strike burned a small hole in the fabric without starting a fire, thus confirming that the paint is not flammable. The interested reader can read, in exhaustive detail, the mistakes in this hypothesis on the web at:
http://spot.colorado.edu/%7Edziadeck/zf/LZ129fire.htm

The most important hypothesis underlying the IPT is that the paint on the outer cover was an incendiary substance, disguised as paint (in the airship/aircraft trade, paint is formally called "dope"), and that this paint could burn fast enough to account for the speed of the fire's propagation. Fatal flaw — The chemical composition of the *Hindenburg* paint is known, and it burns too slowly. The base for the paint, at that time sold under the trade name Cellon, is cellulose acetate butyrate, which is rated, "combustible but not flammable". We made replica samples of the *Hindenburg* painted fabric to experimentally determine the burn rate. Following the recipe of its original builders, we mixed in aluminum powder and iron oxide powder as specified, and we applied this mixture to cotton fabric to produce samples of the *Hindenburg* outer cover. We burned the samples and measured their burn rates. Details of the preparation of the samples and the burn tests are available in a paper, "Airship *Hindenburg*: Experimental study of the involvement of the outer covering paint (dope) in the disastrous final fire", at www.sas.org/tcs/weeklyIssues/2004-12-17/project1/index.html

As expected from the published properties of cellulose acetate butyrate, the samples burned poorly and slowly. If this paint had been responsible for the spread of the fire, it would have taken nearly 40 hours to burn the *Hindenburg*. Unpainted cotton burned faster — the paint with its aluminum powder **slowed** the burn of the fabric. We also used a cellulose-nitrate paint base, which, with aluminum powder, is a form of solid rocket propellant, but again, as expected from known properties of cellulose nitrate, the burn rate, although about 5 times faster, was still too slow to account for the rapid spread of the *Hindenburg* fire. Finally, we used a TV demonstration presented by Bain of the burning of a piece of actual *Hindenburg* painted fabric. It burned at the same speed as did our faux *Hindenburg* fabric, i.e., 4,000 times too slow to explain the speed of the *Hindenburg* fire.

In this paper, we have demonstrated that Addison Bain's Incendiary-Paint Theory (IPT) is fatally flawed and hence is not applicable to the *Hindenburg* fire. We do not defend any competing theory as being correct. Our conclusions regarding the IPT are based on experiments and on established principles of physics and physical chemistry that are not subject to negotiation. Because the hypothesis of a rapidly burning incendiary paint is fundamental to the IPT, and because the hypothesis is wrong, the incendiary-paint theory of the *Hindenburg* fire must be regarded as invalid.

A final thought — even if one believes that the paint did it, hydrogen gas nevertheless requires extraordinary care in handling if unwanted explosions or fires are to be avoided.

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