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# TECHNICAL STUDY OF THE BAT WING SHIP (THE HORTEN HO 229 V3)

LAUREN HORELICK, MALCOLM COLLUM, PETER McELHINNEY, ANNA WEISS,  
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## ABSTRACT

This article describes a technical study of the Horten Ho 229 V3, a unique World War II, German plywood jet affectionately called the Bat Wing Ship. The aircraft has been in the collection of the Smithsonian National Air and Space Museum since 1952 and has never been exhibited due to its badly deteriorated plywood skin. The jet has been popular with enthusiasts who believe it to be the first stealth fighter because the jet's designer is reputed to have once said he added radar-absorbing charcoal to the plywood, though no tangible evidence exists to support or refute this claim. Plans to move the fragile jet from storage for display provided an opportunity for a technical study to characterize its original, historic materials, to inform treatment approaches, and to clarify the historical record about the presence of "stealth materials." This article describes the characterization of the jet's wooden components, adhesives, paint layers, and inclusions within the adhesives by Raman and infrared spectroscopies, X-ray fluorescence spectrometry, polarized light microscopy, and X-ray diffraction. Findings were compared with historical accounts of WWII era experimental aircraft construction materials and techniques.

## 1. INTRODUCTION

The Bat Wing Ship is a one-of-a-kind German jet-powered aircraft that was built during World War II and now is part of the Smithsonian's National Air and Space Museum (NASM) collection (fig. 1). The aircraft is also known as the Gotha Go 229 and the Horten H IX V3 (described as the Horten in this article). The Horten is an experimental prototype designed by brothers Reimar and Walter Horten in 1945, and built by the *Gothaer Waggonfabrik* workshop (referred to as *Gotha* throughout). The designation "V3" relates to the version number of this particular airframe design. The Horten brothers had designed and built a V1 and V2, but both crashed catastrophically during test flights. They were in the middle of production of the V3 in 1945 when the Allies invaded Germany and found the *Gotha* workshop where the body of the jet was nearly complete. The wings were recovered from a different location. With twin jet engines, a plywood skin, and tubular steel framework, the Horten possesses an unconventional combination of the most advanced technologies of the time, paired with traditional materials. American and British journalists embedded with the Allied troops called the newly discovered and incomplete jet the "Nazi Bat Wing Ship" for its unique tailless (or all-wing) design for which the Horten brothers are known. The nickname Bat Wing Ship has stuck through to the present day (Myhra 2002; Shepelev and Ottens 2006; Lee 2011).

Another thing that stuck was an idea. Later in his life, Reimar Horten's aviation career was faltering. Possibly as an attempt to bolster his reputation, he promoted the idea that the Horten Ho 229 V3 was intended to be built as a stealth aircraft, which would have placed this jet's design a decade ahead of its time. Reimar Horten claimed that he wanted to add charcoal to the adhesive layers of the plywood skin of the production model to render it invisible to radar, because the charcoal "should diffuse radar beams, and make the aircraft invisible on radar" (Horten and Selinger 1983, Russ Lee translation). This statement was published in his 1983 co-authored book *Nurflügel* (which translates as "only the wing"). Although this statement refers to the never-made production model, it stands to reason that the experimental charcoal addition could have been used on the Horten Ho 229 V3 prototype. The mere mention of early stealth technology sparked the imagination



Fig. 1. The Horten Ho 229 V3 (plywood, wood, adhesives, ferrous alloy, aluminum alloy, and paint. 274 cm height, 762 cm length, 304 cm wide, with a 55.4 wingspan, constructed 1945 (NASM A1960 0324 000) (Courtesy of Eric Long, National Air and Space Museum, Smithsonian Institution)

of aircraft enthusiasts all over the world and spurred vibrant debate that is rich with conjecture and is ongoing in the aviation community; however, to date, there has been no tangible evidence to support or refute this claim.

The stealth myth has been growing since the 1980s and was invigorated when the National Geographic Channel, in collaboration with Northrup Grumman, produced a documentary called “Hitler’s Stealth Fighter” in 2009. The program featured the Horten Ho 229 V3 as a potential “Wonder Weapon” that arrived too late in the war to be used (Myth Merchant Films 2009). The documentary also referred to the jet’s storage location as “a secret government warehouse,” which added to the mystique of this artifact. Since the airing of the documentary, public pressure has increased to remove the jet from its so-called secret government warehouse and put it on display. In fact, this warehouse is the Smithsonian Institution’s Paul E. Garber Facility in Suitland, Maryland, where a team of conservators, material scientists, a curator, and aircraft mechanic has been evaluating the aircraft (fig. 2). After 70 years in storage, the plywood skin has deteriorated considerably, which complicates plans to relocate the aircraft to the museum where it can be exhibited with a more accurate interpretation.

## 2. MOTIVATION AND GOALS

The initial motivation for the current research was to develop a plan to safely move the jet from the Garber facility to the Steven F. Udvar Hazy Center (UHC) in Chantilly, Virginia, where it will be



Fig. 2. The Horten center section at NASM's Garber facility (Courtesy of Ben Sullivan, National Air and Space Museum, Smithsonian Institution)

exhibited. Moving the jet is complicated by its deteriorated condition (fig. 3). In particular, the plywood, which is a composite material composed of many layers of thin wood veneers bonded together with a polymeric adhesive, has suffered from water damage and fungal attack causing delamination and structural failure. The plywood is also the focus of speculation about stealth, so any attempt to consolidate the plywood before the move could interfere with characterizing the original, historic material. Curator Russ Lee was very interested to know if we could validate or debunk Reimar Horten's claim of charcoal within the plywood adhesives to create the world's first stealth aircraft; thus, the project goal expanded to include a search for physical evidence, derived from the artifact, to clarify the historical record. The comprehensive technical study also would inform the stabilization methodology before the jet's move and its eventual conservation treatment.

The jet incorporates many historic materials, but the research presented here focuses on the composite layered structure of the plywood and the search for charcoal. The technical study aimed to characterize the composite plywood panel construction, shown in figure 4. The panels that make up the aircraft's skin and underlying spacer blocks are plywood. We wanted to (1) characterize the wood species used to make the plywood veneers, structural supports, and spacer blocks; (2) identify the adhesives that bond the veneers into plywood boards and spacer blocks, and those that attach wooden structural supports to the plywood panels; (3) determine whether charcoal was added to the adhesives in concentration sufficient to make the jet invisible to radar; and (4) characterize the green protective coating found on the underside, and selectively on the top surfaces of the plywood panels.





Fig. 3. Details of delaminated plywood veneers on the tail and side of the jet (Courtesy of Ben Sullivan, National Air and Space Museum, Smithsonian Institution)

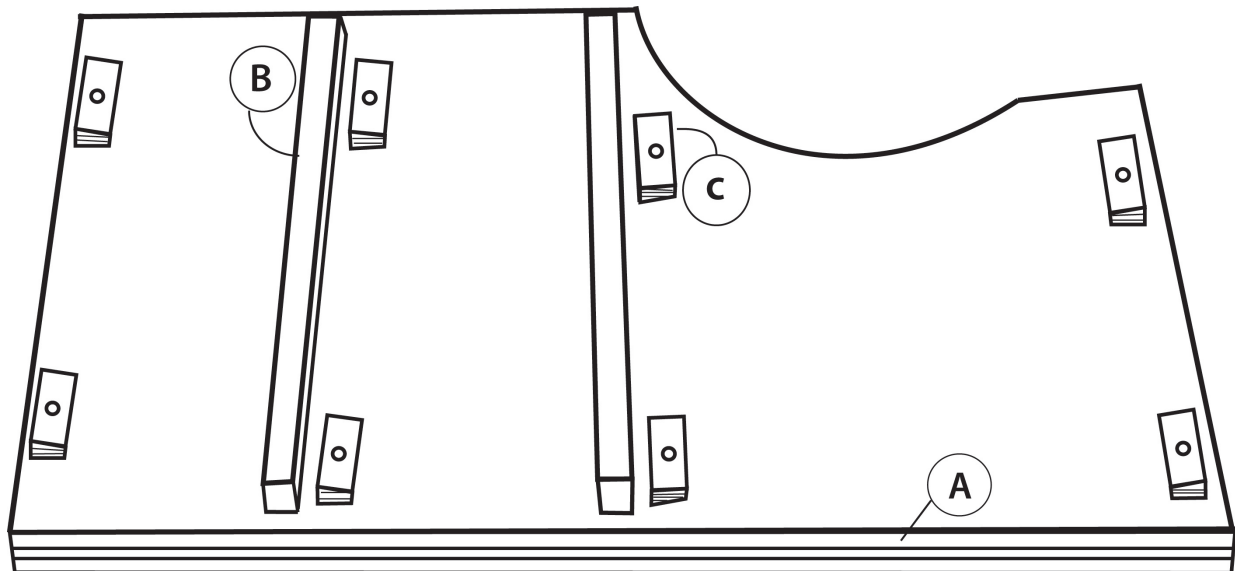


Fig. 4. Diagram of a plywood panel composed of (a) wood veneers adhered at 90 degrees to one another forming a plywood board, (b) structural supports adhered to the plywood board, and (c) spacer blocks made from wood veneers adhered together (Courtesy of Lauren Horelick)

In the conservation field, technical studies of macro-technological artifacts, such as air and spacecraft, are unusual because typically the production specifications are available. This is not the case with the Horten because it was constructed toward the end of the war when resources were scarce, supply lines were compromised, and record keeping was perfunctory. Additionally, there is no documentation from the *Gotha* workshop about material specifications. Our technical study aimed to compare physical evidence on the jet with historical wartime accounts of materials used to contextualize our findings.

### 3. THE HORTEN HO 229 V3: CONSTRUCTION, ACQUISITION, AND CONDITION

The Horten stands 9 ft. tall, has a 55-foot wingspan, and is 22 ft. long. It is constructed in five main sections: a center section made from a steel tubular framework that encompasses two engines, the cockpit, the landing gear, and two wings. The center section framework is covered with a plywood skin made up of multiple panels that are attached to structural wooden supports with steel hardware. Steel fairings protect the engines at the back of the aircraft and are secured over the plywood to protect the wood from exhaust heat (fig. 5). A green protective coating is present on the interior surfaces of the plywood panels and selectively on the exterior wooden surfaces. The wings are constructed of wooden structural members and plywood skin.

The exterior surface paint that we see on the Horten today dates to its postcapture history. Before the aircraft entered the NASM collection, the United States Army displayed it in 1946 at Orchard Park, which is now Chicago O'Hare International Airport. At that time, the army attached the wings to the jet, added aluminum panels to uncompleted areas, and painted the exterior gray-blue. They added swastikas to the tail and stenciled numbers on the engine fairings (Myhra 2002; Shepelev and Ottens 2006).

The National Air Museum (as NASM was called then) acquired the Horten in 1952 when there was a shortage of storage facilities. Consequently, it sat outdoors in wooden crates from 1952 until 1974, and that is where most of its condition issues originate. Extensive plywood veneer delamination, material loss, biological growth, and coating delamination are evident throughout the aircraft. The metal components are corroded, fasteners have failed, and numerous small parts are missing.

The plywood skin has presented the biggest conservation dilemma. We needed to stabilize this material before moving the jet, and conservation treatment potentially conflicted with our desire to study the plywood. The solution was to carefully disassemble the fragile metal fairings and plywood panels. Each part was carefully packed and shipped to NASM's Emil Beuhler conservation laboratory at UHC. This allowed us to study the plywood panels with their associated protective coatings in an undisturbed state.

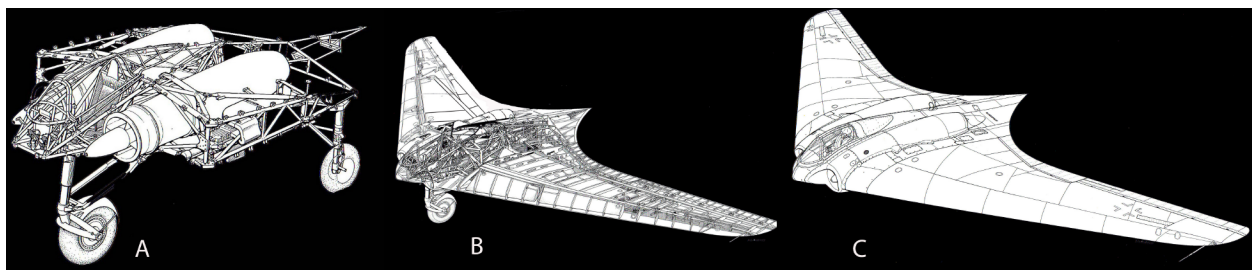


Fig. 5. Illustration showing the (A) tubular framework with engines, (B) plywood support structure, (C) plywood skin and metal fairings (Courtesy of Arthur Bentley)

## 4. RESEARCH METHODOLOGY

### 4.1 LITERATURE REVIEW

A literature review of plywood technology was the starting point for developing a list of likely materials that we could expect to find on the Horten as well as the techniques by which they were applied. The research emphasized natural and synthetic plywood adhesives and protective coatings that were in use in Germany before and during World War II. In addition to published literature, many sources were found in the “Combined Intelligence Objectives Sub-Committee Reports” found in the Library of Congress and “German Captured Air Technical Documents,” which are microfilmed in NASM’s archives. The Combined Intelligence reports (ca. 1946) are summaries and full manuscripts of interviews and interrogations conducted by British and American intelligence officers who gathered detailed information about German industry and individuals of interest, including the Horten brothers. The German Captured Air Technical Documents are scientific reports from 1943 to 1946 acquired by the Allies from German factories and laboratories. These reports, largely in German, describe material property tests of plywood, wood veneers from differing species, adhesive formulations, and protective coatings.

### 4.2 REFERENCE MATERIALS

Reference samples of cured thermosetting urea and phenol formaldehyde resins were obtained from Georgia Pacific Chemicals. Mr. Matthias Schleinker and Mr. Josef Griener of Bitz Co., Mr. Hans Vornlocher of Eichelsdörfer (both aircraft restoration companies), and Peter Selinger provided plywood samples made of adhesives mentioned in the literature review. Wooden elements on the Horten were compared to a set of wood reference samples prepared by wood identification experts Dr. Terry Connors, from the University of Kentucky, and Larry Osborn from the University of West Virginia.

### 4.3 SAMPLING METHODS

A protocol was established for removing small samples from representative and undeteriorated areas of the Horten. Samples of plywood in cross section, individual veneers, adhesives, inclusions within the adhesives, and original protective coatings were carefully recorded, numbered, and photographed with a high-resolution Hirox KH-7700 digital microscope.

Sampling the plywood was initially complicated due to the extensive deterioration, which made obtaining intact samples difficult; however, once we removed the steel fairings we discovered areas of sound wood that had been protected from the elements and chose to take our samples from there.

In our search for charcoal in the plywood adhesives, two methods were devised to extract black particles for analysis:

**Method 1:** The adhesive was crushed with a mortar and pestle, followed by soaking in sodium hydroxide (pH 14) for several hours to further break apart the adhesive matrix and release any inclusions. Particles were pipetted onto a glass slide, allowed to dry, and the black particles were separated out with tweezers.

**Method 2:** Intact samples of adhesive were prepared into thin sections (30–50  $\mu\text{m}$ ) by embedding the sample in clear polyester resin, followed by cutting the cured resin sample with a diamond blade saw, and polishing with Micro-mesh sheets. Samples were examined and photographed with a Nikon, Eclipse E600 POL Research Microscope equipped with a Leica DFC290 HD camera in transmitted, bright field, and under crossed polarization.

### 4.4 ANALYTICAL TECHNIQUES

Scientific analysis of samples and reference materials was performed at the Smithsonian’s Museum Conservation Institute (MCI) and NASM using multiple techniques.



Polarized light microscopy was used to examine the Horten's adhesives, wood, paint, and black particles extracted from the adhesive. Samples were examined on glass microscope slides with a Nikon, Eclipse E600 POL Research Microscope using transmitted light in bright field and crossed polarization with a magnification range of 50–1000x.

FT-Raman spectroscopy (FT-Raman) was performed with a NXR FT-Raman module coupled to a Thermo Nicolet 6700 FTIR spectrometer (Thermo Electron Corporation, Madison, Wisconsin, USA). The NXR module was equipped with a continuous wave Nd:YVO<sub>4</sub> excitation laser (1064 nm), CaF<sub>2</sub> beam splitter, and thermoelectrically cooled InGaAs detector. Instrument control, data collection, and spectral interpretation were managed by OMNIC 7.2a software (Thermo Fisher Scientific). Laser power was chosen empirically to optimize spectral quality and minimize risk to the samples. No baseline correction or smoothing was applied.

FTIR was carried out on reference adhesives, Horten adhesives and green paint samples with a Thermo Nicolet 6700 FTIR spectrometer in attenuated total reflectance (ATR) mode with a single bounce, 45° Golden Gate ATR accessory with diamond crystal, and an electronically cooled DTGS detector. Spectra were a co-addition of 64 scans at 4 cm<sup>-1</sup> spectral resolution, and were ATR corrected. Each sample was analyzed three times.

XRF was performed with a Bruker Tracer III-V handheld XRF spectrometer equipped with a rhodium anode. Spectra were collected without a filter at 40 kV for 120 seconds live time accumulation. Spectra were collected and examined with SiPXRF software followed by observation with Artax software.

XRD was used to identify the black particles in the adhesive matrix. The instrument was a Rigaku D/Max Rapid Micro X-ray Diffractometer with copper target and operated at 50 kV, 40 mA, and 2.00 kW. Samples were mounted on a glass fiber with Elmer's jell.

## 5. RESULTS AND DISCUSSION

### 5.1 LITERATURE REVIEW

The literature review provided valuable information about plywood technology. In particular, plywood production methods of German industry from 1930 to 1945 are described in the Combined Intelligence reports. These reports document that European birch was originally specified for aircraft plywood veneers, but beech was soon introduced for reasons of supply (Knight et al. 1945). The reports describe how thin veneers were created by peeling water soaked logs along the tangential plane. The veneers were dried, and a layer of synthetic or natural adhesive was applied to the tangential planes and the veneers were stacked one atop the next with the wood grain aligned at ninety degrees. Alternating grain direction created a strong, multilayered composite material and overcame the inherent weakness of wood across the grain (Perry 1942; Gordon 2006). The Combined Intelligence reports describe extensive experimentation to produce lightweight composite plywood that would have excellent performance characteristics, including resistance to moisture, biological attack, excesses in heat and cold, jet fuel, and extreme physical stresses. Protective coatings for wood that were intended to impart properties such as waterproofing, fireproofing, temperature indication, invisibility to infrared photography, resistance to petrol, and heat are also described.

Synthetic adhesives developed for aircraft plywood are described extensively in the Combined Intelligence reports. The reports indicated that phenol formaldehyde and urea formaldehyde adhesives were extensively used for plywood construction. Trade names of various types of adhesives and their chemical composition mentioned in these reports are listed in table 1. The Horten brothers were also interrogated as part of post war intelligence gathering (Blot 1945). In their interview, they give explicit details about the materials and construction of many of their tailless aircraft; for example, they went so far as to offer that the wings of the V2 were constructed with a urea formaldehyde resin with the trade name *Kauritleim W* and *Kauritleim WHK* adhesives (Blot 1945). Unfortunately the Horten Ho 229 V3 is not mentioned at all.



Table 1. WWII-era German Adhesive Trade Names, Chemical Composition, and Preparation

Adhesive Trade Name	Chemical Composition	Preparation
<i>Kaurit/</i> <i>Kauritleim</i>	Urea formaldehyde	Prepared with urea formaldehyde with 10–40 % beech wood flour or potato meal.
<i>Kaurit</i> <i>W Pulver</i>	Urea formaldehyde	Prepared by 1 mol of urea and 2 mol of formaldehyde (30% solution) reacted together to form a 36% resin solution. This was concentrated by heating (65 degrees C) in [vacuum]. Then 8–10% of wood, rye, or potato flour was added to yield a mixture composed of 55% resin, 10% flour, and 35% water neutralized to pH 7 with sodium hydroxide.
<i>Kaurit</i> <i>MS-Pulver</i>	Urea formaldehyde	Prepared from <i>Kaurit W. Pulver</i> , potato meal, wood flour, and methyl cellulose.
<i>Kaurit</i> <i>WHK-Pulver</i>	Urea formaldehyde	Prepared from <i>Kaurit W-pulver</i> , and <i>Trolitan-Prossabfallo</i> , a phenolic powder prepared from rejected moldings or flash at Troisdorf, which is ground and passed through a 0.3 mm sieve.
<i>Polystal</i>	Poly-isocyanate resins	Made by the reaction of a di-isocyanate with a polynhydroxy compound.
<i>Polystal U II</i>	Isocyanate resin	Mixture of toluene and hexamethylene di-isocyanate and ethyl acetate. These are mixed in the proportion of 40 parts UI to 100 parts U2 immediately before applying.
<i>Tego-film/</i> <i>Tego glue</i>	Phenol formaldehyde	Prepared by precipitating phenol formaldehyde onto a sheet.

## 5.2 CHARACTERIZING WOODEN ELEMENTS

### 5.2.1 Plywood Veneers and Spacer Blocks

Cross sections of the Horten's plywood skin showed a composite structure whereby 5-ply plywood sheets were laid up, one on top of the other, to form a thick plywood board (fig. 6a detail of a 5-ply assembly). The veneer thickness within each one ply was measured at approximately 0.2 mm, which is consistent with historical research of wartime aircraft plywood production (Perry 1942; Lacey et. al 1945). The species of wood used for the veneers was identified as European beech (*Fagus sylvatica*) on the basis of the distribution and width of ray cells on the tangential plane, which is all that is available for observation when the sample is a thin veneer (fig. 6b). The species of wood used for the veneers of the spacer blocks was also identified as European beech from the same microfeatures observed in the tangential plane, but these veneers were rotary cut to a greater thickness (1 mm) (figs. 6c, 6d).

### 5.2.2. Structural Supports

The structural supports are solid lengths of milled wood; the species was identified by observation of the wood in the transverse section, and the regular, radially aligned arrangement of cells indicates that the material is softwood. The presence of resin canals immediately narrowed the species identification to one of four genera-*Picea*, *Larix*, *Pinus*, and *Pseudotsuga* (Spruce, Larch, Pine, Douglas-fir). The distribution of resin canals and associated cells, and the abrupt transition from early to late wood were also of diagnostic value (figs. 7a, 7b). Lemon-shaped cross-field pits were also observed in the



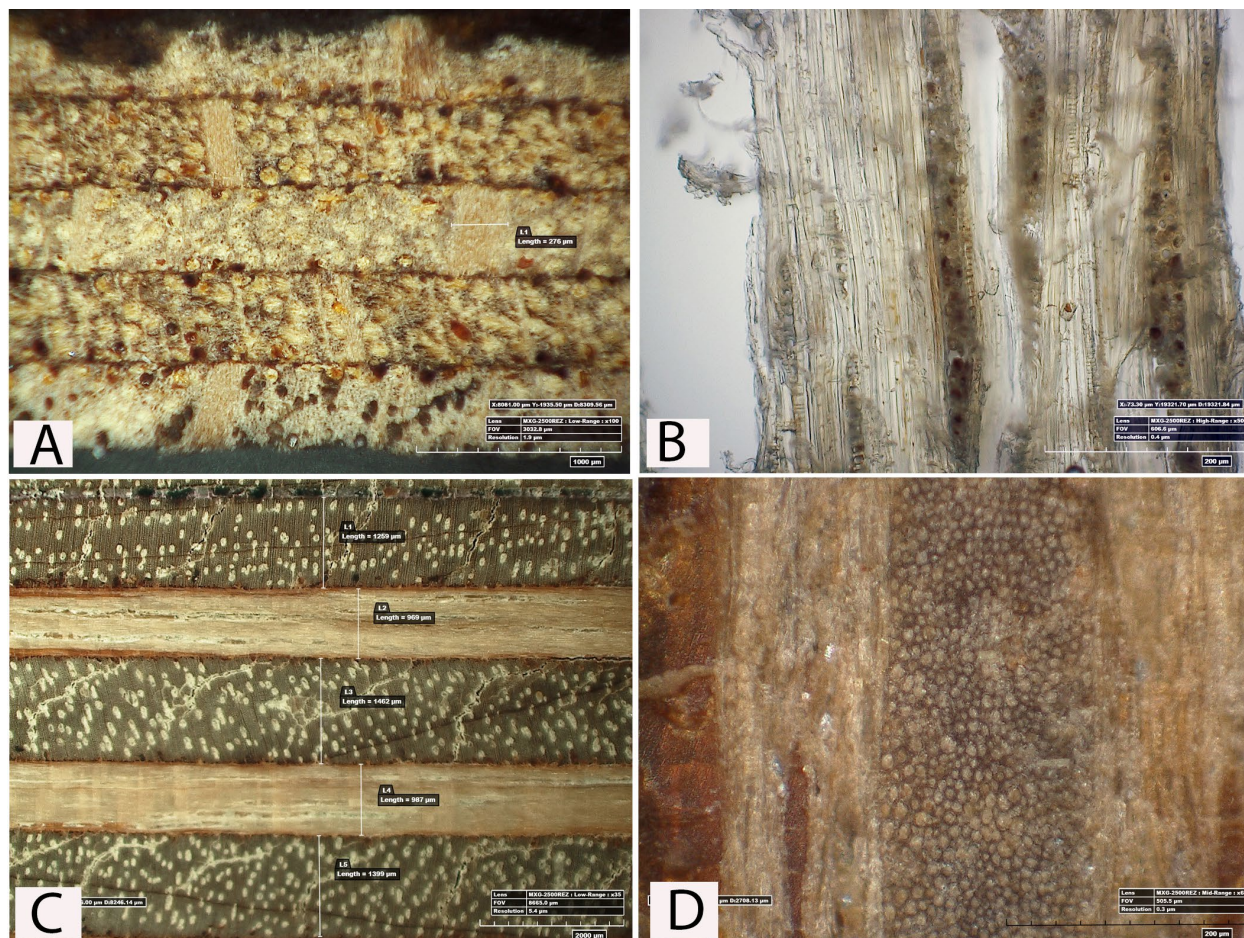


Fig. 6 (a) Detail cross section of the Horten's plywood skin showing the construction of a 5-ply board, (b) tangential view of the veneer showing the diagnostic ray width and distribution, (c) cross section of spacer block construction with 1 mm thick veneers, (d) tangential view of spacer block showing a diagnostic ray (Courtesy of Peter McElhinney)



Fig. 7 (a) Transverse view showing regular, radially aligned arrangement of cells and abrupt transition from early to late wood, (b) detail of resin canals in transverse plane (Courtesy of Peter McElhinney)



lumber sample (known as fenestriform pits) in combination with dentate walls in the ray tracheids, both of which are characteristic of Scots pine (*Pinus silvestris* L.).

Although historical research helped narrow down either European beech or silver birch (*Betula pendula*) as the two most likely species of wood that could have been used for the plywood veneers, the choice of Scots pine for the structural supports is somewhat unusual, as it does not appear to be a widely recognized aircraft wood. Spruce is typically preferred for wooden aircraft structural members, primarily for its excellent strength-to-weight ratio. The natural habitat range for spruce in Europe includes all but the most Southern regions of Norway, Sweden, and Finland, and would therefore appear to have been available to the Germans at the time of production. It is unclear at this time why this particular species of pine was selected over spruce, other than as a result of material shortages prevalent toward the end of World War II (Markwardt 1930).

### 5.3. CHARACTERIZING ADHESIVES

#### 5.3.1 Adhesive Along the Structural Supports and Spacer Blocks

A thick adhesive bead is found consistently around the structural supports and gluing together the spacer blocks. This adhesive is hard, brittle, and black; however, under the microscope, the samples have multiple, colorful inclusions (figs. 8a–8d). Samples taken from varying locations around the jet's

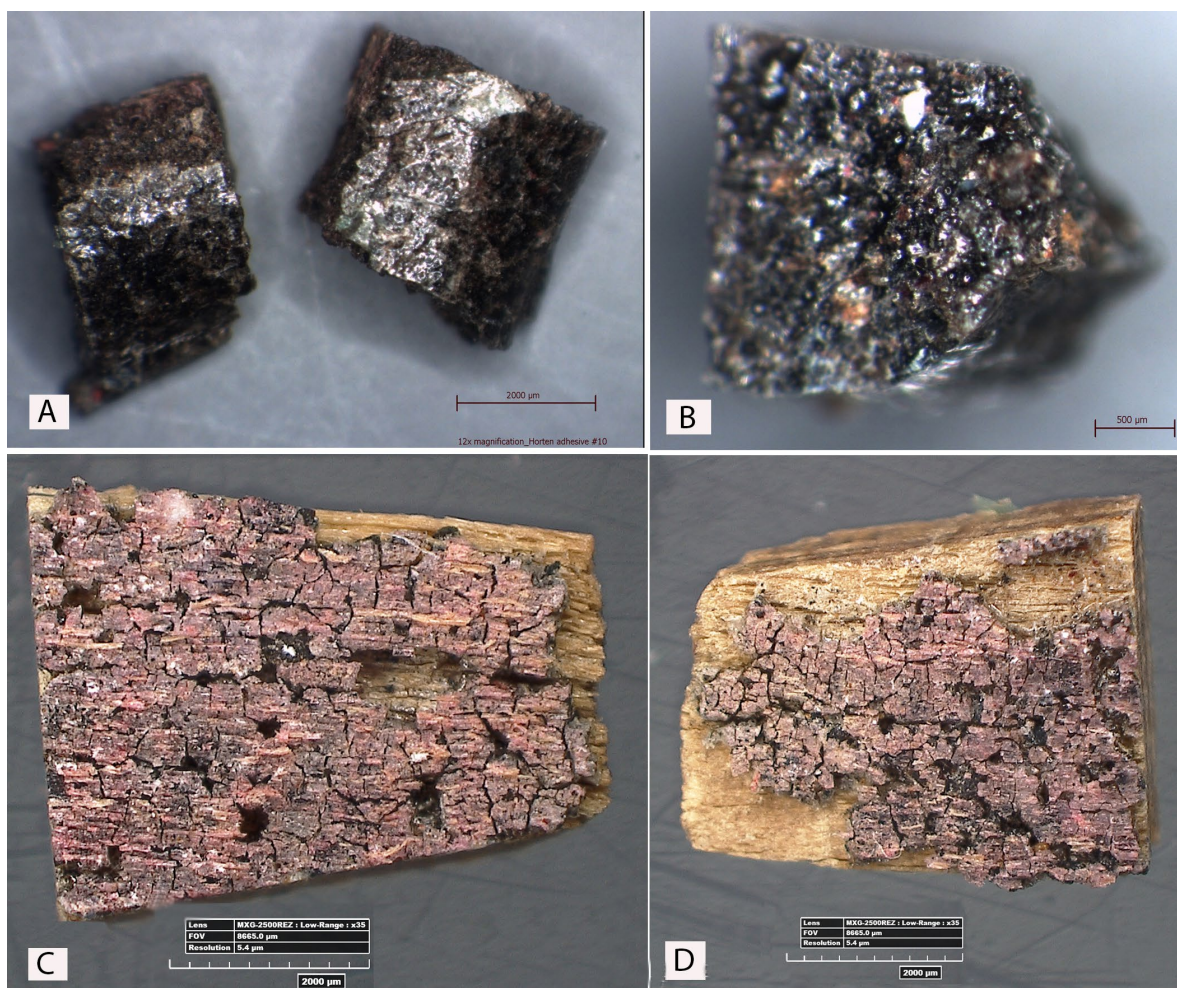


Fig. 8 (a)(b) Adhesive samples from around the structural supports, and (c)(d) pink and black material is the adhesive layer used to form the spacer blocks (Courtesy of Lauren Horelick and Anna Weiss)



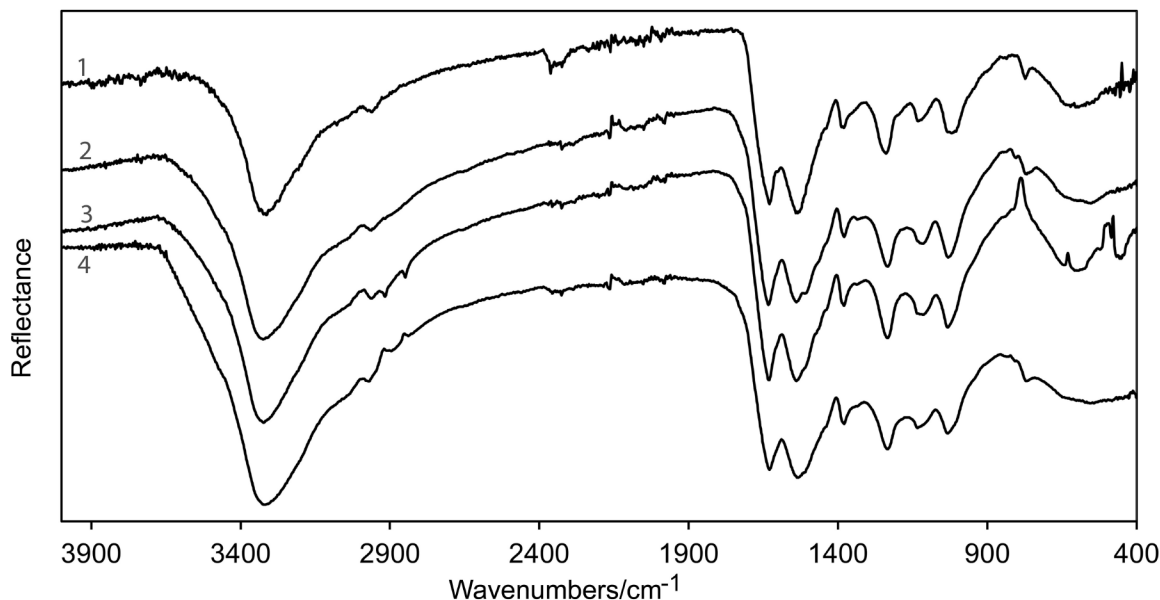


Fig. 9. Spectrum (1) Georgia Pacific cured urea formaldehyde reference spectrum; spectrum (2–4) adhesive from structural support locations from sample numbers 8, 3, and 10 (Courtesy of Lauren Horelick and Odile Madden)

structural supports were characterized with FTIR and generally resulted in a consistent match with one another and with the reference sample of cured urea formaldehyde (fig. 9). Although there are subtle variations between the Horten samples and a modern reference of urea formaldehyde, spectra share peaks at 3314, 1630, 1541, 1380, 1240, and 1019  $\text{cm}^{-1}$ . Other physical characteristics, such as insolubility to a variety of organic solvents, resistance to strong acids, but weakness to strong bases increased our confidence that the adhesive bead is urea formaldehyde (Eckelman 1997).

The adhesive binding the spacer block veneers was also identified using FTIR as urea formaldehyde. Figure 10 compares the adhesives found within four different spacer blocks veneers to the reference spectrum of urea formaldehyde.

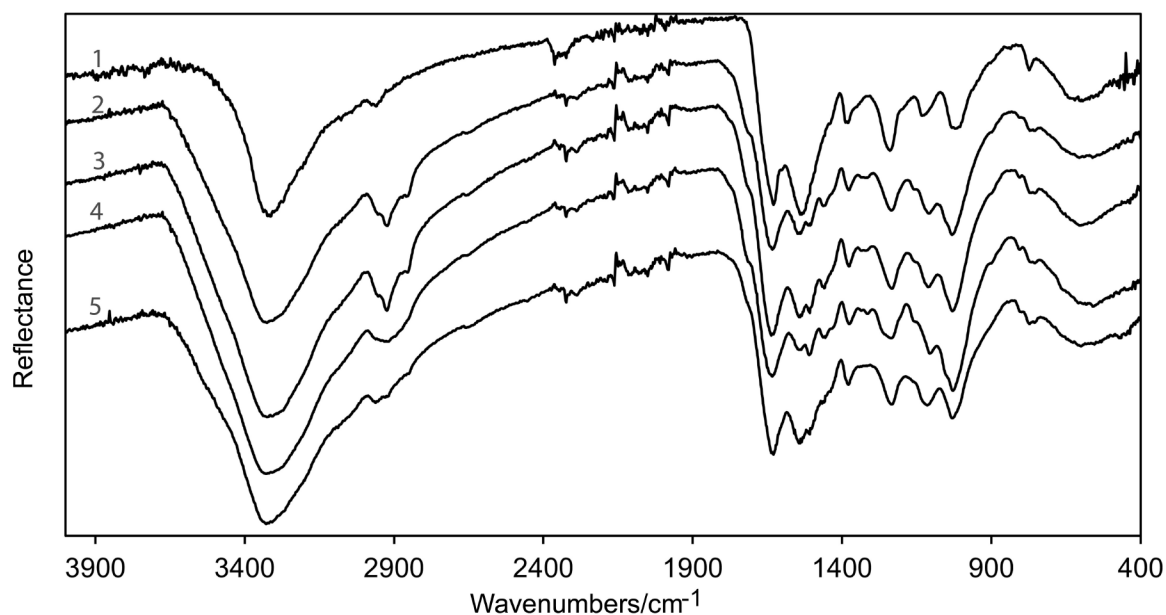


Fig. 10. Spectrum (1) cured urea formaldehyde reference spectrum from Georgia Pacific Chemicals; spectrum (2–5) adhesives holding together four different spacer blocks (Courtesy of Lauren Horelick)

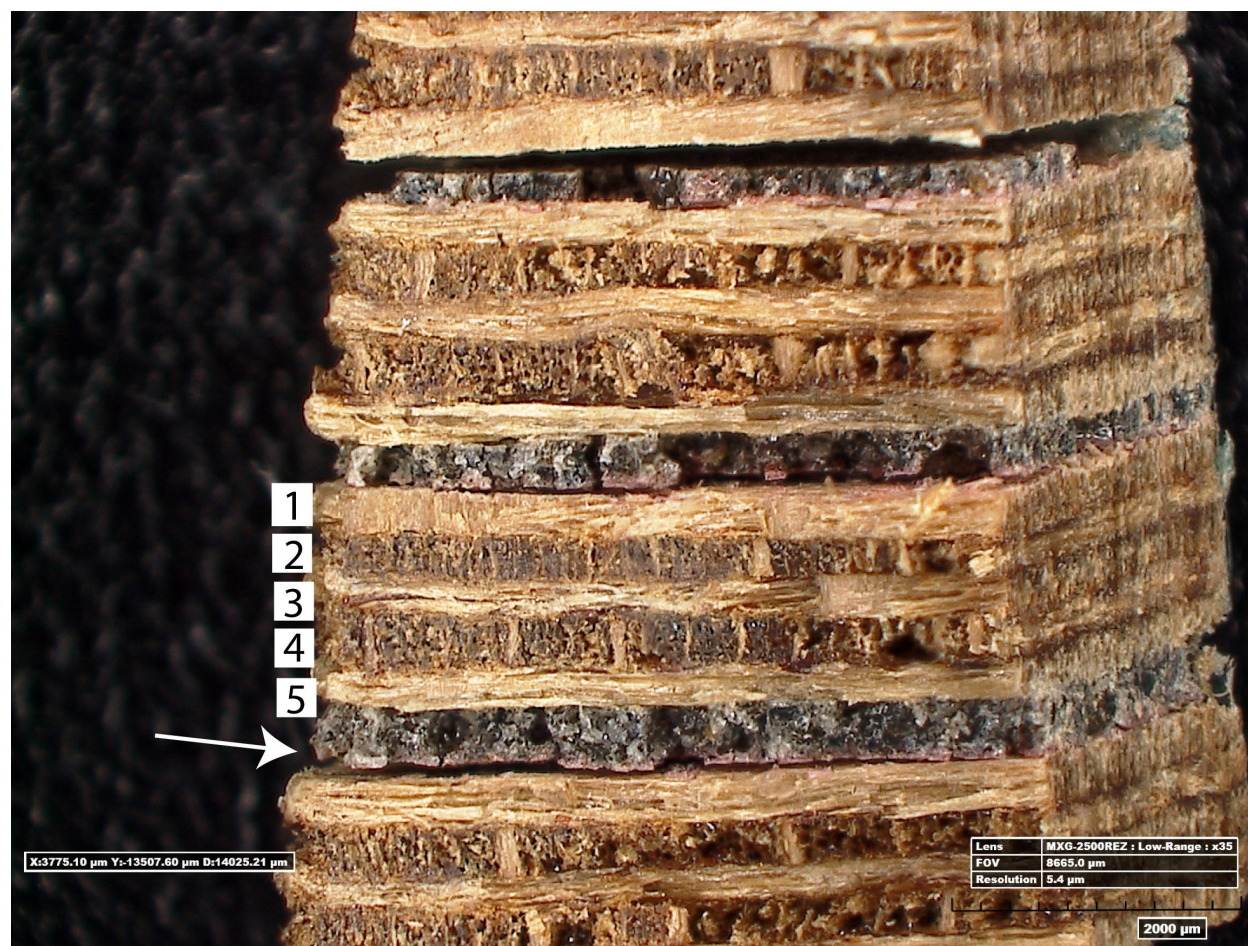


Fig. 11. Annotated cross section of Horten plywood showing the layering (1–5) of 1-ply boards that are adhered together with a thin, translucent amber colored adhesive. Each of the 1-ply boards is composed of approximately 20 veneers. The white arrow points to the thick, black colored adhesive layer that joins the 5-ply assemblies to one another. (Courtesy of Peter McElhinney)

### 5.3.2. Adhesives Used to Create the Plywood Boards

Cross sections of plywood show a layered structure of 5-ply sub-assemblies stacked one on top of the other with a thick black adhesive, as seen in figure 11. The individual 5-ply sub-assemblies, composed of many thin veneers, are adhered with a thin layer of a translucent amber material. Each 1-ply board is composed of approximately 20 veneers. Attempts to peel apart these veneers and the boards to separate the amber colored adhesive layer resulted in barely usable, tiny fragments of the amber colored material with wood still strongly adhered. FTIR spectra were dominated by the signal of cellulose and were not diagnostic for the amber material. With FT-Raman spectroscopy, we were able to analyze an intact cross section by focusing the laser on the amber adhesive layer. The resulting spectrum shared many diagnostic peaks with a reference sample of phenol formaldehyde (fig. 12). Peaks that were not attributed to phenol formaldehyde were consistent with cellulose in the adjacent wood. Phenol formaldehyde is further characterized by its translucent amber color and historic use as plywood adhesive (Perry 1942; Sutton 1963).

In between the 5-ply assemblies is approximately 0.3–0.5 mm thick black material that shared similar color, texture, brittleness, and distribution of inclusions as the adhesives found in between the spacer blocks and around the structural supports. The thicker layer was identified with FTIR, again resulting in a match with the reference sample of urea formaldehyde.

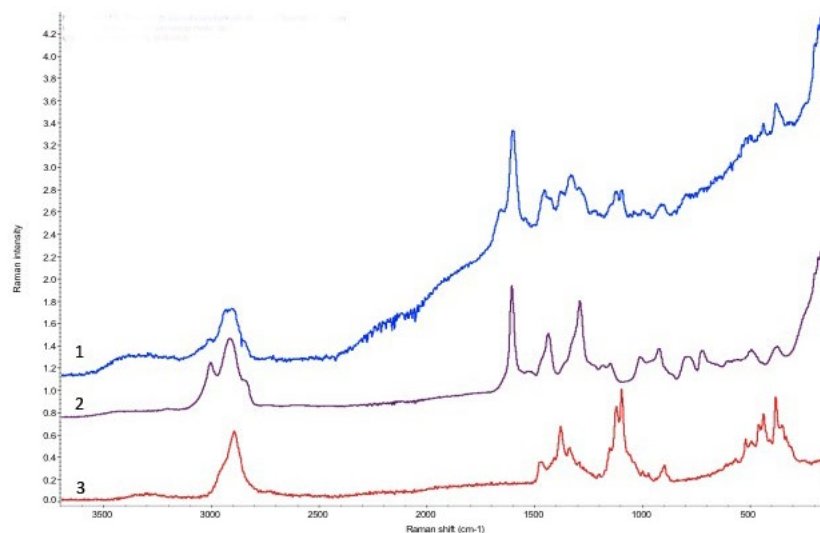


Fig. 12. Spectrum (1) is the amber colored resin layer, (2) reference spectrum of phenol formaldehyde from Georgia Pacific Chemicals, and (3) reference spectrum of cellulose powder (Courtesy of Odile Madden)

Adhesives listed in table 1 and used on historic plywood samples provided to the project by German aircraft restoration companies were characterized with FTIR and Raman in an attempt to correlate these specific materials with those on the jet. Although this work is still in its preliminary phase, comparative spectra of *Kaurit WHK* (a urea formaldehyde-based thermosetting adhesive) and the urea formaldehyde-identified adhesives on the jet revealed many similarities. Figure 13 shows a spectrum from each adhered wood component (in between the spacer blocks, in between the plywood boards, and around the structural supports) compared with *Kaurit WHK*. Although further characterization of the *Kaurit WHK* is needed to conclusively connect the use of this material with what is on the Horten, the spectra in figure 13 suggest a correlation.

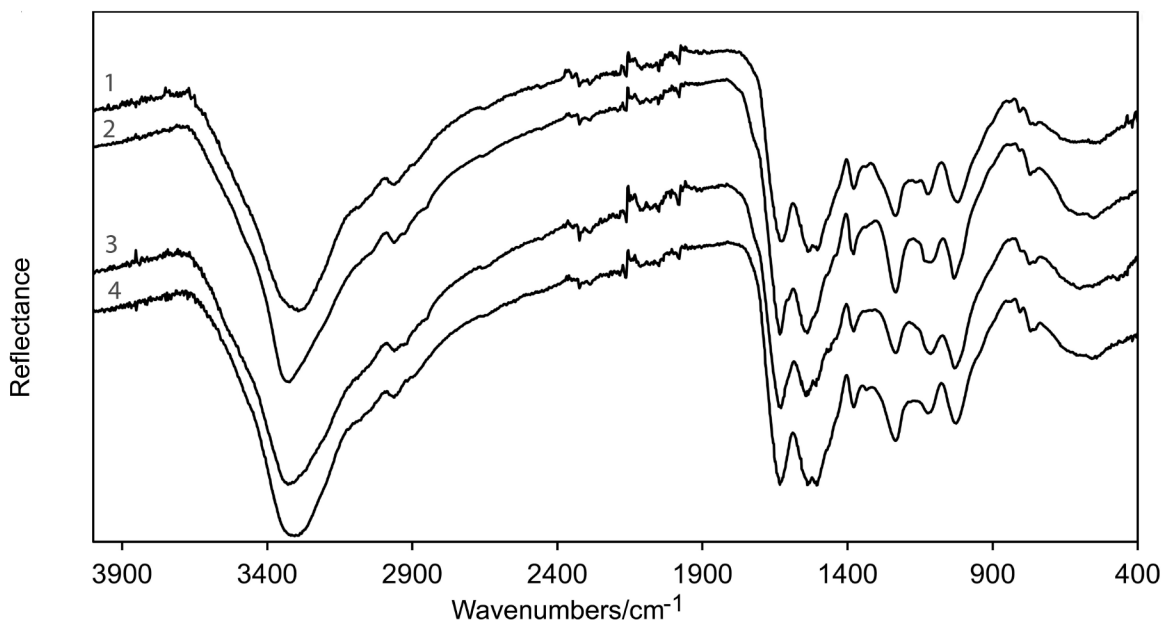


Fig. 13. Spectrum (1) is of *Kaurit WHK* adhesive sample compared with the black adhesive found consistently to match the urea formaldehyde reference sample from locations around the jet. Spectrum (2) is the adhesive from in between the 5-ply assembly. Spectrum (3) is the adhesive from the spacer block. Spectrum (4) is the adhesive used around the structural supports. Spectra 2–4 show close similarities to the *Kaurit WHK*. (Courtesy of Lauren Horelick)



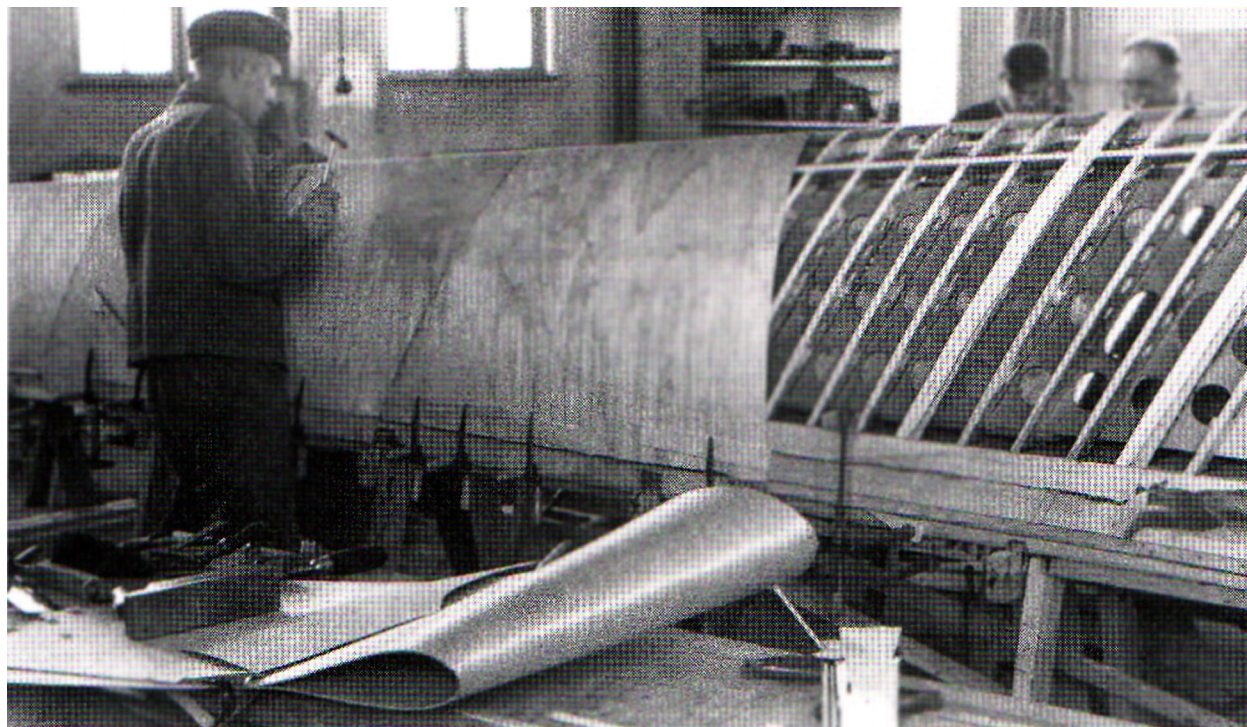


Fig. 14. Image of Horten workers assembling V2 wings. Note the plywood veneer in the foreground and the row of C-clamps at the edge of the wing under construction. (Courtesy of Myhra 2002)

The discovery of urea formaldehyde as an assembly material in three separate locations strongly suggests this as the adhesive material choice of the *Gotha* workshop for assembling the Horten. The FTIR and Raman spectra of the adhesives found within the plywood skin illustrate the use of pre-fabricated phenol formaldehyde bonded 5-ply plywood. *Gotha* workshop craftsmen must have added 5-ply boards to cover over the framework, layer by layer, to achieve the desired thicknesses using urea formaldehyde in between each board's layer. Historical references to urea formaldehyde's use for aircraft indicate its application as a liquid with a working time of up to 4 hours after mixing. It will cure at minimum room temperatures of 70°F, although the quality of the bond is improved and its cure accelerated by the application of heat up to 140°F (Nichols 1943). Historic images of Horten workers assembling the wings of the V2 show the use of clamps and jigs as opposed to ovens or presses (fig. 14).

#### 5.4 SEARCHING FOR STEALTH MATERIALS

The adhesives and wood identification research was somewhat straightforward in both designing a methodology and obtaining results. Searching for the stealth materials was less so. Reimar Horten stated that he wanted to add charcoal to the adhesive layer of the plywood skin, but as we discovered, there are two adhesive layers used to form the plywood skin. The phenol formaldehyde plywood boards were ruled out as a layer to investigate due in part to their pre-fabrication, the absence of inclusions in the adhesive layer, and the fact that phenol formaldehyde does not readily accept filler material (Perry 1942). The consistent use of urea formaldehyde by the *Gotha* workshop suggested this was the only layer in which charcoal could be added. Urea formaldehyde's properties include its ability to accept fillers and extenders, which is consistent with our samples showing multiple inclusions. In particular, we noted suspicious black particles in the adhesive matrix, clearly visible with optical microscopy. Two different methods were devised to isolate these black particles for characterization, which were thin sections and dispersions, as seen in figures 15a–15f.

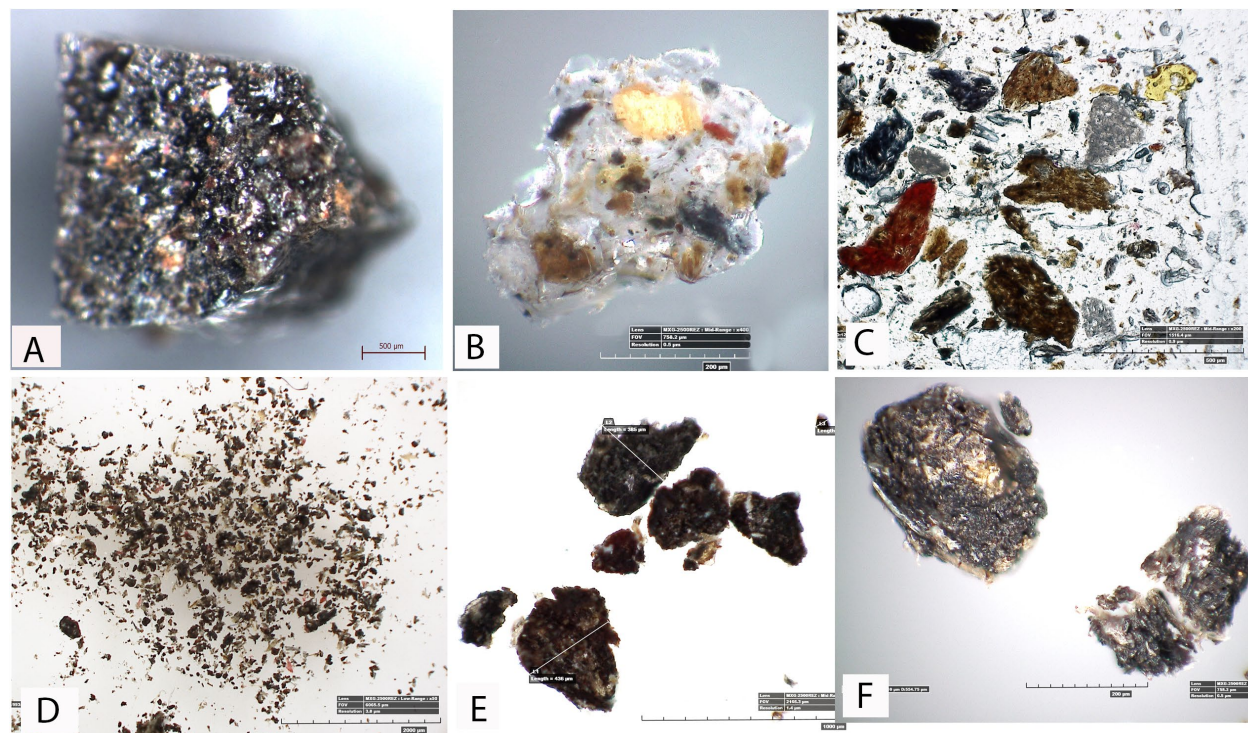


Fig. 15 (a) Adhesive along the structural supports before any manipulation, (b) adhesive once it has been crushed with a mortar and pestle, (c) thin section of adhesive, (d) dispersion of the adhesive, (e) isolated black particles showing measurements between 1 and 436  $\mu\text{m}$ , (f) isolated black particles measured at 200  $\mu\text{m}$  (Courtesy of Anna Weiss and Lauren Horelick)

Under the microscope, the black particles range in size from 1 to 436  $\mu\text{m}$ . They are irregular, rounded, and opaque overall, whereas some particles exhibited red, gray, and blue hues around the edges. With PLM some of the particles were anisotropic, which is not a characteristic of charcoal, according to the particle atlas (McCrone Atlas of Microscopic Particles 2012). Observation of the thin sections with PLM revealed inclusions within the black particles that were anisotropic, appeared fibrous, and exhibited interference colors. Comparatively, charcoal is both isotropic and completely opaque at sub-micron sizes. The thin sections also permitted us to see the location and density of distribution of the black particles within the adhesive matrix. Figure 15c shows a scattered distribution of these particles, as opposed to a cohesive and dense layer.

XRD resulted in an amorphous pattern, which does not rule out the presence of charcoal. With FTIR the black particles resulted in a spectrum showing clear peaks, which is atypical for charcoal, which can block infrared light without producing spectral bands (fig. 16); however, depending on how the charcoal was processed, it will produce a spectrum (Cohen-Ofri et al. 2006; Esteves et al. 2013). In the spectrum of the suspicious black particles, we see a peak attributed to cellulose and hemicellulose at 3300, 2918, and 1029  $\text{cm}^{-1}$ . The peak around 1700  $\text{cm}^{-1}$  is the C=O bond that may be from oxidation. The peaks around 1600, 1500 and 1250  $\text{cm}^{-1}$  relate to a phenolic, whether it is from lignin, a natural phenolic in the wood, or from the presence of a phenolic resin is uncertain (Ellen Nagy of Georgia Pacific Chemicals, personal communication 2014). The FTIR spectrum suggests that rather than discrete particles of charcoal within the adhesive matrix we are finding oxidized, or very aged, wood.

The Combined Intelligence reports state that after 1940 shortages of raw casein and dried blood as plywood adhesives forced the use of *Kaurit* exclusively, which could be extended by adding 10 to 40%



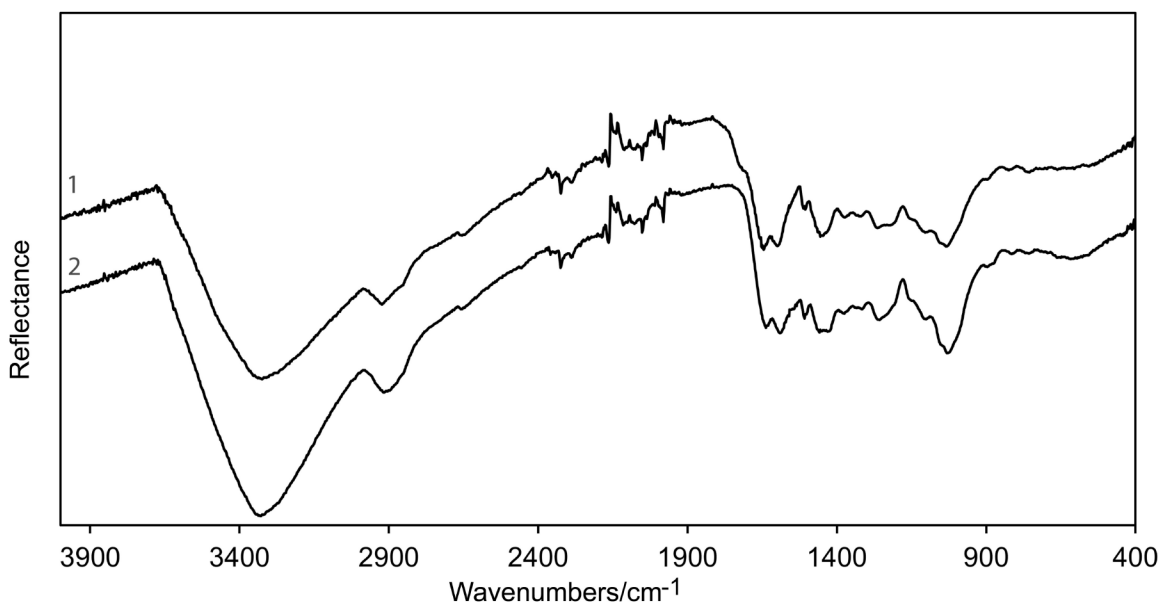


Fig. 16. FTIR spectra of black particles from two different adhesive locations on the jet. Spectrum (1) is from black particles extracted from the adhesive located in between the plywood; spectrum (2) is the black particles extracted from the adhesive around the structural supports. (Courtesy of Lauren Horelick)

beech wood flour or potato meal (Knight et al. 1945; Palmer et al. 1945). Although more study is needed to fully characterize the *Kaurit*, it may be possible that the black particles we see in the adhesive matrix could relate to oxidized beech wood flour thereby explaining the peaks for cellulose, hemicellulose, and the presence of phenols in the spectrum of the black particles.

The search for charcoal as the stealth material at this stage in the research appears inconclusive; however, a more macro view of the problem can be seen in the plywood cross sections, where there is a marked absence of a thick layer of anything except the adhesive. A cohesive and measurable layer of radar absorbing charcoal in between the plywood would suggest a concentrated effort at experimenting with stealth materials. Despite our best efforts to either validate or debunk Reimar Horten's claim, the fact remains that we have a dilemma of scale in pursuit of identifying this material. The problem of looking for something tiny, like charcoal particles, within something huge, like a jet, is that it opens the door for speculative thoughts about looking and sampling in the right or wrong location. We characterized a material within the plywood adhesive that shares many commonalities with charcoal, but is not clearly and definitively charcoal. Reimar Horten's published statement in the 1980s about wanting to add charcoal to the production model is also not to be overlooked, as a production model was never fabricated, only our prototype.

## 5.5 CHARACTERIZING THE GREEN PAINT

Our final goal for the technical study was to characterize the green paint, found on the interior and selectively on the exterior of the plywood panels. The green paint is obscured on the exterior surfaces with over paint applied in 1946 by the United States Army; however, some wooden surfaces that were covered by metal fairings exhibited untouched green paint that we speculated was some kind of protective coating (fig. 17). This particular green tint was rather unusual, even among veteran NASM restoration specialists experienced in working with German aircraft. We, therefore, set about characterizing this paint and sought out historic references that might describe its purpose.





Fig. 17. View of Horten tail section with the metal fairing removed, revealing plywood coated with green paint (Courtesy of Eric Long, National Air and Space Museum, Smithsonian Institution)

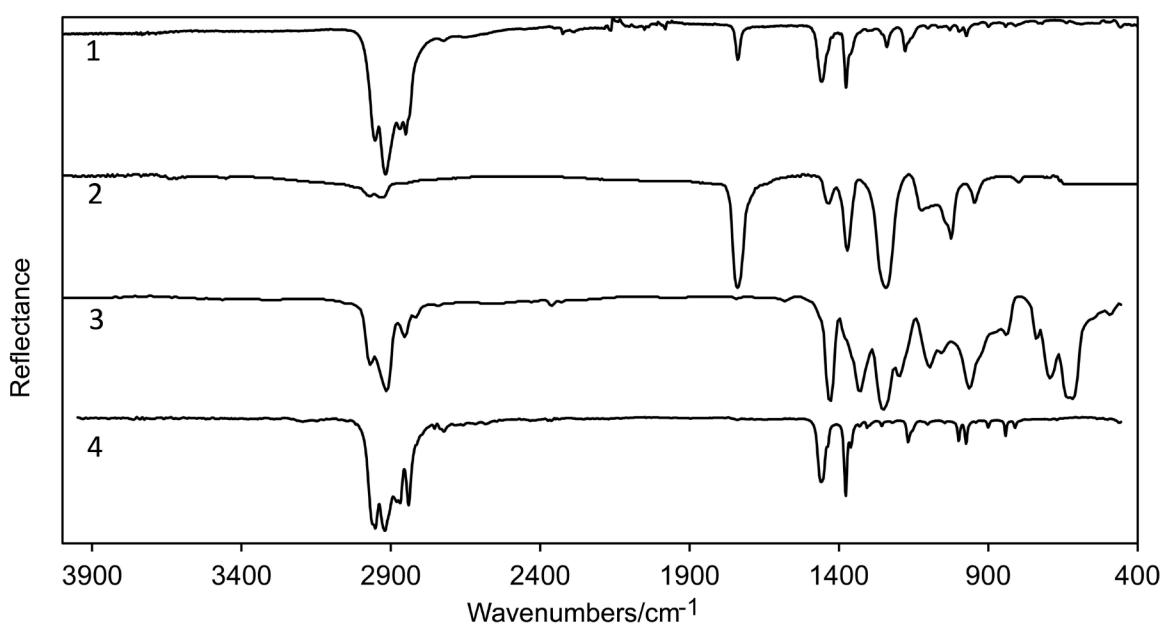


Fig. 18. FTIR Spectrum (1) is the paint binder extracted from the green paint; spectrum (2) is a reference spectrum for PVAC; spectrum (3) is a reference spectrum for PVC; spectrum (4) is a reference spectrum for atactic polypropylene. (Courtesy of Odile Madden)

Preliminary analysis with FTIR of the green paint suggests that the paint binder is a combination of polypropylene, PVC, and PVAC (fig. 18). Chlorine was detected with XRF along with chromium, zinc, and iron. No pigment particles were seen under PLM.

We have since found evidence that fireproof paint based on PVC was developed in Germany during this time. A *Gotha* glider is reported to have been painted with a green fireproof product composed of cellulose acetate and PVC. This paint was supplied under the general trade name “Herbolid” and contained a PVC-based additive called “Vinoflex” (Merrick and Kiroff 2004). “The stability of this resin depended on after-chlorination being pushed as far as it would go to give a product 60 to 66% total chlorine” according to subjects of an interrogation. The subjects also offered their poor opinion of “[its] fireproofing properties on wood, where the weight ratio P.V.C/cellulose was very low” (Palmer et al. 1945, 6). FTIR spectra of the green paint from the Horten more closely resemble a combination of PVC with PVAC and polypropylene, rather than the cellulose acetate described by Merrick and Kiroff, but the possibility that the green paint was a fireproofing coating is tempting given its location in what would have been the jet’s hottest areas.

## 6. CONCLUSIONS

The technical study provided valuable and concrete evidence of the jet’s fabrication and materials. The study has identified the use of beech and Scots pine as the major wooden components and urea and phenol formaldehyde as the adhesives holding the plywood skin together. We have tried to make some correlations with specific German World War II adhesives, finding some striking similarities although nothing conclusive. Although the presence of charcoal as a stealth ingredient appears unlikely, the opportunity to investigate the adhesive matrix revealed a microcosm of additives and inclusions, which can be seen as an artifact of materials availability of the time. The characterization of the green PVC-based paint and its links to the development of fireproof paints reveals the extent to which experimentation in the coatings industry was driving material advancements. All of the results from the technical study provided insights to the material choices of the *Gotha* workshop, which speak to an economy of wartime availability, along with an unusual combination of experimental and traditional material use.

Characterization of the different materials in the technical study allowed us to investigate their physical properties and correlate their deterioration in salient ways; for example, the plywood delamination that we see is consistently located the urea formaldehyde layers, which has less resistance to weathering than phenol formaldehyde-bonded panels (Perry 1942). Discussions about proposed materials and techniques to consolidate the plywood veneers was informed by our research into urea and phenol formaldehyde, which are both cross-linked resins and therefore insoluble in a variety of organic solvents. A literature review of adhesives used for wood consolidation illustrated that many conservation materials do not have all the perfect properties that we desire, and an effective yet reversible treatment may not be possible. The focus has shifted toward materials that would consolidate friable wood effectively and impart structural security without affecting the paint layers. The wood identification part of the technical study informed our decision to use beech wood veneers to replace areas of loss, as this material will have the same mechanical properties of adjacent layers.

Consideration for how far to take the conservation treatment of the Horten is informed by the curator’s interest in exhibiting it in an unrestored, but stabilized state and allowing it to show its age, history, and character. Extant paint and the original plywood skin will be preserved while we aim to stabilize these materials to impart a cared for appearance. Various camps of aircraft enthusiasts will have differing ideas about how they think the Horten should look, although there is a growing trend to exhibit unrestored aircraft. The public links ideas of authenticity with the concept of irreplaceable, which is what

the Horten is. We hope the level of study applied to understanding the original historic materials of this aircraft will encourage similar research on other unrestored technological artifacts.

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## SOURCES OF MATERIALS

### Micro-Mesh Cushioned Abrasives

Micro-Surface Finishing Products, Inc.

1217 West Third St.

PO Box 70

Wilton, IA 52778

[www.micro-surface.com](http://www.micro-surface.com)

### Clear Casting Resin

Douglas and Sturgess, Inc.

1023 Factory St.

Richmond, CA 94801

[www.douglasandsturgess.com](http://www.douglasandsturgess.com)

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