Afterglow of a Myth

Why and how the "Hindenburg" burnt

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Abstract

The outbreak of the fire which destroyed the dirigible LZ 129 "Hindenburg" in Lakehurst 1937 had nothing to do with the hydrogen gas of which great amounts were on board to provide buoyancy. The reasons were the chemical and electrical properties of the paint of the outer shell in connection with the particular meteorological conditions prevailing in Lakehurst on the day of the accident.

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Introduction

"Titanic" — "Hindenburg" — "Challenger": the message these names convey to modern man is similar to what the name "Ikarus" meant for the ancient Greeks. In
every case we were alerted to the dangers man is exposed to when he steps beyond his natural limits by means of technology. Of course, we still proceed beyond them; today's ends include the trip to Mars and genetic research. But the warnings remain.

While the "Challenger" accident has been investigated thoroughly, the other two were until recently still partly mysterious, a fact which makes things even more interesting. The first "Titanic" movie was, after all, produced in Berlin just two months after the event, and it was not the last. Similarly, the "Hindenburg" burnt many times on the movie screens and in the minds of researchers.

What we publish here on the basis of new and newly found facts are background and proceedings of the "Hindenburg" accident. The main result is that, contrary to commonly accepted wisdom, not the hydrogen filling of the airship was responsible, but the paint of its outer shell. An airship filled with Helium would have burnt just as well.

These results might contribute to the healing of the so-called "Hindenburg Syndrome", a rather common but totally unjustified fear of hydrogen.

**Balloons and Zeppelins**

Man's dream of flying is age-old. It is reflected in the legend of Daedalus and Ikarus, which has its counterparts in numerous other cultures. In the 16th century Leonardo da Vinci made plans for flying machines, but he did not have the means to realize them. Two such means were then available in the 18th century: hot air and hydrogen, the latter since 1769.

On December 1st 1783, only 10 days after the hot air balloon of the Montgolfier brothers, the first manned hydrogen balloon started in Paris with Jacques Alexander Charles on board. In 1785 Jean-Pierre-François Blanchard crossed the Channel for the first time with such a device, carrying with him the first air mail in history. In 1793 at the latest the French revolutionary army had balloons for reconnaissance; it is said that they contributed decisively to their victory of Fleurus in that year.

Balloons, however, can only let themselves carry with the wind. They may change their altitude to find layers of the atmosphere with favorable wind conditions, but they have no active steering. Count Zeppelin was the first to develop dirigible airships of considerable size. They came together with the aircraft, but at this time the latter were no match in terms of size, comfort, and safety.

**Hydrogen and Helium**

When Count Zeppelin lived (1838-1917) there was no alternative to hydrogen. Hot air was good for balloons, but nor for large dirigibles. Hydrogen, after all, has a number of advantages:

- It produces more buoyancy than any other gas, and
- it can be produced in a comparatively simple and cheap way by various methods.
There remains one great disadvantage: hydrogen is flammable. (Not explosive — this is something quite different!)

There is one inert gas of a density comparable to that of hydrogen, namely helium. Its standard density is twice that of hydrogen, thus still far below that of air. However, the existence of Helium on earth was not known before 1895. For many years it was available only in small amounts in a few laboratories where it was guarded as a treasure.

During World War I Canada and the USA started with the industrial production of Helium from natural gas. Certain deposits contain up to 2 % of Helium, and the gas was to be used for observation and barrage balloons and dirigibles. Production was continued after the end of the war because the USA created a fleet of dirigibles for its army and navy during the 20s and 30s. Between 1919 and 1937 the army operated about 60 airships, the greatest fleet of the world. These ships, however, were "blimps", more or less balloons with a motor. The navy had four rigid airships of the Zeppelin type; one of them had been built by the Zeppelin works as a World War I reparation. There were no other technical applications for helium in a size worth mentioning at this time. This means that between the wars the Bureau of Mines, an agency of the US Department of the Interior, was the only helium producer in the world.

The course of the Zeppelin works between hydrogen and helium was anything but straight. LZ 127 "Graf Zeppelin" had started its operation in 1928. It was constructed in the conventional way, using hydrogen. The successor, LZ 128, was to be greater, but in principle similar.

But then, on 5. October 1930, the worst accident with British airships happened near Beauvais (Northern France). 48 of 54 persons on board of the ship R 101 died when the latter was driven against a hill chain by bad weather and caught fire. The British aviation secretary was on board, and so were many high-ranking government representatives from India and Australia who were travelling to an Empire conference in India. This was the end of British dirigibles.

The Zeppelin works reacted by deciding to change from hydrogen to helium as lift gas. Due to helium's lesser buoyancy such a ship would have to be much greater than LZ 127. In order to limit the size increase and also the cost increase, helium being very expensive, it was intended to carry hydrogen gas in separate cells within the helium cells. This hydrogen gas could be vented when the crew wanted to make the ship heavier. The hydrogen cells were to have a volume of 73,000 m$^3$, while the total amount of gas was to be 200,000 m$^3$. Planning for LZ 128 was officially stopped, and the helium dirigible was designed under the serial number LZ 129. Many important things, however, were adopted from the plans for LZ 128.

Politics, however, undid these plans. There was only one place on earth in the 30s where there was enough helium for such plans, and this was the USA. The US Helium Act of 1925, however, allowed the bulk use of helium only for US government use. So the decision was inevitable to fill LZ 129 with hydrogen, as its predecessors.
In September 1937, after the "Hindenburg" accident, the US law was changed, and the commercial sale to outside parties became allowed. Germany immediately placed an order for 500,000 m$^3$ [18 million cubic feet]. After much administrative hassle the sale was denied because of the political development in Europe.

The dirigible LZ 129 "Hindenburg"

The manufacture of LZ 129 started in autumn 1931 at Friedrichshafen and lasted until the spring of 1936 (Fig. 1). It remained the greatest man-made flying object until today (January 2000). A few technical data:

- Length: 245 m [804 ft]
- Maximum Diameter: 41.2 m [135 ft]
- Gas content at tautness: 200,000 m$^3 = 18$ t hydrogen gas in 16 cells
- Empty weight: 118 t
- Service weight: 220 t
- Crew: 50 persons
- Payload: 50 passengers (later increased to 72), 11t freight, mail and luggage
- Permanent velocity: 120 km/h [75 mi/h] against ambient air
• Propulsion: 4 propellers with diesel engines at 1000 PS and 1400 rotations per minute each
• Fuel: 88 m³ Diesel in barrels, additional 4500 l lubricant in barrels
• Ballast: 40 m³ water in 23 containers

The official descriptions gives the following details about the outer shroud of the ship fuselage and the aerodynamic surfaces: "They are made of heavy and light cotton and of heavy and light linen, depending on the demand. ... The impregnation consists of five layers of a cellon paint with aluminium added, the basic layer consists iron oxide." (Fig. 2; this is a detail which will turn out to be of crucial importance further down.)

The gas cells consisted of two layers of fabric with a celluloid film sandwiched in between. Then several coats of a gelatin and latex mix were applied. The permeation was given as 1 l per m² and day.

Passengers paid 400 $ for a single ride and 720 $ for a return ride over the Atlantic; multiply the figures by 10 to get a rough idea of today's value. They were certainly entitled to demand something from the equipment of the cabins and the other rooms on board — and they got it. LZ 129 was a flying luxury hotel (Fig. 3). The crew comprised five cooks (!), nine stewards, and a physician. The sleeping cabins were small and expedient, but of first class workmanship and with ultramodern equipment, for example plastic (!) washing basins which could be tipped up after use. Leading interior decorators and designers from the Bauhaus tradition took part in the work even though this school was in deepest disgrace with the national socialistic government. Specially made tablecloth, napkins, cutlery, and china were used in the dining room, there was a piano (made of aluminium) and — believe it or not — even a smoking room: "It is accessible via a revolving door, and use is permitted under constant supervision of a crew member below tautness height."

LZ 129 was given the name of the late German president Paul von Hindenburg, who had died in 1934. After completion of the ship in the beginning of 1936 she made a great number of test rides; on 19. March she was approved for passenger service by the air vehicle test office of the State Aviation Ministry. In the further course of this year until December she made 55 rides over 300.000 km [186.000 mi], crossed the
north or south Atlantic 34 times, carried 2800 passengers and 170 t cargo, and all this without incidents. Before resumption of operation in March 1937 she was examined anew by the test office, and the approval was renewed.

Her longest trip was Frankfurt am Main — Rio de Janeiro on 21. - 25. October 1936 with 11.278 km [7010 mi], the fastest Lakehurst — Frankfurt am Main on 10. and 11. August 1936 with an average speed of 157 km/h [98 mi/h]. Additionally she made propaganda trips to the Olympic Games 1936 in Berlin (together with LZ 127 "Graf Zeppelin") or to the convention of the Nazi party in Nuremberg 1936. During a test in March 1937 the famous pilot Udet tried to dock on the ship with an aircraft.

The Lakehurst accident
The 63rd and last ride of LZ 129 from Frankfurt am Main to Lakehurst began on 3. May 1937 at 20.16 h German local time. 61 crew members were on board, but only 36 passengers, plus 108 kg mail, 148 kg cargo and 879 kg luggage and two baskets with dogs. While the outbound ride was thus only half-booked, all places were sold for the return ride; many had been reserved by Americans who wanted to be in London on 12. May to attend the coronation of King George VI.

The ride took 77 hours and 8 minutes and was 7150 km [4440 mi] long. Of 50,5 t Diesel 42 were consumed until arrival at Lakehurst, 1000 of 4000 kg lubricant, and 21,9 of 40 t water ballast.

The ride prior to the arrival at Lakehurst was uneventful. The route went from Frankfurt am Main over Cologne (mail dropped), the Netherlands, the coast at Vlissingen, to the English coast at Dungeness and further along the Channel. On 4. May at about 08:00 hours the European continent was left with direction North America. The next day at this hour approximately half of the trip was done. Heavy rain, bad sight, and icing delayed the progress, however. The ship was delayed when it reached the
shores of Nova Scotia on the morning of 6. May. In the afternoon around 14:00 hours local time it made a few turns over New York in good weather.

Lakehurst was reached at approximately 15:00, but the landing was not possible at this time because of a wide squall line approaching from the West. So LZ 129 went up and down the coast, first northwards and then southwards, waiting for the weather to improve.

Between 15:30 and 16:30 hours a thunderstorm came down at Lakehurst. Not long after 17:00 LZ 129 was notified that the landing was now possible. About at 18:00 the ship reached the landing field again.

The first approach to the landing site was from WSW with a height of 200 m [650 ft], cloud height 600 to 900 m [2000 to 3000 ft]), 16 °C [61 °F], 98 % relative humidity, rain, and light, rapidly changing wind. Due to the wind conditions, which had changed again, the ship made a wide curve and approached the anchoring mast from north. The usual maneuvers followed: venting gas, dropping ballast, trimming. Then the landing ropes for the ground crew were dropped from a height of 60 m [200 ft]. This way to land, where the ship was pulled to ground from low height, was a specialty of the US Navy. In Germany it was usual to drive the ship right down to height zero.

The actual accident is well documented by newsreels and photos so that even after 60 years it can be described very accurately. About four minutes after the dropping of the first landing ropes, at 18:25 hours local time, a fire broke out on the rear of the left side of the ship, not far away from the fin, near the top. Crew members in the ship saw a reddish fire glow. The fire spread rapidly, burning downwards as well.

The pressure in the lift cells near the fire site rose due to the heat. Once exposed to the flame, one or two of them burst, and the hydrogen escaping under pressure created a thrust. The ship made a "jump" forward. This sudden movement loosened two waste water containers in the front part so that they fell down (Fig. 4). Remarkably, the ship had remained trim (horizontal) up to this moment. Now, however, it became tail-heavy due to the loss of ballast at the front and of lift gas at the rear. The fire could spread even quicker now that the nose pointed upwards, while the persons in the front part of the ship now had a lesser chance to survive.
About half a minute after the outbreak of the fire LZ 129 crashed tail first on the ground (Fig. 5). The US Navy ground crew and also the ship crew, as far as they still could, saved many people from the flames under risk of their own life. Waiting passengers, journalists and other persons present did the same. They could not prevent, however, that 22 of 61 crew members, 13 of 36 passengers and one member of the ground crew died. Many survivors were badly burnt.

Even though popular descriptions of the accident mention an explosion, nothing like this happened. An explosion is defined as the fast chemical reaction between a flammable gas (like hydrogen) and an oxygen carrier (like air) which generates a pressure wave. Nobody on board or on ground would have survived such an event, including the many photo and radio reporters who made the accident a media spectacle. The dirigible burnt. The fire of the hydrogen from the gas cells lasted only less than one minute, and there is no evidence that anybody was directly hurt by it. The fatalities were rather from exposure to burning or falling parts of the ship; smoke poisoning or asphyxiation certainly played also a role. The Diesel fuel for the engines kept burning for hours (Fig. 6).

**Public opinion, published opinion, and facts**

Immediately after the accident both the US and the German government created an investigation committee each. They jointly reviewed the available documents, testimonies, photos and movies and investigated the site of the accident. The German side made additional experiments in the laboratories of the German Research Institute for Aviation in Berlin and of the Zeppelin works in Friedrichshafen to further clarify the event. No clues were found for technical defects, human failure or an attack from inside (bomb with time fuse) or outside (shooting).

Both reports concluded that a flammable hydrogen/air mixture under the cover of the dirigible had formed and then ignited. The fire had first been observed in the vicinity of the gas cells 4 and 5 (the cells were counted from the back); so a leak was assumed in one of these two cells, but a specific reason could not be given. There were speculations about the whiplike action of a broken tension wire. At no point during the whole investigation, however, was there any positive proof or hint to such an event.
Captain Pruss stated in his testimony that there were no hints for gas loss that could be noticed in the Cockpit. The same statement came from crew members who had been at different places in the ship. Most important is that nobody testified to have smelt garlic. The hydrogen was odorized to permit early perception of leaks. The assumption of the investigation committees that there had been a leak was therefore based only on the undeniable fact that there had been a fire.

As reason for the ignition potential differences were assumed which existed between the ship and the ground. When the landing ropes were dropped, they became wet in the rain and formed a conductive connection between ground and ship. While the metal skeleton now was on the same potential as the ground, this was not true for the outer cover which had a lesser electrical conductivity, so that an electric voltage between these two arose, finally producing an electrical discharge. This fitted well with the testimonies of eyewitnesses who had observed something like a St. Elmo's fire for quite a while shortly before the fire broke out. A final explanation could not be given; the means to prove something were mainly destroyed, after all.

Such a situation is a marvelous fertile soil for speculations of all kind. The sabotage hypothesis in all possible variations was evoked again and again down to the recent past without convincing clues. Even Aviation Minister Goering believed in it, at least initially.

It must be admitted, however, that even the reports did not say everything the investigators knew. This is especially true for the German report. As a matter of fact the reasons were perfectly clear within weeks. That reason, however, was found in the way LZ 129 was made, and so nothing was published. It was considered as undesirable to confess to the world that a measure of German engineers was responsible for the doom of a showpiece of the Third Empire.

From this time on until recently it was accepted as fact that the hydrogen on board of the Zeppelin had been the fundamental reason for the accident. There was a hydrogen fear not justified by the facts and completely out of proportion, a state of mind commonly called "Hindenburg Syndrome". Until recently it blocked many efforts to introduce hydrogen as sustainable and environmentally benign energy carrier which could replace coal and oil.

A few question marks remain

It appears easy to explain a fire when a gas which forms easily flammable mixtures with air is around in huge amounts. Careful examination of the proofs, however, shows that there are still a few things not so easily explained and open questions. The mere combustion of the hydrogen appeared to be not the final answer to all questions.

- A mixture of hydrogen and air burns explosively. An ignition of it under the cover would probably have destroyed the latter instantaneously, and also the lift cells in the vicinity. The fire that consumed LZ 129, however, lasted about one minute be-
fore the ship crashed on the ground, and the ship remained horizontal for a great part of the time.

- All eyewitnesses and the photographic evidence show that the fire burnt with a very bright flame. It was compared to a bonfire (Fig. 7). A hydrogen fire, however, emits light mainly in near UV around 310 nm, thus outside the visible range. The flame is almost invisible under daylight conditions. During the start of a Space Shuttle the observer sees a great flame from the auxiliary rockets, but almost nothing between them where the hydrogen from the additional tank burns (Fig. 8).

- The fire burnt also downwards from the very beginning. The density of hydrogen is only 1/14 of that of air, so that a hydrogen fire would have burnt upwards only.

So the possibility had to be taken into account that the hydrogen had not at all been the starting point of the fire. Back in 1937 during the initial investigation one member of the German investigation committee, Prof. Max Dieckmann, had thought a lot about the electric properties of the paint of the outer cover. This paint was a new development for LZ 129. It had not been used on other airships, and apparently its electric properties were not too well known either.

After his return from Lakehurst to Germany Dieckmann got himself original samples of the outer shell of the "Hindenburg" as well as of the "Graf Zeppelin" and made experiments with wet cloth, a metallic counterelectrode, a hydrogen/air mixture, and an electric field to simulate the conditions during the ill-fated landing at Lakehurst. During the experiments with the "Hindenburg" cover he regularly produced a spark which
ignited the gas mixture. This result was included in the report of the investigation committee to provide an explanation for the origin of the energy which ignited the hypothetical gas/air mixture. But an important result was not communicated: there was not a single ignition during the same experiments with the cover of the "Graf Zeppelin"! This was not stated in any other German publication either, but the only place where this was mentioned was a note added to the American translation of a paper by Dieckmann. The translator had his knowledge from persons who had visited Dieckmann in Berlin during his experiments and who remained unnamed.

The role of the paint thus unsettled, why did everybody assume as given that hydrogen was guilty? This was what the former NASA member Addison Bain could not understand either. He had been involved in hydrogen for about 30 years, in particular with safety matters. After a while he made up his mind to go to the bottom of the matter. He dug himself through museums and archives, in particular that of the Zeppelin Museum at Friedrichshafen (Germany), asked many eyewitnesses, begged for still existing pieces of the cover and made use of his excellent connections to research laboratories at NASA and elsewhere.

**A flying match known as "Hindenburg"**

The search through the papers and the results of the investigation of the samples lead to the conclusion that the paint of the outer cover was a highly flammable mixture. The first layer contained iron oxide. Then followed five layers of cellulose butyrate acetate with aluminium powder added. The paint had a number of functions: protection from moisture, protection from rot, tautening of the cover, reflection of sunlight. An additional property of it had apparently been remained unnoticed given the knowledge of this time: this mixture burns extremely easily. Experiments with samples were impressive. As a matter of fact, the fuel of solid fuel rockets (like the Shuttle boosters) has a very similar composition. LZ 129 was literally painted with rocket fuel. The combination of aluminium, iron, and oxygen can start an aluminothermic reaction if enough ignition energy is provided. Such a fire produces extremely high temperatures and can not be extinguished.

Additionally, the paint had a low electric conductivity which made it difficult to even out existing electrical potential differences. This had been the reason for the results of the Dieckmann experiments mentioned above. The joining of the different pieces of the cover had been done in a technique which did not create conductive transitions either.

Finally, the connection between the outer shroud and the aluminium structural frame was not very conductive. Ropes made of ramie fibers were used, which have many useful properties, but they are poor conductors. Potential differences between shroud and frame could be maintained for quite a while this way.

The Zeppelins were not the only who were worried about the paint. The British ships as well were covered with iron oxide and several layers of cellulose nitrate with pow-
dered aluminium. How exactly this contributed to the accident of the ship R-101 can no longer be clarified. The US ships as well were painted similarly.

What happened really?
When the ship approached the Lakehurst landing site there was still a thunderstorm weather situation. Witnesses report that lightning could be seen at the horizon. The ship had assumed the electrical potential of the atmospheric layers it came from, and this was significantly different from that of the ground, as it is typical for a thunderstorm. There was an electrical voltage between ship and ground.

When the manila landing ropes were dropped, they got wet in the rain and created a conductive connection between the frame they were anchored to and the ground. These two were now on the same potential, but not the outer shroud. The voltage which had previously been between ship and ground was now between frame and shroud.

This situation was by no means new for a Zeppelin airship. LZ 127 "Graf Zeppelin" had done scheduled service over the north and south Atlantic for years, experiencing storms and thunderstorms, and there had never been an accident. In the case of the "Hindenburg", however, the novel construction elements now proved to be fatal.

It can not be said with final certainty where and how exactly the fire started. The most likely process is this: Since also parts of the poorly conductive shroud could be on different potentials relative to each other, there was a tension between them which created an electrostatic discharge setting the shroud on fire. High voltage are preferably between protruding parts of an object, and as a matter of fact the fire started near the fins.

It is also possible that the potential difference between shroud and frame tried to equalize. The only way to do this was a current through the dry ramie cords connecting them. The latter might have been heated due to their poor conductivity and could have caught fire.

Once the fire had started there was no way to save the ship. Of course, during the accident also the hydrogen in the lift cells burnt, but this contributed very little to the accident. If the ship had been filled with helium the incident would not have been very different if the construction of the outer shroud would have been the same.

The secret which wasn't any
The reasons for the Lakehurst accident are still occasionally presented as mysterious, and they may have been to the general public because important facts were withheld from it. The Zeppelin works, however, knew very soon what had happened. The Dieckmann experiments had already shown where to look for the reasons. The official report gave only half of the truth, but the full truth was certainly known at Friedrichshafen. This is evident from two letters in the archives which were written by an electrical engineer named Otto Beyersdorff, who was involved in the investigation.
He described the result like this: "The actual cause of the fire was the extremely easy flammability of the covering material brought about by the discharges of an electrostatic nature." He further states that in laboratory tests the material proved to be easy to inflame.

The Zeppelin engineers reacted quickly to the accident. This is evident from the construction of the dirigible LZ 130 "Graf Zeppelin II" which was being built then. Above all, the composition of the paint was changed. Calcium sulfamate was added, a substance which was then generally used by the textile industry for fireproof impregnation. Then the aluminium was replaced by powdered bronze, which is heavier, but not flammable and even more conductive. The ropes connecting the shroud with the frame were treated with graphite to make them conductive. It is obvious that exactly those constructive features were changed in 1937 which according to today's knowledge had been responsible for the doom of the "Hindenburg".

Why neither the Zeppelin works nor the German government ever published a word about the causes of the accident though they knew them well can only be guessed. As a matter of fact even Zeppelin chairman Hugo Eckener took part in the condemnation of the hydrogen. It is very likely that the reasons were political in nature. Presumably the Third Empire feared the public blame.

Another speculation is that the cover-up was done to fraud the insurance. The ship was property of Deutsche Zeppelin-Reederei GmbH; the assets of this company were essentially its ships. The "Hindenburg" was insured for 6 Million Reichsmark, and this sum was paid in full. Passengers and crew were also insured against loss of life or invalidity. It is difficult to say how the insurance company would have reacted if the suspicion of at least partial responsibility of the Zeppelin works would have existed.

**Hydrogen: not guilty!**

The facts presented here show that the presence of hydrogen in the lift cells was not the starting point in the fire of LZ 129, and that it did not contribute too much to the further course of the accident either. A dirigible with helium lift cells would have burnt just as well. The role of hydrogen was negligible. That hydrogen was the culprit is probably a pretext, in any case a myth, and one very difficult to get rid of.

The safety record of the Zeppelin dirigibles as a whole is very favorable. In the whole commercial German airship operation from before World War I until 1937 there was not a single incident with fatalities. There was one indeed with the British dirigible R 101 in 1930, but which role exactly the hydrogen played in it is not known. It is a fact, however, that the paint of the shroud of this ship was very similar to that of the "Hindenburg" and that this had worried the designers well before the Lakehurst accident. It was similar in the USA. The US navy, on the other hand, had many fatalities when it lost two airships due to bad weather in 1933 and 1935 — and these dirigibles were filled with helium! (The operation of dirigibles was, after all, the reason why the USA
produced and stored Helium.) Hydrogen or not hydrogen is obviously not the ques-
tion when it comes to the safety of airship operation.

Lakehurst is frequently presented as the flaming end of the airship era, because after
the accident there was no more commercial operation of dirigibles in Germany, and
neither elsewhere. LZ 127 remained grounded by order of Aviation Minister Goering.
There were desperate attempts to procure helium, but without success. LZ 130 was
designed for hydrogen, like LZ 129, but with the changes mentioned above. She was
completed and entered the test program, but was never used commercially.

The era of dirigibles, however, was over anyway. From the military point of view the
Zeppelins were totally useless. Consequently Goering had the Zeppelin installations
on Frankfurt airport destroyed in 1940. The aluminium frames of the remaining ships
were melted down and used for armament production. The aircraft development was
already that far that they would have replaced the airship in the commercial sector as
well very soon, anyway.

Today's knowledge about chemical safety engineering and plant engineering could
have prevented the accident, but not the knowledge of then. The Zeppelin dirigibles
were a spectacular piece of high-tech for its time, and even the fatal paint was the
product of much thinking and experience. Synthetical fibers whose properties can be
tailored to size did not exist, after all. The achievement as a whole which was em-
bodyed by the Zeppelin airships is in no way decreased by the results presented
here.

How dangerous is hydrogen?

For today's reader the discussion of the safety or unsafety of dirigibles of the 30s
may appear rather academical. However, the question comes up with great regularity
whenever the use of hydrogen as energy carrier is discussed. It could well replace
fossil fuels like coal, oil or natural gas, and together with electricity it could be a tool
for marketing renewable and sustainable primary energies. This works only, how-
ever, if its use is not associated with undue risks.

Hydrogen under normal conditions is a gas without characteristic color or smell. Both
the atom and the molecule (H$_2$) are very small and light. Hydrogen thus has a very
low density and disperses quickly by buoyancy, convection, and diffusion. For stor-
age and transport purposes it is frequently converted to a liquid by cooling it to 20 K.

Hydrogen is flammable, and it forms explosive mixtures with air. As far as the flam-
mability is concerned it does not differ significantly from other energy carriers as
natural gas. As a general rule, hydrogen and natural gas are rather similar in their
safety relevant as well as in their other properties. There are a number of risks that
are not associated with hydrogen; it is for example neither toxic nor corrosive.

The basic statement about the safety of hydrogen is that its use is not associated
with greater problems than that of the energy carriers everybody is used to (oil, natu-
ral gas, coal, propane, etc.). Neither are the risks associated with it any greater. The
The chemical industry is using hydrogen in large amounts for a century now, and no fundamental safety problems have been found. The town gas which was present in our houses until not so long ago before it was succeeded by natural gas consisted of about 62 energy carrier is investigated in various pilot applications and demonstration projects both for mobile and stationary applications. Safety is a regular part of all of them. Extensive experiments and studies have shown that hydrogen may even offer safety advantages, especially in accidents or in dangerous situations. Some reasons for this are:

- Hydrogen is stored in pressure vessels. These are much more resistant against mechanical damage than oil or gasoline tanks. This is true for liquefied hydrogen as well. In this case the vessels are double-walled to make the thermal insulation possible.

- If hydrogen escapes from a damaged tank, valve, or pipe, it will because of its low density move upwards, which is away from most ignition sources. Natural gas raises slower, LPG remains near the ground, and liquids raise not at all. The latter can also pollute the soil and the ground or surface water, something which can not happen with gases.

- If escaped hydrogen is ignited, it burns away rapidly. Pools of liquid fuel can burn for a long time.

- Hydrogen burns without producing harmful substances. Only water is produced.
Hydrogen flames radiate much less heat than the flames of carbon containing substances.

These statements were confirmed experimentally on many occasions. In the framework of the Euro-Québec Hydro-Hydrogen Pilot Project (EQHPP) the Federal Institute for Materials Research and Testing (BAM) made spill experiments in an abandoned barrack ground near the village of Drachhausen (about halfway between Berlin and Dresden). Liquid hydrogen and liquid propane were released to study their evaporation and dispersion. The statements made above about the dispersion of accidentally released hydrogen and propane clouds were confirmed. Figures 9 to 12 show the release of propane and hydrogen from the liquid phase between buildings during experiments of BAM in the framework of the EQHPP project. The different behavior of the gases is obvious: while the propane cloud remains near the ground, the hydrogen cloud rises. (Neither gas is visible; the white cloud of condensed water gives a rough idea of the domain of an explosive mixture.)

In another context liquid hydrogen tanks for cars were subjected to experiments which included a fire test or the impact of a big concrete weight. These tests as well confirmed the high level of safety of hydrogen technology. Experiences from actual accidents confirms this. And finally, there are many theoretical studies of this subject.

It goes without saying that the use of hydrogen requires due care. This is a property of all energy carriers, however.
This there is neither reason for unreasonable anguish nor for extreme caution when hydrogen is handled. The properties of hydrogen do not justify this, and neither does the "Hindenburg" accident, as it has been shown here.

References

- "What really downed the Hindenburg?", *Popular Science*, November 1997
- R. G. van Treuren: "Odorless, Colorless, Blameless", *Air & Space* April/May 1997
- "Der Absturz des Zeppelins Hindenburg — Neue Enthüllungen nach sechzig Jahren", Panorama (German TV, 1st channel) of 24. April 1997 (see text under http://www.ndrtv.de/panorama/archiv/19970424.html)

Internet Links

- [Zeppelin Museum Friedrichshafen](http://www.zeppelin-museum.de): exhibitions, events, library, archives
- Zeppelin Museum Zeppelinheim (near Frankfurt airport)
- Hindenburg (various)
- Zeppelin Documentaries
- Navy Lakehurst Historical Society (who would know Lakehurst if not ...?)
- Airships (not only, but particularly for philatelists)
- Vidicom (commercial video)

Picture credits

Fig. 1 to 3: Archives of Luftschiffbau Zeppelin GmbH, Friedrichshafen, Germany
The authors

- **Addison Bain**: Dr. Bain started his career in the Space Program in 1959. While working for NASA he designed the hydrogen equipment and wrote operating procedures and hydrogen safety manuals. He is a founding member of the International Association for Hydrogen Energy, National Hydrogen Association and of the ISO Technical Committee 197 "Hydrogen Technologies" and served on the first panel of the US Department of Energy's Hydrogen Technical Advisory Panel.

His interest in the Hindenburg disaster was spawned many years ago in his dealings with hydrogen issues and projects. Over time he realized the inconsistencies about the event as published in many articles, books, and movies. Studying original film footage of the historical event and information in a number of archives, he realized perhaps the role hydrogen played was suspect. He spent considerable time traveling, meeting with various experts, eye witnesses, and performing laboratory experiments. Unpublished information eventually collaborated his suspicions that the dopant process used to protect the outer envelope of the Hindenburg was the major flaw.

- **Ulrich Schmidtchen**: born 1956 in Berlin, study of physics at the Free University of Berlin. Since 1986 scientific member of the Federal Institute for Materials Research and Testing (BAM) in Berlin as expert for the safe handling of compressed gases. Special topic: safety of hydrogen technology. Participant in various studies and experimental programs about this topic (EQHHPP, Cryoplane) as well as in a number of standardization and regulation committees in this field. Member of the board of the German Hydrogen Association (DWV).