The Hindenburg Hydrogen Fire: Fatal Flaws in the Addison Bain Incendiary-Paint Theory

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ABSTRACT

A theory of the Hindenburg fire that has recently gained popular acceptance proposes that the paint on the outer surface of the airship caused both the fire and its rapid spread. However, application of physical laws and numerical calculations demonstrate that the theory contains egregious errors. Specifically: (1) The proposed ignition source (an electrical spark) does not have sufficient energy to ignite the paint. (2) The spark cannot jump in the direction demanded by the theory. If a spark were to occur, it could jump only in the direction that the author of the theory has shown will not cause a fire. (3) The most obvious flaw in the theory is the burn rate of the paint, which, in the theory, is likened to solid rocket fuel. The composition of the paint is known, and it is not a form of solid rocket fuel. Even if it were, it would, at best, burn about 1,000 times too slowly to account for the rapid spread of the fire. For example, if the Hindenburg were coated with exactly the same solid rocket fuel as that used in the Space Shuttle solid rocket boosters, it would take about 10 hours for the airship to burn from end to end, as compared to the actual time of 34 seconds. The arguments and calculations in this paper show that the proposed incendiary paint theory is without merit.

INTRODUCTION

The motivation for this paper is to examine quantitatively three of the hypotheses that underlie a popular, novel theory of the fire that ended the life of the airship Hindenburg. In this theory it is claimed that it was the paint on the outer fabric covering of the Hindenburg that was both the point of ignition and the prime mover for the spread of the fire, not the hydrogen that lifted the airship. This theory, which we will refer to as the incendiary-paint theory, was developed by Addison Bain[1] and made public with the assistance of Richard Van Treuren[2]. The most recent publication of this theory is in a book by Van Treuren with one chapter written by Bain[3]. In these publications, they claim

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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, FL, 2001.

the paint[4] to be either a form of solid rocket fuel or perhaps thermite, and the 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.

Bain's **incendiary-paint theory** (referred to herein as the **IPT**) and its underlying hypotheses are most clearly put forth in the earlier writings (footnotes 1 and 2). A book by Richard Van Treuren[3], which is the most recent publication, is not as specific on details of the theory. Because the entire book, including Bain's chapter, which he refers to as a "study", is less specific than the earlier publications in describing how the fire started and how it spread, I will concentrate on the ideas as laid out in the earlier publications. The primary hypotheses in the earlier publications are not changed in the book.

The exact sequence of events in the Hindenburg fire cannot be known with certainty. The IPT is the most recent, and perhaps the most novel, of the many theories that have been offered to explain the fire. Each theory is supported by available evidence and logical inference. None of the theories is perfect — all suffer uncertainty. Most significant are uncertainties contained in one or more premises or hypotheses, whether they are explicitly identified or not. These hypotheses are important because they are foundations upon which a theory is built. Hypotheses, unfortunately, can be flawed. A hypothesis that is shown to violate a basic scientific principle 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 complete agreement on any theory of the cause of the Hindenburg fire, it may be easier to reach a consensus that the incendiary-paint theory is not a realistic possibility. There may well be new hypotheses put forth to take the place of the ones shown in this paper to be fatally flawed. Such replacement hypotheses can be examined after they have been set out for examination.

In this paper, we identify and quantitatively examine rigorously the three hypotheses upon which the IPT rests. The hypotheses are: (1) an electrical discharge (a spark) was created at the painted outer fabric surface of the Hindenburg, the spark having sufficient strength and duration to set the paint on fire; (2) the spark traveled inside the paint, parallel to its surface; and (3) the observed speed of the fire's propagation was determined by the paint. We will see that all three of the hypotheses are fatally flawed: (1) the spark is too weak and its duration too short to ignite the paint; (2) sparks must be perpendicular to the surface of the paint and cannot be parallel to it; and (3) the paint is not a form of solid rocket fuel, and even if it were, solid rocket fuel burns too slowly to account for the rapid spread of the fire (and there was not enough iron oxide in the paint to support a thermite reaction).

The incendiary-paint theory (IPT) contains other hypotheses. The three hypotheses that are examined here were chosen because they can be assessed quantitatively, using fundamental scientific principles, without interjection of inferences or eyewitness accounts. We note that inferences can be flexible and variable, and eyewitness accounts have earned a reputation for being erratic and unreliable. For example, in Teutonic understatement, the German Accident Board noted, "The testimony about the location of

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

origin of the fire is, to a great extent, widely divergent."[5] . Here we rely solely on basic physical laws. We can reject, with confidence, any hypothesis or theory that is in conflict with these laws.

Conclusions reached by seemingly logical inferences are suspect if physical laws and mathematical demonstrations do not support them. For example, it does not feel like and it does not look like the Earth is moving. Further, it looks like the Sun, Moon, stars, and planets are moving around the Earth. Using this train of reasoning, following our sense of how things "look", we reach the conclusion that the Earth is the center of the universe. We will see that this same method of inference underlies the IPT. But make no mistake, this form of argument can be convincing. For example, Aristotle's view of a motionless Earth surrounded by a moving universe was the common view for nearly two thousand years. Not until the telescopic observations of Galileo and Newton's laws of gravity were at hand was the modern view widely accepted. And, now the IPT is popularly accepted.

The Logic Behind the Incendiary Paint Theory

An example of a hypothesis within the IPT that rests heavily on inference is that, early in the fire, only paint and not hydrogen was burning. The reason for this hypothesis is that "it did not look like a hydrogen fire"[6]. Bain argues that because hydrogen burns with an almost invisible, pale blue flame, and the fire was quite visible, the hydrogen was not burning. The critical response, of course, is that both were burning, with the hydrogen burning first and being unnoticed until it sets the fabric on fire. Then the fabric would emit light because it was burning. There would also be bright visible light produced because the fabric and the wires and girders within the fire acted as a mantle. (In a gas lantern, pale burning gas is made to produce a bright light by putting a mantle in the flame. It would be the same for a hydrogen flame.) Thus, the material surrounding the burning hydrogen both burned with a visible flame and acted as a mantle making visible the burning hydrogen[7]. The conventional view is that the hydrogen started burning first and was the agent responsible for the rapid spread of the fire.

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

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[5] Eckener, H., J. Breithaupt, G. Bock, M. Diekmann, L. Duerr, and F. Hoffman, 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, Section II, pp 1-20, 7 C's Press, Riverside, 1938.

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

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

[8] Eckener et al., p. 16, ibid.

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 a hydrogen fire. All of these airships burned with bright flames that were visible for miles even though the fabric covers of the earliest WWI ships were partially coated with a clear paint (no added aluminum or iron oxide powders), the upper third was bare, unpainted fabric. Later WWI German airships had black paint on only their undersides to foil searchlights. There are two reasons *all* burning hydrogen-filled airships burned with a bright, visible flame. First, the burning hydrogen starts the gas cells, fabric, etc. burning, and these burn with a highly visible flame. Second, although the hydrogen flame is faint, the material surrounding the burning hydrogen acts as does a brightly glowing mantle in a gas lantern.

Similarly, applying Aristotelian logic to the fact that the tail stayed level even though the fire had already involved the aft section of the airship (Fig. 1a and b), the IPT concludes that 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 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 can see in Fig. 1a,b the airframe buckling as the tail, which has no 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.

But these criticisms of the IPT do not have the force of quantitative analysis. In other words, they are at the same level as the Aristotelian arguments put forth to support the IPT —the counterarguments regarding flame visibility and tail stability do not demonstrate violation of basic physical laws. Specifically, the interpretation of the visibility of the fire involves simple extensions of existing experience but nothing quantitative. The matter of the updraft holding the tail level) can be calculated quantitatively, but because neither the updraft speed as a function of time nor the timing of the burning of the various hydrogen gas cells is known with precision, the calculation would suffer comparable uncertainties. In contrast, the following investigations of specifically selected critical hypotheses are in a different class. The investigations are simple, and they utilize neither eyewitness accounts nor non-quantitative Aristotelian inferences. If the IPT is to remain a viable possibility, proponents of the IPT must show where I have made an error. Inferences and qualitative arguments will not suffice. Numerical calculations utilizing physical laws are needed because they have both force and precision.

The three hypotheses critical to the IPT selected for quantitative examination are:

Hypothesis 1. “Outer cover ignition” was caused by electrical charges on “unique, isolated panels, each developing its own unequal charge”, and the spark had sufficient duration and energy to ignite the paint. More recently Bain has quoted a suggestion from a private report [p. 170, footnote 3] that the paint ignited because the rope that was dropped from the nose of the Hindenburg to ground allowed, "an abrupt strong electric

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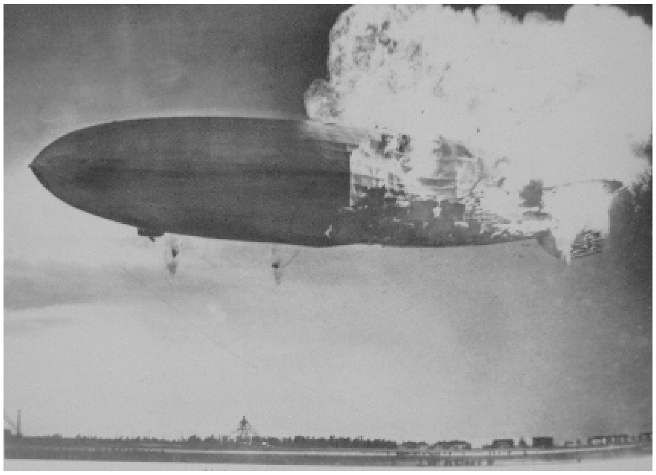
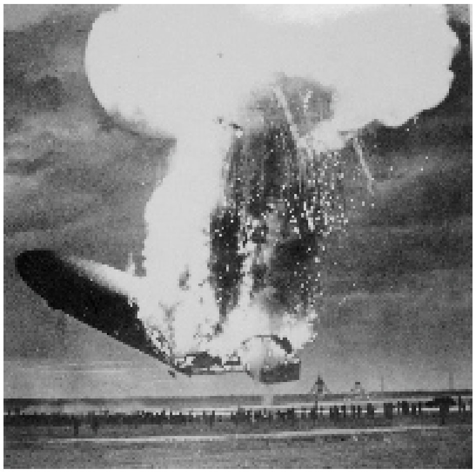
[9] Robinson, D.H., *The Zeppelin in Combat*, 410 pp., Schiffer, Atglen, 1944.

[10] Alan Sherwood, Personal communication.

current flow through the aluminized paint layer." This second idea will be ignored for now, as will other replacement hypotheses, until they are presented in sufficient detail to allow their analysis.


(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, these vertical features would not be present.

>Fig. 1b. Why is the tail still level? Although the hydrogen in the rear cells has burned, the fire-created updraft acts to keep the tail level. This shows that a level tail is not sufficient to conclude that the gas cells are intact and hydrogen is not burning.

Hypothesis 2. There was “panel-to-panel arcing”; “the discharge traveled parallel to and along the covering surface; not perpendicular to, but through the grain”.

Hypothesis 3. The paint coating the fabric cover burned rapidly enough to account for the speed of the fire’s spread. Specifically, the IPT proposes that the paint burned as does solid rocket propellant or perhaps thermite.

In order to make the analysis easier for a reader to follow, I have separated the presentation into (a) text that contains the results of the calculations, and (b) appendices that contain formulas used and the assumptions and approximations introduced to make calculations tractable. The appendices also contain estimates of the range of uncertainty in chosen parameters. When selecting physical parameter from within a range of possible values, I have selected values that favor the IPT. The fundamental flaws in the incendiary-paint theory are so profound that I found it pointless to quibble over the most reasonable values.

HYPOTHESIS 1 — Electric Charging and Sparking of an Isolated Panel

The first hypothesis is that “outer cover ignition” was caused by a spark generated by electrical charges on “unique, isolated panels, each developing its own unequal charge”. There is another part to this hypothesis not made explicit by Bain, viz., that the spark emerging from this panel is of sufficient duration and energy to ignite the paint. A related basic premise, namely that the panels are electrically isolated from one another, is unsound (see Hypothesis 2). We must provisionally accept Hypothesis 2 in order to test Hypothesis 1. We will show that Hypothesis 1 fails because (a) the spark jumps in the wrong direction, (b) the spark does not enter the paint, and (c) the spark is too brief and too weak to ignite the paint. Further, in understanding why the Hindenburg survived a number of lightning strikes that burned holes through the paint and the underlying fabric, we shall see that the paint is not all that flammable.

Let us consider how much energy is required to ignite the paint and compare this with the spark energy that is available. At the moment of ignition, the Hindenburg was wet, or, at least damp. It had been flying in rain, and it had started to rain again as the final-approach maneuver began. The relative humidity was 98%. In order for a spark or flame to ignite wet paint, the spark must contain enough energy to first evaporate the water/moisture on the surface and then have sufficient energy to heat the paint to above its ignition temperature. Once a fire has started, this small amount of water on the paint yet to burn is not important, but it is vital to considerations of initiating the fire. Obviously, moisture inhibits the initiation of combustion.

An electrical discharge travels the path of least resistance, which, depending on circumstances, is either through the conducting surface layer created by the rain and high humidity (in which case no spark could be created) or through the air just above the paint, not the underlying insulating paint and fabric. However, if we assume, for the moment, that the spark were somehow able to travel inside the paint, it would have to first dry a narrow path to allow the thin layer of paint to heat to its ignition temperature. As detailed in Appendix C, approximately 23 joules is required, which is not much. However, the energy available from one charged panel is, at most, only 0.01 joule (Appendix A), which is more than 2000 times too small to accomplish the ignition of the paint as proposed in the IPT (Appendix B).

The “demonstration” of burning a scrap of original Hindenburg fabric shown by Bain in television documentaries is immaterial to the Hindenburg fire. For the ignition source, instead of a momentary spark, he employs a *continuous* spark created by a Jacob’s Ladder plasma-arc-generator. Typical arc parameters are a hot (5,000 Celsius) and energetic (100 joules/sec) continuous arc. A plasma arc can be likened to a blowtorch, only hotter. It is significant that Van Treuren and Bain discovered that even this plasma arc, when oriented perpendicular to the surface, could not set the painted fabric on fire[11]. They thus inadvertently demonstrated that the Hindenburg fabric is not extremely flammable. To start a fire, they found it necessary to orient the fabric so the arc, (which they incorrectly label a "spark") was forced to be parallel to the surface. The TV demonstrations show the hot, energetic arc encountered the entire width of the fabric sample from below. The arc passed through the fabric and, with noticeable hesitation,

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[11] 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.

started a localized fire having an unimpressive burn rate. (The burn rate is examined in the analysis of Hypothesis 3.)

Why Didn't the Hindenburg Burn When Struck by Lightning?

In its flying career, lightning had struck the Hindenburg a number of times. These strikes burned holes (diameter up to 5 cm) in the fabric[12] but did not cause a paint/fabric fire. Why not? Lightning strikes are powerful and they do cause fires, typically forest and building fires. If, as proposed by the IPT, the paint on the Hindenburg is a form of rocket fuel or thermite, why didn't lightning strikes set the Hindenburg paint and fabric afire?

The answer can be seen from the fact that a continuous plasma arc can do the job if it is forced to be parallel to and in persistent contact with the painted fabric, as would a blowtorch held under the fabric for a few seconds. However, the lightning strike, or the plasma arc, when perpendicular to the plane of the fabric, did not start fires because, in each case, even though a hole was burned through the fabric, the adjacent fabric did not get hot enough to catch on fire. The only burning is where the hole is formed because the painted fabric is not very flammable. This is why hydrogen-filled airships were safe from lightning strikes (as long as there was no free hydrogen present).

Although the Hindenburg paint and fabric is not very flammable, it will burn if encouraged. The reason that so many scraps of fabric survived the fire to be picked up by souvenir hunters is that, once carried out of the hydrogen fire by the updraft, the paint could not maintain itself above the ignition temperature, so the burning stopped. Neither rocket fuel nor thermite would behave this way— once started, they continue to burn, even after the ignition source is removed.

In contrast to the impossibility of igniting a layer of Hindenburg paint with a perpendicular spark, a hydrogen-air mixture is easily ignited by either weak sparks or, of course, by lightning[13]. For example, two airships caught fire when struck by lighting while venting hydrogen, from which came the rule, "Never blow off gas in a thunderstorm[14]." Operationally, great care was taken to avoid all sources of sparks onboard or even close to a hydrogen-filled airship.

The scenario envisaged by the IPT for the setting Hindenburg paint on fire is not physically possible. It requires the ignition be accomplished by a short-duration electrostatic snap from a single spark that carried at least 2000 times too little energy to ignite even dry fabric. It would be like rapidly brushing a blowtorch flame across the surface. One can move one's hand quickly through a flame without getting burned if the time the hand stays in the flame is sufficiently brief. For a demonstration of the IPT to be realistic, and therefore relevant to the Hindenburg, the painted surface should be wet, or at least damp, and the spark should have an energy of less than 0.01 joule and a duration of less than a microsecond. This failure of Hypothesis 1 of the IPT is so extreme that no

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[12] Uman, M.A., The diameter of lightning, *Jour. Geophys. Research*, *69*, 583, 1964.
Archbold, R., *Hindenburg: An Illustrated History*, p 144, 230 pp., Warner Books, New York, 1994.

[13] Gas-air mixtures are relatively easy to light with a spark. We know from personal experience how a spark in a cigarette lighter or a kitchen stovetop starts a natural gas (i.e., methane) fire (even though methane is less flammable than hydrogen). Powders are the next easiest to ignite (e.g., gunpowder, aluminum or magnesium powder, fine wood shavings, and coal or grain dust). Solids are the most difficult.

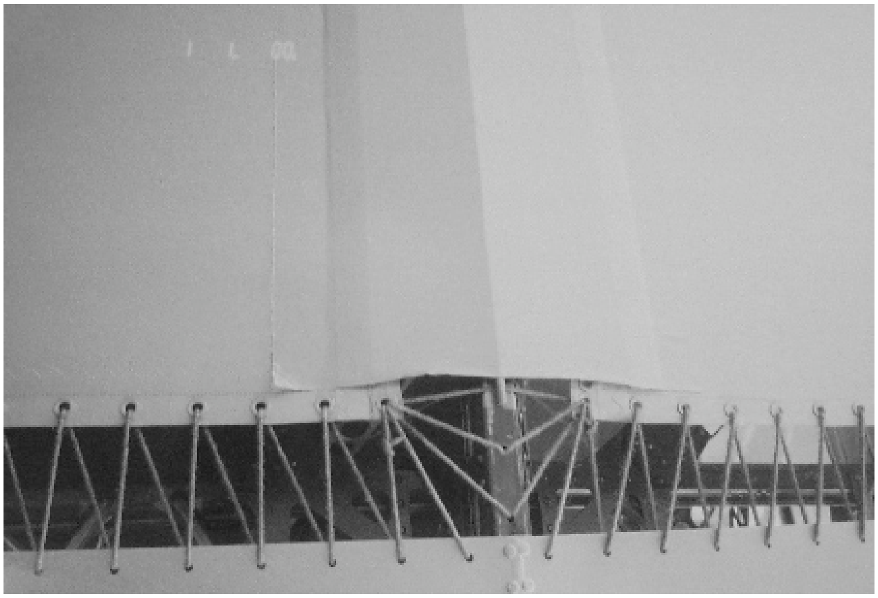
[14] Archbold, R., ibid. p 144.

fiddling with the parameters used in the calculations in Appendix A allows the possibility of a spark carrying more than 0.01 joules of energy and lasting longer than a microsecond. Further, the charging time we calculate in Appendix A limits the spark rate to no more than one spark every few minutes.

Thus, Hypothesis 1 suffers a fatal flaw — the hypothesized spark, even if it could somehow jump along the desired path, is too brief and too weak to ignite the damp or wetted paint. The IPT lacks an ignition mechanism. However, in order to continue our study of the other two hypotheses, we will, for the moment, ignore the fact that this first hypothesis is fatally flawed.

HYPOTHESIS 2 — Panel-to-Panel Arcing Parallel to and within the Paint

Bain asserts that there was "panel-to-panel arcing", and he requires that "the discharge traveled parallel to and along the covering surface, not perpendicular to, but through the grain". This required path is, obviously, most unlikely. Note that Bain offers no analytic evidence to show that the spark can, in fact, travel parallel to and "within the grain" of the paint. Nor does he identify this claim as a hypothesis. We show below that this hypothesis is fatally flawed on at least two levels:



>Fig. 2. Hindenburg fabric attachment to aluminum airframe [Zeppelin Museum, Friedrichshafen], which illustrates a fatal flaw in the IPT. Separate fabric panels are lashed to the aluminum airframe, and then fabric strips connect them to one another. Only then are coats of paint applied. Thus, the paint forms a single, continuous electrical surface. There are no isolated blocks of paint, as is assumed by the IPT.

(1) The hypothesis fails at a simple, conceptual level. As pointed out by Peake[15], the panels are not separate. They are attached to one another with fabric strips, and then the entire outer cover is painted. As shown in Fig. 2, paint on the outer cover of the Hindenburg forms a continuous, electrically connected surface. One should not be distracted by the fact that the underlying fabric is glued together. It is the paint that is the

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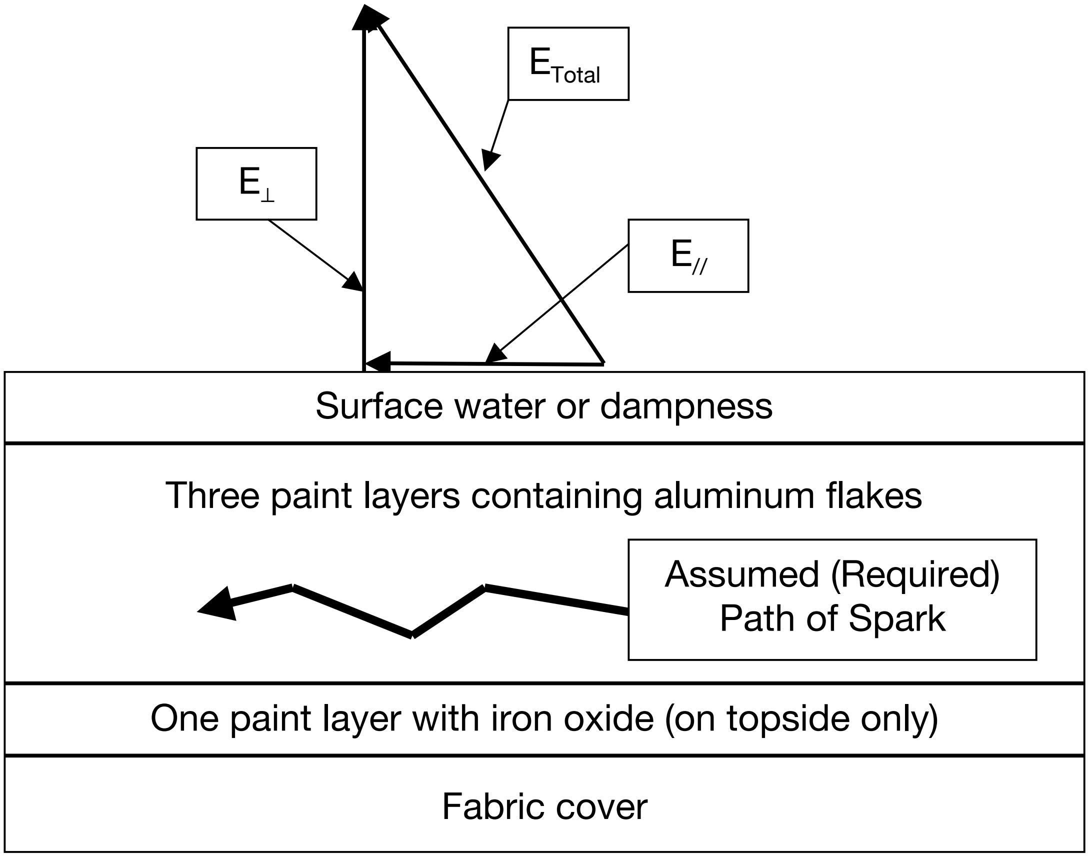
[15] Peake, N., What happened to the Hindenburg? *Dirigible*, *11* (2), 14-15, 2000.

electrical surface, and it is continuous. There are no gaps between the panels to support the assumption in the IPT of "unique, isolated panels, each developing its own unequal charge" or "panel-to-panel arcing".

The lowered electrical resistance of the surface presents an even more serious contradiction for the incendiary-fabric theory. A wet or damp surface, such as the outer cover of the Hindenburg at the time of the fire, is sufficiently conducting to form what is called an equipotential surface in which accumulated charge creates an electric field that is, at the painted surface, perpendicular to that surface, i.e., there is no component of electric field parallel to the surface. For such a static equipotential surface, by definition, the $E_{//}$ in Fig. 3 is zero. Sparks tend to follow the electric field that creates the spark. Therefore, a spark from a panel must also be perpendicular to the surface (the paint) and not parallel to it as assumed by Bain.



>Fig 3. Schematic sketch (not to scale), in cross-section, of relevant features of the outer cover of the Hindenburg. The surface of the paint was either wet from rain or damp from water adsorbed from the humid air at the time of the fire. The effect of moisture is to reduce the electrical surface resistance and short out the parallel electric field $E_{//}$. With a small or zero value of $E_{//}$, there is only a perpendicular field $E_{\perp}$. The IPT requires that the spark pass within the grain of the paint as illustrated. With zero $E_{//}$ this spark path is physically impossible. This vitiates a key hypothesis of the IPT.

(2) Hypothesis 2 fails again when we examine the physics of electrostatic discharges. The surface of the paint was either damp from the high humidity at the time of the

accident (reported to be 98%[16]), or the surface was wet from rain. In conditions of high humidity, water is adsorbed onto exposed surfaces, which decreases surface electrical resistance, i.e., a damp surface is a better electrical conductor. Increasing the relative humidity from 50% to 90% causes the surface resistivity to drop by factors that run between a thousand and a million[17] (Appendix B). If the surface were wet from rain, the surface resistance would drop even more. Because the panels are electrically attached to one another, there can be no voltage difference between panels, which makes it physically impossible for a spark to jump from one panel to another.

The easiest path for the spark, and hence the path the spark would follow, is perpendicular to the fabric. A spark could jump at right angles to the fabric, internal to the cover, from the aluminum airframe or a bracing wires. Another possibility is, again perpendicular to the painted fabric, but into the air exterior to the airship in the form of a corona discharge, brush discharge, or St. Elmo's Fire (different names for the same phenomenon). Bain has already demonstrated in his experiments (and correctly concluded) that a spark perpendicular to the surface (even a plasma arc or a powerful spark such as lightning) will not start a fabric or paint fire.

Finally, for the arrangement represented by the Hindenburg, a parallel electric discharge (i.e., a spark), would not jump parallel to and "through the grain" of the paint simply because that is not the easiest way for a spark to go. Electrical currents (which include sparks) take the celebrated "path of least resistance". The paint for the Hindenburg was primarily cellulose acetate with either iron oxide or aluminum powder added. The amounts of iron oxide and aluminum added to the paint were so small that they would have had little influence on the electrical properties. Iron oxide (iron rust) is an electrical insulator. More importantly, the iron oxide and aluminum powder additives do not touch each other. The cellulose acetate paint forms a matrix in which the individual flakes are suspended. This is proved for the aluminum additive by of the high electrical resistance of the dry Hindenburg painted fabric as reported by Bain. Aluminum is a good electrical conductor, so, if the aluminum flakes touched each other, the electrical resistance of the paint would be lowered considerably. Cellulose acetate is a tough insulator with an electrical breakdown strength (dielectric strength) of 100 kV/cm. The available electric field, as shown in Appendix A, is no more than approximately 10 kV/m = 100 V/cm, which is too weak (by a factor of between 400 and 1,000) to produce the electrical discharge required by the IPT[18]. Any putative spark would have to find an easier path, or it would be blocked.

We have shown above that Hypothesis 2 suffers two fatal flaws: (1) The paint forms a layer that covers both the panels and their connecting strips of fabric, so the painted surfaces of the panels are not electrically isolated from one another; the paint forms a single, continuous surface. (2) Physical conditions do not allow the spark required by the IPT: namely one that is "parallel to and along the covering surface; not perpendicular to,

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[16] Trimble, S., Jr., R.W. Schroeder, and D. Mulligan, Report of the United States Department of Commerce Accident Board on the Hindenburg accident, in *The Hindenburg Accident*, edited by R.W. Knight, Section III, pp 1-68, 7 C's Press, Riverside, 1938.

[17] We know this from personal experience. On cold, crisp winter days, we suffer static-charge buildup on our body and subsequent sparking when we walk (or worse, shuffle) across a carpeted floor and reach for a doorknob. On warm, humid days, there is no such problem because the surfaces of our bodies, clothing, and the carpet are better electrical conductors, and the static charge is bled off peaceably by the improved conductivity instead of by an impulsive spark.

[18] Covino, J., and F.E. Hudson, Current assessment methodology for electrostatic discharge hazards of energetic materials, *Jour. Propulsion and Power*, *7*, 894-903, 1991.

but through the grain”. As before, we must ignore the fatal flaws in these first two hypotheses in order to consider Hypothesis 3.

HYPOTHESIS 3 — The Hindenburg Paint Burns as Does Solid Rocket Fuel or Thermite

This hypothesis is the most crucial to the IPT. It is also the easiest of the three to demonstrate to be fatally flawed. The Hindenburg paint cannot be classified as a solid rocket fuel because it lacks an oxidizer (such as the ammonium perchlorate in the space Shuttle solid rocket propellant). And worse, even if it were like solid rocket fuel, it would not burn at the high speed necessary to explain the Hindenburg fire. Finally, a significant thermite reaction in the paint is not possible.

First, let us do away with the idea that the paint has the properties of thermite. Thermite is composed of fine aluminum and iron oxide powders mixed in a specific ratio. It burns rapidly, and with an almost unquenchable, hot flame. The chemistry of thermite is well known. To burn properly, it must contain, by weight, roughly 1 part aluminum, and 3 parts of iron oxide. For the Hindenburg, the ratio of aluminum to iron oxide was all wrong to make thermite (see Appendix C). To get the proper proportions for thermite, either approximately 10 times more iron oxide or 10 times less aluminum is required. Further, the iron oxide on the Hindenburg was placed only on its topside (to protect the fabric beneath from solar UV). Even on the topside, where a small amount of iron oxide was present, it was in a separate coat of paint — not mixed with the aluminum. The paint binder acts to keep the reactant separated so, even if there had been 10 times more iron oxide, a thermite reaction would have been prohibited or, at best, muted.

Another bit of evidence against a thermite reaction can see in Fig. 1a. If a thermite fire had taken place, it would apply to only the top half of the airship. We can see that there is no visible evidence of a demarcation line between the top half of the airship fire (where a small amount of iron oxide was present) and the lower half. In contrast, as can be seen in even a cursory examination of Fig 1a, there are clear vertical fire lines.

The thermite suggestion fails because (a) there is only 1/10th the iron oxide required to produce a chemical thermite reaction. (a) Given the composition of the Hindenburg paint, a thermite reaction as proposed in the IPT is chemically impossible, and (b) there is no horizontal fire line at the ship's equator where application of the iron-oxide paint began.

The Hindenburg Paint is Not Solid Rocket Fuel

Now we examine the most fundamental idea within the IPT, namely that the paint burns as does solid rocket fuel, and that solid rocket fuel burns rapidly. First, the Hindenburg paint differs from solid rocket fuel in an important respect — it does not contain a source of oxygen to sustain combustion. The fuel segments (called grains) in the Space Shuttle Solid Rocket Boosters (SRBs) contain ammonium perchlorate, which breaks down when heated to produce free oxygen (see Appendix C). This allows the rocket fuel to burn without air. The primary constituent in the Hindenburg paint (to which aluminum and iron oxide was added) is cellulose acetate. It will burn in air, but not well. If ignited inside a rocket case, where no air is available after the rocket fires, its combustion products would smother the flame, and the burning would stop for lack of oxygen. An alternate (and less expensive base for the paint) cellulose nitrate could have been selected by the Zeppelin builders. Cellulose nitrate, which carries within its nitrate radical a source of oxygen, is highly flammable. Cellulose nitrate could be a base for a rocket fuel, but, because it was recognized as a hazard, it was not used on the Hindenburg.

Two thirds of the Space Shuttle SRB propellant is ammonium perchlorate, a chemical source of oxygen. In contrast, the Hindenburg paint had to get oxygen from the air, which explains why pieces of fabric were scattered and found on the ground unburned after the fire. The painted fabric simply did not burn well. Once carried away from the flaming hydrogen by the fire-induced updraft, the painted fabric scraps stopped burning. If the paint burned as well as does solid rocket propellant, no pieces of the painted outer cover would have survived the fire.

Solid Rocket Fuel Burns Slowly

But, there is a more significant flaw in this hypothesis. The roaring, dazzling flames exiting the nozzles of the 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 fuel as our example[19], the burn rate is surprisingly slow. The burn rate for Space Shuttle SRB propellant is only 0.37 inch/sec (1.0 cm/sec) at 625 psi. It is even slower if the fuel were outside the rocket case because the burn rate is pressure dependent. At atmospheric pressure, the burn-rate slows to about 0.1 inch/sec. To avoid any argument over the exact rate at atmospheric pressure, I will use double this rate, 0.2 inch/sec (0.5 cm/sec, or 1 foot per min). We already know that a burn rate this slow 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 fuel grain. This distance is only about 5 feet. So, inside the Space Shuttle SRBs, the rocket fuel burns only 5 ft in 124 seconds. If the pressure were reduced to atmospheric pressure, the burn time would at least double. In comparison, to account for the speed of the Hindenburg fire, if it is to burn the length of the Hindenburg in 34 seconds, the burn rate must be about 7 m/sec, 25 ft/sec, or 1,500 ft/min. A burn speed this high is unlike any rocket propellant, but it is what one expects for a hydrogen fire.

The relationship between burn rate and pressure for rocket-type fuel was discovered over 100 years ago, and the physical chemistry of the rocket-fuel burning process has been textbook material for at least half a century[20]. 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. 4). The composition of a sparkler is much the same as solid rocket fuel (an oxidizer, such as ammonium perchlorate, and aluminum or magnesium powder mixed in a binder, with a small amount of iron powder to make the sparkles). Sparklers, as one should expect, burn at about the same speed as solid rocket fuel, which is too slow by a factor of approximately 1,000 to explain the rapid spread of the Hindenburg fire.

The fundamental hypothesis underlying the IPT is that the paint on the Hindenburg is a form of solid rocket fuel and that it burned with great vigor and speed. No measurements are offered by proponents of the IPT on the burn rate of either solid rocket fuel or of the painted fabric. Would the painted Hindenburg fabric, absent being placed in a hydrogen fire, burn faster than the same fabric covered with, say, paint used regularly for fabric-

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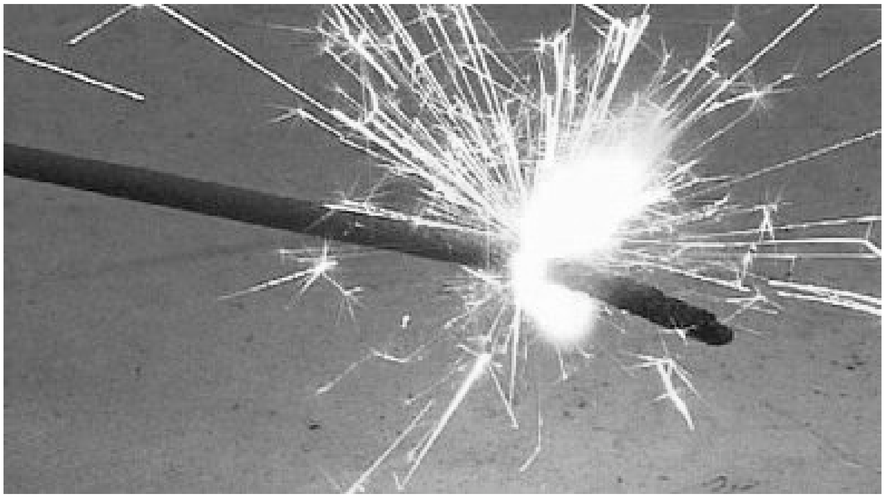
[19] The information is from a letter from David Ricks, NASA/MSFC, 3 Nov. 2000.

[20] 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.

covered aircraft? Would it burn faster than 1 ft/min? Finally, there is no evidence that either Hindenburg paint or solid rocket propellants burn fast enough to spread the fire in seconds from one end of the Hindenburg to the other. Evidence is quite the contrary.



>Fig. 4. Sparklers are much like solid rocket fuels in composition and burn rate. At atmospheric pressure, they burn at about the same speed as Space Shuttle Solid Rocket Booster (SRB) propellant, which is less than about 0.2 inches per second at atmospheric pressure. A sparkler takes about 1 minute to burn from one end to the other.

We see that the most vital of the IPT hypotheses is fatally flawed. (1) There was not enough iron oxide in the paint to support a thermite reaction. (2) The paint does not have the characteristics of solid rocket fuel. (3) Even if the paint had been made of Space Shuttle solid rocket fuel, its burn rate is so slow that it would have taken at least 10 hours for the burning paint to consume the Hindenburg. It is important for the reader to recognize that knowledge of burn speed of solid rocket fuel is based on theoretical and experimental research carried out over many decades and is well known.

DISCUSSION AND CONCLUSIONS

The incendiary-paint theory of Addison Bain is subject to many criticisms. The advantage of limiting this paper to a thorough examination of just three selected hypotheses that underlie the theory is that, for these three hypotheses, the analyses 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 rough inferences based on what is happening (e.g., the tail is not falling, therefore the hydrogen has not burned). Rather, the arguments focus on basic physical principles and their application.

The three hypotheses have been investigated and their quantitative flaws are:

Hypothesis 1 — Bain supposes that a Hindenburg fabric panel could create a spark of sufficient strength and duration that it could set the panel paint on fire. Fatal flaw — A spark that could have been created at the time of the landing, could not jump as described in Bain's theory, and it would be too weak and too brief (0.01 joule and less than a millionth of a second) to set the damp (or wet) Hindenburg fabric on fire. A spark of longer duration and containing at least 1,000 times more energy is needed, but it is not available.

Hypothesis 2 — The IPT requires the spark that ignites the paint must travel parallel to the outer fabric surface and within the paint as illustrated in Fig. 3. Fatal flaw —The insulating properties of the paint prohibit a spark passage parallel to and through the paint. Further, because of the high humidity and rain at the time of the fire, the surface of the outer cover is electrically conducting. As a consequence, a spark parallel to the surface is not possible. Even if it were, a spark would take the path of least resistance, which is through the moist surface just outside the paint. It could not do it if it wanted to, and it would not want to if it could.

Hypothesis 3 — An essential argument supporting the IPT is that the paint has the properties of either thermite or solid rocket propellant. Then follows the implication that this incendiary mixture, disguised as paint, burns fast enough to account for the speed of the fire's propagation. Fatal flaws — The chemical composition of the Hindenburg paint is known, and it lacks an essential ingredient required to make it a solid rocket propellant. Solid rocket propellants burn fastest when under high pressure, and then at rates of only around 1/2 inch per second. At atmospheric pressure, the burn speed is reduced. The paint on the Hindenburg, even if it were made of Space Shuttle solid rocket fuel, burns about 1,000 times too slowly to account for the rapid propagation of the fire. As for the thermite suggestion, the paint layers have only 10% the amount of iron oxide required to make thermite. Further, the two constituents (aluminum and iron oxide) were in separate layers and not mixed together, and the iron oxide was applied to only the upper half of the Hindenburg. There was no line of demarcation of flame propagation indicating a different character for the fire on the upper half of the airship where the iron oxide was present. The thermite idea can be safely discarded.

An interesting challenge for proponents of the IPT is to measure the flame propagation speed of appropriately painted fabric. The composition of the Hindenburg paint is well documented, so it could easily be reproduced. Rather than sacrifice rare pieces of the original outer cover, a, say, 10 ft x 10 ft reproduction of the cover could be made by painting suitable fabric with the replica Hindenburg paint. The underlying framework would not have to be replica of the Hindenburg airframe — wood lathing would do as well. Then the painted fabric could be ignited with a match or torch in an upper corner and a measurement obtained for the time to burn diagonally across to the lower corner. If conditions were similar to those at the time of the Hindenburg fire (light rain and 98% humidity with damp fabric), I predict that the fire will go out before it gets to the lower corner. If conditions are more benign, I predict it will take about15 minutes to burn the entire distance.

In this paper, we demonstrate only that the IPT is fatally flawed and hence is not applicable to the Hindenburg fire. We do not defend any competing theory as being correct. Three key hypotheses critical to the IPT show quantitative failures by factors of at least 100. None of the numerical results presented can be reasonably stretched in a direction more favorable to the IPT by as much as a factor of two. The analyses are based on established principles of physics and physical chemistry. They are not subject to negotiation. Because each of the three hypotheses is fundamental to the IPT, and because each hypothesis is found to be fatally flawed, the entire incendiary-paint theory of the Hindenburg fire is 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.

APPENDICES

Appendix A — Atmospheric Electricity and Energy in a Spark

The Earth has a net negative electrical charge delivered to it by cloud-to-ground lightning amounting to a current of 2000 Amperes (A). The Earth is thereby charged to a potential of 180 thousand volts (kV) relative to the upper atmosphere. A distributed worldwide return current with an average current density of 4×10^{-12} A/m^2 stabilizes this voltage[21]. The lower atmosphere is not a good conductor, so a strong electric field is needed to drive the required current. Away from lightning activity, there is at the Earth's surface a downward directed electric field, typically 120 volts/meter (V/m). Earth's electrical potential is stabilized by this electric field, which falls rapidly with altitude, dropping by about a factor of 10 at an altitude of only 6 kilometers. However, when under an electrically active cloud, which normally covers an area of more than 100 km^2 the electric field is reversed, and it has a higher numeric value. A thunderstorm electric field can rise to 10 kV/m. For the Hindenburg, under a cloud issuing a light rain, with distant lightning, the electric field could be as high as perhaps 5 kV/m, with 3 kV/m being a more reasonable value. There were no telltale signs of more pronounced electrical activity such as thunder, nearby lightning, or hair standing on end, etc.

Direct measurements[22] show that the electrical conductivity of the atmosphere beneath a thundercloud is about the same as in fair weather. Therefore, the current that is driven through the atmosphere is simply proportional to the electric field. For our assumed maximum electric field of 5 kV/m, the fair-weather current density of 4×10^{-12} A/m^2 is increased by the ratio of storm to fair weather electric field 5000/100 = 50. Thus, the downward current density j flowing in the vicinity of the Hindenburg is $j = 2 \times 10^{-10}$ A/m^2. There is some focusing of the current onto the panel because of the aforementioned distortion of the electric field by the conducting airframe[23]. This increases the current flow onto an upper panel by a factor of 1.5 to give $j_p = 3 \times 10^{-10}$ A/m^2

The electrical charge density σ on a surface is $\sigma = \varepsilon E$, where σ is the charge density in coulombs/m^2, ε is the dielectric constant of the ambient medium (for air $\varepsilon = 8.85 \times 10^{-12}$), and E is the electric field in volts/m. The value for E is approximately 1.5 times the ambient value at the top of the airship because of the electrical conductivity of Hindenburg cover or its aluminum airframe. If we assume the electric field over Lakehurst at the time of the Hindenburg landing is 5 kV/m, then this field could be increased at a panel to as much 7.5 kV/m. At a relatively sharp edge, such as the tail or virtually any protrusion, the electrical field is higher. There is a practical limit of about 10 kV/m, at which point corona (brush) discharge or lightning is possible, the limiting electric field depending on the fine-scale surface roughness. We take 7.5 kV/m as a reasonable maximum electric field at a panel. For this value of E, $\sigma = \varepsilon E = 6.6 \times 10^{-8}$ coulomb/m^2. The electrical charge on one panel is σ times the area of the panel. For the region just forward of the tail, the panels are 5 m wide and 2.7 m high so the area of a fabric panel near the tail is A = 13.5m^2. The total charge on a panel is $Q_p = A\,\sigma = 9 \times 10^{-7}$ coulomb. The panels farther rearward are smaller, so an electrical charge on them would be reduced in proportion to their surface area. The time required to electrically charge a

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[21] Dolezalek, H., Atmospheric Electricity, *Handbook of Chemistry and Physics*, edited by R.C. Weast, pp. F-151-F153, Chemical Rubber Publishing Co., Boca Raton, 1987.

[22] Blakeslee, R.J., and E.P. Krider, Ground level measurements of air conductivities under Florida thunderstorms, *Jour. of Geophys. Research*, *97*, 12,947-12,951, 1992.

[23] Calculations are carried out to only one or two significant figures, consistent with our knowledge of the conditions.

panel is $\tau_c = \sigma/j_p = \varepsilon E/j_p$, where τ_c is the charging time constant, σ is the charge accumulation per square meter, and j_p is the current density at the panel, estimated above to be 3×10^{-10} A/m^2. For the derived values of charge and current densities, $\tau_c = 220$ sec ≈ 4 minutes.

We next estimate the energy (W) released in a spark discharge from an isolated panel. First, we must know the electric potential (voltage) Φ of a panel relative to wherever the spark is going. A key hypothesis of the IPT is that a spark jumped from an isolated, ungrounded, charged panel to an adjacent grounded panel. It is the energy of this spark that we wish to estimate. We proceed with this calculation despite the finding in Appendix B that such a spark is not physically possible in order to show that such a spark would have insufficient energy to ignite the paint on the outer cover.

Although the grounded airship is at a potential of approximately 180 kV relative to the clouds above, this is not the voltage we seek. 180 kV is the potential that would be operant if a bolt of lightning were to strike the airship. Instead, we need the voltage between the charged panel and an adjacent grounded panel. This is readily obtained because we already know the electric field at a charged panel. This maximum value of 7.5 kV/m will not change when the adjacent panels are grounded because the electric field is determined by $\sigma = \varepsilon E$, and the charge on the isolated panel is fixed over the time interval of interest. Although the electric field is distorted when all but the isolated panel is grounded, an order of magnitude estimate of the potential between them is El. The distance l is the physical scale length between panels, which, for 5 x 2.7 m panels, we take to be 4 m. Thus an upper limit to the potential between an isolated panel and an adjacent grounded panel is $\Phi = El = 30$ kV

The electrical energy W of an isolated panel relative to a neighboring grounded panel is $W = Q_p \Phi/2 = 9 \times 10^{-7} \times 3 \times 10^4/2 = 1.4 \times 10^{-2}$ joule, or roughly 0.01 joule. This is not much energy. In Appendix C we shall see that 0.01 joule is 1000 times too small to ignite the paint, even if it has the characteristics of rocket fuel.

It may be useful in considering future alternative calculations of the energy in sparks that might be related to the Hindenburg to know the electrical capacitance of the entire airship. The electrical energy on a charged body is a function of its capacitance and voltage. The capacitance for shapes such as cylinders, spheres, and airships is roughly independent of the exact shape and varies approximately with the size of the object. We will demonstrate this by calculating the capacitance of (1) a prolate spheroid (cigar shape) having the dimensions of the Hindenburg, and (2) a right circular cylinder with approximate Hindenburg dimensions.

The formulas for electrical capacitance C are[24]:
(1) For a prolate spheroid, the capacitance $C = 4\pi\varepsilon(a^2 - b^2)^{1/2} / \tanh^{-1} [1 - (b/a)^2]^{1/2}$ where a = half the length of the Hindenburg (122.5 m) and b = half the maximum diameter (23.4m). For these parameters, $C = 5.7 \times 10^{-9}$ Farad (F)
(2) For a right circular cylinder, $C = [8 + 6.95(l/d)^{0.76}]\varepsilon d/2$ where the cylinder is of length l and diameter d. If we take l = 240 m and d = 40 m, $C = 6.2 \times 10^{-9}$ F.

These approximations give roughly the same value for the electrical capacitance of the Hindenburg $C = 6 \times 10^{-9}$ Farad.

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[24] Smythe, W.R., and C. Yeh, Formulas, in *American Institute Handbook*, edited by D.E. Gray, pp. 5-12, McGraw-Hill, New York, 1957.

Appendix B — Parallel Electric Field and Spark in Painted Fabric

The electrical conductivity of the painted surface, wetted by rain or dampened by high humidity at the time of the Hindenburg landing, is good enough to make the surface an electric equipotential, which prevents the development of any significant electric field parallel to the surface (i.e., $E_{//}$ in Fig. 3 is kept small). Without an electric field parallel to the surface, there can be no spark parallel to the surface, hence no "panel-to-panel arcing" or the spark illustrated in Fig. 3.

How low does the surface resistivity need to be in order to constitute a "good" conductor that would make the Hindenburg paint an equipotential surface having no parallel electric field? When charge is deposited unevenly on a surface, there is a component of electric field parallel to that surface. For the surface to cancel the parallel component of field and maintain only a perpendicular electric field (which makes the surface an equipotential}, the conductivity need be sufficient to allow charge flow that annihilates the parallel component of electric field during a time-interval of interest. There is no such easy route to reduce the perpendicular electric field, $E_{\perp}$ in Fig. 3.

Charge introduced inside a body having a resistivity ρ_v ohm-m (the subscript v designates a volume resistivity) moves to the outside of the body in a time $\tau = \varepsilon\rho_v$. For a two-dimensional geometry, such as a Hindenburg fabric panel, with a resistivity ρ ohms/square, the time for the charge to disperse is $\tau = \varepsilon\rho r$ where r is the radius of an area with an excess charge placed on it.

Before calculating values of τ, we must examine the effect of water or high humidity on surface resistivity. Standard handbook data show that humid air at a surface reduces its resistivity. In conditions of high humidity, water is adsorbed on the surface. For example, simply going from 50% to 90% relative humidity, the surface resistivity of Bakelite drops from $\rho = 3 \times 10^{11}$ ohms/square to 2×10^8 ohms/square; hard rubber (as in some pocket combs) drops from 3×10^{15} to 2×10^9 ohms/square; and fused quartz goes from 3×10^{12} to 2×10^6 ohms/square[25]. Another factor of possible importance is that the Hindenburg had been flying for three days over the ocean at low altitudes (typically 300 m), during which time microscopic salt particles from evaporated whitecap spray would attach to the paint to form a surface contamination. (These airborne salt particles explain why things corrode so quickly at the seashore.) For the Hindenburg paint, such salt particles further reduce the surface electrical resistivity when humid or wet.

Bain mentions the resistivity of the painted fabric, "electrical tests showed the [Hindenburg] outer cover measured 10×10^{13} per unit square". We will provisionally assume this is a typographic error[26] and Bain meant "ohms per unit square" (ohms/sq). But application of this value to the Hindenburg fabric at the time of the fire is not reasonable. As shown in the preceding paragraph, decreases in resistivity of factors of 10^3 to 10^6 can be expected if the humidity were increased to just 90%. At the time of the landing, a light rain was falling and the humidity was 98%[27], so the surface would have

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[25] Hodgman, C.D., R.C. Weast, and S.M. Selby, *Handbook of Chemistry and Physics*, 3456 pp., Chemical rubber Publishing Co., Cleveland, 1958.

[26] Bain, A. Colorless, nonradiant, blameless: a Hindenburg disaster study, *Gasbag Journal*/Aerostation (39: March), 9-15 Aerostation Section, 1999. This interpretation is not certain as indicated by an Editor's Note: "At press time, *Aerostation* could not get clarification of the units used."

[27] Trible et al., ibid.

been moist if not wet. If liquid water in the form of rain is added, plus contamination including sea-salt particles, the surface resistance falls even more. To be applicable, Bain should measure the resistivity after exposing the fabric to sea-air for three days and then sprinkling the painted sample with rainwater. We can safely assume that the surface resistivity would be lowered by a factor of at least 10^3, perhaps by as much as 10^6. Thus, the surface resistivity would drop from the (presumed) dry value of $\rho = 10 \times 10^{13}$ ohm/square reported by Bain to $\rho = 10 \times 10^7$ to 10×10^{10} ohms/sq.

We now return to the calculation of time constant for dispersal of excess charge on a painted fabric panel. Using the largest value for the surface resistivity of 10×10^{10} ohms/sq, we obtain $\tau = \varepsilon\rho r = 0.88$ seconds for charge accumulated in an area 2 m across. For the lower value of resistivity (10×10^7 ohms/sq), τ is less than a millisecond. Any value of τ less than about 100 seconds would keep the Hindenburg an equipotential surface because this is less than the charging time of approximately four minutes. The maximum value of ρ necessary to keep $E_{//}$ at low levels is 10^{13} ohms/sq, only a factor 10 less than the (presumed) value reported by Bain for dry fabric under laboratory conditions of low humidity. The moist or wet Hindenburg paint conducts electricity well enough that, within seconds, any electric field is forced to be perpendicular to the painted surface.

Bain makes several inappropriate references to Covino and Hudson's study of electrostatic hazards in handling solid rocket fuel elements. The paper he cites is relevant to the accidental ignition of the propellant in a Pershing II missile "following the separation of dissimilar dielectric materials in a cold, dry climate."[28] The accident occurred in Germany in Jan 1985 on a cold, dry winter day. Such conditions are ideal for the buildup of static electrical charges. The Pershing II accident would not have occurred under the conditions of the Hindenburg landing[29] (i.e., in light rain with moderate temperature and high humidity).

Bain correctly quotes from the Covino and Hudson paper as to the mechanics of spark ignition. But, in the next sentence he says [p. 12], "The safety study [by Covino and Hudson] concluded such material that exhibited greater than 10×10^{10} ohms per unit measure would be vulnerable to electrostatic discharge ignition. The … LZ-129 outer cover measured 10×10^{13} per unit square." Aside from the confusion of units (remarked on in Appendix B), Bain incorrectly represents Covino and Hudson's findings. In their equation (1) they define a "breakdown coefficient" and give for its critical value $P_{crit} = 10^{10}$ ohm-m, which is the number quoted. In the above quotation, the surface resistivity of the Hindenburg paint is compared to the breakdown coefficient P_{crit} of solid rocket fuel. Unfortunately, P_{crit} is a coefficient, not a resistivity, so they cannot be compared directly. Further, P_{crit} starts with a volume (not a surface) resistivity that is then modified by ratios of terms such as volume and weight percentages of binder and aluminum powder as well as the cube of the ratio "diameter of finest fraction of conducting particles" divided by "diameter of finest fraction of nonconducting particles". This last term is perhaps most important because, for the Hindenburg paint, it is apt to be a large number when cubed. Bain's comparison of P_{crit}, an index that involves the volume resistivity of solid rocket fuel, with the surface resistivity of the Hindenburg fabric is meaningless. And he does not calculate the coefficient P_{crit} for the Hindenburg paint.

Bain does not acknowledge that the relative humidity was less than 30% during the measurements reported by Covino and Hudson and that they say that P_{crit} is "temperature,

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[28] Covino and Hudson, ibid.

[29] David Ricks, Personal communication

humidity, and time dependant". The last item, time dependence, draws into question the validity of measurements made on 60-year old samples of Hindenburg outer cover. But the neglect of realistic humidity control is perhaps the most important. At the time of the Hindenburg fire, the relative humidity was 98% and a light rain was falling[30]. If the Pershing fuel element had been wet from rain and in high-humidity, the 1985 accident would not have happened because static charge buildup caused by rubbing does not occur in such conditions[17].

Another important finding of Covino and Hudson, which is not reported by Bain, is that, in laboratory tests, for temperatures above 50 F, the energy of a spark must exceed 10 or 15 joules in order to ignite a dry solid rocket fuel sample. In the discussion of Hypothesis 1 and Appendix A, the electrostatic energy available from a single panel is no more than 0.01 joules, or a factor of at least 1000 too small to ignite even dry rocket fuel in conditions of low humidity. For wetted paint and high humidity, the quantitative failure of Hypothesis 3 is more extreme.

Finally, we note the obvious — a wet object is harder to light than a dry object because it must first be heated until it is dry. Let is assume that there is a layer of water on the paint surface of thickness 0.5 mm, that the spark travels only 1 cm parallel to the surface, and it evaporates a swath only 1 mm wide. The volume of water that must be heated and evaporated is 5×10^{-3} cm^3, which weighs 5 milligrams. The specific heat of water is 4.2 joules/gm-K and its heat of vaporization is 2.3×10^3 J/gm. The total energy that must be added to first bring the small quantity of water to the boiling point (a temperature increase of, say, 80 K) and then boil it away is 13 joules. This energy, plus the 10 to 15 joules needed to ignite paint, implies that the spark energy must exceed 23 joules. Although this is not much, it is large compared to the upper limit of 0.01 joules of a possible Hindenburg spark.

Appendix C — Hindenburg Paint and Solid Rocket Propellant

David Ricks (NASA/MSFC) supplied much of the following information on Space Shuttle SRB propellant. Information on propellants in general was obtained from Zaehringer and Maxwell[31]. For solid rocket fuel, the burn rate R_b, given in inches/sec, is $R_b = a P_c^n$, where a is a constant typically 0.05 to 0.001, P_c is the combustion chamber pressure in pounds per square inch (psi), and n is a coefficient that must remain less than unity if the rocket is not to explode and greater than zero if the rocket is to perform. The coefficient n is typically between 0.5 and a bit less than 1. The burn rate thus varies with the pressure. The burn rate of solid rocket fuel is slow even under pressure. For example, the burn rate of the Space Shuttle SRB fuel is 0.368 inch/sec (0.93 cm/sec) at 670 psi. At atmospheric pressure (15 psi) the burn rate falls to less than 0.2 inch/sec (0.5 cm/sec). The high propagation speed of the Hindenburg fire averaged about 7 m/sec (nearly 300 inches/sec), which is more than 1000 times faster than the burn rate of Space Shuttle solid rocket propellant at atmospheric pressure.

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[30] Trible et al., ibid.

[31] Personal communication from David Ricks, Manager, Reusable Solid-Rocket-Motor Propellant Subsystem, NASA Marshall Space Flight Center.
Zaehringer, A.J., Combustion, in *Solid Rocket Technology*, edited by M. Shorr, and A.J. Zaehringer, pp. 129-146, John Wiley, New York, 1967.
Maxwell, W.R., Solid Propellant Rocket Motors, in *Rocket Propulsion*, edited by N.H. Langton, pp. 59-87, American Elsevier, New York, 1970.

To understand the reason for the burn-rate pressure dependence, we must understand that the solid fuel itself does not burn. Instead, the solid, when heated, emits combustible gases and particulates that flow from the surface of the solid – it is these gases and particles, which contain both fuel and oxidizer, that burn, as do the gases coming out of a welder's torch. This is different from explosives where the burning/explosive reaction goes quickly beneath the surface and through the body of the explosive.

Inside a solid rocket motor, burning gases heat the surface of the solid fuel. In response, the surface of the propellant that is next to the flame, foams, fizzes, and produces a combustible mixture of gas and small particles streaming away from the solid. The production of gas is an evaporative or ablative process that keeps the solid from getting too hot, i.e., the outer surface acts as an ablative heat shield to keep the inner solid material from overheating. The evolved gases flow outward with a speed just equal to the inward flame speed. If the gas moves too slowly, the flame gets closer to the surface, the surface gets hotter, more gas flows outward at higher speed, and the flame is blown away from the surface. If the flame should move too far from the surface, it cools a bit, and the gas outflow speed drops below the flame speed, so the flame again approaches the surface. The whole process is a marvel of stability. This is demonstrated by the two Space Shuttle SRBs, which must maintain essentially equal thrusts and then burn out at the same time in order to avoid an unacceptable asymmetry in thrust.

The reason high pressure produces a faster burn rate (as compared to the slower burn rate at atmospheric pressure) is because the gas density, and hence the heat output of the burning gases, is higher at higher gas pressures. A greater heat output from the gas heats the surface of the solid, which, in turn, foams and fizzes to produce more combustible gas, and so on. At atmospheric pressure, the heat transfer to the surface of the solid is smaller so relatively small quantities of combustible gases are produced. This is why solid rocket fuel burns with enthusiasm under high pressure and benignly at atmospheric pressure.

The Hindenburg paint differs significantly from solid rocket propellant in that it does *not* carry its own source of oxygen. SRB propellant consists of[32] 69.6% ammonium perchlorate for the oxygen source, 16% aluminum for fuel, 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.

Finally, we must consider the suggestion in the IPT that the aluminum powder and iron oxide perhaps burned like thermite. The thermite reaction is very different from the burning of solid rocket fuel in that the iron oxide supplies oxygen to burn the aluminum. The reaction is $2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$. The reaction is hot (~3000 K), and the reaction products are molten iron and molten aluminum oxide. A thermite fire is difficult to stop. It is dangerous to douse one with water because the heat of the thermite fire turns the water to steam almost explosively. The expansion of the steam scatters the burning thermite and its molten reactants.

To obtain a thermite reaction, a mixture of 74.7% iron oxide and 25.3% aluminum (approximately a 3 to one ratio by weight, with iron oxide being the principal constituent) must be finely ground and thoroughly mixed. If the reactants are in different proportions, the burning reaction is adversely affected because only some of the material will burn and

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[32] Shuttle Flight Operations Manual, Vol. 8B, NASA Document JSC-12770.

the remaining material will act to cool the fire perhaps to the point of preventing sustained burning.

In the Hindenburg paint, both the application and the proportions of iron oxide and aluminum are inappropriate for thermite. According to numbers supplied by Bain [p. 169, footnote 3], the ratios by weight are 25% iron oxide and 75% aluminum, which is far from the required ratio given above, i.e., the coats of paint contained, by weight, about 10 times too little iron oxide. The fact that the constituents were mixed in a paint binder is also a problem because the paint gets in the way of chemical union of the iron oxide and the aluminum by acting to keep the particles apart. Also, the iron oxide was applied to the fabric as a first coat and the aluminum bearing paint was applied in separate coats, so the constituents were not mixed. Finally, the iron oxide paint was put only on the topside of the Hindenburg, and there is no noticeable demarcation line between the burning of the upper half (which is claimed to be thermite) and the lower half.

The proportion of each constituent is a more serious problem for the IPT. If, somehow, all of the iron oxide were somehow consumed in a thermite reaction, only about 10% of the adjacent aluminum powder would be involved. The volume of thermite reactants is such a minor part of the total volume of the paint that it would appear that a thermite reaction could not proceed — the reactants are too dilute. The effect of dilution is as if small amounts of hydrogen and oxygen gases were mixed in 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.

ACKNOWLEDGEMENTS

I wish to thank Mr. David Ricks, Manager, Reusable SRM Propellant Subsystem, NASA Marshall Space Flight Center, Huntsville, AL, from whom I obtained needed information and assistance regarding the burning of solid rocket fuel and the specific characteristics of the Space Shuttle SRB propellant. Also, I am grateful to Prof. Philip Krider, Dept. of Atmospheric Science, Univ. of Arizona, and to Dr. V. M. Vasyliunas, Director Max Plank Institute, Lindau, Germany for their help with the electrical calculations in Appendices A and B, Mr. Alan Sherwood, Senior Structural Engineer, Aerospace Technologies of Australia, Ltd. helped with analysis and suggestions on the aerodynamic effect of an updraft. I obtained useful advice and comments from Mr. Rick Zitarosa, Prof. D. M. Hunten, Univ. of Arizona, and Prof. F. C. Michel, Rice Univ. Finally, I thank Mr. Don Overs for his persistence in encouraging me to finish this paper and for his many very helpful comments and suggestions.

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