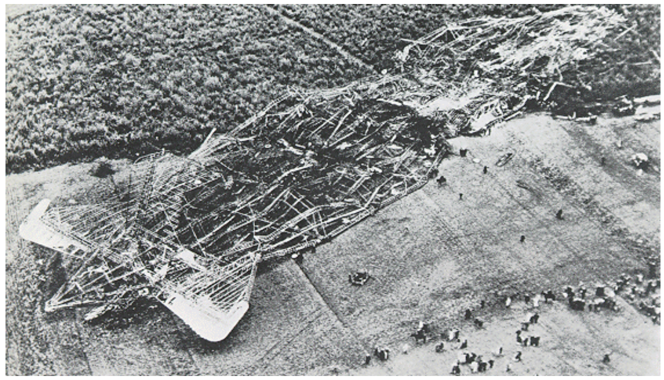
National Aeronautics and Space Administration

System Failure Case Studies

APRIL 2007 Volume 1 Issue 6

INNOVATION PUSHED TOO FAR TOO FAST

The R101 Airship story is one of political leadership spurring investment in new technology, but at the same time driving that new technology to a premature implementation and subsequent disaster. The maiden voyage of British-built airship R101 in October of 1930 ended in a fiery crash that killed 48 people when bad weather forced the massive airship down over Beauvais, France.



The charred remains of R101 near Beauvais, France.

BACKGROUND

An Imperial Lighter-Than-Air Route

The golden age of lighter-than-air vehicle aviation peaked just after World War I, extending into the mid 1930s. Though not useful in combat situations, airships proved to be quite useful for long-range reconnaissance, and, later, as luxury commercial transportation in Europe and the U.S.

The Imperial Airship Scheme was launched in 1924, designed to link Britain with Australia, Canada, South Africa, and India by means of six rigid airships in commercial service along an Imperial Air-Route. To encourage innovation, the British government commissioned two prototypes. One airship (R100) would be built by Vickers Ltd., a private contractor, and the other (R101) by the Royal Airship Works in Cardington, England. R100 was designed using proven techniques and had a successful round trip to Canada in July of 1930. Meanwhile, the builders of R101 moved away from traditional airship designs, incorporating many new technologies.

R101 was approved in 1924 with great expectations for a commercially operational vehicle by 1926. Design stretched into 1927 with escalating costs as well as pressure from the skeptical press and impatient Parliament to demonstrate results.

Flight testing began in late 1929, with the first "operational flight" delayed until October of 1930. Several prominent British officials had staked their reputations on the success of the R101, including Secretary of State for Air, Lord Thomson of Cardington, and Sir Sefton Brancker, the Director of Civil Aviation, who were to be passengers on the maiden voyage.

Innovation and Technology Risk

The R101 design team set out to push the envelope of technology in many ways: by employing diesel engine technology for the first time in a rigid airship; using steel for the first time in airship rib structures; employing newly designed pressure valves on the flotation bags; implementing (unsuccessfully, in that it was not incorporated into the test flights) innovations in outer skin manufacturing; and unsuccessfully attempting to develop and implement hollow metal reversible propeller blades.

WHAT SHOULD HAVE HAPPENED?

The nominal R101 mission was to depart from Cardington on October 4, 1930, climbing to a cruising

In October of 1930, the R101 crashed, killing 48 people.

Proximate Cause:

- Loss of forward buoyancy, due to weather-induced damage, causing the nose to pitch down violently
- Hot engine contacting extremely combustible hydrogen gas leaking from airship

Underlying Issues:

- Time and development pressures
- Off-nominal weather conditions
- Ignored stand down call
- Fundamental buoyancy and control issues

altitude of 1,500 feet, for a luxurious, amenity-laden, steamship-like trip to Karachi, India with a brief stop-over in Ismailia, Egypt to host an on-board diplomatic dinner. The R101 would then return to London no later than October 20.

WHAT HAPPENED?

The R101 left Cardington, England at 6:30 PM on the cold, rainy night of October 4, 1930 despite foreboding weather reports and under pressure from Lord Thomson. Weather conditions worsened as R101 navigated over northern France later that evening, but the crew responded by increasing altitude. Between 11 PM and 2 AM, the crew changed watches and sent out their final message, reporting that most of the passengers and some crew members had gone to bed.

At 2 AM, R101 flew over Beauvais, France, a mountainous area well known by aviators for its dangerous, gusting winds. Survivors recalled that during this phase of the journey the ship began to have trouble with the increasingly powerful winds.

A Steep Dive

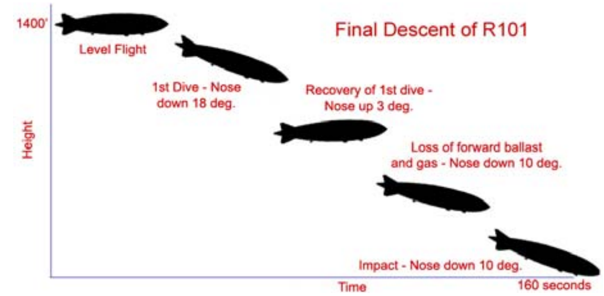
R101 then made a steep dive, causing many crew members to lose their balance and furniture to slide across the floor. The accident investigation suggests that severe weather caused a tear in the nose area, exposing a hydrogen envelope that rapidly deflated and started to accumulate rain water. The loss of hydrogen buoyancy combined with added weight of the rain-soaked nose section caused R101 to pitch down at an angle of 18 degrees for up to 90 seconds.

Failed Intervention

The crew pulled hard up, but was barely able to achieve a positive angle of 3 degrees above the horizon. The Captain ordered the engines slowed or fully stopped and emergency water ballast in the nose to be drained.

At an altitude of only 530 feet (R101 was 777 feet in length), the ship went into a second dive as the crew tried unsuccessfully to steady the ship. The Captain called for an emergency landing and sounded the bells to alert the passengers onboard. R101 impacted the ground at a relatively gentle 13.8 mph leaving a trench two feet deep and nine feet long where the nose touched down.

Survivors reported that there was no violent movement upon impact and that the ship bounced slightly and then leveled. The force of the crash twisted the starboard forward engine around on its struts, bringing it into contact with and igniting hydrogen from the ruptured forward envelope. Flames quickly engulfed the R101, killing 48 of the 54 passengers and crew aboard.



After the first dive, the R101 crew was able to regain control and steady the flight pattern. They were unable to do so after the second dive and crashed.

EVENT CHAIN/PROXIMATE CAUSES

Each of the two primary events, the crash and the fire, constitute distinct failures. The proximate cause of the crash was a loss of forward buoyancy due to weather-induced damage, which caused the nose to pitch down violently. It is believed that strong winds tore back the nose area's outer covering, exposing and rupturing the foremost gas bag. Rain accumulation in the damaged nose section further hindered the crew from correcting the nose-down pitch. Once on the ground, the proximate cause of the destruction of R101 was the fire caused when the hot diesel engine contacted extremely combustible hydrogen gas leaking from the airship's envelope.

UNDERLYING ISSUES

Time Pressure/Technology Risk

R101 is a classic schedule-driven technology disaster. The cumulative political pressure, attendant press coverage, and competition with the R100 team all brought pressure on the R101 design/build team to move forward without the necessary operational testing.

Weather Conditions

Weather has always been the bane of aviation and played a major role in the demise of the R101. Strong winds, heavy rain, possible downdrafts, and wind shear created a hostile operating environment (off nominal conditions) for which the R101 was unprepared. Effects of rain saturation were untested and unknown. Structural loading and response was unknown. Controllability operating limitations were unknown. The R101 literally "flew off the edge" of safety.

Unheeded Call to Stand Down

In July of 1930, concerned with leakage and buoyancy issues, Mr. F. McWade, Inspector in Charge of the Aeronautical Inspection Directorate at Cardington (the airworthiness certification official for the Air Ministry) sent a very strong letter to the Air Ministry in London advising the Ministry to revoke the temporary "Permit to Fly," and to refrain from issuance of further permits or certificates. The letter was never delivered to the most senior management and was discounted by middle managers.

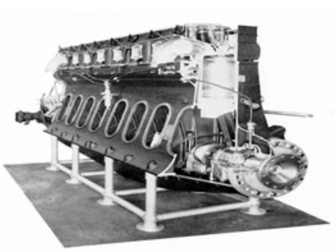
Additionally, the program manager (Director of Airship Development), Wing-Commander Colmore, was responsible for advising the Secretary of State on the safety of the vehicle, an inherent conflict of interest.

Buoyancy and Control Issues

The R101 had significant issues with buoyancy and control over its entire development spectrum:

- Overall lack of an appropriate systems engineering discipline in the design process, particularly in the improper management of buoyancy and control design margins and trade spaces, which was further exacerbated by the increased risks associate with the decision to simultaneously develop and use new technologies.
- Lack of proper design verification flight tests combined with the failure to couple design and flight test issues and communicate them to senior management.
- Poor operational decisions.

<u>Engine Selection and Design:</u> Whereas the R100 airship team experimented with and rejected diesel engines, the R101 team doggedly stuck with an intrinsically flawed diesel engine option, citing safety concerns, as diesel fuel is less volatile than gasoline. Ironically, the fuel safety hazard concern unwittingly introduced much greater safety risks which reduced flight safety margins for buoyancy and control.



A Beardmore engine replica.

The R101 engines were constructed by joining together two four-cylinder Beardmore diesel engines. This arrangement provided less power than anticipated (585 brake horsepower (bhp) actual vs. 700 bhp expected), and at 17 tons the five engines were 6 tons above the design weight. In addition, the diesel engine rotational frequencies (both idling and cruising) excited natural resonant vibrations in piping and structures, resulting in leaks and cracks.

In the end, the engines were underpowered, overweight, structurally unsound, and ironically required gasoline starter engines, reintroducing the gasoline safety hazard.

<u>Leaking Gas Envelope:</u> Driven by spiraling weight issues, R101 designers had to reduce the space (margin) between the internal gas bladders and the outer metal ribbing by allowing increased expansion and buoyancy. This complicated adjustment resulted in the bladders contacting the outer frame, introducing hundreds of small holes, even during minor roll conditions, causing a gradual reduction in buoyancy during flight. Though special pads were installed on the inside of the ribbing to minimize the recurrence of this problem, the potential for leakage remained an ongoing concern.

<u>Oversensitive Gas Valves:</u> Gas valves provide three functions; first, to protect against overexpansion of the gas bladder (opening at a pressure referred to as the pressure height), second, as a means to dump gas to reduce buoyancy during docking and close maneuvering operations, and third, as a stability balance control mechanism to counter roll conditions. The new-design valves proved to be oversensitive (opening in only a five-degree roll condition) and during severe buffeting in the stormy weather, opened and diminished the buoyancy when most critically needed. Between leak and valve problems it was estimated that R101 lost 22,588 cubic feet of gas every 24 hours!

<u>Aero Envelope Design:</u> The outer envelope of the R101 was designed with pressure equalization vents fore and aft to balance pressure as the airship climbed from sea level to its operating altitude. It is believed that the introduction of heavy rain into these vents resulted in an accelerating nose-down condition leading to the crash.

<u>Aero Envelope Fabric: Manufacturing Quality Control:</u> The R101's novel technique of doping the canvas membrane before stretching across the ribbing resulted in a brittle, crumbling skin that had to be stripped off and reinstalled using traditional methods. It has been suggested that not all of the faulty canvas was replaced at the very inaccessible top of the structure before the first flight, and that these areas leaked in the heavy rain.

<u>Operational Decisions: Inadequate Buoyancy Margin:</u> Even when fully filled with hydrogen, R101 provided just under 50 tons of "disposable lift" compared to the 60 tons for which it had been designed. In the end, operational decisions concerning use of the disposable load (manifest of passengers, luggage, carpeting, food, amenities, and fuel) created a very thin margin of safety, a result of a failure in design margin management.

<u>Inadequate Response to Flight Testing:</u> During a journey to participate in a Royal Air Force Air Display (air show) in June of 1930 (amidst flight testing), the R101 showed a disturbing propensity to enter steep nose down postures that were difficult to correct. In addition, test flight crews described her handling properties as heavy and sluggish. This is the point where flight test personnel and designers should have dug in their heels and called for a stand-down until weight, lift, control, and stability issues could be addressed via design verification flight testing.

<u>Summary:</u> Though aeronautical flight testing embraces the philosophy of gradual and incremental expansion of

the operational and/or environmental envelopes within controlled conditions, the R101, with unproven performance characteristics, took radical leaps in both operational and environmental conditions simultaneously with disastrous effect. Most significantly, this leap took place in the face of known problems related to control and stability.

AFTERMATH

The loss of the R101 put an end to Britain's lighter-than-air vehicle program. Although successful in flight, R100 was decommissioned and sold for scrap along with the wreckage of R101 in 1931. Even with the shift from explosive hydrogen to inert helium gas, civilian and military support shifted towards airplanes because they were faster, cheaper, more easily maneuverable, and less susceptible to bad weather.

APPLICABILITY TO NASA

The R-101 case study reflects the early aviation penchant for empirical experimentation with emerging technology, and a less-than-mature approach to design verification testing. Lessons learned from R101 include:

- The need to carefully evaluate technology readiness and ensure that sufficient testing is conducted before incorporation in a new design.
- Understanding the danger of introducing so many innovations at the same time.
- A reminder to embrace the philosophy of incremental change in safety-critical systems.
- The need to understand, evaluate, analyze, and act to correct off-nominal test or performance behavior within any aerospace system.
- The need to ensure that qualification testing reflects the full range of operating environments.
- The necessity to define specific meteorological operating constraints in the face of ever-present weather dangers.
- The need to perform proper systems engineering to continually couple/integrate design, test, and operational environments.
- The need to establish clear, technical and operational checks and balances in high risk developments.

References:

The Millionth Chance: The Story of R101, by Leasor, James, Reynal, and Company, New York, 1957.

When Technology Fails: Significant Technological Disasters, Accidents, and Failures of the Twentieth Century, by Neil Schlager (Editor), Nell Y. Schlager (Editor), Gale Group, New York, 1994.

Inviting Disaster: Lessons from the Edge of Technology, by James R. Chiles, Harper Business, New York, 2002.

Questions for Discussion

- How do safety and/or mission success concerns match up with schedule pressures on the program or project, in the office?
- Is there an aggressive curiosity to understand any off nominal test or performance outcomes within the program or project?
- Are safety-critical design margins clearly defined and have they been verified through testing?
- How can external factors (political, schedule, cost) exacerbate design problems?
- To what extent is the program or project relying on heritage hardware or software? How is usability determined?
- Have design weight budgets been met? traded for reduced margins? other impacts?
- Discuss program/project design decision tradeoffs that may have had collateral system effects (integrated hazards analysis)
- Is there adequate, independent access to upper management with safety concerns?

"Balloon Fabrics Made of Goldbeater's Skins," by Capt. L. Chollet, S.T.Ae., *L'Aeronautique*, August 1922.

"Airship, R101, and Breadmore Engine, " Wikipedia, the Free Encyclopedia. <http://en.wikipedia.org/wiki/Airship>

"R101 – The Final Trials and Loss of a Ship."Airship Heritage Trust. <http://www.aht.ndirect.co.uk/airships/r101/Crash/R101_Crash.htm>

Illustration of Dive and Ship Plan. [Online Image] Available. The Airship Heritage Trust. <http://www.aht.ndirect.co.uk/airships/r101/Crash>

R101 Wreckage. [Online Image] Available. <http://www.euro-tongil.org/swedish/english/er101.htm>

SYSTEM FAILURE CASE STUDIES
A product of the NASA Safety Center

Executive Editor: Steve Wander stephen.m.wander@nasa.gov

To view this document online and/or to find additional System Failure Case Studies, go to https://nsc.nasa.gov/SFCS

NASA SAFETY CENTER